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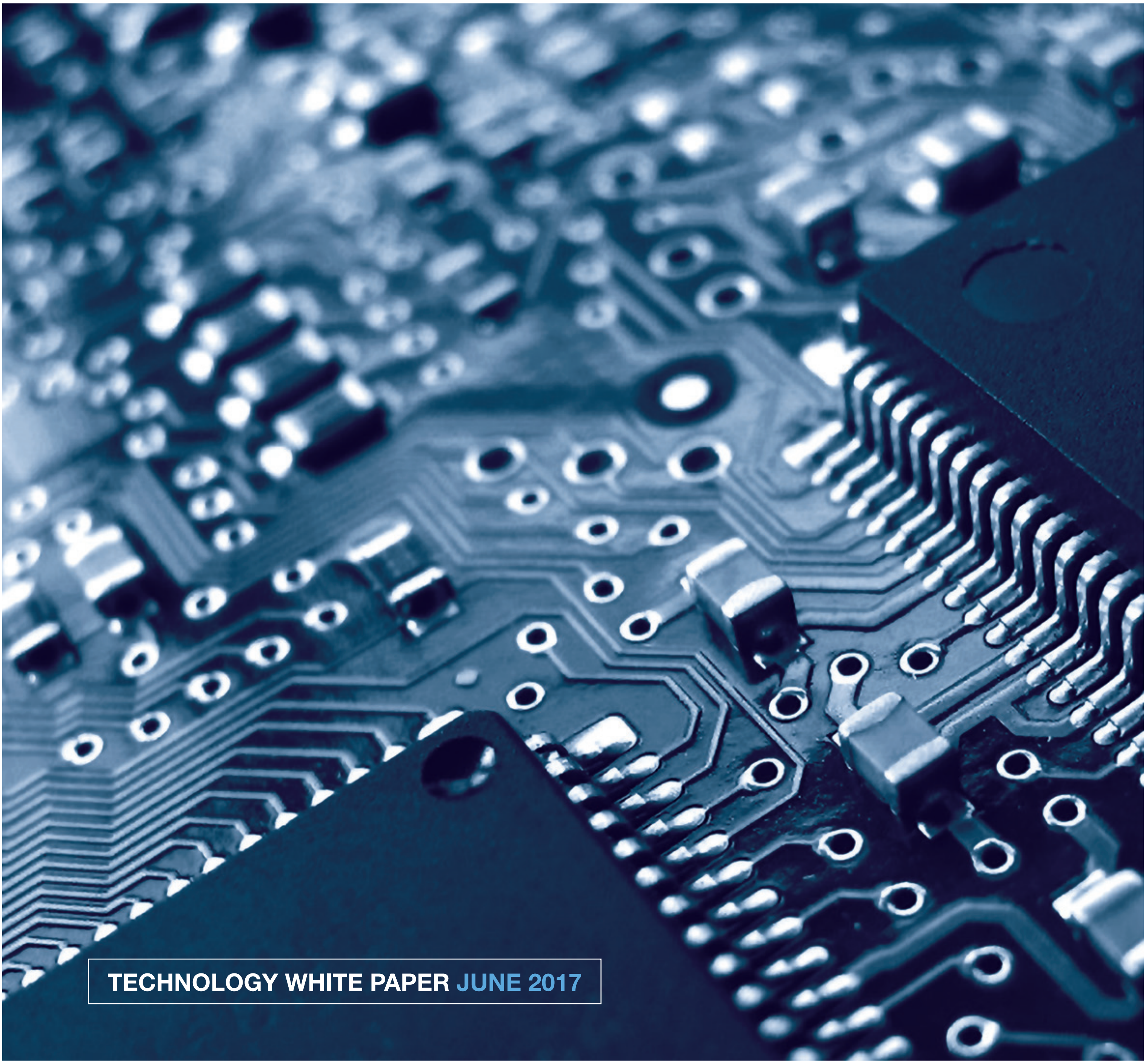
3D SENSING AND THE POTENTIAL OF AUGMENTED REALITY



TECHNOLOGY WHITE PAPER JUNE 2017

Contents

Despite the success of the popular game Pokémon Go, augmented reality (AR) – which makes it possible for virtual objects to interact with the real world – has made little progress on smartphones. The limiting factor is technology, specifically the problem of creating sensors that can build a 3D view of the world. However, Time-of-Flight technology, already used on smartphones to detect proximity, could be the breakthrough that enables AR to take off on smartphones and beyond.

Augmented reality: the next mobile revolution? The smartphone market is slowing down as a result of market saturation and a lack of innovative functionality. Augmented reality (AR) is one area of interest, with Apple, Google and Baidu all developing applications. Beyond gaming, AR could also be used to improve smartphone cameras, offer gesture control, and provide information overlays in vehicles or in industrial and biomedical applications. But as Pokémon Go demonstrated, while AR has potential on smartphones, it is currently limited by the fact that these devices cannot yet create the 3D view that AR needs. Smartphones depend on a power-hungry combination of sensors and algorithms to run AR apps.

Time-of-Flight (ToF) sensors could be the solution. For AR to be convincing, devices need to be able to sense their environment in 3D. Current technologies use complex algorithms and infrared sensors, which cannot measure distance and are susceptible to the reflectance of a surface. ToF sensors, which use laser light, do not have this problem and can measure distance accurately. The challenge with this technology is to make sensor units with the small size, high resolution and energy efficiency needed to be viable in smartphones.

ToF is evolving. ToF sensors are already used in smartphones to measure distance: for example, the STMicroelectronics VL53L0 manages screen shutdown on the iPhone 7 when the phone is held close to the ear. One of several firms working on ToF, STMicroelectronics is, in our view, building a competitive advantage through its use of silicon on insulator (SOI) wafers, which improve sensor performance, and by using micro-mirror technology, which helps to generate the 3D view needed for AR.

DORIAN TERRAL
Equity Research Analyst | Semiconductors

1. 2017: the year of augmented reality?

1.1. THE NEXT OPPORTUNITY FOR SMARTPHONE INNOVATION

Today's smartphones are more powerful than ever. Their ability to carry out a growing range of daily tasks has made them indispensable to users. However, for several quarters we have noticed a slowdown in the market, resulting from market saturation and a lack of genuinely new functionality.

Where will smartphone innovation come from? We see two areas of interest at the moment:

1.) foldable screens that transform a smartphone into a tablet; and
2.) a step change in the smartphone's ability to run augmented reality (AR) using 3D sensors. In this paper, we focus on AR.

To date, the few smartphone AR applications in the market have been unconvincing because of hardware limitations. Smartphones cannot see the world in 3D, so AR applications need to get by using a combination of camera, gyroscopes, accelerometers and GPS.

Despite this, there is tangible interest in AR. The best example remains the success of Pokémon Go, a game that inserts virtual creatures into the real world. However the game also revealed two major shortcomings of AR on smartphones: poor rendering in most situations; and high power consumption and battery drain from the need to have complex algorithms working permanently. Unfortunately, Pokémon Go is not the only example of poor rendering. Virtually all AR applications suffer from similar issue (see Fig. 1).

The few examples of AR in the smartphone market today highlight how the technology is currently limited by handset hardware.

FIG. 1: UNRELIABLE RENDERING DIMINISHES AR OPPORTUNITIES SO FAR

Expected immersive rendering | **Actual unconvincing rendering**

Well integrated virtual items. | Numerous glitches appear as there is currently no way to sense real world dimensions.

Source: Bryan, Garnier & Co.

We believe that Time-of-Flight (ToF) sensors could be the solution to these problems. Because they are the only sensors capable of measuring distance, they enable smartphones to see the world in 3D, a prerequisite for convincing AR.

This would open up a huge range of possibilities: from mobile apps for ordering tailor-made suits or fitting furniture into a room, to camera images enhanced with useful information, and of course mobile games that interact with the real world.

We believe Time-of-Flight (ToF) sensors could be the solution to the performance problems of AR on smartphones.

FIG. 2: VR HONOURED AT THE 2016 MWC

Source: Mobile World Congress

1.2. AUGMENTED REALITY IN 2017

Barely a year ago, augmented reality seemed to be eclipsed by virtual reality (VR). However today there is growing interest in AR.

The 2016 Mobile World Congress saw the introduction of several dedicated VR appliances, including the Samsung's Gear VR, the commercial version of Vive by HTC and the 360 VR from LG. And to welcome these, Facebook's Mark Zuckerberg made an astounding entrance to the congress, taking to the stage while all members of the audience wore VR glasses.

While virtual reality stole the limelight in 2016, the spotlight has since moved towards augmented reality.

During the second half of 2016, the focus gradually moved towards augmented reality. While VR plunges the user into a virtual world, augmented reality is intended to enhance our perception of the real world.

Pokémon Go remains the most well-known AR application: although very popular, its capabilities are limited compared to the true potential of AR. Several major groups have also shown interest in AR, including Apple, which by contrast has said little about VR.

1.3. APPLE'S AR VISION

In November 2013, Apple revealed its interest in AR by acquiring PrimeSense, an Israeli fabless group specialised in 3D processing.

Between 2014 and 2016, the publication of the PrimeSense/Apple patent revealed the Cupertino group was continuing to work on device-control technologies using movement detection.

This little-known company was behind the technology used in Microsoft's XBox Kinect. In its first version, which embedded PrimeSense technology, Kinect used a complex triangulation system using a traditional camera, an infrared camera, an infrared projector and a complex algorithm. Apple spent around USD360m on PrimeSense. To date, the deal has not seen its technology embedded in an Apple device, despite many predictions that it would feature in the iPhone 6.

Between 2014 and 2016, publication of the PrimeSense/Apple patent revealed the Cupertino group was continuing to work on device-control technologies using movement detection. PrimeSense technology is based on analyzing a 3D scan of the object's environment. However, this technology and the associated material is well suited to augmented reality.

In August 2016, Apple CEO Tim Cook started to discuss where AR fitted into the group's vision. In his view, it could be an "enormous phenomenon" – which suggests AR could represent a significant evolution in Apple products on a par with the impact of multipoint capacitive touchscreens and inertial navigation units (gyroscopes and accelerometers) in the smartphone.

At the same time, Cook stated that the group was investing significant amounts in this technology and indicated an investment in R&D over more than five years.

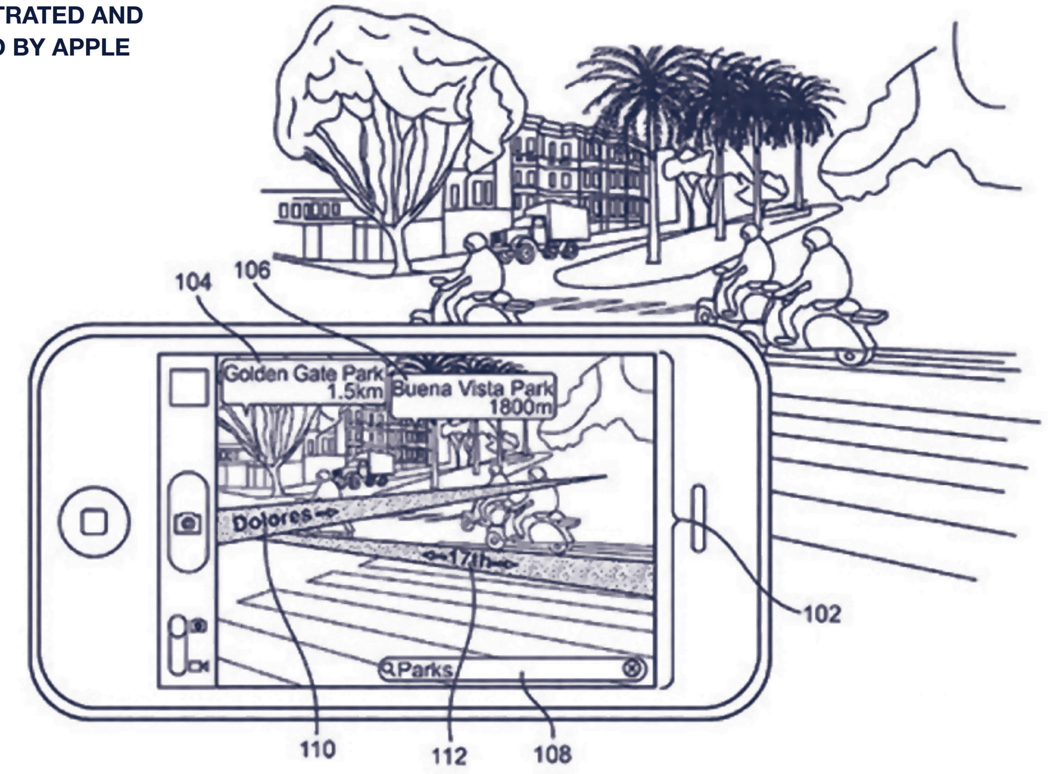
In Cook's view, AR is far more easily accepted by consumers than VR, which is held back by three factors:

1.) Cost – VR headsets retail for around USD500;
2.) Convenience - headsets are bulky and VR needs high-powered hardware (PC or console) to do more once users want to go beyond the demo;
3.) Applications – VR tends to be best suited to complex video games and professional applications, limiting potential volumes and therefore the interest for developers to invest in this technology.

AR is different. Applications are easier to develop, as mapping systems and casual games show, because it is much easier to implement AR in games compared to VR, and requires fewer resources.

In November 2016, specialised news website Appleinsider published an article highlighting a US patent filed by Apple relating to the use of AR for its mapping and route guidance systems. It showed how an "evolved guidance" system could work, with information inserted into a real-world view filmed by the smartphone's camera.

FIG. 3: AR ILLUSTRATED AND PATENTED BY APPLE



Source: Appleinsider, via the US Patent and Trademark Office

AR seems like a natural technology for Apple, just as touchscreens are now natural for smartphones. While expectations are now for Apple to deliver solutions that are not gadget-based, AR could help the group stand out again in this field.

It is general knowledge that Apple is particularly patient when it comes to integrating a new technology into its products. Above all, it wants new technologies to feel natural (like a capacitive touchscreen, Siri, or inertial scrolling). For this reason, we are not surprised to see the company looking at the use of AR in its products.

> *"AR I think is going to become really big. [… It's] gonna take a little while, because there's some really hard technology challenges there. But it will happen. It will happen in a big way. And we will wonder, when it does [happen], how we lived without it. Kind of how we wonder how we lived without our [smartphones] today."* **TIM COOK** | APPLE CEO

FIG. 4: MEASURING SPACE TO SEE HOW NEW OBJECTS WOULD FIT

Source : Google

1.4. GOOGLE'S AR PLANS

By early 2017, only two consumer devices had the hardware needed to work with Tango, (Google's own AR project) limiting the initiative.

Google is pursuing its own AR project, Tango, which began in 2014. The project aims to roll out a platform that groups together artificial vision applications (computer-assisted vision).

In concrete terms for Google, this means an Android-integrated software device capable of making the most of a range of sensors, including movement sensors and above all Time-of-Flight sensors that map the smartphone's environment in 3D.

Via a dedicated website, Google gives two examples of how its technology can be used. The first illustrates how virtual elements can be precisely measured and integrated into a real environment – in this case, a bed chosen from a furniture catalogue is projected into a room to see how it would fit. The second example shows how games could interact with the real world, with virtual dominos laid on a real table and interacting with other real-world objects.

By early 2017, only two consumer devices had the hardware needed to work with Tango, limiting the initiative. These are the Lenovo Phab 2 Pro, launched in August 2016, and the Asus ZenFone AR, which was presented at the 2017 CES.

For the moment, no teardown (in-depth study by component suppliers) of these two devices has been made public, such that doubts remain over the supplier of depth sensors.

FIG. 5: BAIDU AND KFC ARE DEVELOPING A NEW "INTIMATE" VIRTUAL HOST CONCEPT

Source: TechCrunch

1.5. FOR BAIDU, AR IS ALREADY IN PRODUCTION

The Chinese internet search giant started work on AR more than two years ago, but only very recently built a centre dedicated to developing services for education, health, tourism and marketing.

Baidu has indicated it is already in close collaboration with several major groups including Yum! (Taco Bell, KFC, Pizza Hut…), Lancôme, L'Oreal and BMW. The L'Oréal, application, for example, enables users to play with AR and L'Oréal products to obtain promotional offers. A Yum! collaboration, presented at the end of December 2016, involves a smart order device for Chinese KFC restaurants that can analyse a consumer's face to suggest products or even a full menu. The unit can analyse factors such as age, type and facial expression, and then integrate suggestions into an AR video flow sent to the user. To facilitate consumer acceptance, the smart units include AR games such as photos modified by stickers. At present, the games units have been installed in 300 restaurants in China, but only one test restaurant has the version of the unit where facial recognition is activated.

Another Baidu application enables Beijing metro users to see a modified version of the city that shows its historical doors, only relics of which remain today.

"There is an appetite for this technology; we are seeing rapid adoption by our partners in a range of industries."

ANDREW NG
CHIEF SCIENTIST OF BAIDU & HEAD OF BAIDU RESEARCH

2. Time-of-Flight sensors

While augmented reality applications are likely to take off soon, pushed by sector giants, technical limitations to their success remain, especially the lack of dedicated and adapted components.

But while augmented reality applications are likely to take off soon, pushed by sector giants, technical limitations to their success remain. For AR to be convincing, smartphones need to be able to analyse (sense) the surrounding 3D environment. Current technologies are restrictive because they depend on complex, power-hungry algorithms and very limited proximity sensors. However, Time-of-Flight technology opens numerous possibilities and seems to provide exactly the right answer.

2.1. PROXIMITY SENSORS: EXISTING TECHNOLOGIES

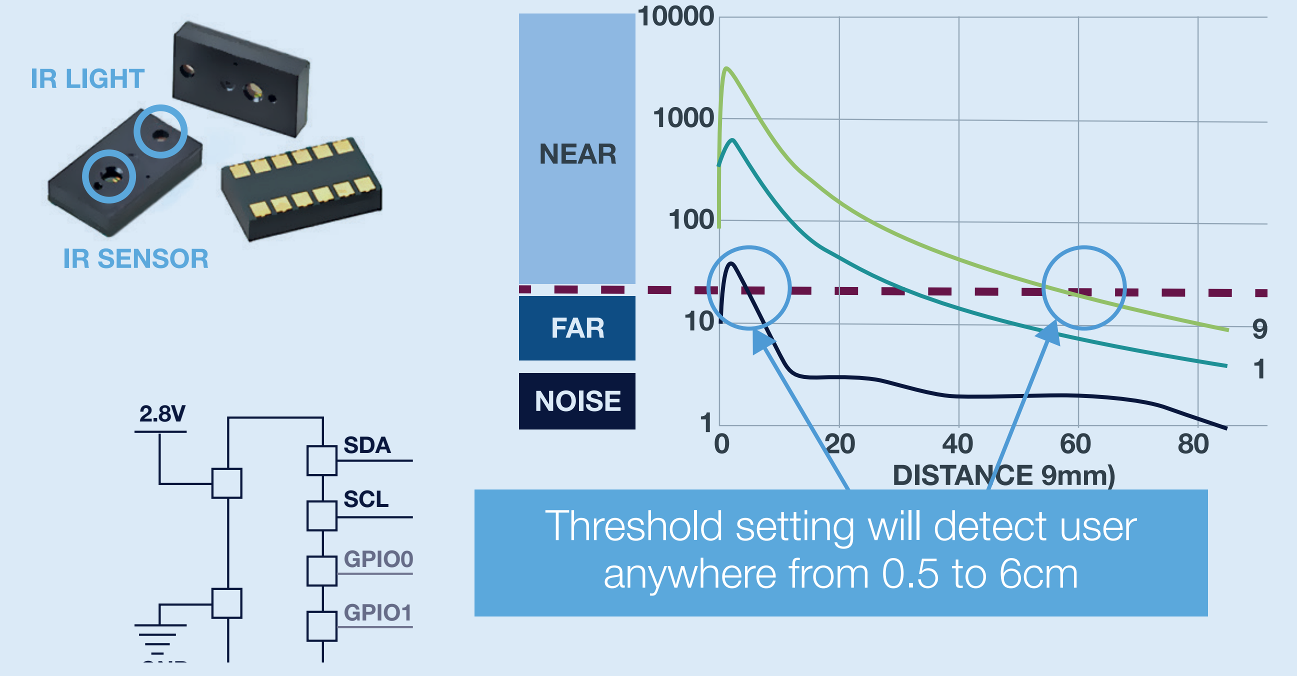
2.1.1. HOW CURRENT PROXIMITY SENSORS WORK

Technologies that enable the generation of a 3D view already exist, with the Microsoft Kinect the best example. At present, these technologies are based on an infrared (IR) sensor/emitter which, when combined with an algorithm, helps build a 3D scene.

Similarly, many smartphones already have embedded proximity sensors. These deactivate the screen when the device is close to the user's face to avoid accidentally hanging up during a call.

While these sensors partly respond to a need, they are very limited. They function on the principle of infrared light intensity, using an infrared emitter and a receptor that measures the return of the emitter's light in real time. If an object is close enough to the emitter, it automatically reflects the light ray, which is returned to the sensor. So if the sensor detects sufficiently powerful radiation, this means that an object is fairly close. At a certain threshold of light intensity, the receptor will trigger an action (turning off the phone screen for example). The technology embedded in the Kinect uses a more complex triangulation system, which is based on several sensors and requires substantial calculation power.

FIG. 6: CURRENT PROXIMITY SENSORS USE THE AMPLITUDE OF A SIGNAL



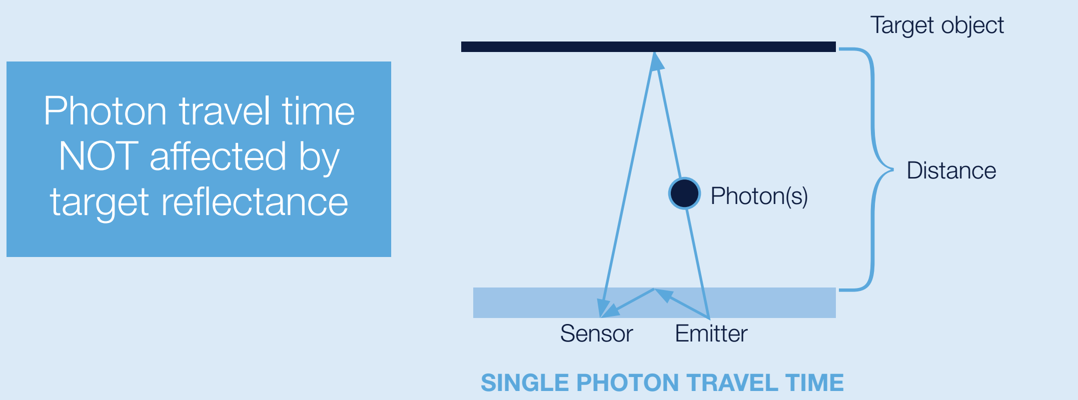
Source: STMicroelectronics

Current proximity sensors are made up of an infrared (IR) emitter, and a receptor which is responsible for measuring the emitter's light return in real time.

2.1.2. LIMITATIONS OF INFRARED SENSORS

Paradoxically, the simplest proximity sensors (such as those generally embedded in smartphones) cannot measure distance. Because these sensors use the amplitude (power) of a light signal, the reflection of the object located opposite the sensor will have a significant impact on the result. For example, a mirror placed a few metres away will trigger a sensor more rapidly than a matt-black surface just a few centimetres away. According to ST Microelectronics, this is why people with very dark hair often have problems with accidental hanging-up during a call. The reflection from black hair is so low that once the smartphone is positioned close to the ear, the sensor near the hair decides there is no obstacle nearby. Existing distance sensors are also very sensitive to ambient light.

FIG. 7: TOF SENSORS MEASURE THE TIME TAKEN BY A PHOTON TO TRAVEL THE DISTANCE BETWEEN THE EMITTER AND THE SENSOR



Source: STMicroelectronics

Compared to IR proximity sensors, ToF sensors are not sensitive to the reflectance of the target and are able to provide a precise measure of the distance.

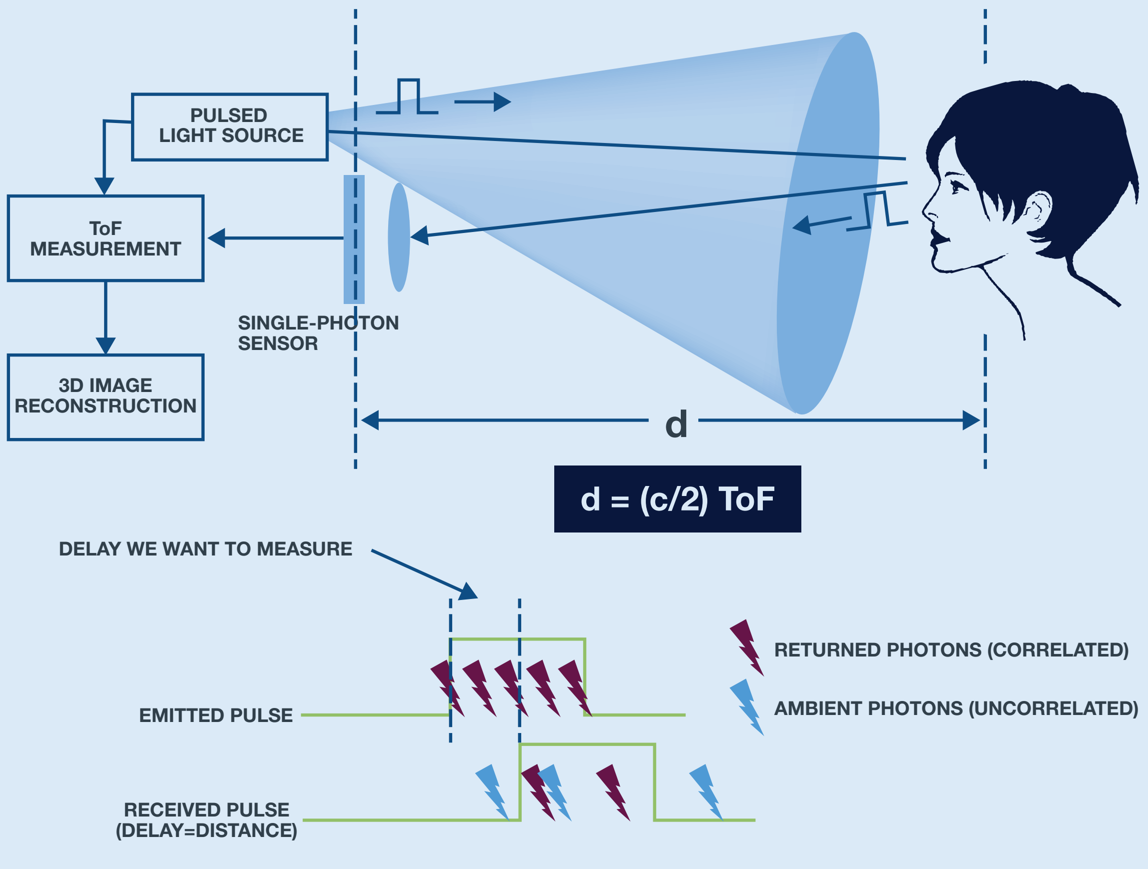
2.2. TIME-OF-FLIGHT SENSORS: A CLEAR INNOVATION IN PROXIMITY SENSING

2.2.1. HOW TIME-OF-FLIGHT SENSORS WORK

Like traditional proximity sensors, ToF sensors are made up of two elements, a light source and a receptor – except in this case the light source is a laser. The other key difference is that to calculate the distance with the first object the laser encounters, a ToF sensor measures the time it takes for photons to travel.

The first advantage of this method is that it is not sensitive to the reflectance of the target. The second advantage is that it helps provide a precise measure of the distance. This measurement is arrived at by simply dividing the time taken by the photon to travel between the laser and the receptor by two, and multiplying the result by the speed of light.

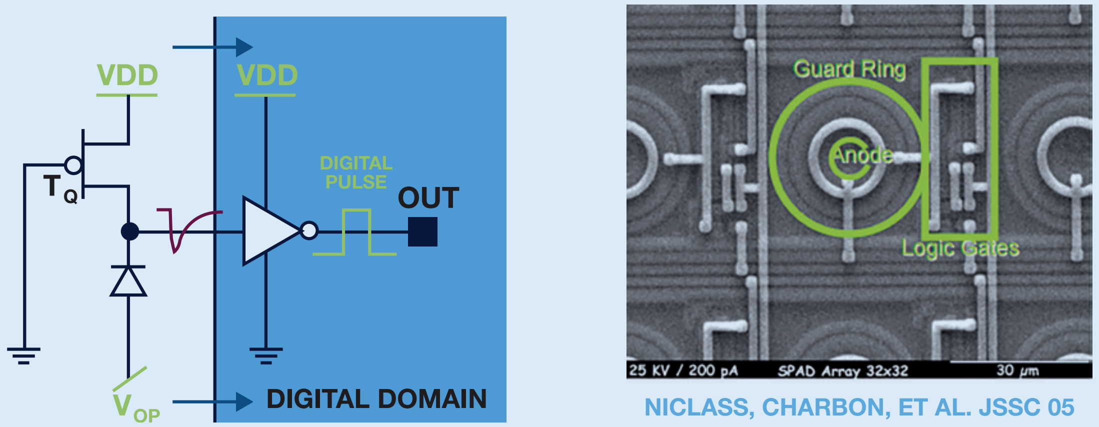
FIG. 8: AN EFFICIENT WAY TO MEASURE DISTANCE



Source: STMicroelectronics

The receptor of a ToF sensor is made up of one or more photodiodes called Single Photon Avalanche Diodes or SPADs. These can be produced on complementary metal oxide semiconductors or CMOS wafers (the traditional manufacturing process for computer chips) and therefore placed next to the digital circuit responsible for counting the photons and measuring the arrival time. The resulting digital output is comprehensible for a processor.

FIG. 9: SPAD ARCHITECTURE

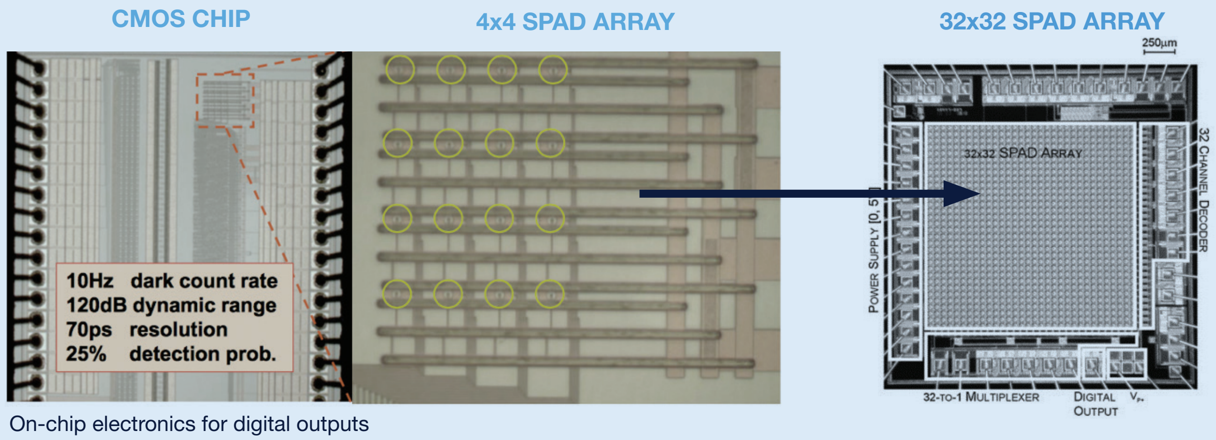


NICLASS, CHARBON, ET AL. JSSC 05

Source: CERN

To improve the performance of ToF sensors, especially their resolution, the number of diodes can be multiplied to create a SPAD grid.

FIG. 10: MORE SPADS = BETTER SENSOR PERFORMANCE



On-chip electronics for digital outputs

Source: CERN

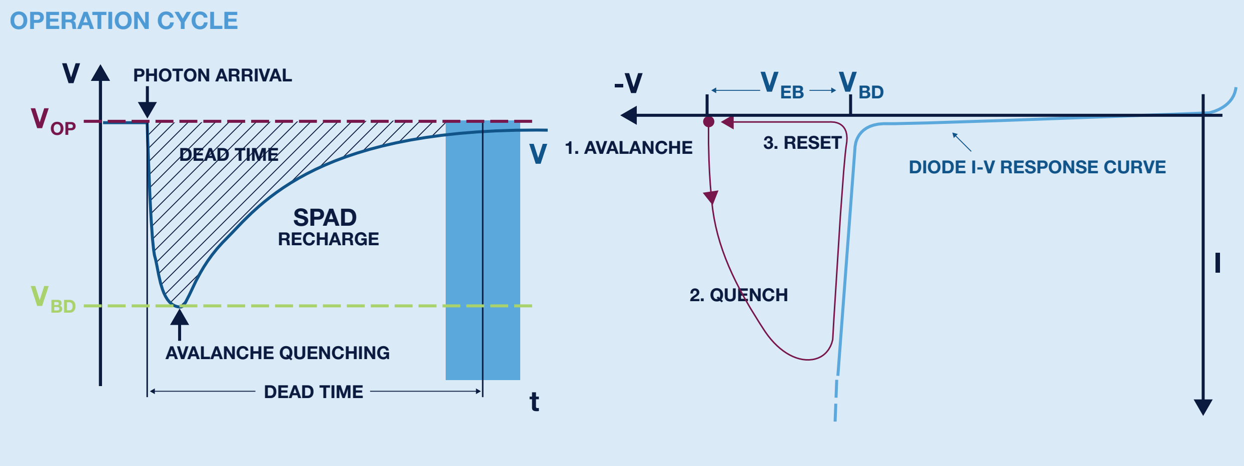
2.2.2. LIMITATIONS OF CURRENT TOF SENSORS

The use of SPADs is practical in terms of integration because it implies CMOS construction, and hence a smaller chip and lower production costs. However it still has limitations. The first is the actual construction of the diode: once the diode is triggered by a photon, it requires time to return to its original state. This is "dead time", during which the diode is no longer active. If other photons arrive, they cannot be counted, which leads to a high loss rate. In addition, multiple SPADs require a degree of uniformity in the dead time to ensure the component performs correctly.

Since SPADs are dynamic units, a digital impulse is automatically generated when a photon is detected. However, unlike the more complex and costly charge-coupled devices (CCDs) SPADs cannot store photocharges proportional to the number of photons received. Time-of-Flight, and hence the distance, must therefore be calculated immediately, via an associated digital circuit. This is manageable as long as the number of pixels is not too high, but it becomes problematic as the number of SPADs increases to improve the definition of the sensor. One of the traditional methods for reading CMOS image sensors, Random Access Readout, rapidly becomes inefficient for ToF sensors because its default is to read information from one pixel at a time before moving to the next one. The information from the other pixels is therefore lost. Because ToF sensors depend on measuring the speed of light and being perfectly synchronized with the laser emitter, the results generated by this processing method rapidly become incoherent.

SPADs need dead time to be controlled to enhance the sensors performance.

FIG. 11: SPADS: THE NEED TO CONTROL DEAD TIME



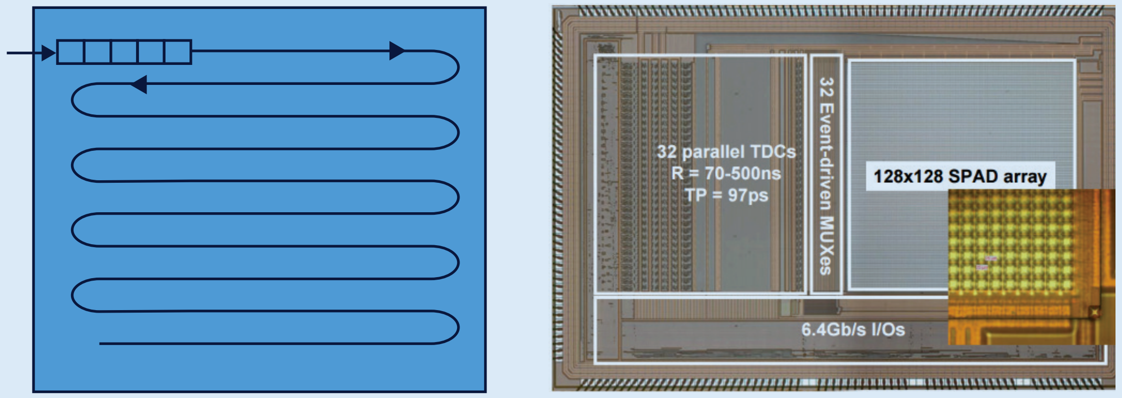
Source: CERN, STMicroelectronics

While CMOS RAR sensors are relatively simple and therefore cheaper to produce, they have the disadvantage of deforming images or measurements during motion, or in the case of a ToF sensor, during synchronisation with the laser.

Several other methods have been developed, but none currently makes it possible to create a high-resolution, high-frequency Time-of-Flight sensor. It is against this backdrop that we believe STMicroelectronics has a portfolio of technologies capable of resolving some of the sticking points and offering a sensor that is:

1.) small enough to be integrated into a smartphone,
2.) produced at an acceptable price using proven production techniques,
3.) energy efficient enough to not impact the autonomy of a smartphone.

FIG. 12: THE RANDOM ACCESS READOUT METHOD USED FOR CMOS IMAGE SENSORS IS NOT OPTIMAL FOR TOF SENSORS

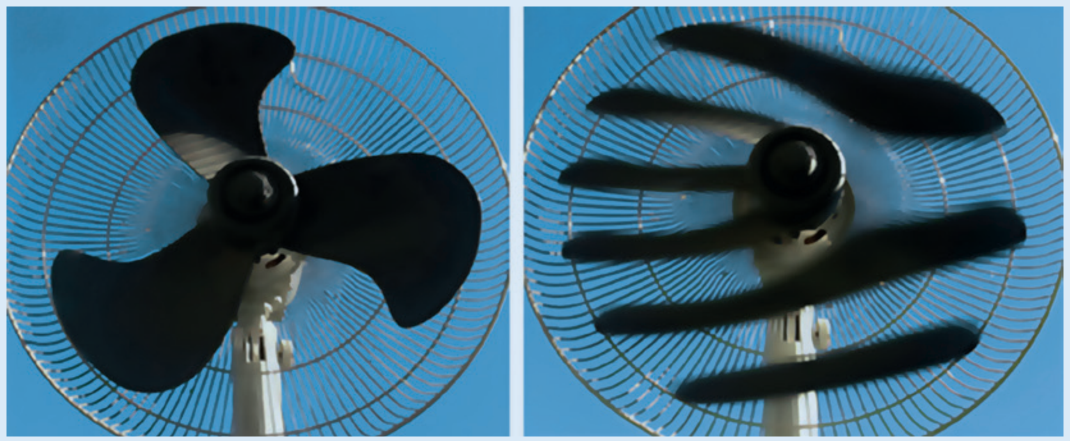


RANDOM ACCESS READOUT METHOD

NEED FOR PARALLEL TIME TO DIGITAL CONVERTER ARCHITECTURE

Source: CERN

FIG. 13: ROLLING SHUTTER VERSUS GLOBAL SHUTTER – EXAMPLE WITH A PHOTO

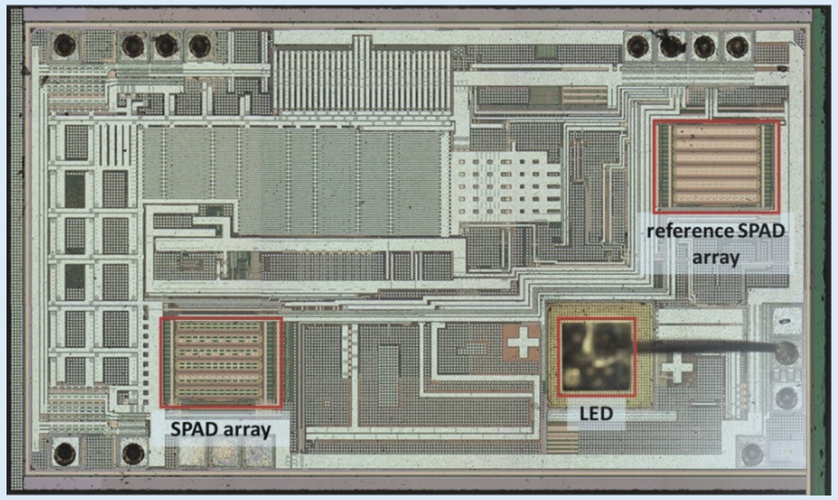


GLOBAL SHUTTER (CCD)

ROLLING SHUTTER (CMOS)

Source: Qimaging

FIG. 14: STMICROELECTRONICS VL53L0, A SIMPLE TOF SENSOR ALREADY USED IN THE IPHONE 7



Source : Chipworks

2.2.3. POSSIBLE EVOLUTION OF TIME-OF-FLIGHT TECHNOLOGY

STMicroelectronics (ST) has had a ToF sensor available since H2 2014. However, in its current form, this sensor cannot reconstruct a 3D scene, but simply measures the distance between two points. A version of this sensor is currently used in the iPhone 7 as a simple proximity sensor. Positioned on the front face close to the front camera, it manages screen shutdown when the phone is held by the ear.

STMicroelectronics current ToF devices only allow measurement of the distance between two points.

According to STMicroelectronics, this simple version of the ToF VL53L0 sensor is currently used in 70 smartphone models. In addition, it is important to note that STMicroelectronics is not the only player to have developed a ToF sensor with a maximum of 12 measurement points. But we believe the group has an edge over its rivals thanks to differentiating technologies. Competitors include the small German company PMD Tec, and Heptagon, recently acquired by ams.

To overcome the problems with ToF, we believe STMicroelectronics is working on a number of innovations both for the receptor and the laser.

First, we believe ST is looking at a material improvement in SPAD performance. Here, the company's mastery of SOI (silicon on insulator) technology could be a differentiator. SOI wafers make it possible to produce CCDs or very high-performance CMOS on the same die (piece of silicon), capable of instantaneously sensing all the pixels in the sensor, or rather from the ToF sensor. (This is illustrated in Fig. 13's comparison of Global Shutter with Rolling Shutter). Studies undertaken in IEEE laboratories have shown the interest and potential for using FD-SOI wafers to develop CCD image sensors juxtaposed with a CMOS circuit. For ToF sensors, this means perfect synchronisation between the emitter and the sensor, and therefore improved precision and resolution.

Second, it is also coherent to think that STMicroelectronics is looking to leverage its micro-mirrors technology. This is a miniature mirror (Micro-Electro-Mechanical Systems - MEMS) capable of reflecting several thousand movements a second. It can be used to direct the laser's light rays to generate the grid pattern needed to generate a 3D view of the scene filmed.

2.3. TIME OF FLIGHT – POTENTIAL BEYOND AR

Beyond augmented reality, other applications could rapidly emerge for ToF sensors. These range from improving the smartphone cameras in the short term, to medical applications that are likely to require more time before becoming tangible market opportunities.

2.3.1. AN IMPROVEMENT IN SMARTPHONE CAMERAS WITH BOKEH

The most immediate opportunity for ToF beyond AR is to add depth of field to images generated by a smartphone photo sensor. Because of their association with very compact optics, these sensors limit the reduction of depth of field available to highlight a subject.

With improved ToF sensors alongside image sensors, smartphones should be able to capture the various levels of depth in a scene. It would then be possible to precisely apply an out-of-focus (bokeh) effect to the background area while keeping the subject perfectly clear.

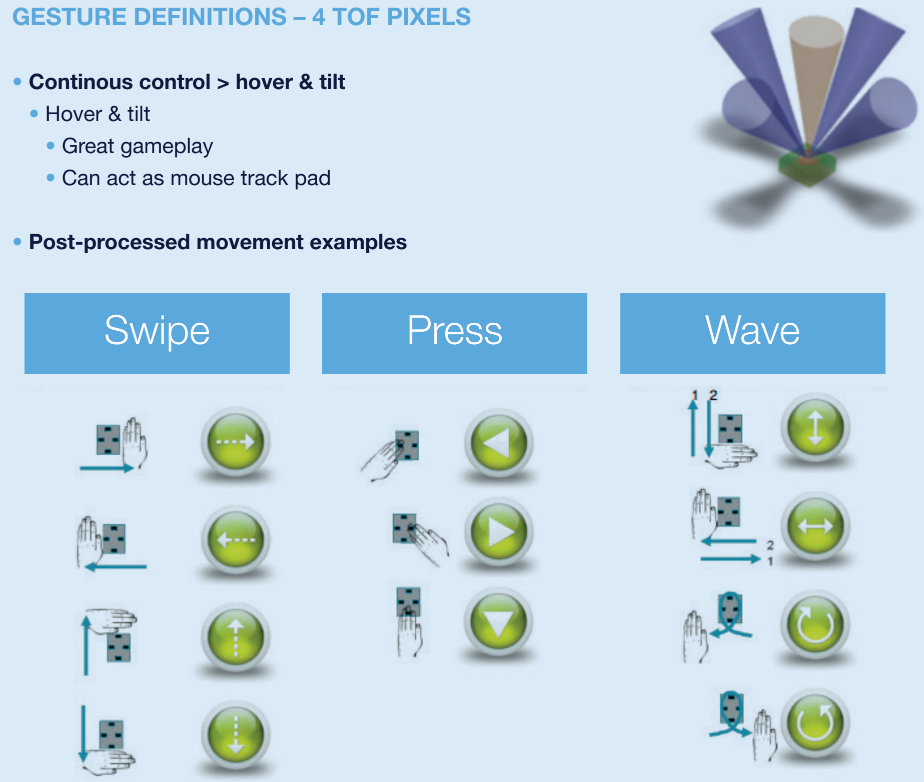
FIG. 15: DEPTH OF FIELD AND BOKEH

Source: QImaging

2.3.2. GESTURE RECOGNITION

We also note the potential for ToF technology in movement recognition. This could, for example, help control a smartphone only by movements, with no screen contact. For this type of application to work, the sensor needs to be positioned at the front of the phone.

FIG. 16: STMICROELECTRONICS EXAMPLES OF GESTURE RECOGNITION APPLICATIONS



Source : STMicroelectronics

2.3.3. MULTIPLE APPLICATIONS IN AUTO AND MEDICAL

Beyond smartphones, we see a huge field of possibilities for ToF sensor usage. They could be used in cars to control the driver's state of fatigue or the attention they pay to the road. And they could improve the performance of Lidars (distance sensors) over short distances, during parking for example. Also, because ToF sensors could help control a computer using gestures, there are potential applications in the biomedical field or even in human-machine interfaces.

FIG. 18: INDUSTRY

Source: Bosch

FIG. 17: IN-CAR GUIDANCE

Source: STMicroelectronics

3. ToF sensors: European leadership

Currently, the offering in ToF sensors is limited. Few semiconductor manufacturers have both the expertise to combine a laser and a sensor in a small package, including optical elements.

3.1. STMICROELECTRONICS

A leader in this field, STMicroelectronics was the first semiconductor manufacturer to produce ToF sensors in high volume. Its first reference product, the VL6180, has been available since 2014.

Currently, STMicroelectronics supplies ToF sensors for more than 70 smartphones. This includes the design win in the latest iPhone 7/7 Plus. We believe the group is working on an evolution of its solution with a higher resolution allowing more precise measurement and, as such rendering.

3.2. INFINEON

Infineon also develops 3D sensors under the REAL3 brand. Currently, the group focuses on the development of the light sensor but is not involved in the production of illumination solution and optical elements.

The group collaborates with PMD Tec, another German company in charge of the production of a complete ToF component. It is the solution currently embedded in the two Tango devices, the Lenovo Phab 2 Pro and the Asus ZenPhone AR.

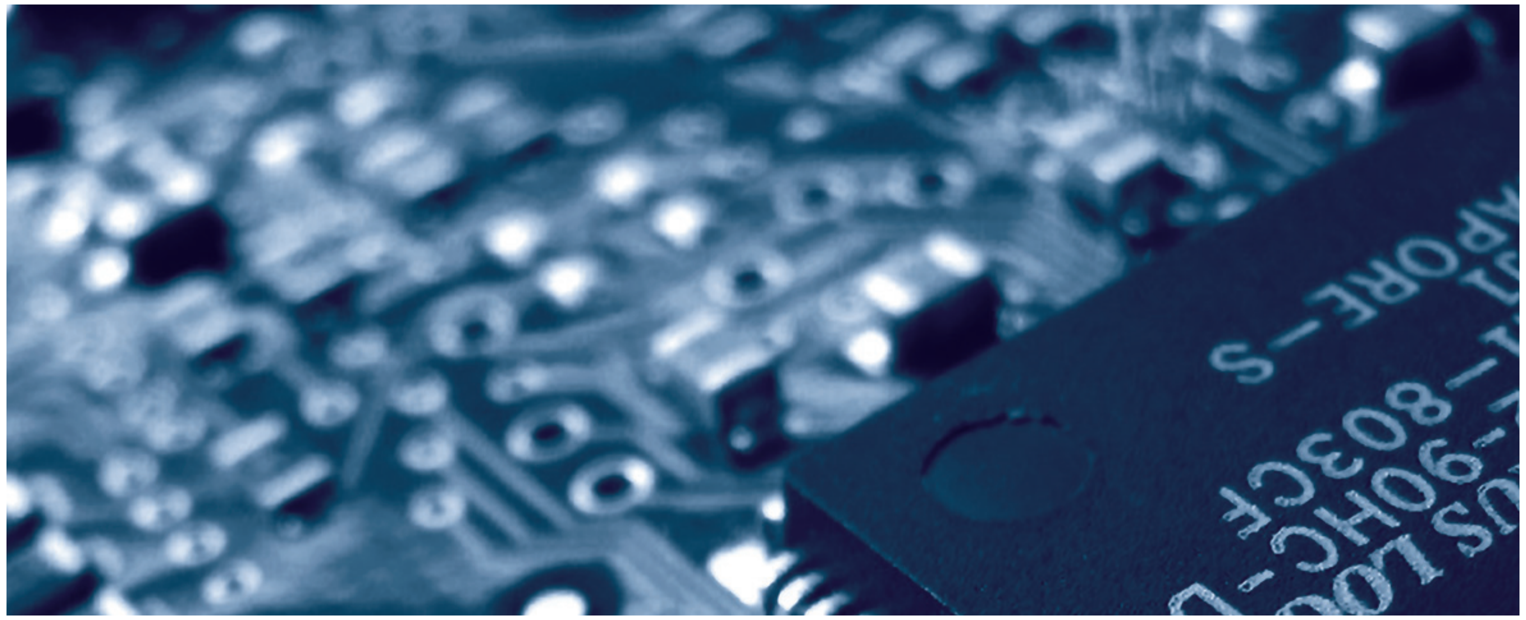
3.3. AMS

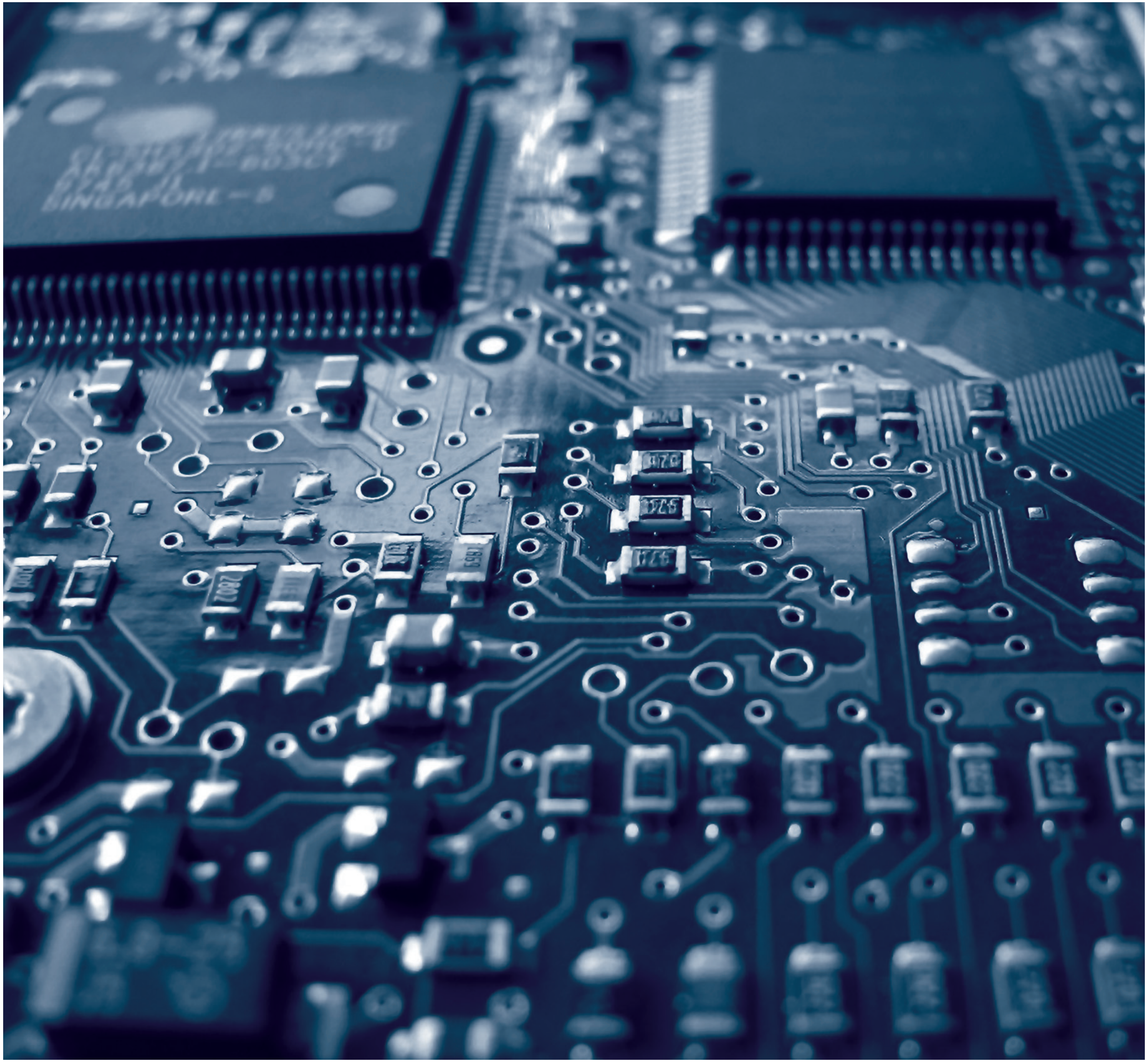
This company strengthened its ToF expertise through the acquisition of Heptagon in November 2016 and more recently Pinceton Optronics. While ams has a solid expertise with image sensors and was able to develop the sensor part of the ToF solution, Heptagon has a strong experience in manufacturing and packaging optical elements together with silicon. Additionally, the acquisition of Princeton brings to ams' portfolio the illumination.

As such, ams should be a solid player in the ToF sensors market going forward. The group already announced a successful evolution of its solutions and also said that customer interests for these components are strong. The group target consumer market first but it also enjoy a strong traction from industrial and automotive market segments.

3.4. MELEXIS

The Belgian semiconductor company has also developed a ToF sensor. Currently, this solution is used as an interface to control in-car infotainment system. Melexis ToF sensors have received a warm welcome from automotive manufacturers. BMW is already using this solution in it cars.





4. Appendices

MULTIPLES TABLES

FIG. 19: FABLESS

FABLESS (11)	MKT CAP	SALES		SALES GROWTH		EBIT MARGIN	
		FY17	FY18	FY17	FY18	FY17	FY18
Cirrus Logic	3,675	1,539	1,639	31.6%	6.5%	25.7%	24.2%
Dialog	3,148	1,377	1,558	15.0%	13.1%	19.0%	20.5%
Marvell	7,830	2,318	2,396	-15.0%	3.4%	13.8%	23.9%
MediaTek	11,639	261,017	278,415	-5.3%	6.7%	5.6%	7.5%
Melexis	2,969	511	558	12.0%	9.3%	25.0%	25.5%
Nvidia	79,661	6,910	8,251	37.9%	19.4%	28.0%	28.4%
Qorvo	8,468	3,033	3,179	16.2%	4.8%	23.3%	27.1%
Qualcomm	75,827	22,704	22,784	-3.4%	0.4%	31.6%	29.6%
Semtech	2,086	550	621	12.1%	13.0%	22.8%	27.1%
Skyworks	17,093	3,628	4,015	10.3%	10.7%	37.9%	38.9%
u-blox	1,232	431	502	19.5%	16.5%	14.5%	14.8%
Xilinx	14,225	2,349	2,494	6.1%	6.2%	29.8%	29.7%
FABLESS AVERAGE	**19,944**	**27,576**	**29,385**	**11.0%**	**9.5%**	**23.1%**	**24.6%**
FABLESS MEDIAN	**7,830**	**2,318**	**2,396**	**12.0%**	**9.3%**	**25.0%**	**25.5%**
FABLESS AGGREGATE	**219,385**			**-4.0%**	**6.6%**	**8.9%**	**10.5%**

FABLESS (11)	PERF YTD	EV/SALES		EV/EBIT		P/E	
		FY17	FY18	FY17	FY18	FY17	FY18
Cirrus Logic	14.26%	-	-	-	-	14.4x	14.2x
Dialog	1.11%	2.1x	1.8x	11.2x	8.7x	17.5x	13.9x
Marvell	25.8%	2.1x	2.9x	15.2x	12.2x	27.7x	15.8x
MediaTek	14.8%	0.9x	0.8x	16.7x	11.2x	19.4x	16.1x
Melexis	15.5%	6.1x	5.6x	24.5x	21.9x	27.5x	24.5x
Nvidia	40.5%	8.9x	8.8x	31.7x	31.1x	58.4x	48.5x
Qorvo	41.5%	3.0x	2.6x	12.9x	9.6x	16.3x	13.3x
Qualcomm	-11.8%	2.9x	2.9x	9.2x	9.9x	13.5x	14.2x
Semtech	12.7%	0.0x	0.0x	0.1x	0.1x	25.8x	19.2x
Skyworks	39.0%	4.4x	4.3x	11.6x	11.1x	16.4x	14.4x
u-blox	0.9%	2.7x	2.3x	18.3x	15.4x	27.1x	22.7x
Xilinx	6.4%	5.3x	5.7x	17.9x	19.3x	27.7x	25.8x
FABLESS AVERAGE	**14%**	**3.5x**	**3.5x**	**16.1x**	**14.1x**	**25.0x**	**20.8x**
FABLESS MEDIAN	**14%**	**2.8x**	**2.9x**	**15.9x**	**11.7x**	**25.8x**	**16.1x**

FIG. 20: LOGIC AND ANALOG INTEGRATED DEVICE MANUFACTURERS

LOGIC & ANALOG IDM (13)	MKT CAP	SALES		SALES GROWTH		EBIT MARGIN	
		FY17	FY18	FY17	FY18	FY17	FY18
ams	4,876	937	1,211	70.3%	29.3%	13.4%	22.2%
Analog Devices	26,126	5,028	5,690	47.0%	13.2%	36.6%	40.0%
Broadcom	86,952	17,603	18,866	NM	7.2%	44.5%	45.3%
Cypress	4,009	2,217	2,348	14.2%	5.9%	15.1%	19.3%
Elmos	414	246	261	7.8%	5.8%	11.2%	12.1%
Infineon	22,026	7,101	7,654	9.7%	7.8%	15.8%	16.8%
Intel	150,206	60,164	61,731	1.1%	2.6%	28.8%	29.8%
Maxim	11,785	2,303	2,403	4.9%	4.3%	32.3%	34.1%
Microchip	17,014	3,811	3,949	NM	3.6%	36.5%	37.6%
ON Semi.	5,908	5,252	5,359	34.4%	2.0%	13.9%	15.3%
Renesas	13,857	719	752	52.6%	4.6%	1.6%	1.3%
STMicroelectronics	12,719	7,871	8,479	12.9%	7.7%	10.1%	12.3%
Texas Instruments	72,091	14,330	14,828	7.2%	3.5%	38.3%	38.8%
LOGIC & ANALOG IDM AVERAGE	**31,175**	**9,330**	**9,765**	**23.2%**	**7.3%**	**23.0%**	**25.1%**
LOGIC & ANALOG IDM MEDIAN	**13,288**	**4,419**	**4,654**	**23.2%**	**7.3%**	**19.5%**	**24.6%**
LOGIC & ANALOG IDM AGGREGATE	**436,450**	**130,613**	**136,709**	**10.3%**	**4.7%**	**29.4%**	**30.8%**

LOGIC & ANALOG IDM (13)	PERF YTD	EV/SALES		EV/EBIT		P/E	
		FY17	FY18	FY17	FY18	FY17	FY18
ams	116.96%	5.3x	4.2x	39.5x	18.7x	42.2x	19.9x
Analog Devices	9.80%	6.7x	6.0x	18.4x	14.9x	18.2x	17.2x
Broadcom	37.3%	6.8x	6.3x	15.4x	13.9x	15.4x	14.2x
Cypress	19.1%	2.6x	2.5x	17.3x	12.7x	19.3x	13.3x
Elmos	44.8%	1.7x	1.6x	15.3x	13.2x	21.6x	18.7x
Infineon	17.5%	3.0x	2.8x	19.0x	16.4x	21.9x	19.6x
Intel	-1.5%	2.9x	2.8x	10.2x	9.4x	12.5x	12.0x
Maxim	21.1%	5.1x	4.8x	15.7x	14.0x	22.1x	19.7x
Microchip	29.5%	5.1x	4.7x	14.0x	12.5x	16.7x	15.5x
ON Semi.	23.3%	1.6x	1.5x	11.6x	9.6x	12.2x	10.5x
Renesas	19.8%	2.4x	2.1x	151.7x	161.5x	21.4x	19.2x
STMicroelectronics	29.6%	1.6x	1.5x	16.2x	12.4x	21.1x	16.4x
Texas Instruments	11.1%	5.7x	5.4x	14.8x	13.9x	20.6x	20.0x
LOGIC & ANALOG IDM AVERAGE	**30%**	**3.8x**	**3.5x**	**26.6x**	**23.8x**	**20.1x**	**16.4x**
LOGIC & ANALOG IDM MEDIAN	**22%**	**3.0x**	**2.8x**	**15.6x**	**13.5x**	**20.0x**	**16.8x**

SELECTED TRANSACTIONS IN THE SEMICONDUCTOR SPACE

YEAR	TARGET	DESCRIPTION	ACQUIRER	TOTAL DEAL VALUE ($B)
2016	NXP	Semiconductor manufacturer	Qualcomm	39.0
2016	Linear Technology	Integrated circuit manufacturer	Analog Devices	14.8
2016	ARM	Microprocessor IP (Intellectual Property)	Softbank	32.0
2015	SanDisk	Flash memory products manufacturer	Western Digital	19.0
2015	Altera	PLD (Programmable Logic Devices) manufacturer	Intel	16.7
2015	Broadcom	Semiconductor manufacturer	Avago	37.0
2015	Freescale	Integrated device manufacturer	NXP	11.8
2014	Spansion	Flash memory designer and manufacturer	Cypress	5.0
2013	LSI	Semiconductor and software designer	Avago	6.6

Source: IC Insights

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€ 100 000 000	Undisclosed	€ 209 000 000	Undisclosed	€ 75 400 000
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