



FROM TECHNOLOGY TO MARKET

AR/VR 2025 From Optics and Displays to Advanced Sensing and Processing

Market and Technology Report



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AI : Artificial Intelligence	LBS : Laser Beam Scanning	VAC : Vergence Accommodation Conflict
ALS : Ambient Light Sensor	LCD : Liquid Crystal Display	VHG : Volume Holographic Grating
APD : Avalanche Photodiode	LCoS : Liquid Crystal on Silicon	VR : Virtual Reality
APU : Application Processing Unit	LLM : Large Language Model	WG : Waveguide
AR : Augmented Reality	MEMS : Micro-Electro-Mechanical Systems	
AVP : Apple Vision Pro	NIL : Nano-imprint Lithography	
BLU : Backlight Unit	NIR : Near Infrared	
BOM : Bill of Materials	OEM : Original Equipment Manufacturer	
CMOS : Complementary Metal-Oxide-Semiconductor	PIN : P-type / Intrinsic / N-type Diode	
CPU : Central Processing Unit	PMIC : Power Management Integrated Circuit	
DLP : Digital Light Processing	PPD : Pixel per Degree	
DOE : Diffractive Optical Element	PVG : Polarization Volume Grating	
DoF : Degree of Freedom	ROE : Reflective Optical Element	
EMG : Electromyography	SLM : Spatial Light Modulator	
FoV : Field of View	SPAD : Single-Photon Avalanche Diode	
HOE : Holographic Optical Element	SRG : Surface Relief Grating	
IMU : Inertial Measurement Unit	ToF : Time of Flight	



IDENTITY CARD

What will you find in this report?

Markets

- Automotive & Mobility
- Defense & Aerospace
- Industrial
- Medical
- Mobile & Consumer
- Telecom and Infrastructure

Frequency update

- Quarterly
- Yearly

Systems tracked

Augmented Reality glasses
Smart eyewear
Virtual Reality headsets
Augmented Reality headsets

Technology

LCoS	APU
MicroLED	Event-based
OLED-on-Si	3D imaging
LBS	MEMS
DLP	CIS
LCD	IMU
MiniLED	e-compass
DOE (SRG)	Microphone
HOE (VHG)	
ROE	

Depth analysis

System
Module
Sub-module
Component
Process
Wafer
Material
Equipment

Key metrics

2020-2025-2030
Timeframe

Players

Trends

Units

Value

Wafer

Market shares

Supply chain

Strategy

Financial analysis

Business news

Technology status

Technology Roadmap

Quick summary

This report provides an in-depth analysis of Augmented Reality (AR) and Virtual Reality (VR) applications in headsets, with a specific emphasis on display and optical technologies but also adding views on computing and sensing means

Key Features

- AR and VR devices 2020-2030 forecast
- AR technology roadmap
- VR technology roadmap
- Identification of the key bottlenecks in terms of energy and price
- 2020 -2030 Computing chips market forecast
- 2020 – 2030 Sensing modules forecast for AR and VR with a taxonomy of products breakdown
- 2020 – 2030 Display for AR and VR market forecasts
- 2020 – 2030 optics for AR market forecast
- Main players strategy analysis



- Yole has been covering the Augmented and Virtual Realities fields since 2018. However, our analysis has consistently focused primarily on displays and optics—critical components of the design, at the core of the user experience, and the main sources of technological bottlenecks and challenges.
- Nevertheless, these devices also integrate other modules essential to delivering the intended user experience. As use cases become clearer—largely thanks to AI—and as the market begins to show early signs of validation, such as the sales volume of Ray-Ban Meta smart glasses, we felt adopting a more comprehensive approach to analyzing these devices was relevant.
- While we continue to assess display and optics technologies competing to address this market, we now also consider them in the context of an overall device budget in terms of weight, power consumption, and cost—key factors shaping the future of these devices. Thus, we have integrated sensing modules and computing chips into our analysis and quantitative forecasts.
- As the considered market matures, its segmentation becomes clearer, and we revise our own accordingly to better reflect the reality of the product taxonomies in play. Each type of offering is associated with a tailored mix of technological solutions and follows its market dynamics.



- This report aims to provide readers with a clear overview of the different product taxonomies within the AR and VR fields.
- It seeks to establish a link between technological advancements and the user experiences they enable.
- For these experiences and related devices, the report explores the targeted markets and their growth dynamics. These markets are analyzed in terms of size and segmented by end systems (headsets, glasses), and modules.
- The growth of AR is closely intertwined with technological advancements, particularly in displays and optics. This report identifies key bottlenecks, major challenges, and the strategies employed to address them.
- Market players come from various world regions, differ in size and positioning, yet all contribute across the supply chain. This report outlines who is doing what and highlights partnerships, relevant collaborations and competition.



Yole's market forecast model is based on the matching of several sources:

Comparison with existing data
Monitoring of corporate communication
Using other market research data
Yole analysis (consensus or not)

Comparison with prior Yole reports
Recursive improvement of dataset
Customer feedback

Preexisting information

Top-to-bottom approach
Aggregate of market forecasts
@ System level



Market
Volume (in Munits)
ASP (in \$)
Revenue (in \$M)

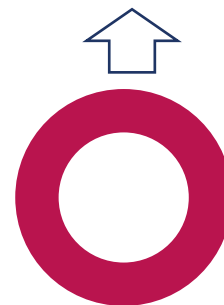


Bottom-up approach
Ecosystem analysis
Aggregate of all players' revenue
@ System level

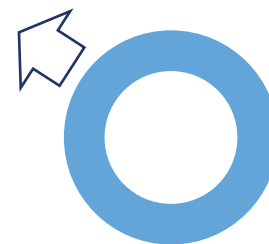
Primary data

- Reverse costing
- Patent analysis
- Annual reports
- Direct interviews

Top-to-bottom approach
Aggregate of market forecast
@ Semiconductor device level



Semiconductor foundry activity
Capacity investments and equipment needs



Bottom-up approach
Ecosystem analysis
Aggregate of key players' revenues
@ Semiconductor device level

Secondary data

- Press releases
- Industry organization reports
- Conferences

Information Aggregation

COMPANIES CITED*



3D Micromac, AAC, ACW, AddOptics, AdHawk, AGC, Aledia, Alibaba, Amazon, Ambarella, ams OSRAM, Analog Devices, Anduril, Ansys, Apple, Applied Materials, Asia Optical, ASML, A-Star, AUO, Avegant, BOE, Bosch, Brilliant Labs, Brillnics, Broadcom, ByteDance, Cellid, Cirrus Logic, Coherent, Corning, Critical Manufacturing, Delo, Digilens, Diodes Incorporated, Dispelix, eMagin, Emteq labs, Engo, Epson, EssilorLuxottica, Eulitha, EV Group, Even Realities, Foxconn, GIS, GlobalFoundries, GML, Goertek, Google, Himax, Hoya, HTC, Huawei, Infineon, Inkron, INMO, Innolux, Innovision, Jabil, JBD, JDI, JSG, Knowles, Lenovo, LightTrans, Lumens, Lumileds, Luminit, Luxexcel, Luxshare, Lynx, Magic Leap, Meizu, MEMSensing, Meta, Micledi, Micro Resist Technology, Micron, Microoled, Microsoft, Mitsui Chemicals, MojoVision, Morphotonics, Moxtek, Murata, Myrias, Nano Scribe, NIL Technology, Nokia, NS Nanotech, NSC, Nuvoton, Nvidia, Ohara, Omnivision, OpenAI, Oppo, Oqmented, Oxford Instruments, Pico, PlanOpSim, Plessey, Porotech, Prophesee, Q-Pixel, Qualcomm, Quanta Computer, Raith, Raontech, Raysolve, Renesas, Rokid, Rohm, Samsung, Saphlux, Sapien Semiconductors, Schott, SCIA systems, SCIL, Scivax, SeeYa, SEMISIC, Senodia, Shiftall, SICC, Sidtek, Siemense, SK hynix, Skyworks, Snap, Soft-Epi, Solnil, Sony, ST Microelectronics, Sumitomo Chemical, Sundiode, Sunny Optical, SÜSS MicroTec, Swave, Synopsys, TankeBlue, TCL CSOT, TCL RayNeo, TDK, TDK Invensense, Teckscend Photomask, TEL, Tencent, Texas Instruments, Tobii, Tooz, TSMC, Ultraleap, USI, Varjo, Veeco, Vivo, Vuzix, WaveOptics, Windbond, Wolfspeed, Xiaomi, Xreal, Zeiss, Zenni and more.

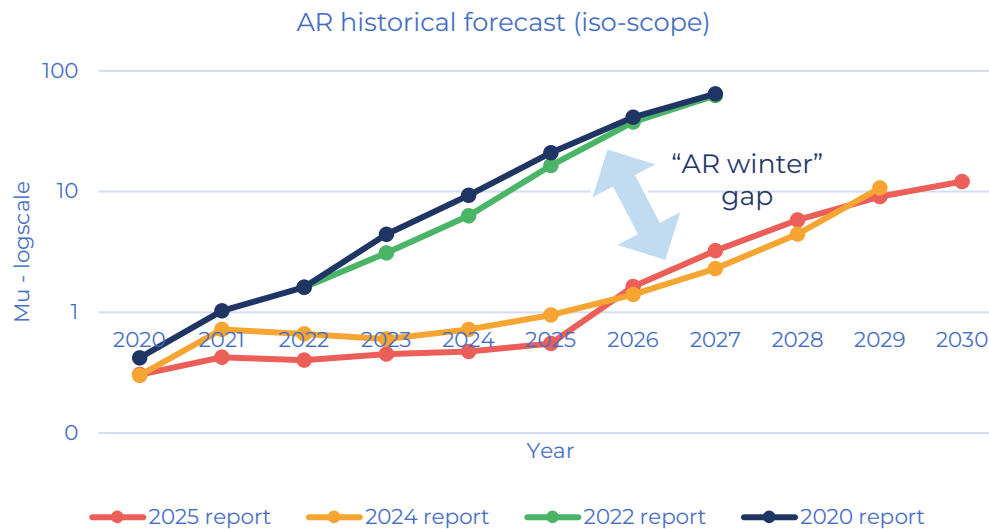
*non-exhaustive list

WHAT WE GOT RIGHT, WHAT WE GOT WRONG



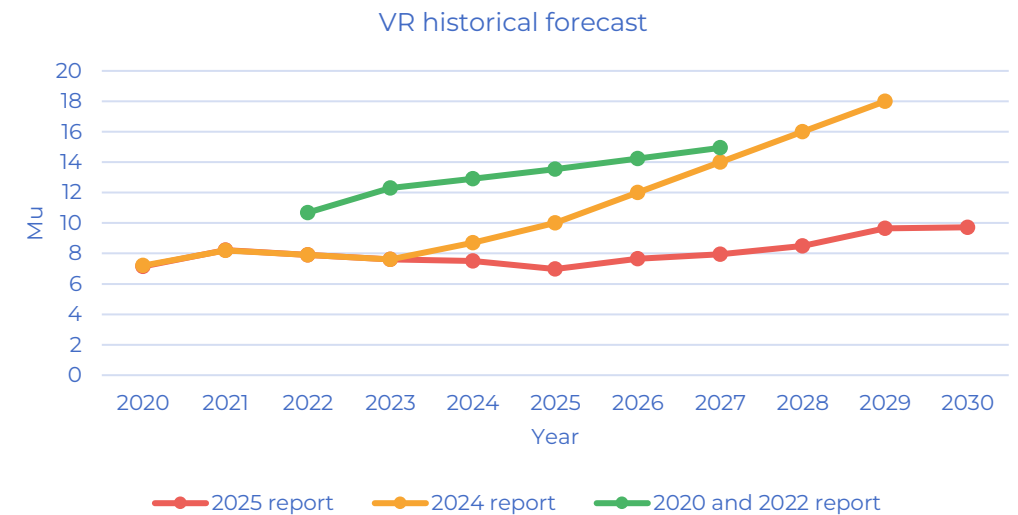
What we got right

- In the field of consumer AR, the microLED and DOE (or SRG) couple is still considered as a promising solution
- We have seen evidences of AR benefitting from the hype around AI
- The VR market is bigger than AR one but should keep being a niche while AR is at the core of the tech giant strategies and prove it has better potential to fit with consumer market
- An inflection point in AR market should occur before 2028. Green light signals and giants roadmaps are confirming



What we got wrong

- LCoS moment in AR may be narrowed and delayed compared with our expectations
- We overestimated the positive impact Apple's involvement would have on the VR market – particularly its high-end segments



3 PAGE SUMMARY



MARKET SUMMARY

AR and VR, as markets, will have two very different dynamics

- The VR market is expected to hit saturation around the **10 million units annually**. Despite Meta's effort and Apple's recent legitimization of the devices via a new marketing approach, such range of devices still fails to appeal enough to consumers and spread.
- AR has much more potential to meet a real market ignition. We estimate that those wearables are much more poised to trigger *FOMO*. We should now consider smart eyewear as a continuum of products will be offered from audio only to more and more immersive/interactive solutions. We expect **the smart eyewear market to reach around 15 million units by 2030, and we project the solutions with a display to account for about 85% of that total in 2030**.
- Therefore, we expect the **AR and VR markets will experience very different dynamics with respectively 45% and 4% 2024-2030 CAGR (in terms of units)**. It is a matter of maturity, VR is already there, while AR still has to ignite, but it is also a matter of the very nature of the market being targeted.
- The VR market is essentially revolving around gaming and professional use cases. AR did target professional use cases with former generations of products, but technologies are getting ready (in terms of performance and scalability) to address consumer audiences now. With consumer AR, the targeted market is eyewear and what we call smart eyewear should represent a significant part of it. As part of this market, fashion aspects are critical, and the brands will play an important role in the wide adoption. Except the aesthetic aspect, the value proposition of such electronics embedding glasses is AI. Through 2023 and 2024, many OEMs even rebranded their smart glasses or AR glasses as AI glasses. Ultimately, what is sold is no longer a device but the physical interface with an LLM.
- Such **link between AR and AI** is key to understanding both the rapid adoption we anticipate and the siloed nature of markets that will emerge. Indeed, the front runners of both LLMs and smart eyewear devices are tech giants from the **US** (Meta, Google) and **China** (Xiaomi, Tencent, Alibaba). Access to these services could be restricted, and ongoing trade tensions and tariffs might further encourage a more domestic supply chain tailored to specific geographic markets.



SUPPLY CHAIN SUMMARY

AR and VR Supply Chains: Two Distinct Biomes, One Set of OEMs

- For both AR and VR, downstream the supply chain, the OEMs are the same: consumer electronics giants like **Apple, Google, Samsung, Xiaomi** but also newcomers in the field of hardware like **ByteDance** and more importantly **Meta**.
- That being said, the nature of AR and VR ecosystems (technology bricks providers) is essentially related to the maturity of the technologies needed.
- VR relies on proven technologies but but the emergence of new solutions still conditions AR's success. Most VR modules are manufactured by large companies that are well-versed in assembling and manufacturing of technological building blocks that have become almost commoditized (LCD, Fresnel lenses and pancake lenses are a good illustration).
- On the other hand, the AR ecosystem is typical of a market that hasn't emerged yet. Many technologies, sometimes incompatible or competing, are investigated simultaneously. This exploration is ensured by start-ups mainly. To illustrate this, we can mention tracking technologies where **NILT, Prophesee** and **AdHawk** develop different approaches to a similar purpose. The same can be said about waveguide optics, where different players consider several options (both in terms of manufacturing and materials). In the end, this phenomenon is the most obvious in the field of microLED micro display for AR. Indeed, this self-emissive technology is poised to become the standard. Still, it is not ready yet, and many players intend to solve challenges differently (**Porotech** with their proprietary DPT, **Aledia** with nanowire arrays, **JBD** and **Q-Pixel** with vertical stacking, to name a few).
- This rich and wide-ranging exploration is likely only possible thanks to Meta's unwavering commitment. Indeed, **Meta Reality Labs' loss is about 4 to 5 billion dollars a quarter**, and a significant amount of that is very likely to be injected into this ecosystem. The image we can use to describe **the current landscape of start-ups is a garden tended by Meta's dedication to make AR happen. Meta cultivates many species there, but the final bouquet it offers for consumers will include only a select few, leaving many others by the wayside.**
- To materialize, the AR market requires breakthroughs driven by new technologies. However, in the long run, suppliers from more mature markets—such as the smartphone industry—will also play a key role. This includes sensing specialists like **Bosch, Texas Instruments, ams OSRAM, and STMicroelectronics**, as well as computing players such as Qualcomm. Lastly, traditional eyewear companies, with **EssilorLuxottica** at the forefront, will be instrumental thanks to their experience and established presence in the field.



TECHNOLOGY SUMMARY

The dualities of AR and VR: Headsets for depth, Glasses for daily AI integration and style

- The devices covered in this report can be divided into **two groups**: Those aiming to deliver a **fully immersive experience** to niches — meaning almost no compromises in terms of weight, aesthetics, or form factor (and sometimes even price); and those targeting mass adoption with a clear value proposition: **allow all day long wearability while offering a seamless interface between the user and an AI**.
- In the first case, we refer to **headsets**, which can be equipped with a multitude of modules and large batteries (like the Quest 3). In the second, we refer to **glasses**, for which designers must cleverly reduce or eliminate certain modules so as not to compromise **weight or energy budget** (like the battery capacity of the Ray-Ban Meta).
- **Displays are crucial in the user experience in both cases** but the criteria by which they are evaluated differ. The best example is **OLED-on-Si**, which is the optimal technology for VR but completely unsuitable for AR due to its low brightness (< 100,000 nits). This lack of brightness is a major issue because **waveguide-based optics**, the use is a given due to their slim form factor, lightness, and scalable manufacturing processes, offer **very low optical efficiency** (<1%). Such constraints put therefore a lot of constraints on the display engine which should deliver enough brightness without having it's form factor neither its power consumption scaling to much. Due to these set of requirements, LCoS and MicroLED are poised to battle up for the coming years as they can deliver **millions of nits within less than 1cc**. LCoS must be adopted for first generations of products, but **MicroLED is the ultimate choice before moving to volumetric AR** (requiring then **SLM-based display engines**). In the field of MicroLED, many approaches are currently investigated to reach the right level of performance and achieving RGB. Hard to know which one will be succeeding to cross threshold level of performance, and after that will come the question of price.
- **AR because of its very ambitious purpose and constraints will be pushing the boundaries of semiconductor processes and architecture on both displays, processing and sensing.**

EXECUTIVE SUMMARY

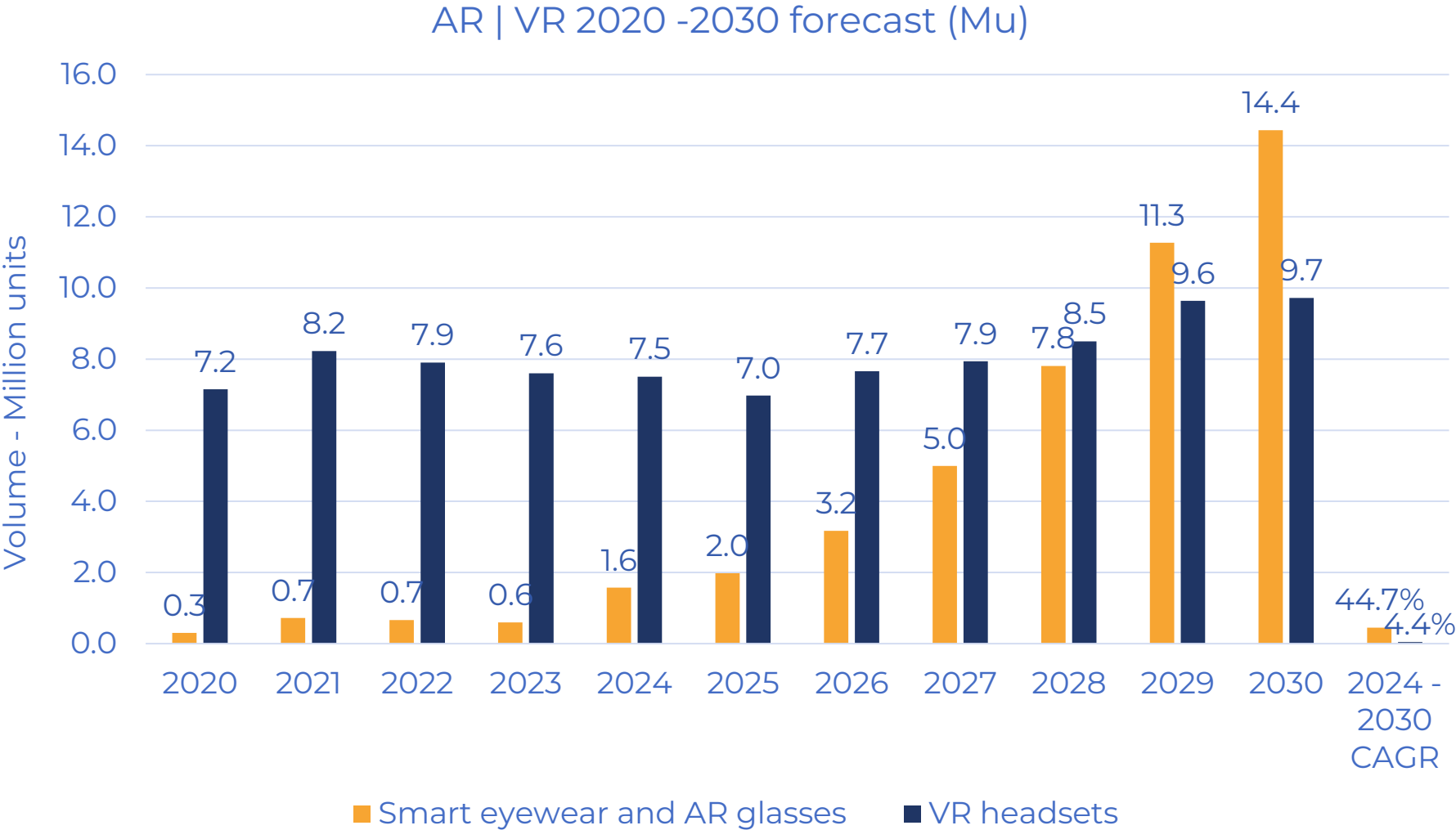


EXECUTIVE SUMMARY

AR and VR 2020 – 2030 market forecasts (Mu)

- We have been observing:
- Meta didn't succeed at making VR a mass consumer electronics market
 - Neither Apple (with a \$3,500 device though)
 - Audio only (Ray-Ban Meta) sent a green light signal for the upcoming AR (as smart eyewear with a display in it) market

- We expect:
- VR will meet a glass ceiling around 10 Mu/year before 2030.
 - Smart eyewear is poised to trigger FOMO, address pain points and grow exponentially. 10 Mu/year to be crossed before 2030



EXECUTIVE SUMMARY

The 3 aspects of AR glasses design



These three phases can help us approach the design of AR glasses.



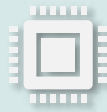
A pair of glasses remains a pair of glasses even enhanced with embedded electronics. It is therefore a fashion asset and must appeal to consumers as such. **AI functions are as used as they are stated to be used.**



We can expect the OEMs to compete within the visual experience with larger and larger FoV, crisper and crisper resolution and saturated colors but in a second time.



The glasses must deliver the use cases associated with the devices. This means it should be possible to use it for all day long under every or most lighting conditions for different purposes. This forces the modules to be individually highly optimized and the overall system to leverage synergies to save energy and power consumption as much as possible. Ultimately, the operating system, app ecosystem and the hardware contribute equally to the user experience.



The last part of AR design depends on the business model. For the OEMs, there is a chance it will only be about selling the glasses. App, services and AI-subscription will be the core of the glasses-related revenue stream. We can also imagine that the tracking of the user will matter somehow. It is the current business model of Meta which is also the most prominent player in AR. Sensors to track the gaze could also be used to track one's emotions, which is a valuable data when the context is known in parallel.



Image: Tobii

Make it appealing...

Make it work...

Make it pay off

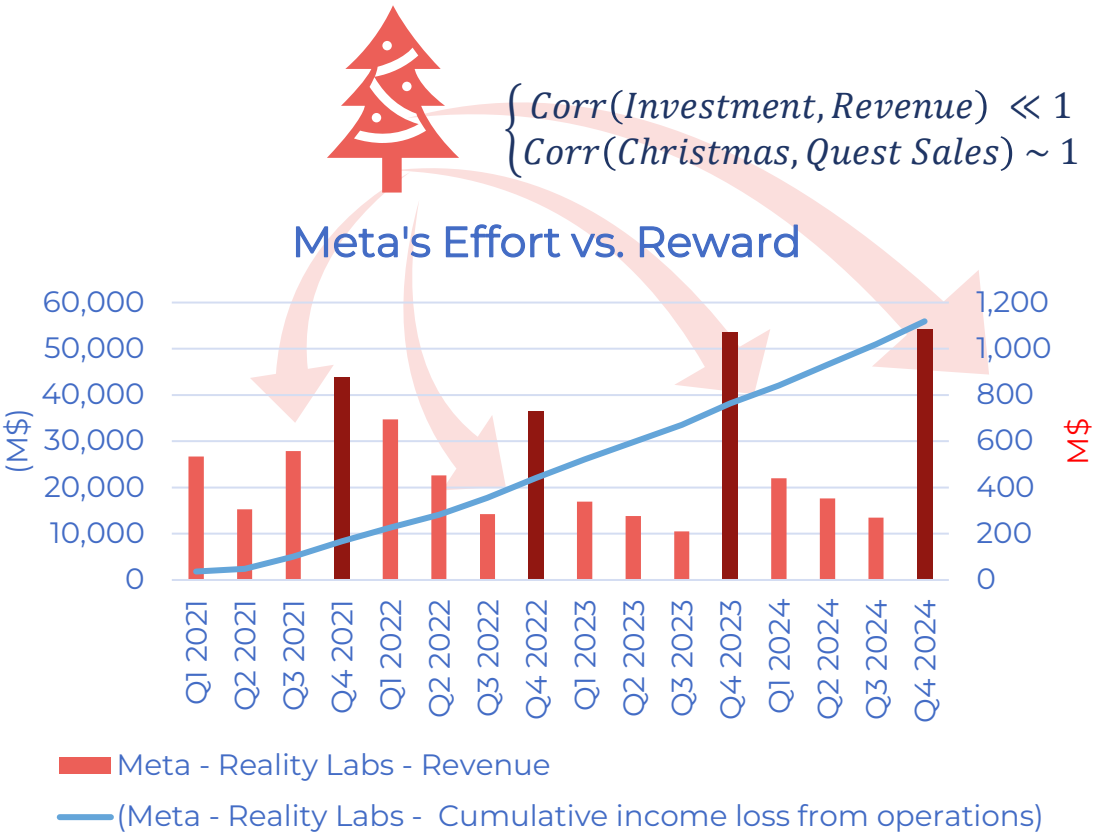
Volumetric, sticking virtual objects and large FoV could motivate the use of eye trackers and other sensing modules to better render the content



EXECUTIVE SUMMARY

What does the long-term Meta's involvement reveal?

- Meta's investment in AR and VR, which can be accounted for as the Reality Labs operating loss, remained constant over time and reached **\$56B by the end of 2024**.
- Such consistency underlines Meta's long-term ambitions, but the Quest series fails to fulfill them.
- This path of suffering must precede a strong payoff that only a smart eyewear product range can offer.
- Indeed, smart eyewear is a more promising market in terms of size, with better potential to spread. **A product designed to be worn all day and used as an interface between the world and its user seems to be the ultimate piece of hardware to serve Meta's interests.**
- Meta exhibits a strong ambition, which is a given for the industry, but the remaining question is: When will the inflection point occur? And as Meta is the figurehead of AR, **when will Mark Zuckerberg appear on stage with a consumer product closer to the consumer expectations, with a display in it?**





Where it intend to penetrate:

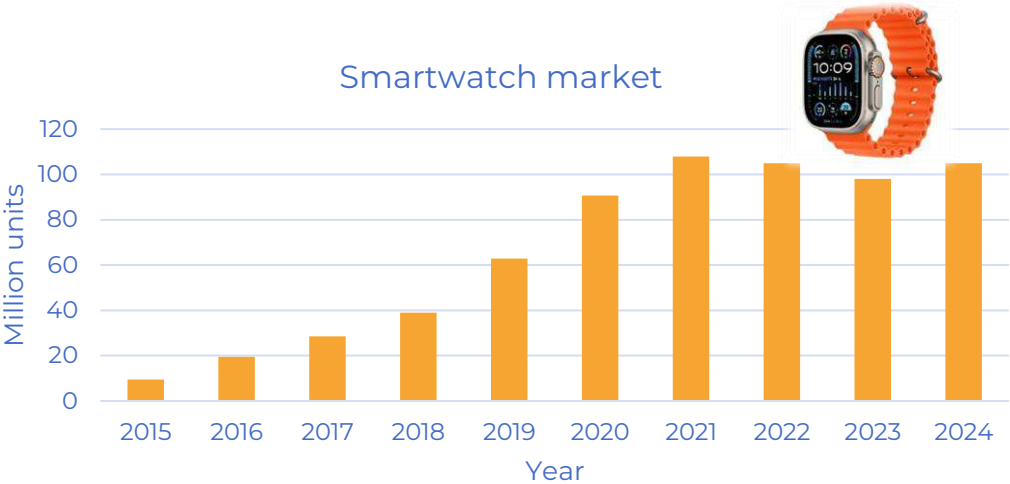
AI enthusiasts should be the first to adopt those glasses. It is definitely the value proposition behind the hardware: it is the service. The embedded electronic-like sensing modules and computation power should support the AI assistant's operation; the other parts, like display and speakers, will be there to materialize its presence and enable interactions. Ultimately, the devices will be seen and sold as a bridge to “superpowers”. The new AI-enabled skill sets have a strong potential to convince new adopters, as the chart below advocates:



The global eyewear and eyecare market is worth \$120B (price to consumer) according to EssilorLuxottica and Euromonitor. To penetrate this very market, a technical solutions must be found to integrate prescription without prohibitive frictions or loss of comfort for the users.

What it looks like:

Let’s be clear, unlike VR, consumer AR glasses we expect will compose most of the market will be meant to be worn all day by users and worn on the face. It is not just consumer electronics; on the one hand, it will be mainly fashion, a visual asset, a statement. There are not many equivalents in electronics devices like this one. It’s true that the smartphone is now a status good (for some at least), but the exponential growth of the smartphone market was also due to gathering so many features into one device. These are things that glasses could achieve, but not before matching a much better level of performance than what is targeted today. An obvious example that is good to think of is a watch. Not necessarily a smart one, but watch in general where the brands matter and luxury is very present. Like the smart glasses pushed by Meta a lot, the smartwatch was developed by Apple, and a few players share the market. It makes the Smartwatch market very similar to smart glasses: a market which grew very fast before reaching a ~100 million units volume in 2020



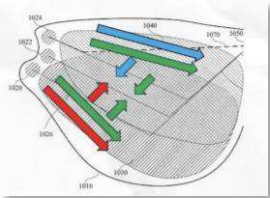
EXECUTIVE SUMMARY

AR adoption life cycle



Here we are: An exploration phase of possible use cases via LLM interfacing.

Sensitive to the technological solution itself.



Techies

1st Crack

YOLE Group

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2025-05-13 00:22

Sensitive to the use cases being AI-agent. The rebranding of AR glasses experienced in 2024 is consistent with the address of the visionaries' market



Visionaries

The Chasm

The engines of adoption easing:

- Price must go down
- Form factor and weight should shrink
- Friction should be reduced via agreement with classical eyewear supply chain and distribution

Sensitive to compelling and proven use cases. At this point, what is sold is a complete solution including hardware, software and brand—for this segment, referencing matters a lot. It means that the majority of members (rather than Pragmatists or Conservatives) refer to other group members. This causes organic growth in early markets like Techies and Visionaries to stop. A new communication angle must be found, and well-known tech companies are more likely to succeed as they have already earned consumer trust.

The mature solution to be sold to the bulk of the market:

AI + OS

+

Brand

+

Trusted OEM

Ex: Gemini Android XR Ray-Ban BOLON Apple SAMSUNG Google Meta

Historical OEMs

Historical advertisers

Pragmatists

2nd Crack

Conservatives

Laggards

This last segment has no room in the time frame considered in this report. They will be not aware or even building arguments to discourage the use of such devices.

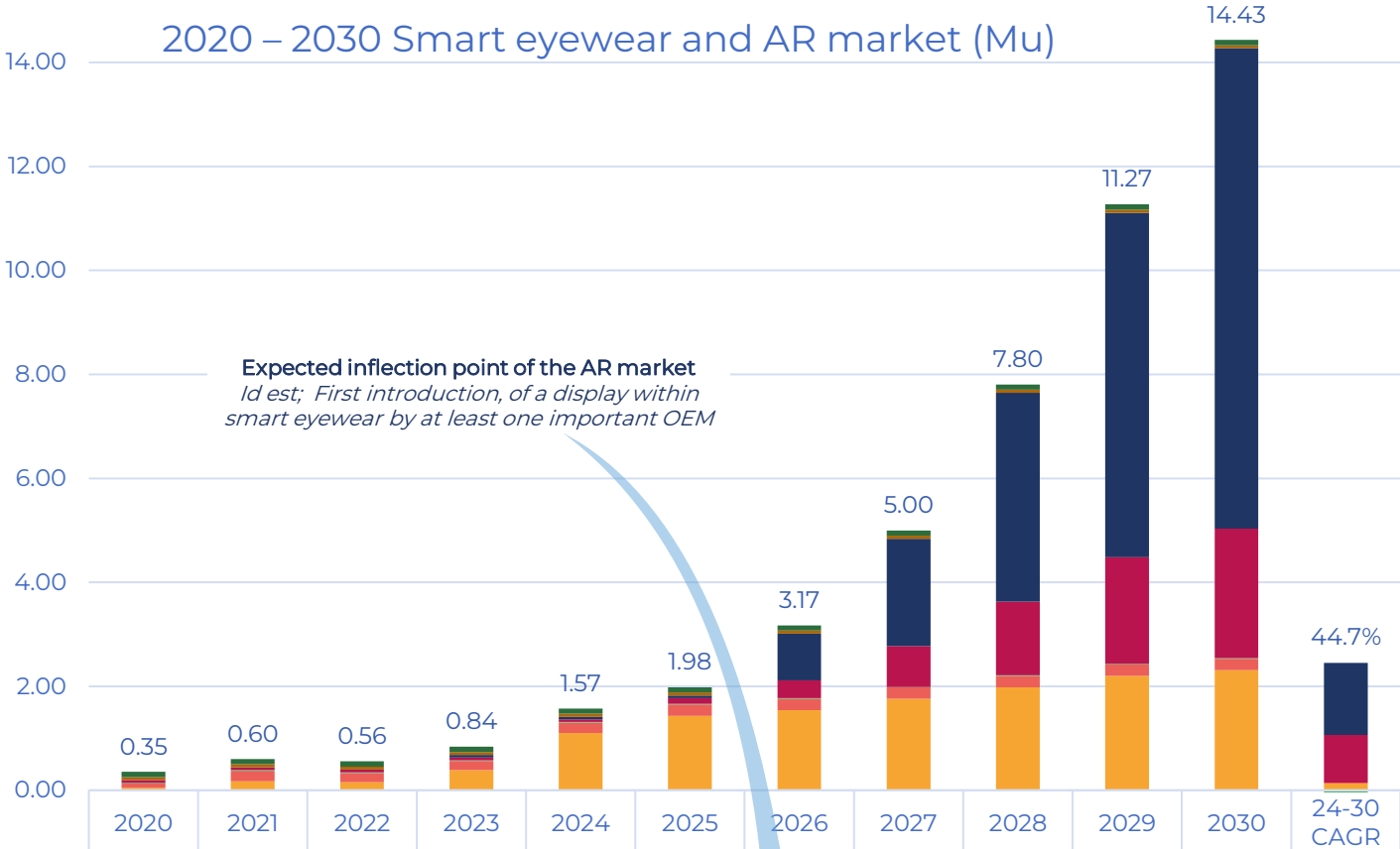


EXECUTIVE SUMMARY

2020 – 2030 Smart eyewear and AR market (Mu)

- This forecast takes a wide range of product into account: From audio (Ray-Ban Meta-like) only to large FoV birdbath-based with waveguide-based in between.
- In the long term, we can expect the waveguide-based solution to dominate (AR, entry, AR Mid to High-end) as it improves the HMI and make the solution more consistent and consumer compliant. Yet, the audio-only should benefit from their current strong momentum and keep representing a significant proportion.
- We expect birdbath-based glasses like XREAL to remain trapped within niche for indoor content consumption.

Volume - Million units



TOTAL	0.35	0.60	0.56	0.84	1.57	1.98	3.17	5.00	7.80	11.27	14.43	44.7%
Others	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.0%
Sport/Outdoor	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.0%
Consumer AR (Mid to High-end)	0.00	0.00	0.00	0.05	0.05	0.05	0.90	2.06	4.02	6.63	9.24	138.7%
Consumer AR (Entry)	0.05	0.05	0.05	0.05	0.05	0.11	0.35	0.79	1.42	2.05	2.49	91.9%
AR for Professional	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	-6.5%
Birdbath-based	0.08	0.20	0.18	0.18	0.20	0.22	0.22	0.22	0.22	0.22	0.22	1.6%
Audio only	0.05	0.18	0.15	0.39	1.10	1.43	1.54	1.76	1.98	2.20	2.31	13.2%

EXECUTIVE SUMMARY

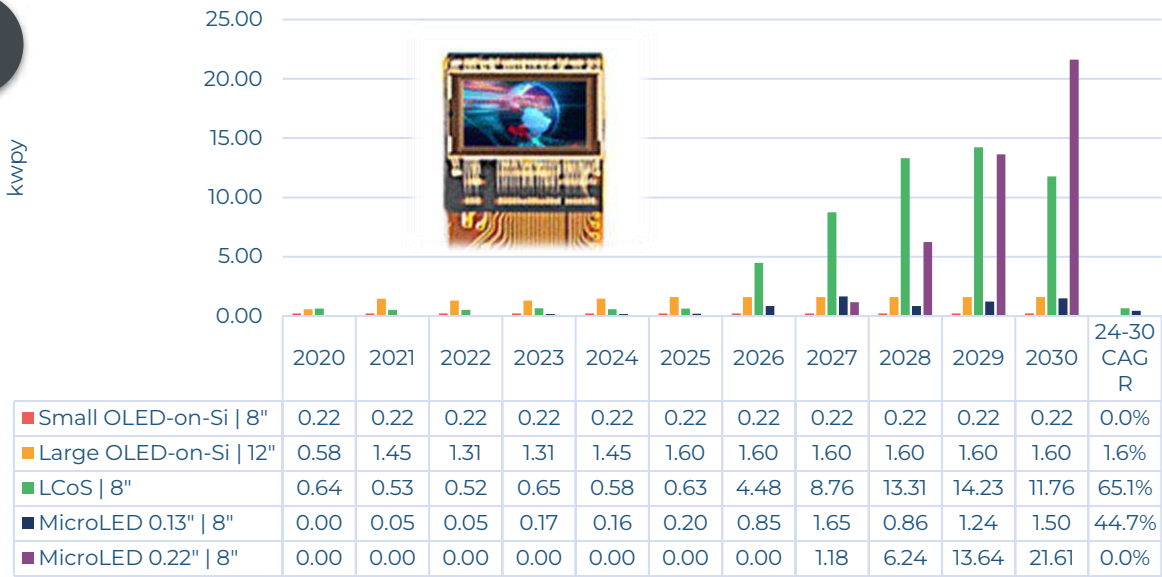
2020 – 2030 AR-related material usage forecast (kwpy)



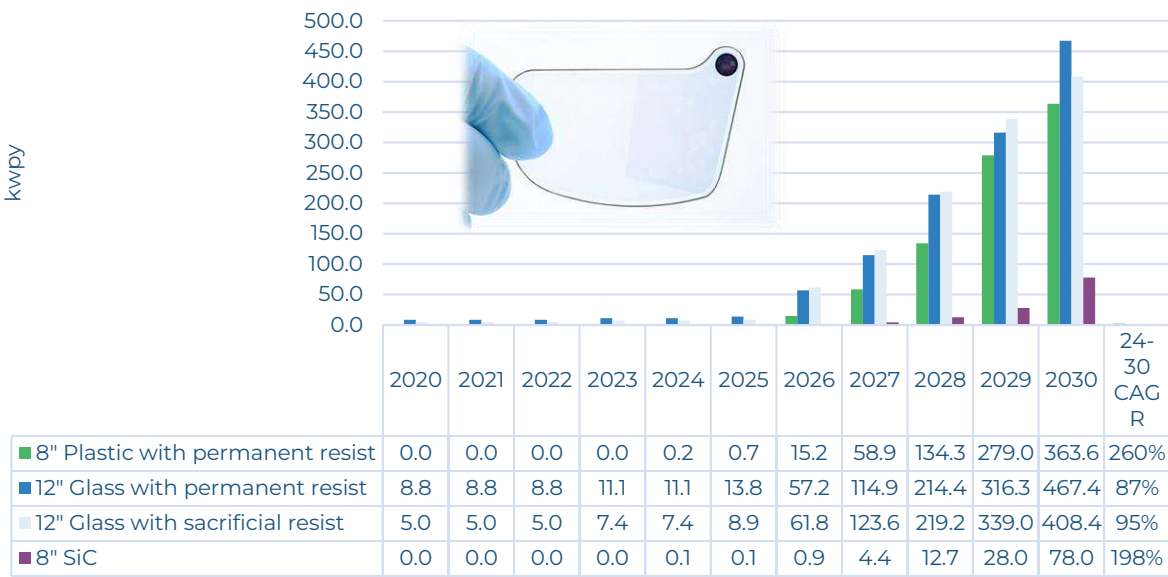
Si

kwpy

2020 - 2030 Wafer for AR microdisplay backplane forecast (kwpy)



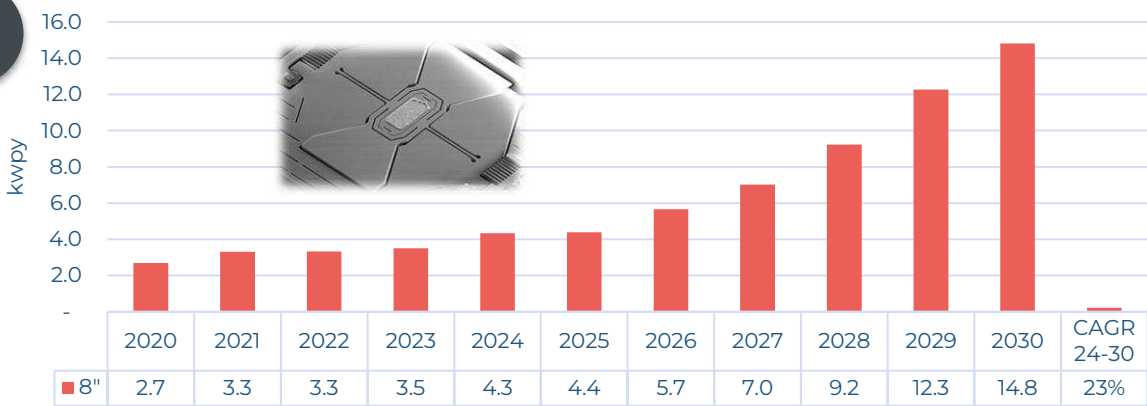
2020 – 2030 Raw wafers for AR waveguide forecast (kwpy)



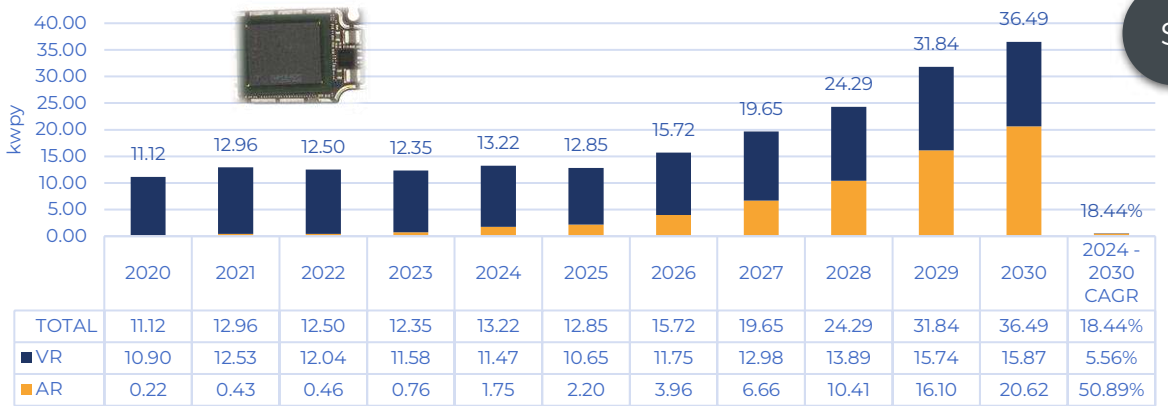
Si

kwpy

2020 – 2030 Wafer for MEMS sensing + ASIC for AR and VR forecast (kwpy)



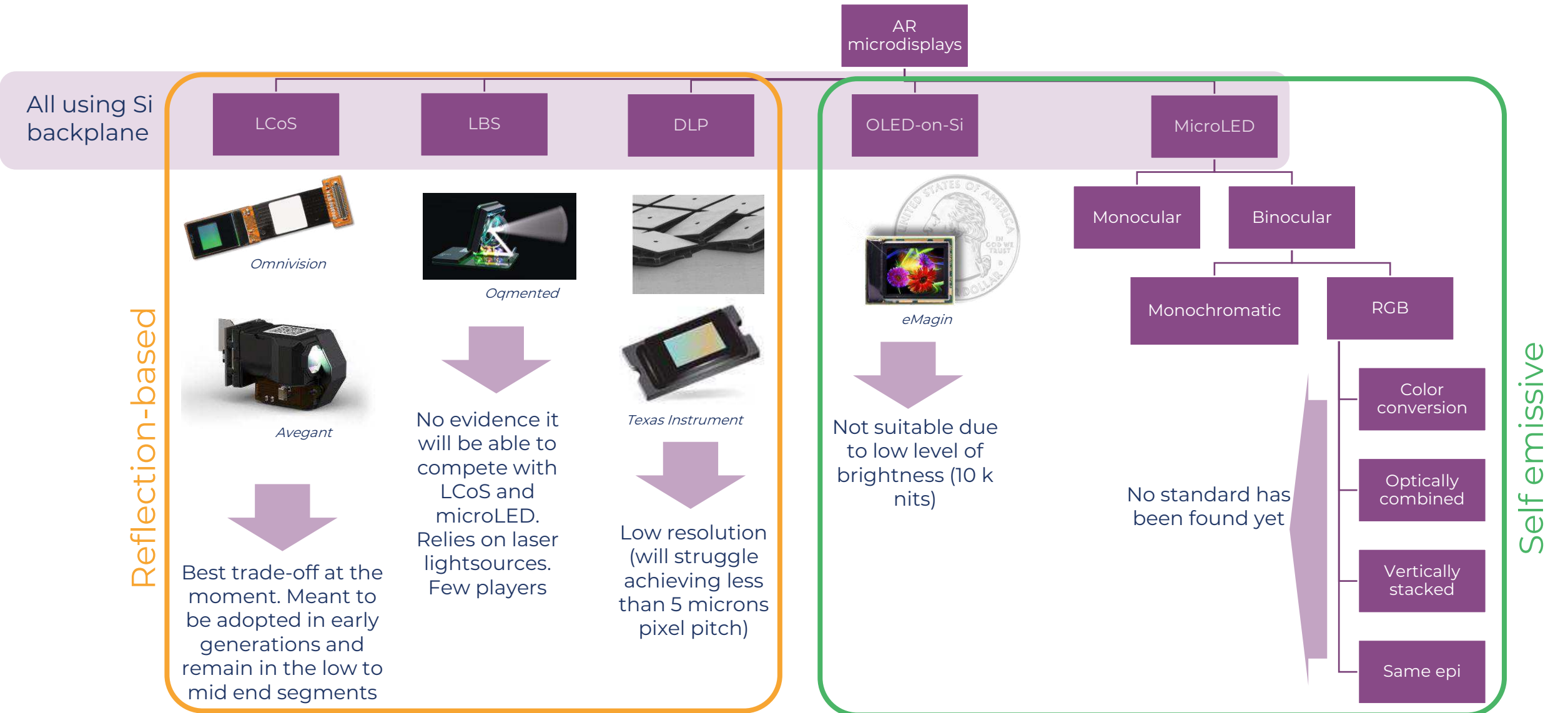
2020 – 2030 Wafer for computing for AR and VR forecast (12" - kwpy)



Si

EXECUTIVE SUMMARY

AR microdisplay technologies



EXECUTIVE SUMMARY

Micro display technologies history (Using waveguide-based optics)



HoloLens 1

MagicLeap 1

MagicLeap 2

Snap Spectacles 2024

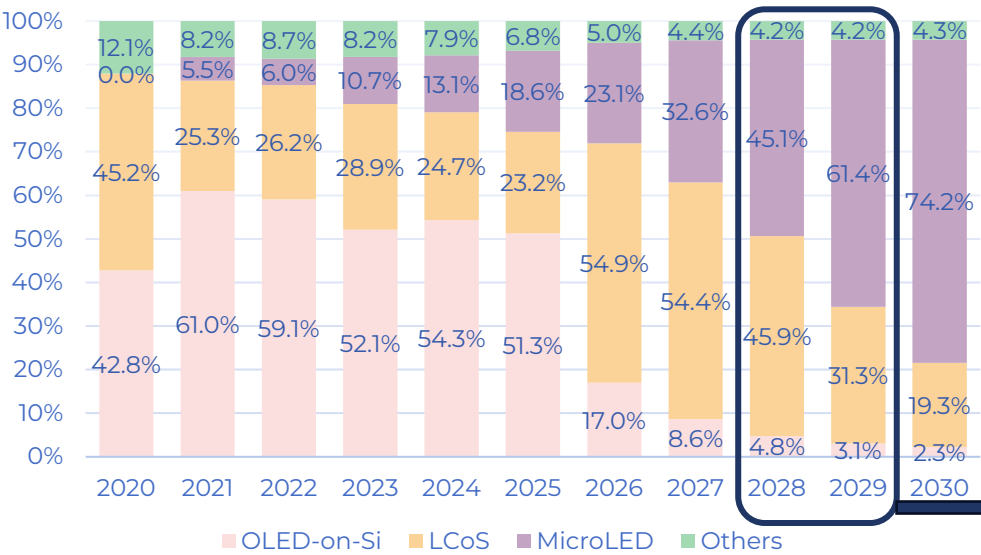
LCoS is by far the most proven solution and the technology offering the best trade-off between high brightness and a small form factor

HoloLens 2

North Focal

LBS is an interesting alternatives that could enable different architectures like North Focal or Covestro POCs. Yet it seems it has lost a lot of traction and may see its opportunity vanish in favor of MicroLEDs.

In the end, the laser-based projection engine could end up enabling phase modulation has LCoS and PCM players intend to do. (See emerging display technologies section of this report).



Vuzix Shield

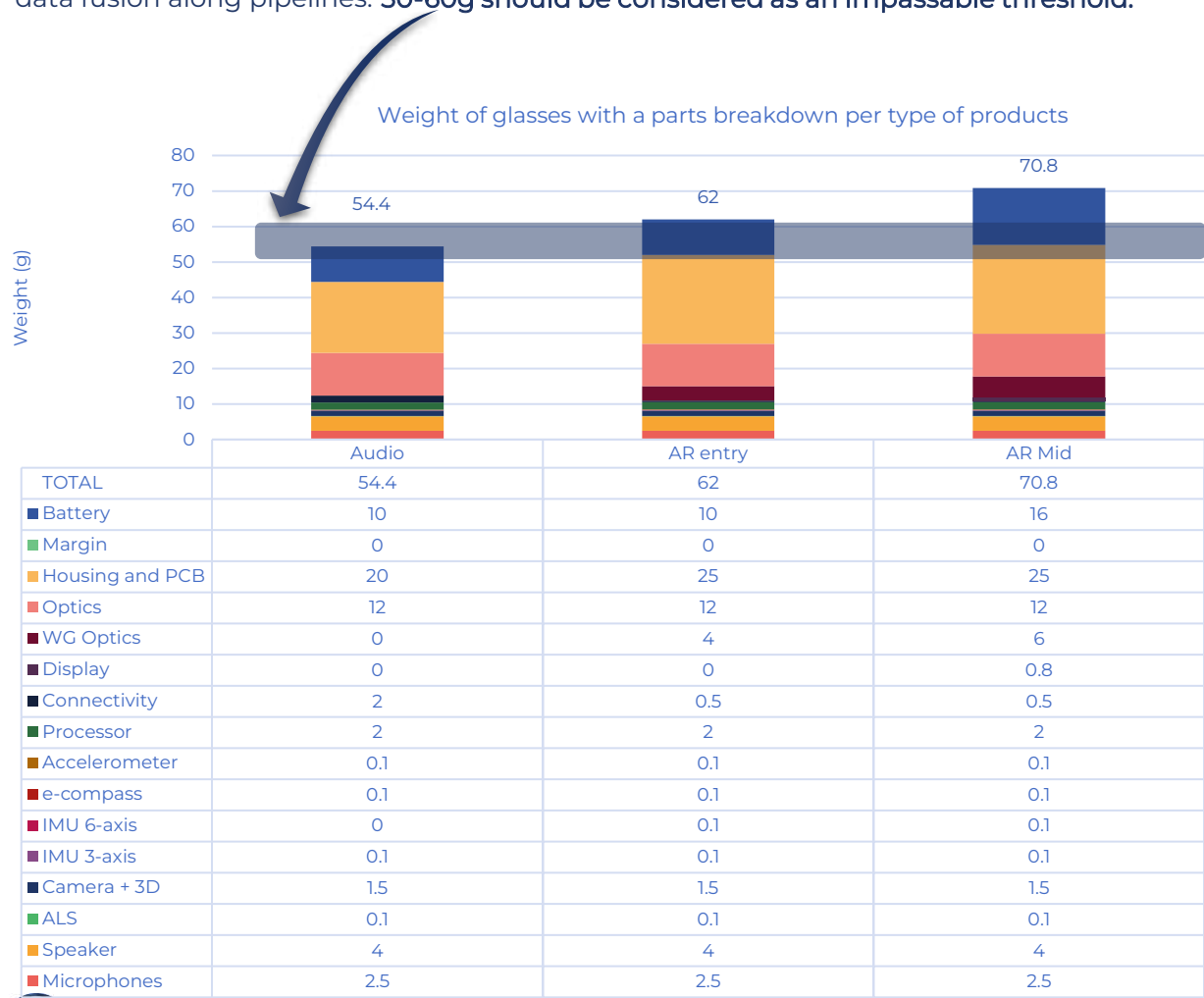
Even Realities G1

Ray Neo X3 Pro

MicroLED appeared as a product only from 2022 and still suffers from low maturity and narrow supply chain . Yet the OEMs are betting a lot on this technology which can be consider as pretty ideal on the time frame we consider

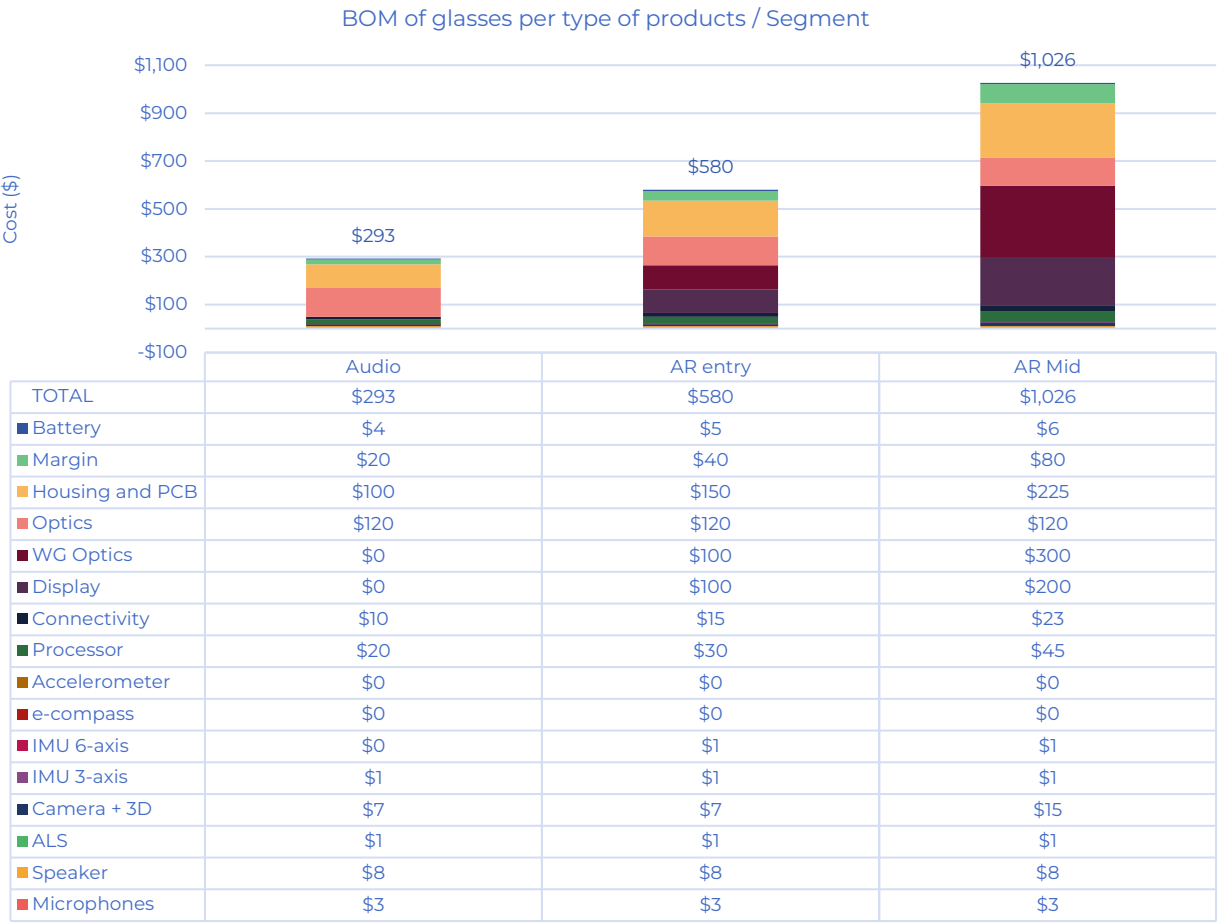
Thanks to tech giants' products releases, the proportion of LCoS (first in 2026- 2027) will grow significantly as the consumer AR opens. Then the shares should get equalized around 2028-2029.

As the number of modules increases, the packaging does too. More modules, for more functions mean more power consumption so bulkier batteries. The question of the weight is very critical. Design will include cannibalism of functions, particularly sensing and a relevant data fusion along pipelines. **50-60g should be considered as an impassable threshold.**



We can compare the cost structures on the right to existing products and perspectives:

- Audio → Ray-Ban Meta starting at \$329
- AR Entry → Even Realities G1 starting at \$699
- AR Mid → Meta’s CEO often positions the AR glasses with a display in the range of smartphone flagships (~ \$1,000)

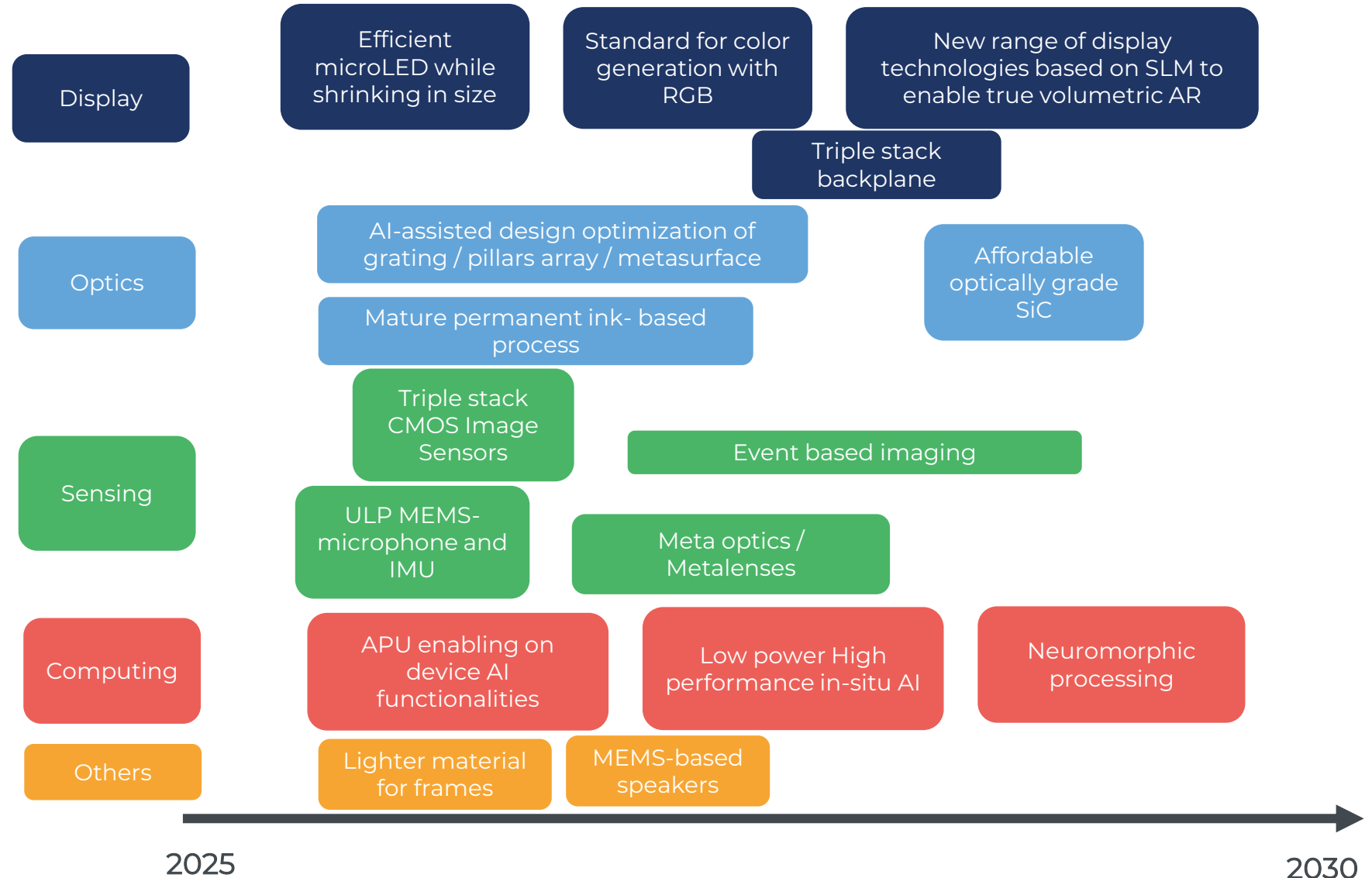




EXECUTIVE SUMMARY

AR - Breakthroughs by thematic roadmap

- The core motivation behind the innovations that AR needs is miniaturization. In the end, OEMs want as many features as possible to be embedded in their frames, as this will provide consumers with a compelling offer. **Reducing form factor, weight, power consumption and price will be the very main driver of innovations.**
- Also, we can think of a breakthrough in material manufacturing (affordable optically graded SiC) and display engines to enable a new and more appealing range of experience (volumetric AR) and maximize adoption.

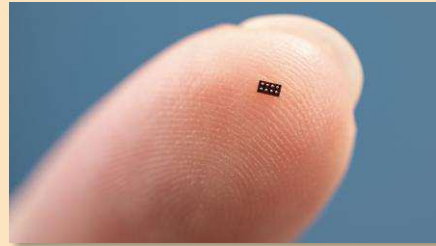


EXECUTIVE SUMMARY

Consumer AR: Where fashion, UX, AI and semiconductor technology join to make a new market happen

An engineering problem is matching specifications with technical/technological means. A marketing problem is making a given technical solutions accepted and appealing. With AR both dynamic are at work. Parts makers strive to shrink module to make them fit within as thin frame as possible, while designers promote bulier form factor.

Technological improvements



Texas Instrument



JBD

Fashion



Ray-Ban



Meta



Even Realities

At some point, making tech visible could be part of the aesthetic identity. It's already something claimed by the brand Nothing, praised by tech enthusiasts.

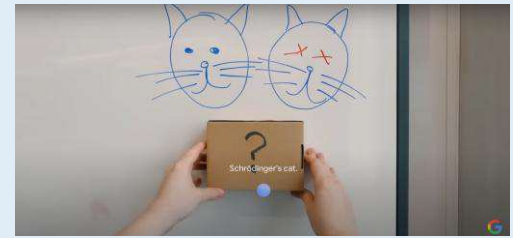
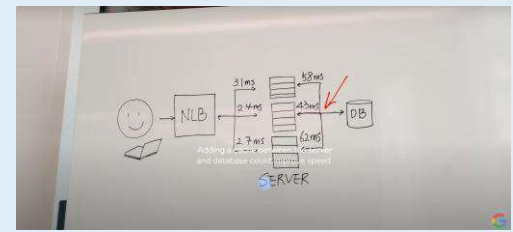
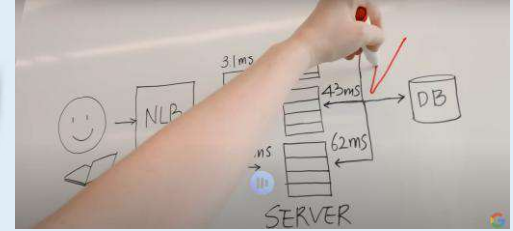


Nothing



Nothing

AI enabled use case and seamless UX

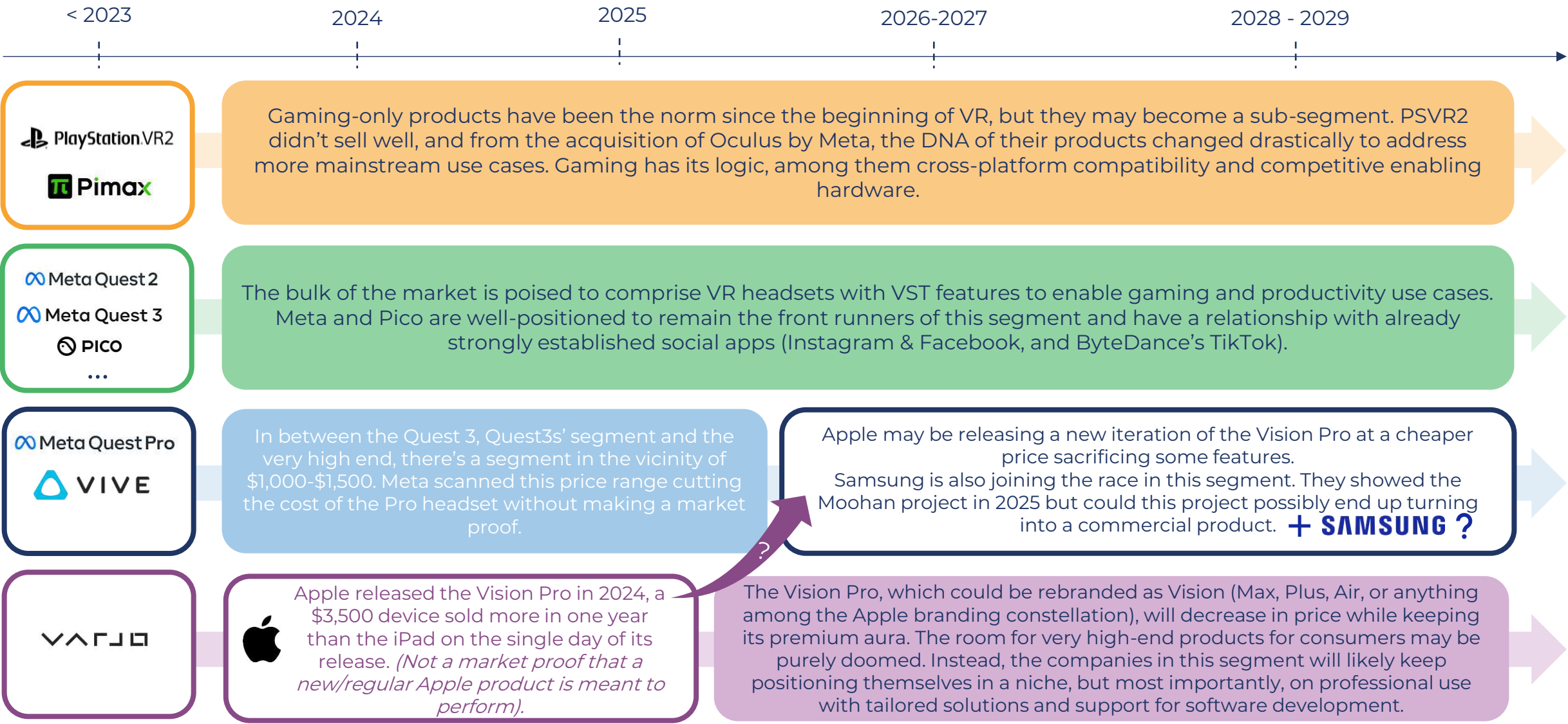


Google



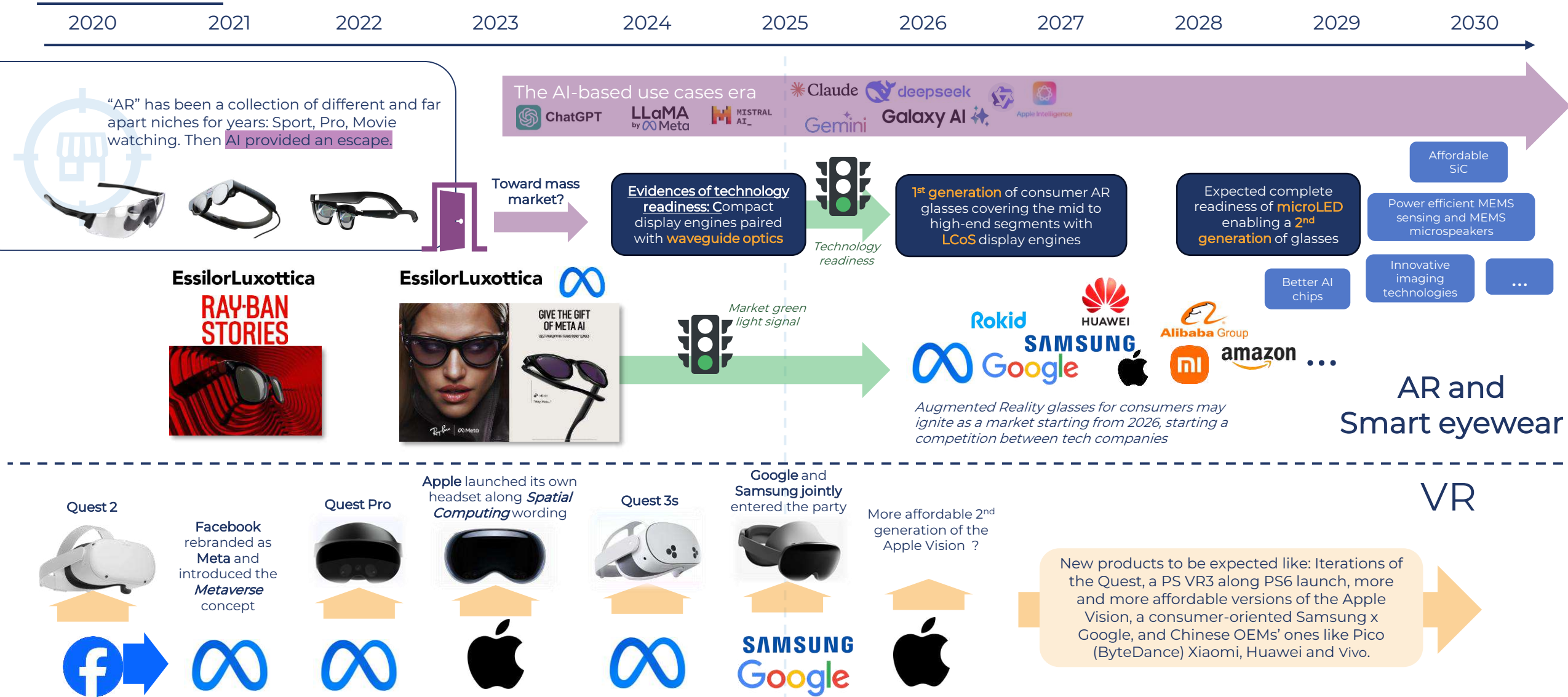
EXECUTIVE SUMMARY

VR products roadmap



EXECUTIVE SUMMARY

Comprehensive AR & VR roadmap (2020-2030)



EXECUTIVE SUMMARY

2024 – 2030 AR and VR market forecast - Units

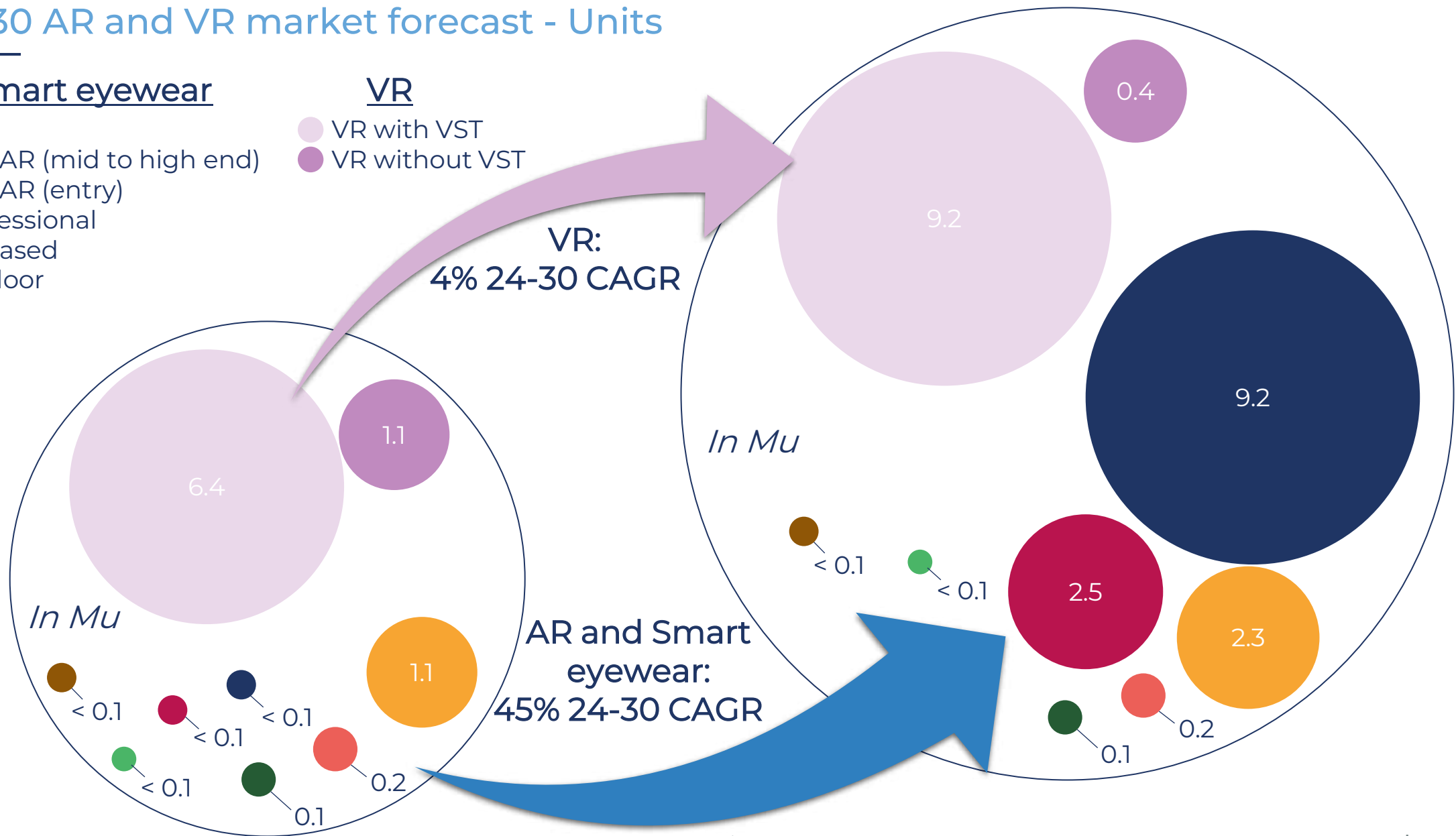


AR and Smart eyewear

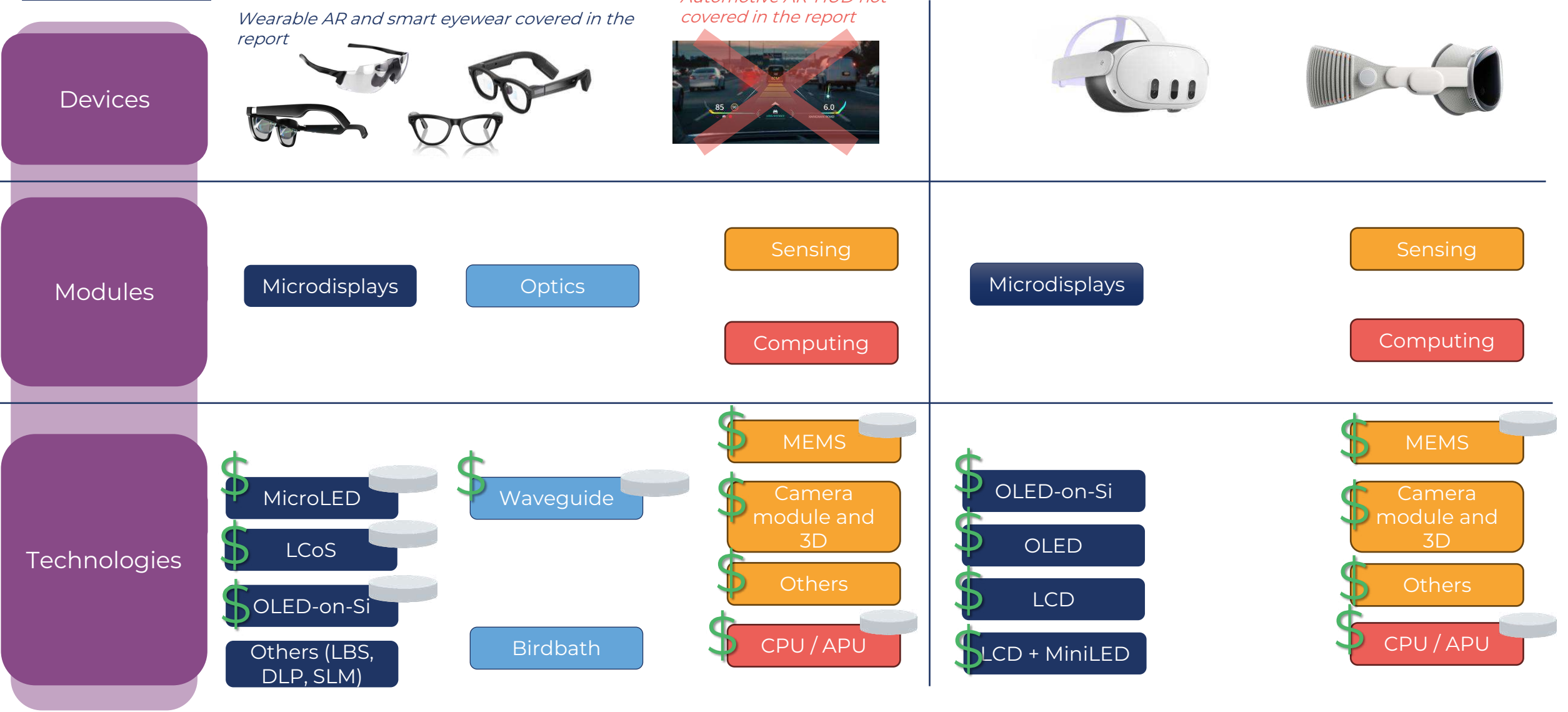
- Audio-only
- Consumer AR (mid to high end)
- Consumer AR (entry)
- AR for Professional
- Birdbath-based
- Sport/Outdoor
- Others

VR

- VR with VST
- VR without VST



CONTEXT



- The border between AR and VR is often blurred by companies' communications and marketing with MR or XR. At Yole, we consider that they are completely different technological archetypes. A good way to make the distinction is to define them as follows:
 - VR is when displays exclusively emit the light captured by the eyes
 - AR is when the light captured by the eyes is a blend of emission from displays and reflections from objects in the physical environment.
- Starting from these definitions leads to very different solutions for both the optics and the display engine:



DOE (or SRG)
HOE (or HVG)
PVG
ROE
Birdbath

MicroLED (LED-on-Si)
LCoS
OLED-on-Si
MEMS (DLP and LBS)

Pancake
Fresnel

LCD (+ MiniLED)
OLED
OLED-on-Si





CONTEXT

What AR is finally becoming concretely

- For years, the pledge of Augmented Reality has been very ambitious: Displaying additional objects, sometimes quite voluminous, sometimes with depth (volumetric holography) within a large field of view.
- Such ambition contributed to blur the frontier between AR, VR and MR in between.
- Up to now, no products have succeeded in bringing such experience to the consumers. The products making such promises never succeed in meeting consumers' compliance whether in terms of form factor, weight, price or even use cases.
- Instead, AR glasses, or smart/AI glasses are poised to be oriented toward displaying of text-based content (via audio or visual inputs).

2014



Image: Magic Leap website cover

2024



Image: Jade Bird Display



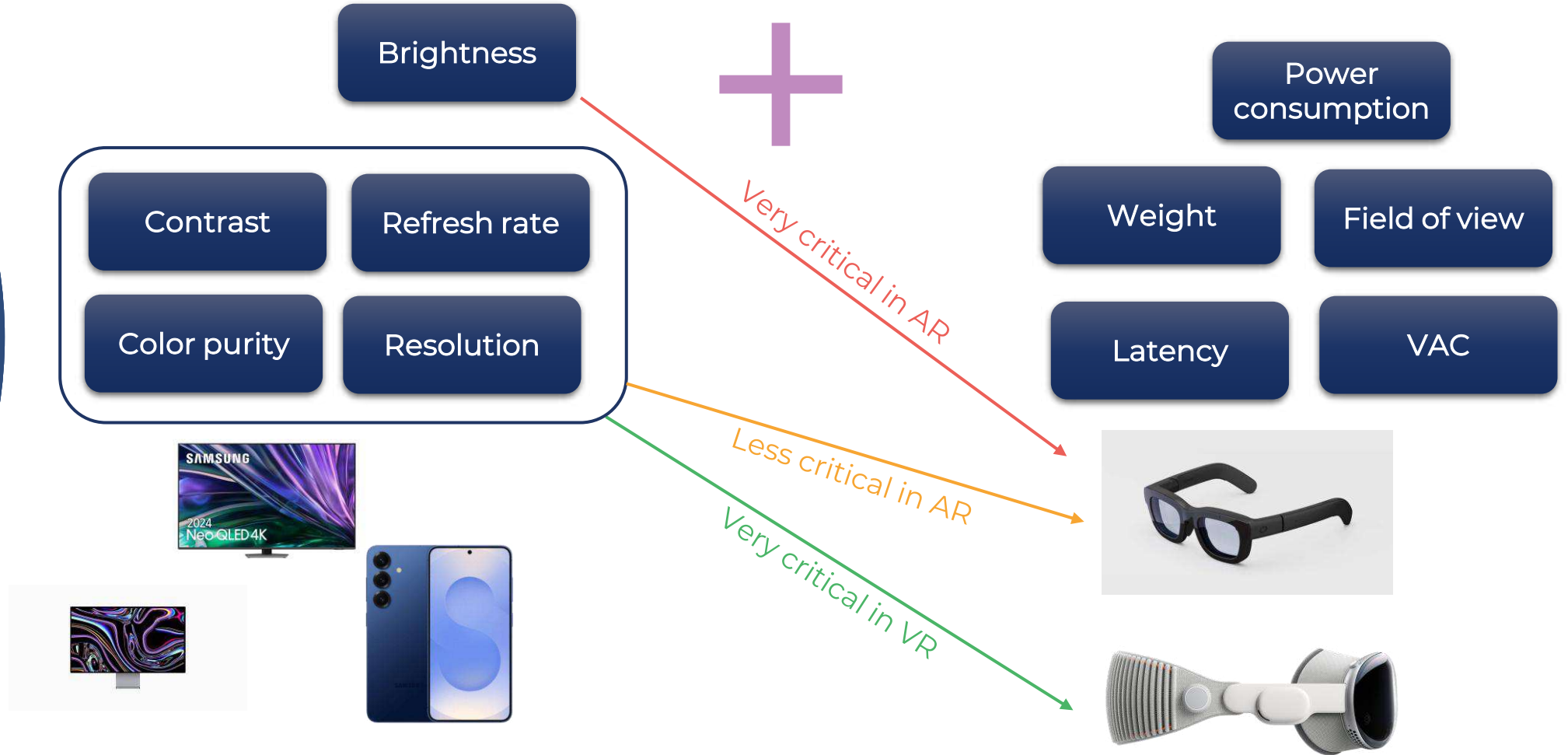
CONTEXT

AR VR MR in the realm of displays – New constraints

Displays KPI are not sufficient to characterize the experience with AR | VR devices.

Usual KPIs keep being important...

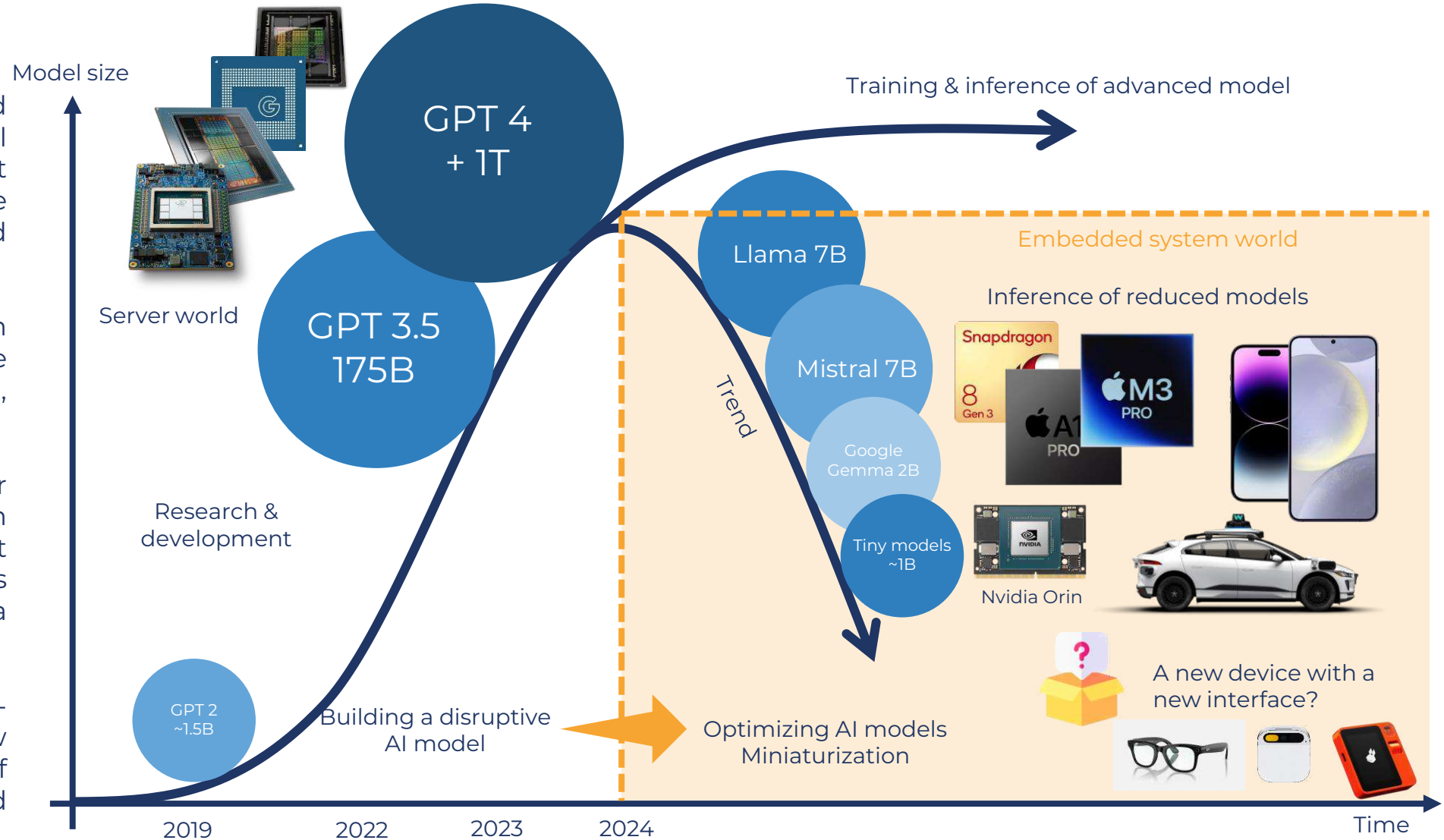
but a new range of concerns rise due to the nature of the devices.



CONTEXT

The AI trend

- In 2022, OpenAI launched ChatGPT, marking a pivotal moment in AI development and showcasing the potential for super-powered artificial intelligence.
- New models with even more parameters have appeared (Google Gemini, Claude, Ernie, etc.).
- Around 2023, smaller models appeared with performance similar to that of larger models such as Mistral 7B or Meta's Llama 7B.
- From an era of results-driven R&D, we're now entering an era of optimization and miniaturization.



Will AI become the magic wand that enables consumer AR?

- AR glasses will integrate more and more AI-enabled functionalities and help create compelling use cases for consumers
- Since 2023, OEMs have implemented AI-based functionalities in AR glasses prototypes and products. Example include live speech or document translation, captioning etc.
- Some have even rebranded their “AR glasses” into “AI glasses”
- AI could also help with the human/machine interface challenge, allowing devices to interpret complex vocal commands.
- While it doesn’t have a display, the 2nd generation of the Ray-Ban Meta smart glasses offers a glimpse of what could become possible and has been well received. We expect the next generation, to be available in 2026 and feature a display.
- AI implementation will likely increase power demand: the processor (edge AI) and wireless (Cloud-based AI) chips will consume more, so the display must consume less.



Image: Google



Image: Meta



Images: Brilliant Labs

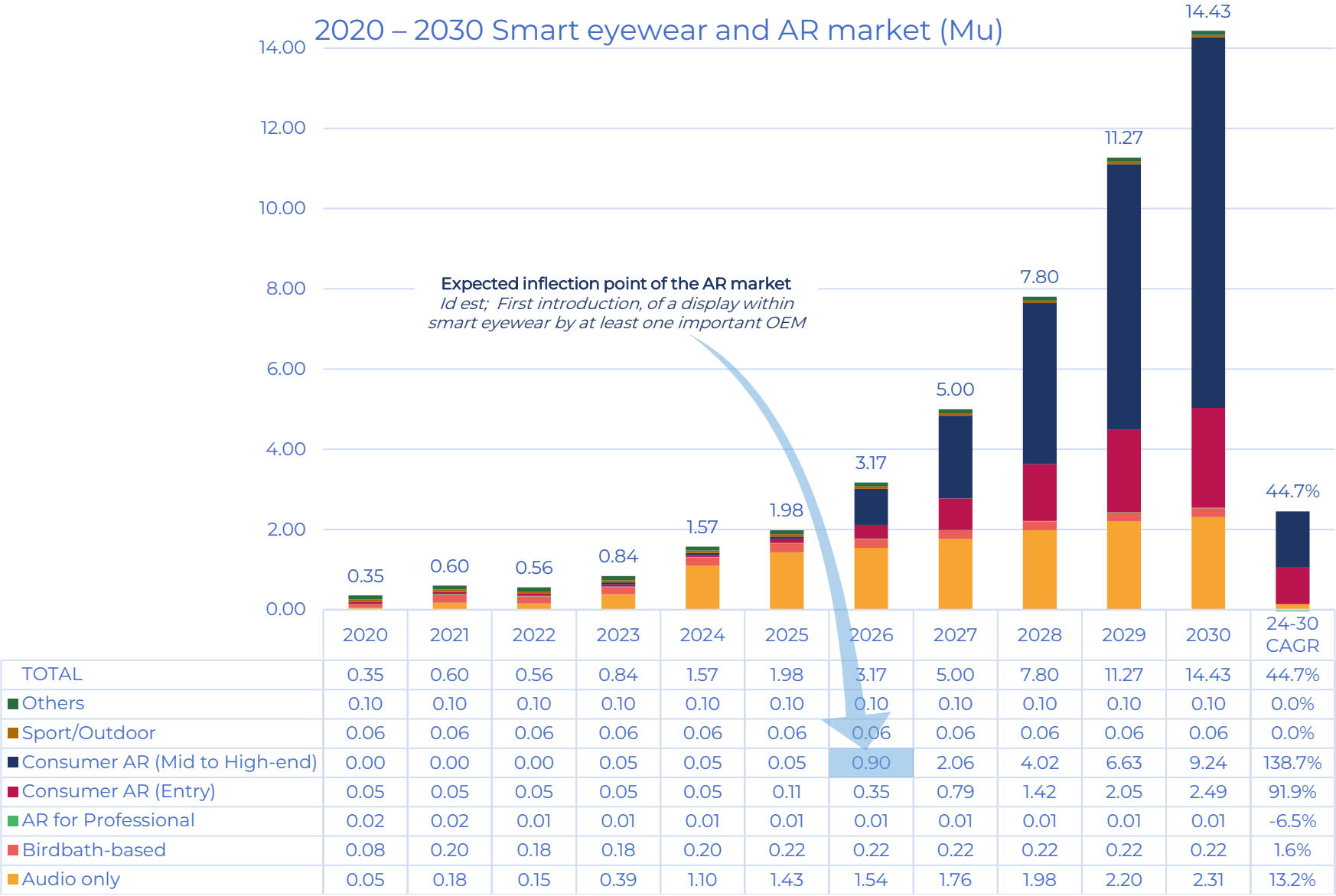
MARKET FORECASTS

MARKET FORECAST

2020 – 2030 Smart eyewear and AR market (Mu)

- This forecast takes a wide range of product into account: From audio (Ray-Ban Meta-like) only to large FoV birdbath-based with waveguide-based in between.
- In the long term, we can expect the waveguide-based solution to dominate (AR, entry, AR Mid to High-end) as it improves the HMI and make the solution more consistent and consumer compliant. Yet, the audio-only should benefit from their current strong momentum and keep representing a significant proportion.
- We expect birdbath-based glasses like XREAL to remain trapped within niche for indoor content consumption.

Volume - Million units



MARKET FORECAST

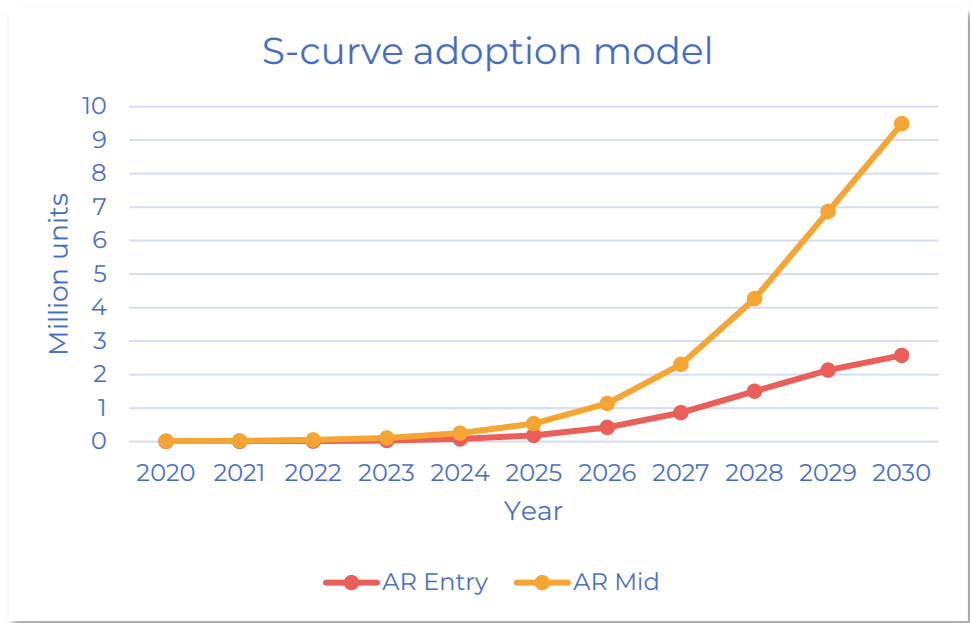
A comment on mass market AR dynamic

- AR entry and mid-end are still markets that have yet to emerge. We consider an S-curve adoption to forecast its rise, considering the market size at maturity and the inflection point. It is now quite certain that consumer AR will exist, but its dynamic of adoption, when it will finally come, is still unknown. The parameters of our S-curve, as the S-curve itself, are shown below.

	Maximum volume (Million units)	Inflection point	r
Entry	3.0	2028	0.90
Mid	13.8	2029	0.80



- These figures can appear quite low in the realm of consumer electronics, but we do not expect AR to be able to replace SmartPhones in any way in the time frame considered here. We can expect those glasses not to be a replacement for prescription glasses but an addition to them.
- Let's consider a scenario quickly:
Smart glasses are poised to keep having a low battery lifetime, like 2 hours. However, the case allows the glasses to charge when not in use. Depending on which glasses suit the best for different situations, there would then be a kind of shift system. The same kind of shift people wearing prescription glasses experience during summer, with sunglasses.



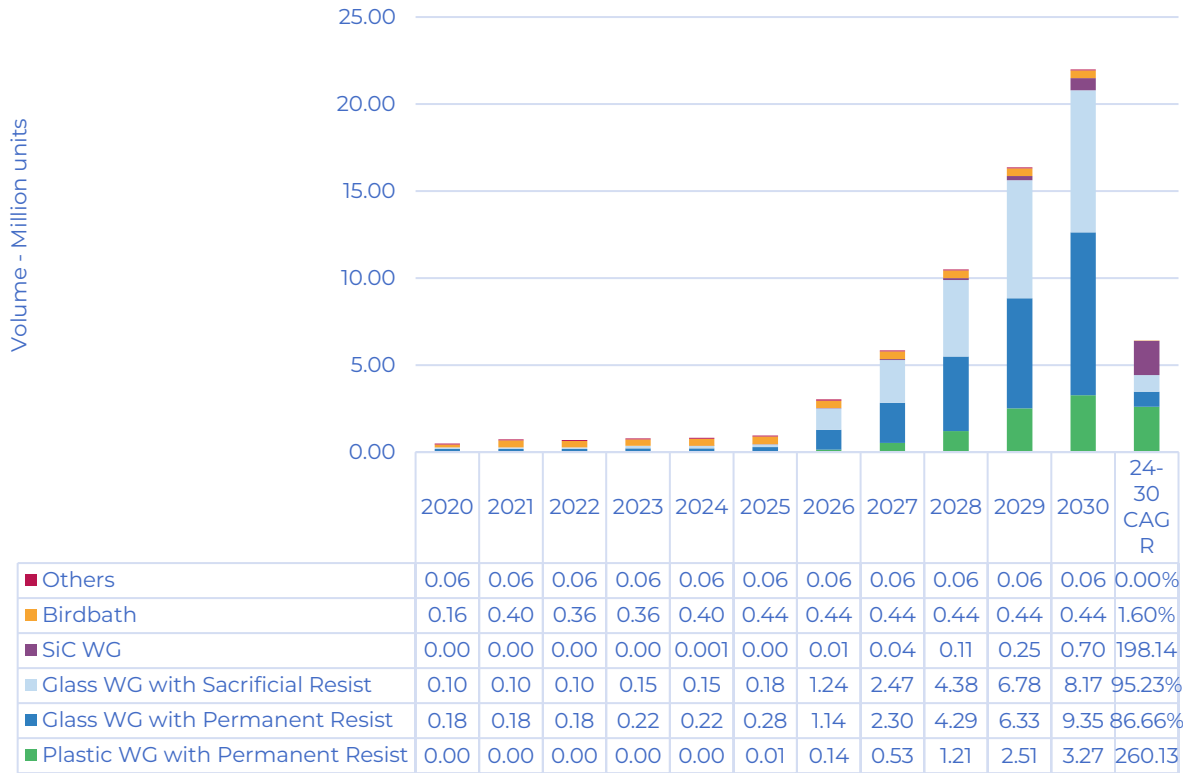


MARKET FORECAST

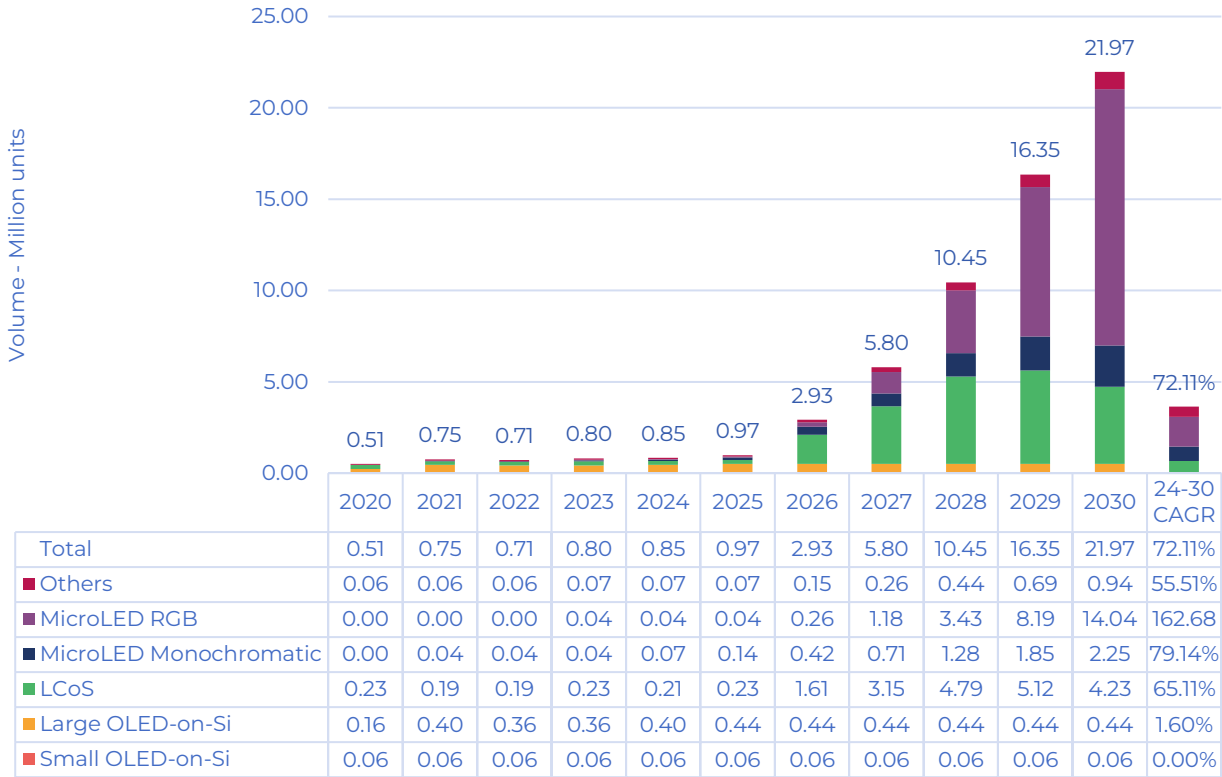
2020 – 2030 AR micro displays and optics market forecast (Mu)

The technology breakdown of optical combiners and microdisplays is strongly correlated. Indeed, **large OLED-on-Si are paired with birdbath optics** (Xreal-like architecture) and small OLED-on-Si with mirrors (Engo-like). On the other hand, the bulk of the market—entry, mid, and high-end segments for consumers should be all waveguide-based. As the right trade-off between a slim form factor and high enough brightness must be found, those waveguide optics, rather than polymer or glass, **should be paired with LCoS or microLED - RGB or monochromatic**.

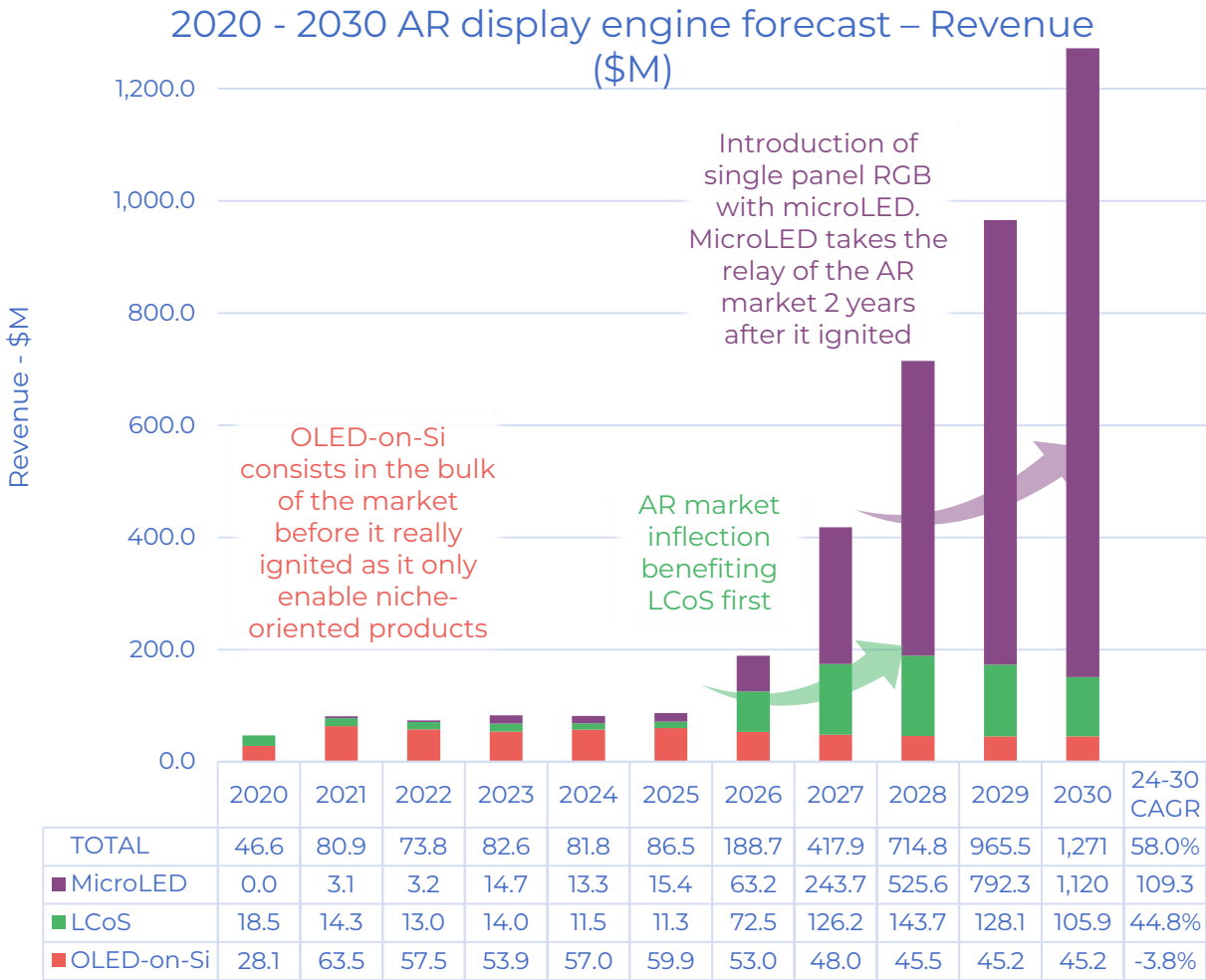
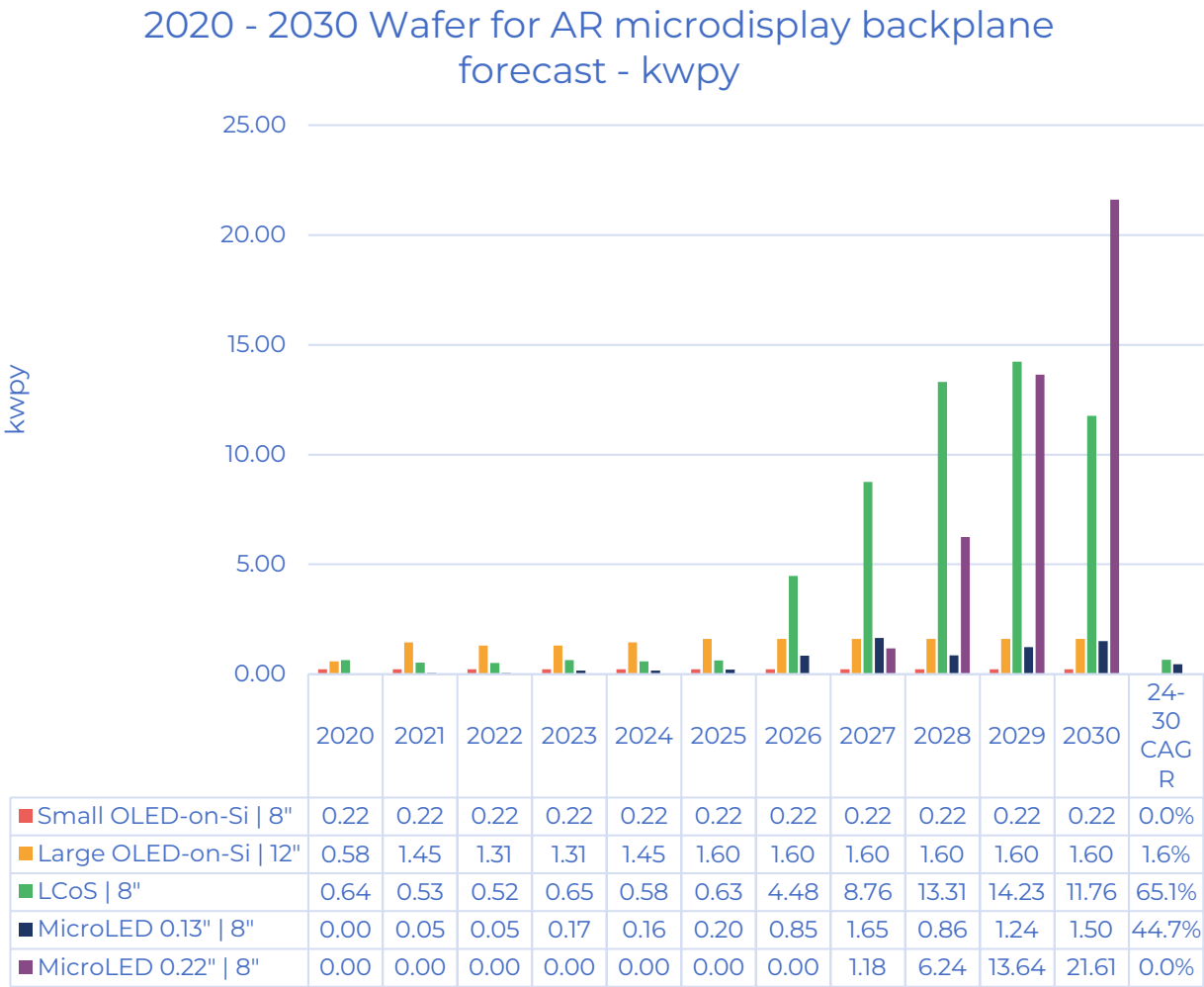
2020 - 2030 Eyepieces for AR forecast (Mu)



2020 – 2030 Microdisplays for AR forecast (Mu)



Only MicroLED, LCoS and OLED-on-Si market sizes are shown here. In Others, the technology mix doesn't allow for an accurate estimation.



MARKET FORECAST

Eyepiece per wafers

- There is no consensus yet on the number of eyepieces feasible per wafer. However, this ratio is very important in estimating the number of wafers needed to address the market.
- It will depend on the size of the wafer, of course, which depends on the chosen material platform, as well as the size of the eyepiece itself, and ultimately, the yields.
- The very design of the grating will also dictate what is possible to do in terms of freedom in the layout: Binary gratings could be oriented differently without causing issues during etching or imprint.
- For the following estimation, we consider:

Wafer size	Eyepiece per wafer
12" (maximum for glass)	20
8" (maximum for polymer and SiC)	10

Meta
4 eyepiece / 6" wafer



WaveOptics
SCHOTT
23 eyepiece / 12" wafer

APPLIED MATERIALS
24 eyepiece / 12" wafer

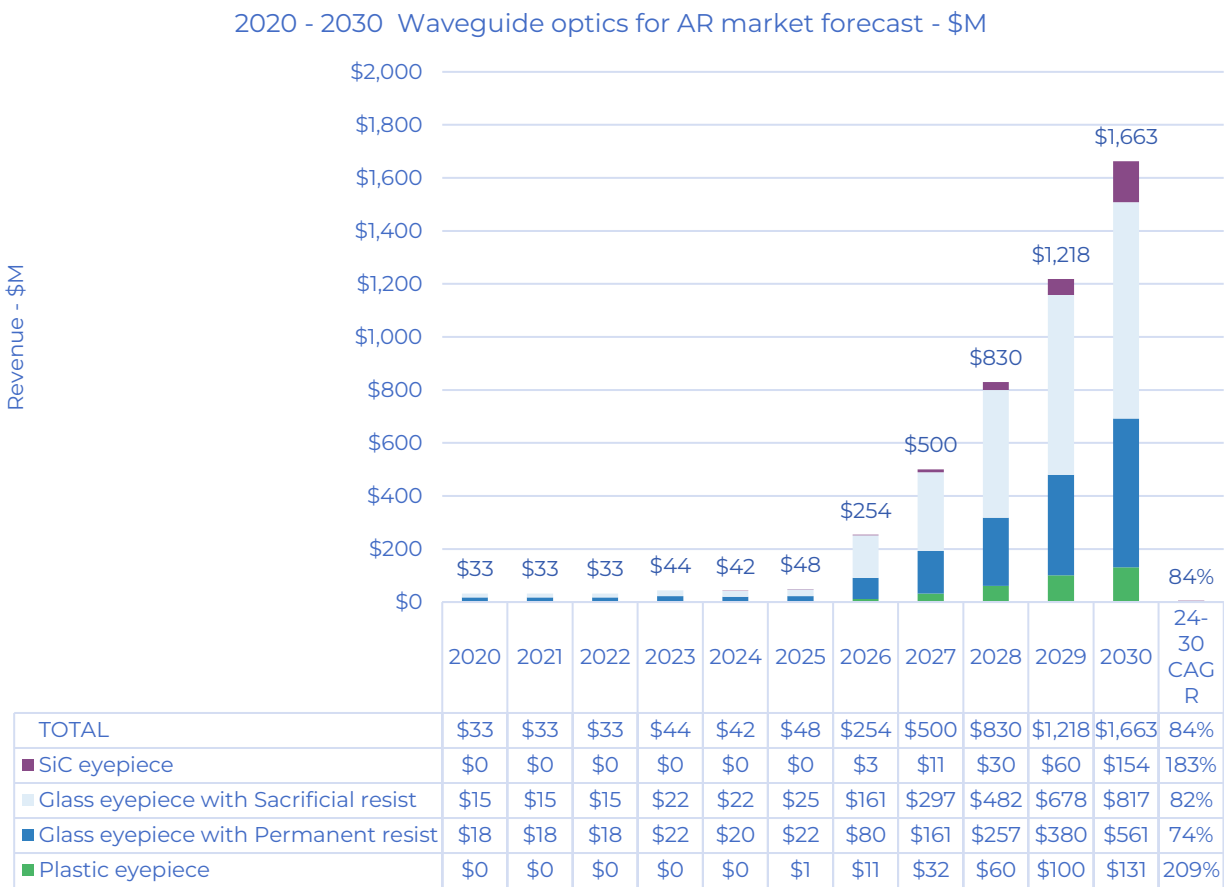
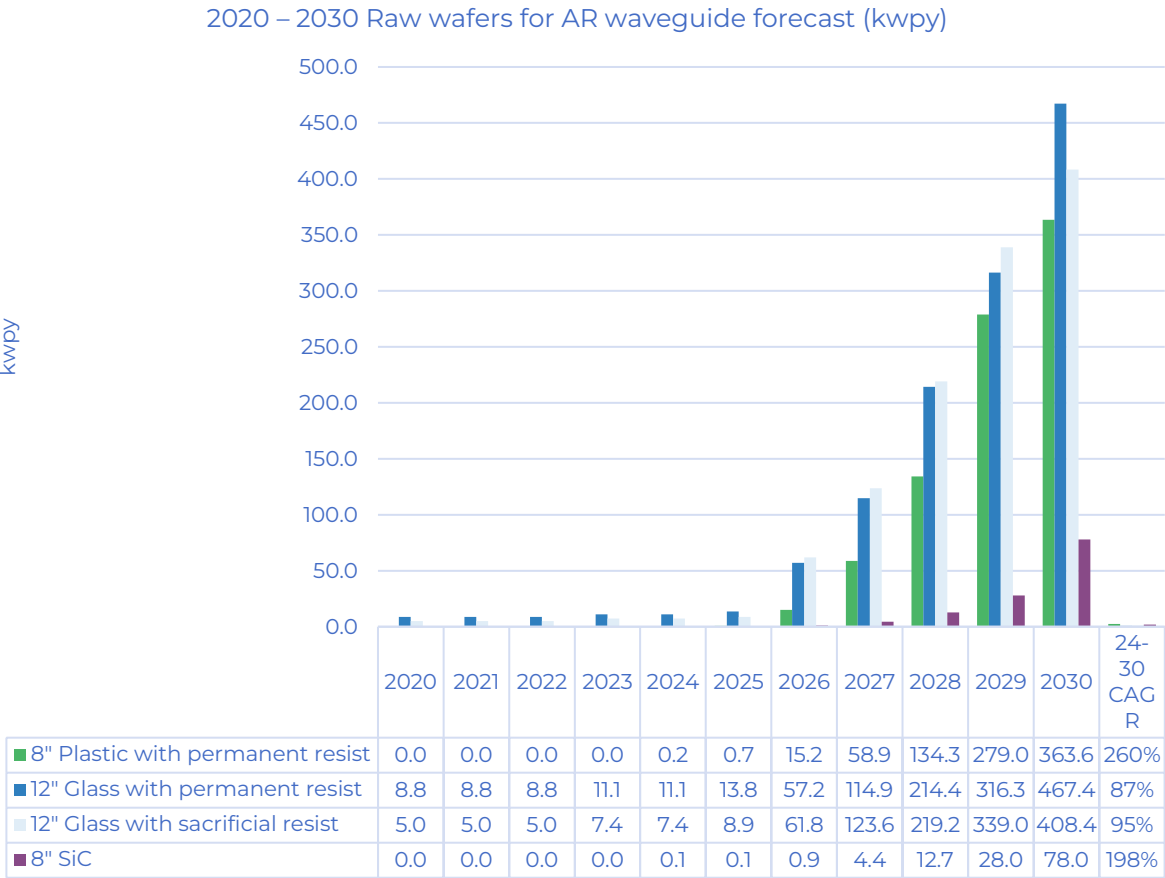
MORPHOTONICS
25 eyepiece / square 12" wafer

CORNING
18 eyepiece / 12" wafer

Mitsui Chemicals
INKRON
10 eyepiece / 8" wafer

WaveOptics
SCHOTT
10 eyepiece / 8" wafer

Here, we consider only the optics for AR consumers (For entry and mid to high-end). Those optics are poised to be waveguide-based, and we consider 100% of them will be manufactured out of glass, polymer, or SiC wafers. We expect DOEs (or SRGs) to overdominate the market in the coming years. Still, the breakdown lies in the manufacturing process, whether the ink is meant to remain on the eyepiece or consist of a sacrificial layer before etching (RIE). Plastic can't be etched, so pairing it with a permanent resist is the only option. SiC is poised to remain very marginal, within high-end products before 2030.



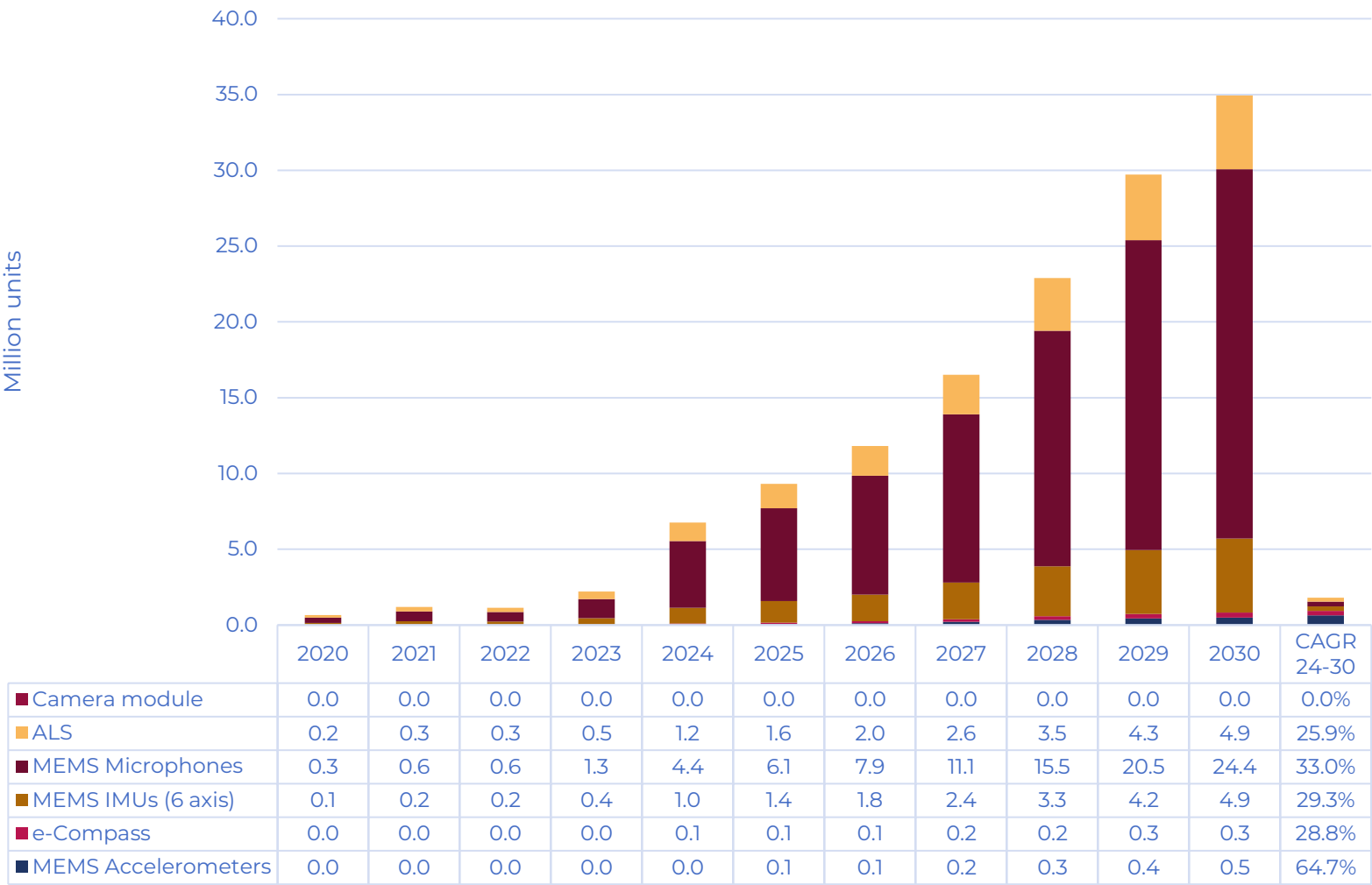
MARKET FORECAST

2020 – 2030 Sensing modules for 0 DoF content devices forecast - Mu



- As of today, the 0DoF content kind of products dominated by Ray-Ban Meta – audio-only glasses. With such glasses the interaction is achieved via speakers (not MEMS-based yet), microphones and visual inputs (12 MP CMOS image sensors).
- To better render the user’s voice over surrounding ones, a matrix of microphones is required: 5 in total in the Ray-Ban Meta.
- Even when no display brightness needs to be tuned, ALS is still necessary to adapt the sensitivity of the CMOS.
- The same applies to the IMUs which help stabilize the image.

Sensing and Actuating modules for 0 DoF content devices - (Mu)



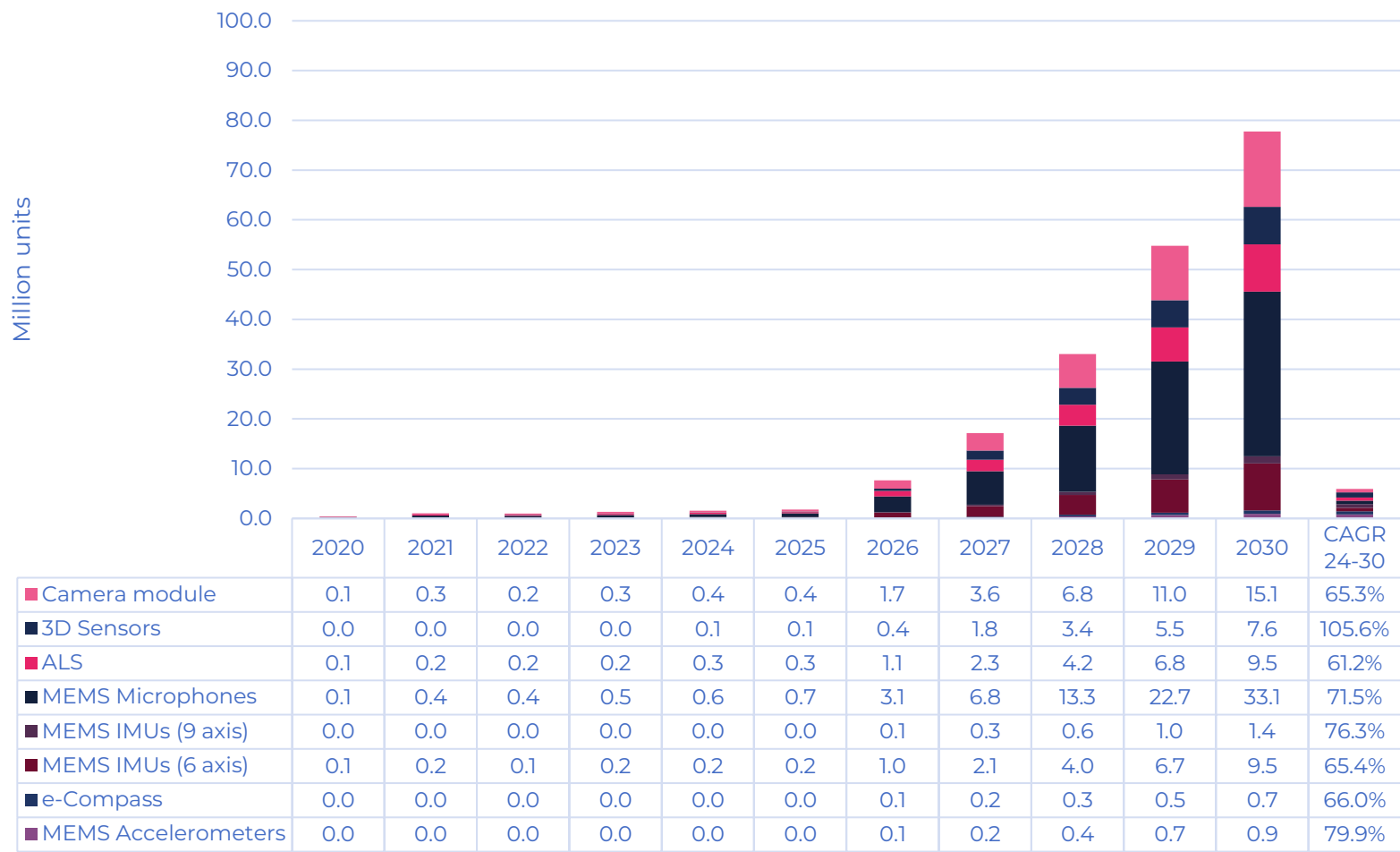
MARKET FORECAST

2020 – 2030 Sensing modules for 3 DoF content devices forecast - Mu



- Birdbath-based, movie-oriented glasses now dominate the 3 DoF content category, but lighter AR should be the norm in the coming years. In both cases, there is a need to monitor the position of the head so that the displayed content does not move with it and rather sticks to the physical environment.
- A CMOS image sensor would be required during the second phase of consumer AR products, but the ALS module is necessary even if only the display's brightness must be tuned.

Sensing and Actuating modules for 3 DoF content devices - (Mu)

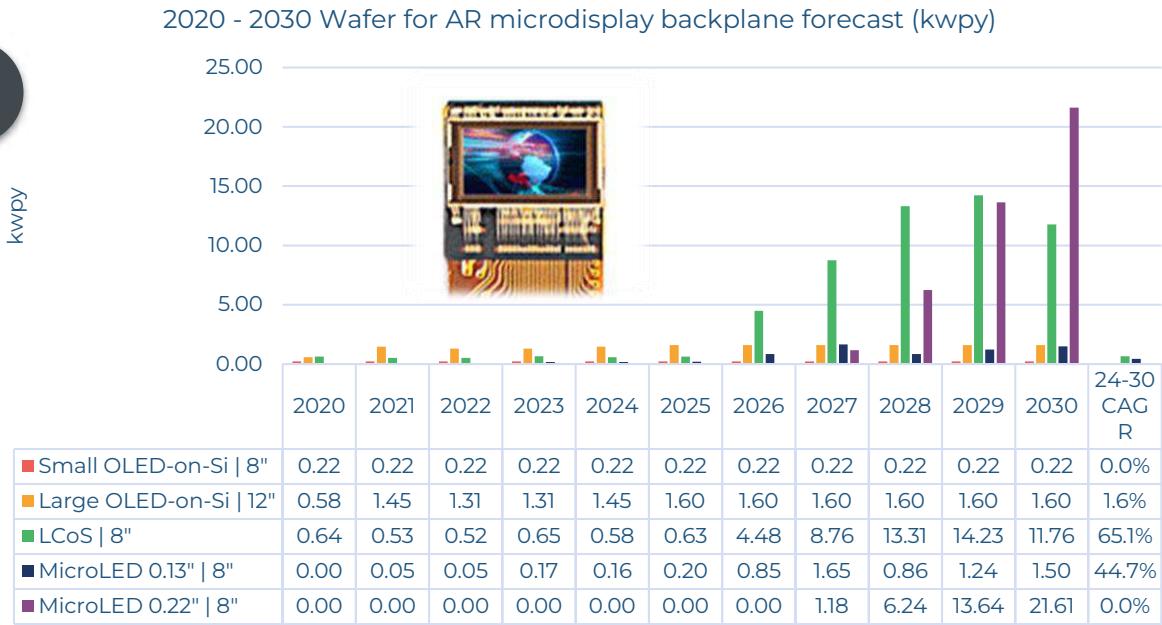


MARKET FORECAST

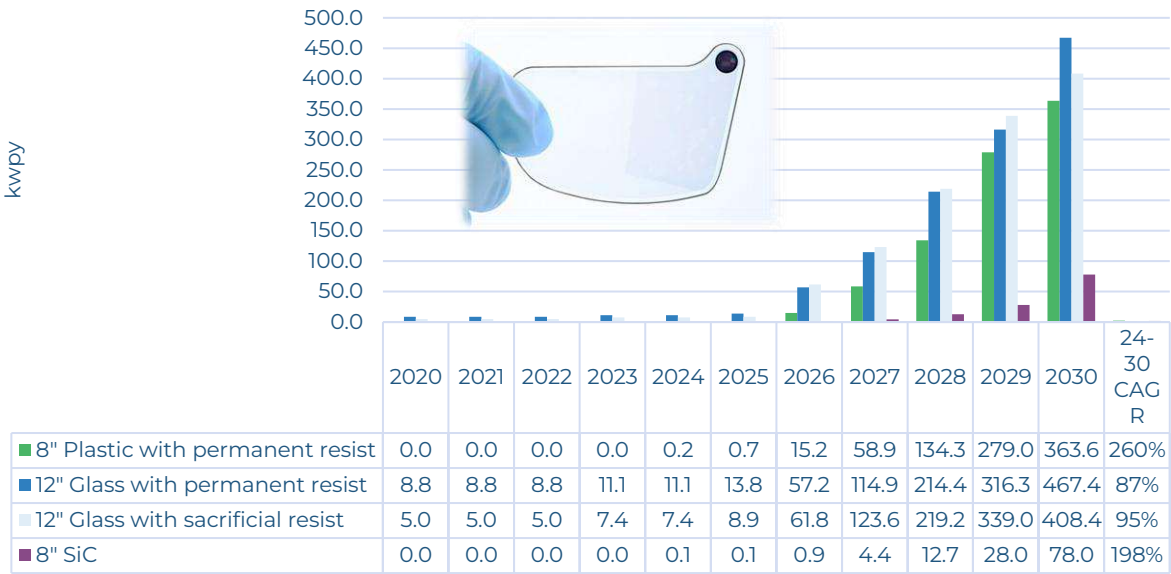
2020 – 2030 AR-related material usage forecast (kwp)



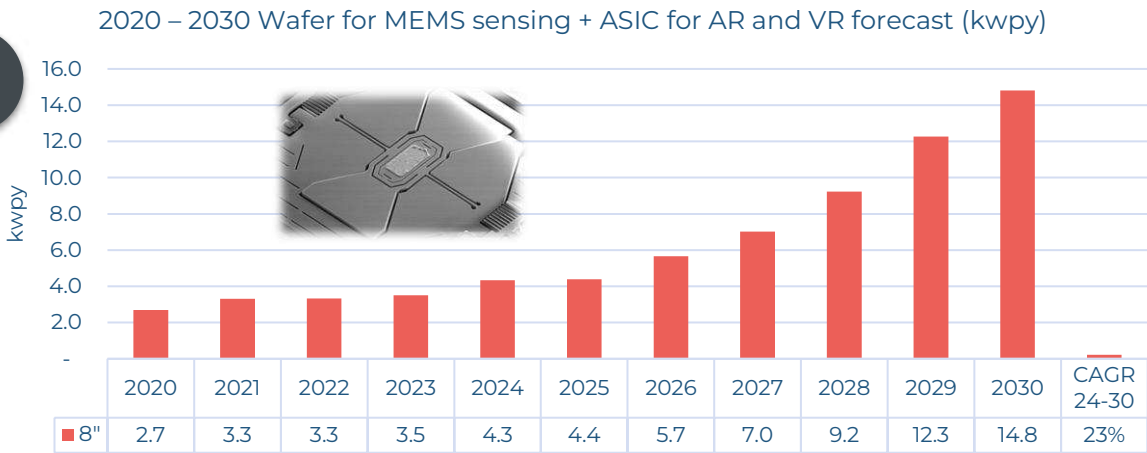
Si



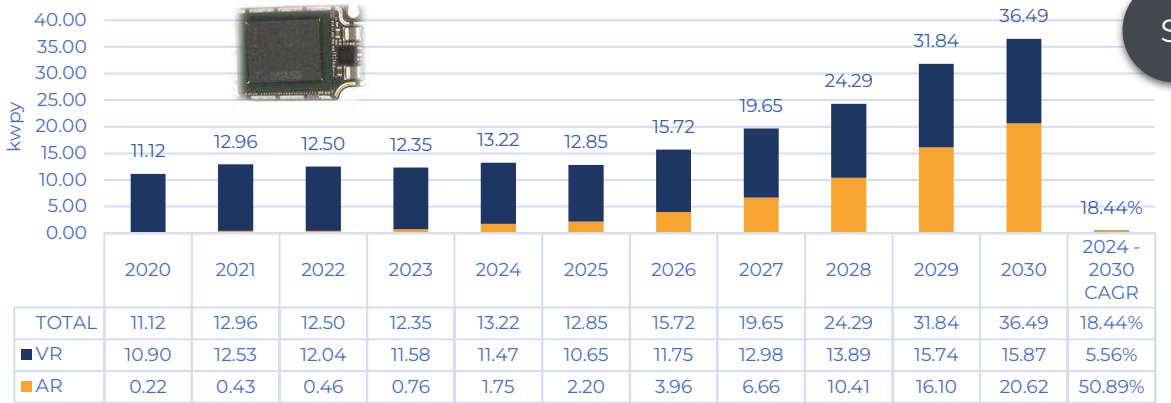
2020 – 2030 Raw wafers for AR waveguide forecast (kwp)



Si



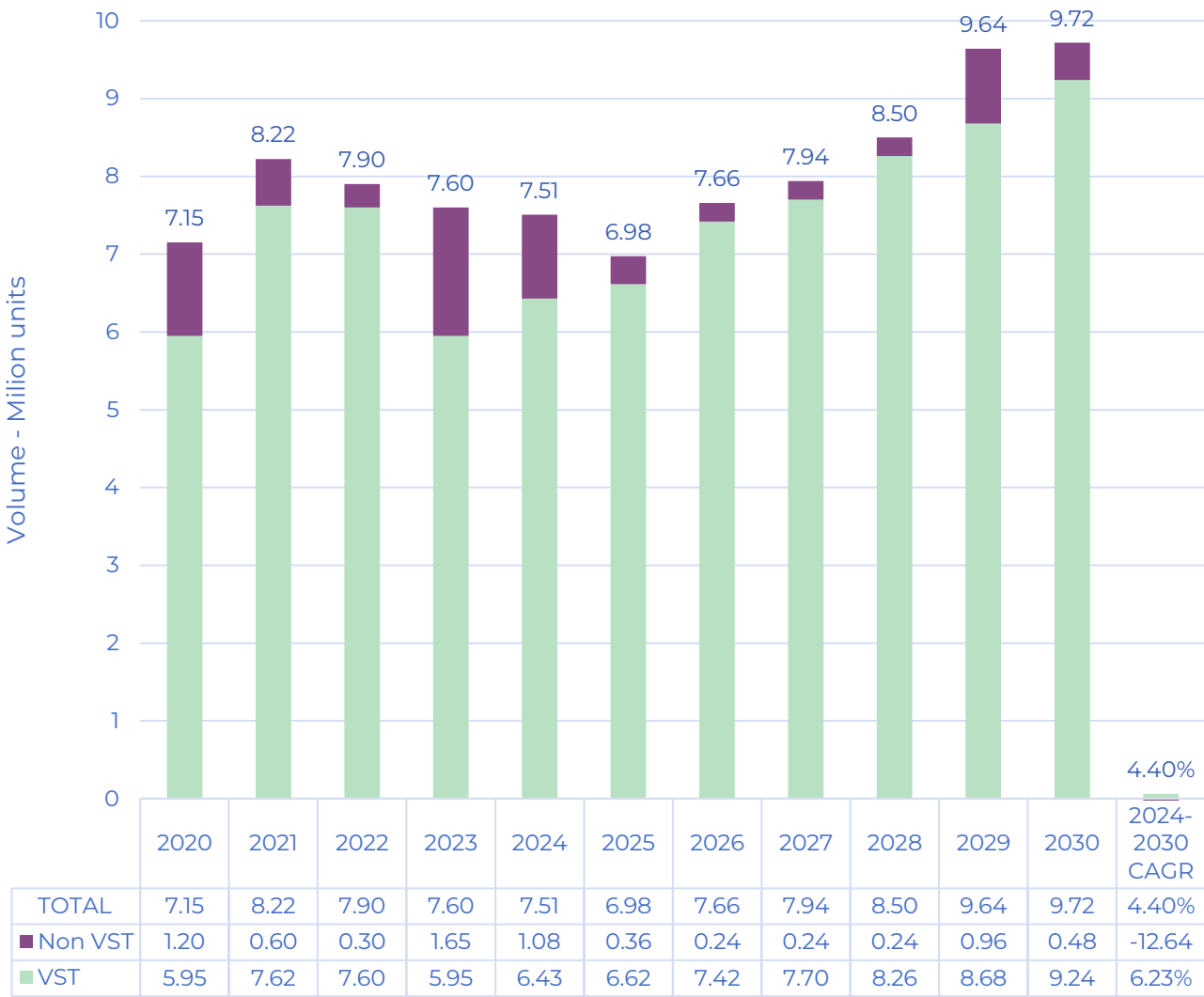
2020 – 2030 Wafer for computing for AR and VR forecast (12" - kwp)



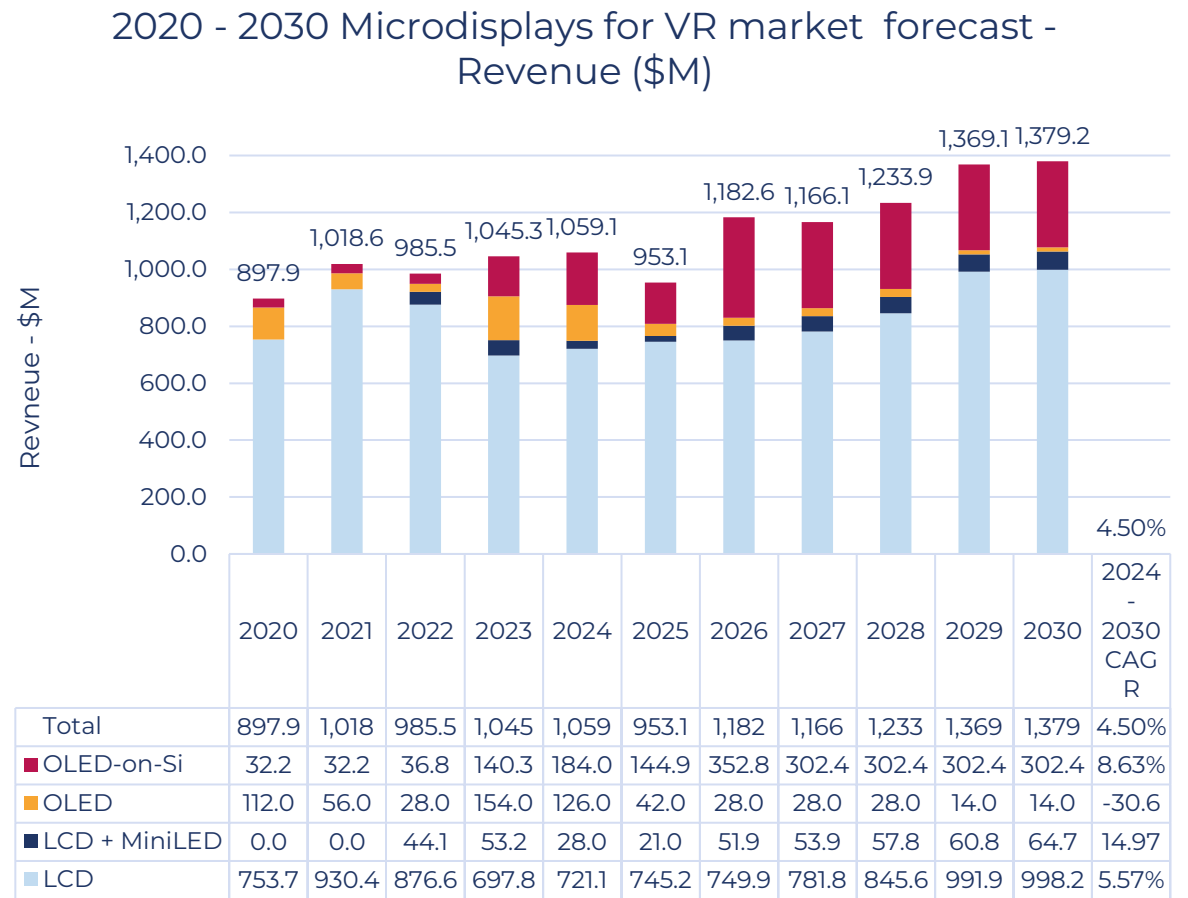
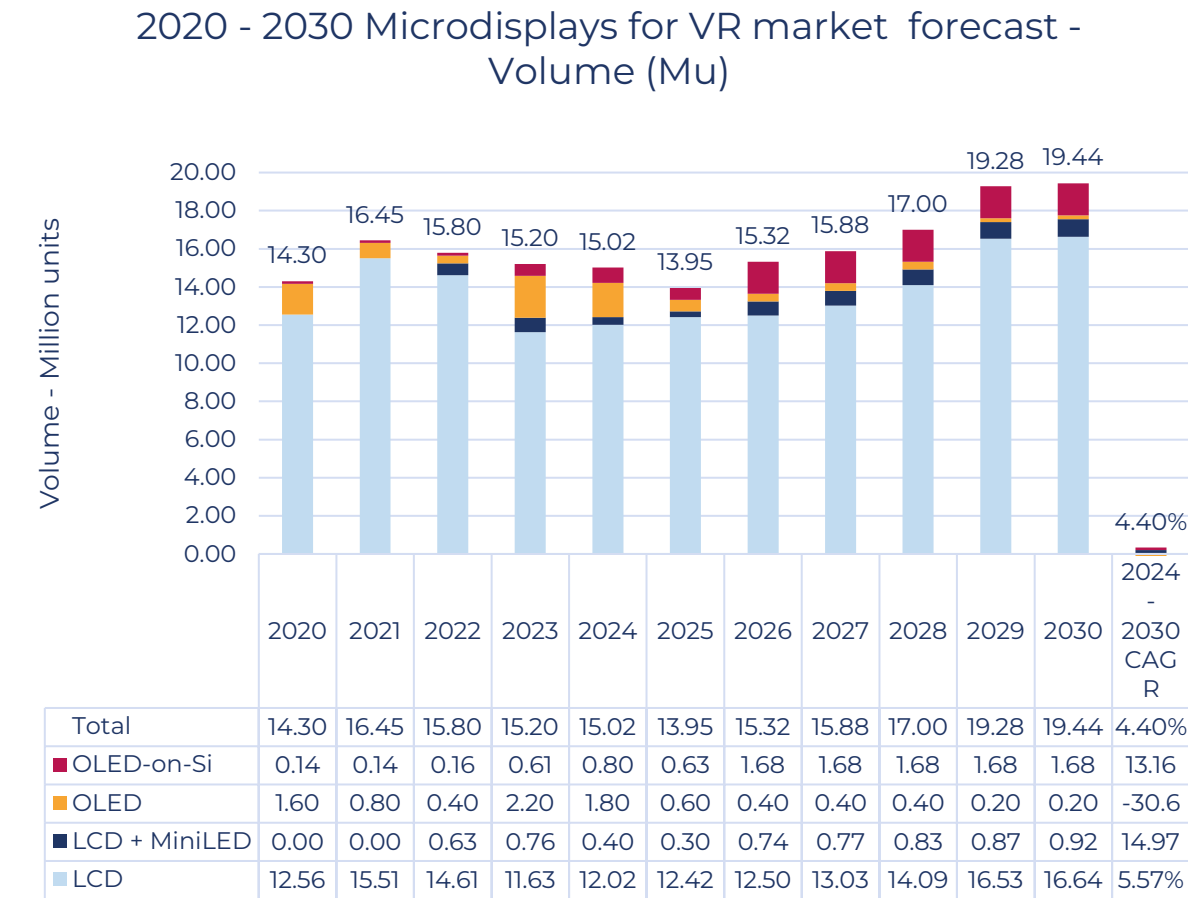
Si

- The VR market faced a slowdown from 2022 to the present. VR is considered part of consumer electronics but doesn't fulfil urgent needs. They stick with gaming and entertainment uses. It suffered the post-COVID inflation (2021: 4.7; 2022: 8, 2023: 4.1) (figures observed in the US) as the consumers weren't willing to acquire these as a priority.
- For this market to grow, it needed to be rebranded and reintroduced to consumers under a new proposition: shifting from the misunderstood metaverse to a more concrete concept like spatial computing. It is no longer a Virtual Reality headset but an actual computer you wear on your head. Apple has brought this proposition along with the Vision Pro presentation. Though buying a headset to convince the masses was too expensive, no market proof was given in the end. Ultimately, Apple legitimized the VR industry, which should benefit Meta's Quest series.
- Looking at Meta Reality Labs' results, it seems the sales of the Quest series have not evolved much despite Meta's tremendous efforts. The VR market faces a glass ceiling, and 10 million units a year is the size.

2020 – 2030 VR headsets market forecast – Volume (Mu)



LCD should remain dominant in the coming years. Quest 3 and Quest 3s used those; their price aligns with the bulk of the market. The OLED-on-Si displays of the Vision Pro alone cost as much as the Quest (3 and 3s) devices in retail. We are still expecting OLED to decrease significantly, while MiniLED offers a good trade-off in terms of price and contrast, so that it may be earning shares between low to entry and high-end products.

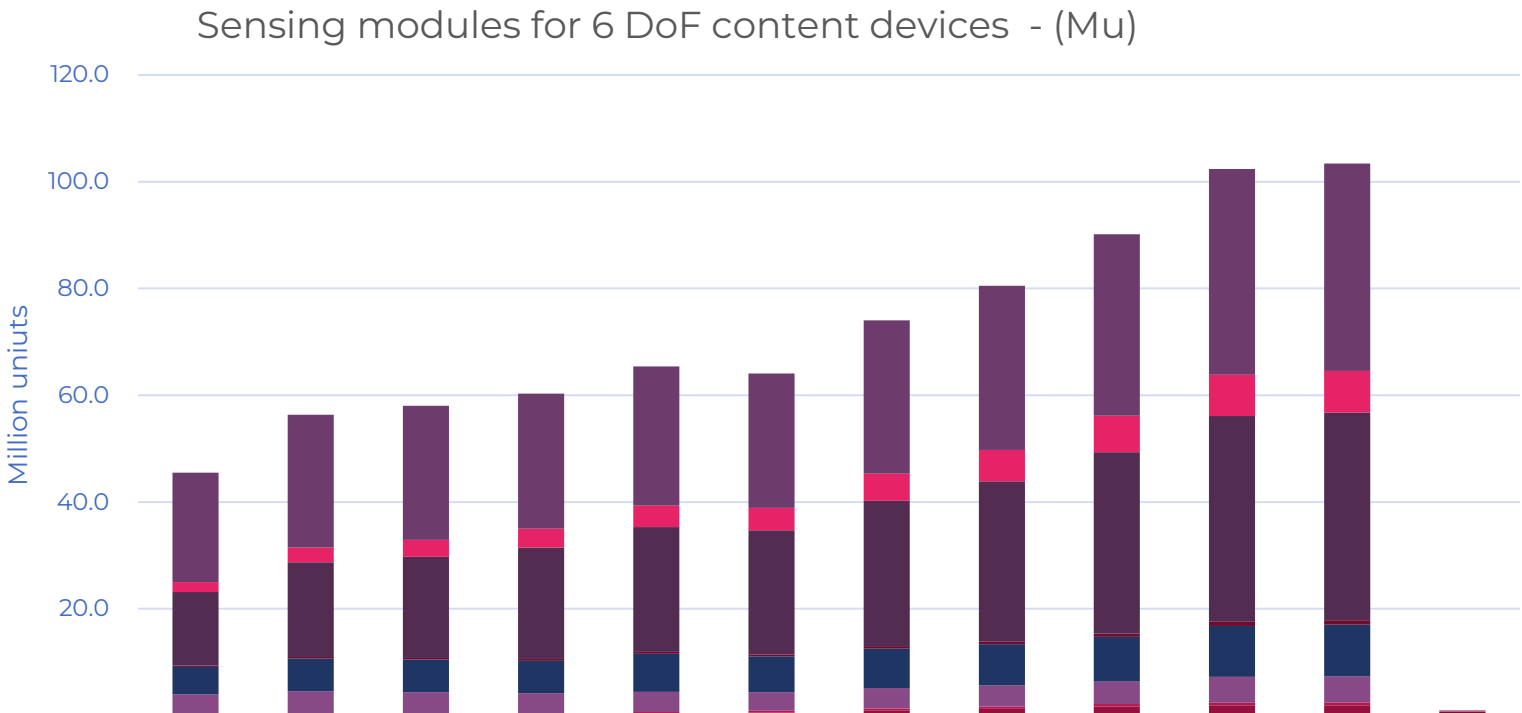


MARKET FORECAST

Sensing modules for 6 DoF content devices 2020 – 2030 forecasts - Units



- 6 DoF content devices are essentially VR headsets for which the power consumption of modules and weight is less of an issue (often more than 500g). On the other hand, latency reduction and fidelity of the physical environment (with VST feature, which becomes the norm) is crucial.



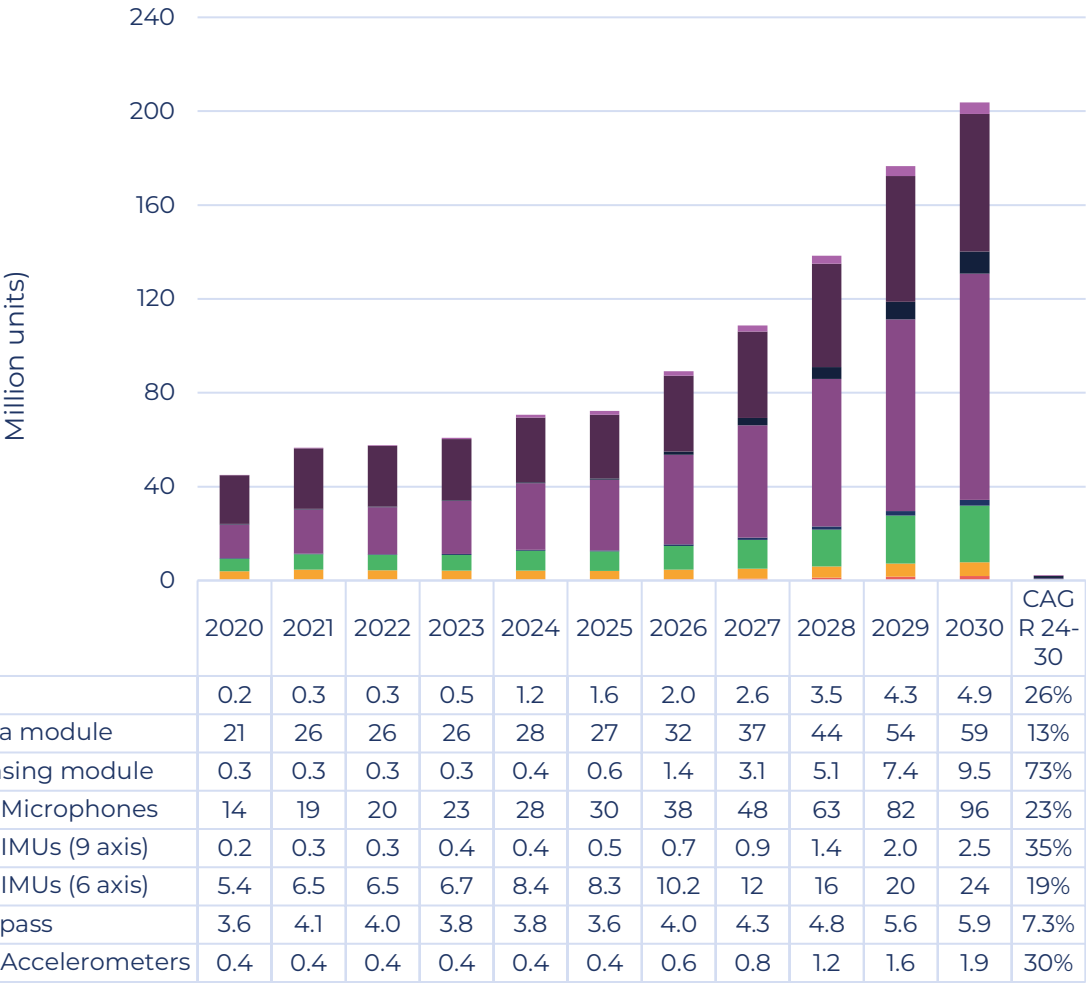
	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	CAGR 24-30
Camera module	20.5	24.9	25.1	25.3	26.1	25.2	28.7	30.8	34.0	38.6	38.9	6.9%
Temperature Sensors	1.9	2.7	3.2	3.5	4.0	4.2	5.1	5.8	6.8	7.7	7.8	11.7%
MEMS Microphones	13.8	17.7	19.0	20.9	23.4	23.3	27.2	30.0	34.0	38.6	38.9	8.9%
MEMS IMUs (9 axis)	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.8	0.9	15.1%
MEMS IMUs (6 axis)	5.2	6.2	6.1	6.1	7.1	6.7	7.4	7.7	8.4	9.6	9.7	5.3%
e-Compass	3.6	4.1	4.0	3.8	3.8	3.5	3.8	4.0	4.3	4.8	4.9	4.4%
MEMS Accelerometers	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.4	0.4	0.5	0.5	4.4%
3D Sensing module	-	-	-	-	0.3	0.6	0.9	1.3	1.7	1.9	1.9	36.5%

MARKET FORECAST

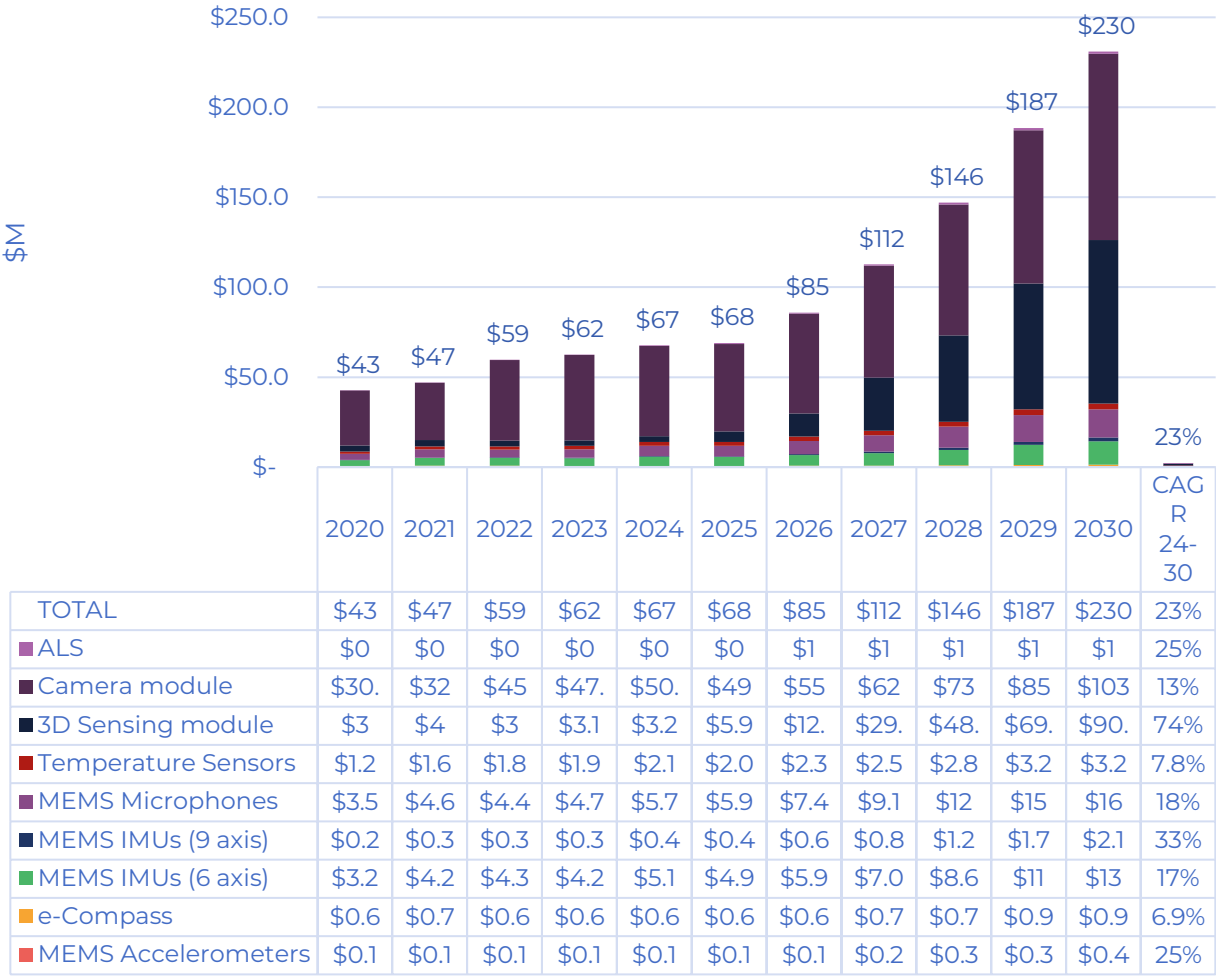
2020 – 2030 Sensing forecast (in Mu and \$M)



2020-2030 Sensing for AR & VR market forecast – Volume (Mu)

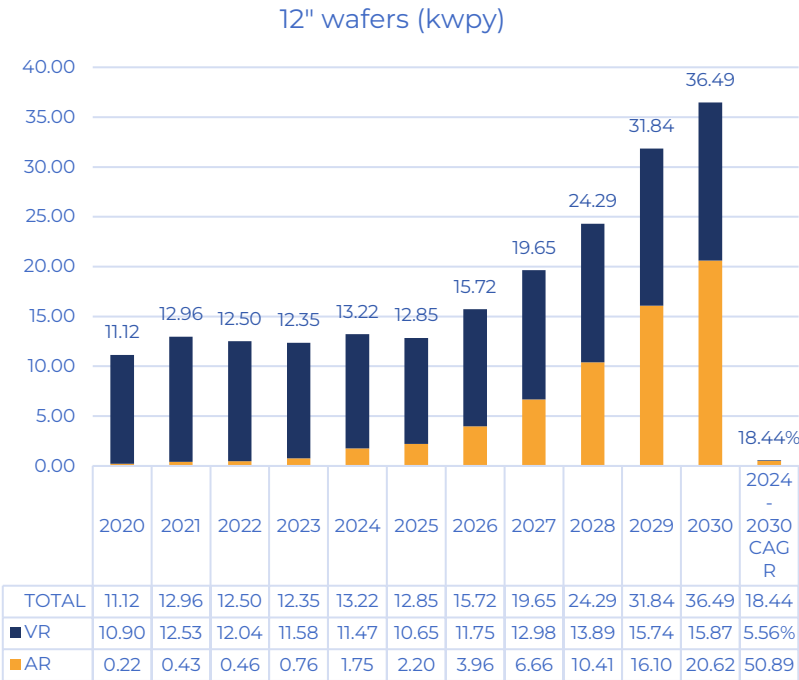
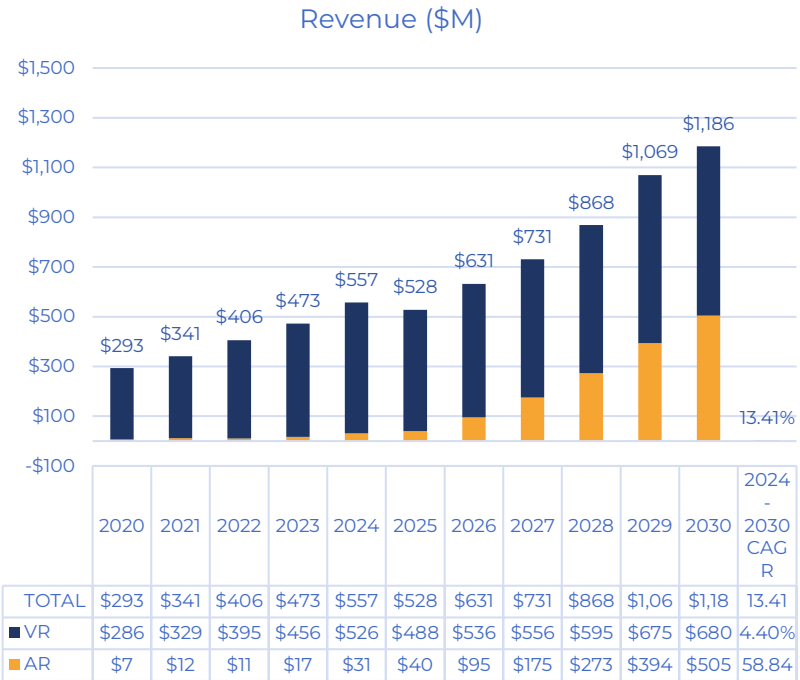
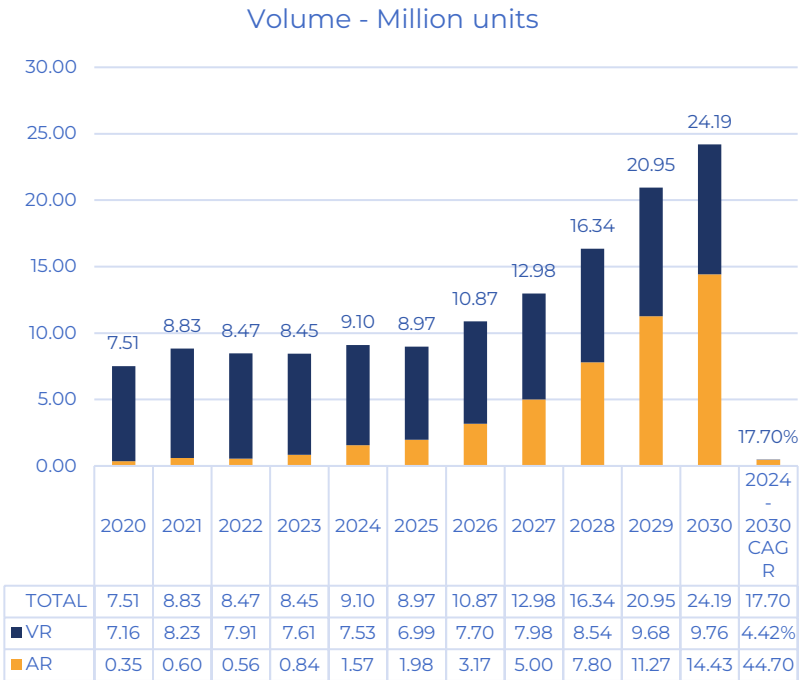


2020 - 2030 Sensing for AR & VR revenue forecast – Revenue (\$M)



The depicted growth of both the number of chips, the surface, and the market size (particularly for AR applications) underlines a compounding set of effects:

- The AR market is poised to experience exponential growth
- The AI-driven AR adoption will impose computing chips to deliver more and more compelling functions, adding complexity and increasing the number of transistors (a trend which have already been observed within an early generation of glasses).



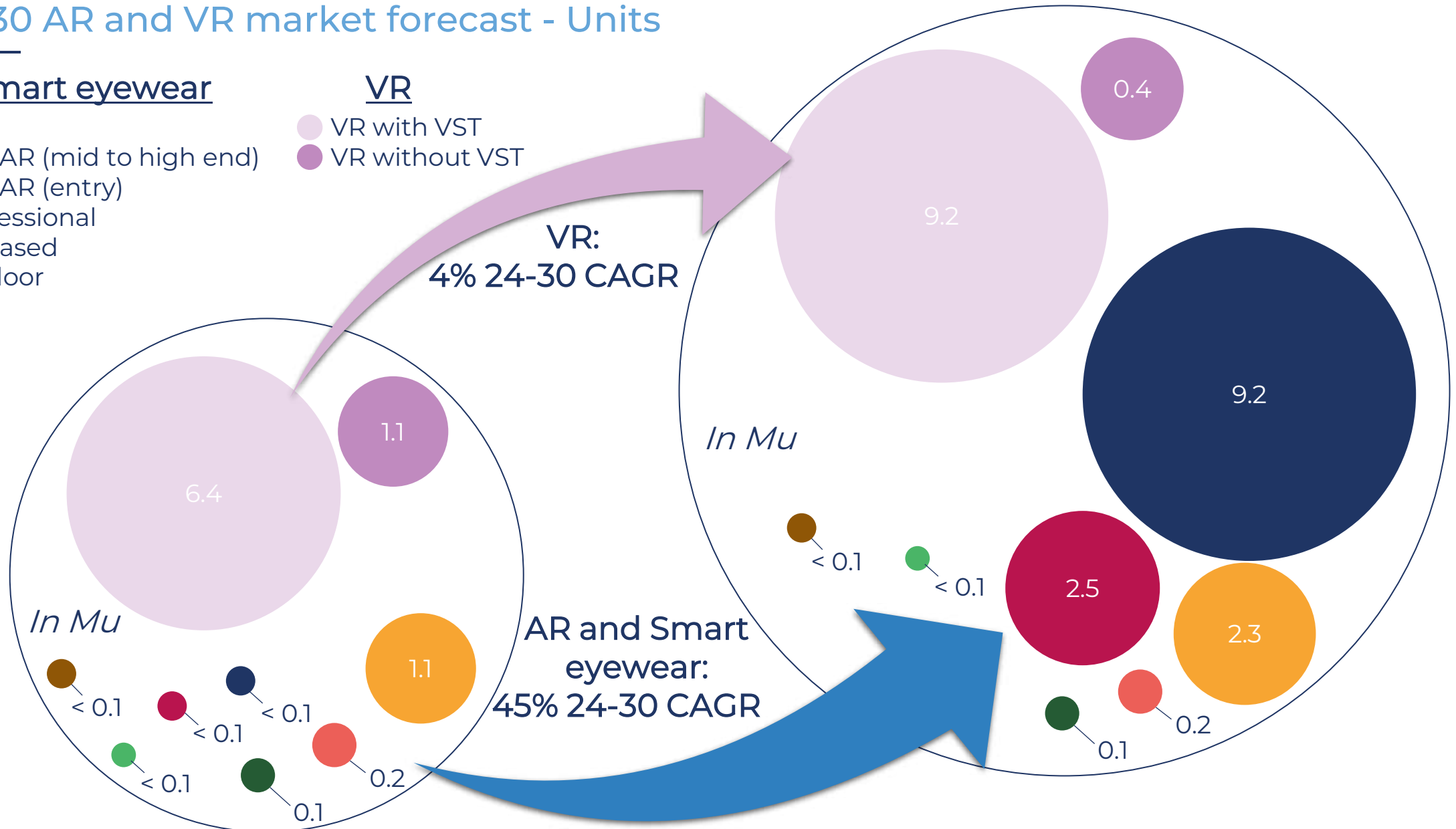
Market forecast - Synthesis

AR and Smart eyewear

- Audio-only
- Consumer AR (mid to high end)
- Consumer AR (entry)
- AR for Professional
- Birdbath-based
- Sport/Outdoor
- Others

VR

- VR with VST
- VR without VST



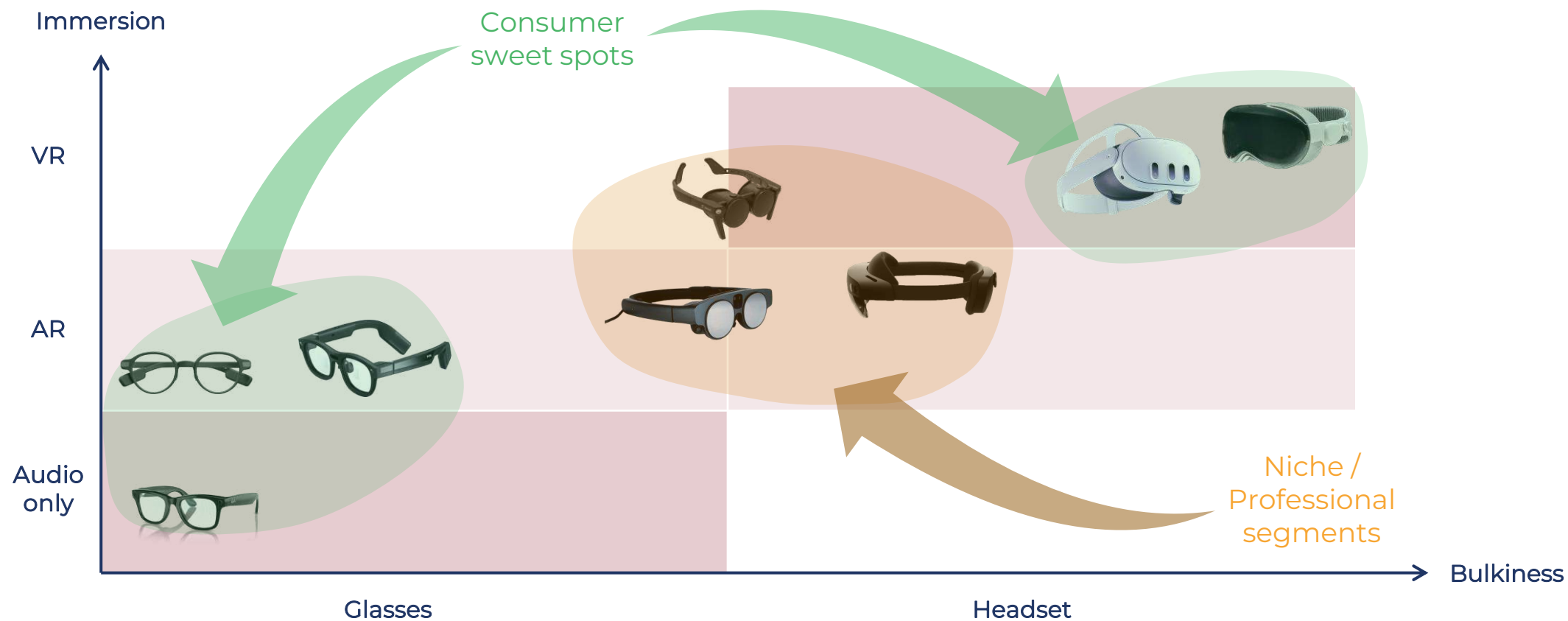
MARKET TRENDS

MARKET TRENDS

Immersion vs. Bulkiness



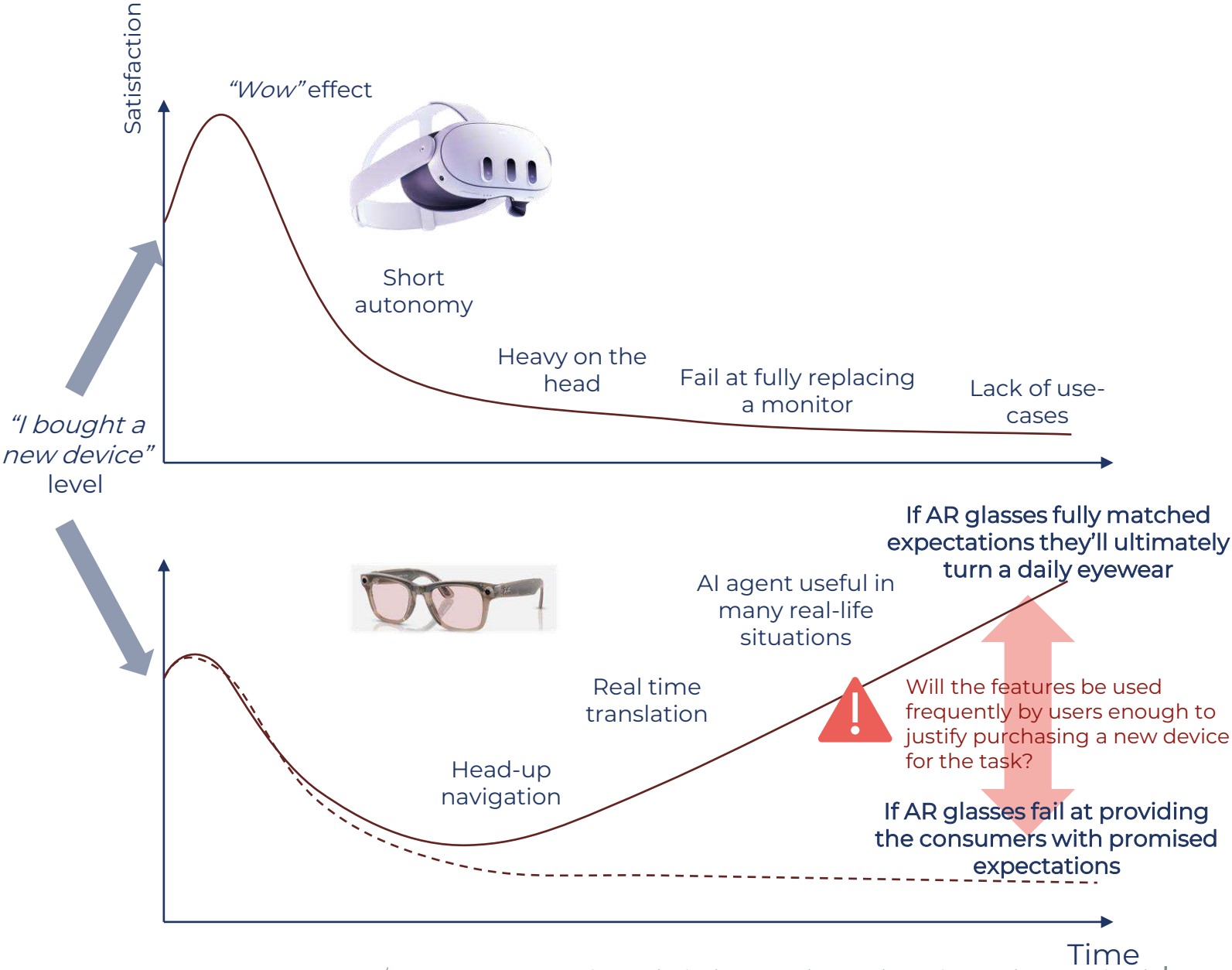
The AR and VR products belong to a **continuum of form factor and degree of immersion**. Consumer products are most likely to belong to the most extreme location of this spectrum, while professional/industrial/medical/defense-oriented products could be located anywhere in.



MARKET TRENDS

Stickiness

- The device's stickiness is essential to conquer a bulk of the market. This means that the device fully matches the value proposition for which it has been sold, and consumers can advocate for its adoption among wider and wider people.
- This stickiness would be even more appreciable as they are meant to be worn all day even outside so it would be seen and recognized as a pair of AR glasses.
- So, if targeting the right niche matters for OEMs, making it stick on their face is even more important. For the marketing to be cost-efficient, the audience has to be warmed up by word of mouth. The physical presence of the devices is a critical beachhead before the wider adoption of AR glasses.



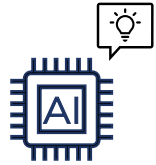
Market trends - AR



MARKET TRENDS

A glimpse at AR market

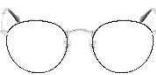
Where it intend to penetrate:



- AI enthusiasts should be the first to adopt those glasses. It is definitely the value proposition behind the hardware: it is the service. The embedded electronic-like sensing modules and computation power should support the AI assistant's operation; the other parts, like display and speakers, will be there to materialize its presence and enable interactions. Ultimately, the devices will be seen and sold as a bridge to “superpowers”. The new AI-enabled skill sets have a strong potential to convince new adopters, as the chart below advocates:

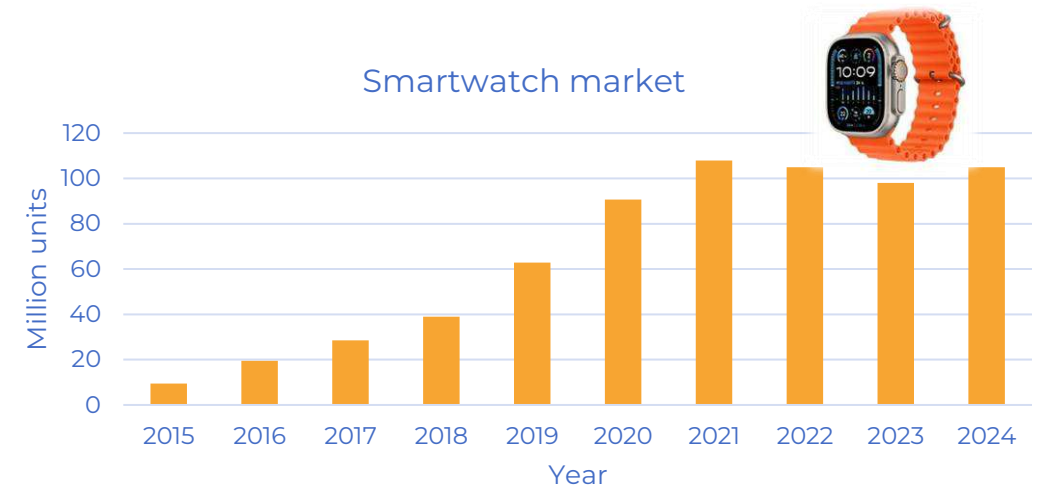


- The global eyewear and eyecare market is worth \$120B (price to consumer) according to EssilorLuxottica and Euromonitor. To penetrate this very market, a technical solutions must be found to integrate prescription without prohibitive frictions or loss of comfort for the users.



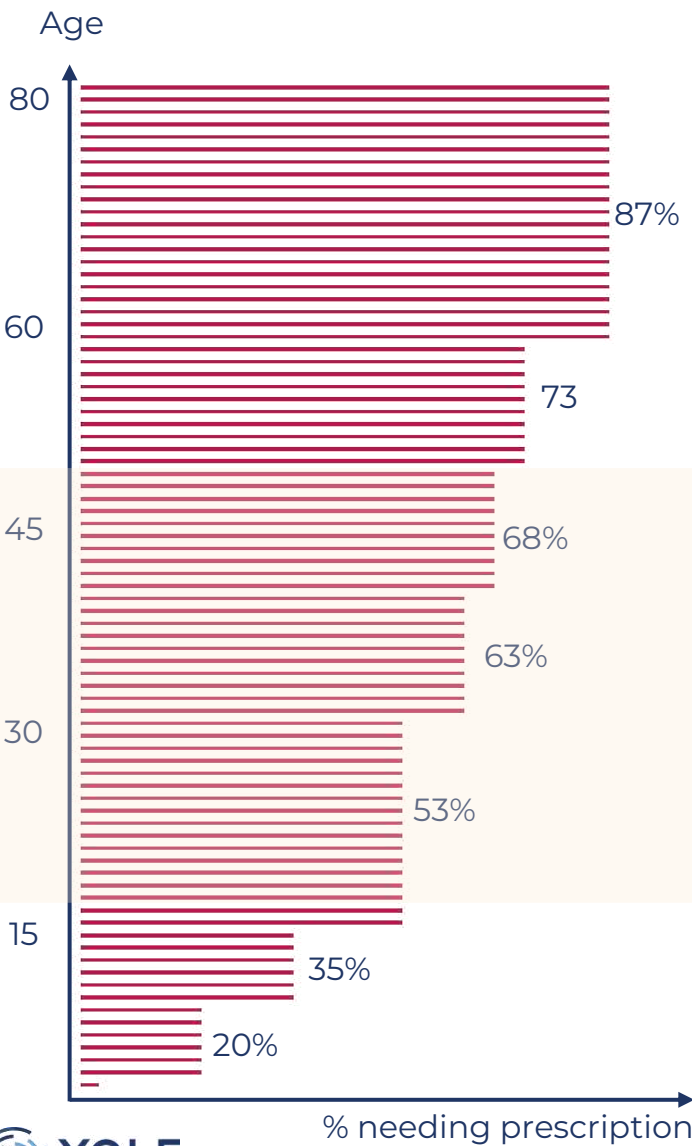
What it looks like:

- Let's be clear, unlike VR, consumer AR glasses we expect will compose most of the market will be meant to be worn all day by users and worn on the face. It is not just consumer electronics; on the one hand, it will be mainly fashion, a visual asset, a statement. There are not many equivalents in electronics devices like this one. It's true that the smartphone is now a status good (for some at least), but the exponential growth of the smartphone market was also due to gathering so many features into one device. These are things that glasses could achieve, but not before matching a much better level of performance than what is targeted today. An obvious example that is good to think of is a watch. Not necessarily a smart one, but watch in general where the brands matter and luxury is very present. Like the smart glasses pushed by Meta a lot, the smartwatch was developed by Apple, and a few players share the market. It makes the Smartwatch market very similar to smart glasses: a market which grew very fast before reaching a ~100 million units volume in 2020



MARKET TRENDS

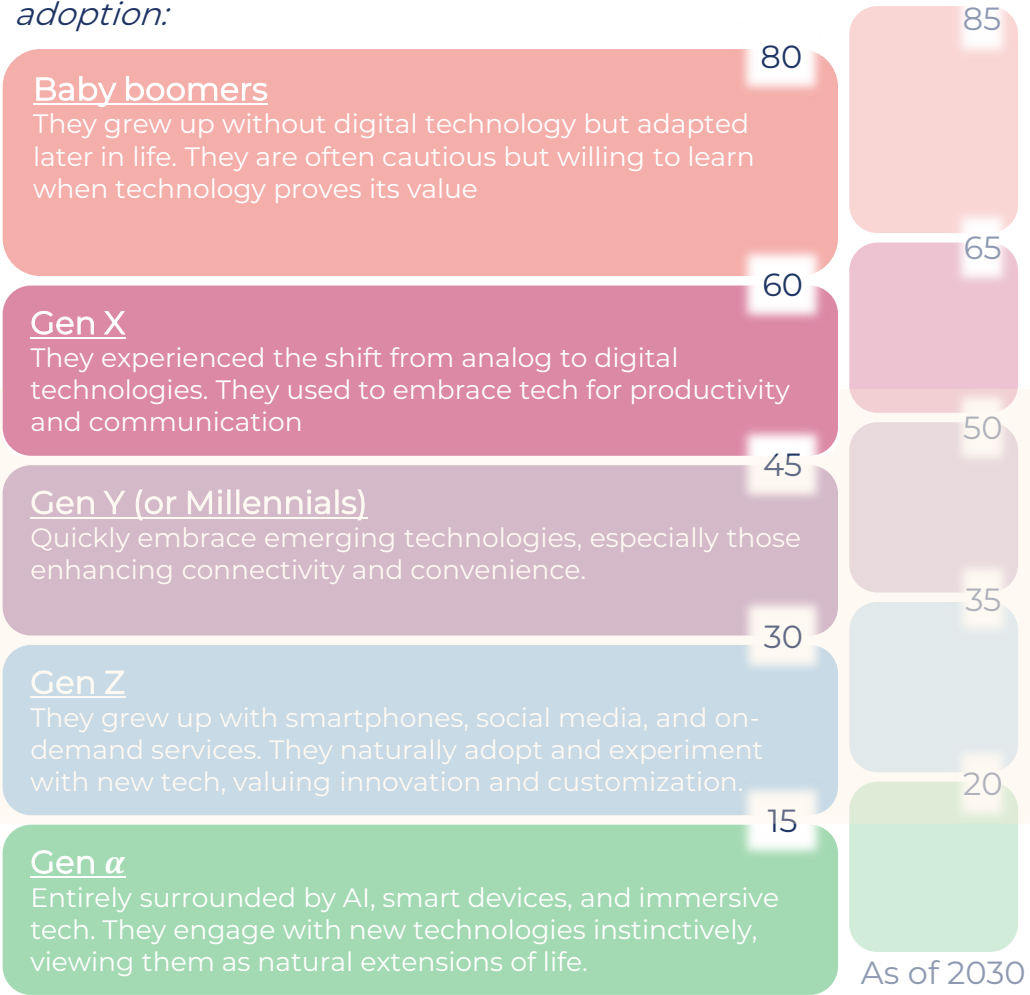
Demographics



Designing the right device and experience requires accurately identifying its target. AR glasses are meant to provide a new platform for “computing” and an AI interface, replacing a daily pair of prescription glasses. Crossing the existing use of corrective lenses and the relation with tech leads to Gen Z and Millennials turning respectively 35 and 50 in 2030 (for the oldest), with a significant proportion of the population needing glasses (>50%).



Even if the definition of generations is not hard science and it may depend on regional singularities, the fact is that getting more and more related to the use of technologies can help us understand the demographic dependence of the AR/AI adoption:



MARKET TRENDS

The promises AI makes to AR



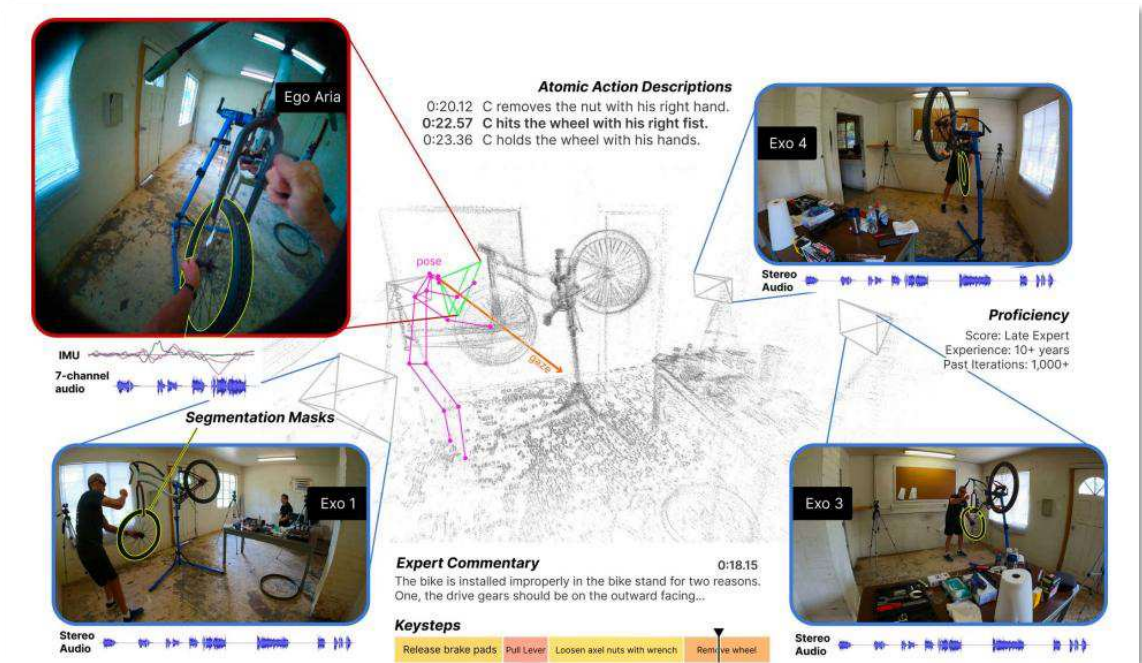
Meta



EGO-EXO4D

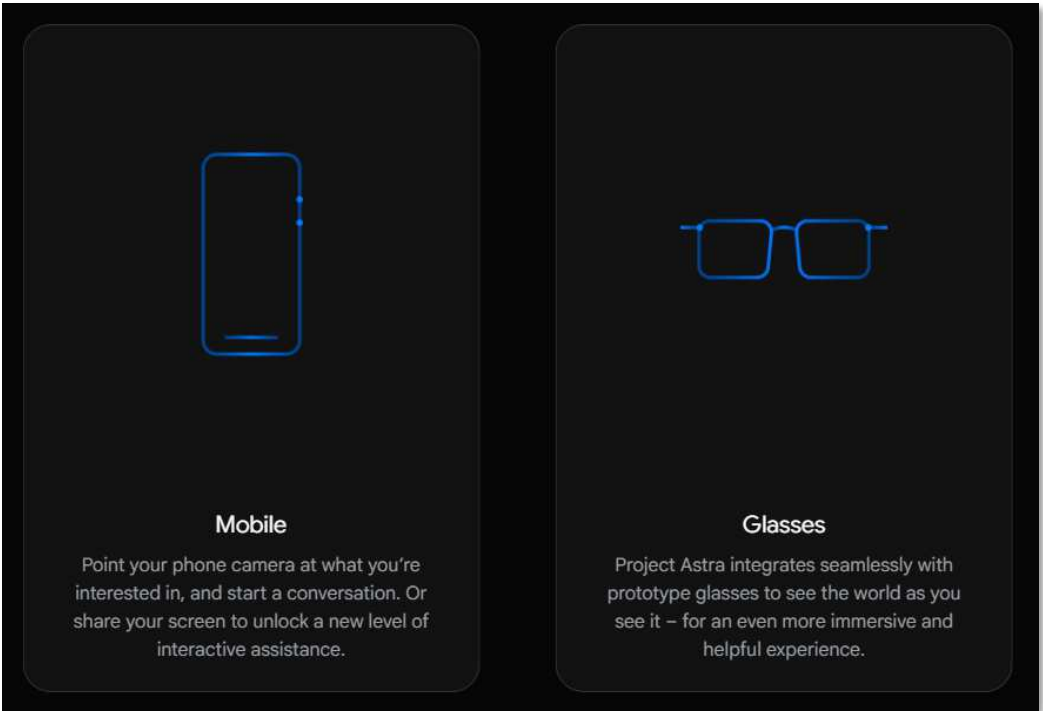


Meta's **Ego-Exo4D** and **Aria** projects focus on **egocentric AI**, leveraging first-person video and sensor data to train AI models capable of understanding and interacting with the world through **AR glasses**. The **Ego-Exo4D** dataset combines **first-person (ego)** and **third-person (exo)** views, allowing AI to learn from multiple perspectives, improving spatial awareness and human-object interaction modeling. Meanwhile, **Project Aria** is a hardware-driven initiative collecting real-world data from **smart glasses with cameras, microphones, and sensors**, enabling AI to build **context-aware assistive applications**. These efforts are shaping **next-gen AI assistants** that understand user intent, recognize objects, and provide real-time contextual feedback, paving the way for immersive AR experiences.



DeepMind

DeepMind's **Astra** takes a broader **generalist AI** approach, aiming to develop an agent capable of **understanding, reasoning, and acting** across multiple domains. Represents a shift towards **embodied AI that can operate in the physical world**, potentially complementing future AR or robotics applications. While Meta's projects are more **wearable-focused**, Astra aims to create a versatile intelligence layer applicable across different hardware and interfaces – **smartphones and Glasses**.



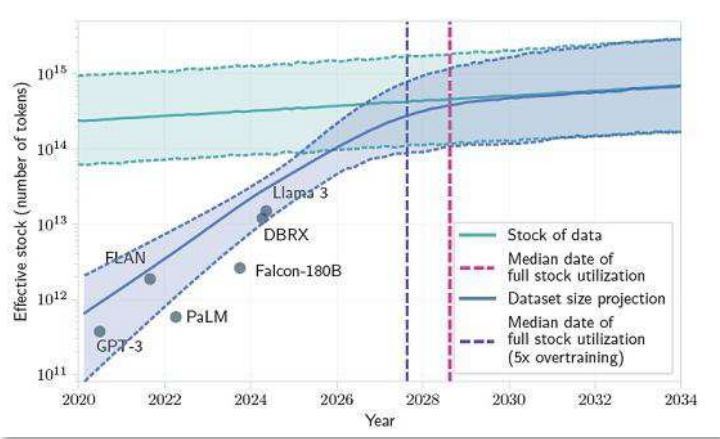
MARKET TRENDS

The AI-related uncertainties

Machine Learning and Generative AI are bringing a lot of use cases, changing habits – some are transferable into AR devices. However, it also relies on a huge amount of data and energy.

Energy and AI chips are costly, so the training of the models (\$100M to \$1B).

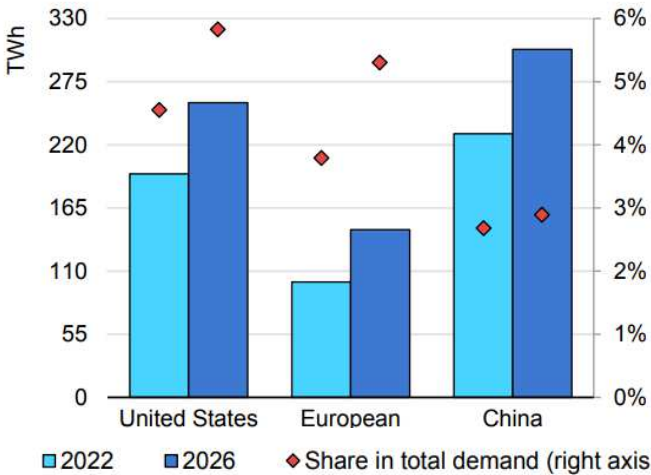
Then, the questions related to ethics and policies remain. Some regions, like the EU, are more cautious, releasing many regulations preventing AI from invading their space.



Source: doi.org/10.48550/arXiv.2211.04325

The training of LLM may face a barrier due to the lack of relevant data. Indeed, the data creation on the internet has a slower slope than the current model size acceleration. The improvement pace of the models we know as of 2024 may not last after 2030 in this regard.

Estimated data centre electricity consumption and its share in total electricity demand in selected regions in 2022 and 2026



Power consumption of data centers is poised to keep growing due to the need for massive computation of AI models. Along with the chips acquisition, energy forces a high investment pace, which may not be sustainable. In terms of sustainability, increasing power consumption may not be aligned with people’s will and governance in the long run.

Source: International Energy Agency



MARKET TRENDS – AR

AI regulations

- AI is both:
 - A highly debated topic by countries from an ethical point of view, which triggers regulations to occur
 - The value proposition behind tech giants' products: An indispensable tool behind tech giants' business model.
- The battle over AI regulation in Europe is an arm wrestle between governance and corporate power, with Meta firmly backed by the U.S. administration. In July 2024, Meta halted the rollout of an AI model in the EU, citing regulatory roadblocks. Weeks later, the company warned that excessive oversight risked sidelining Europe in AI advancement. Despite this, by November 2024, Meta launched AI-driven Ray-Ban Meta smart glasses across key EU markets, proving its ability to maneuver within regulatory constraints.
- The question remains: Who will prevail in this ongoing arm wrestle - the regulators or the innovators?



July 07, 2024

Meta stops EU roll-out of AI model due to regulatory concerns

July 23, 2024

FINANCIAL TIMES

Meta warns EU regulatory efforts risk bloc missing out on AI advances

Meta

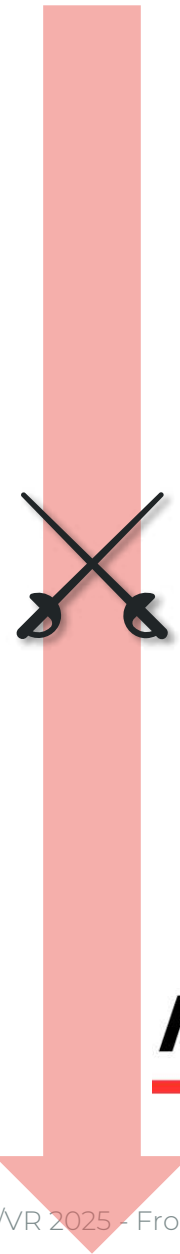
November 18, 2024

Meta AI Begins Roll Out on Ray-Ban Meta Glasses in France, Italy, Ireland and Spain



February 11, 2025

JD Vance rails against 'excessive' AI regulation in a rebuke to Europe at the Paris AI summit





MARKET TRENDS – AR

AR ecosystems and markets – Geographic breakdown

- The Augmented Reality glasses market is poised to be a strongly regulated one, as:
 - It consists of a **medical** device (when embedding a prescription)
 - It seamlessly integrates **AI** (which is regulated on its own)
 - It is promoted by companies experiencing prohibition abroad (Meta's and Google's services have been banned in China since 2009 and 2010, respectively, and ByteDance's TikTok has already feared a ban in the US).
- In the end, **frame designs and technological bricks** should travel **freely** while OEMs' markets are likely to be domestic. If regulations are matched, Europe remains an open market for CN and US players.

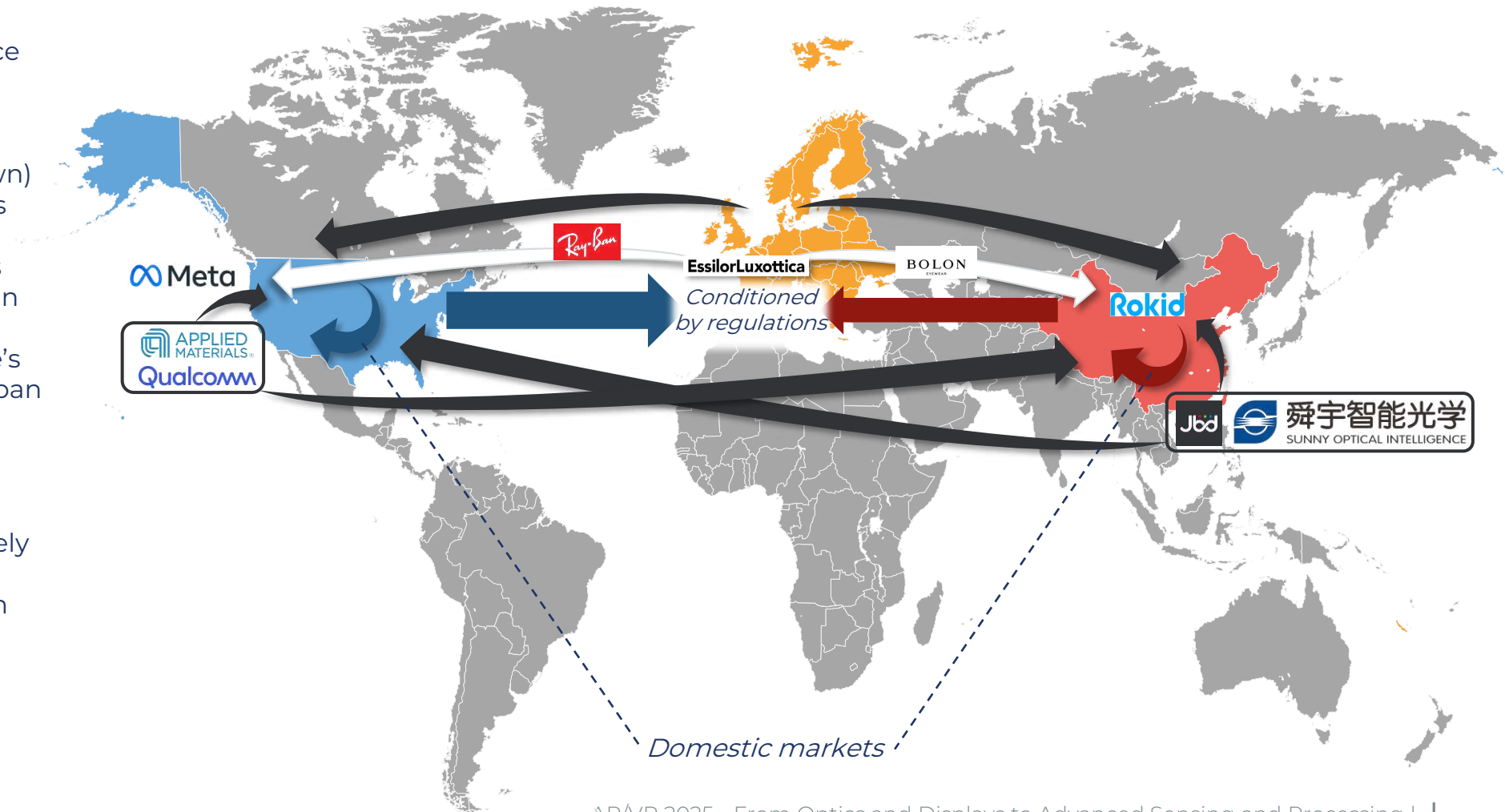
Illustrations of what the exchange could look like between Europe, North America and China

Technological sales

Frames sales

US OEMs sales

CN OEMs sales

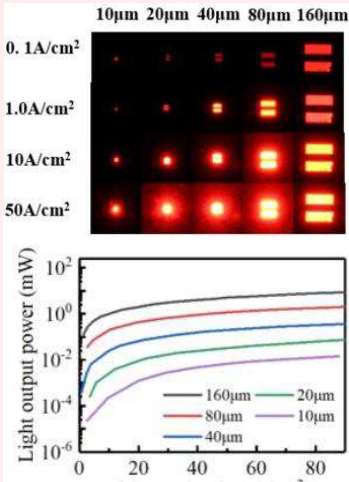


One important discussion to have, envisaging the rise of AR glasses with displays, is the question of chromaticity. Having 3 colors like in any other consumer display devices triggers challenges on the optical side (with several plates for the waveguide or a more challenging single one – some like AMAT, Cellid, or Dispelix demonstrated it was possible), but also on the display side, and more intensely with microLED. Indeed, with an LCoS, it is a matter of temporal integration with Red, Green and Blue being lit up sequentially in the LC unit, but with microLEDs pixels, they need to be Red, Green and Blue on the first hand.

1 color

Red

The issue with red is the low efficiency of the LED dies. Particularly with microLED, the Red efficiency is always the limiting parameter of white peak brightness and may not allow daylight compatibility.



Kaili Fan, *et al.*, « Size effects of AlGaInP red vertical micro-LEDs on silicon substrate », Results in Physics, Volume 36, 2022, 105449,

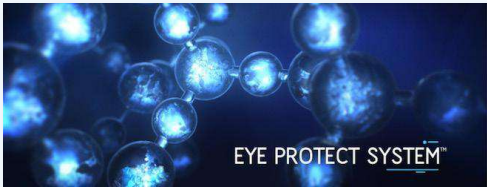
Green

Green is the color that microLEDs are the most efficient in, AND the color that the human eye is most sensitive to. It makes it the best color to use for performing devices. The already existing waveguide-based microLED-based AR glasses advocate it. However, a monochromatic green HUD may be associated with military/tactics use cases and may not appeal to consumers.



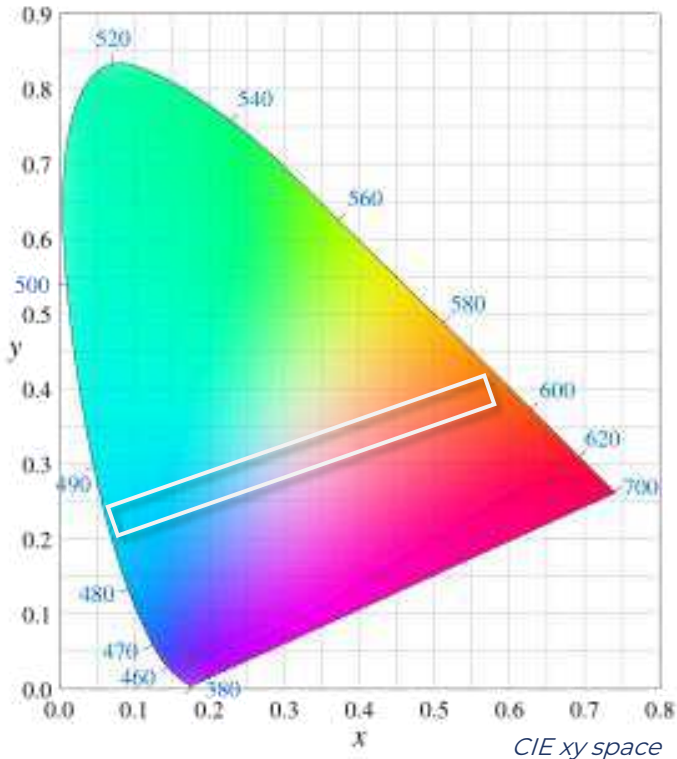
Blue

Blue LEDs are very efficient and less sensitive to die size shrinkage. Also, the color is less tinted than green for other HUD applications, or negativity (red light means “Don’t go” right). On the other hand, blue light has been pointed out to be damaging and causing eye fatigue. Indeed, historical eyewear players have been communicating that they were offering the possibility of having blue-light cutters on the lenses. What if they send it directly to the eyes of the users now with projectors in the temple?



2 colors

No usual Display LED single color is ideal. An odd take could be 2 colors instead of 3, with an Amber/Turquoise display enabling a white in between. Such a non-standard design, however, would present a risk for the light source supplier.



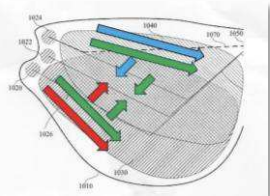
MARKET TRENDS – AR

AR adoption life cycle



Here we are: An exploration phase of possible use cases via LLM interfacing.

Sensitive to the technological solution itself.



Techies

1st Crack



Sensitive to the use cases being AI-agent. The rebranding of AR glasses experienced in 2024 is consistent with the address of the visionaries' market



Techies

1st Crack



The engines of adoption easing:

Price must go down

Form factor and weight should shrink

Friction should be reduced via agreement with classical eyewear supply chain and distribution

Sensitive to compelling and proven use cases. At this point, what is sold is a complete solution including hardware, software and brand—for this segment, referencing matters a lot. It means that the majority of members (rather than Pragmatists or Conservatives) refer to other group members. This causes organic growth in early markets like Techies and Visionaries to stop. A new communication angle must be found, and well-known tech companies are more likely to succeed as they have already earned consumer trust.

The mature solution to be sold to the bulk of the market:



Pragmatists

2nd Crack

Conservatives

This last segment has no room in the time frame considered in this report. They will be not aware or even building arguments to discourage the use of such devices.

Laggards

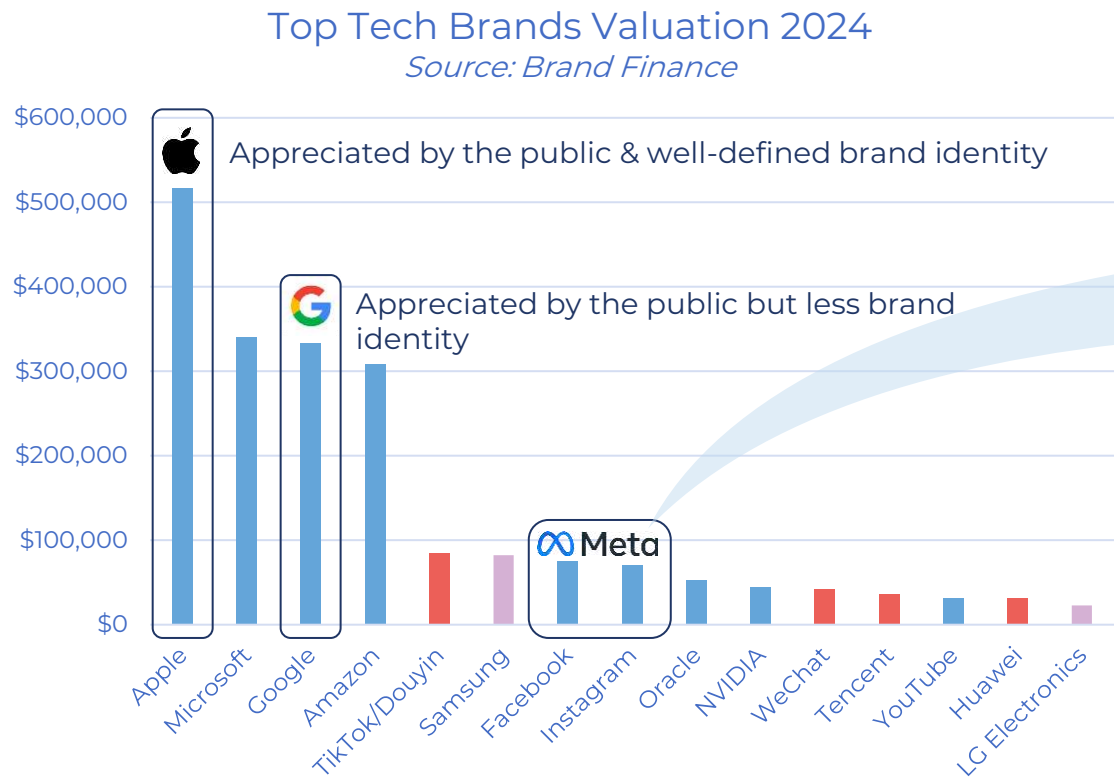
MARKET TRENDS – AR

Multiple design may lead to delays in the adoption life-cycle

- AR glasses can embed many different sensing modules or a display, or not, making the price, the weight, and the form factor vary along a continuum of devices.
- As the BOM expands, so does the price, form factor, and weight; the friction before adoption increases and delays the conquest of bulkier and bulkier consumer markets.
- Moreover, it is also the nature of the modules, so the **features enabled may prevent wider adoption**. Having cameras looking at one's environment, microphones, and eye-tracking features embedded in wearable devices worn all day could scare off potential consumers.
- That being said, consumers' acceptance is a moving obstacle. Surveillance and sharing have been increasingly accepted - incentivized by government policies - and ubiquitous recordings with smartphones and systematic uploads on social networks of daily life.



AR glasses are eyewear in the first place. They are meant to be worn and be part of one’s aesthetic identity. The look matters, it is not like any other piece of consumer electronics, it is a visual statement. An iconic frame from renowned brand is part of the signal sent with the device. By wearing a pair of Ray-Ban Meta, one has access to the feature enabled by the smart eyewear but also displays to the public: *“I am wearing a pair of smartglasses, and it is a pair of Ray-Ban”*.



A partnership between the Tech Giant pushing the most and biggest brand asset in the eyewear industry just feels natural

EssilorLuxottica

alain mikli	AL	ARNETTE	BLIZ
BOLON	Bolton	BURBERRY	BURBERRY
CHANEL	CHAPS	COACH	COSTA
DByD	DOLCE & GABBANA	EMPORIO ARMANI	FEDON
FERRARI	FOSTER GRANT	GIORGIO ARMANI	JIMMY CHOO
LUXOTTICA	MICHAEL KORS	MIU MIU	MOLSION
MONCLER	NATIVE	OLIVER PEOPLES	OLIVER PEOPLES
Persol	POLO RALPH LAUREN	PRADA	PRADA
RALPH LAUREN	RALPH	Ray-Ban	RAY-BAN
Secon	Sferoflex	SWAROVSKI	TIFFANY & CO.
TORY BURCH	UNOFFICIAL	VERSACE	vogue eyewear

MARKET TRENDS – AR

Style matters

- A key question around smart glasses is: When can the frames get thick? Weight is a matter of comfort; volume, let's say, is a matter of style.
- That is the brand's duty to reinvent the trends of glasses frames and enlarge the range of form factors so that the ones embedding electronics do not appear odd. The Ray Ban Meta series was available in different frames:



Thick temples



- In February 2024, Ray Ban appointed ASAP Rocky as the brand's first Creative Director. He wore thick frames with temples that could embed display engines for his press presentation. The brand also released pictures showing new frames to be part of the new identity. The frames thus shown were meant with no doubt to entice with an orientation towards modernity, a futuristic aesthetic within thicker shapes.

Reinforcing its values of innovation, pioneering spirit and courage, global multi-hyphenate artist A\$AP Rocky is now the first-ever Creative Director for Ray-Ban Studios, bringing his distinctive vision and trendsetting influence to guide creative projects that will shape the future of the brand.

This exclusive collaboration is expected to develop the next chapter for Ray-Ban, kicking off with the 'Blacked Out Collection' expected in April 2025.

The collection brings bold ideas to life, with Rocky launching **disruptive frames** that blend classic elements alongside bold and **modern influences**. It includes traditional iconic styles turned 'Mega,' featuring gold-plated details and brand new ultra-black lenses.





MARKET TRENDS – AR

Distribution channels

- Therefore, the acquisition process of a wearable device, intended to be worn on the head – in front of the eyes, is not equivalent to purchasing of usual piece of electronics.
- Before buying a Smartphone, a Notebook or a TV, one would define a budget, its use of the products, look at some reviews and may even buy online without seeing the product physically. These considerations are less true with a Smartwatch and Headphones and Earbuds. In this case, comfort plays a more important role as the rendering in the case of audio products.
- If the act of purchasing AR glasses tends to be within physical places, what will these places be like:

Tech OEMs' physical stores

- Tech companies will benefit strongly from having physical stores to let people try out their AR VR products.
- With respectively >3,000 stores over 60 countries and >500 stores over 27 countries Samsung and Apple are very well positioned.
- Also, Apple has been already been capable of providing a convincing Vision pro experience compatible with almost any prescription thanks to a partnership with Zeiss which provided the inserts.



Image: Samsung



Image: Apple

Historical eyewear franchises physical stores

- Historical eyewear store franchises hold most of the flux and will be necessary to penetrate somehow to address a significant part of the consumers. For instance, EssilorLuxottica has >17,000 stores (including franchising and licensing) and a global presence.



Ultimately, if a flat substrate is a requirement for eyepiece manufacturing, the path to curved lenses enabling prescription could be “encapsulation” of the waveguide within push-/pull lenses.

Patent No.: US 11,630,325 B1
Date of Patent: Apr. 18, 2023

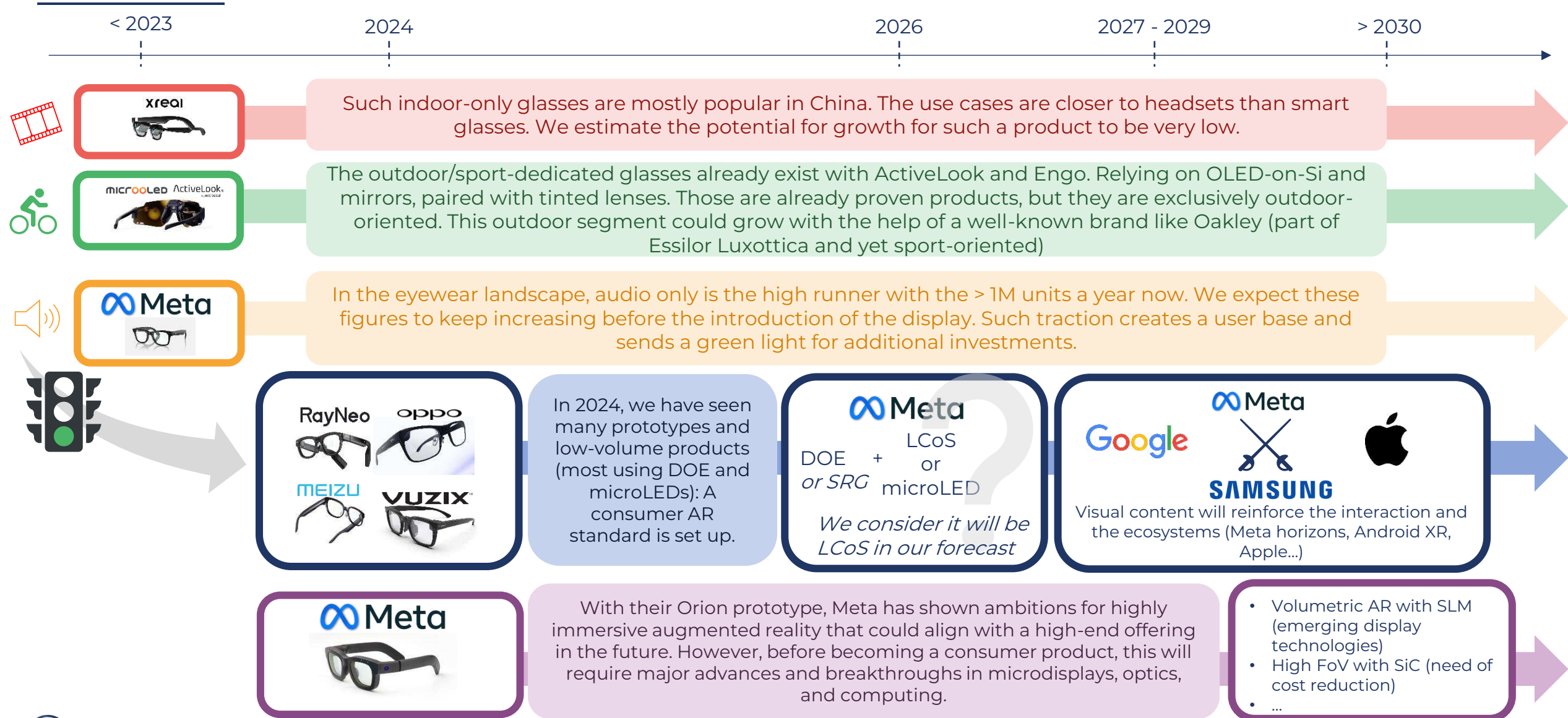
Pub. No.: US 2021/0103146 A1
Pub. Date: Apr. 8, 2021

3D printed lenses

Cellid developed its own proprietary SCL (Small base Curved Lens) which consists in full lamination of the diffractive element on the lens.

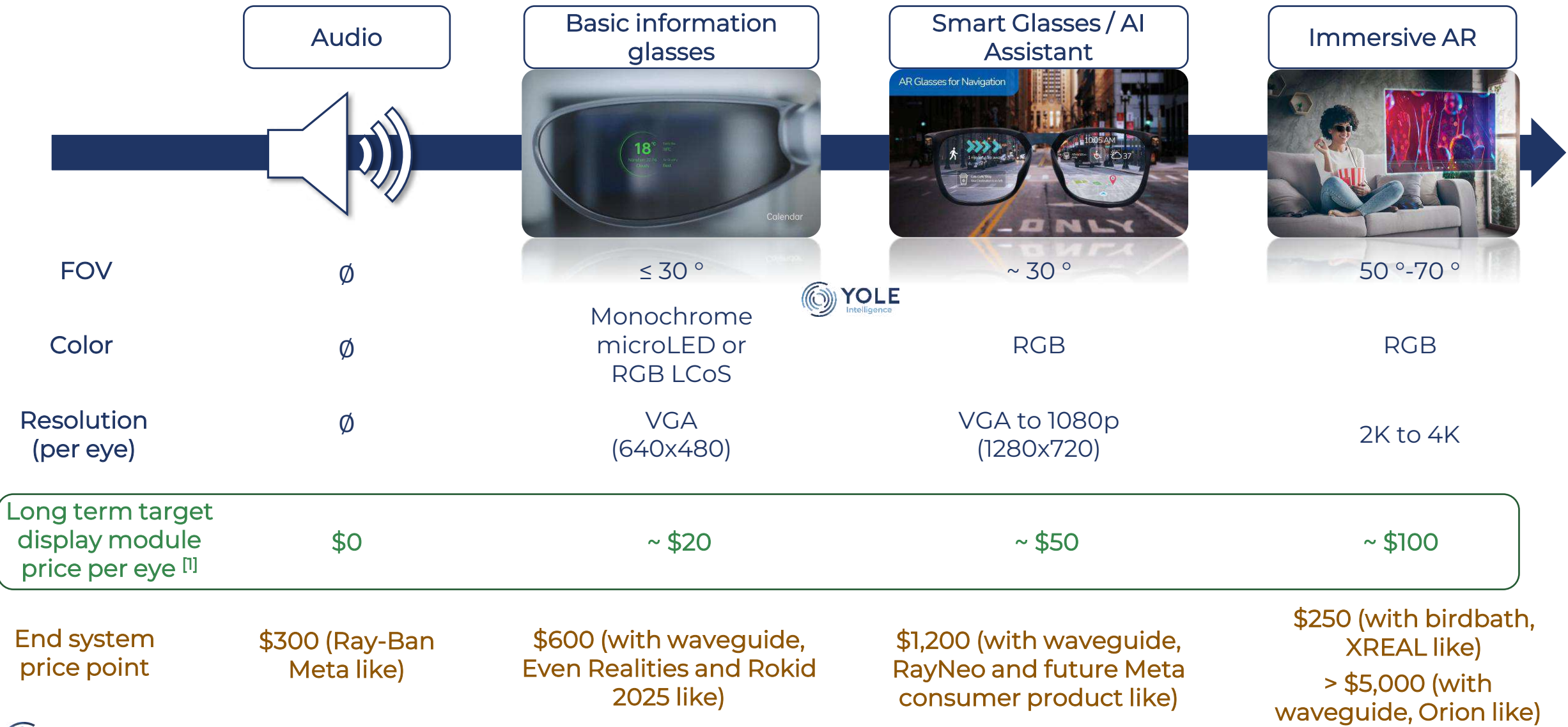
MARKET TRENDS – AR

Consumer AR roadmap



MARKET TRENDS – AR

Taxonomy dependent price point



Market trends - VR

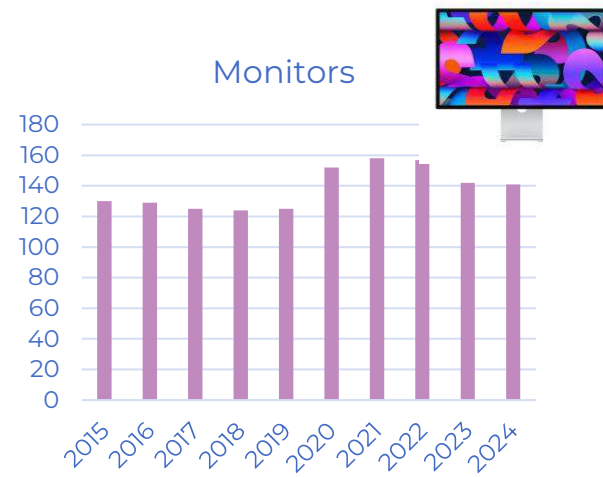
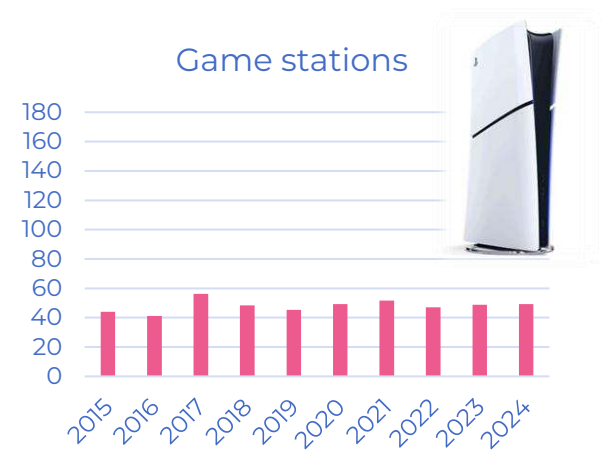


MARKET TRENDS – VR

Broaching the VR market

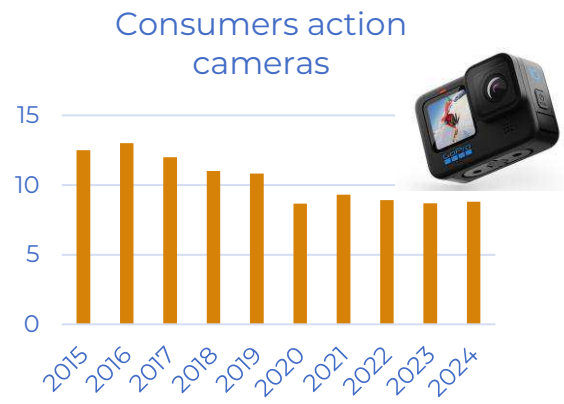
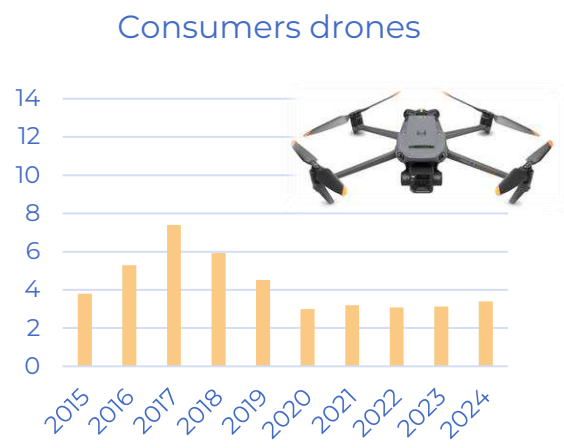
Where it intend to penetrate:

- Historically, the evolution of VR headsets has been deeply intertwined with gaming. Palmer Luckey developed the prototype of the Oculus Rift almost exclusively with this purpose in mind, and the current proportion of games on the Meta Quest store is about 70%.
- After Spatial Computing's rebranding by Apple, productivity use cases have been more targeted, and headsets are envisioned as big monitors. This market is larger and more mature than gaming only and will benefit players with computers being part of their offers, like Apple.



What it may looks like:

- In terms of dynamics, we expect the VR headsets market to face a glass ceiling. This means that as soon as the niche that is sensitive to the value proposition of this kind of device is conquered, the adoption will not propagate to other segments. This is because VR headsets are not convenient. They can not be worn in many conditions, in the street, at work (if it is not part of one's job), socializing etc. It is not like the smartphone or the watch, which cannot trigger a FOMO effect.
- Consumer drones are our reference market for VR. They have a lot in common: there are frictions to using it, few situations allow its use, the value propositions' scope remains narrow, and so does the price. In other words, it's not for everyone.



Discussion on the Apple's VR roadmap

- VR enthusiasts saw the Apple Vision Pro as a savior. Finally, it brings a serious contender to compete with Meta. A more than established player with a great expertise in designing consumer electronics products was about to show its take on VR. For Apple, it was the occasion to demonstrate a superior device in terms of performance with the best-in-class OLED-on-Si Sony display and two processing chips—an M2 and the R1, a specifically VR-oriented chip specifically designed for the Vision Pro.
- It turns out the price was prohibitive. A first-ever VR headset from the fruit company is something special with no equivalent, but if we may risk a comparison, the best option is the release of **the first iPad: 300,000 units were sold within the first 24 hours.**
- Will further iterations, more aligned in terms of performance and price point with consumer expectations, be released? Very likely, but as always with Apple, only rumors feed the « hype » engine.



This renaissance painting-like picture of the journalists has captured the day of its reveal emphasizing on the weight of expectations.

Photo credit: Justin Sullivan



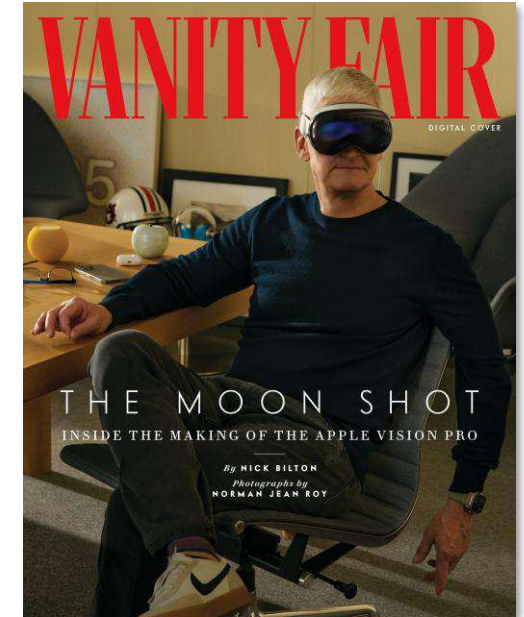
Apple reportedly slashes Vision Pro production, pushes back cheaper model



Apple Vision Pro 2 tipped for 2026 launch, but cheaper headset planned before that



The cheaper Apple Vision Pro will still be painfully expensive, new price rumor claims



Apple has reportedly failed to sell through its entire inventory of the first-generation Vision Pro and has consequently halted its production. The manufacturing volume of OLED-on-Silicon displays does not appear to be the bottleneck; rather, limited demand at such a prohibitive price point is the main constraint. Apple is now said to be focusing on the development of a more affordable version of the product, though it is expected to retain several differentiating components — which will likely keep the overall cost relatively high.

MARKET TRENDS – VR

Some VR use cases



VR remains an experience. The goal is to produce the “wow effect”, to escape for a moment. This was the duty of gaming, where one is immersed in the content by doing, interacting with it. Naturally, this application and the device have created a huge synergy. Oculus has been purchasing it, Meta is pursuing it with Quest, and Sony added the PSVR to their game station. This very use case is still driving the market. At some point, this may be both a boon and a trap, because gaming is associated with an image, and conquering a wider market means getting rid of it.



Meta



Apple



As a VR headset allows for a new modality of interaction with the content, it could lead to new ways of creating art and designs. Here, the target is the Creative/Pro and prosumers – a niche, in other words. The main constraints here are to define new standards for the files to be shared and exploited, adapt software for these new platforms, and build new hardware to enable such production, like the VR brush by Logitech.



Logitech



Ford



Meta often communicated about how their VR products could ease remote work. Employees could use it to connect to the virtual meeting room and bring a sense of presence while working from home. If one may doubt the effectiveness of any possible device to do so, the last back-to-work policy from Meta seems to indicate that on-site meetings are not so easy to mimic.



Meta



hrmasia

Meta continues reversal of remote work policy



Lufthansa



Apple

Meta and Apple both insisted on using VR headsets during long flights. One is through a partnership with Lufthansa, and the other is via its ad campaign. It is not certain that the VR is a painkiller here. The go-to solution should remain a noise-cancellation headset (combined with a blindfold).

Most would better stick with



Apple

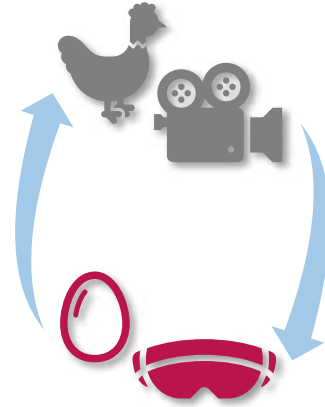
Sony



MARKET TRENDS - VR

Resolution of the display vs. Resolution of the content

- During the Apple Vision Pro demo, anyone can try it in an Apple Store, and several Spatial shots are shown.
- Some stereoscopic videos were captured with the iPhone 15, some with the Apple Vision Pro. The 3D impression is achieved within those, but without the premium look one would expect from a \$3,500 headset.
- At the end of the demo, though, much better-quality shots are shown. Therefore, those were filmed using a dedicated setup combining dual 8K cameras. With these, the experience is completely different and takes advantage of the 23MP resolution of the displays.
- Consuming video footage with a VR headset would be a completely new experience, triggering a chicken-and-egg problem. The experience must be convincing for the viewer to be adopted. Still, a combination of a very high-resolution display and high computation power (within the headset) with the right image-capture device to produce the content will do so.



4K
360°
\$1,000



8K
360°
\$5,000



8K per eye
<180°
\$\$\$

MARKET TRENDS - VR

Prescription compliance of the headsets

- About 60% of the adult population has prescription lenses. Unlike AR headsets, those additional lenses are not visible from the outside, so they don't damage the device's acceptance and compensate for the impossibility of designing a tailored pancake stack for everyone.
- It does increase the price of the overall purchase (<\$100 with Zeiss lenses in AVP, \$50 with Zenni's ones in Quest 3) but improves the user's experience (regarding comfort and immersion).



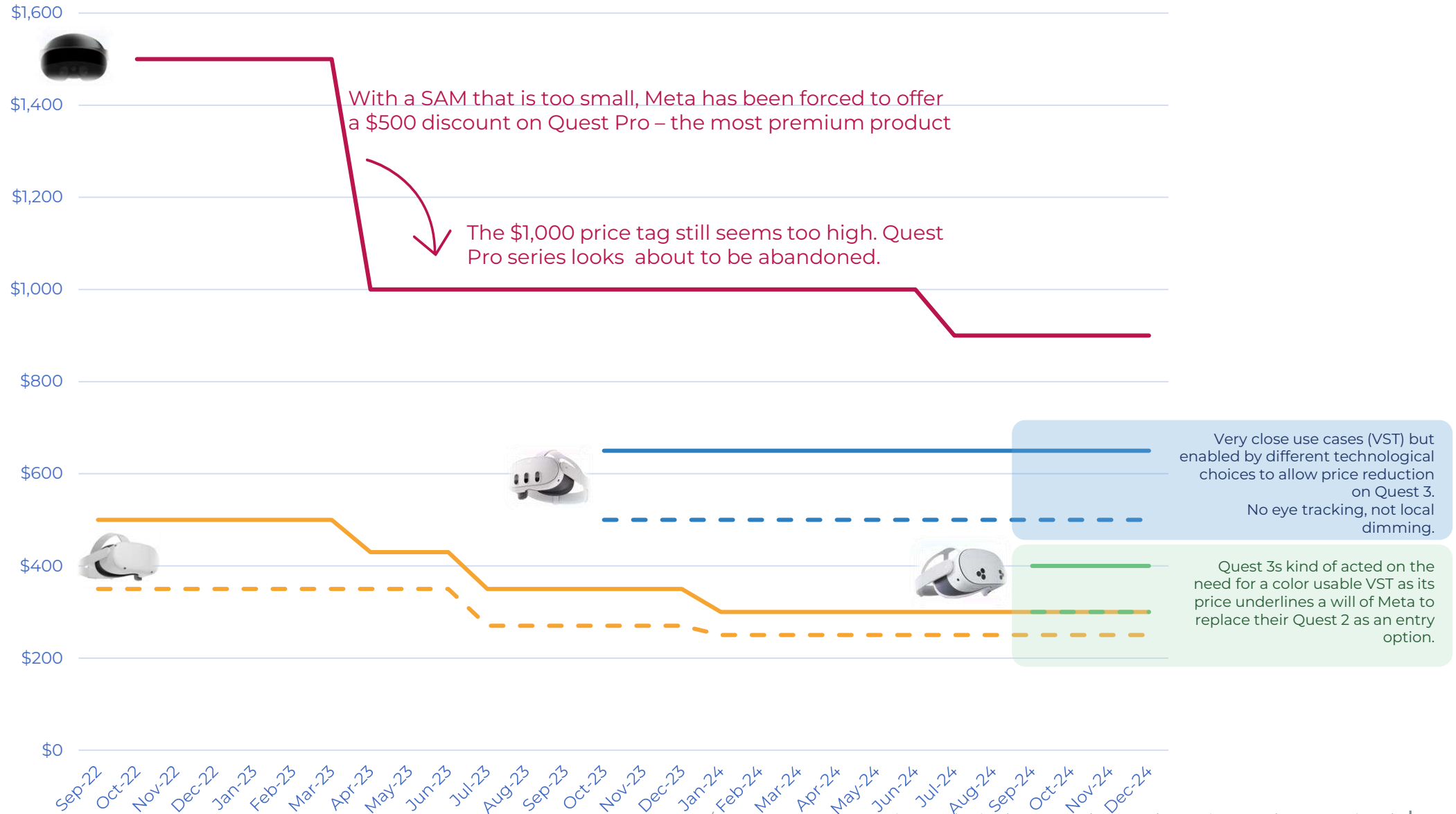
*Image: Zeiss lenses in
Apple Vision Pro*



MARKET TRENDS - VR

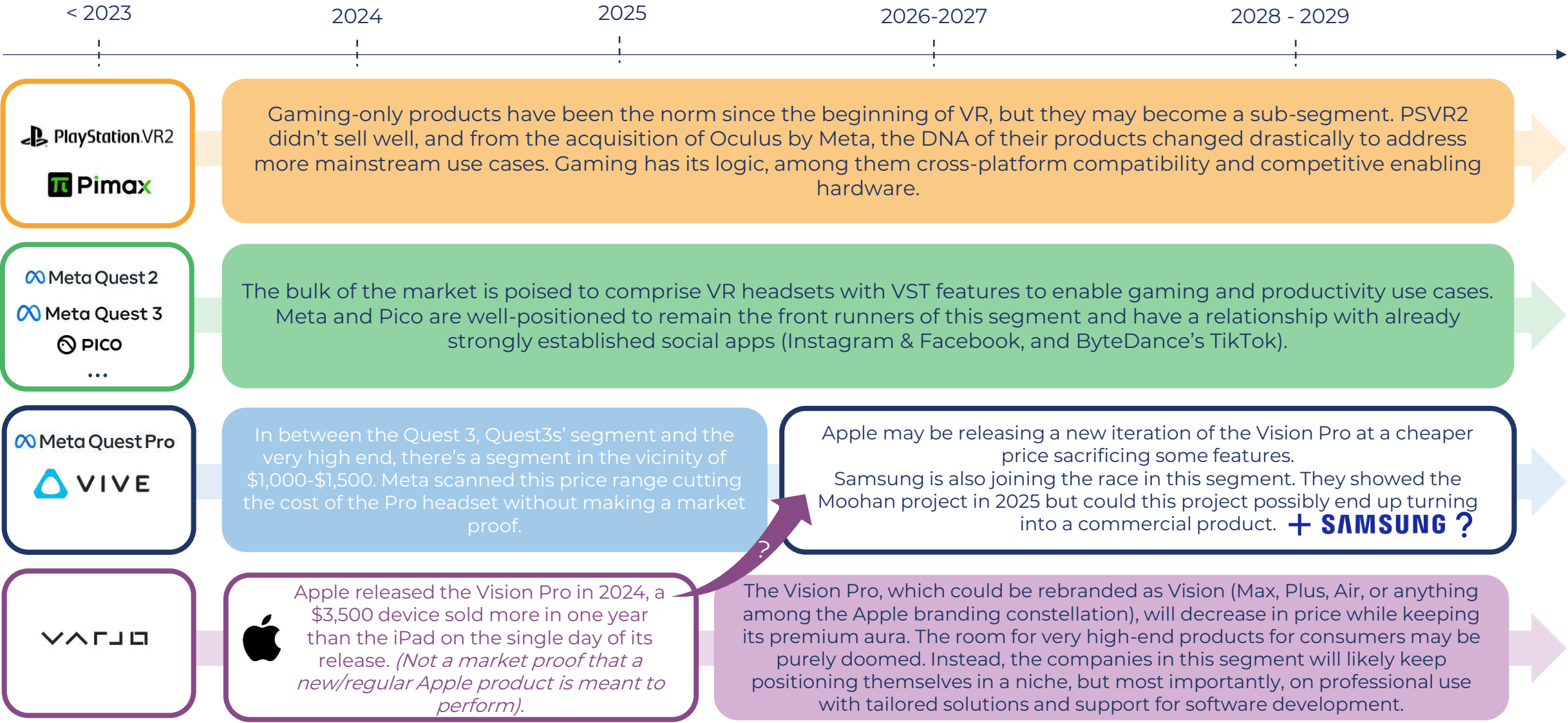
A glimpse at Meta's pricing and positioning

Meta scanned a wide price range before they identified \$300 to \$600 to be the price range of VR for consumers.



MARKET TRENDS – VR

VR products roadmap



Market trends Synthesis



MARKET TRENDS - SYNTHESIS

AR and VR, as markets, will have two very different dynamics

- The VR market is expected to hit saturation around the **10 million units annually**. Despite Meta's effort and Apple's recent legitimization of the devices via a new marketing approach, such range of devices still fails to appeal enough to consumers and spread.
- AR has much more potential to meet a real market ignition. We estimate that those wearables are much more poised to trigger *FOMO*. We should now consider smart eyewear as a continuum of products will be offered from audio only to more and more immersive/interactive solutions. We expect **the smart eyewear market to reach around 15 million units by 2030, and we project the solutions with a display to account for about 85% of that total in 2030**.
- Therefore, we expect the **AR and VR markets will experience very different dynamics with respectively 44% and 4% 2024-2030 CAGR (in terms of units)**. It is a matter of maturity, VR is already there, while AR still has to ignite, but it is also a matter of the very nature of the market being targeted.
- The VR market is essentially revolving around gaming and professional use cases. AR did target professional use cases with former generations of products, but technologies are getting ready (in terms of performance and scalability) to address consumer audiences now. With consumer AR, the targeted market is eyewear and what we call smart eyewear should represent a significant part of it. As part of this market, fashion aspects are critical, and the brands will play an important role in the wide adoption. Except the aesthetic aspect, the value proposition of such electronics embedding glasses is AI. Through 2023 and 2024, many OEMs even rebranded their smart glasses or AR glasses as AI glasses. Ultimately, what is sold is no longer a device but the physical interface with an LLM.
- Such **link between AR and AI** is key to understanding both the rapid adoption we anticipate and the siloed nature of markets that will emerge. Indeed, the front runners of both LLMs and smart eyewear devices are tech giants from the **US** (Meta, Google) and **China** (Xiaomi, Tencent, Alibaba). Access to these services could be restricted, and ongoing trade tensions and tariffs might further encourage a more domestic supply chain tailored to specific geographic markets.

ECOSYSTEM AND SUPPLY CHAIN

ECOSYSTEM AND SUPPLY CHAIN

Major consumer AR ecosystems



ECOSYSTEM AND SUPPLY CHAIN

Industry news 1/2



2018



In 2018, Apple acquired Akonia Holographics, a startup initially specializing in holographic data storage which pivoted to in holographic waveguide for AR.

2019



Facebook acquired Ctrl-Labs (developing wristband based on EMG technology)

2020



In Mar. 2020, Facebook signed a deal with Plessey, which appears to have since transitioned into its epi service anch



In Oct. 2020, Nagase – trading and manufacturing chemicals and advanced materials company - fully acquired Inkron

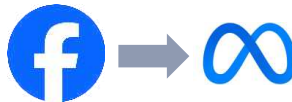


Google acquired North (LBS-based AR glasses maker)

2021



In May. 2021, Snap acquired WaveOptics for \$500M



Facebook was rebranded as Meta and started promoting Metaverse



Byteance acquired the VR company Pico for \$3B



Varjo (VR high-end) raised \$54M

2022



In Jan. 2022, Snap acquired Compound Photonics (LCoS and MicroLED)



Snap acquired Nextmind (brain-computer interface start-up)



In May. 2022, Google acquired Raxium, a LED-on-Si start-up



Microsoft and Qualcomm announce a partnership to develop chips specifically for AR headsets, supporting Microsoft's Mesh and Qualcomm's Spaces

ECOSYSTEM AND SUPPLY CHAIN

Industry news 2/2

2023



In May, 2023, Samsung acquired eMagin (OLED-on-Si) for \$218M



In Feb. 2023, Samsung, Google and Qualcomm announced starting a collaboration to deliver a product within the AR|VR|MR space



Meta acquired Luxexcel, a printed optics solution provider



Porotech integrated Foxconn microLED micro display supply-chain



Snap, Inc acquired GrAI Matter Labs in Oct. 2023

2024



Cellid started collaborating with GIS and Ohara.



Vuzix started a partnership with Quanta Computer including a 3 phases \$20M investment to boost their manufacturing capabilities



In May, 2024, Google and Magic Leap announced a strategic technology partnership leveraging on Magic Leap's expertise in optics



In Sep. 2024, Meta and Essilor Luxottica announced a new long-term agreement



Rokid announced partnership with Bolon (EssilorLuxottica group) during their Jungle event in Nov. 2024



Vuzix (OEM) and Avegant (display engine maker) announced a joint design development



NILT raised \$31M to increase manufacturing capacities



In Jun. 2024, Ultraleap announced a strategic partnership with Prophesee and TCL RayNeo



In Jan. 2024, Sony and Siemens announced a partnership to make a pro-oriented VR headset



In Sep. 2024, ROE acquired NILT for \$300M



Xiaomi and Goertek were reported partnering to make AI/AR glasses in Nov. 2024

2025



Swave raised \$28M as a Serie A funding.



Dispelix and Mitsui Chemicals started collaborating on polymer-based AR eyepiece



Cellid raised \$13M to scale AR eyepiece manufacturing



Vuzix has acquired an advanced waveguide R&D facility in Milpitas, California, to strengthen partnerships with OEMs and ODMs



Microoled, Quanta and ST Microelectronics partnered to release a reference design



Google acquired AdHawk (MEMS-based eye-tracking) for \$115M



ASMPT subsidiary Critical Manufacturing has announced that Plessey has implemented its Manufacturing Execution System (MES) to support MicroLED's experimental manufacturing processes.

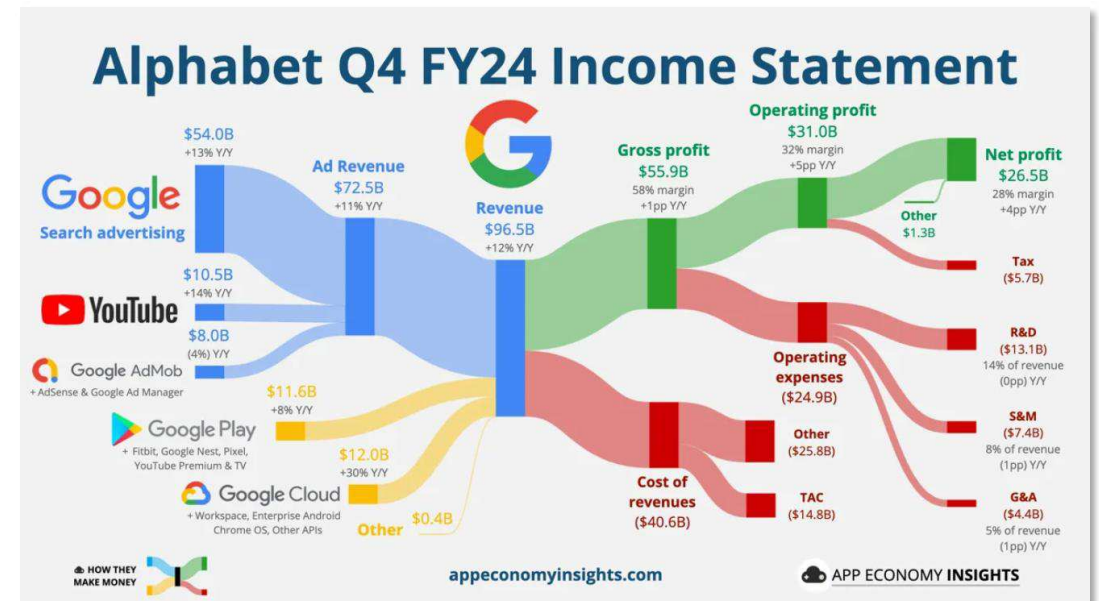
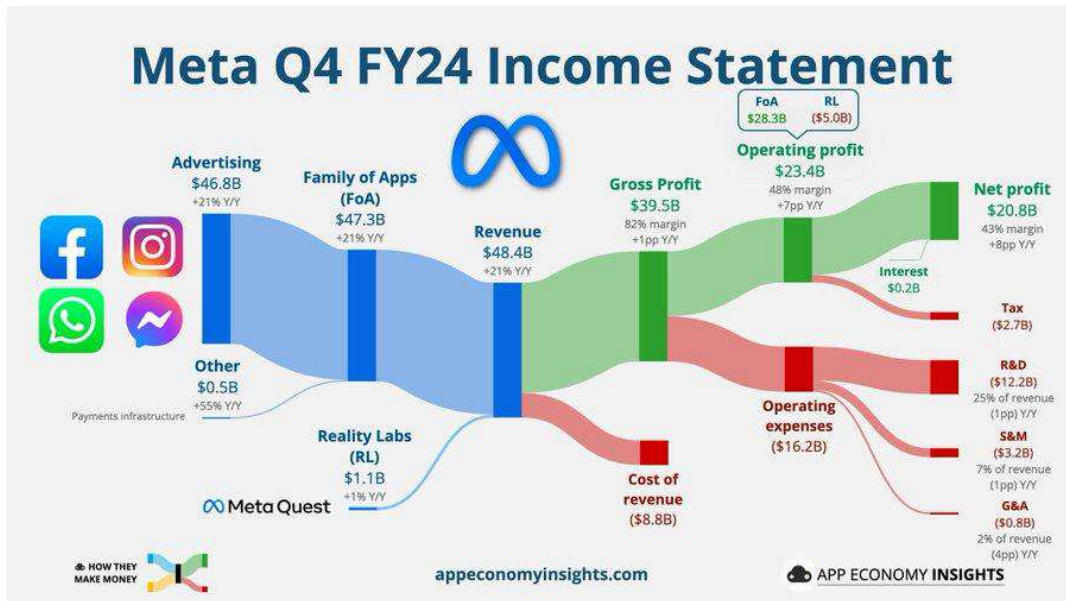
Ecosystem and Supply Chain - Players analysis



ECOSYSTEM AND SUPPLY CHAIN - PLAYERS ANALYSIS

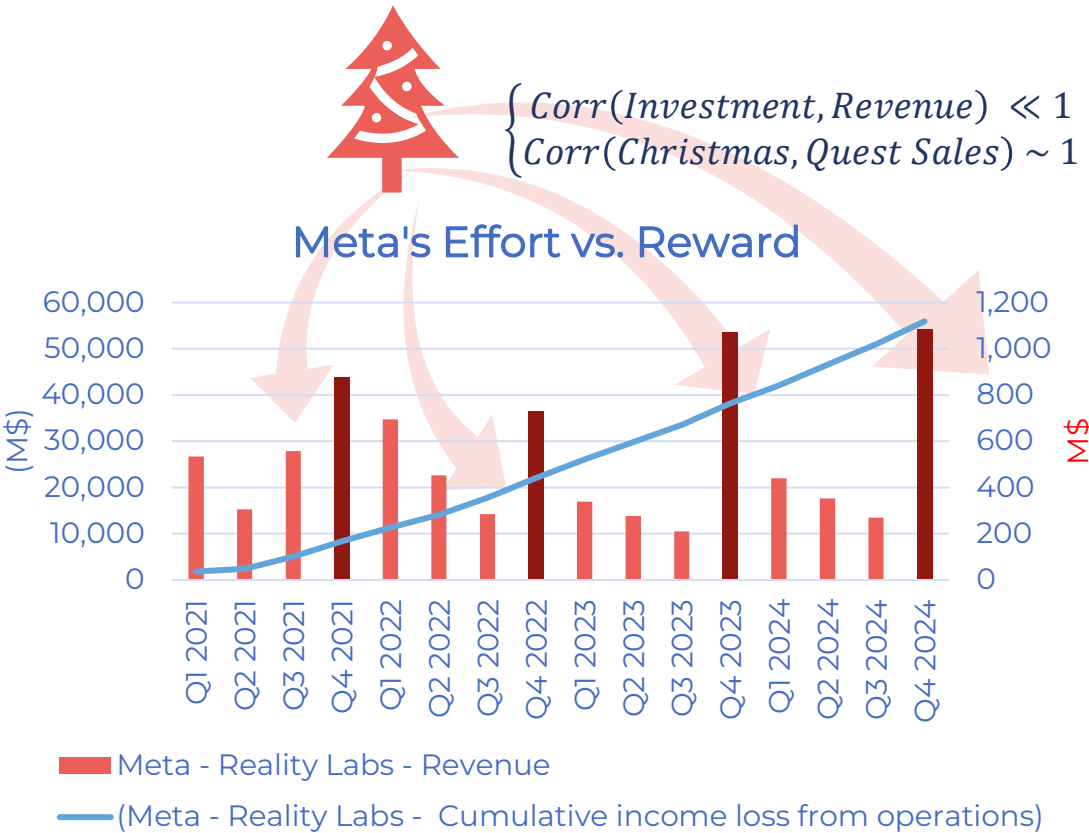
The strategy behind Meta and Google's push towards AR adoption

- **Meta** and **Google** are essentially advertising companies, with this segment accounting for > 90% and > 80% of their revenue, respectively.
- That being said, their advertising revenue streams result from a bit different strategies. For instance, behavioral understanding and recommendations algorithms play a more important role among Meta's Family of Apps (Instagram ahead) rather than Google search-based advertising.
- In other words, the **engagement modality differs from Meta to Google**. In a caricatural way, you could say that a meta user is passive, whereas a Google user is more proactive.
- "How would these business model differences translate in terms of design within the AR realm, and how would such devices be consistent with their business models?" are the right questions to answer.
- Unlike Meta, Google has a record in mainstream consumer electronics hardware design with phones (from 2010) and watches (from 2022). Google failed with its Glass hole in 2012, while Meta failed with its Metaverse wording.



What does the long-term Meta's involvement reveal?

- Meta's investment in AR and VR, which can be accounted for as the Reality Labs operating loss, remained constant over time and reached **\$56B by the end of 2024**.
- Such consistency underlines Meta's long-term ambitions, but the Quest series fails to fulfill them.
- This path of suffering must precede a strong payoff that only a smart eyewear product range can offer.
- Indeed, smart eyewear is a more promising market in terms of size, with better potential to spread. **A product designed to be worn all day and used as an interface between the world and its user seems to be the ultimate piece of hardware to serve Meta's interests.**
- Meta exhibits a strong ambition, which is a given for the industry, but the remaining question is: When will the inflection point occur? And as Meta is the figurehead of AR, **when will Mark Zuckerberg appear on stage with a consumer product closer to the consumer expectations, with a display in it?**

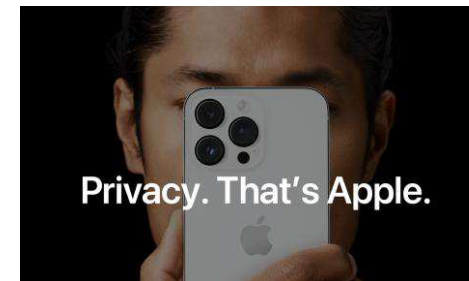
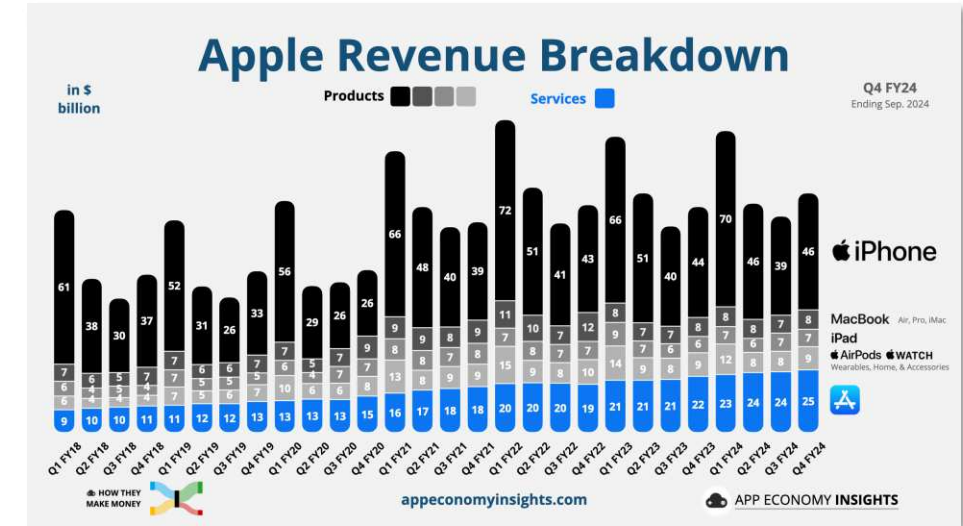


ECOSYSTEM AND SUPPLY CHAIN - PLAYERS ANALYSIS

Apple long term strategy on AR & VR



- Apple's revenue breakdown leaves more room for services, apps and cloud.
- On the other hand, AI, which is ultimately the value proposition of AR glasses as we think, strongly adopts the SaaS model.
- ChatGPT runs inference in clusters, which is demanding regarding energy and bandwidth, so a one-time purchase could not amortize the costs.
- In the end, Apple could send glasses with the intention of generating revenue from feature subscriptions.
- If, as we expect, VR is poised to keep being niche while AR has the potential to conquer a bulkier part of the consumer electronics market, the Vision Pro consists of claiming to have the better conception of what augmented or mixed reality, or spatial computing must be.
- In the end, a \$3,500 VR headset can not conquer more shares than the early adopters/innovators pool. They may propose another iteration with fewer features (fewer cameras, no exterior display etc). Such a test could be a good opportunity to test if Apple can enter a niche among the early majority and further expand (where Meta didn't succeed).



Images: Apple's communication

From an optical technology to an augmented vision system for military, the story of the HoloLens.

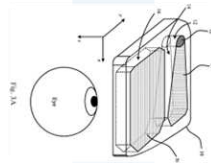


A FINNISH CONNECTION: THE MYSTERIOUS TALE OF HOLOLENS

January 29, 2015

Nokia's expertise in optical technologies may have influenced Microsoft's HoloLens development after the 2014 Nokia acquisition. While HoloLens was already in progress before the acquisition, Nokia's research, patents, and talent likely accelerated its advancement, particularly in optical technology.

NOKIA



Microsoft is discontinuing its HoloLens headsets

Oct 1, 2024

Microsoft has officially discontinued its HoloLens 2 mixed reality headset. Production has ceased, and while existing units remain available for purchase until stock is depleted, no successor has been announced. This move signifies a strategic shift for Microsoft in the mixed reality space. The company planned to focus on first-party software solutions and services, partnering with other mobile and mixed reality hardware providers.



REUTERS

Anduril takes over Microsoft's \$22 billion US Army headset program

February 11, 2025

Defense technology startup Anduril, founded by Palmer Luckey – also the founder of Oculus - is set to take over Microsoft's \$22 billion contract to develop and produce the U.S. Army's Integrated Visual Augmentation System (IVAS). The IVAS program aims to enhance soldiers' situational awareness by integrating augmented reality (AR) and virtual reality (VR) technologies into a wearable system. Under this agreement, Anduril will manage future hardware and software development and delivery timelines for IVAS, with Microsoft Azure serving as Anduril's preferred cloud platform for all related workloads. The agreement is pending approval from the U.S. Department of Defense. Additionally, Anduril has partnered with OpenAI and Palantir to enhance the use of defense data for artificial intelligence training.

ANDURIL



ECOSYSTEM AND SUPPLY CHAIN - PLAYERS ANALYSIS

Magic Leap's evolution

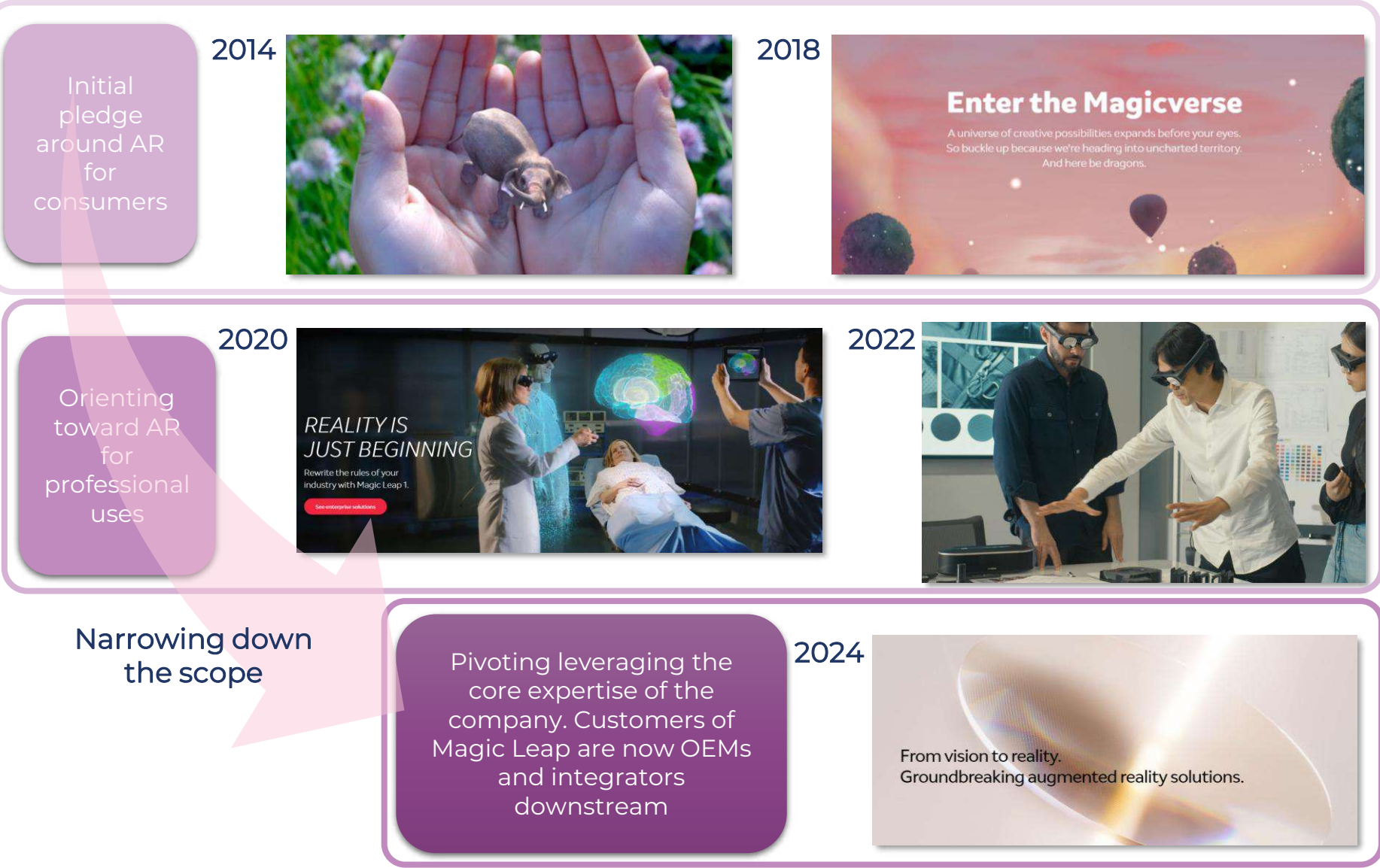
- Magic Leap's evolution speaks for the whole AR ecosystem.
- During 2010, AR faced technical challenges related to optics and displays, but there was also a lack of use cases. The value proposition was still nebulous.
- MagicLeap had to pivot around the pledge made to consumers and reorient into professional use cases – targeting low volumes but still struggling to meet them.



Magic Leap 1, 2018

Magic Leap 2, 2022

- By the second half of 2024, their positioning will be clearer. They intend to capitalize essentially on their expertise which is waveguide design and engineering. They may do that concretely through a partnership with Google, a long-time partner present at most fundraising events.



ECOSYSTEM AND SUPPLY CHAIN - PLAYERS ANALYSIS

EssilorLuxottica's critical role and ambitions

- EssilorLuxottica is dominant in the eyewear/eyecare market they estimate around \$120B a year. They lead in terms of market shares and leverage a wide range of assets including complete supply chain, brands, frame design, global sales channel with physical stores franchise, trust etc.
- There is no doubt that EssilorLuxottica is the ideal ally for any company with ambition in the AR field.
- The company is turning more and more into tech with the acquisition of technological bricks and a partnership with OEMs.



Occurrence of the terms in their Universal Registration Document:

Meta	0	0	14 (Facebook)	10	5	30	34
Augmented reality	1	1 (Mentioned as a risk of new range of competitors)	1	1	7	6	2
Smart eyewear + Smart glasses	2	2	5	21	36	24	30
TOTAL	3	3	15	32	48	60	66

Growing interest



nuance audio
in tune with life





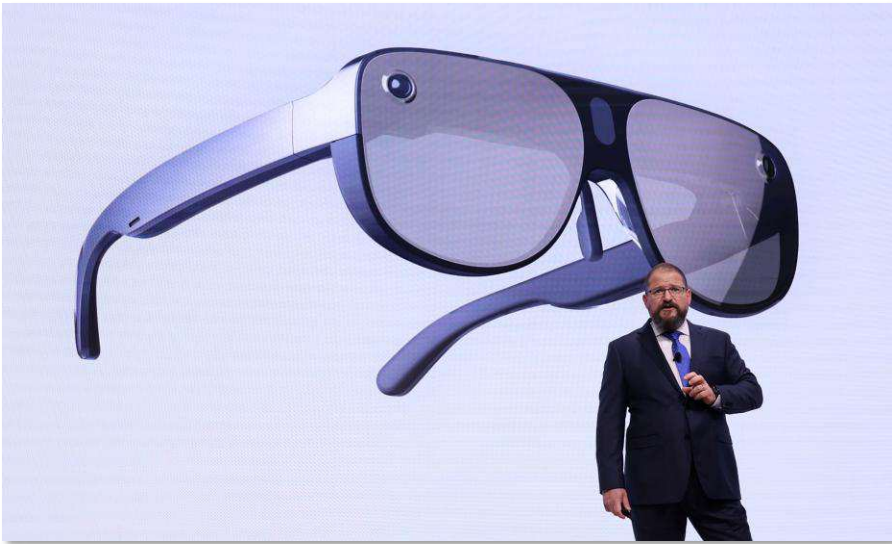
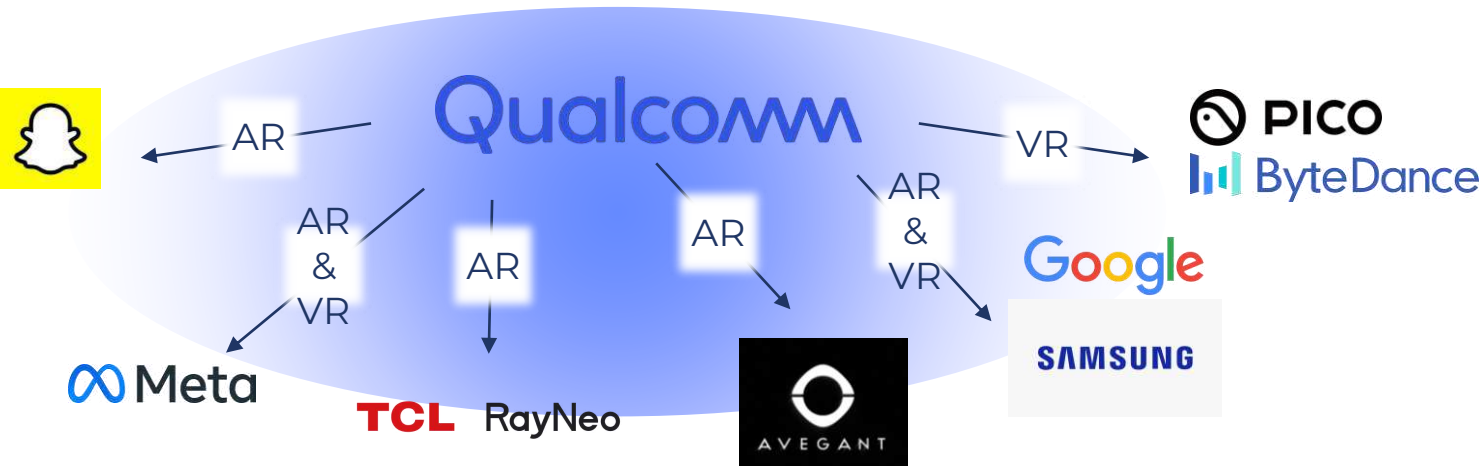
YOLO
Group

huguodong@cmbchina.com

2025-05-13 00:22

Qualcomm

- Qualcomm is poised to lead the processing chips supplier for AR and VR devices. Most mobilizable assets already have a strong presence in wearables, portable consumer electronics, chips, and expertise in AI-embedded functions on chips.
- As AR glasses (and VR headsets) are wearables with AI being at the core of the value proposition, Qualcomm should naturally be a key player in AR adoption, contributing to the effort and being rewarded with a large share proportion.

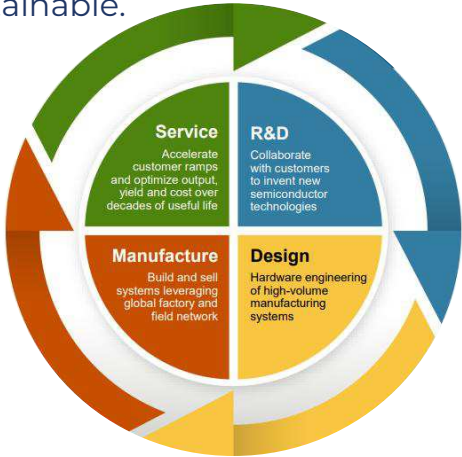


ECOSYSTEM AND SUPPLY CHAIN - PLAYERS ANALYSIS

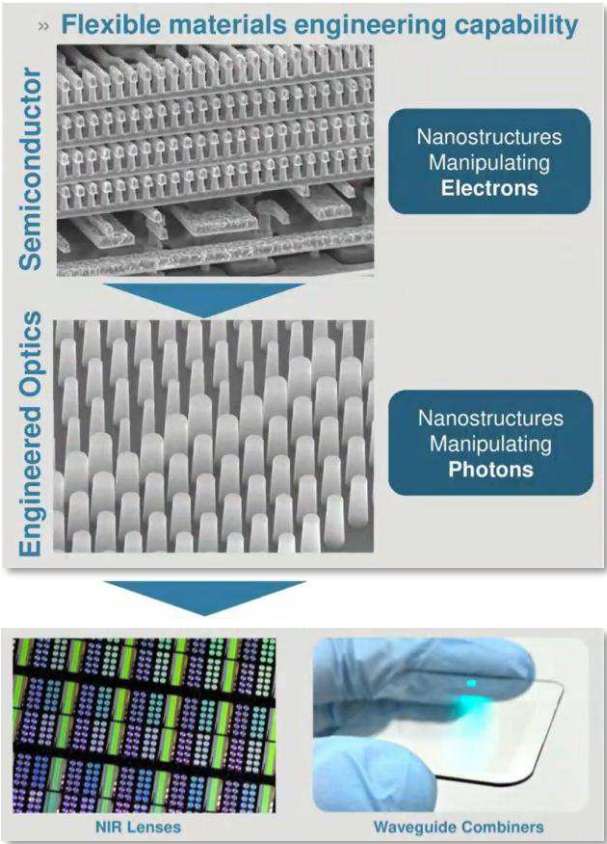
Applied Materials



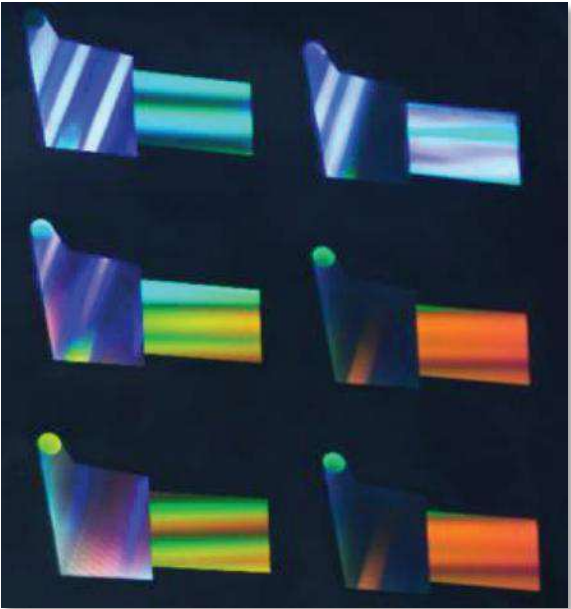
- AMAT is confirming the manufacturing synergies between AR eyepieces and metasurfaces-based optical components to operate in NIR.
- Such a move also underlines the relevance of the manufacturing platform's role in the optical metasurfaces ecosystem. A big, already renowned company could address the manufacturing of various and ambitious designs from both a performance and scalability point of view.
- Amid its Engineered Optics platform, Applied Materials intends to provide the ecosystem with a one-stop shop to manufacture metasurfaces on up to 300mm wafers for various applications, including AR waveguides and NIR lenses.
- Their capabilities include UV or nanoimprint lithography and etching, both binary and slanted gratings are obtainable.
- The manufacturing platforms are occupying a central position in the emerging supply chain.
- Therefore, such service providers will have to grapple with issues related to the OEMs' needs, design issues, manufacturing limitations, etc.



Scheme from Applied Material earning calls



AMAT's transfer of technology to optics



AR waveguides fabricated by AMAT and based on Dispelix design

ECOSYSTEM AND SUPPLY CHAIN - PLAYERS ANALYSIS

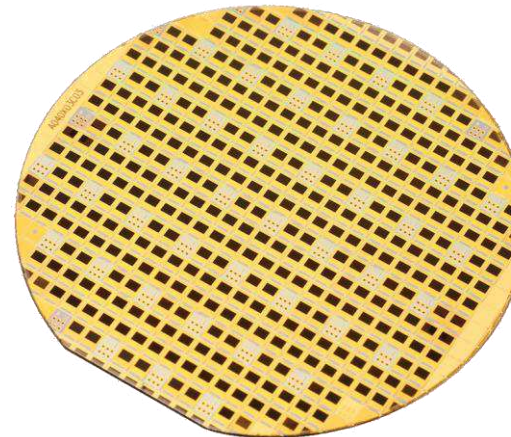
Jade Bird Display



- JBD is, as of Q1 2025, the only company shipping microLED products in volumes.
- We estimate that JBD has raised more than \$233M to date. Strategic investors include **Samsung**, **BYD**, **Geely**, and **Alibaba**. The company has more than 550 employees.
- In October 2023, JBD completed phase 1 of its new fab in Heifei for \$205M (RMB 1.5b).
 - 52,000m² with 14,000m² of clean room.
 - Integrates all manufacturing steps from epitaxy to display testing.
 - Current capacity as of June 2023: 3000 x 4" wpm.
 - Design capacity of 20k x 4" wpm (~100M displays per year)^[2].
- Full integration from epitaxy to module enables fast development cycles and control of every aspect: a strong differentiator against its LED-on-Si competitors which are mostly fabless and rely on various partners for each process step.



Views of JBD's recently completed Heifei Fab (source: company)



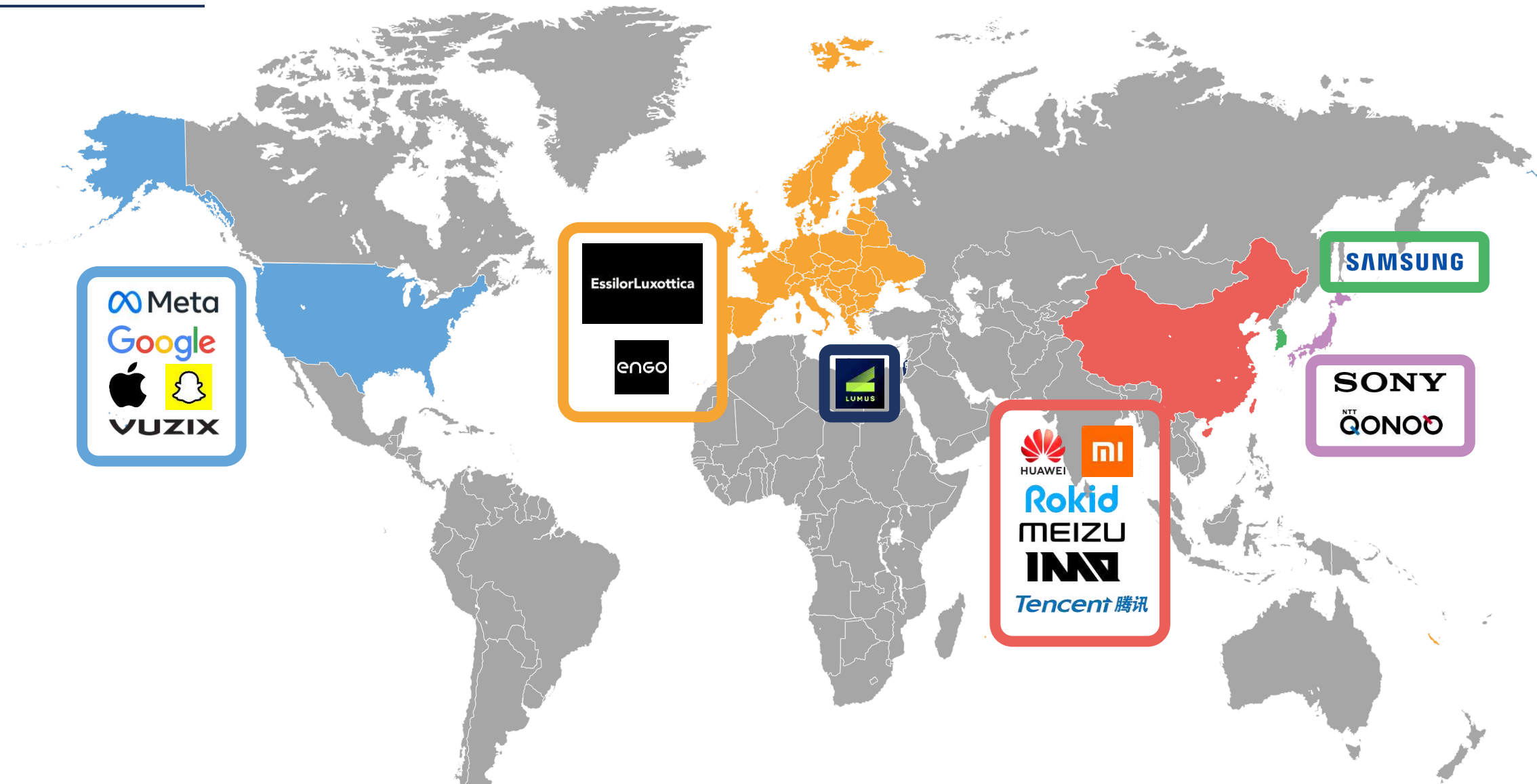
More than 300 x 0.13" microLED array chips are produced on each of the 4" sapphire or GaAs wafers that the company uses in production.

Seven of those 4" wafers are then hybridized on 300mm CMOS backplanes (see the technical section of this report).

Ecosystem and Supply chain – AR

ECOSYSTEM AND SUPPLY CHAIN – AR

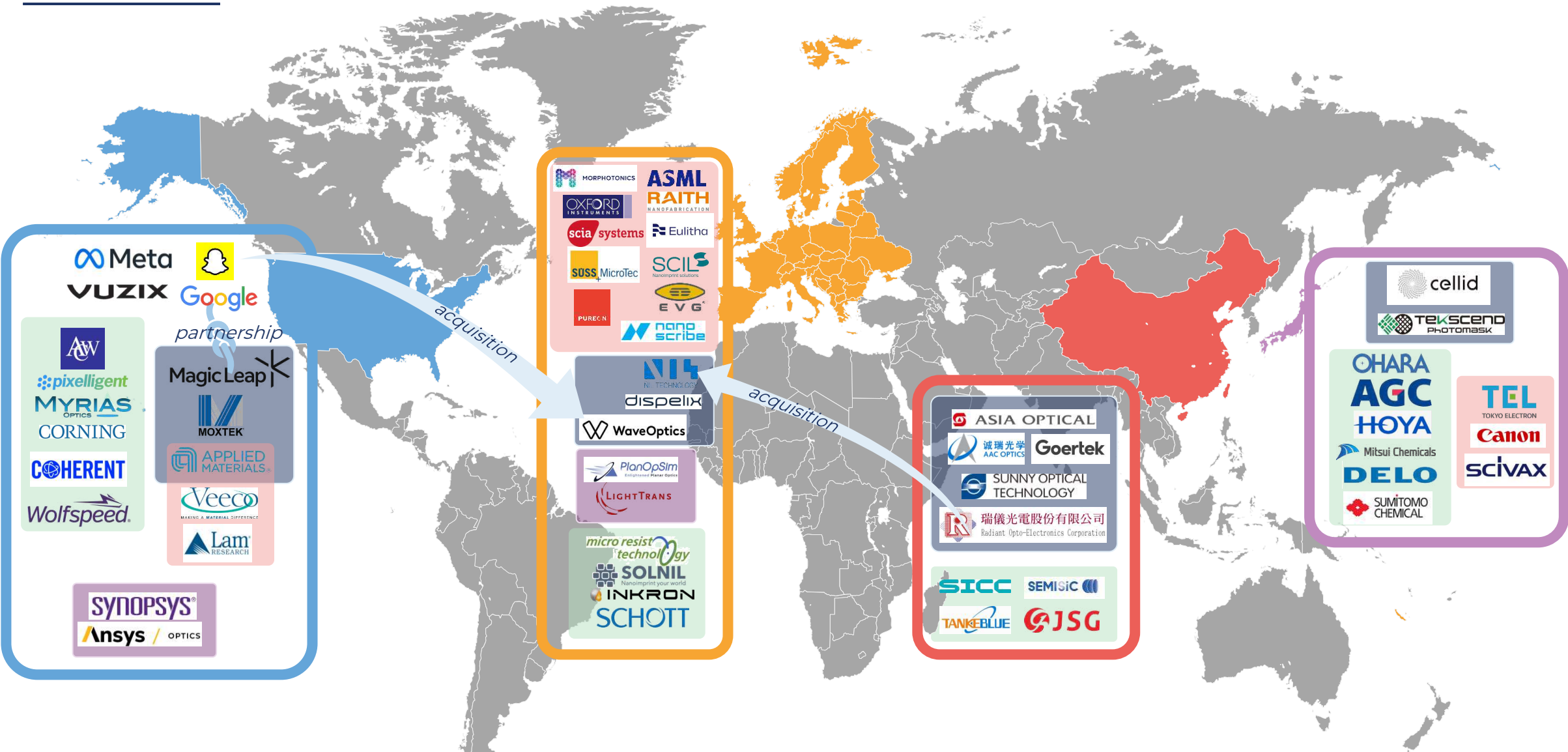
The map of the AR OEMs



ECOSYSTEM AND SUPPLY CHAIN – AR

The map of the AR optics makers

- Equipment
- Design and/or manufacturing
- Material
- Simulation tool



ECOSYSTEM AND SUPPLY CHAIN – AR

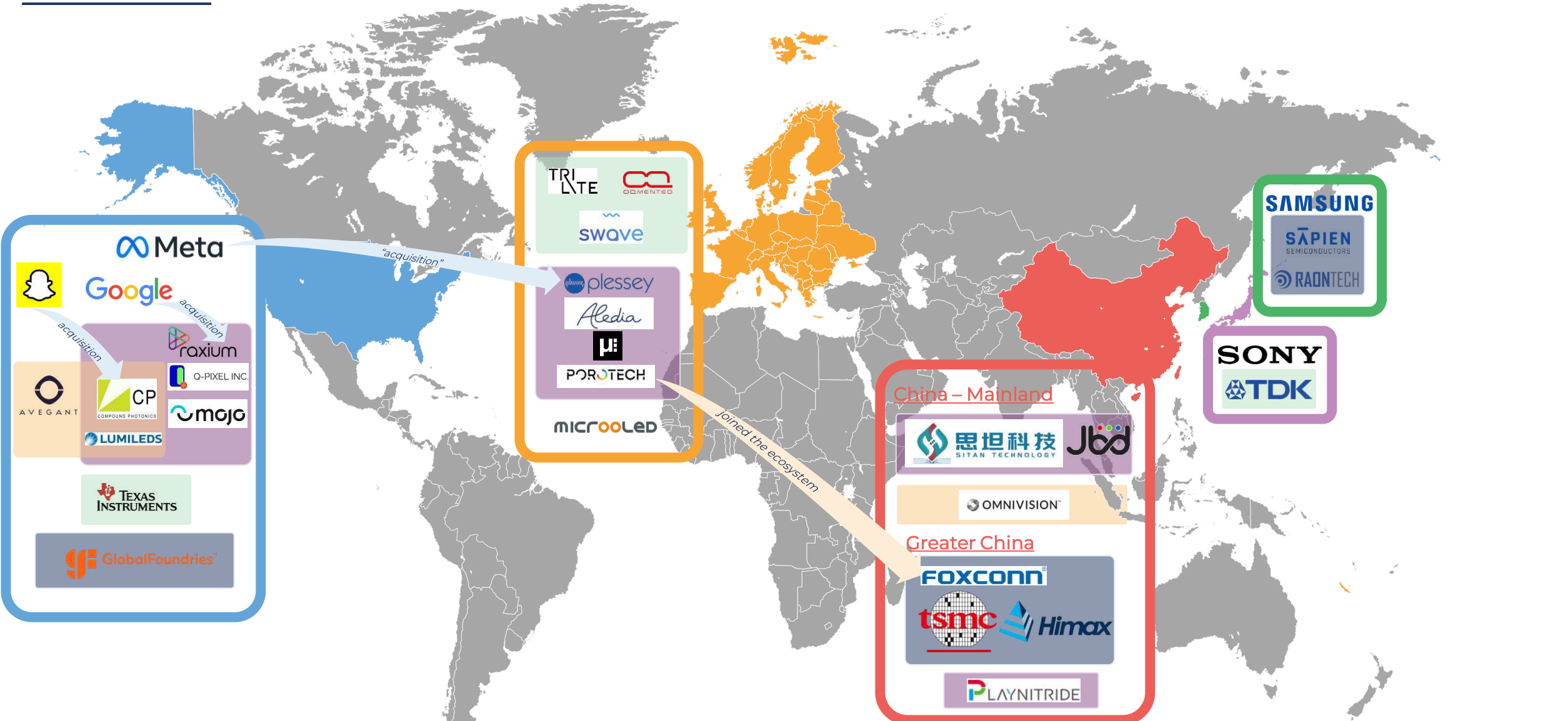
The map of the display engine makers

LCoS

Laser-based
(DLP, LBS, others)

MicroLED

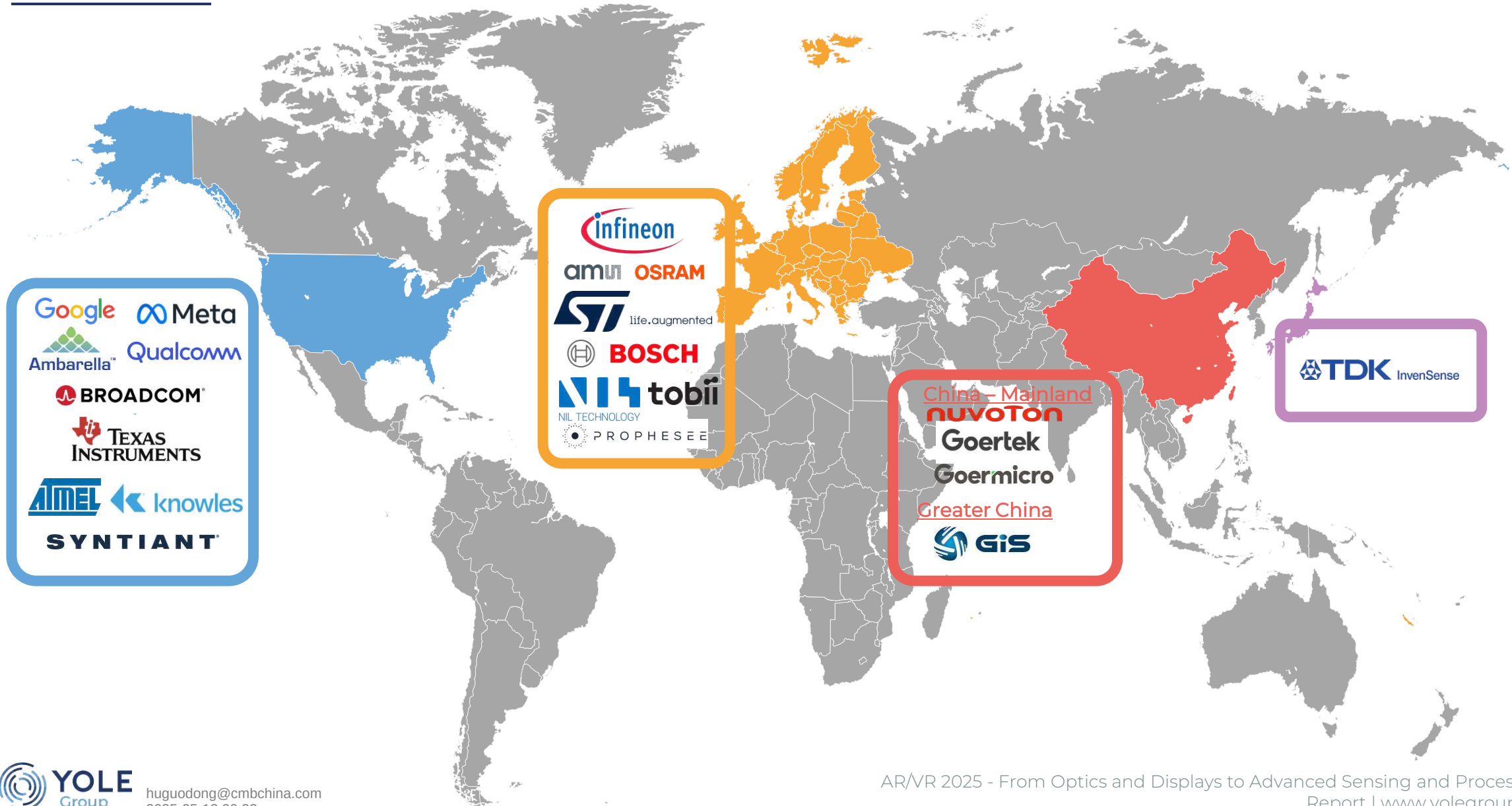
Backplane





ECOSYSTEM AND SUPPLY CHAIN – AR

Map of the AR parts (non display and optics) makers





ECOSYSTEM AND SUPPLY CHAIN – AR

A strong ambition in China

- In March 2021, the “14th Five-Year Plan” outline was officially released, and Virtual Reality and Augmented Reality were included in the key industries of the digital economy for building a digital China.
- In October 2022, the Action Plan for the Integration and Development of Virtual Reality and Industry Applications (2022-2026) was released, proposing that Virtual Reality, Augmented Reality, and Hybrid Reality are important cutting-edge directions in the new generation of information technology, which will profoundly change human production and lifestyle.
- Therefore, during this period, China will provide strong support (including investment) for the development of AR by developing **specialized chips, microdisplays, optics, and terminal products**, building an AR operation platform, and widely using AR technology for offline daily life.

Extracts of the: 14th Five-Year Plan for National Informatization

« Accelerate the construction of audio and video transmission capabilities based on 5G networks; enrich 4K/8K, **virtual/augmented reality (VR/AR)**, and other new multimedia content sources in the fields of education, sports, media, entertainment, and others. »

« **Implement a digitization strategy for cultural industries.** »

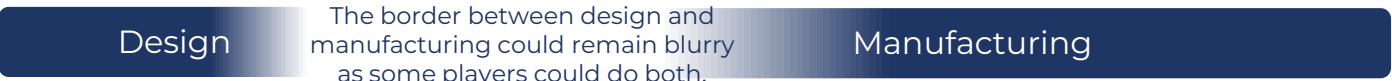
« Stimulate the mutual convergence of the cultural industries and new generation information technologies; develop next-generation immersive experience cultural industry products and services based on 5G, ultra-high definition, **augmented reality, virtual reality**, artificial intelligence, and other such technologies. Promote research and development of digital creativity, high and new audiovisual technologies, and equipment; accelerate the development of novel cultural enterprises, cultural business models, and cultural consumption models. Enrich online music, online cartoons, online performances, digital art, online presentations, online fitness, online competitions, live sports broadcasts, and other such digital content; enhance the digitization levels of cultural and sports product exploitation and service design. Forcefully develop digital cultural trade, vigorously use online platforms to display Chinese culture, and create and promote Sino-foreign cultural exchanges and mutual civilizational learning. »

AR is mentioned as an area of focus in the 14th 5-year plan (2022-2026).

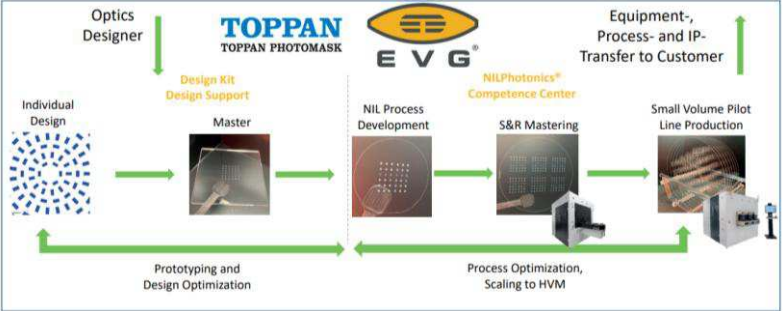


ECOSYSTEM AND SUPPLY CHAIN

Display and Optics co-design and manufacturing



Good agreement between the eyepiece design and the display engine is crucial to achieve the expected level of performance. It leads to collaboration from these players to maximize the chance of design wins downstream. Among these, the main microLED-based microdisplay player, JBD, announced an R&D partnership and collaboration with both Sunny Optical and Dispelix.



Schematic pipeline exhibiting the need for collaboration between players at the different stages of the supply chain. Here, the design house, the master manufacturer (like Toppan Photomask), and the equipment makers (like EV group) provide the manufacturing platform with complete turnkey solutions along with materials (substrate and resist). (From Toppan and EVG joint White Paper)

Integration

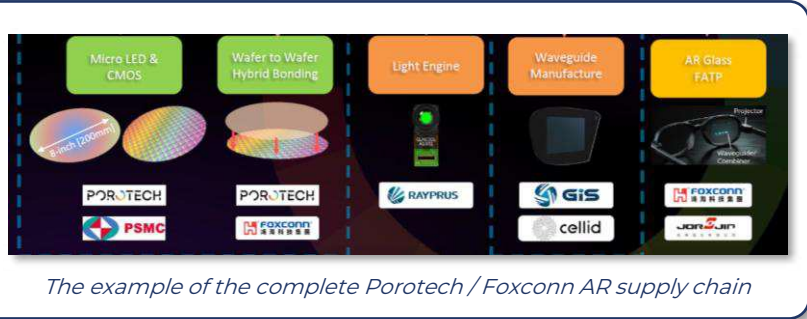
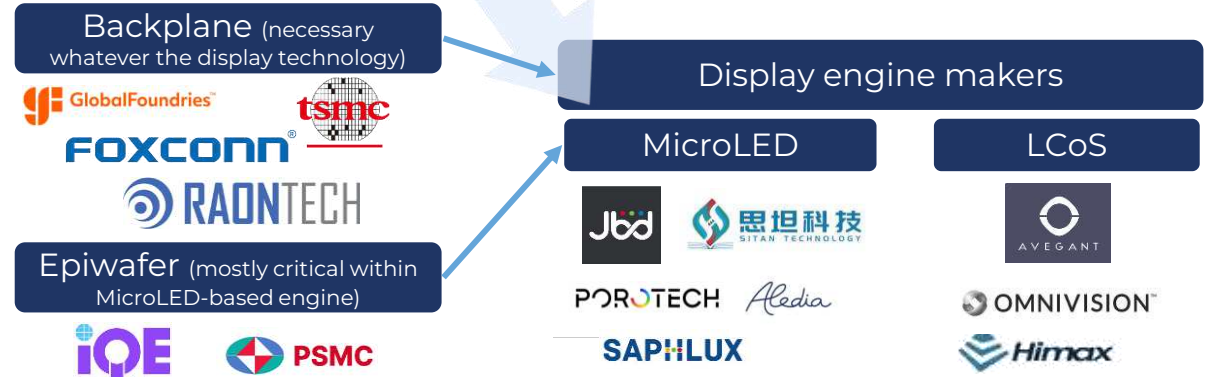


Some supply chains may require integrators to combine properly the different parts, including the display and eyepiece. These players are also expected to play a significant role in prototyping full-stack solutions.

OEMs



Ultimately, the OEMs are the ones to make decisions on the design to fit with the consumer expectations dealing with FoV, colors, tolerance for uniformity, and so on. This set of specifications is given to design houses, display engine makers, etc.

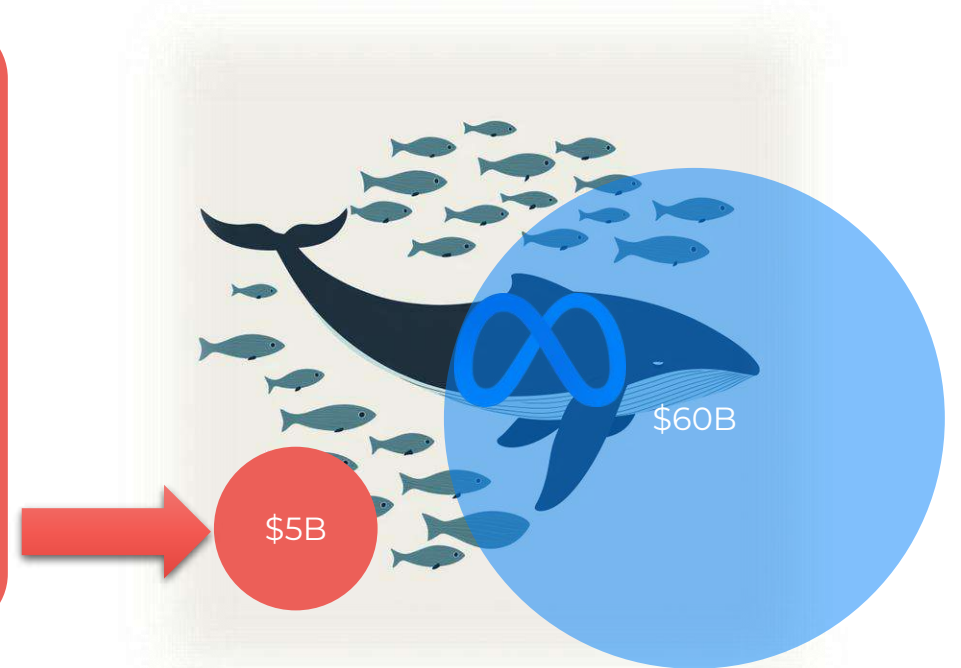
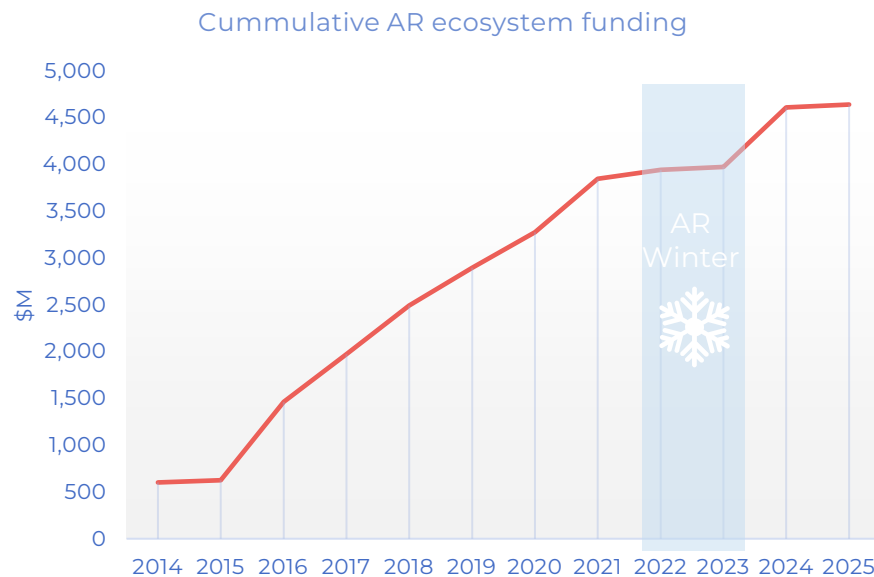


ECOSYSTEM AND SUPPLY CHAIN

AR-related investments

- The investments in start-ups and companies whose topics are strongly related to AR reached approximately ~\$5B in Q1 2025.
- *The list of considered companies is given on the left of the chart.*
- *Companies like Aledia (FR) and PlayNitride (TW) which dedicate a significant part of their activity to AR but not exclusively are not accounted for.*

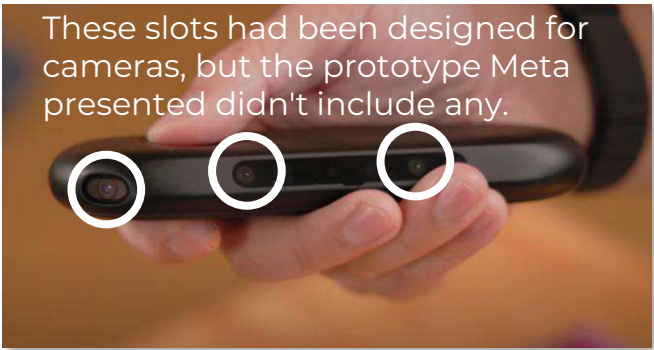
- The image we have in mind to understand the proportion of the conceded efforts by the start-up ecosystems compared with the effort of the frontrunner – Meta – is a big whale surrounded by a school of fish.
- Since 2021, Reality Labs has started to appear in Meta Platforms' results, and the cumulative losses reached ~\$60B by 2025.



During Connect 2024, Meta exhibited its **Orion** AR glasses. However, in the end, it does not consist only of a pair of glasses but of a 3-device suite. It therefore includes a **Wristband** with sensing features allowing interaction with the OS and a **Compute Puck**.

Compute puck

- Battery
- Additional computational power
- **WiFi 6E**

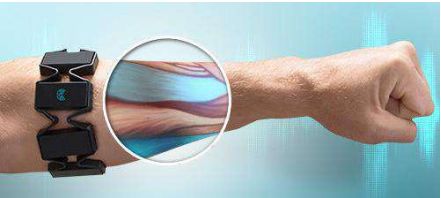


Smartphone-like form factor



Wristband

The control is based on electromyography (EMG): a diagnostic procedure originally used to evaluate the health of nerve cells and muscles. EMG tools track and monitor motor neurons, examining the electrical signals that cause muscles to contract or relax.



Smartwatch-like form factor

Which companies already sell Smartphones and Smartwatches and may have Smart glasses ambitions?



ECOSYSTEM AND SUPPLY CHAIN – AR

The AR Alliance and what it may means for LBS

- ST Microelectronics started the LaSAR (Laser Scanning for Augmented Reality) Alliance in October 2020. At the beginning, the cohort counted 5 companies:



- By March 2021, few other companies joined:



- In October 2023, the alliance was rebranded as AR Alliance only enticing the industry with the fact that they were enlarging their scope and not focusing anymore on the LBS display engine only.



- Through 2024, several key players joined:

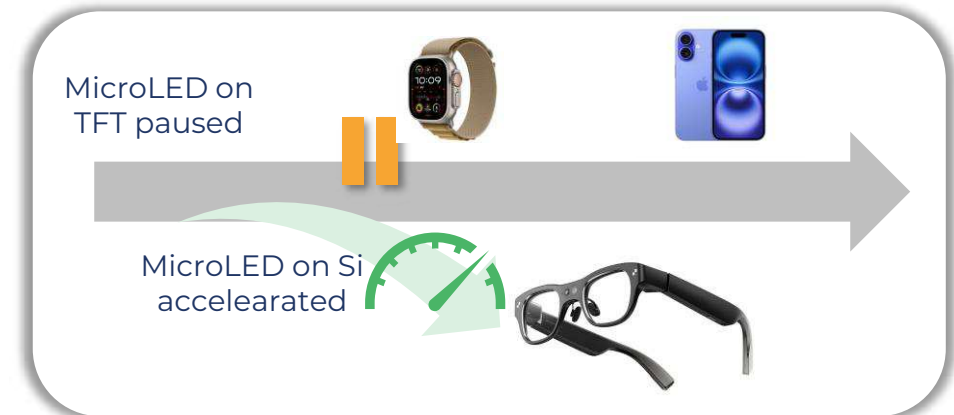
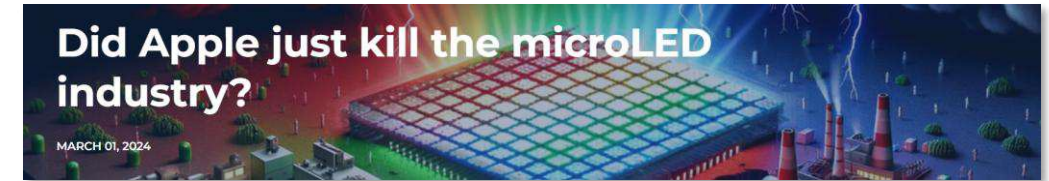


- The widening scope of the AR Alliance (formerly the LaSAR Alliance) is a key signal that LBS may not be the appropriate display technology for the next generations of consumer AR.

ECOSYSTEM AND SUPPLY CHAIN – AR

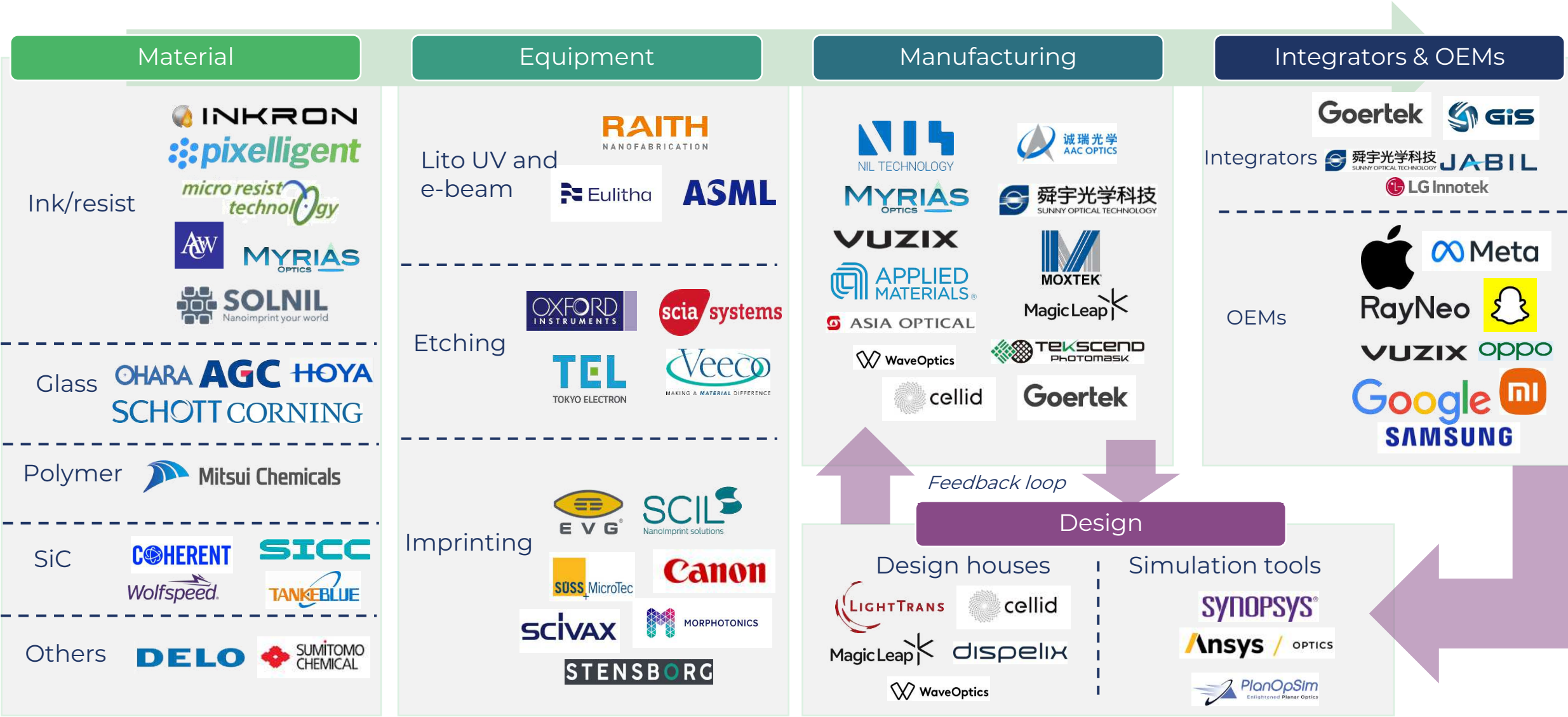
AR: The application microLED pivoted towards

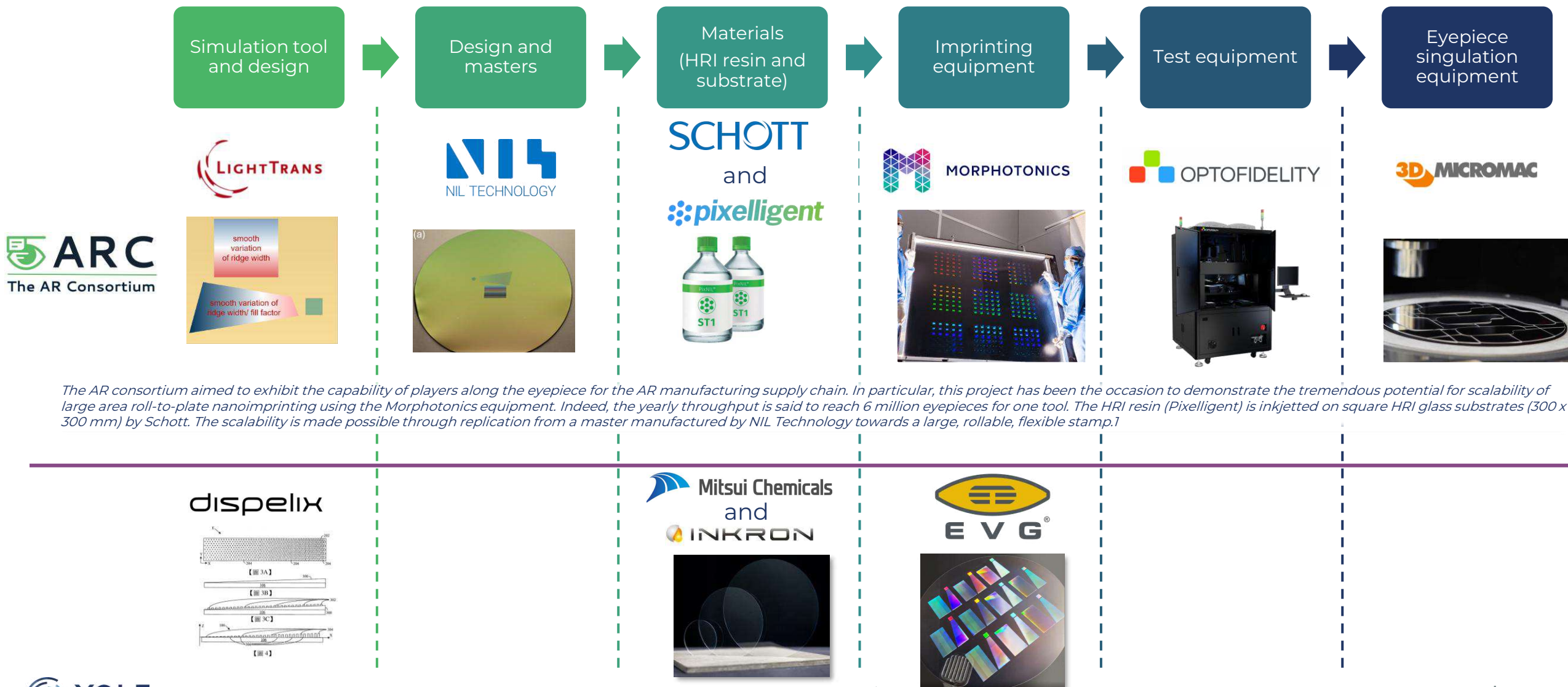
- In February 2024, Apple unplugged its microLED for the SmartWatch project. After 10 years since the acquisition of LuxVue and \$2B spent on developing the technology, they decided to abandon the effort. They bet on this promising technology to offer their high-end Watch Ultra a display with better brightness, better reliability, wider angle of view, and a long run of new features like sensing embedded in the plane of the display. On the even longer run, it may have been about embedding a microLED display within the iPhone to differentiate on applications that significantly matter in consumer electronics.
- As they decided to cut the effort, the industry received it as a blow. The question was: Is it the end of microLED, then? At Yole, our answer was: No. Thanks to Apple, on the one hand, the technology has gained enough traction so it can now keep going on its ride. MicroLED is a worldwide technology with several applications.
- Near-eye display is now the most promising among the addressable applications as microLED for AR relies on Si CMOS backplane. It turns out to be a completely different technology from TFT-based, bypassing the main microLED challenges related to pick and place issues. MicroLED for AR gets closer to standard semiconductor processes, with the bonding of epiwafers on CMOS BP.



ECOSYSTEM AND SUPPLY CHAIN

Waveguide optics manufacturing





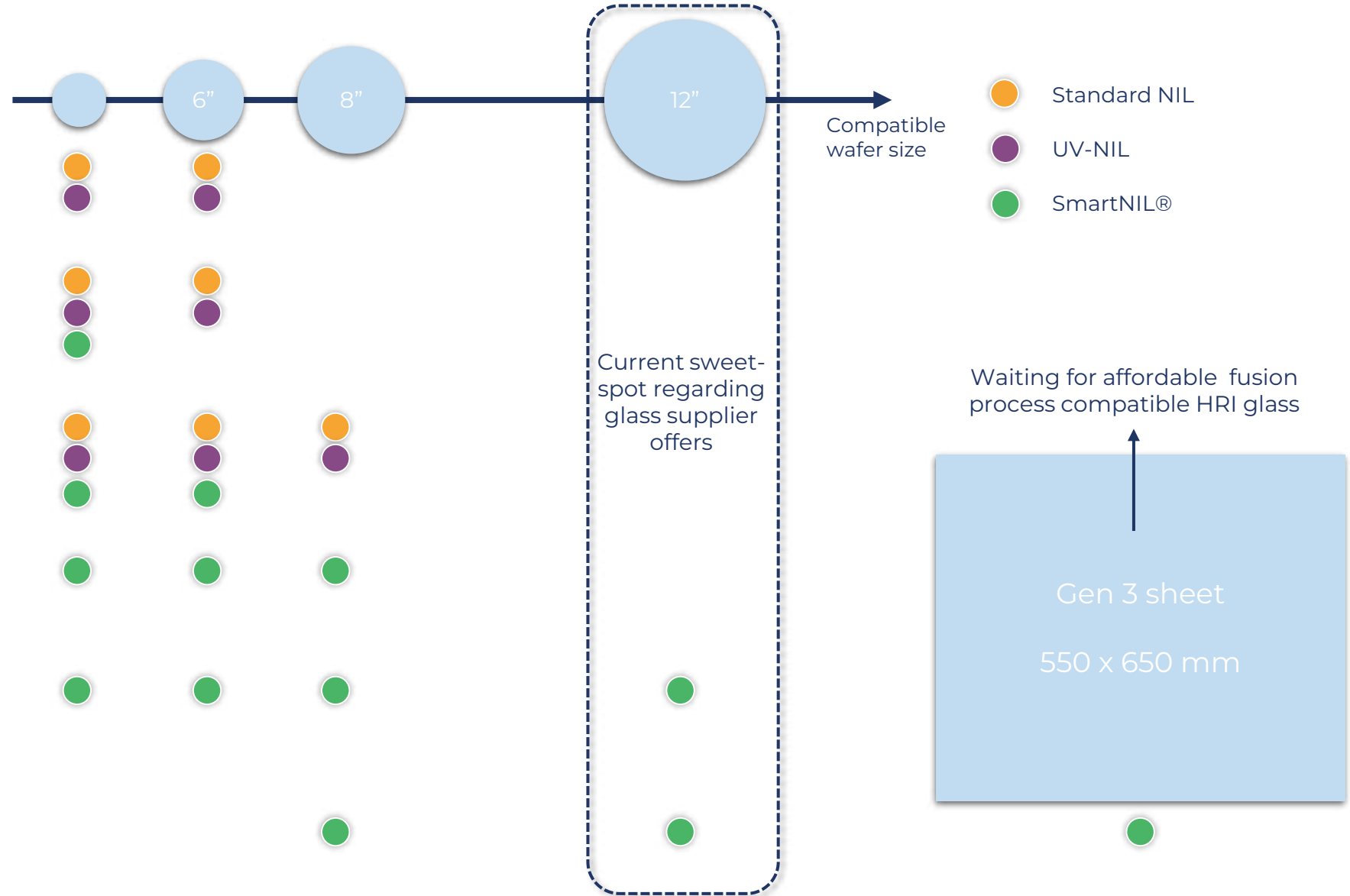
The AR consortium aimed to exhibit the capability of players along the eyepiece for the AR manufacturing supply chain. In particular, this project has been the occasion to demonstrate the tremendous potential for scalability of large area roll-to-plate nanoimprinting using the Morphotonics equipment. Indeed, the yearly throughput is said to reach 6 million eyepieces for one tool. The HRI resin (Pixelligent) is inkjetted on square HRI glass substrates (300 x 300 mm) by Schott. The scalability is made possible through replication from a master manufactured by NIL Technology towards a large, rollable, flexible stamp.¹



ECOSYSTEM AND SUPPLY CHAIN – AR

Wafer size sweet spot

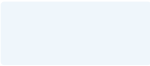
- EV Group is the current leader of nanoimprint tools. Looking at their offering gives a glimpse of the sweet spot for mass manufacturing eyepieces.
- 12-inch HRI wafers would maximize the number of eyepieces manufactured per run (up to 24, the biggest amount demonstrated).
- Chinese players like SemiSIC and SICC have demonstrated 12-inch SiC, but some parameters, like the thickness, still need to be improved before their utilization in AR.
- The largest plastic substrate is 8-inch, but if 12-inch is the preferred platform for AR, it could be a good reason to move to 12.



Ecosystem and Supply chain – VR

ECOSYSTEM AND SUPPLY CHAIN – VR

The map of the VR OEMs



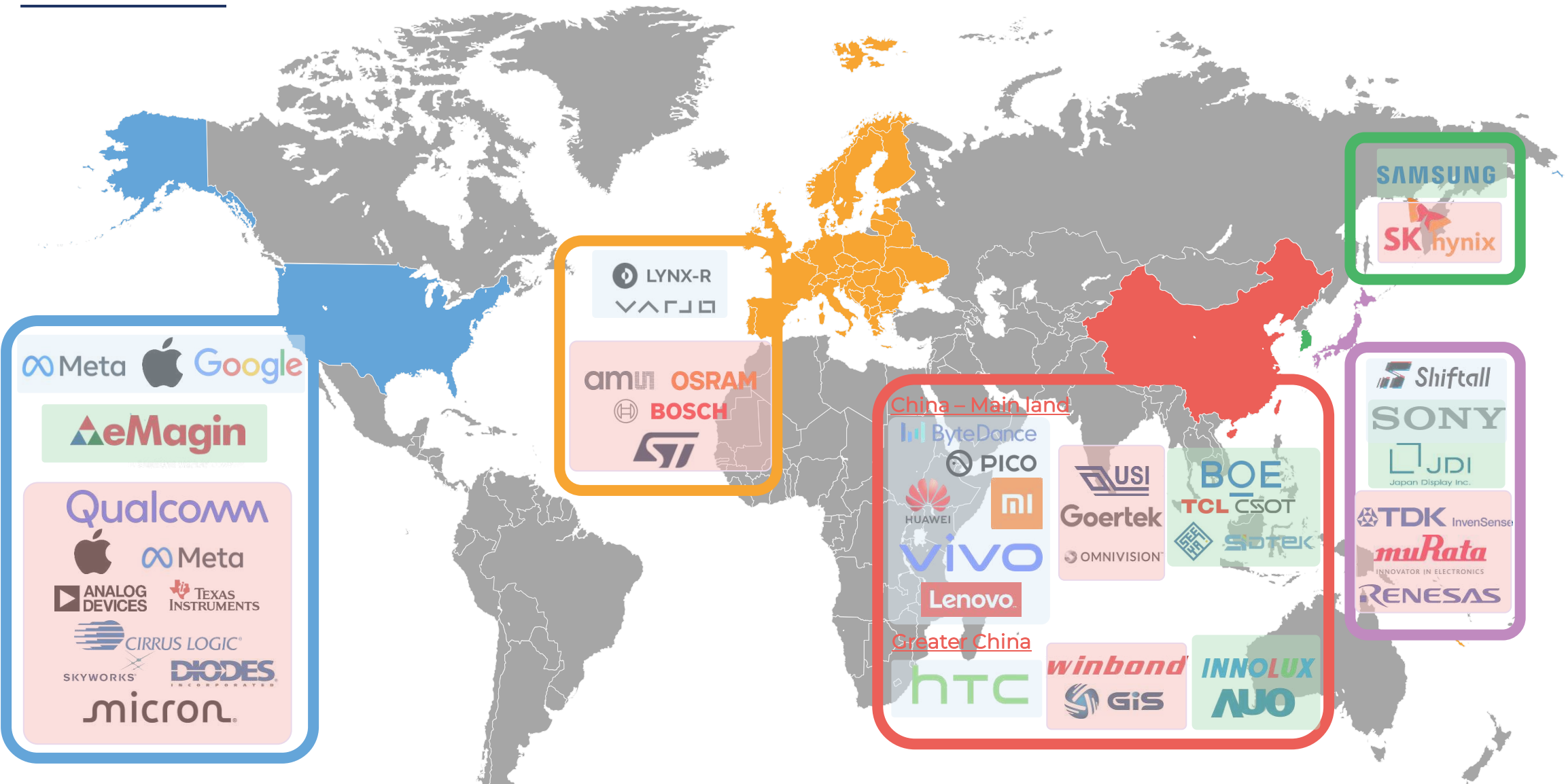
OEMs



Display makers



Parts makers





ECOSYSTEM AND SUPPLY CHAIN – VR

Apple Vision Pro's supply chain

- In the scope of devices addressed in this report, the Apple Vision Pro may be the pinnacle of complexity with 12 cameras, 6 sensors, 2 processing chips with 1 dedicated to sensing (R1).
- The suppliers of the electronic components are:

SONY

ANALOG DEVICES

CIRRUS LOGIC

USI

winbond

tsmc

SK hynix

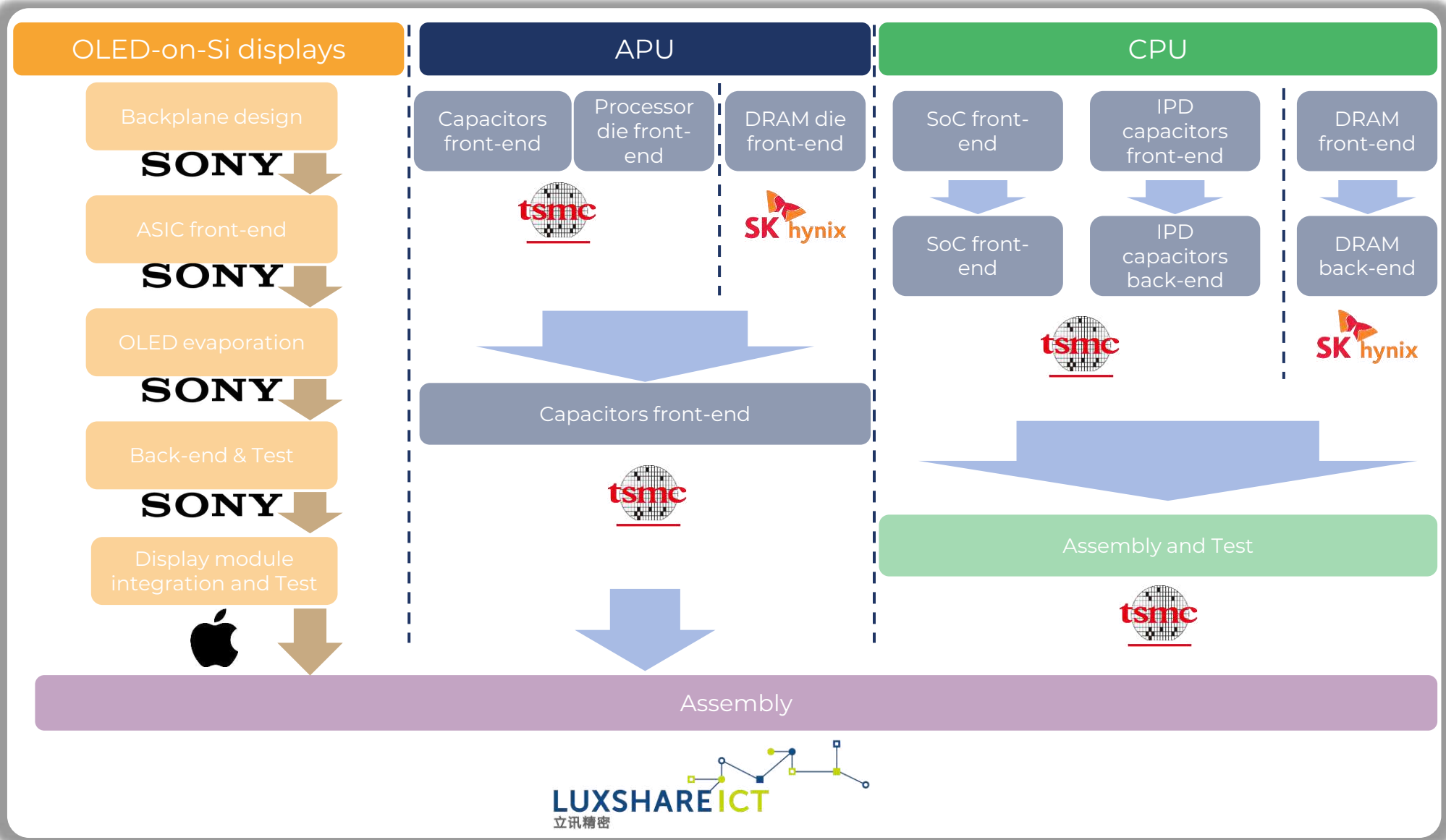
muRata

SKYWORKS

BOSCH

DIODES

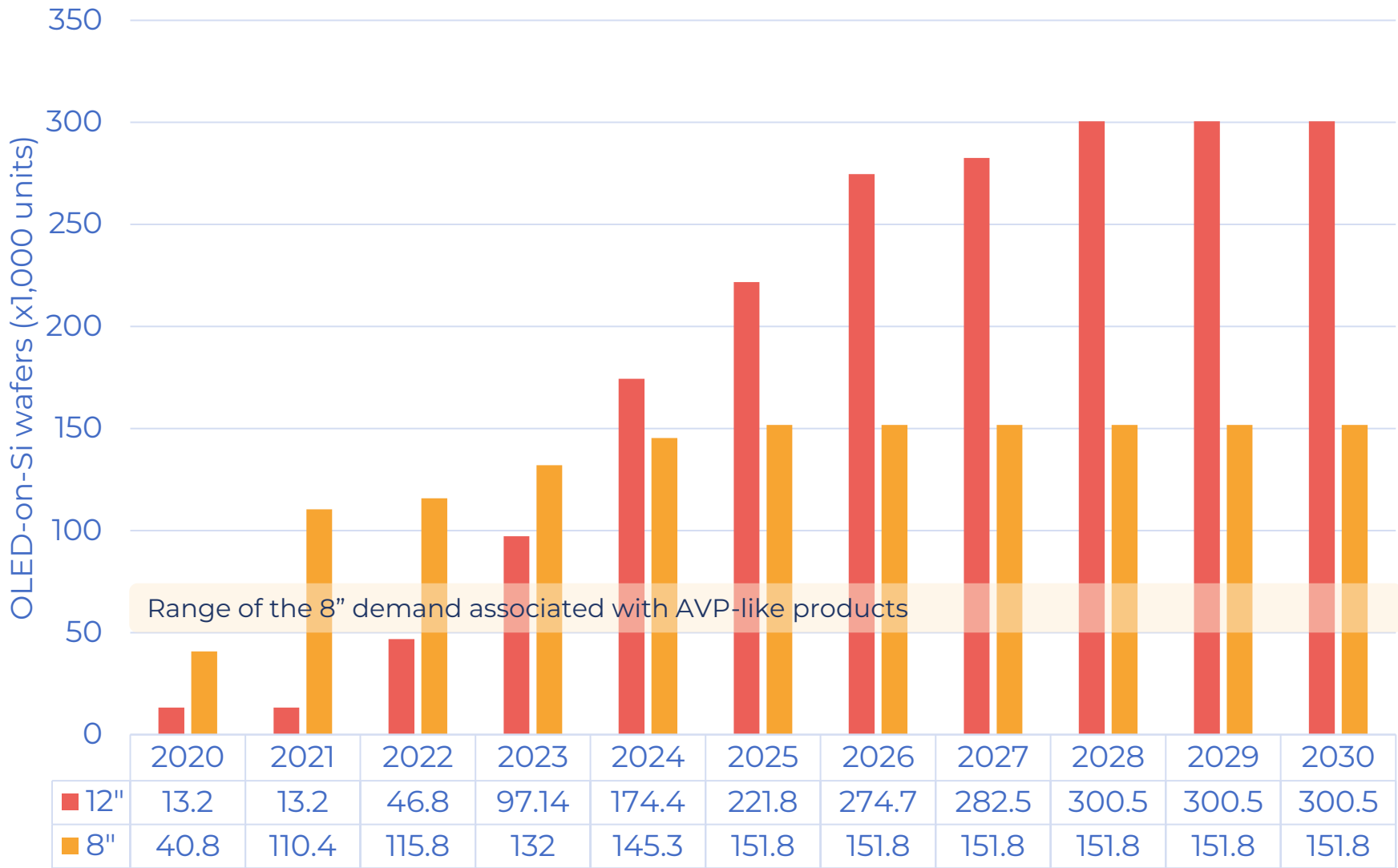
- The supply chain of some of the most critical elements is detailed on the right →



- The Apple Vision Pro created an air gap, encouraging the supply to increase its capacity. Many companies, essentially in China, announced tremendous capacity increases through 2023 following the announcement from Apple.



- Given the outcome of the sales through 2024 and the issues related to yield, we present this updated forecast of OLED-on-Si global capacity



Ecosystem and Supply chain – Synthesis



ECOSYSTEM AND SUPPLY CHAIN – SYNTHESIS

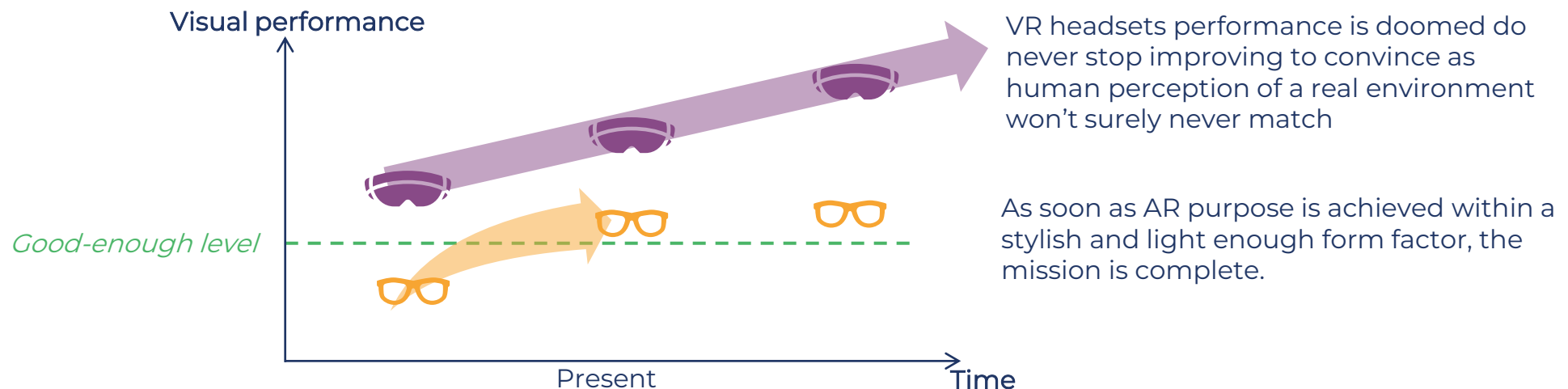
AR and VR Supply Chains: Two Distinct Biomes, One Set of OEMs

- For both AR and VR, downstream the supply chain, the OEMs are the same: consumer electronics giants like **Apple, Google, Samsung, Xiaomi** but also newcomers in the field of hardware like **ByteDance** and more importantly **Meta**.
- That being said, the nature of AR and VR ecosystems (technology bricks providers) is essentially related to the maturity of the technologies needed.
- VR relies on proven technologies but but the emergence of new solutions still conditions AR's success. Most VR modules are manufactured by large companies that are well-versed in assembling and manufacturing of technological building blocks that have become almost commoditized (LCD, Fresnel lenses and pancake lenses are a good illustration).
- On the other hand, the AR ecosystem is typical of a market that hasn't emerged yet. Many technologies, sometimes incompatible or competing, are investigated simultaneously. This exploration is ensured by start-ups mainly. To illustrate this, we can mention tracking technologies where **NILT, Prophesee** and **AdHawk** develop different approaches to a similar purpose. The same can be said about waveguide optics, where different players consider several options (both in terms of manufacturing and materials). In the end, this phenomenon is the most obvious in the field of microLED micro display for AR. Indeed, this self-emissive technology is poised to become the standard. Still, it is not ready yet, and many players intend to solve challenges differently (**Porotech** with their proprietary DPT, **Aledia** with nanowire arrays, **JBD** and **Q-Pixel** with vertical stacking, to name a few).
- This rich and wide-ranging exploration is likely only possible thanks to Meta's unwavering commitment. Indeed, **Meta Reality Labs' loss is about 4 to 5 billion dollars a quarter**, and a significant amount of that is very likely to be injected into this ecosystem. The image we can use to describe **the current landscape of start-ups is a garden tended by Meta's dedication to make AR happen. Meta cultivates many species there, but the final bouquet it offers for consumers will include only a select few, leaving many others by the wayside.**
- To materialize, the AR market requires breakthroughs driven by new technologies. However, in the long run, suppliers from more mature markets—such as the smartphone industry—will also play a key role. This includes sensing specialists like **Bosch, Texas Instruments, ams OSRAM, and STMicroelectronics**, as well as computing players such as Qualcomm. Lastly, traditional eyewear companies, with **EssilorLuxottica** at the forefront, will be instrumental thanks to their experience and established presence in the field.

TECHNOLOGY TRENDS



- Technology dynamics – especially optics and display– differ greatly from AR and VR. Indeed, VR can rely on mature technologies like LCD and Fresnel lenses (the most innovative solutions being OLED-on-Si and Pancakes). On the other hand, AR players were hoping until very recently that the technology readiness of display optics would be mature enough to bring an acceptable solution to the consumers.
- Now the alliance of diffractive waveguide optics and microLED microdisplay starts to deliver the right level of performance for AR, both dealing with brightness and form factor – the difference between AR and VR lies precisely in the fact that AR only needs to be good enough. In contrast, VR must deliver the best possible immersive experience.
- In other words, in AR, and to exaggerate a bit, the matter is settled as soon as the challenge is met, while in VR, it's a never-ending story.
- For this reason, and because the technologies are very different from AR to VR, this section is segmented into two parts.

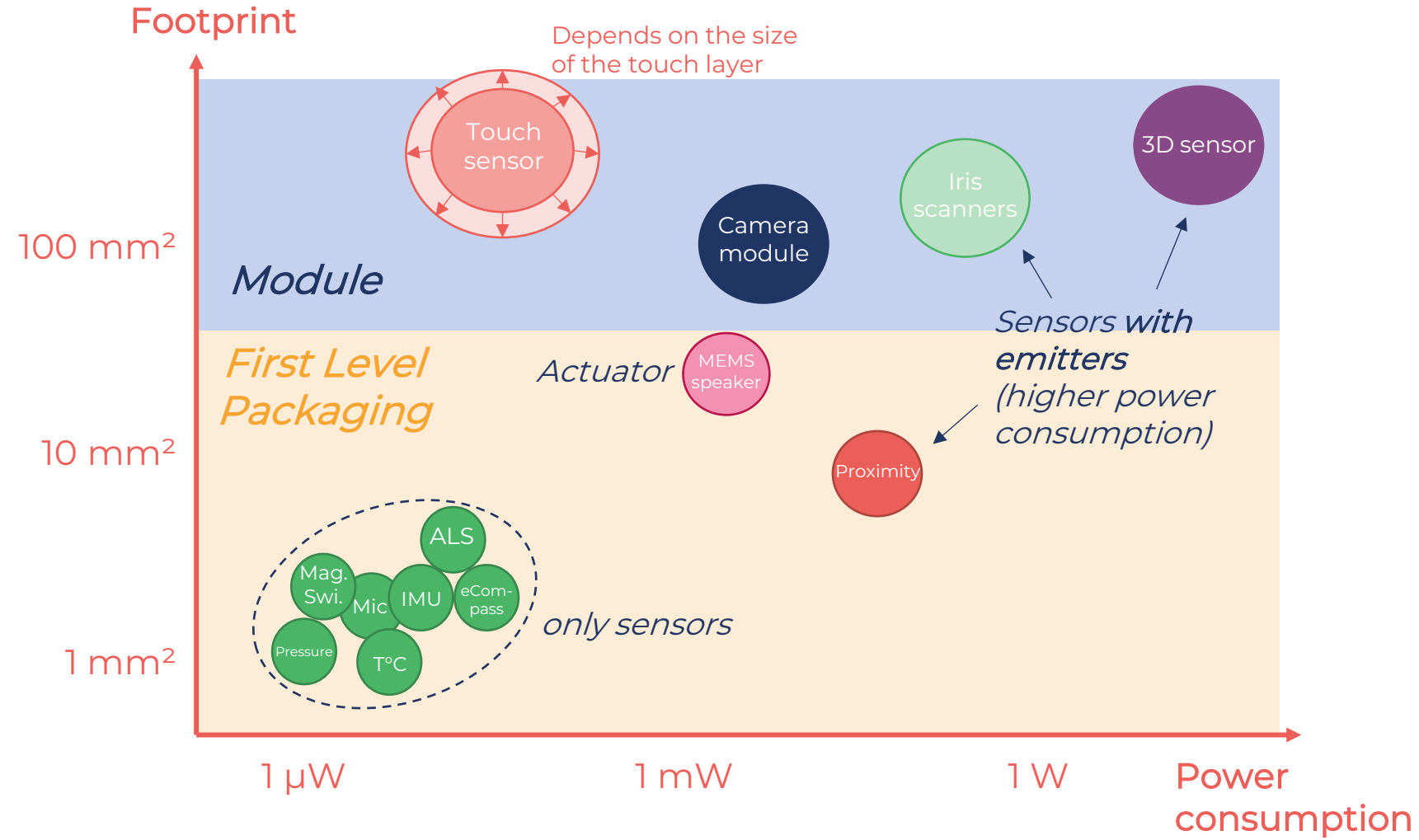


TECHNOLOGY TRENDS

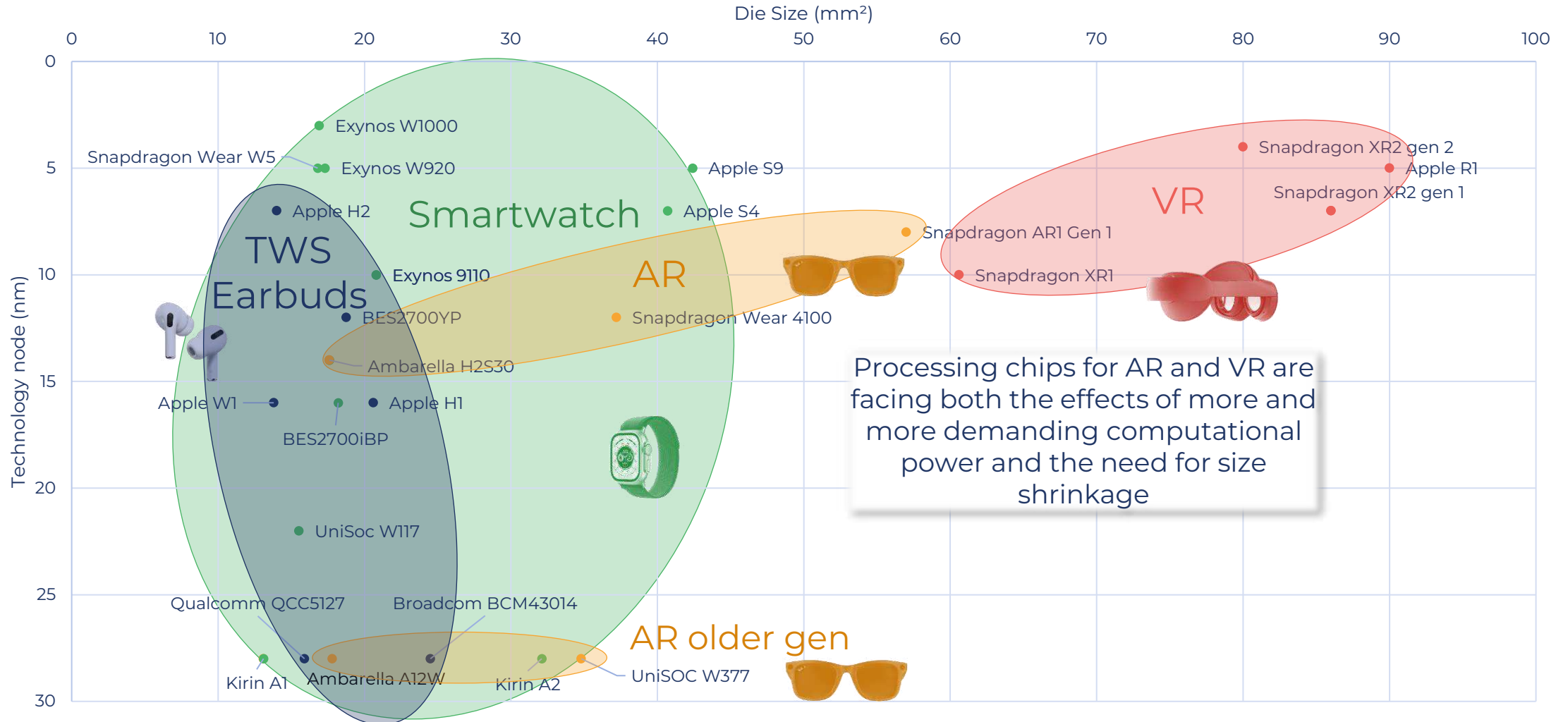
For wearables, footprint and power consumption constraints matters

- MEMS sensors at first-level packaging are the easiest to integrate into end-systems, since they are cheap, small, and consume less power than modules.
- However, some modules or devices with emitting parts are more expensive and power-intensive. Hence, their integration needs to be justified and within the power budget.
- Moreover, the device's weight is also crucial and cannot exceed 50g for consumer applications.

* Only the die's form factor and power consumption are considered here. We do not take into account all the wires, interconnections, and additional processing devices (which are also important).



Computing die size vs. technology node (mm²)

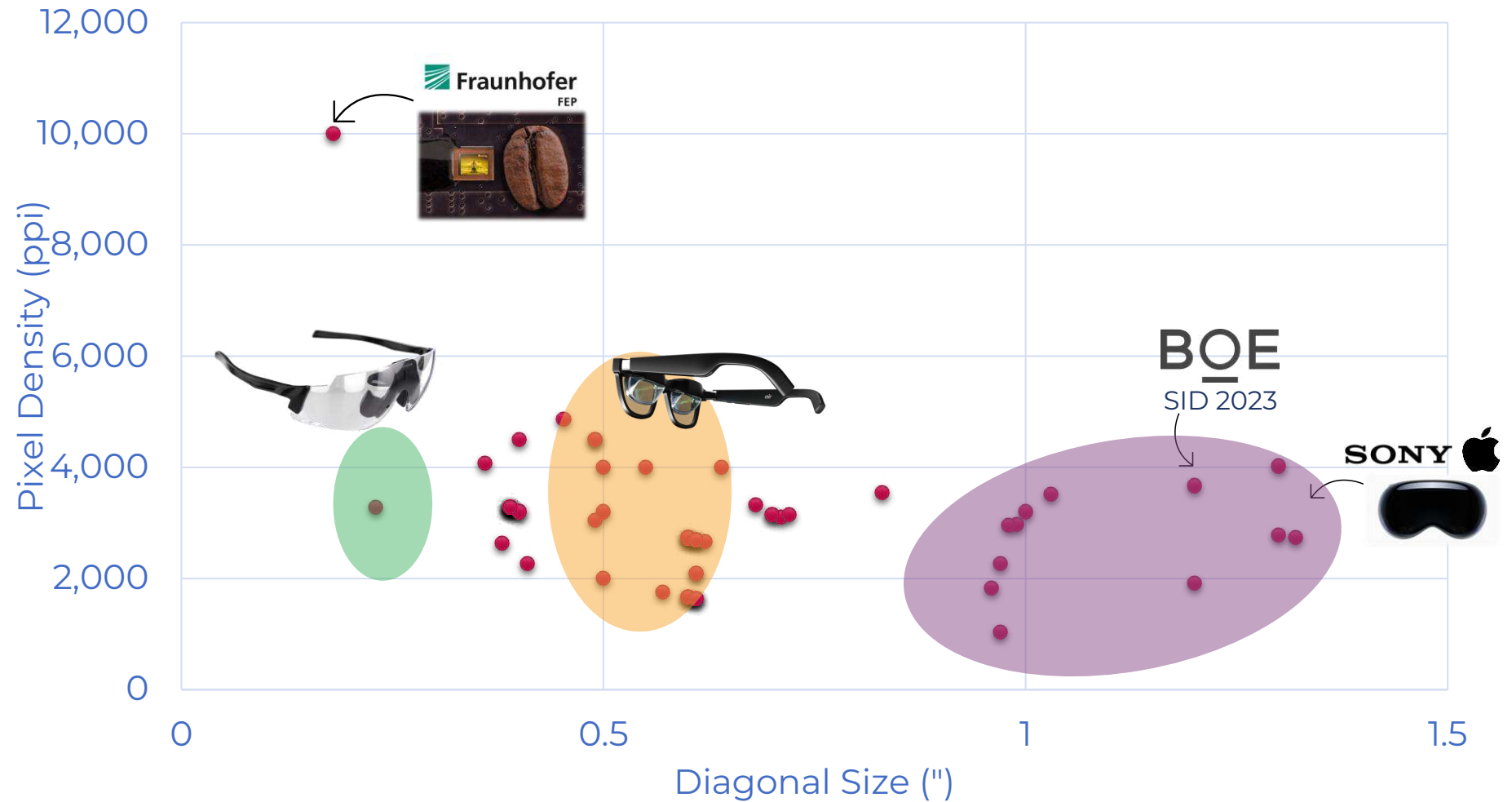


Processing chips for AR and VR are facing both the effects of more and more demanding computational power and the need for size shrinkage

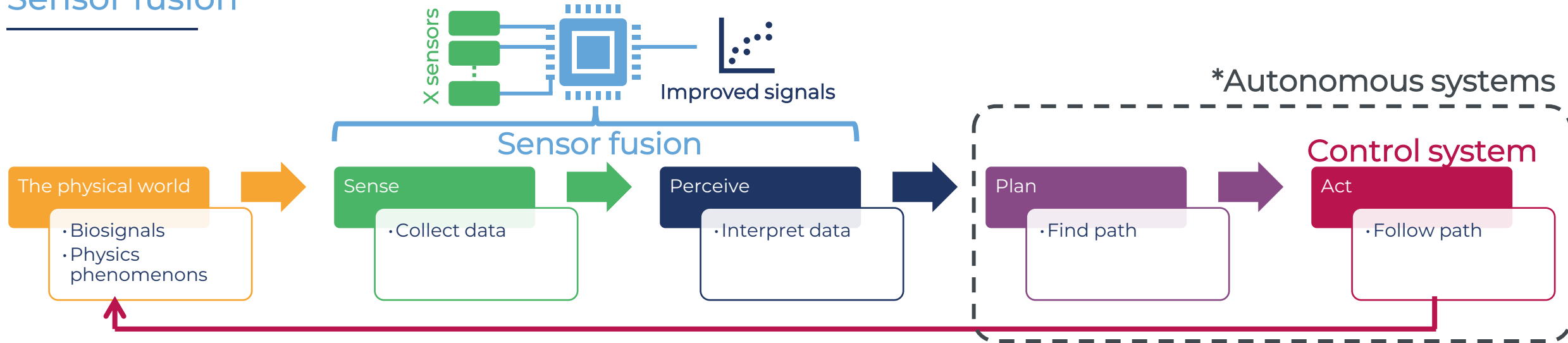
TECHNOLOGY TRENDS

Resolution and display size – An application defendant trade-off

- OLED-on-Si can address many applications from viewfinder for DSLR to VR, light AR, and birdbath-based AR. With every application is associated a Diagonal vs. Resolution couple
- Sony's OLED-on-Si in the Vision Pro is the extremum size, but higher resolution has been demonstrated: In particular, Fraunhofer with their 10,000 ppi monochromatic.



Technology trends - Sensing



Sensor fusion can help in four different cases:

- Increase data quality (i.e., reduce noise)
 - Adding multiple similar sensors helps reduce noise, where more sensors lead to less noise (e.g., with x sensors, noise is reduced by $1/\sqrt{x}$).
 - Integrating data from different types of sensors (e.g., magnetometers and gyroscopes) provides a more robust signal.
- Increase reliability (data combining)
- Estimate unmeasurable states
 - Combining similar or different sensors enables estimating otherwise difficult states to measure. For example, blood pressure measurements can be enhanced by combining data from PPG and IMUs, or distance can be evaluated using two imagers.
- Increase coverage (i.e., 360° detection by combining several microphones)

Sensor fusion could be done at different levels, from on-edge (like SLAM) to in-edge (like event-based imaging). With AI advancements, manufacturers are increasingly integrating sensor fusion directly into sensor packaging, enhancing capabilities directly at the hardware level.

TECHNOLOGY TRENDS – SENSING

0DoF, 3DoF and 6DoF

As more modules are to be embedded, more processing is required to deal with the inputs of the sensors and a more immersive experience is to be consistently displayed. These headsets are getting bulkier as the degrees of freedom increase.

0 DoF content



Audio-only and basic displayed information.

No dedicated tracking sensors needed due to the displayed content

3 DoF content



More elaborate information glasses and content consumption, plus a non-VST VR headset.. The content gets stuck if the user moves their head. Glasses like the TCL RayNeo X3 can relate to Ambient computing, while the Xreal provides virtual displays.

IMU (Accelerometer, Gyro, Magnetometer)

6 DoF content



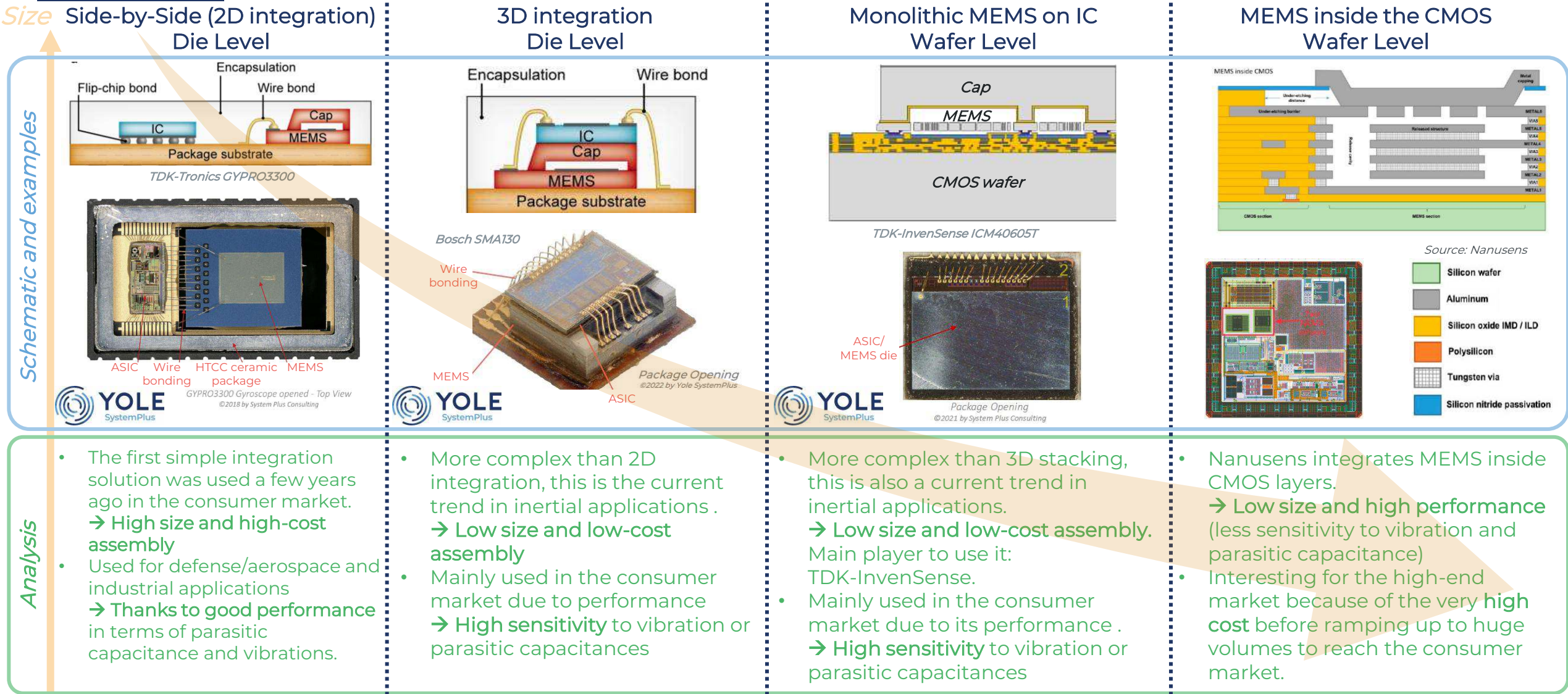
Here, the content can stick to the point of the space (x,y,z) in addition to the 3d rotations. It allows use cases introduced as Spatial computing.

IMU to monitor both head rotations and (x, y, z) displacements



TECHNOLOGY TRENDS – SENSING

Inertial sensors modules shrink as their complexity increases





TECHNOLOGY TRENDS – SENSING

Different architecture and methods for depth sensing

PIN:

- PIN photodiodes are used to measure light intensity. This makes them compatible with contrast imaging and iToF. However, they cannot count photons, which is done in dToF.

APDs:

- APDs are more sensitive than PIN photodiodes. They can be used to make intensity measurements, which are more sensitive than PIN photodiodes but have lower dynamics. They can be compatible with dToF, depending on the readout circuit.

SPADs:

- SPADs are photon counters that perfectly fit with dToF measurements.
- Academic and industrial research projects aim to perform either iToF or low-light contrast imaging using high-resolution SPAD arrays.

Photodetector architecture:	Contrast imaging or detection	iToF	dToF
PIN	High compatibility	High compatibility	Impossible
APD	Possible	Possible	High compatibility
SPAD	Possible	Possible	High compatibility



High compatibility



Possible



Impossible

This table is valid whatever the imaging technology, not just for SWIR wavelengths.



TECHNOLOGY TRENDS – SENSING

Tracking technologies

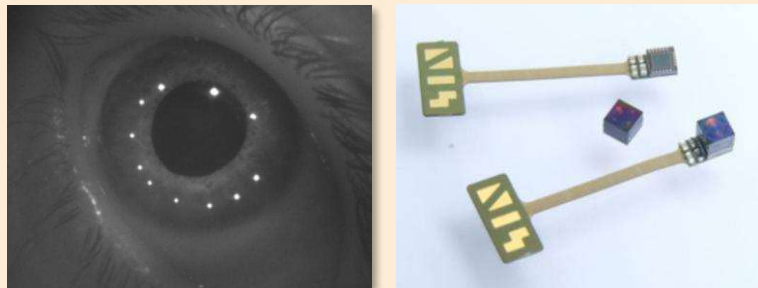
Tracking is an important part of the HMI. Both eyes and hands must be tracked to ensure a good interaction. Also, gaze tracking could also serve better rendering of objects in space and volumetric AR in further generations of products relying on more advanced but still emerging display technologies. Several approaches can be envisaged to address gaze tracking.

Metasurface assisted dot projection + CIS

The **NIL Technology** eye-tracker module relies on a **metalens**, enabling the replacement of a 3 to 4-layer refractive lens stack. This makes the module barrel-free, making it more compact (1.64 mm x 1.64 mm x 2.17 mm) and easier to embed within the headset frame. The module is meant to operate in a **40 nm wide spectral range around 850 nm** and a **90° FoV**.



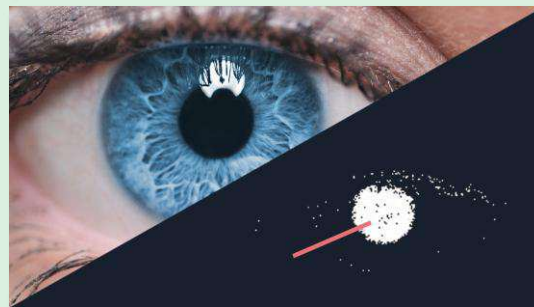
Acquired by Radiant Optoelectronics



Images: NILT

Event-based CIS

The **Prophesee's** event-based imaging technology allows for high refresh rates and low energy consumption. Such technology falls into the neuromorphic category as it is meant to mimic the behavior of human eyes. Particularly, the behavior of rods in the periphery of the sight is responsible for noticing movements.



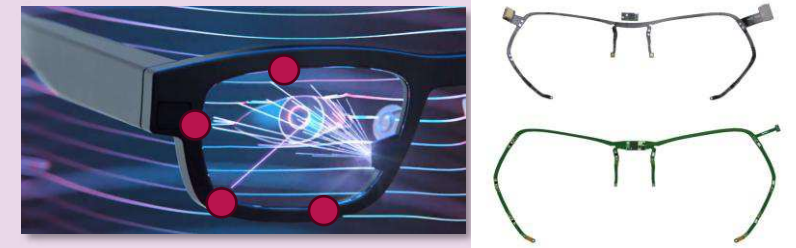
Images: Prophesee

MEMS scanner + photodetectors set

AdHawk's eye-tracking system is MEMS-based and, therefore, CMOS-free. It relies on using a MEMS scanner and a set of 4 photodetectors placed on the frame. The footprint is around **2.5 mm by 2.5 mm**, and the weight of the scanner and its flexible PCB is 0.422g. In terms of integration, it may be required to redesign the flex PCB and module placement along it to fit each frame that an OEM would want it to be compatible with.



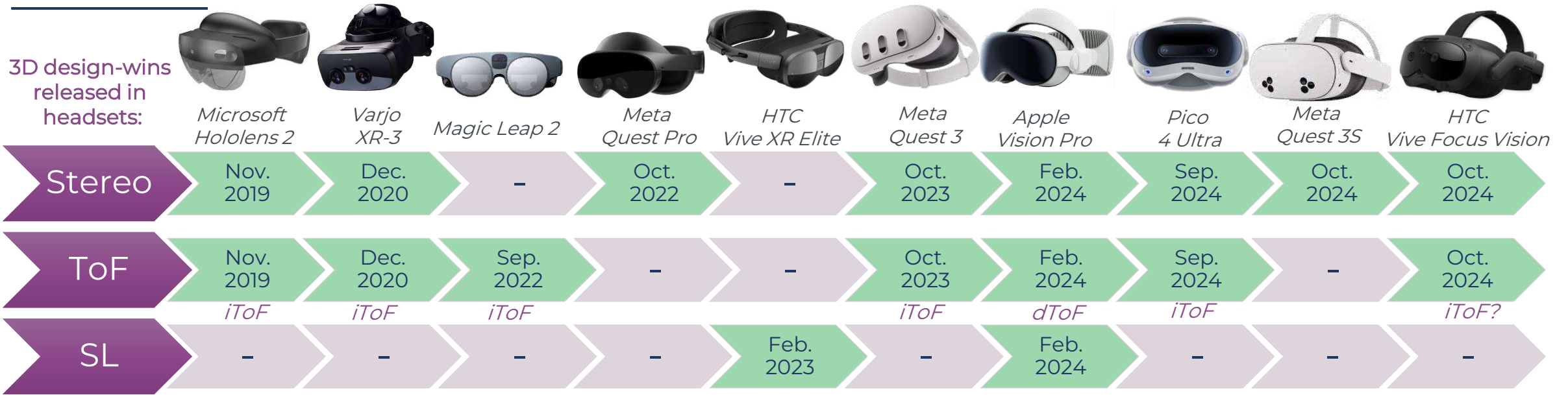
Acquired by Google



Images: AdHawk

TECHNOLOGY TRENDS – SENSING

Evolution of imaging modules embedment in headsets



- Most headsets have natural 3D stereoscopic capability and are more or less explicitly used. **ToF cameras have come to bring superior accuracy to environmental tracking.** The use of SL remains quite marginal, as it is known to deliver its best performance for shorter range distances in consumer size-constrained systems (baseline distance is limited).
- Apple Vision Pro combines an SL module (similar to the iPhone or iPad Pro FaceID) with its dToF LiDAR device (same as the iPhone Pro rear LiDAR camera modules), to bring the best of both worlds: superior accuracy at short distances with SL and longer range with ToF.
- There is a **proliferation of sensors for XR**, and the concept of spatial computing requires numerous cameras and sensors in headsets, including 3D sensing modules that use active light. **We need a new imaging technology paradigm to unlock lower power and latency approaches.**

Vision Pro cameras teardown

Source:



TECHNOLOGY TRENDS – SENSING

Triple stack CMOS image sensor for AR



Triple-stack is a new kind of CMOS image sensor architecture that more and more players in the imaging field have investigated. We can cite **Sony, Samsung, ST Microelectronics, Omnivision, and Meta** (collaborating with **Brillnics**). Such a stack allows for a smaller form factor, so less surface is covered by the CMOS area for the same number of pixels, as the processing and memory circuitry is below. It makes a lot of sense for augmented reality, where the surface occupied by each module needs to be shrunk, and edge-AI requirements are demanding in terms of functionalities

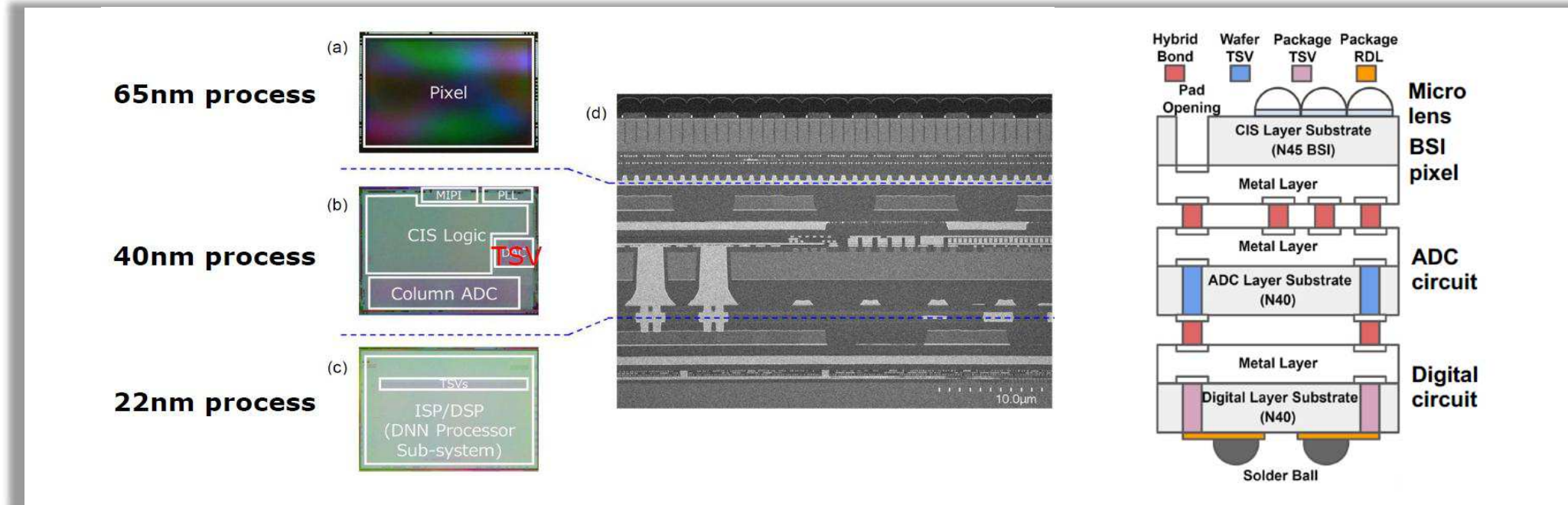


Image by Meta

BRILLNICS™

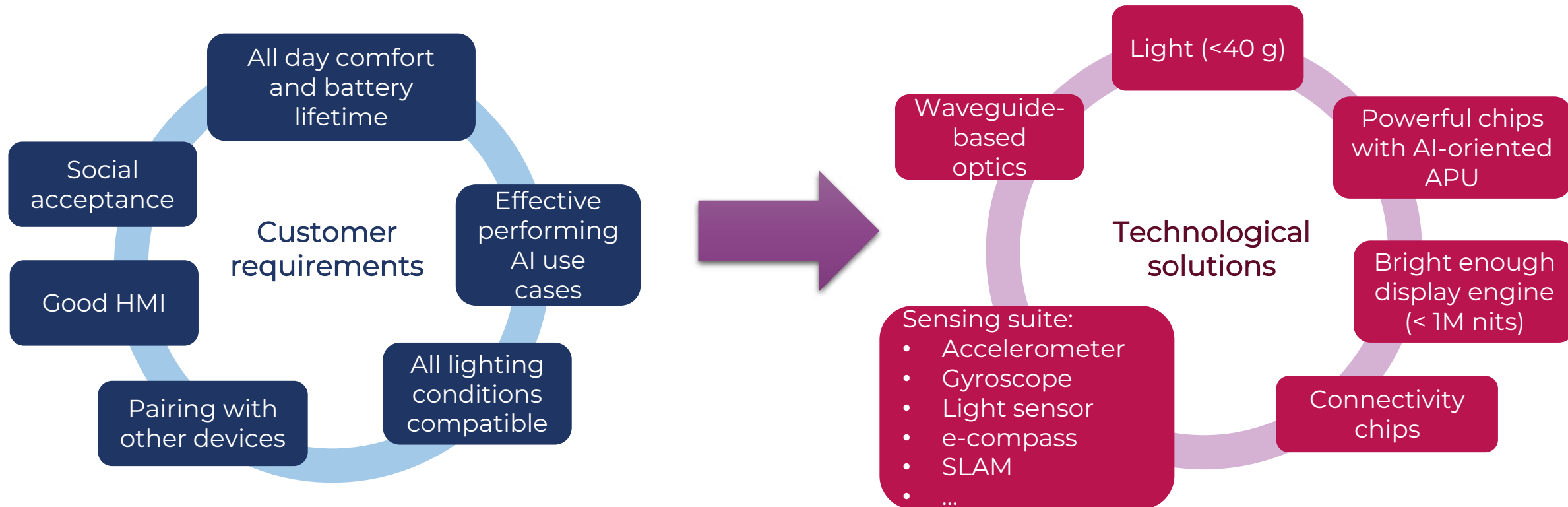
Technology trends - AR



TECHNOLOGY TRENDS – AR

Consumer AR taxonomies of products and technological archetypes

- This part aims to define the modules to be embedded in AR glasses, depending on the targeted use cases. Every situation comes with a different set of needs; therefore, only consumer-oriented glasses are envisaged here.
- The section is organized starting from taxonomies of product definitions and the technological archetype it corresponds with. In particular, greater attention is being paid to what we believe will be the consumer AR.
- Starting from the requirements associated with consumers' expectations, we narrow down the technological choice for different parts: processing chips, sensors, displays and optics.





TECHNOLOGY TRENDS – AR

Which features for which use cases

							
		Phone call	Voice translation	Camera	Text translation	AI assistant	Multimodal interaction
Microphone							
Speaker							
Display			and/or			and/or	
Visible camera							
Advanced imaging and sensing			Could improve people speaking detection	Improve image quality with auto-focus		To better understand context	Eye and hand tracking, facial expression recognition...
Antenna				Sending into a paired device or local memory		To perform computing on clusters and do web search	

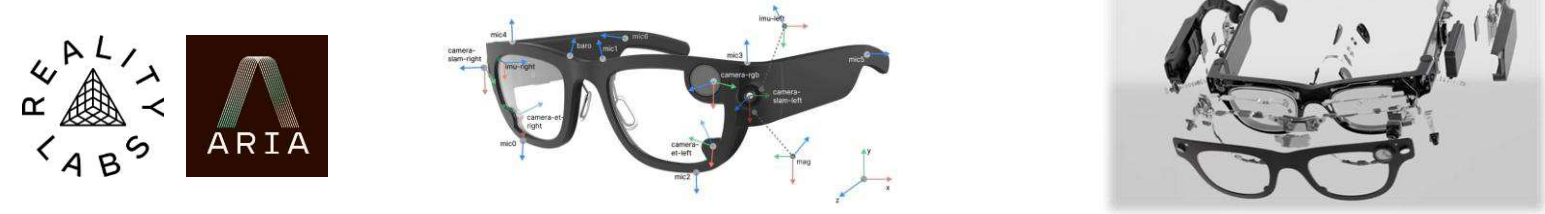
Note: The purpose of this table is to exhibit the module dependence use cases. Of course, some are not covers like comfort improvers and navigation enablers: IMUs and e-compasses.

TECHNOLOGY TRENDS – AR

Aria project: A glimpse at the sensing arsenal



- Meta's Aria is a research hardware platform for smart glasses that aims to assist in the development of augmented reality by recording rich, contextual data from everyday life. Initially introduced in 2020, Aria glasses allow researchers and developers to examine and understand real-world interactions, a step toward more natural and contextually aware AR experiences.
- With its 2nd generation, Meta significantly ups Aria's specifications with the addition of advanced sensors—such as heart-rate monitoring (PPG) and better voice isolation—and custom silicon for advanced on-device AI processing. Each of these developments addresses Meta's vision of integrating AR with personal health, everyday usability, and seamless user interactions, mapping a clear trajectory towards the future of wearable augmented reality technology.



Feature	Aria First Generation (2020)	Aria Second Generation (2025)
Visual Sensors	- 2 Mono Scene Cameras: 640x480, 150° HFOV, 120° VFOV, 30 FPS, global shutter	- RGB Camera (upgraded)
	- 1 RGB Camera: 2880x2880 max, 110° HFOV/VFOV, 30 FPS, rolling shutter	- SLAM Cameras for precise 6DoF tracking (new)
	- 2 Eye-Tracking Cameras: 640x480, 90 FPS, global shutter	- Eye-Tracking Cameras (enhanced accuracy)
Non-Visual Sensors	- IMUs (1000Hz & 800Hz)	- IMUs (improved precision)
	- Magnetometer (10Hz)	- Magnetometer (upgraded)
	- Barometer (50Hz)	- Barometer
	- 7-channel Spatial Microphone (48kHz)	- GNSS (enhanced GPS)
	- GPS Receiver	- Spatial Microphones (improved clarity)
Compute & Performance		- PPG Sensor for heart rate monitoring
	- Qualcomm Snapdragon 835	- Contact Microphone in nosepad for voice isolation
	- 4GB RAM	- Meta-designed custom silicon
	- 128GB Storage	- Optimized for on-device AI processing (SLAM, eye/hand tracking, speech recognition)
Battery Life	- ~1.5 hours continuous recording	- 6–8 hours continuous use (significant improvement)
Weight & Design	- Weight: 75g	- Weight: 75g
	- Frame width: 147mm & 152mm	- Foldable arms for portability (new)
Audio Capabilities	- 7-channel spatial microphone array	- Spatial microphones (enhanced)
		- Open-ear, force-canceling speakers (new)

TECHNOLOGY TRENDS – AR

A glimpse at what can be harvested

- The more data is collected from the users, the more use cases are enabled. For instance, tracking the sight may allow for overlaying content on physical environment elements.
- As modules are added to track the user and enhance their experience, they also allow for the harvesting of useful data.
- Emteq Labs positions its OCOsense glasses as a solution to measuring emotional and behavioral responses in *real-world settings*.
- The Tobii's design includes a 106° FoV camera to get the context, 16 illuminators, and 4 cameras to track the eyes. (The illuminators and the cameras are directly embedded in the lens.)

1. Researchers

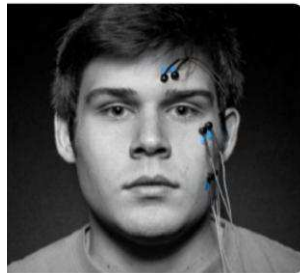
2. Health

3. Consumer wellness

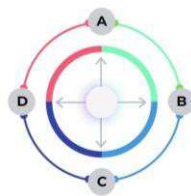
4. Consumer Insights

5. Gaming & Personalised experiences

6. Training and Rehabilitation



Facial electromyography



A High Arousal (high energy states)
B Positive Valence (happy, approving)
C Low Arousal (low energy states)
D Negative Valence (unhappy, disapproving)

What is the user's reaction

What is seen



tobii

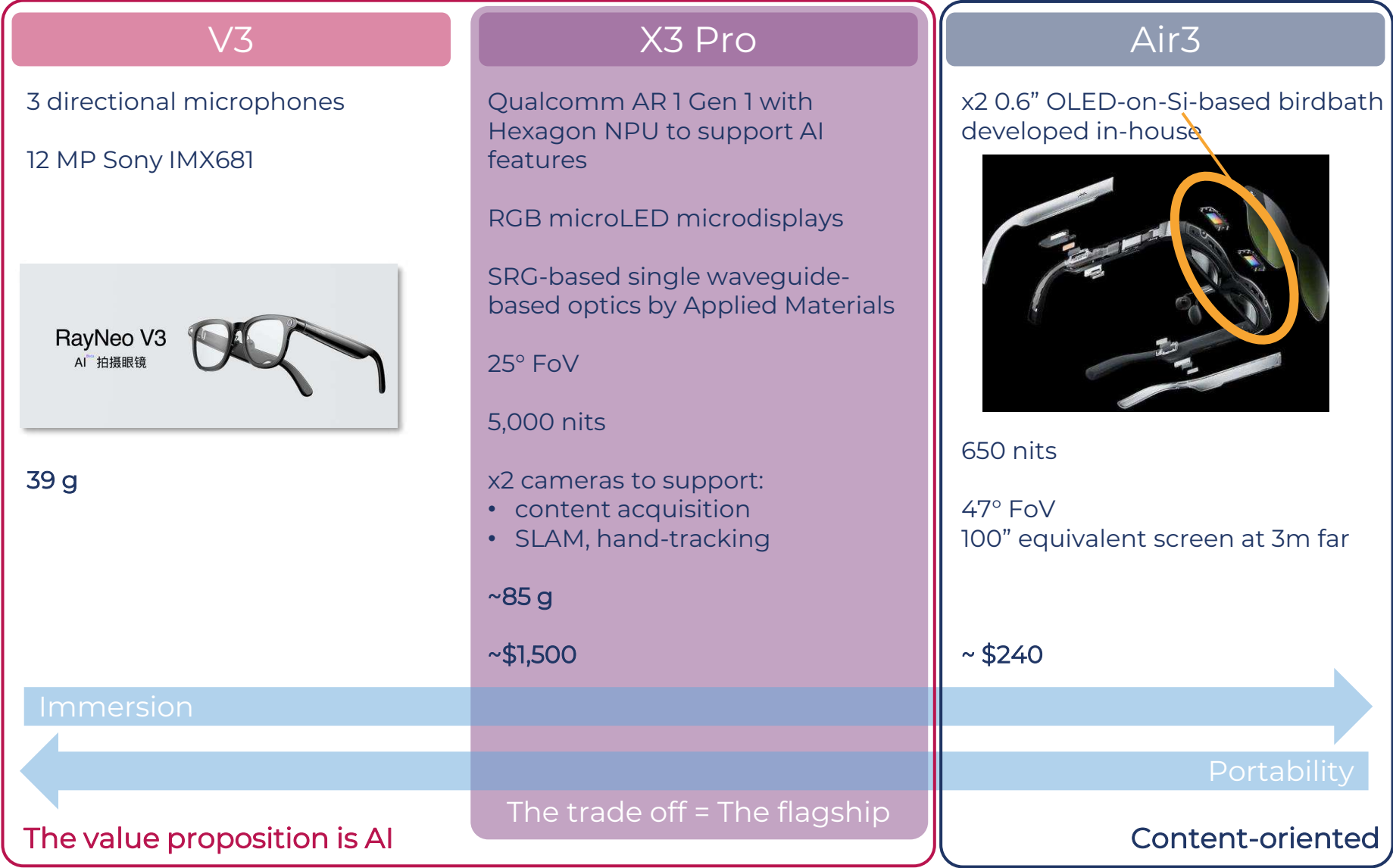


Tobii

TECHNOLOGY TRENDS – AR

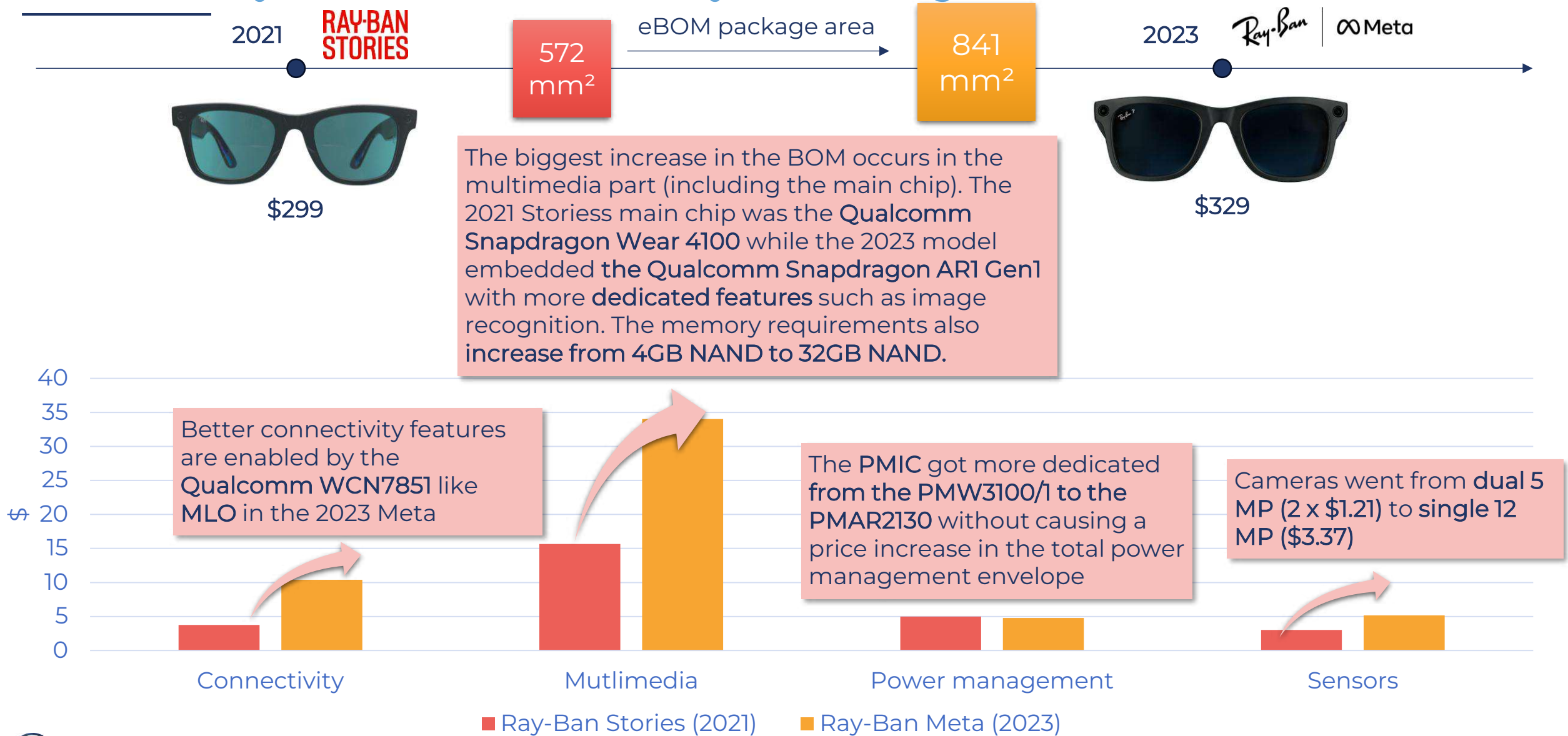
A look at 2025 RayNeo's lineup

- The TCL RayNeo AR lineup presented at CES 2025 gives a good idea of the taxonomy of products to be expected in the AR realm. It declines in:
 - Content creation (with microphones and cameras)
 - AI assistant (with microphone, microdisplays and cameras)
 - Content consumption
- The form factor scales over the degree of immersion, so as the device becomes more appealing, friction is added to its adoption. In the end, a **trade-off** appears – the X3 Pro in the RayNeo line-up – presented as the **flagship**.



TECHNOLOGY TRENDS – AR

The audio-only kind - Evolution of the Ray-Ban smart-glasses



TECHNOLOGY TRENDS – AR

The large FoV kind – The Xreal

- The value proposition of birdbath-based AR glasses is definitely content watching, like movies. They enable quite **large FoV (> 50°)** and leverage high OLED-on-Si resolution (> 4,000 ppi).

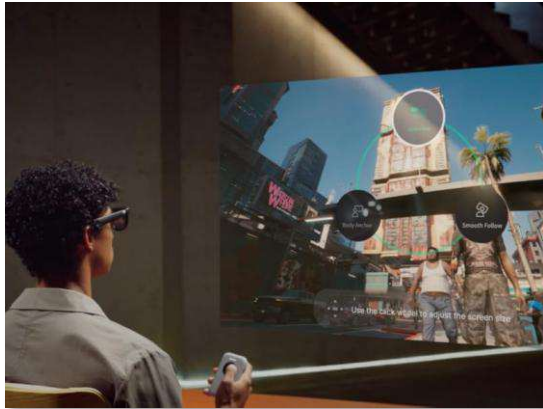
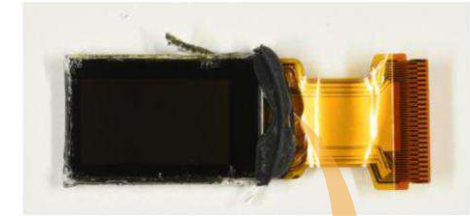


Image: Xreal

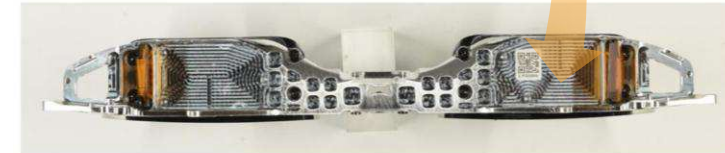
- As HMI is not the goal of such devices, in the XREAL Air2, few sensors can be found. Among them are an **Accelerometer** and a **Gyroscope**. Keeping the window in which the content is displayed while mimicking a large physical screen is essential.
- In the end, these devices remain very display-oriented, with display being < 80% of the BOM.

Sony
OLED-on-Si
0,55"
1,080 x 1,920



Complete OLED-on-Si + Birdbath optics

From top



From front



From bottom



From rear

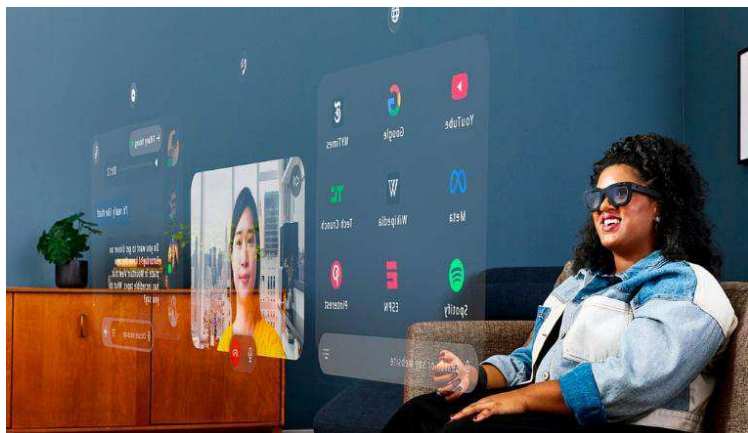


TECHNOLOGY TRENDS - AR

Wide field of view



Why?



Increased immersion and engagement with the content. Justify the user tracking of the eyes, gestures, and more. Consistent with Meta's advertising and data harvesting business model



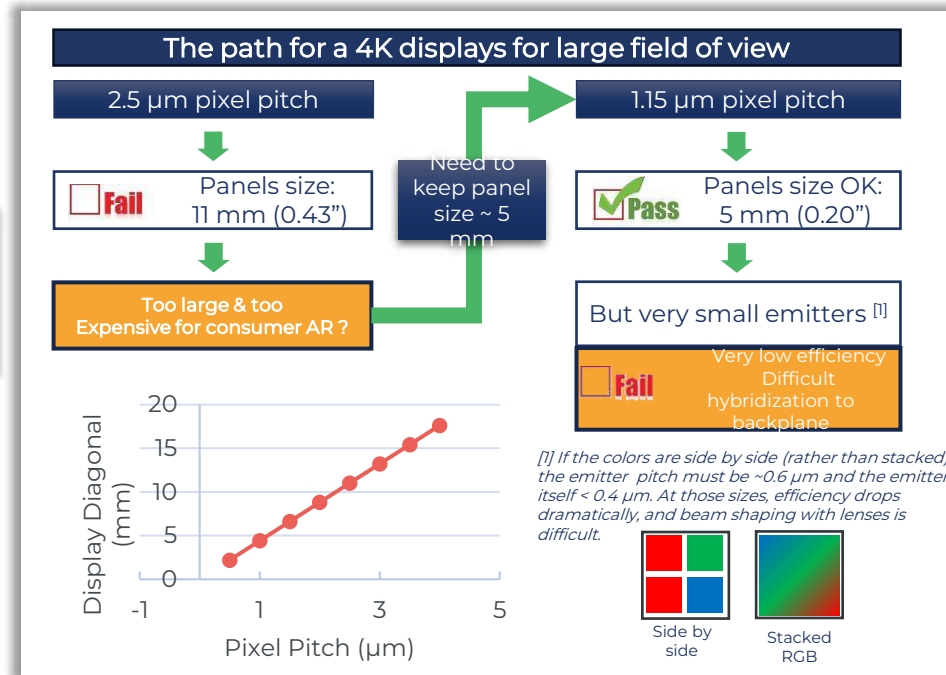
Meta's Orion presentation

Why not?

- For now, and with existing DOE (or SRG) waveguide technology, such a wide FoV requires using SiC. The price of the raw material, around **\$1,500 for an 8"** - for 10 eyepieces – made **\$300 the SiC raw material for a pair of glasses** → **Prohibitive, for consumers**. We estimate that the SiC alone accounts for an important part of the announced \$10,000 Orion manufacturing cost. Yet it is not only a matter of price.
- The **Orion weight is nearly 100 g**, while some computations have already been done on a computer puck. Also, the battery life must not be compliant with consumer expectations, as it was not the duty of this device to be sold in volume.
- Computation and battery usage scale over the FoV and the content's richness.



Meta's custom BP for the microLED displays (1 per color)



TECHNOLOGY TRENDS – AR

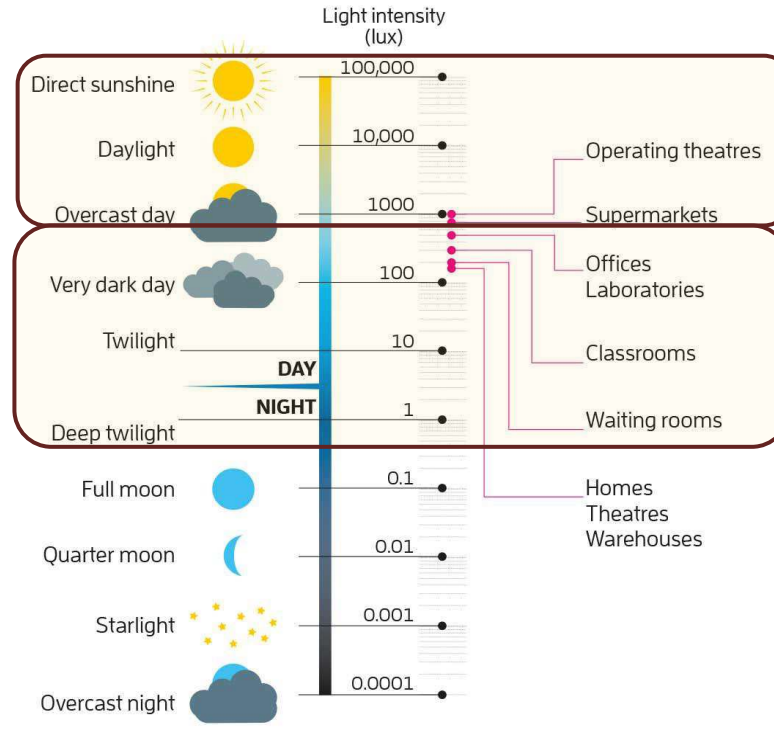
Brightness range-related challenges



- To be used on a daily basis in most environments, the display must be able to deliver the right amount of light under direct sunshine without dazzling when the pupil is fully open in the dark or dimmed lighting. These essential requirements force the display engine to operate over a wide range of 4 orders of magnitude.
- This causes issues related to the driving of the backplane to rise, but above all, it is the maximum brightness level that is the most challenging to match without sacrificing the resolution or producing too much heat.

The light in our lives

Even the brightest indoor spaces are dim compared with the outdoors in daylight



SOURCE: NATIONAL OPTICAL ASTRONOMY OBSERVATORY



MicroLED Champion [1]:
6,000 Nits



[1] Announced September 2024 by JBD using its 3-panel Hummingbird solution



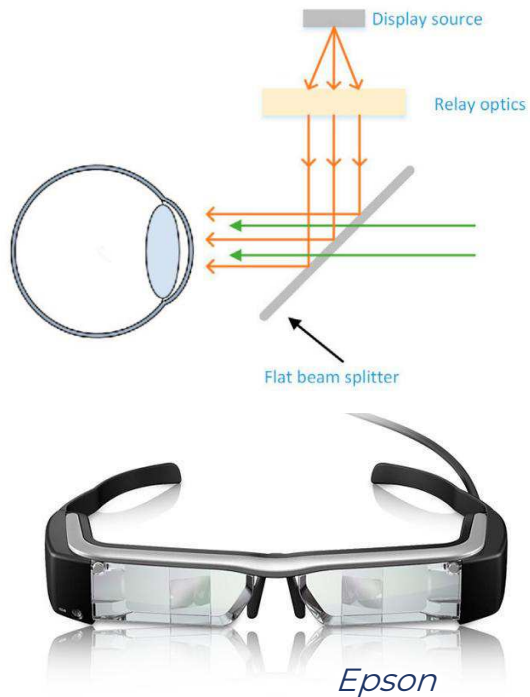
Technology trends - AR optics

TECHNOLOGY TRENDS – AR OPTICS

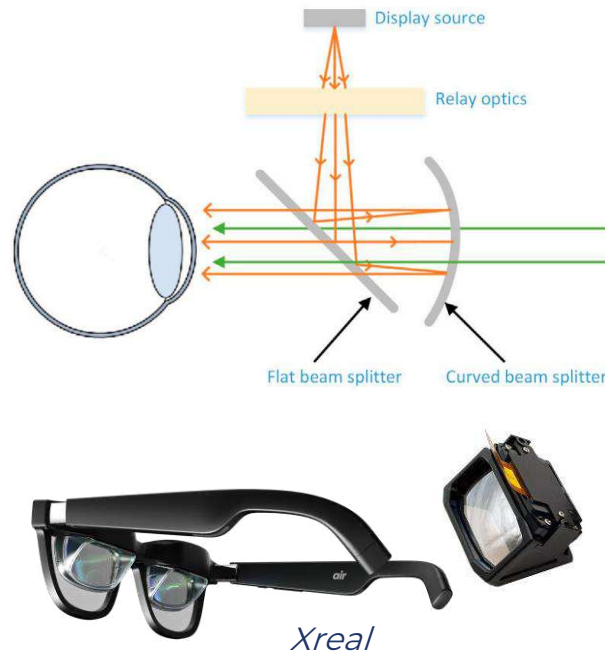
Free space vs. Waveguides: Bulk vs. Slim

Free space optics

Single partial mirror



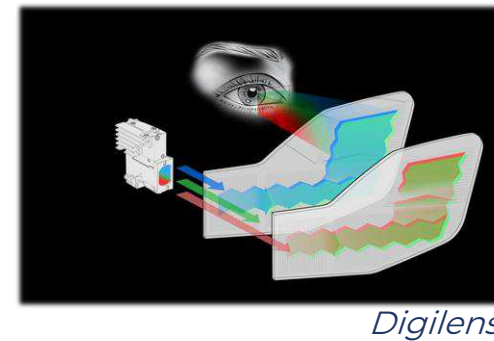
Birdbath optics



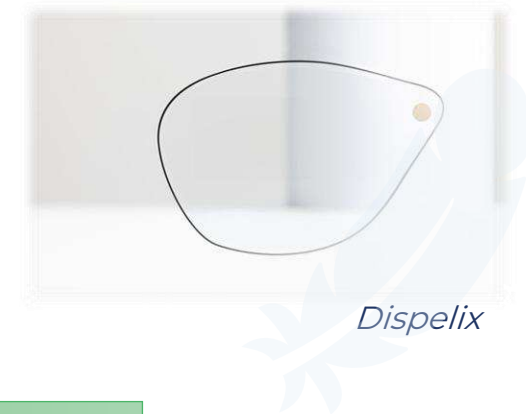
To bulky for a widely accepted consumer-oriented product

Waveguide optics

- The waveguide-based optics comprise several subcategories depending on how the light is out-coupled and in-coupled. (See next slides for details on: Surface relief grating, Holographic volume grating, Polarization volume grating, Mirrors)
- These technologies have in common the fact that total internal reflection (TIR) is leveraged to guide light.
- However, the maximum angle depends on the material's refractive index.



Digilens



Dispelix

Enable slim enough form factor to match consumers expectations

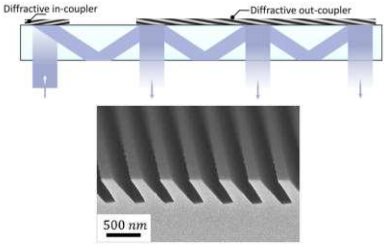
TECHNOLOGY TRENDS – AR OPTICS

AR waveguide technologies



Diffractive waveguides

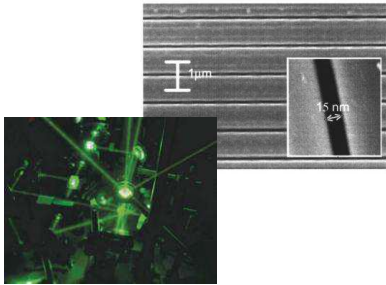
Surface Relief Grating (SRG)



- Well-established CMOS-compatible process
- Allow better control of the uniformity due to gradient of depth and HRI material (thanks to ink-jet coating prior to imprint with varying pattern depth size or gray scale lithography)
- FoV limited by refractive index
- No consensus on material, manufacturing and design
- Rainbow effect needs to be mitigated

Industrial standard

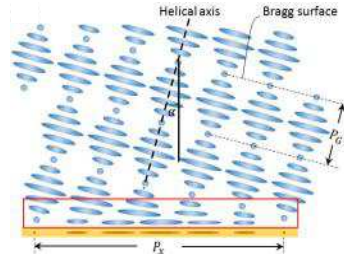
Volume Holographic Grating (VHG)



- All optical manufacturing process (no etching or contact-based technique)
- Requires precise volume holography setup for manufacturing so less poised to reach scalability
- Less control over uniformity due to constant thickness

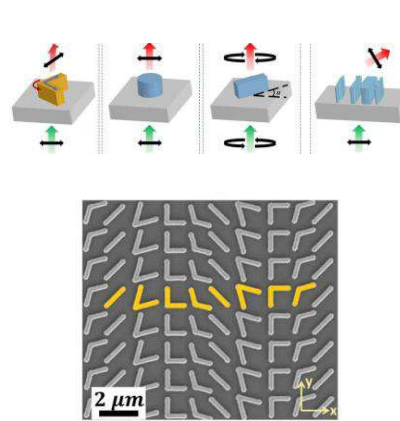
Fully optical exposure-based manufacturing process

Polarization Volume Grating (PVG)



- All optical manufacturing process (no etching or contact-based technique)
- Less control over uniformity due to constant thickness

Meta-atoms

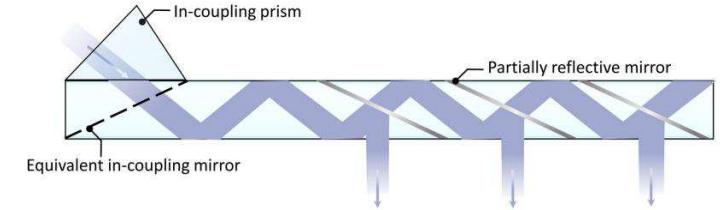


- Highly customizable
- Highly functionalizable
- Much more challenging design and manufacturing

Emerging

More common

Geometric waveguides



With this approach, the light travels leveraging TRI still but gets extracted thanks to mirrors.



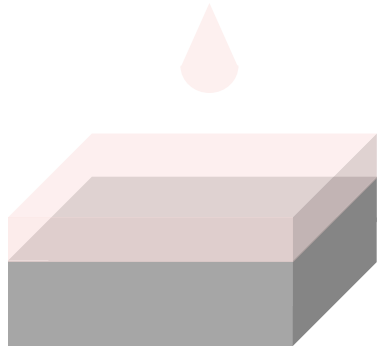
The mirrors can be pin mirrors like LetinAR example (on the left) or straight ones like Lumus example (on the right).

- Very efficient in terms of light extraction
- Enables large FoV much more easily

- No scalable manufacturing process due to non compatibility with CMOS like processes
- Mirrors are visible

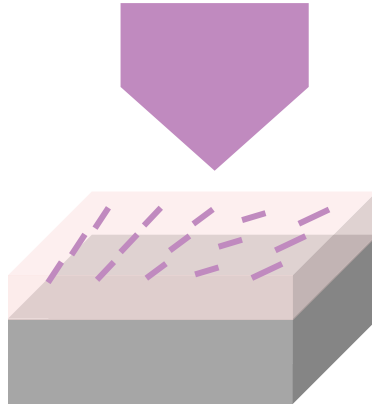
PVG fabrication process

All optically manufactured PVG



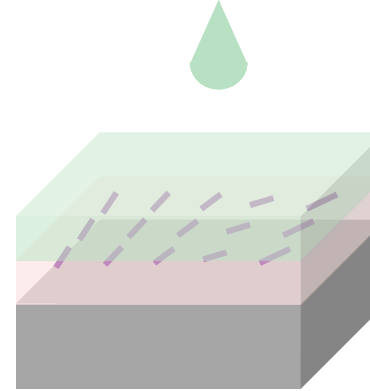
Photoalignment layer deposition

Photoalignment material (SD1 molecule with azo group) is deposited onto the substrate via spin, slot-die, or spray coating, achieving a uniform thickness of nearly 10-30 nm.



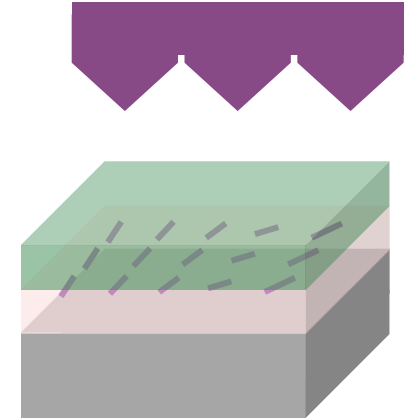
Pattern formation (direct or duplication)

Polarization holography with a UV-VIS light source patterns the PAL, generating spatially varying alignment (change in shape as absorbing the light, trans to cis transform).



Reactive mesogen deposition

Reactive mesogen with a chiral dopant is deposited onto the PAL, which it self-aligns to the pattern, forming a cholesteric liquid crystal (CLC).

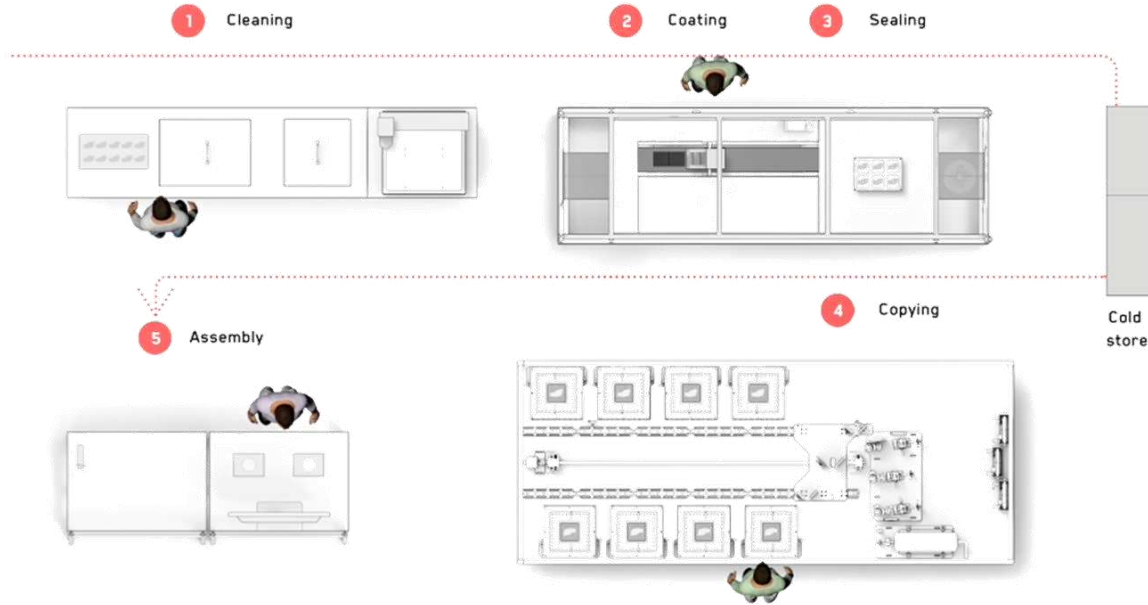


UV curing polymerization

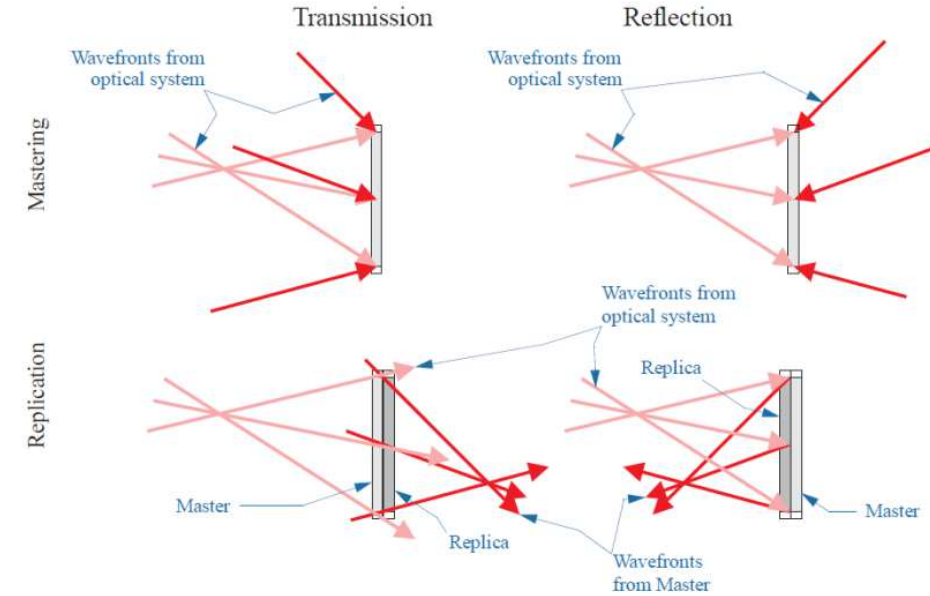
The CLC undergoes UV curing polymerization and then its structure becomes stable. Another type of reactive mesogen can be deposited on top to form a multi-layer.

TECHNOLOGY TRENDS – AR OPTICS

VHG (or HOE) manufacturing process



- Cleaning pre-cut eyeglass parts using industry-standard ultrasound and plasma washers.
- Coating DigiLens photopolymer onto the waveguide with an inkjet printer in a few seconds.
- Sealing with a vacuum press cover glass over the thin photopolymer film, then store in the fridge with a six-month shelf life.
- Copying is where waveguide gratings are exposed using a DigiLens laser scanner copy machine, similar to a photocopier. The process occurs in seconds and is 100% repeatable.
- Assembly is performed after an optical quality check; red and blue waveguide components are bonded into an eyeglass frame in a few seconds.



Scheme: The path to mass manufacturing: master with two beams and replica with one.



Image: HOE mass production tool.

(Source: Luminit)



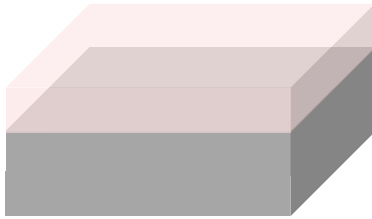
TECHNOLOGY TRENDS – AR OPTICS

Hard master manufacturing process flow

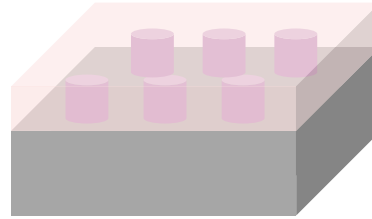
UV or e-beam lithography



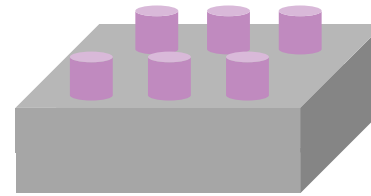
It starts with a raw substrate.
(Mostly Si is used as generally IR-metalenses and master for NIL are targeted)



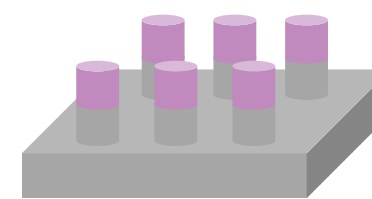
Resist deposition
It can be Negative or Positive and depends on the nature of the insolation beam (photons or electrons)
Spin-coating is mostly used here.



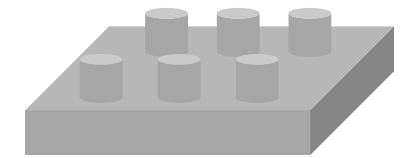
Insolation process
In the example above, the squared pillar array are exposed within a positive resist.



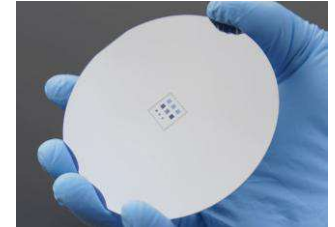
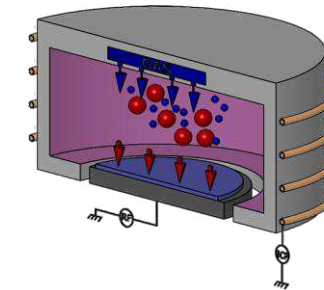
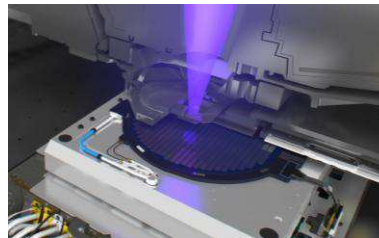
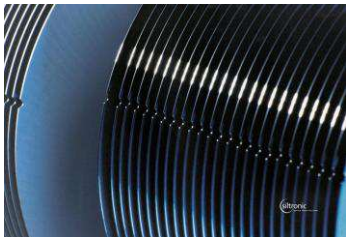
Resist development
After these steps, only the exposed area remains in the case of positive resist. *(If a negative resist is used, only the not exposed areas remain)*



Etching step
Plasma-based dry etching allows for directional engraving of the substrate, which is no longer covered by the resists anymore. *(This angle can be tuned to make blazed and slanted gratings)*



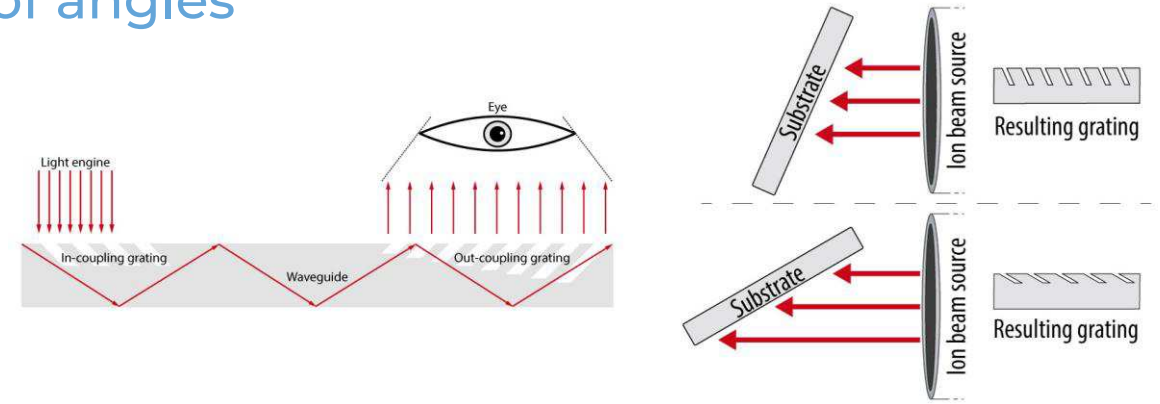
Resist removal
The last step consists of removing the resist to end up with the structure within the material substrate only. *(This step can be done via dry or wet etching depending on the used resist as any direction selectivity is needed)*



TECHNOLOGY TRENDS – AR OPTICS

Dry-etching – Trimming to address the variety of angles

- The main advantage of Ion beam etching over NIL is the ability to engrave the substrate directly. Here, there's **no need for any HRI resist** to maximize the optical index contrast.
- The main drawback of this technology is there are **fewer possibilities for scalability**.
- Tilting the substrate allows for high angles (~60° at best vs. ~30° with NIL).
- However, gratings with different angular orientations must be realized in separate runs, unlike NIL.



Regular etching

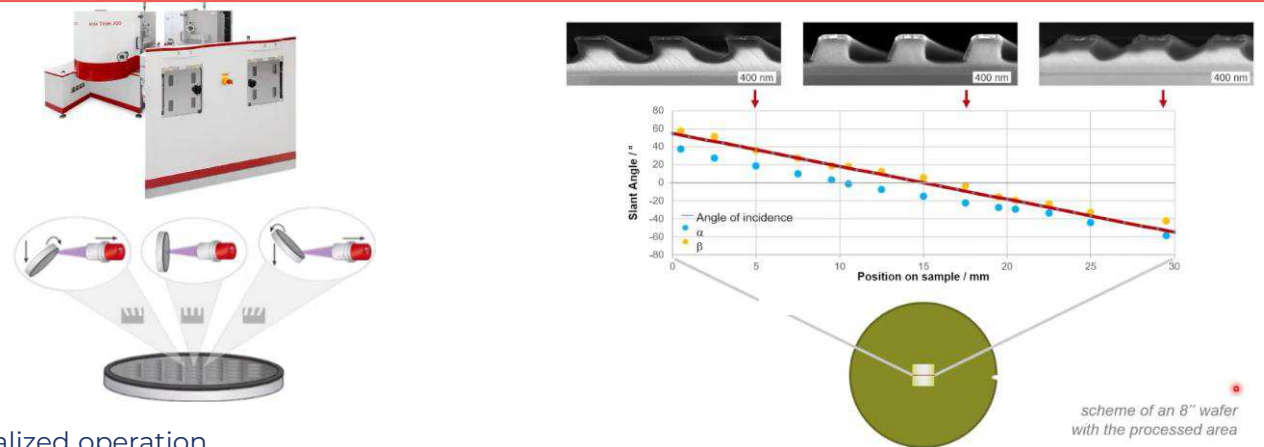


Reactive Ion Beam Etching RIBE

constant slant angle and etching depth over the whole grating

- Full wafer operation
- One angle at a time
 - A different mask must be made for each angle

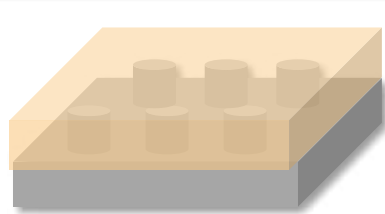
Trimming



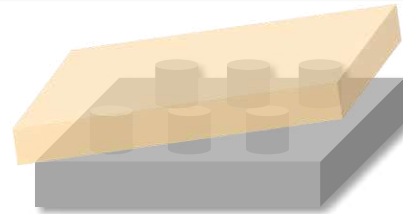
- Localized operation
 - The ion beam FWHM is about 6 mm, so a mask (Cr) is still needed on the substrate.
 - Longer manufacturing run duration.
- Enables varying angles within one run using one mask:
 - Let more parameters free during design optimization. It allows a better uniformity of the waveguide and defect correction.
 - In the end, as the mask can be replicated many times, losing time at its manufacturing step could be worth it.

Stamp manufacturing

One master can be used to make hundreds of soft stamps

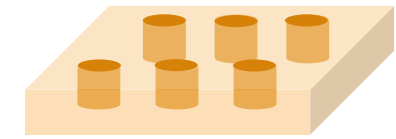


Stamp material infiltration



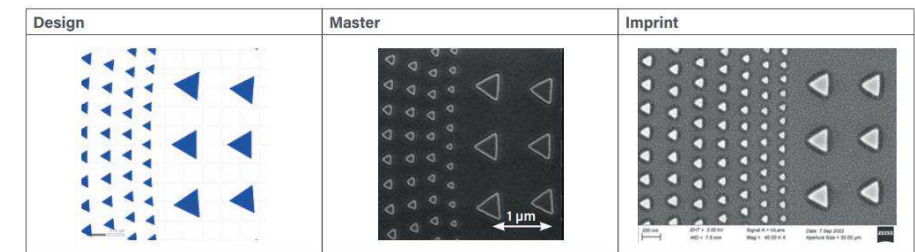
Stamp peel off

Polydimethylsiloxane (PDMS) is commonly used as a stamp material. Its solution is realized by mixing the precursor with curing agents. The solution is then poured on top of the master. A degassing step is necessary to remove any bubbles that may have formed. Then, the polymer is cured with heat, UV, pressure, or a mix of these.



Flexible stamp

Note that it does consist in the negative of both the master and the final design.



From Toppan Photomask and EVG White Paper

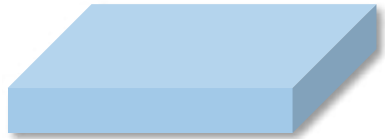
This step is key in the nanoimprinting lithography pipeline as it is a very enabler of scalability. Indeed, out of 1 master, 100 stamps and 1 stamp can be used to imprint 100s of wafers. In the AR field, if we consider 15 eyepieces per 12-inch wafer, 1 master would be the root of the manufacturing of 150,000 eyepieces. In practice, it may be lower than that to diversify design, etc. Still, it gives a good order of magnitude to understand better the potential for scalability of such a replication-based process.

TECHNOLOGY TRENDS – AR OPTICS



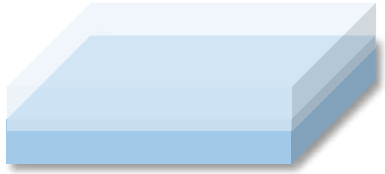
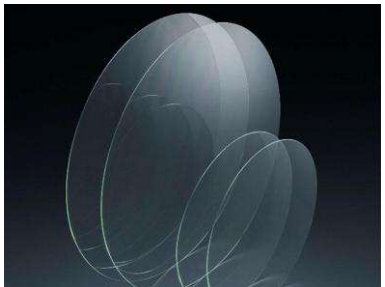
Permanent resist nanoimprinted eyepieces manufacturing process from stamps

Optical metasurfaces manufacturing  One stamp can be used to make hundreds of gratings



It starts with a raw substrate.

It would be HRI plastic or glass for the AR eyepiece or Si for the IR metalenses

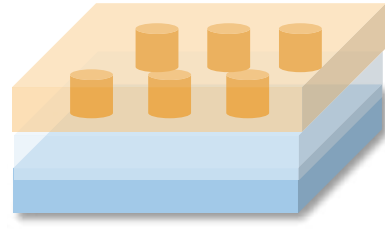


Resist deposition

At this step, the deposited resist may belong to one kind or another:

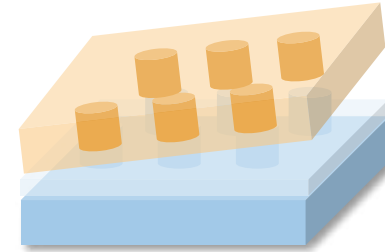
- Whether it is meant to stay and must fit with the right optical property of the final structures.
- Or it is a sacrificial layer, and only morphological, chemical, and mechanical characteristics matter.

Depending on the level of control that is needed, particularly on the thickness, the resist can be spin-coated or inkjetted. *(Spin-coating gives uniform height, while ink-jet may allow for accurate control of the density)*



Imprint step

During this step, the resist fills the holes left free in the stamp. The right pressure may be applied to reproduce the desired pattern fully and produce an accurate residual layer. Before the stamp is removed, the resist is cured using UV light (if the stamp is transparent at this wavelength) or heat.



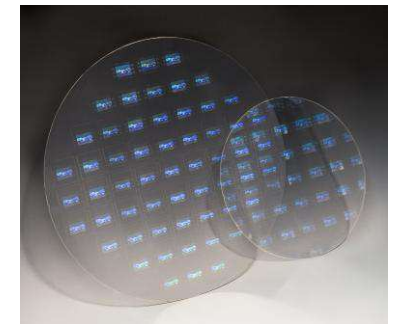
Stamp removal

After the resist is cured, the stamp is removed from the surface. It is crucial not to damage the pattern in this step. If the master material allows it, it may be good to salinize the surface, so it doesn't stick too much. Also, using a flexible stamp allows for not perfectly vertical features like slanted gratings for AR eyepieces.



We end up with an imprinted resist on top of the substrate.

Note that the resist may stay or be used as a sacrificial layer prior to an etching process to transfer the pattern into the substrate itself.



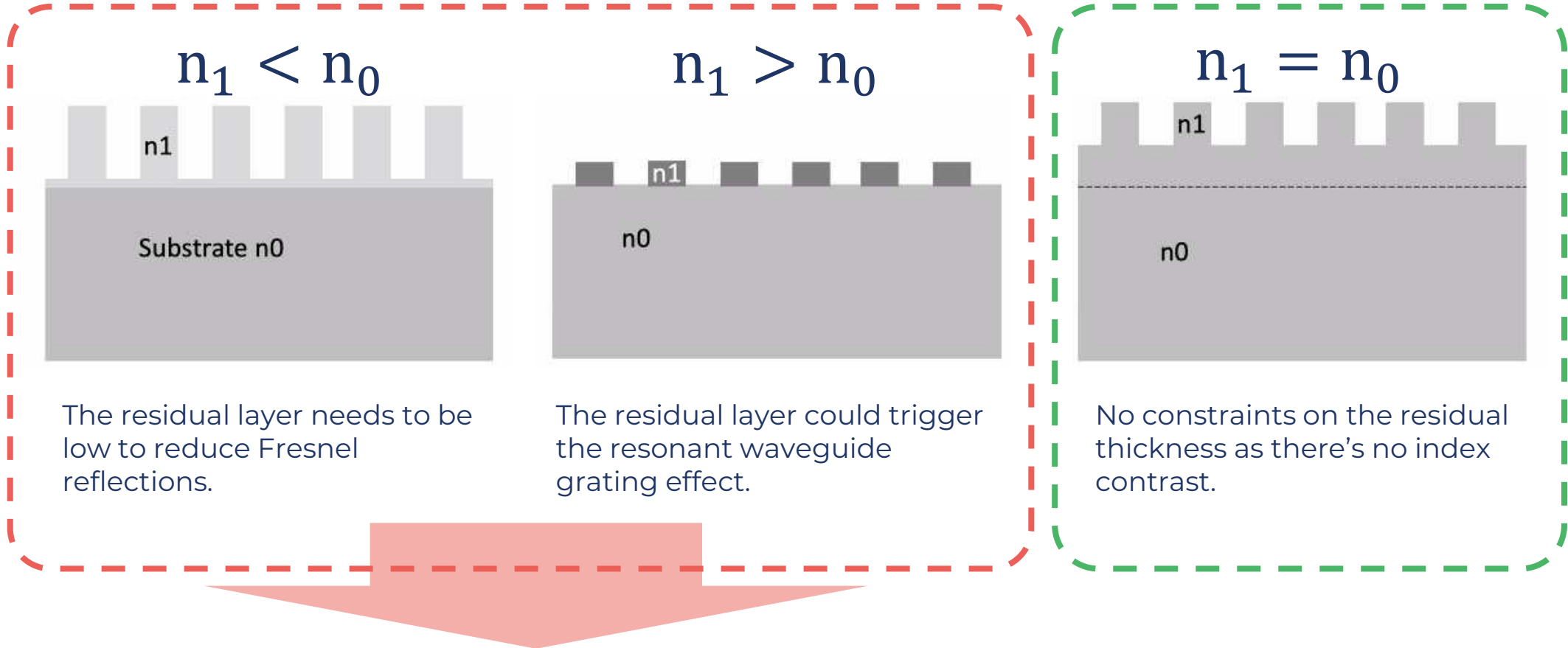
TECHNOLOGY TRENDS – AR OPTICS

Geometry brings manufacturing and material specifications



Manufacturing a grating using a resist on top of the substrate, the choice of the material lead to 3 different cases:

Some material choices impose control over the residual thickness of the etching / imprinting process.



It is imperative to control the residual thickness accurately during the process.



TECHNOLOGY TRENDS – AR OPTICS

Choosing high-index materials for eyepieces – The substrates

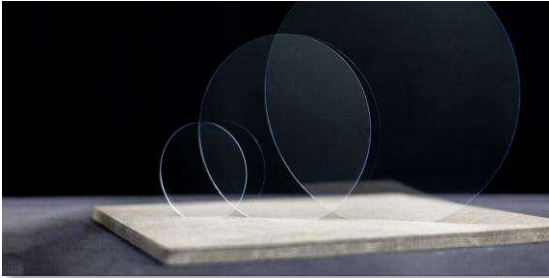
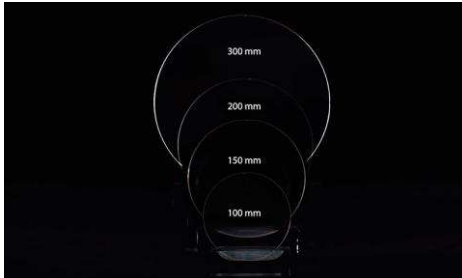
	HRI polymer	HRI glass	SiC
Suppliers	 Mitsui Chemicals	SCHOTT HOYA CORNING AGC OHARA	COHERENT Wolfspeed. SICC TANKEBLUE
RI / FoV	Up to 1.7 / 20°	Up to 2.0 / 35°	Up to 2.6 / 70°
Weight (for 2 eyes)	3.5g	6.6 – 9.6g	6g
Compatible processes	Permanent NIL	- Permanent NIL - Direct etch	- Permanent NIL (with HRI solgel) - Direct etch
Available wafer size	Up to 8"	Up to 12"	Up to 12" but too thick
Price per wafer (for 8")	\$100 <i>More costly now as there is no standard in terms of mass production and only one player front running the development but poised to turn cheaper than glass in the future</i>	\$100	\$1,500 for 8"
			

Image: Mitsui Chemical

Image: Schott

Image: Meta



TECHNOLOGY TRENDS – AR OPTICS

Glass-based waveguides

With only 5 eyepieces on 6" wafers and 15 on 12" ones, the potential market for HRI glass wafers is huge in AR (see Market trends section of this report). Prior to addressing the AR market, all glass manufacturers must comply with requirements on refractive index, Total Thickness Variation TTV, surface roughness, and thickness. As their catalogs testify, they are all able to do so. The competition will occur on 2 things:

- The trust they'll earn from the other players (OEM, equipment makers, manufacturing platform)
- They can increase substrate size to scale manufacturing.

CORNING

SCHOTT

AGC

OHARA

HOYA

Refractive index	1.8 – 1.9 – 2.0	1.9 – 2.0 (>2 with TiO ₂ coating)	1.8 – 2.0	1.8 - 2.001	1.7 – 1.8 – 1.9 – 2.0
Size (up to)	12"	12"	8"	12"	12"
TTV	≤ 0.5 μm	< 0.8 μm	1 μm	1 μm	?
Thickness	≥ 0.3 mm	≥ 0.3 mm	> 0.4 mm	< 0.2 mm	≥ 0.3 mm
Surface roughness	0.25–0.91 nm (with coatings)	1 nm	≤ 0.5 nm	~ 2 Å	?

Schott is also involved in the manufacturing of ROE waveguides for Lumus and also provides HRI glass wafers for DOE imprinted eyepiece.

TECHNOLOGY TRENDS – AR OPTICS

Plastic-based waveguides

- The interests of plastic are multiple:
 - Lightweight: 3.5 g for a pair, twice as light as glass-based
 - Conformable: It can bend without breaking
 - Robustness: It doesn't break during the ballistic test
 - Compatibility with the NIL process within the permanent HRI resist approach. Available wafer size up to 8"
 - Yet high refractive index: Up to 1.7
- The price is still higher than glass due to the lack of suppliers and solutions for polishing it to match waveguide e-manufacturing expectations. Yet it has better potential for cost reduction than glass at scale.
- A solid ecosystem is building around, with a strong incentive from Japan being part of that.



Mitsui Chemicals

Sony DADC



cellid



dispelix

MagicLeap

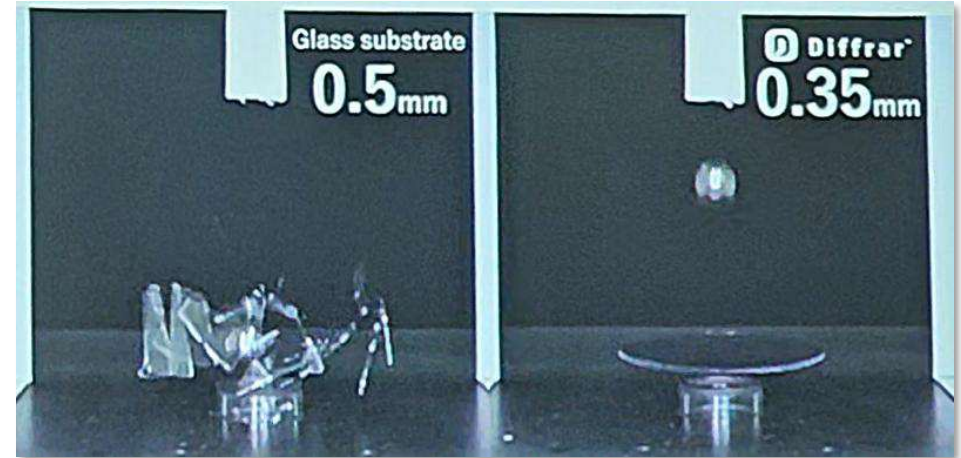


Image: Drop test on glass and plastic wafers by Mitsui Chemicals

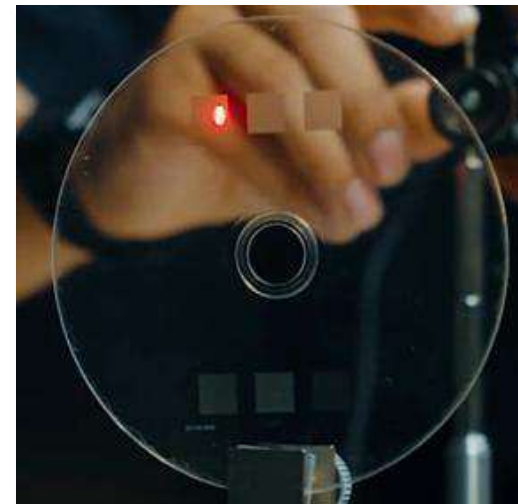


Image: Sony DADC

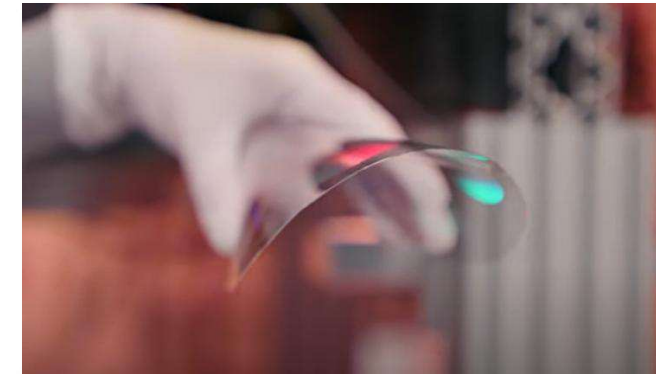


Image: Magic Leap



TECHNOLOGY TRENDS – AR OPTICS

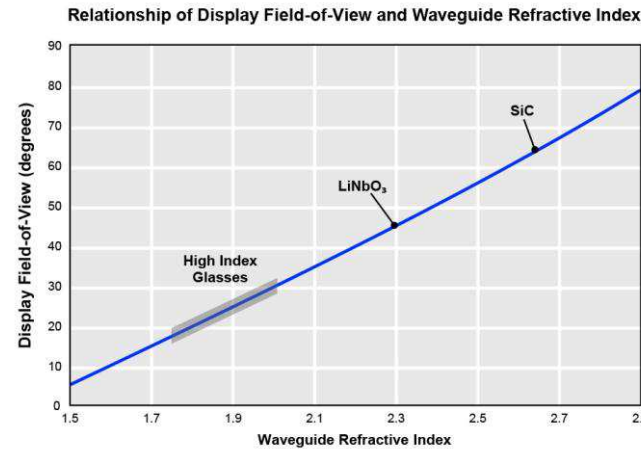
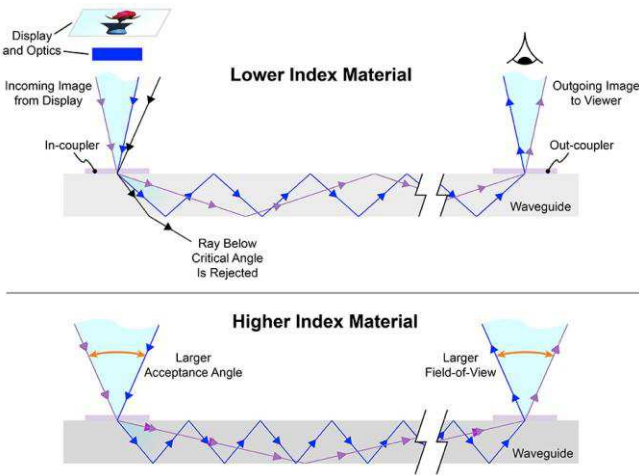
SiC-based waveguides

For the last decade, SiC has been widely adopted in power electronics, aerospace, and automotive systems, where its ability to operate at high voltages, frequencies, and temperatures outperforms traditional silicon. Optical grade SiC is currently being pushed by Meta to be produced on a scale, meaning it will be at a non-prohibitive price. This pull from Meta is because they want to enable wide FoV AR. As the FoV of waveguide-based optics depends on the material's refractive index, SiC is poised to be the best-in-class solution. Yet, some challenges to be tackled:

- Optical purity
- Polishing and grinding
- Cost and scalability (12" availability)

PHOTONICS
spectra

Silicon Carbide Bridges the Gaps Between Electronics and Photonics



Coherent



SICC



JSG



SICC



SemiSiC

Scalability of optical-grade SiC for AR at an affordable price could come from China. Several SiC players even demonstrated 12" capability (not matching already existing specifications of the industry) at SEMICON CHINA 2025.

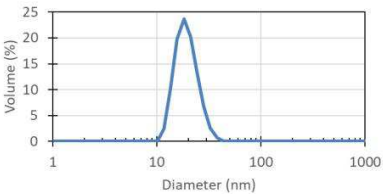
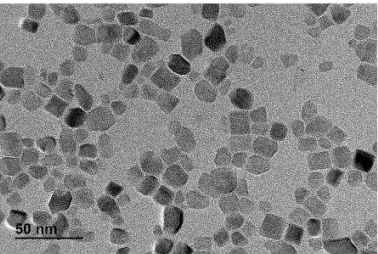
TECHNOLOGY TRENDS – AR OPTICS

The HRI permanent resists

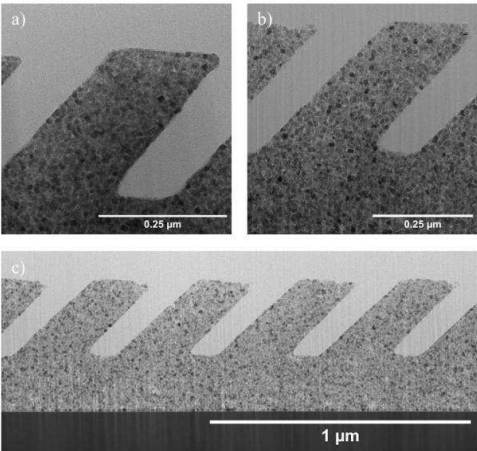
Polymer resists



Polymer-based materials are doped with TiO₂ nanocrystals to increase their index ratio.



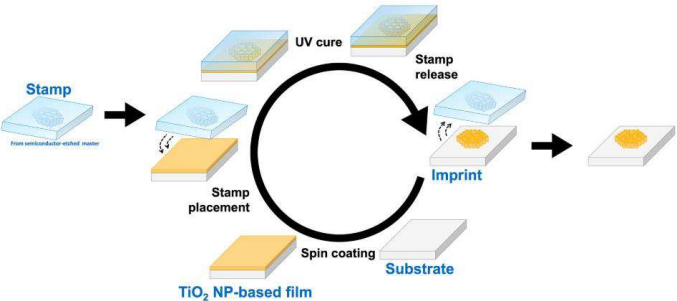
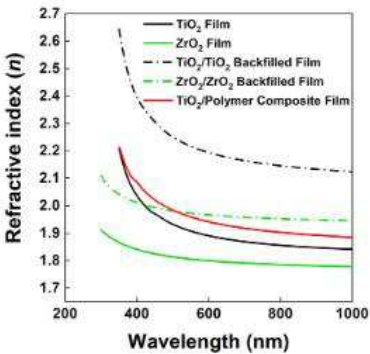
After imprint



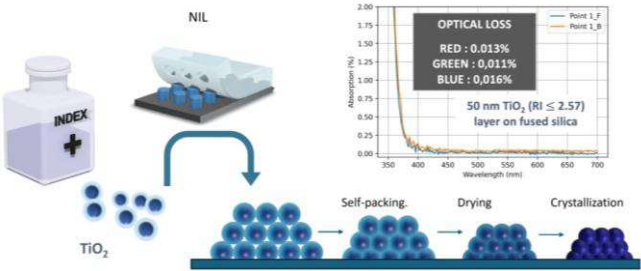
All-inorganic



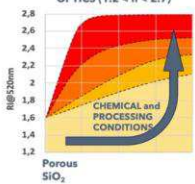
By eliminating organic binders and resins, Myrias ensures that their optics are non-yellowing, UV-stable, and capable of withstanding high-temperature environments.



Solgel



INKS with adjusted REFRACTIVE INDEX from SOLNIL
Combining low index and high index inks to control refractive index between 1.2 and 2.7.



Fully miscible in all proportions high index (+) and low index (-) inks to adjust the refractive index between 1.2 and 2.7 with +/- 0.005 precision.

MATERIALS	RI@520nm	STRUCTURE
TiO ₂	2.6 - 2.75	Rutile
TiO ₂	2.3 - 2.6	Anatase
TiO ₂	2.0 - 2.3	Amorphous
SiO ₂	1.45	Amorphous
SiO ₂ Hydrophobic	1.39	Amorphous
SiO ₂ Porous	1.2	Amorphous
Al ₂ O ₃	1.6	Gamma
ZnO	1.7	Wurtzite
HfO ₂	1.95	Monoclinic
VO ₂	3.3	Monoclinic

Technology trends - AR microdisplays

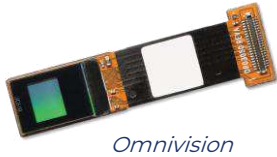
TECHNOLOGY TRENDS – AR MICRODISPLAYS

AR microdisplay technologies



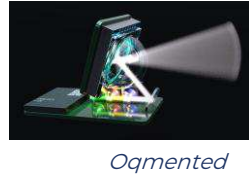
All using Si backplane

LCoS



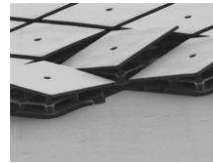
Omnivision

LBS



Oqmented

DLP



Texas Instrument

Avegant



Best trade-off at the moment. Meant to be adopted in early generations and remain in the low to mid end segments

No evidence it will be able to compete with LCoS and microLED. Relies on laser lightsources. Few players

Low resolution (will struggle achieving less than 5 microns pixel pitch)

AR microdisplays

OLED-on-Si



eMagin

Not suitable due to low level of brightness (10 k nits)

MicroLED

Monocular

Binocular

Monochromatic

RGB

No standard has been found yet

Color conversion

Optically combined

Vertically stacked

Same epi

Self emissive



TECHNOLOGY TRENDS – AR MICRODISPLAYS

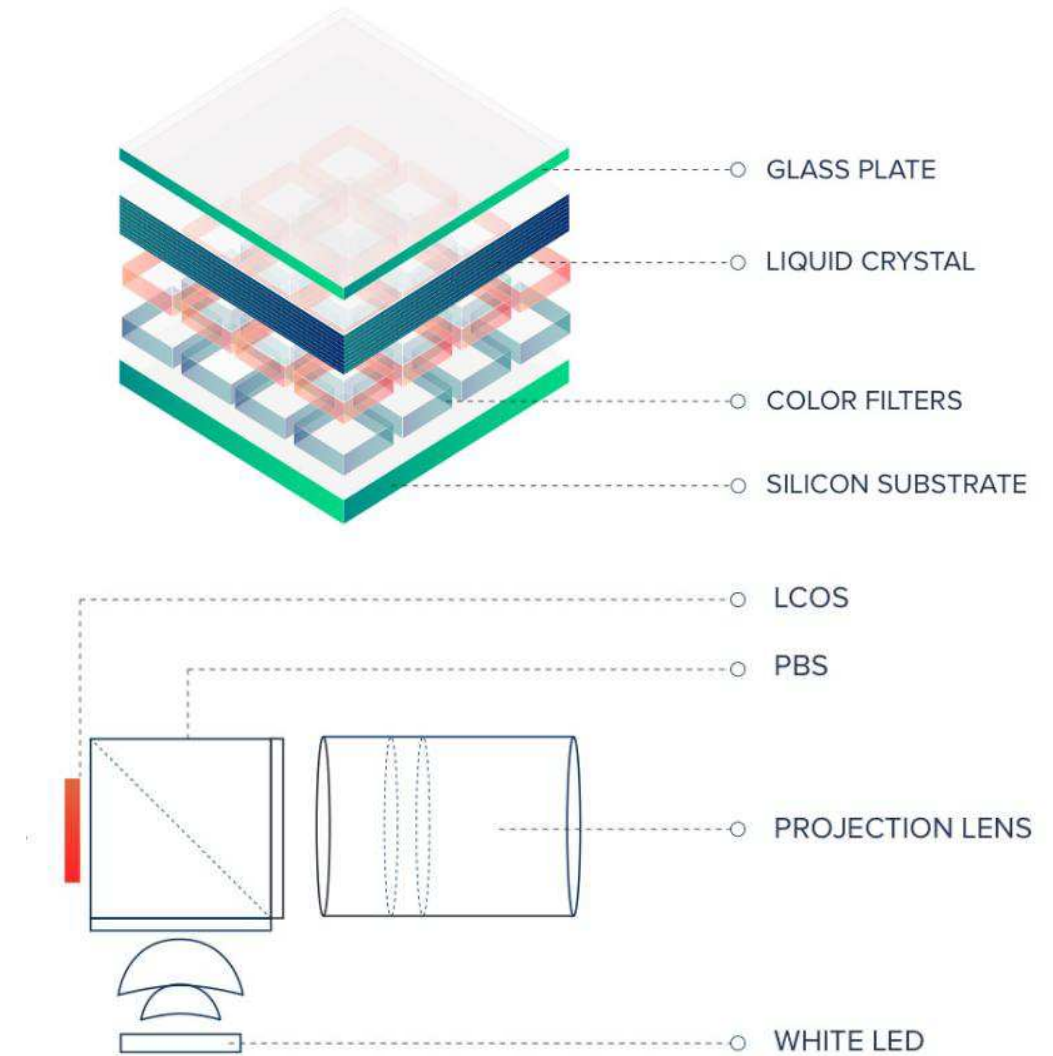
Microdisplays technologies comparison

The table below allow to compare microdisplay technologies. It only includes the main ones being LCoS, microLED (LED-on-Si), LBS, DLP and LBS. For further deep dive on emerging display technologies, check the slides at the end of this section.

	OLED-on-Si	MicroLED	LCoS (Liquid Crystal on Silicon)	DLP (Digital Light Processing)	LBS (Laser Beam Scanning)
Brightness	28,000 nits at best	Million nits (for Green or white)	Depends on the light source. Can reach millions	Depends on the light source. Can reach millions	Depends on the light source. Can reach millions
RGB ?	Yes but lower spectral purity than the others	Yes with different approaches. See slide XXX	Yes with sequential lighting (RGB LEDs)	Yes with sequential lighting (RGB LEDs)	Yes with sequential lighting (RGB lasers)
Resolution	3-4 microns pixel pitch	Down to 2 micron pixels monochromatic. 4 micron pitch in RGB when not combined with a prism	Down to 1 micron pixel at best	Down to 5.4 microns	Depends on refresh rate and content size  Trade off
Refresh rate	90 Hz	60 Hz	60 Hz	Up to 240Hz	60 Hz
Power consumption	Can be very low (<10 mW) in current outdoor products. But those are paired with mirrors optical relay not waveguide so very low brightness out of the display engine	Between 50 to 100 mw for current monochromatic solution at 10% APL	Around 50 mw for 10% APL and using local dimming strategy	Typically higher than LCoS due to faster modulation and electronics	Highly content-dependent and varies with scan parameters
Maturity	Mature	Low but with a wide room for improvement. Highly investigated	Mature with room for improvement	Mature	Low

LCoS depiction

- LCoS microdisplays are formed by growing the reflective and LC technology on top of a Si-based CMOS backplane. The CMOS technology of choice is usually for older nodes because there is a need for voltage values that are high enough to ensure that the LCs switch rapidly. The density and complexity possible with CMOS circuitry allow for the integration of row and column access circuitry onto the LCoS chip and the use of much more sophisticated pixel circuitry than is possible with thin-film transistor active-matrix displays.
- Due to the price of CMOS technology on Si, LCOS panels are usually small - hence the “microdisplay” designation. The typical panel size is ~0.8”. Resolution can increase to several thousand PPI.
- LCoS panels are mainly used as projection sources. A light source can go through different series of optics⁽¹⁾ to light up LCOS panels, which will modulate the light accordingly before reflecting it to where the image is recombined and projected.
- The light source defines spectral purity. LEDs are typically used.



Schemes: Himax technologies



TECHNOLOGY TRENDS – AR MICRODISPLAYS

LCoS vs. MicroLED: A use case dependent outcome

Depending on the use case, the APL percentage will vary and give the advantage of power consumption to LCoS or MicroLED.

A sweet spot is to be found for MicroLED to win against partitioned LCoS

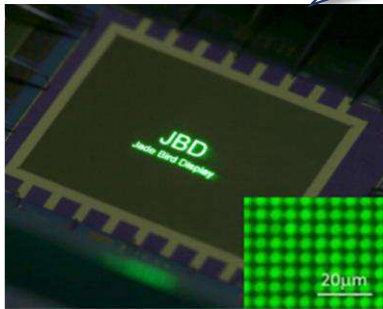
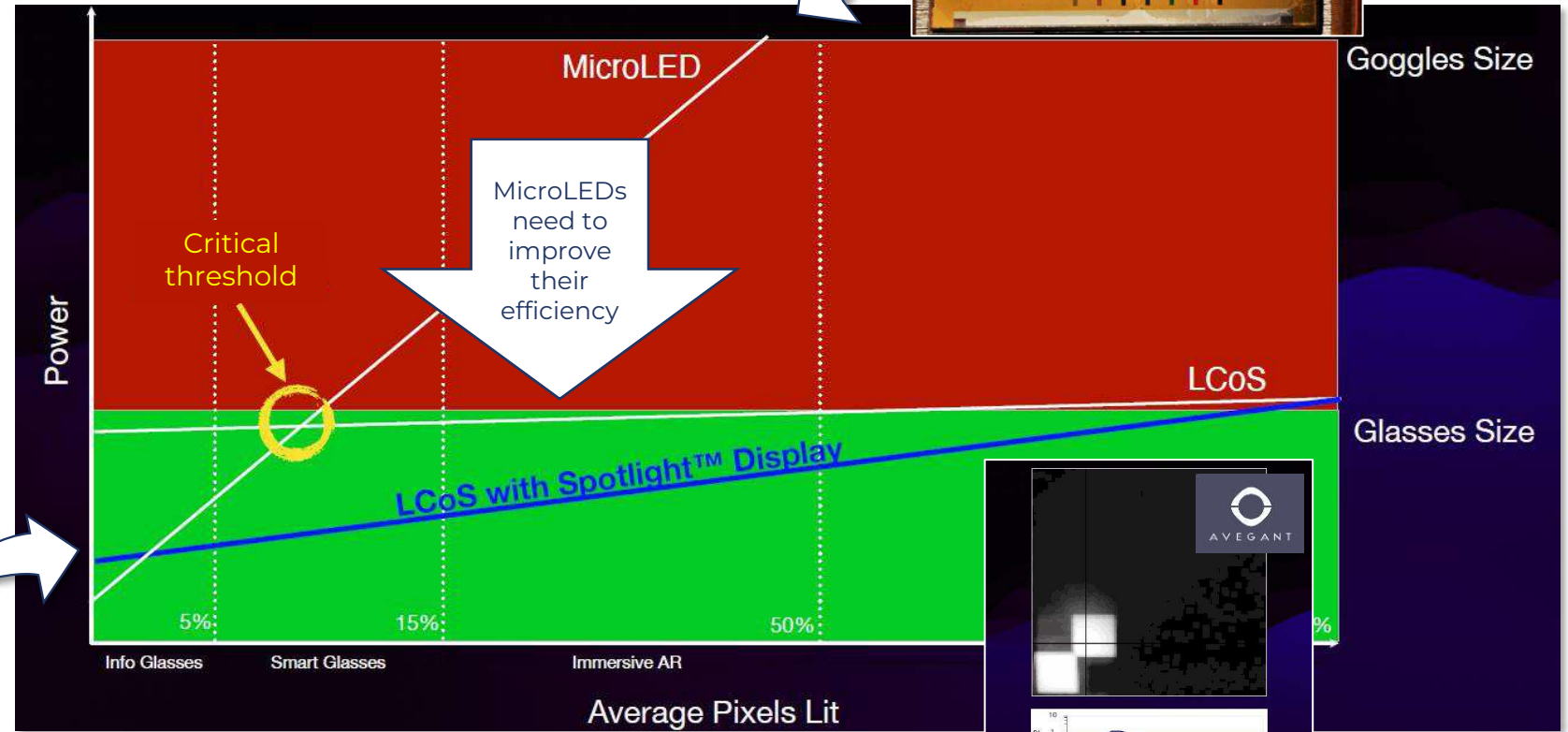


Image: JBD



Like with MiniLED for backlight, partitioned illumination for LCoS allows for scaling the power consumption with content and competing with self-emissive technologies even for low APL.

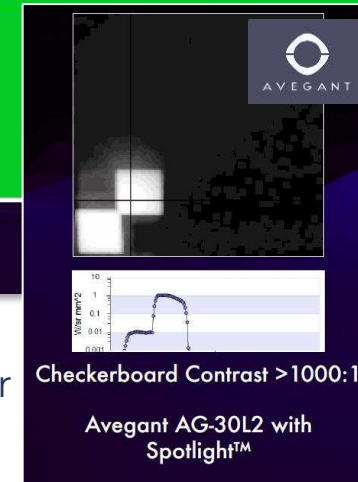


Image: Avegant

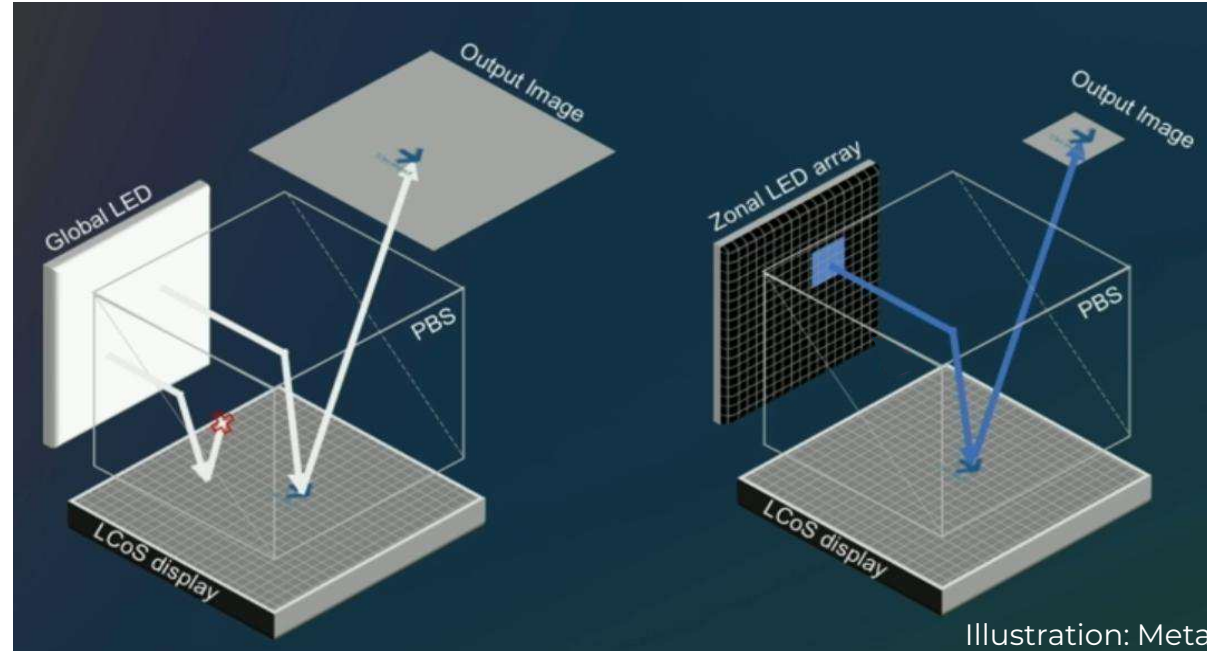
TECHNOLOGY TRENDS – AR MICRO DISPLAYS

Partitioned LCoS's front-light

LCoS is a relatively mature technology. However, it keeps improving. Notably the size of the projectors has shrunk considerably, to < 1 cc by eliminating the bulky Polarizing Beamsplitter (PBS).

In early 2024, Avegant presented its Spotlight™, segmented mini/microLED illuminators. Similar to full array local dimming backplanes in large LCDs, it enables improved contrast and reduced power consumption.

Vuereal (ColourFusion™) and Meta have discussed similar concepts.

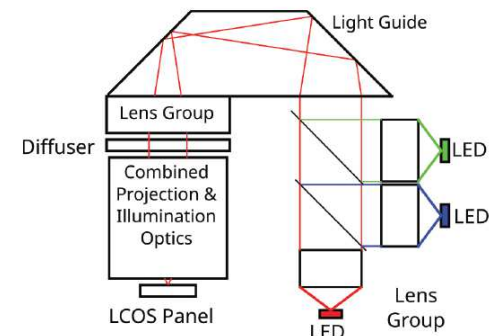
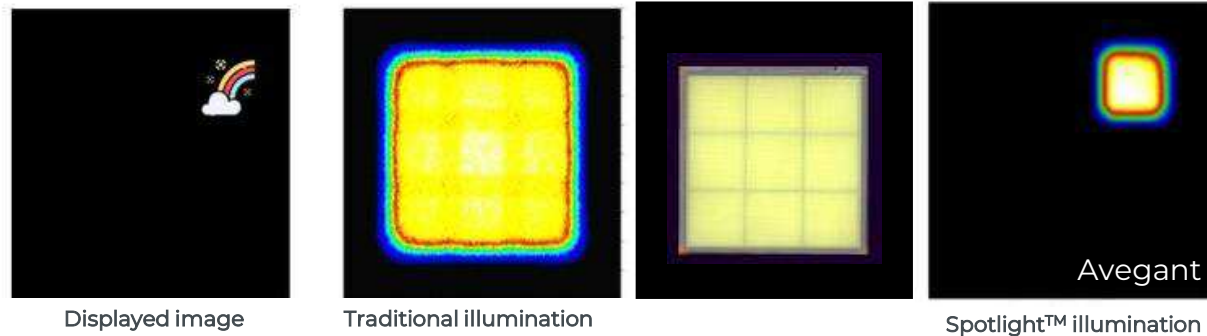


Top: In a traditional LCoS, the illuminator lights up the entire display area.

Only the area where an image is displayed is illuminated with zonal illumination.

Bottom: Avegant Spotlight™ LCoS projector uses 0.6x0.6 mm, 3x3 segmented red, green and blue LEDs from Lumileds as the illuminator.

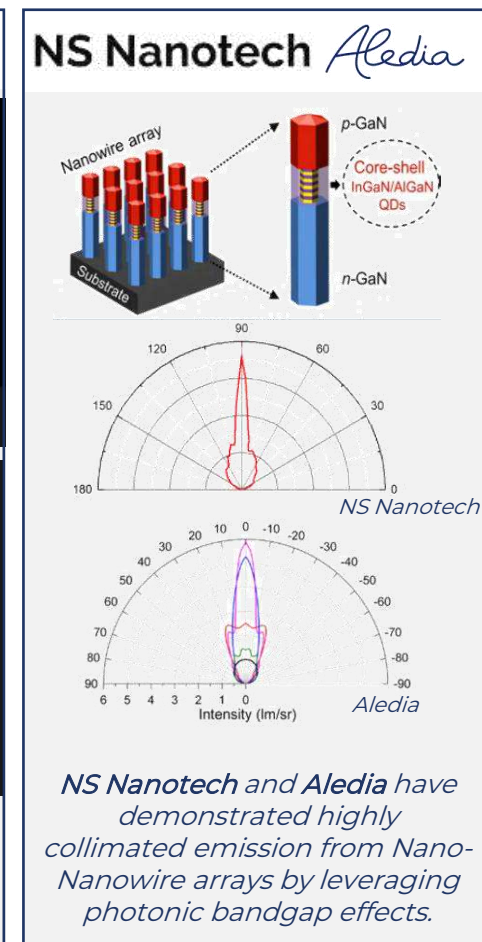
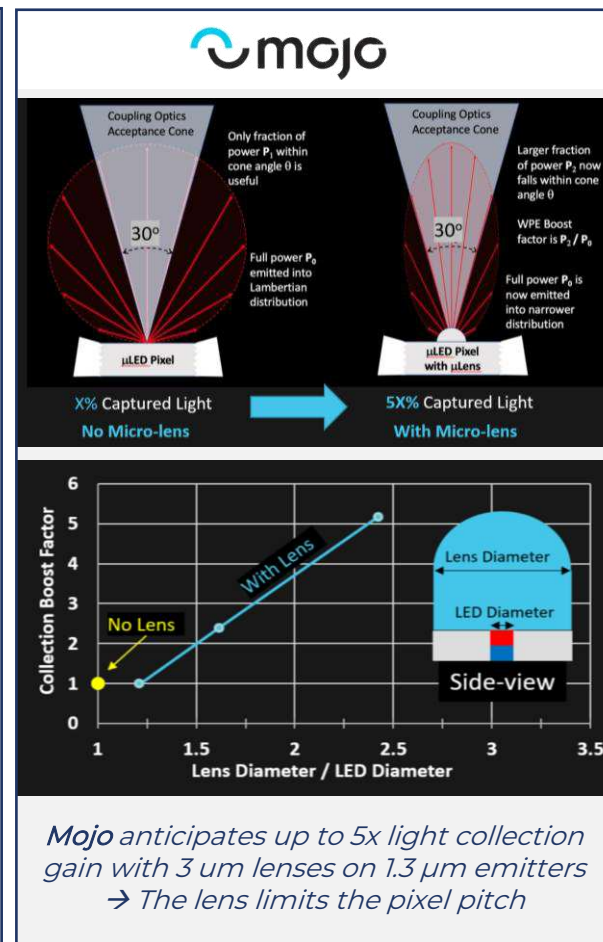
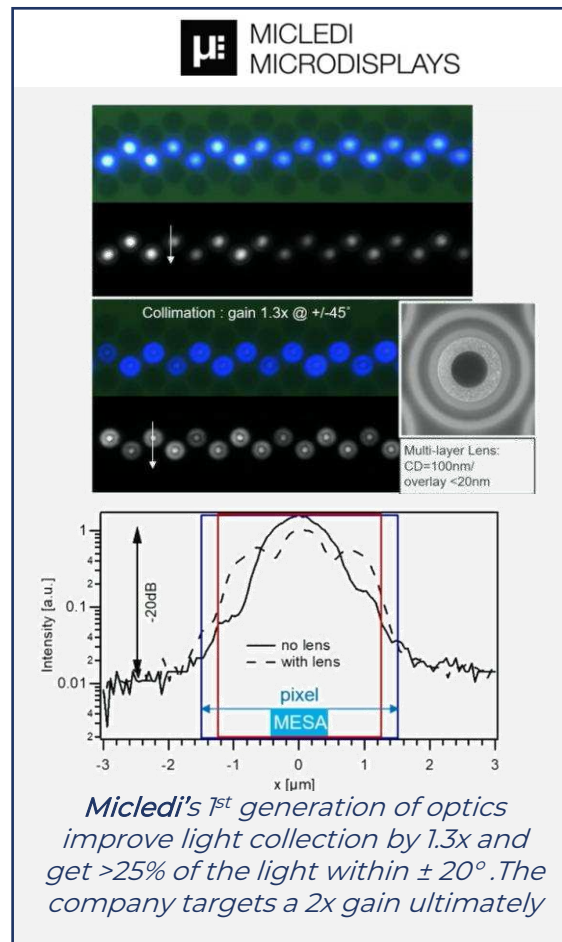
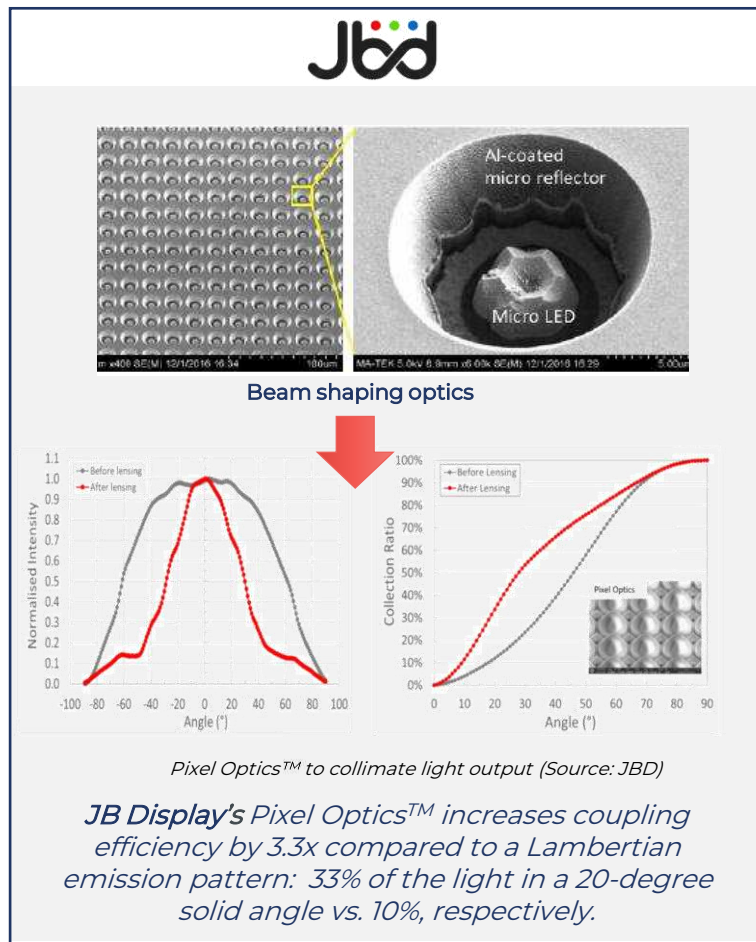
When a single segment needs to be illuminated, the power consumption is 1/9th that of traditional illuminators. The black level is improved 100x. Work is in progress on the visibility of the segment gaps.



TECHNOLOGY TRENDS – AR MICRODISPLAYS

Shaping the LED emission for better coupling into the waveguide optics is critical

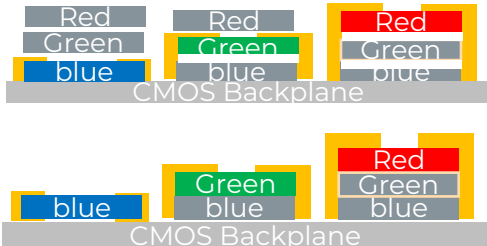
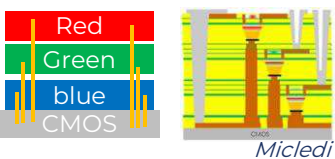
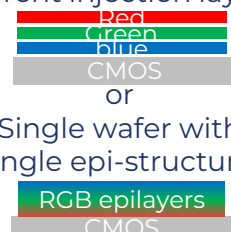
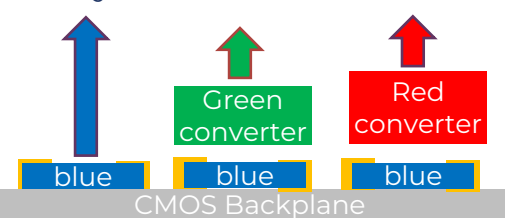
Waveguide optics typically have acceptance angles around $\pm 15^\circ$. **Beam shaping is therefore critical to maximize coupling.** To efficiently collect the light, the lens diameter must be larger than that of the emitter. This restricts pixel density. Alternatively, photonic bandgap effects in nanowires could deliver very narrow emission (NS Nanotech, Aledia)



TECHNOLOGY TRENDS – AR MICRODISPLAYS



Many options are being explored to deliver full color microdisplays, but none has yet reached volume production

	Lateral single plane RGB <i>Slow development</i>	Stacked staggered multiplane <i>Complex manufacturing</i>	Stacked vertical RGB <i>Complex assembly and driving</i>		Color conversion (CC) <i>QD patterning and stability</i>
Description	The three native R,G,B emitters are side by side on the same plane. Achieved by starting from a true RGB epiwafer (with three colors on the same epiwafer) 	R,G,B emitters are laterally separated but staggered on different planes. 	Stacked, thinned bonded R,G,B led structures with ability to individually address each color (e.g.: through vias) 	Single wafer with stacked R, G, and B layers. Controlled via current injection layers  or Single wafer with single epi-structure. 	Patterned color conversion layer (quantum dots: QD) on top of blue emitters. Alternatively: doping the LED MQW with rare earth metals. 
Challenges	- Limited pixel density - Development of epiwafers with the three colors on the same plane is progressing very slowly. - Alternatively, each color can originate from different wafers and be assembled via mass transfer of individual dies. In that case, pixel density is more limited.	- Limited pixel density - Complex manufacturing: colors are grown successively on the same wafer. Then, complex masking + etch-back processes are used to define each color. - Alternatively, the 3 colors are grown on separate wafers, and then bonded onto the CMOS backplane in such a way that each color is laterally separated.	- Complex assembly (bonding) and interconnects → yields. cost - Interconnects limit PPI - Light extraction, crosstalk. 	- Driving (wide range of current or voltage) → complex backplane - Color purity? - Challenge to address full-color range (needs good red GaN)	High resolution QD patterning. QD material stability at high brightness. QD absorption (impacts layer thickness) Emission pattern: color converters are Lambertian emitters → poor coupling with waveguides: 
Players	Aledia, Analogue Devices, Intel, NS Nanotech and many academic research labs Formerly: Glo (no longer in activity)	Intel, GlobalFoundries, SiPhoton, Seoul Semiconductor/Viosys	Innovision, Monolithic 3D, OKI, Ostendo, Sundiode, Seoul Semi, Chipfoundation, JBD, Lumileds, MIT, Rayleigh Vision, Lumens, Miledi, West Lake etc.	Lumileds Ostendo Porotech Q-Pixel, Raxium (?), Sundiode	Ascending Optronics, Ennostar-Unikorn, JunWan, Mojo Vision, PlayNitride, Plessey, Porotech Prima Opto, Raysolve, Saphlux, Sharp, Sitan Technology and others.



Upcoming “Phoenix” platform.

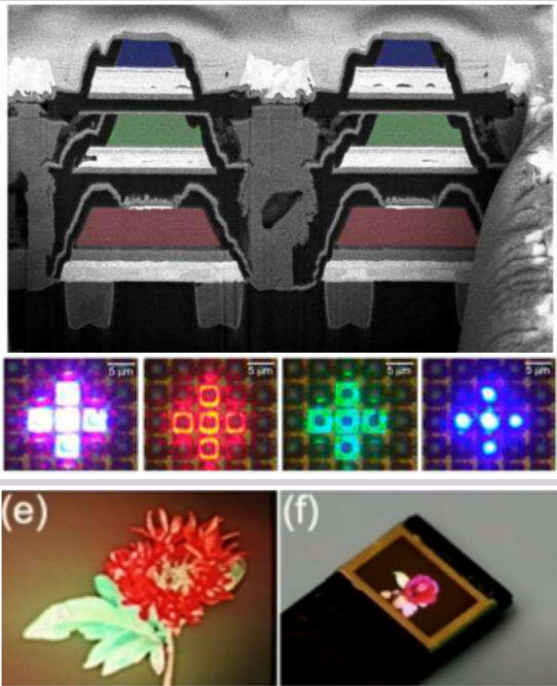
Bonded GaN green and blue + AlInGaP red structures.

5µm-wide vertical pixels. Switched from metal to **dielectric bonding** to avoid blocking red light

Each color is addressable separately

First 0.22” display prototypes in Q3-2023.

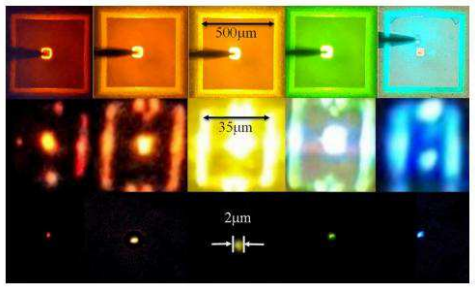
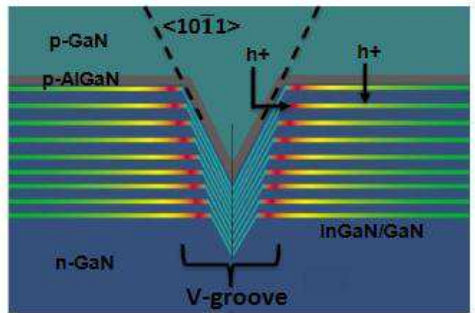
Target 500k Nits white by the end of 2024 with microlenses



All InAlGaN structure.

Makes use of ‘V-Grooves’, in the GaN layers where indium incorporation and emission wavelength vary along the crystallographic planes.

Electron-blocking layers allow **controlling color by adjusting the current.**



Dynamic Pixel Tuning[®]

A **single, all InAlGaN epitaxial structure** is grown on a single substrate. The structure creates large electrical fields and leverage the quantum confined stark effect to shift the emission color of the multi-quantum wells.

Patents also hint at the possible use of **V-grooves**.

Sequential field color, driving → during each picture frame:

- The **color** is tuned by **adjusting the current density (PAM)**: low current for red, intermediate for green, and high for blue.
- The **intensity** is controlled via **Pulse Width Modulation**.



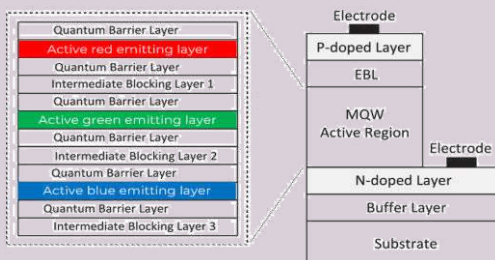
Benefits	Challenges
• Higher pixel densities compared to architectures where the three colors are placed side by side. • For a given PPI, the emitters are larger, leading to higher EQE.	• Covering the entire wavelength range (blue to red): large (20x) range of driving current → challenging for backplane • Field sequential color: can't have simultaneous emission of the 3 colors • Pixel driving: each color must be sequentially addressed within each frame, requiring very short pulses and accurate PWM.

Tunable polychromatic LED pixel ("TP-LED"):

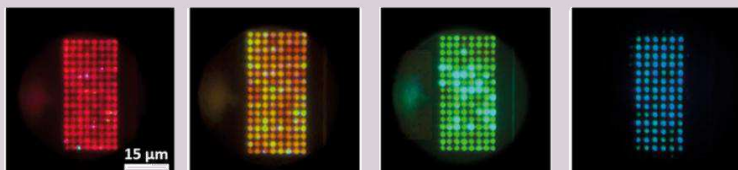
An all InAlGaN structure with 3 distinct sets of MQW (one for each color) separated by current blocking layers that select which MQW the current goes to depending on its intensity.

We believe the structure to be similar in essence to that developed by **Ostendo**, but with a much-reduced voltage / current range to address the full color spectrum: from 70x to less than 4 x

Sequential field color driving.



Ostendo's epitaxial structure. We believe Q-Pixel uses a similar concept.



Full color, 10000 PPI proof of concept (Q-Pixel)



6800 PPI, full color AM microdisplay (Q-Pixel)

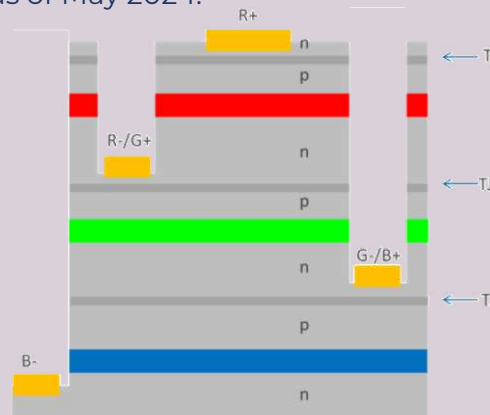


For all InGaN structures, single epitaxial growth is required for the full structure.

Single, vertical mesa with 3 active regions. Tunnel junctions for injection.

4-terminal device: controls each color intensity individually and can simultaneously emit the 3 colors.

Early-stage development: not optimized for light extraction, smallest structure demonstrated = 7 x 9.5 μm as of May 2024.



All illustrations: Lumileds

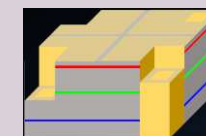
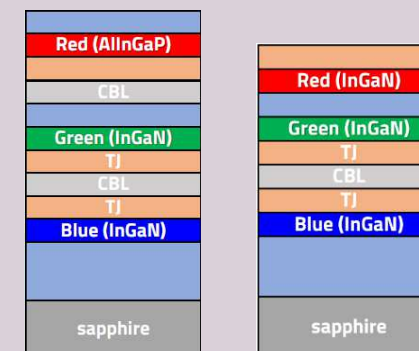


Sundiode has developed two different stacked multi-junction RGB architectures.

- 1) InGaN/AlInGaP: the red AlInGaP is bonded on top of a blue and green multijunction stack.
- 2) Full InGaN: no wafer bonding.

4-terminal device: can have simultaneous emission of the 3 colors

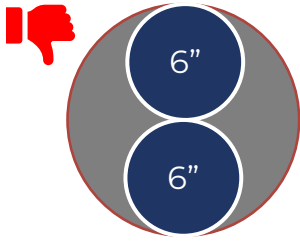
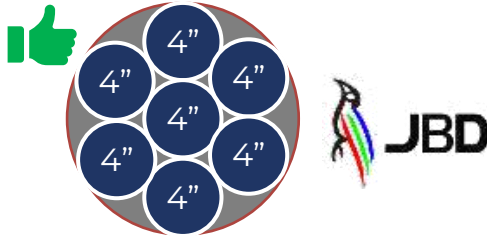
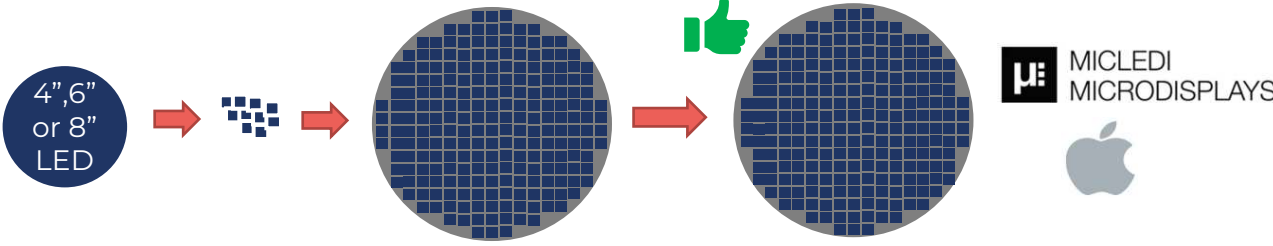
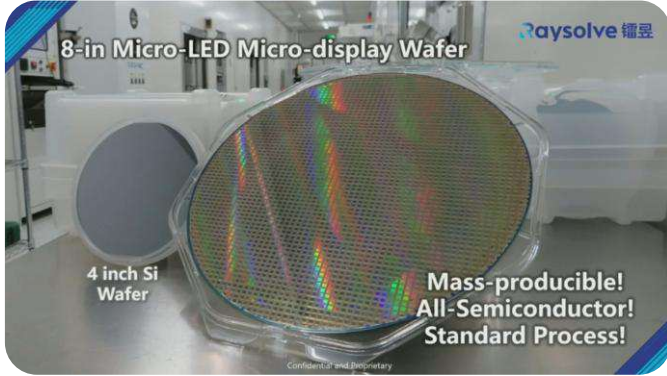
Lumens and its acquired subsidiary **Soft Epi** are developing similar approaches.



All illustrations: Sundiode.

TECHNOLOGY TRENDS – AR MICRODISPLAYS

The choice of a CMOS process node impacts substrate size and manufacturing strategies

Advanced CMOS nodes: < 45 nm, preferably 22-28 nm		Two-chip architecture: a simpler backplane and memory, TCON etc. moved to a separate chip	
Pros: High performance, integrate advanced functionalities at high PPI	Challenges: Advanced CMOS nodes only available on 300 mm , but GaN-on-Si LED is not ready for 300mm and there's no known efforts toward 300 mm AlGaInP red epi (GaAs or Ge substrates)	Pros: Use of mature, cost-effective 200 mm CMOS nodes.	Challenge: Less integrated solutions, possibly lower performance (?) Large display module
Process options:		Process options:	
 1x8" LED on 12" CMOS: ~44% wafer utilization  2x6" LED on 12" CMOS: ~ 50% utilization  7x4" LED on 12" CMOS: ~ 77% utilization 		 8" LED on 8" CMOS: ~ 100% utilization 	
 Smaller LED epiwafer coupons can be pre-assembled on 12" Silicon carrier before hybridization: > 90% efficiency 			

TECHNOLOGY TRENDS – AR MICRODISPLAYS

A path towards cost reduction

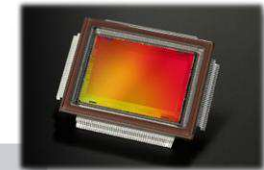
- As the backplane accounts for most of the total microdisplay price, its evolution is critical.
- Most microdisplay makers are still developing their backplanes. For now, they must realize prototypes based on off-the-shelf solutions from CMOS manufacturers. Raising more funds, \$3-4M, will be critical in designing customized CMOS optimized for their displays.
- 300mm, 22nm CMOS wafers for imaging or memory are typically around \$3k.
- It's hard to tell if volumes will allow AR display backplanes to reach similar ranges. For now, the typical backplane cost is around \$10k at volume scale, **or ~\$10 for a 0.26" CMOS backplane.**
- If we were to make a parallel with a mature industry, such as the CMOS Image Sensors. Over 10 years, a close to 50% reduction has been seen in wafer revenues.



BP development
cost of \$3-4M



Mass production
should end up at
around \$5-10k for a
1,000-chip wafer



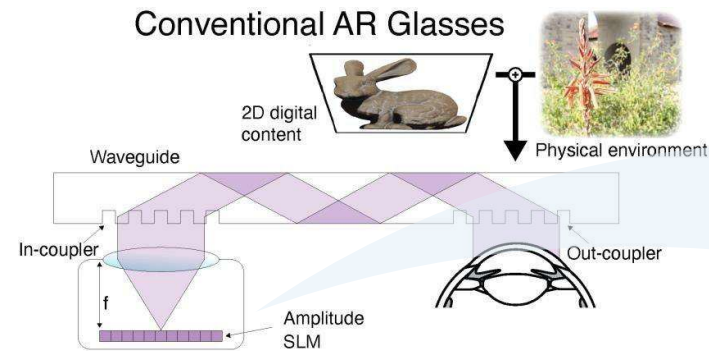
	2011	2022
Wafer volume (Munits, 12" wafer equivalent)	1.03	3.47
Revenue (\$B) / ASP per wafer (\$k)	13.9 / 13.5	23.3 / 6.7

TECHNOLOGY TRENDS – AR MICRO DISPLAYS

Emerging display engines technologies (1/2) – LCoS-based SLM

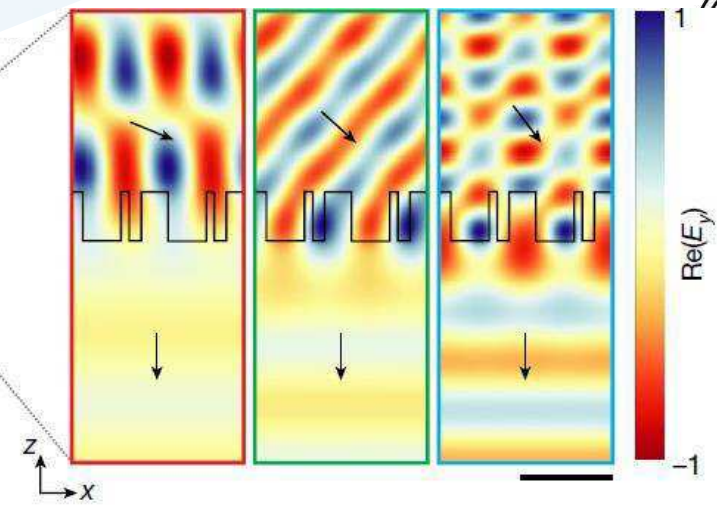
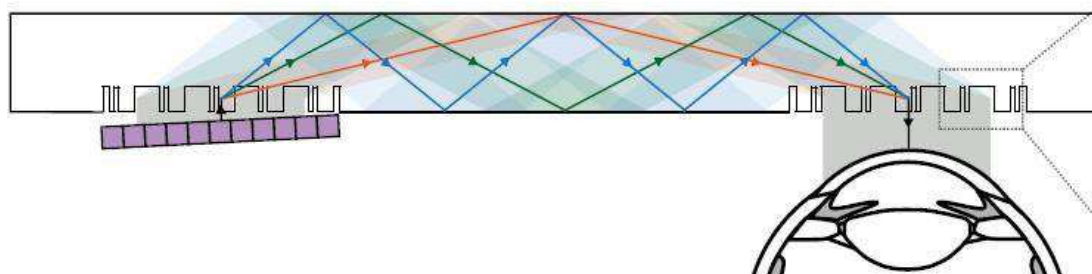
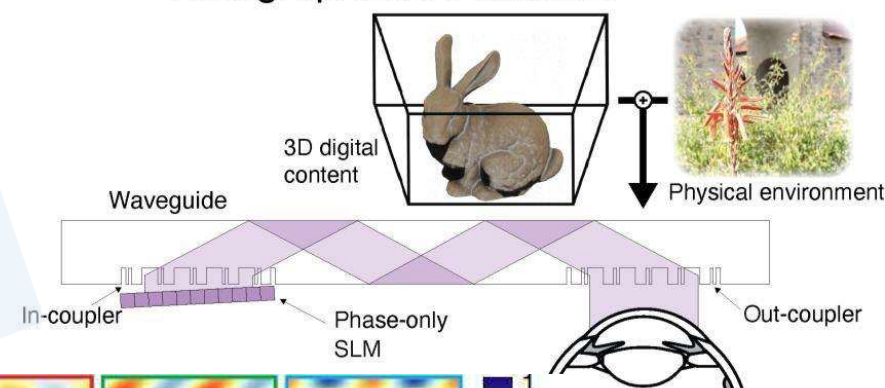


Conventional AR Glasses



LCoS can be used as a Phase modulator. It can leverage interferences to produce volumetric AR paired with a coherent laser light source. Such an approach could therefore solve the well-known Vergence Accommodation conflict by adjusting the depth of the virtual display to the actual depth of focus of the user. Also, the lens barrel's function is to focus light between the SLM and the in-coupler, which can be integrated into the phase modulator. Such a trick would allow a dramatic reduction of the form factor of the display engine.

Holographic AR Glasses



Source: Full-colour 3D holographic augmented-reality displays with metasurface waveguides



TECHNOLOGY TRENDS – AR MICRO DISPLAYS

Emerging display engines technologies (1/2) – PCM-based SLM



Swave Photonics, a spin-off of IMEC (Belgium), is developing true holographic chips.

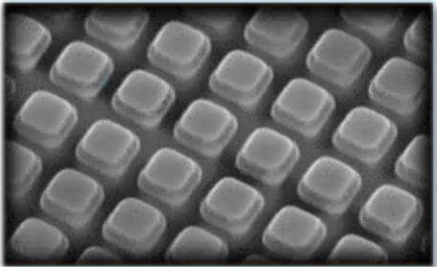
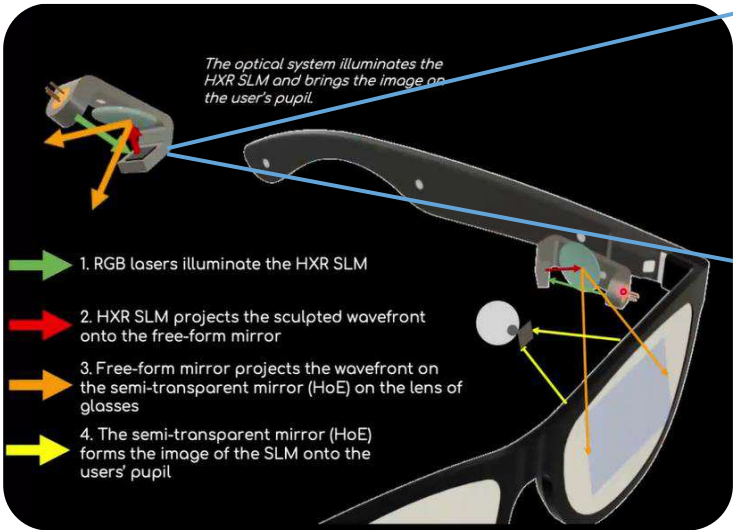
While still at an early stage, the technology could become a credible contender for AR glasses, with the ability to deliver a combination of wide FOV, high resolution, and software-adjustable depth of view.

A Spatial Light Modulator (SLM) is constituted of 256M pixels in a 5 mm by 5 mm array of 16k x 16k, 250 nm “pixels” made of a thermally activated bistable material deposited on a 22 nm CMOS backplane.

The SLM allows the generation of high-resolution true holograms.

The company has shown various proof of concepts of static hologram, demonstrating a wide field of view and the ability to adjust focus via software dynamically.

Swave should have its first dynamic hologram POC by the time this report is released (Q3-2024).



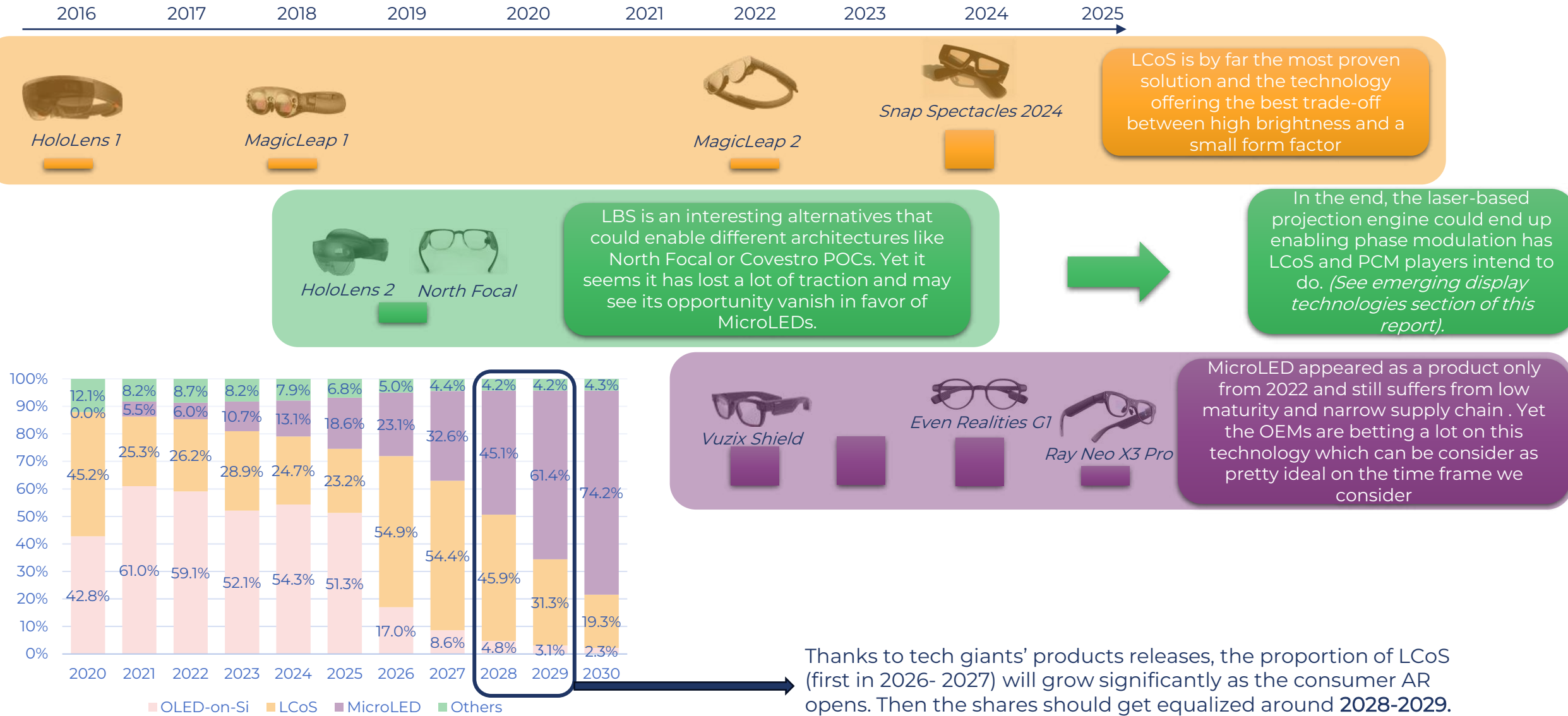
Images and table: Swave

Specification	Value	Notes
SLM Pixel Size	280 nm	Set to approximately half wavelength
SLM Pixel Count	16k x 16k	
SLM Active Area	~5mm x ~5mm	
Eyebox Size	~10mm x ~10mm	Optically magnified by ~2x per equation (1)
FOV	45° Diagonal	Optically demagnified by ~2x per equation (1)
Addressable Image Size	2400 x 1400	Chosen to maximise contrast
Maximum Acuity	~60 Pixels per Degree	
Image Depth	0.5m to ∞	Enabled by wavefront control in hologram computation

TECHNOLOGY TRENDS – SYNTHESIS



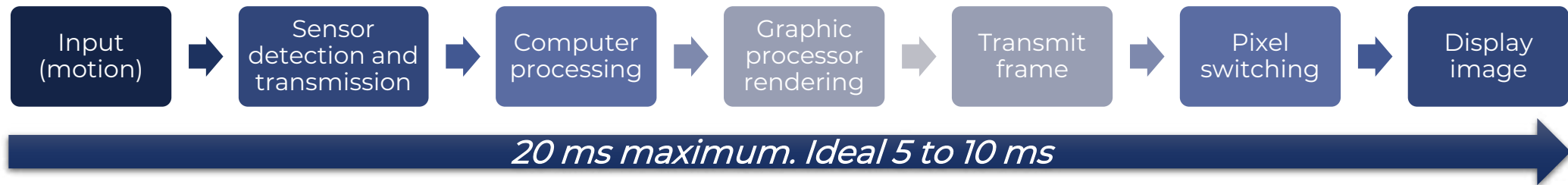
Micro display technologies history (Using waveguide-based optics)



Technology trends - VR



- The major challenge in achieving a successful VR experience is closely matching the virtual world's sensory input and visual cues with the human brain and physiological expectations.
- The perceived latency between the physical motion of the head and body vs. the moment a full frame of pixels reflecting these changes is displayed to the eye is often referred to as “motion-to-photon”.
- A complex chain of hardware and software contributions drives motion-to-photon latency :



- To avoid discomfort, motion sickness, and blur, it is thought that motion-to-photon latency should not exceed 20ms. Requirements for the display are, therefore, even more stringent:
 - Current consumer VR systems feature displays operating between 60 - 90Hz (11 - 17 ms refresh rate);
 - The VR industry ideally targets a 5ms latency in the display (200 Hz operation).
- OLED displays providing high refresh rates were increasingly favored over LCD, which suffered from motion blur and lower refresh rates. R&D efforts are ongoing to push for LCD adoption in VR.
- Apple designed a dedicated chip, R1, to help reduce this delay as much as possible. They claim their headset's latency is only 11 ms: The state of the art among commercial products.

TECHNOLOGY TRENDS – VR

Apple's Vision Pro is built different – powered by two processors

- Released in June 2023, the Vision Pro is Apple's foray into the VR headset market.
- Most VR headsets are centered around a gaming use case. Still, Apple is positioning the Vision Pro to be something else, seemingly much more as a productivity and entertainment tool than as a gaming device. For instance, the headset's wearer can virtually place multiple displays around the room and interact with them separately.
- The processing heart of the device is considerably more advanced than the other common VR headsets, which tend to use some version of a smartphone processor. The Vision Pro uses an M2 APU, which also powers the latest generation of MacBook. The Vision Pro also uses a **second SoC called R1** to handle the signals from the many sensors, external (of the room) and internal (of the wearer's eyes).

Apple Vision Pro, 2024

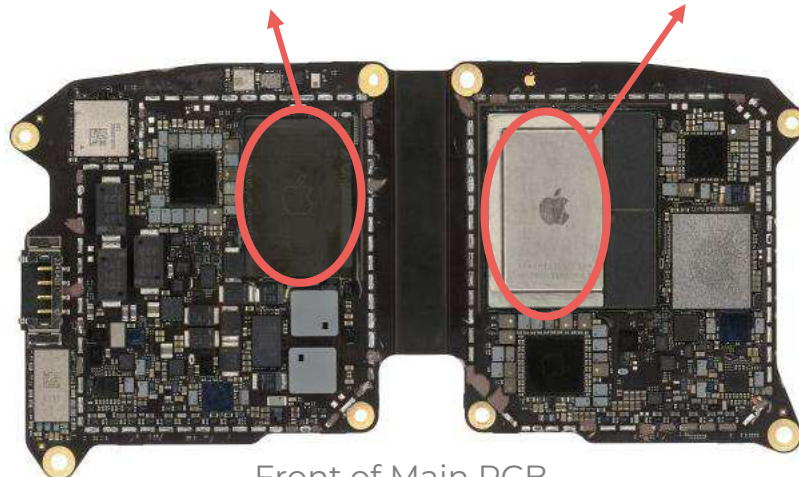


source: Apple

Characteristic	Value
Packaging size	668.7mm ²
Packaging type	FC BGA
Total Die area	792.4mm ²
Number of die	3
Computing die area	133.4mm ²
Computing node	5nm
Estimated ASP	\$136

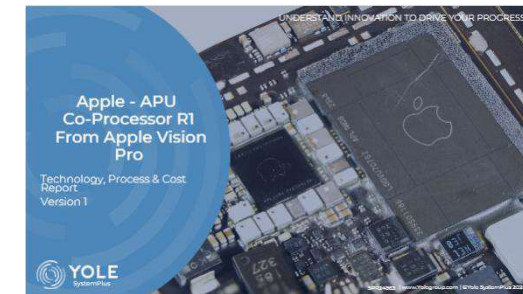
Apple R1 is a co-processor designed especially for Apple Vision Pro.

Apple M2, same processor than for MacBook



Front of Main PCB

Characteristic	Value
Packaging size	345.8mm ²
Packaging type	FC BGA
Total Die area	190.7mm ²
Number of die	6
Computing die area	90.4mm ²
Computing node	5nm
Estimated ASP	\$51.3



TECHNOLOGY TRENDS – VR

Processing trends in stand-alone VR Headsets

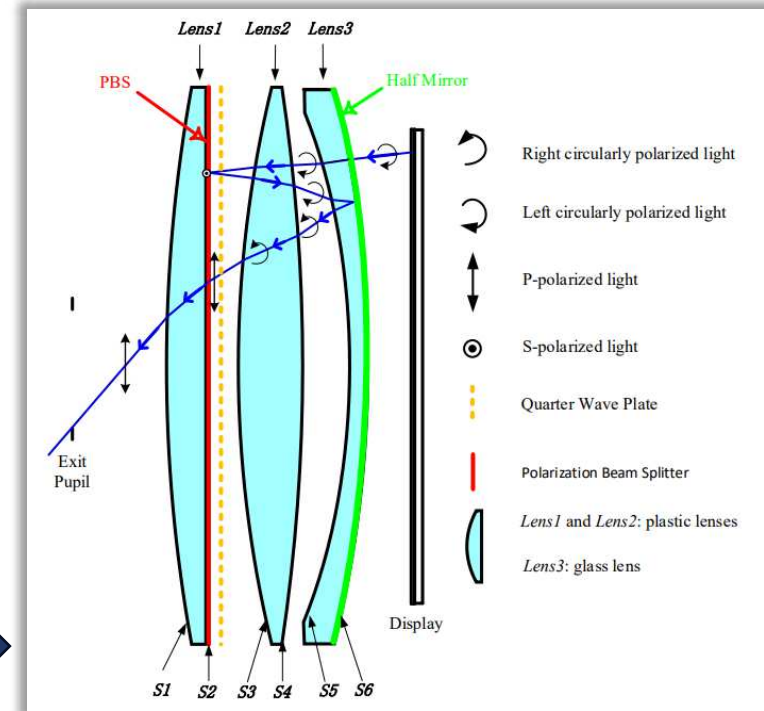
- While in the past AR/VR headsets used high-end smartphone processors, since 2020 the entire industry has shifted to specialized processors such as Qualcomm Snapdragon XR or Apple's R1 chip.



TECHNOLOGY TRENDS – VR

Pancake optics: How does it work?

- Folded optics, like those in pancake lenses, use a series of precisely angled mirrors or lenses to fold the optical path, allowing light to travel a longer distance within a compact space, consequently reducing the physical length of the optical system while maintaining or enhancing performance by altering the light's path. This design enables more efficient space utilization, allowing compact devices without sacrificing optical quality or field of view.
- In the provided example, light is reflected twice and meets a quarter-wave plate and a polarizer to avoid parasitic light.



Example from:
Q. Hou, *et al.*, "Stray light analysis and suppression of a pancake virtual reality head-mounted display.", Vol. 30, No. 25, 5 Dec 2022, Optics Express.



Pros



Cons

Improve acceptance

Improve experience

• Compact form factor

• Wide FoV

- Complex design and manufacturing
- Haze to be solved
- Complex assembly and issues related to plastic injection and birefringence
- Lowered light efficiency

Manageable issues

Not serious for VR

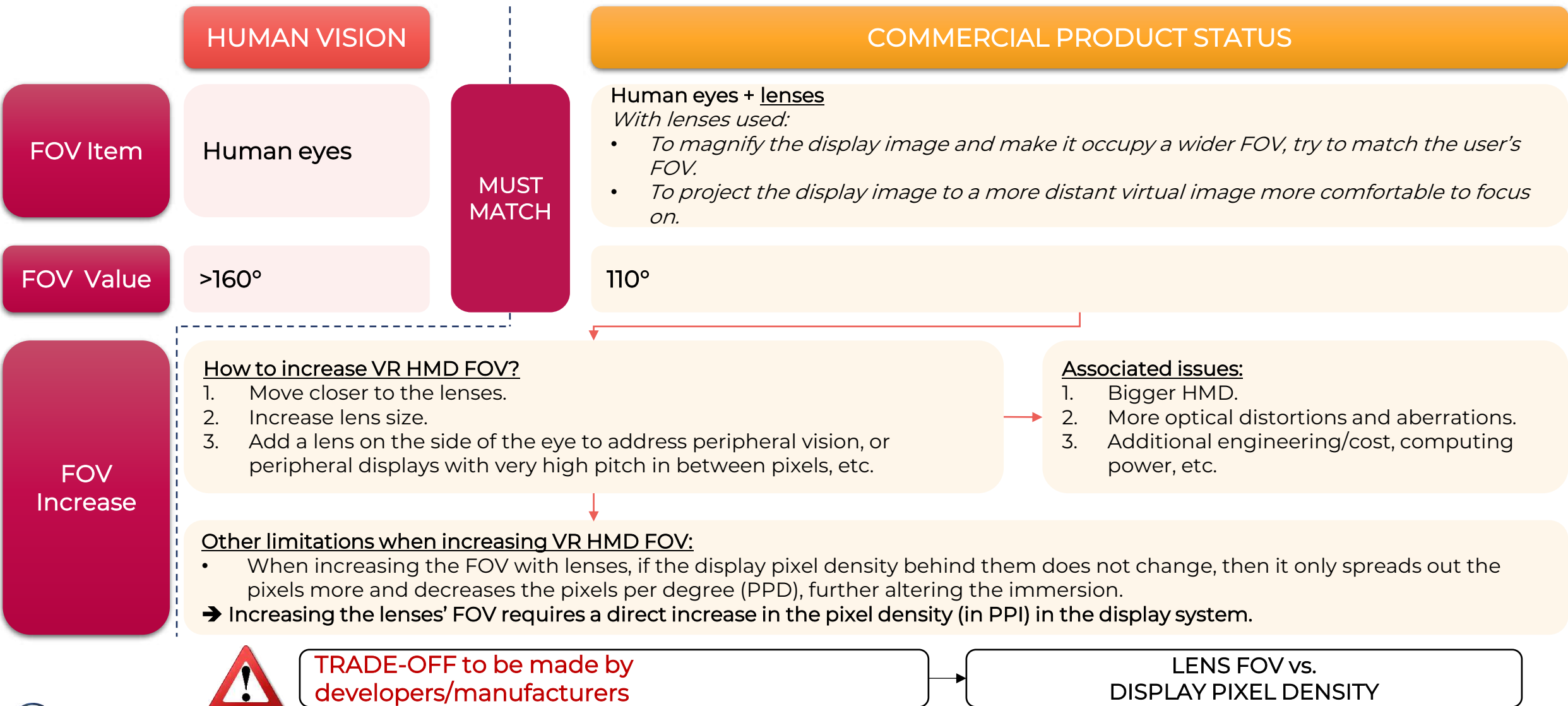
Technology trends - VR microdisplays

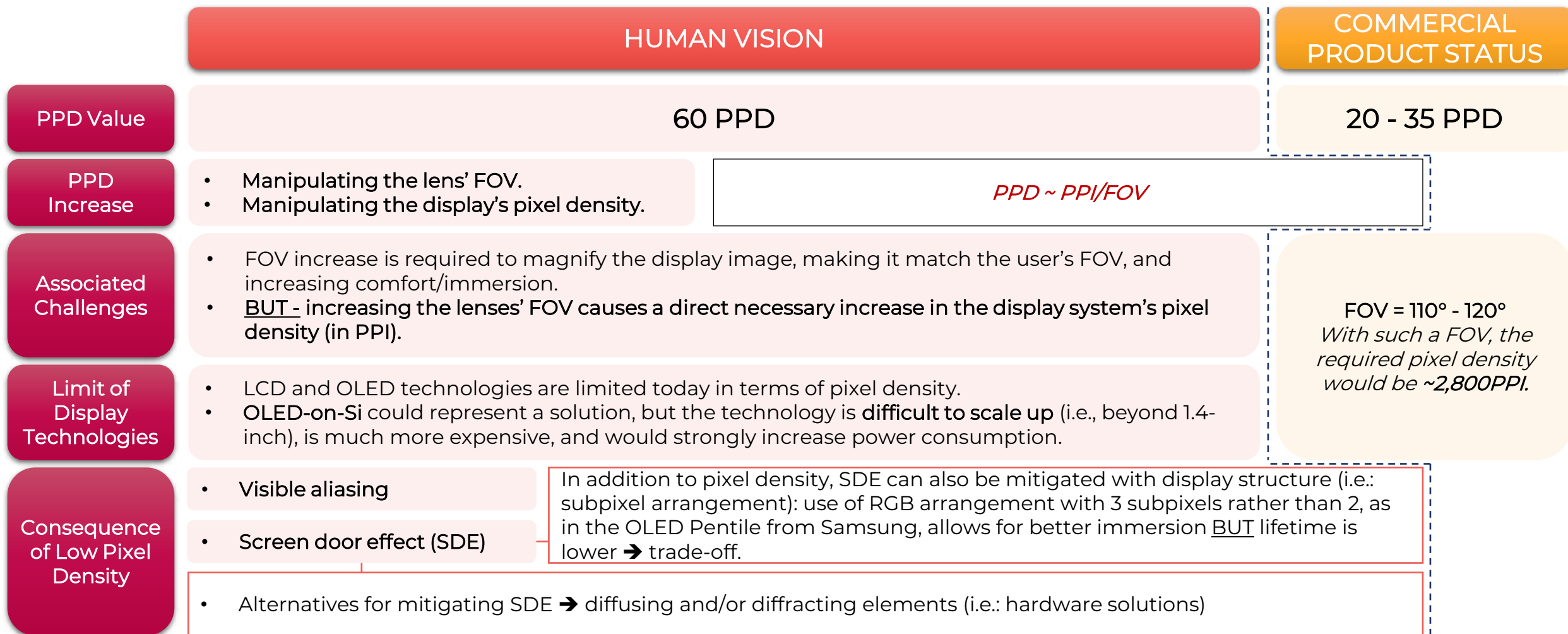
TECHNOLOGY TRENDS - VR MICRODISPLAYS

Main VR headsets comparison



	Meta Quest Pro	Meta Quest 3	Meta Quest 3S	Pico 4	Apple Vision Pro	PlayStation VR2
Resolution	1800 x 1920 per eye	2064 x 2208 per eye	1832 x 1920 per eye	2160 x 2160 per eye	3680 x 3140 per eye	2000 x 2040 per eye
Display technology	LCD with MiniLED BLU (500 zones per eye)	LCD	LCD	LCD	OLED-on-Si (self-emissive)	OLED (self-emissive)
Field of View	110°	110° horizontal, 96° vertical	96° horizontal, 90° vertical	105°	Approx. 100° horizontal	110° diagonal
Optics Technology	Pancake lenses	Pancake lenses	Fresnel lenses	Pancake lenses	Pancake lenses	Fresnel lenses
Processor/Chip	Qualcomm Snapdragon XR2+ Gen 1	Qualcomm Snapdragon XR2 Gen 2	Qualcomm Snapdragon XR2 Gen 2	Snapdragon XR2 Gen 1	Apple M2 and R1 chips	Unspecified
Weight	722 grams	515 grams	514 grams	586 grams	Approx. 453 - 680 grams	560 grams
	MiniLED BLU	LCD			Organic self-emissive	





TRADE-OFF to be made by developers/manufacturers

LENS FOV vs. DISPLAY PIXEL DENSITY

TECHNOLOGY TRENDS – VR MICRODISPLAYS

Will VR headsets be able to match human vision?

- VR headsets are usable already, but the ideal would be to match human vision to create the ultimate impression of reality getting rid of screedor effect regardtdng the resolution.
- Looking at how the different headsets map the FoV vs. PPD plan shows that only using **OLED-on-Si** as a microdisplay is enabling a significant increase of the resolution with a record around **35 ppd**.
- On the other hand, FoV is limited by the optics and meeting a glass ceiling around **120°**.

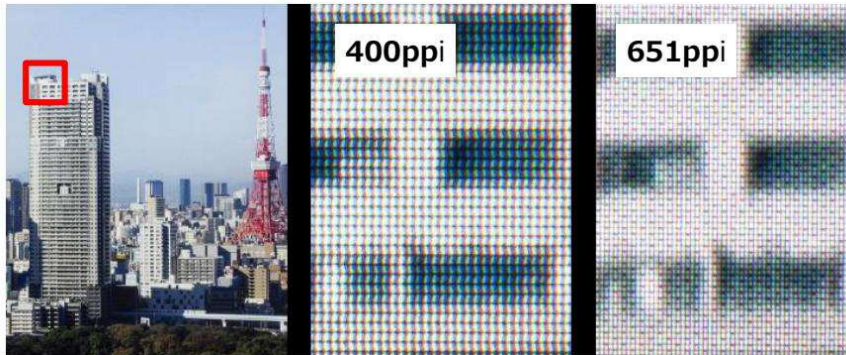
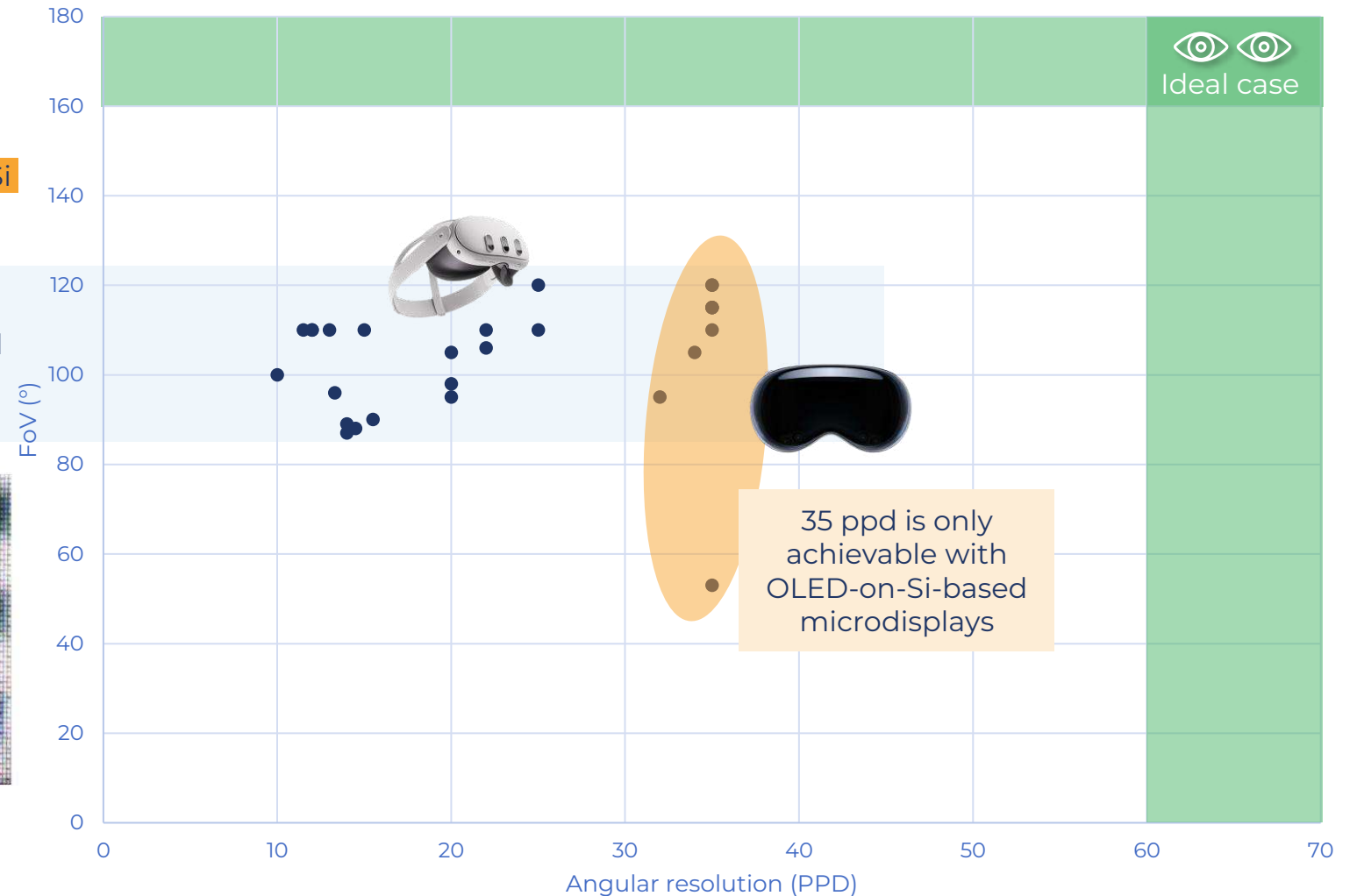


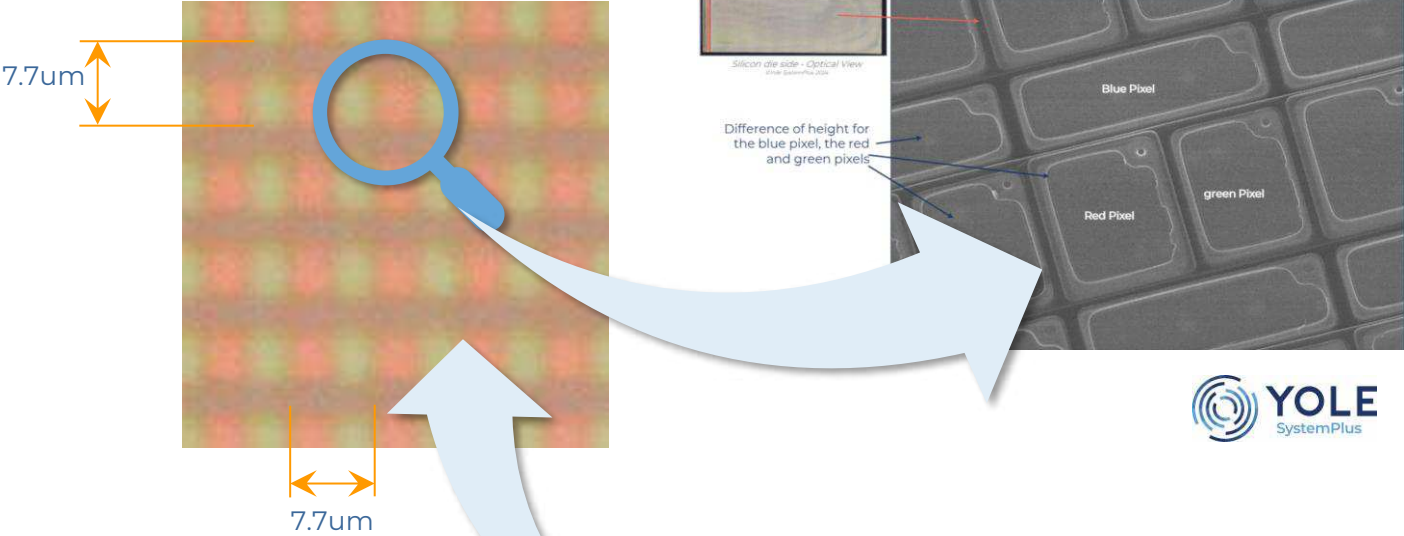
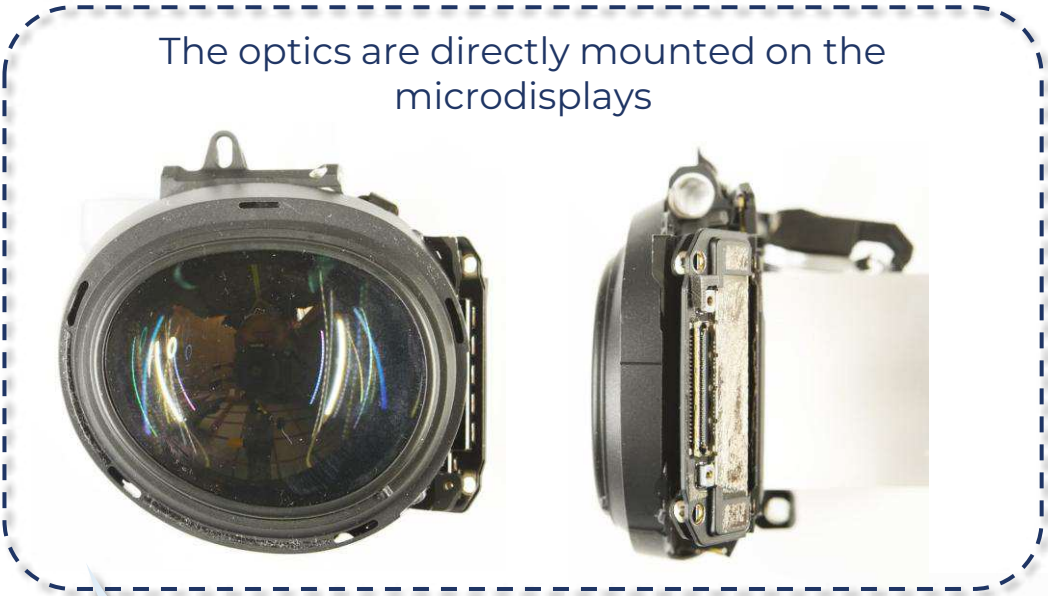
Image: Alleviating aliasing and SDE by increasing pixel density.
(Source: JDI)

VR headsets Resolution vs. FoV



TECHNOLOGY TRENDS – VR MICRODISPLAYS

Apple Vision Pro OLED-on-Si micro displays dismantlement



The module includes:

- The frame,
- the pancake lens stack,
- the eye tracking unit,
- and the OLED-on-Si microdisplay.

Teardown images:



huguodong@cmbchina.com
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TECHNOLOGY TRENDS – VR MICRODISPLAYS

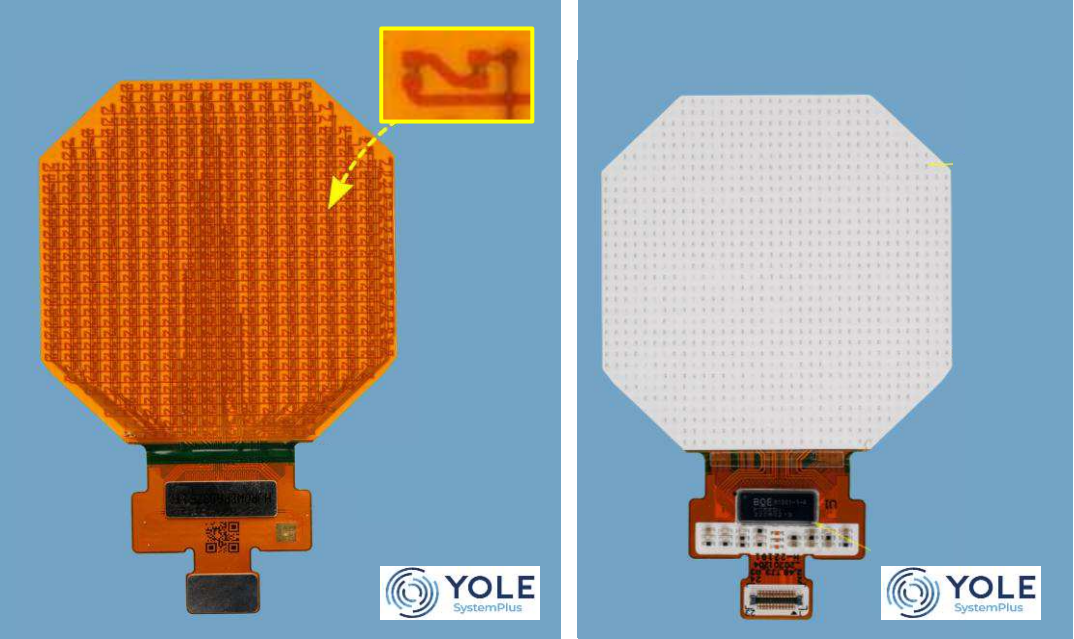
MiniLED: An alternative to self-emissive technologies



Quest Pro,
Released Oct-2022

504 zones of 2 LEDs each = 1,008 LEDs

Passive Matrix driving: 2 LEDs in series addressed by rows and columns with only one driver per eye.



Images: Teardown of the Meta Quest Pro MiniLED Backlight Unit. Panel by BOE. With (right) and without (Left) a white diffuser sheet.

More players have started proposing their own solutions with various numbers of dimming zones, allowing for differentiation even in the LCD + MiniLED space.

INNOLUX

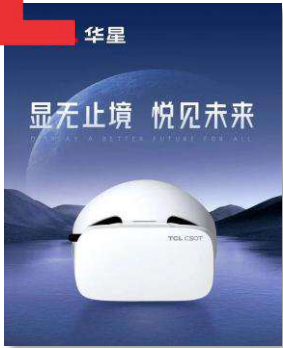
Prototype with 1,024 zones

2117 ppi VR LCD DEMO	
Size	2.56"
Resolution	3840 x 3840
PPI	2117
Active Area (mm)	46.080 x 46.080
LC Mode	AAS
Color Gamut (NTSC)	97%
Response Time (ms)	< 5 (G2G Max.)

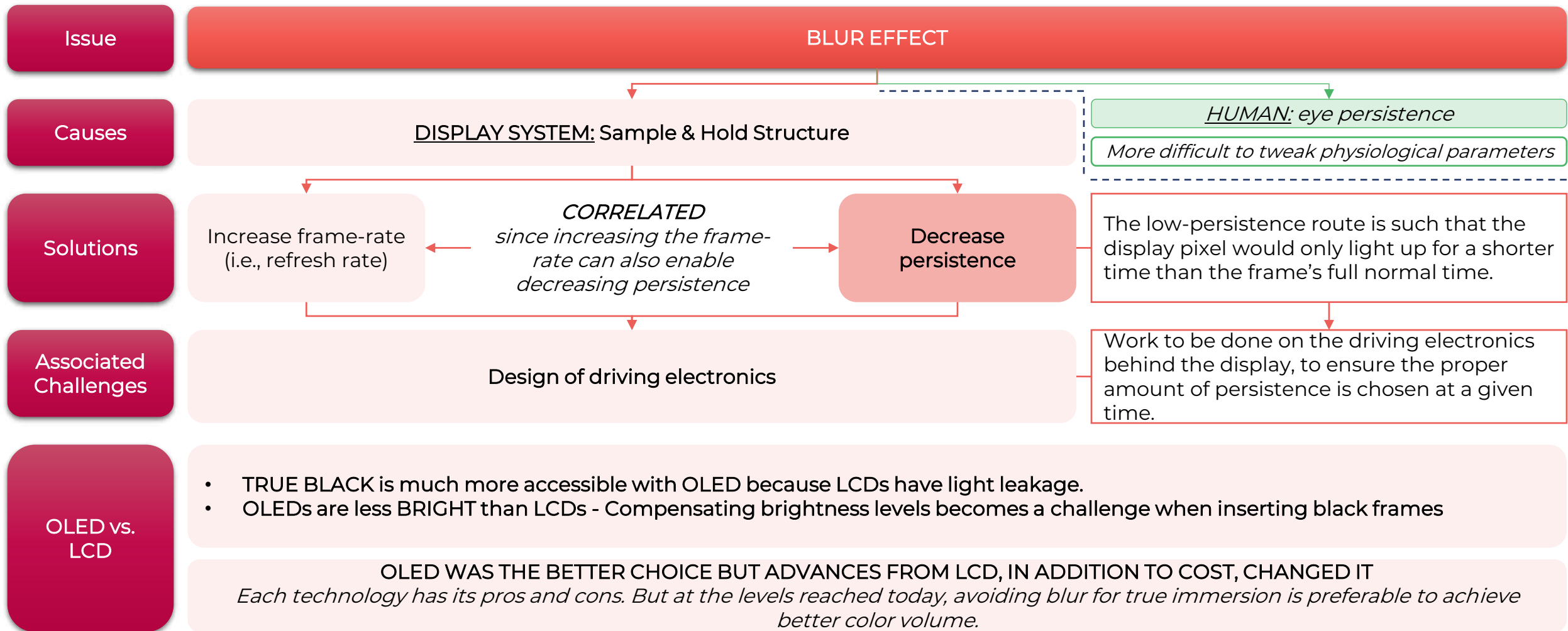


TCL 华星

PPI	1512
Zones	492



Human vision requirements – Persistence



TRADE-OFF to be done by developers/manufacturers

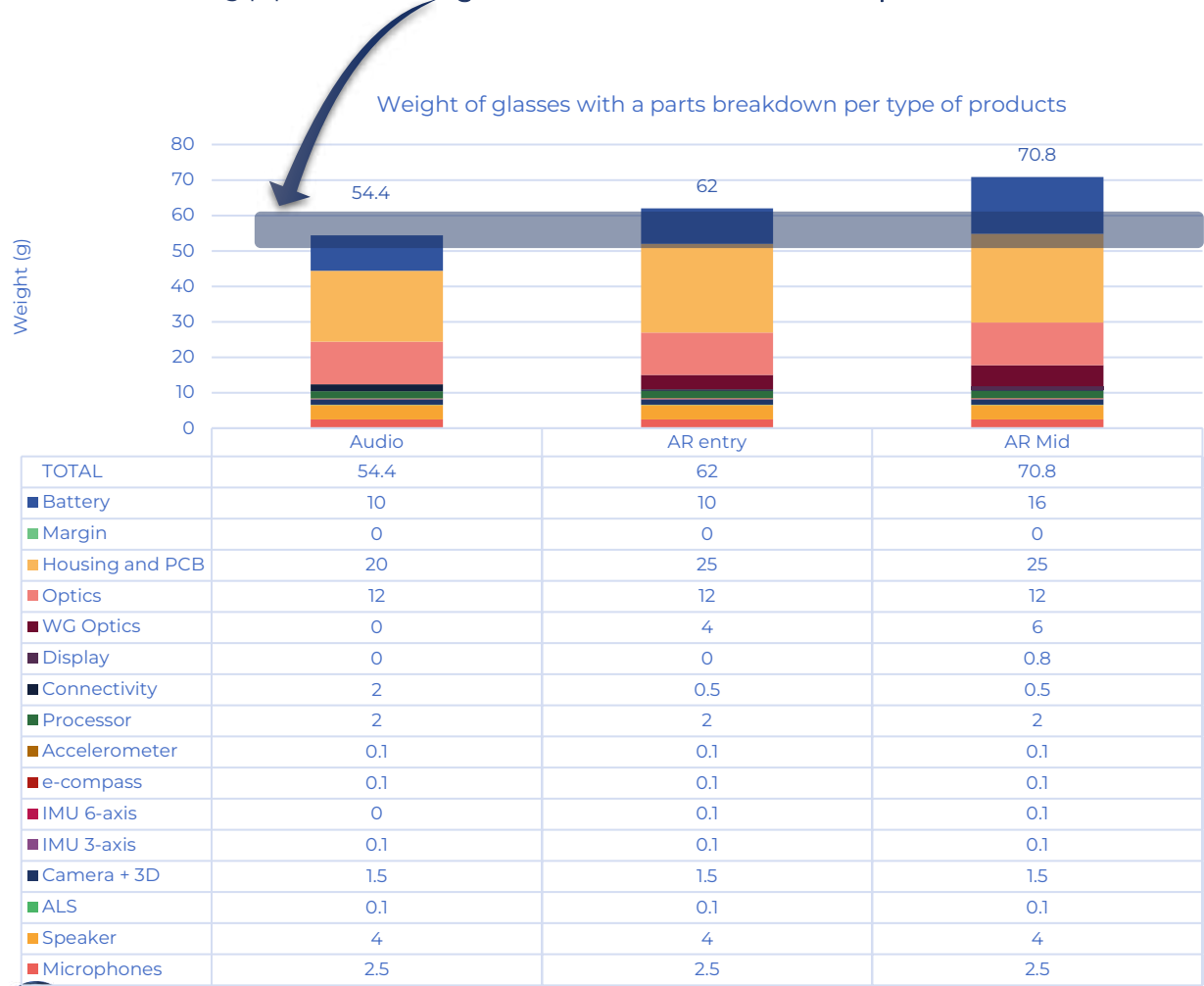
DISPLAY TECHNOLOGY vs. DRIVING ELECTRONICS' COMPLEXITY

Technology trends – Synthesis

TECHNOLOGY TRENDS – SYNTHESIS

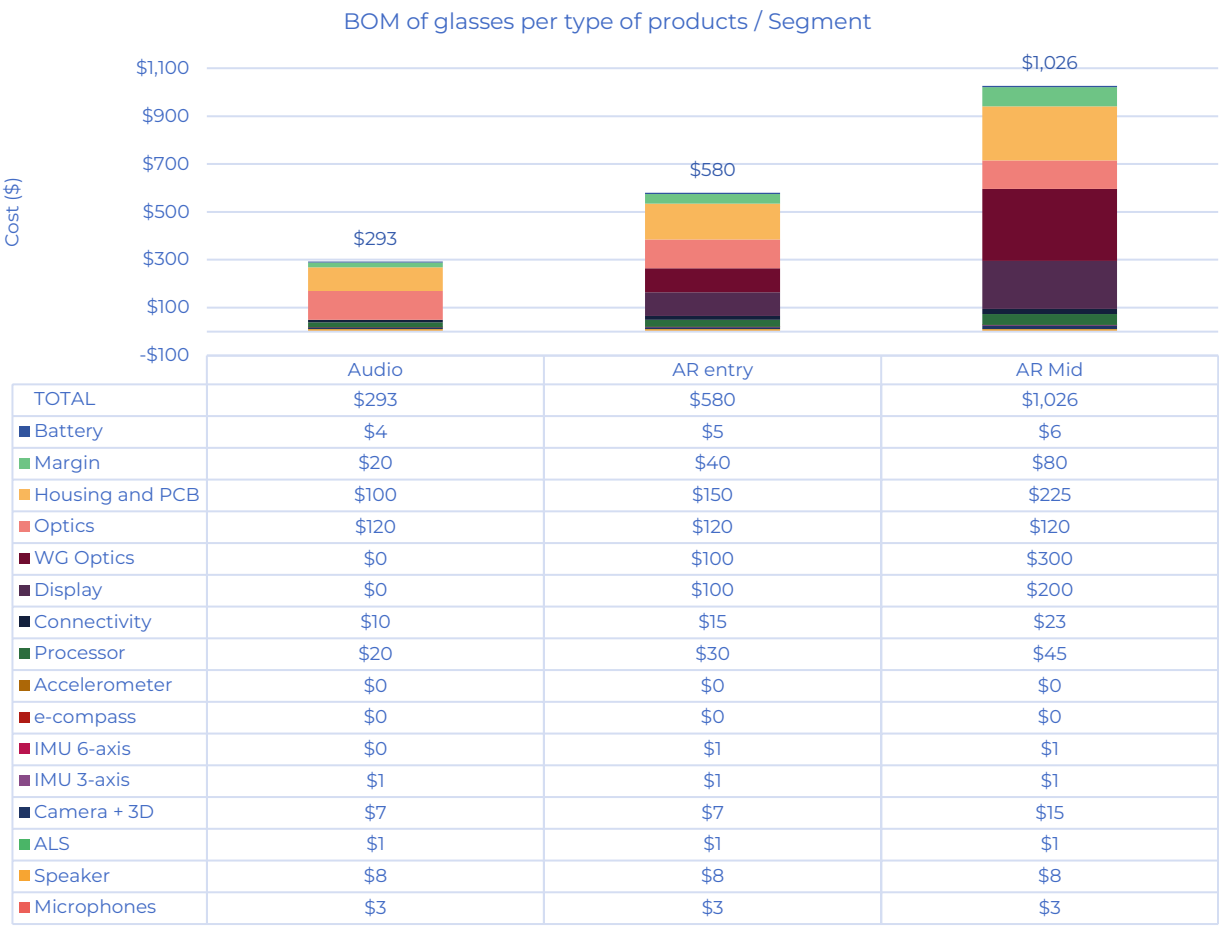
Segment dependent smart glasses cost and weight structures

As the number of modules increases, the packaging does too. More modules, for more functions mean more power consumption so bulkier batteries. The question of the weight is very critical. Design will include cannibalism of functions, particularly sensing and a relevant data fusion along pipelines. **50-60g should be considered as an impassable threshold.**



We can compare the cost structures on the right to existing products and perspectives:

- Audio → Ray-Ban Meta starting at \$329
- AR Entry → Even Realities G1 starting at \$699
- AR Mid → Meta’s CEO often positions the AR glasses with a display in the range of smartphone flagships (~ \$1,000)

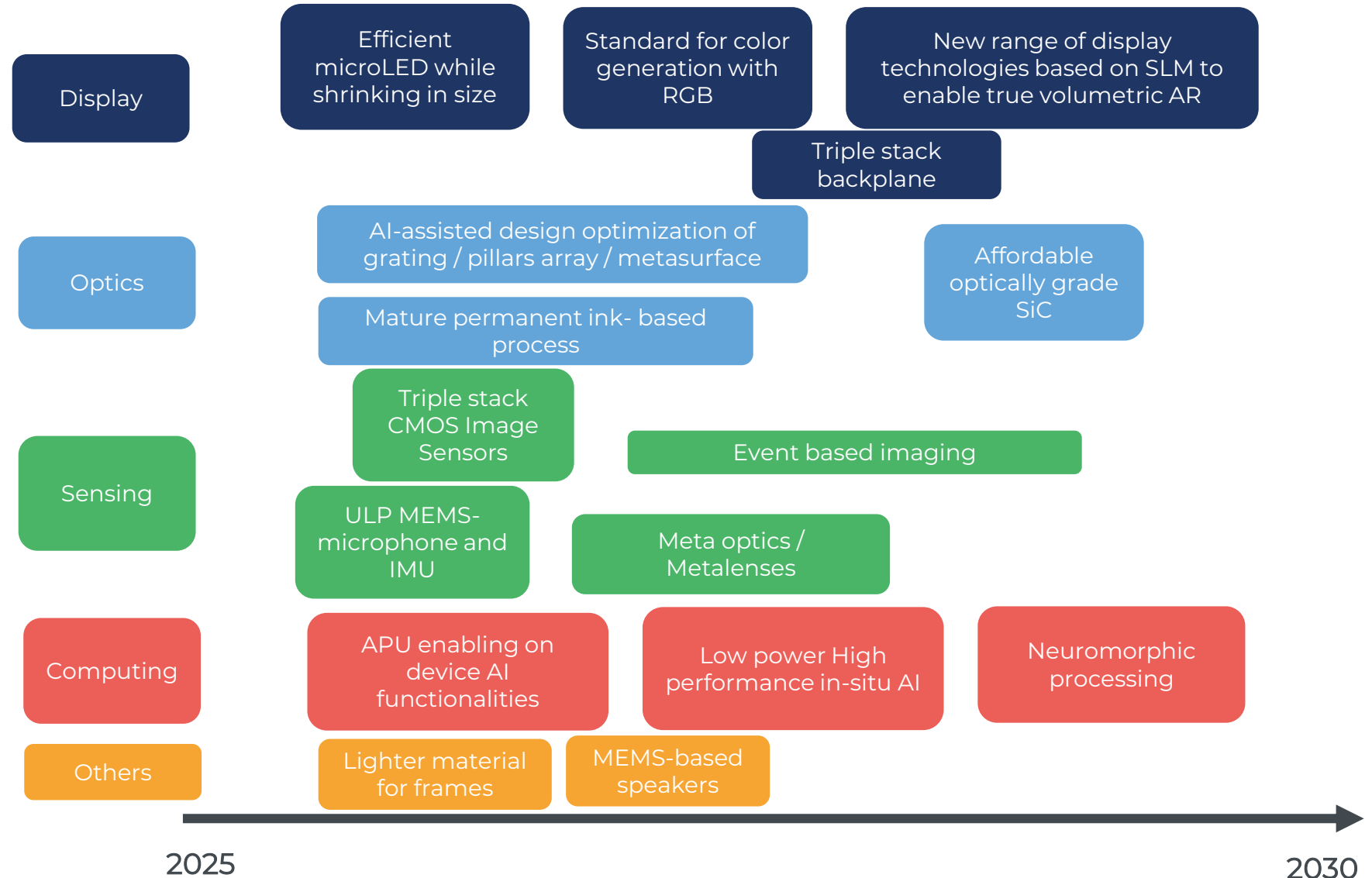




TECHNOLOGY TRENDS – SYNTHESIS

AR - Breakthroughs by thematic roadmap

- The core motivation behind the innovations that AR needs is miniaturization. In the end, OEMs want as many features as possible to be embedded in their frames, as this will provide consumers with a compelling offer. **Reducing form factor, weight, power consumption and price will be the very main driver of innovations.**
- Also, we can think of a breakthrough in material manufacturing (affordable optically graded SiC) and display engines to enable a new and more appealing range of experience (volumetric AR) and maximize adoption.



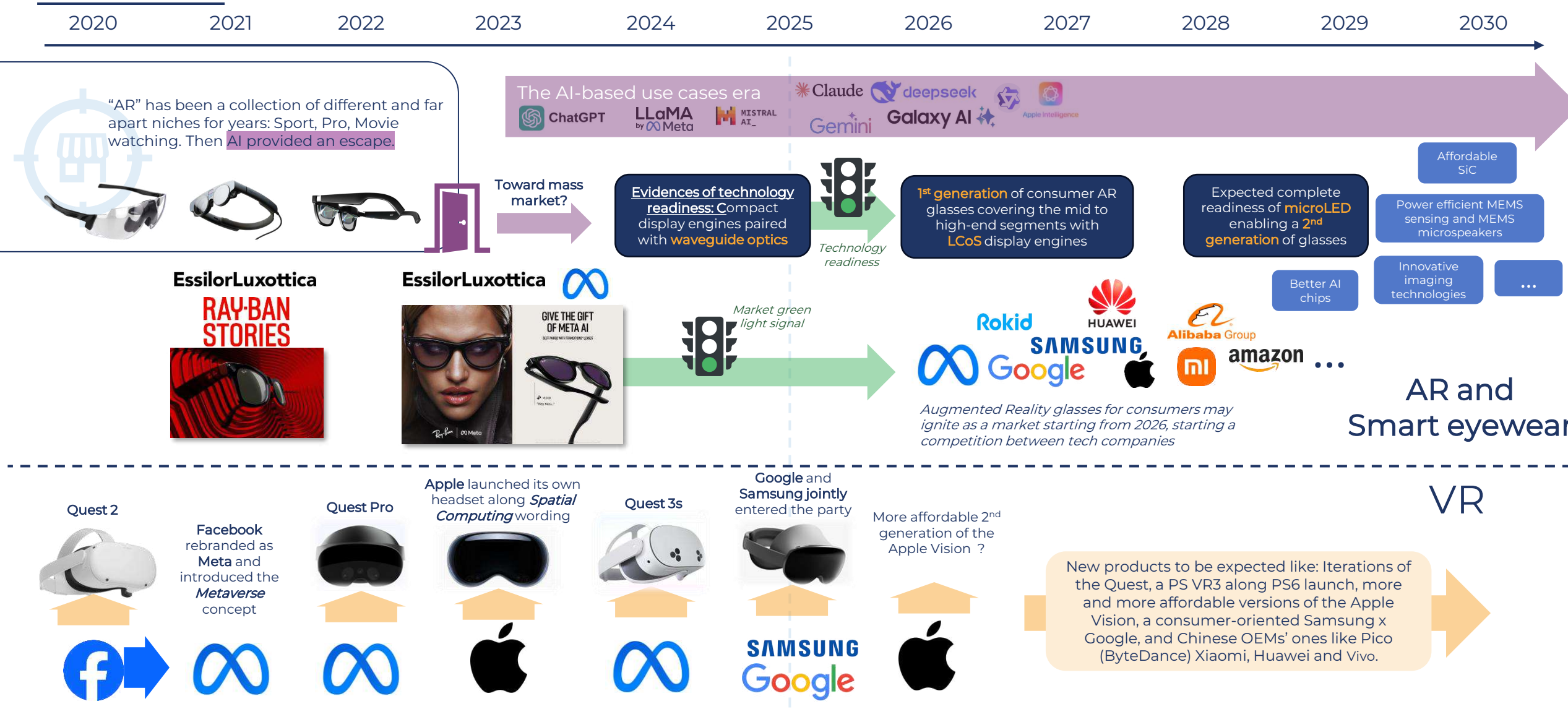


TECHNOLOGY TRENDS – SYNTHESIS

The dualities of AR and VR: Headsets for depth, Glasses for daily AI integration and style

- The devices covered in this report can be divided into **two groups**: Those aiming to deliver a **fully immersive experience** to niches — meaning almost no compromises in terms of weight, aesthetics, or form factor (and sometimes even price); and those targeting mass adoption with a clear value proposition: **allow all day long wearability while offering a seamless interface between the user and an AI**.
- In the first case, we refer to **headsets**, which can be equipped with a multitude of modules and large batteries (like the Quest 3). In the second, we refer to **glasses**, for which designers must cleverly reduce or eliminate certain modules so as not to compromise **weight or energy budget** (like the battery capacity of the Ray-Ban Meta).
- **Displays are crucial in the user experience in both cases** but the criteria by which they are evaluated differ. The best example is **OLED-on-Si**, which is the optimal technology for VR but completely unsuitable for AR due to its low brightness (< 100,000 nits). This lack of brightness is a major issue because **waveguide-based optics**, the use is a given due to their slim form factor, lightness, and scalable manufacturing processes, offer **very low optical efficiency** (<1%). Such constraints put therefore a lot of constraints on the display engine which should deliver enough brightness without having its form factor neither its power consumption scaling to much. Due to these set of requirements, LCoS and MicroLED are poised to battle up for the coming years as they can deliver **millions of nits within less than 1cc**. LCoS must be adopted for first generations of products, but **MicroLED is the ultimate choice before moving to volumetric AR** (requiring then **SLM-based display engines**). In the field of MicroLED, many approaches are currently investigated to reach the right level of performance and achieving RGB. Hard to know which one will be succeeding to cross threshold level of performance, and after that will come the question of price.
- **AR because of its very ambitious purpose and constraints will be pushing the boundaries of semiconductor processes and architecture on both displays, processing and sensing.**

OUTLOOK





MARKET SUMMARY

AR and VR, as markets, will have two very different dynamics

- The VR market is expected to hit saturation around the **10 million units annually**. Despite Meta's effort and Apple's recent legitimization of the devices via a new marketing approach, such range of devices still fails to appeal enough to consumers and spread.
- AR has much more potential to meet a real market ignition. We estimate that those wearables are much more poised to trigger *FOMO*. We should now consider smart eyewear as a continuum of products will be offered from audio only to more and more immersive/interactive solutions. We expect **the smart eyewear market to reach around 15 million units by 2030, and we project the solutions with a display to account for about 85% of that total in 2030**.
- Therefore, we expect the **AR and VR markets will experience very different dynamics with respectively 44% and 4% 2024-2030 CAGR (in terms of units)**. It is a matter of maturity, VR is already there, while AR still has to ignite, but it is also a matter of the very nature of the market being targeted.
- The VR market is essentially revolving around gaming and professional use cases. AR did target professional use cases with former generations of products, but technologies are getting ready (in terms of performance and scalability) to address consumer audiences now. With consumer AR, the targeted market is eyewear and what we call smart eyewear should represent a significant part of it. As part of this market, fashion aspects are critical, and the brands will play an important role in the wide adoption. Except the aesthetic aspect, the value proposition of such electronics embedding glasses is AI. Through 2023 and 2024, many OEMs even rebranded their smart glasses or AR glasses as AI glasses. Ultimately, what is sold is no longer a device but the physical interface with an LLM.
- Such **link between AR and AI** is key to understanding both the rapid adoption we anticipate and the siloed nature of markets that will emerge. Indeed, the front runners of both LLMs and smart eyewear devices are tech giants from the **US** (Meta, Google) and **China** (Xiaomi, Tencent, Alibaba). Access to these services could be restricted, and ongoing trade tensions and tariffs might further encourage a more domestic supply chain tailored to specific geographic markets.



SUPPLY CHAIN SUMMARY

AR and VR Supply Chains: Two Distinct Biomes, One Set of OEMs

- For both AR and VR, downstream the supply chain, the OEMs are the same: consumer electronics giants like **Apple, Google, Samsung, Xiaomi** but also newcomers in the field of hardware like **ByteDance** and more importantly **Meta**.
- That being said, the nature of AR and VR ecosystems (technology bricks providers) is essentially related to the maturity of the technologies needed.
- VR relies on proven technologies but but the emergence of new solutions still conditions AR's success. Most VR modules are manufactured by large companies that are well-versed in assembling and manufacturing of technological building blocks that have become almost commoditized (LCD, Fresnel lenses and pancake lenses are a good illustration).
- On the other hand, the AR ecosystem is typical of a market that hasn't emerged yet. Many technologies, sometimes incompatible or competing, are investigated simultaneously. This exploration is ensured by start-ups mainly. To illustrate this, we can mention tracking technologies where **NILT, Prophesee** and **AdHawk** develop different approaches to a similar purpose. The same can be said about waveguide optics, where different players consider several options (both in terms of manufacturing and materials). In the end, this phenomenon is the most obvious in the field of microLED micro display for AR. Indeed, this self-emissive technology is poised to become the standard. Still, it is not ready yet, and many players intend to solve challenges differently (**Porotech** with their proprietary DPT, **Aledia** with nanowire arrays, **JBD** and **Q-Pixel** with vertical stacking, to name a few).
- This rich and wide-ranging exploration is likely only possible thanks to Meta's unwavering commitment. Indeed, **Meta Reality Labs' loss is about 4 to 5 billion dollars a quarter**, and a significant amount of that is very likely to be injected into this ecosystem. The image we can use to describe **the current landscape of start-ups is a garden tended by Meta's dedication to make AR happen. Meta cultivates many species there, but the final bouquet it offers for consumers will include only a select few, leaving many others by the wayside.**
- To materialize, the AR market requires breakthroughs driven by new technologies. However, in the long run, suppliers from more mature markets—such as the smartphone industry—will also play a key role. This includes sensing specialists like **Bosch, Texas Instruments, ams OSRAM, and STMicroelectronics**, as well as computing players such as Qualcomm. Lastly, traditional eyewear companies, with **EssilorLuxottica** at the forefront, will be instrumental thanks to their experience and established presence in the field.



TECHNOLOGY SUMMARY

The dualities of AR and VR: Headsets for depth, Glasses for daily AI integration and style

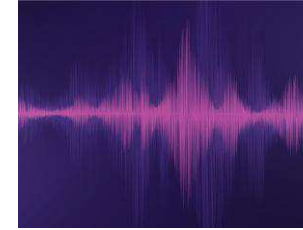
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YOLE GROUP RELATED PRODUCTS

Reports



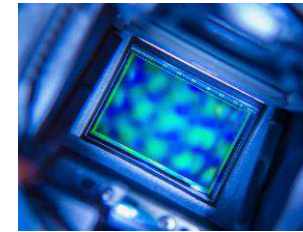
Sensors and Actuators for Wearables 2025



Microphones, Microspeakers and Audio Processing 2025



Optical Metasurfaces 2024



Status of the CMOS Image Sensor Industry 2024

2025 edition coming soon



Status of the Processor Industry 2024

2025 edition coming soon



3D Imaging and Sensing 2025



Generative AI 2025 - Computing and AI for Data Center



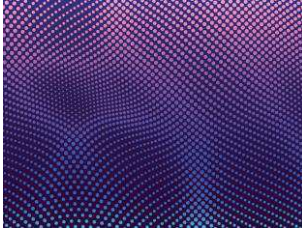
Neuromorphic Computing, Memory and Sensing 2024

Contact our Sales Team for more information

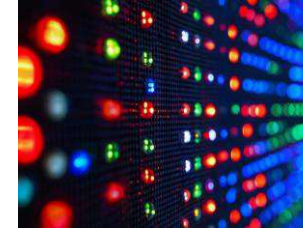


YOLE GROUP RELATED PRODUCTS

Reports



[MicroLED - Markets, Applications and Competitive Landscape 2024](#)



[MicroLED - Technologies, Equipment and Manufacturing 2024](#)



[MicroLED 2025](#)



[MicroLED Displays - Intellectual Property Landscape 2024](#)



[Apple Vision Pro 3D Cameras Comparison 2024](#)



[Apple - APU - Co-Processor R1 - From Apple Vision Pro](#)



[MEMS Microphones Comparison 2025](#)



[Eye Tracking Sensors for AR/VR Comparison 2025](#)

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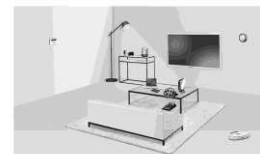
YOLE GROUP RELATED PRODUCTS

Consumer Teardown Tracks



CONSUMER
Phone

Consumer - Phone



CONSUMER
Smart Home

Consumer - Smart Home



CONSUMER
Wearable

Consumer - Wearable



CONSUMER
Tablet, Computing
& Gaming

Consumer - Tablet,
Computing & Gaming

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FROM TECHNOLOGIES TO MARKET

Corporate Presentation

— YOLE GROUP —

We provide industrial companies, financial investors, and R&D organizations, with market research, technology, supply chain, and cost analysis, along with performance evaluation. Our services support informed decision-making on business and manufacturing strategies in the semiconductor, photonic, and electronic sectors.

3 CORE ACTIVITIES BASED ON DEEP SYNERGIES

Market & technology

- Market, technology and supply chain analysis
- Markets trends and forecasts

Teardown reverse engineering and costing

- Technology, process and cost analysis
- Teardown and reverse engineering
- Performance analysis

Custom project

- Strategy consulting
- M&A, due diligence and evaluation of companies

OUR PRODUCTS & SERVICES

REPORTS

INSIGHT

- Yearly published reports
- Market, technology and strategy analysis
- Reverse costing and reverse engineering
- Performance analysis

FORMAT

- PDF files with analyses
- Excel files with graphics and data
- Web access

TOPICS

- All thematic

115+ reports per year

QUARTERLY MONITORS

INSIGHT

- Quarterly analysis with market data and technology trends in units, value at wafer level
- Direct access to the analyst (except for Wafer Data Monitor)

FORMAT

- Excel files with data
- PDF files with analyses graphs and key facts
- Web access

TOPICS

- Advanced Packaging
- Compound semiconductor: SiC, GaN and RF GaN
- Computing: Processor and µcontroller
- Memory: DRAM, NAND
- Semiconductor Manufacturing and Test Equipment
- Wafer Data

15 different monitors
quarterly updated

TEARDOWN TRACKS

INSIGHT

- Teardowns of phones, smart home, wearables and automotive modules and systems
- Bill-of-Materials
- Block diagrams
- Interactive zooming

FORMAT

- Web access
- PDF and Excel files
- High-resolution photos

TOPICS

- Consumer
- Automotive
- Telecom

315+ Single Teardowns Tracks per
year - Daily updates

CUSTOM SERVICES

INSIGHT

- Specific and dedicated projects
- Strategic, financial, technical, supply chain, market and other semiconductor-related fields
- Reverse costing & reverse engineering

FORMAT

- Direct work with the analyst team
- PDF files with analyses
- Excel files with graphics and data

190 custom projects per year

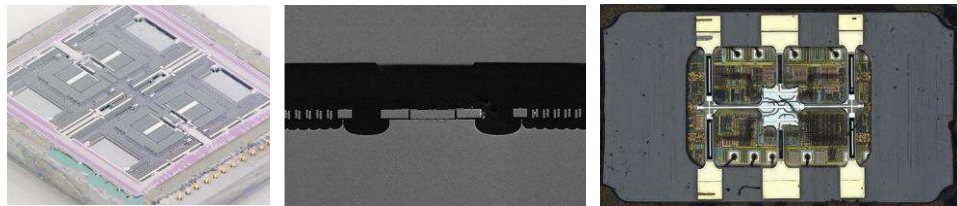
— RESEARCH PRODUCTS —

Annually with data and 5-yr forecast

Market and technology trends analysis



Reverse engineering & reverse costing



	Low Yield		Medium Yield		High Yield	
	Cost	Breakdown	Cost	Breakdown	Cost	Breakdown
CDU De Price	\$61.00	40%	\$22.00	90%	\$487.00	37.6%
Titles De Price	\$1.37	0%	\$1.27	0%	\$157.00	0%
CDU De Fee	\$1.00	30.9%	\$1.00	4.5%	\$24.00	1.8%
Interplay + CDW Cost	\$22.87	14.3%	\$186.37	13.7%	\$1967.07	12.1%
Package Substrate Cost	\$250.00	1.9%	\$250.00	2.1%	\$250.00	2.4%
Thermal Paste/Conductors/Capacitors	\$1.00	0%	\$5.00	0%	\$5.00	0%
Module Frame	\$0.08	0.0%	\$0.08	0.0%	\$0.08	0.0%
Final Packaging & Final Test	\$1.00	0.7%	\$10.00	0.8%	\$10.00	0.9%
Yield Loss	10.0%	0.0%	10.0%	0.0%	10.0%	0.0%
Component Cost	\$1,075.91		\$1,460.87	100%	\$2,124.12	100%

The package size is 58 x 55mm, with 12 Copper layer substrate.

The price of the package substrate cost is estimated to be \$29.

The final component cost (CPU + Filler Die + HBM + Capacitors + Heatsink, Substrate + Assembly) ranges from \$1,214 to \$1,876 according

to yield variations:

The CPU die represents 39.5% of the component cost in middle yield.

The **HMM Stack** (x5) represents 30% of the component cost in middle yield.

The Interposer with **566** process represents 13% of the component cost.

The various substrates are compared and contrasted and used

represent 15% of the component cost.

5

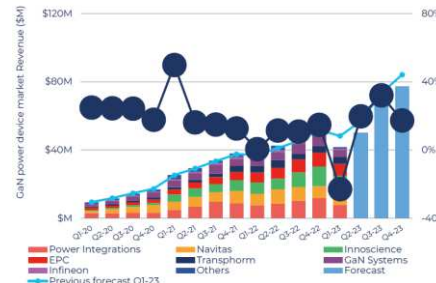
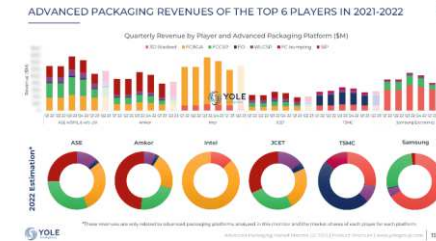
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Quarterly data and analysis

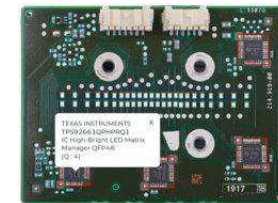
ADVANCED PACKAGING REVENUES OF THE TOP 6 PLAYERS IN 2021-2022 

TEARDOWN TRACKS

Full BOM costing



Dismantling photos from A to Z



Detailed PCB



Block diagram interactive



Bill of materials

— OUR EXPERTISE —

SEMICONDUCTOR INDUSTRY

- Battery

- Compound Semiconductor

- Computing and Software

- Display

- Electronic Systems

- Global Semiconductor Trends

- Imaging

- Memory

- Photonics and Lighting

- Power Electronics

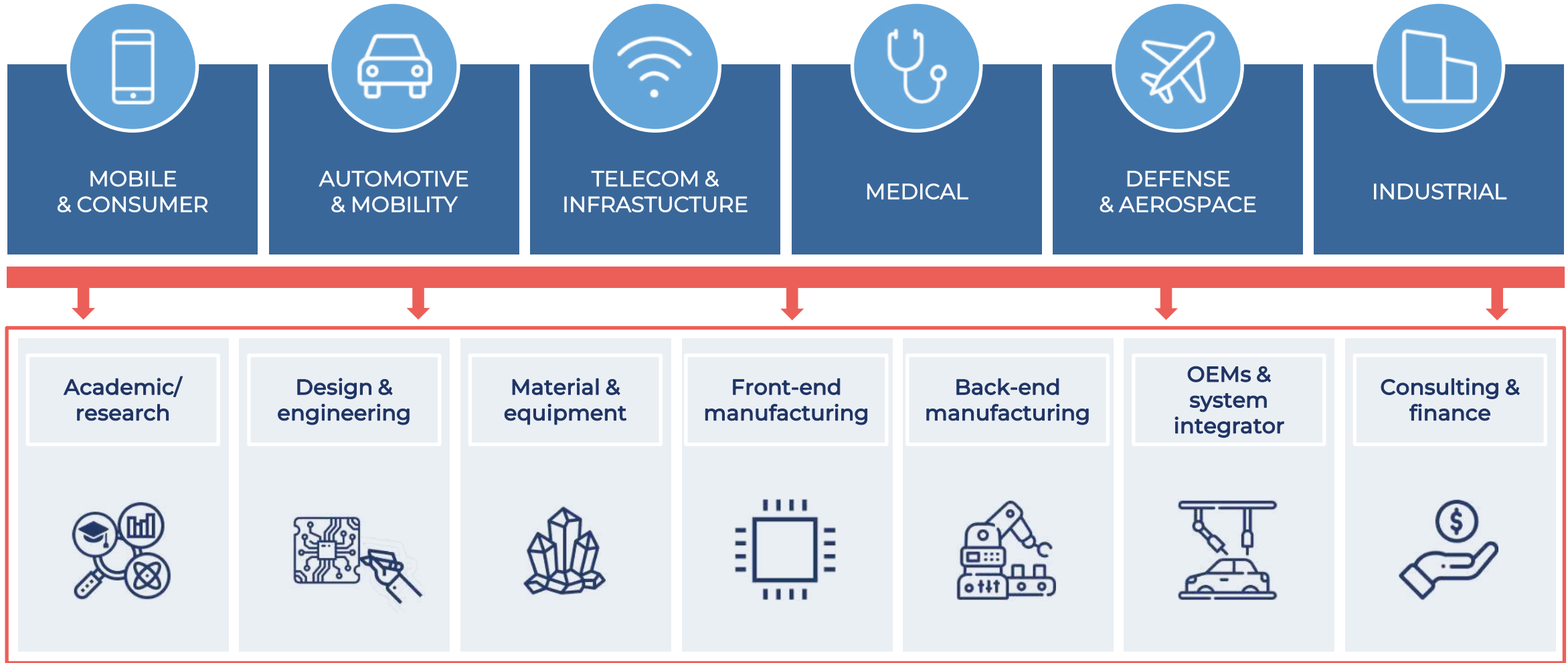
- Radio Frequency

- Semiconductor Equipment

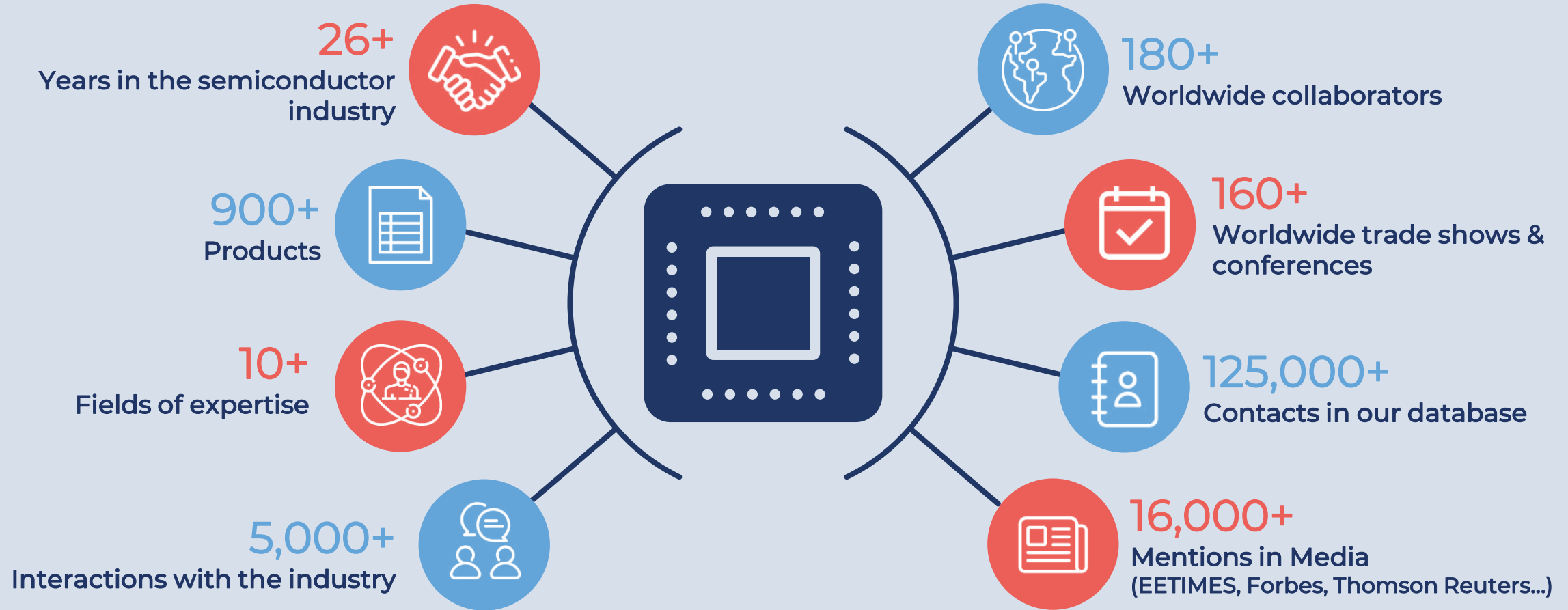
- Semiconductor Packaging

- Sensing and Actuating

— ACROSS THE SEMICONDUCTOR SUPPLY CHAIN & MARKETS —

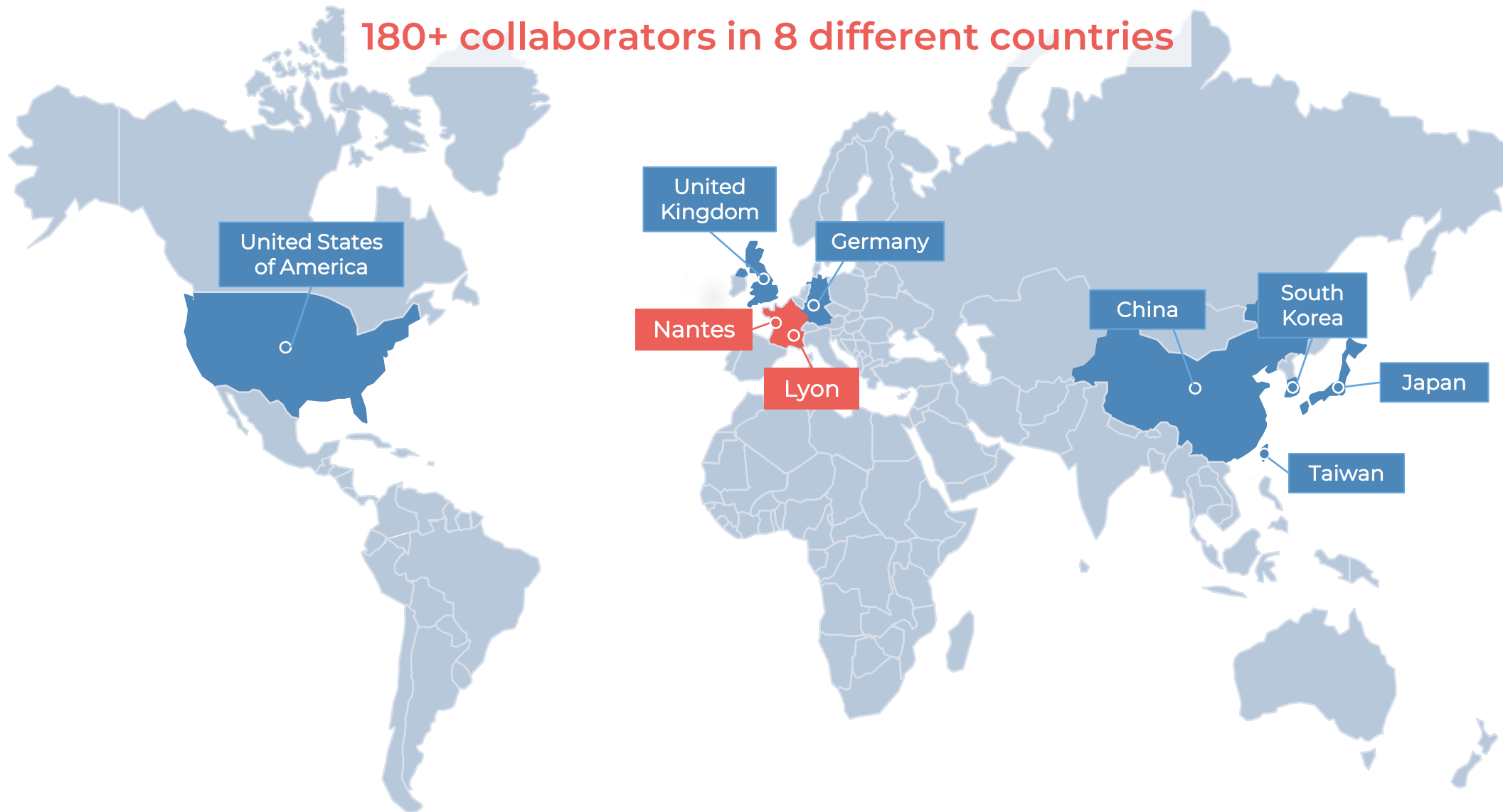


YOLE GROUP – KEY FIGURES



— YOLE GROUP – A WORLDWIDE PRESENCE —

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