Workshop Program, Sunday, October 20th
Room: Sumire/Tsutsuji

From Imaging to Sensing: Latest and Future Trends of CMOS Image Sensors Session Chair: **Sozo Yokogawa** (Sony Semiconductor Solutions), **Erez Tadmor** (onsemi)			
10:00-10:10	Welcome & Introduction		
10:10-10:40	Trends and Developments in State-of-the-Art CMOS Image Sensors	**Daniel McGrath** (Senior Fellow)	TechInsights
10:40-11:10	CMOS Image Sensor Technology: what we have solved, what are to be solved	**Eiichi Funatsu** (VP of Technology)	OMNIVISION
11:10-11:40	Automotive Imaging: Beyond human Vision	**Vladi Korobov** (Vice President and CTO)	onsemi
11:40-13:00	Lunch		
13:00-13:30	Recent Evolution of CMOS Image Sensor Pixel Technology	**Bumsuk Kim** (VP of Technology)	Samsung Electronics
13:30-14:00	High precision ToF image sensor and system for 3D scanning application	**Keita Yasutomi** (Associate Professor)	Shizuoka University
14:00-14:30	High-definition SPAD image sensors for computer vision applications	**Kazuhiro Morimoto** (Senior Engineer)	Canon Inc.
14:30-15:00	Coffee Break		
15:00-15:30	Single Photon Avalanche Diode Sensor Technologies for Pixel Size Shrinkage, Photon Detection Efficiency Enhancement and 3.36-pm-pitch Photon-counting Architecture	**Jun Ogi** (Senior Manager)	Sony Semiconductor Solutions Corp
15:30-16:00	SWIR Single-Photon Detection with Ge-on-Si Technology	**Neil Na** (CTO)	Artilux Inc.
16:00-16:30	From SPADs to smart sensors: ToF system innovation and AI enable endless application"	**Laurent Plaza** (ToF & ALS Product Line Mgr.) **Olivier Lemarchand** (Imaging Innovative App Mgr.)	STMicroelectronics
16:30-17:00	Depth Sensing Technologies, Cameras and Sensors for VR and AR	**Harish Venkataraman** (Depth Cameras Tech Lead)	Meta Inc.
17:00-17:10	Closure		

✓ Each talk has 25 min talk + 5 min Q&A

… invited 30-talk talk for IEEE SENSORS 2024 workshop “Trends and Developments in State-of-the-Art CMOS Image Sensors” …

Trends and Developments in State-of-the-Art CMOS Image Sensors

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Image sensor technology is still a fertile place for development. This is driven by the need to optimize the imaging function: improving responsibility and dynamic range; implementing global shutter to provide synchronous exposure; shifting emphasis to enable non-photographic applications like depth ranging. There is no longer one “killer app” across the technology or even across the application segments. This means that the direction for product specifications is more often driven by the marketing trade space as by the pushing of the technical envelope.

This can be seen in the pixel size trend where there is a stratification for the main camera on smartphones: a shrinking pixel with innovative vertical transfer gates; a growing pixel where the pixel layer is split to separate the photodiode function from the circuit function; a middle ground where multiple manufactures can play.

Technical advances in stacking are forcing a rethinking of the boundaries of the pixel. While there are still competing approaches to introduce storage functionality in the pixel, the incorporation of the MIMcap is an enabler for voltage-domain global shutter and high dynamic range. Combined with the shrinking wafer-to-wafer contact pitch, these can be moved into the image signal processing layer moving the pixel boundary beyond the traditional layer.

While there is a general agreement that increasing responsivity through the advancing of backside processing in the form of backside dielectrics, deep trench isolation and inter-pixel grid formation, there is not a consensus on the process details in implementing these to provide imaging for applications such as ranging and in-cabin operation in the automotive space.

In this presentation these topics will be explored through the lens of reverse engineering, addressing both current results and trends over time.

CMOS Image Sensor Technology:
what we have solved, what are to be solved

Eiichi Funatsu
VP of Technology, Office of the CTO, OMNIVISION, Santa Clara, CA, USA
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Abstract — Nowadays, CMOS Image Sensors (CIS) are used everywhere in many applications including mobile phone, digital still camera, camcorder, security camera, automotive, gaming, etc. Competing with the other image sensor technology, charge-coupled device (CCD), R&D activities of the current CIS were accelerated by the correlated double sampling (CDS) architecture proposed by Eric R. Fossum in 1993. After that, we saw a journey of extensive breakthrough innovations that has led to the current status. This talk will review those innovations from the view point of consumer product application.

CIS was first applied to volume products in late 1990s in toy cameras, PC cameras, etc. The new concept product, camera phone, was realized with CIS in year 2000. Until that stage, CIS was used only in the applications that aimed at low power or low cost, compromising image quality. The following 12 years were the time to establish the base technology of the modern CIS with multiple innovations: first CIS exceeding CCD image quality in mobile phone market (2005), current defacto standard column analog-to-digital converter (ADC) architecture for high speed low power (2006), back-side illumination (BSI) technology for higher sensitivity (2009) and stack technology for higher functionality (2012). After further continuous innovations, the highest resolution CIS in the market is now 200 mega pixels with 0.56 um pixel size.

Resolution was not only one driving force. After 2010, people started pursuing additional on-sensor functions to enhance total camera system performance. Phase detection auto focus (PDAF) and high dynamic range (HDR) are the key competition items still on-going in the category of human vision applications such as digital still camera, camcorder and mobile phone. HDR is also important for security and viewing part of automotive. In these applications, the appearance to human eyes is the improvement point. The other category is machine vision applications in which the image data is not seen by people but used for some recognition or decision by a machine vision system. Global shutter is a major technology for tracking application. Always-on function is key for battery operated cameras in security, mobile phone, PC, etc. Time of flight is used for depth detection in gaming and mobile phone and under development to be used in automotive application.

For each of the innovation, there was some reason for being accepted as a volume product. Sometimes, there was some other reason from the developer's point of view. This talk will also touch upon the thought process behind the scene. The innovation items shown above are not finalized yet. There is more room for innovation. Whenever image sensor is improved, each of the application comes up with new demands. Image sensor side is also working on more challenges in new technology development to create new applications, for example, event vision sensor, on-sensor artificial intelligence, etc. For the future direction, we know what to do and are making efforts for some parts. However, for some parts, we still have no idea. Future of CIS is bright. That is because we have not done everything. And because we need more innovations and new ideas.

Automotive Imaging: Beyond human Vision

Vladi Korobov

Vice President and CTO, onsemi, San Jose, CA, USA

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In this talk, we will discuss the applications and challenges of image sensors in the automotive space. The three primary implementations are advanced driver-assistance systems (ADAS), surround-view, and driver-monitoring systems (DMS). Most ADAS and vision systems are moving to two 8MP frontside sensors, four 3MP rearview cameras, and four 1-3MP surroundview sensors, which require superior low-light performance. Autonomous driving and parking assistance are currently in the initial stages but are anticipated to undergo extensive development in the coming years.

Automotive sensors must use LED flicker mitigation (LFM) methods and have high total dynamic range (HDR) of 130+ dB and long single exposures (SE) to be truly flicker-free (FF)[1]. HDR sensors can simultaneously capture the bright scenes and details in low light often present in automotive environments. A 110 dB dynamic range is needed to avoid saturation in normal scenes, but 130 dB to 150 dB is desired for brighter lights and sunlit scenes [2]. The sensor's dynamic range is constrained by the minimum SNR, which must be at least 25 dB so the noise doesn't obstruct the object [3]. In addition, ADAS and surround-view cameras must employ LFM methods to combat LED flickering. A 90 Hz LED pulse-width modulation frequency is very common and requires an exposure time of >11 msec to average over a full modulation cycle and avoid artifacts. This extended integration time may be achieved using an approach such as pulsing demonstrated in [4].

Several approaches may be used to increase the dynamic range. The multi-exposure method, which combines multiple images, is a well-established approach reaching 140 dB. However, LED flickering and motion artifacts (ghost images) may be present due to the sequential exposures used for the final image [5]. Split-pixels have photodiodes of varying sizes and thus different sensitivities to achieve sufficient low-light and high-light performance concurrently. Nevertheless, the different spectral responses of the two photodiode types affect the low-light performance, the unavoidable crosstalk causes color reproduction issues, and increasing the optical ratio decreases the minimum SNR [6]. Overflow pixels have an in-pixel charge storage element that extends the full-well capacity, yielding SE high dynamic range [7]. The primary challenges are related to reduced speed because the pixel is read more than one time. We thus propose a 2.1 um overflow pixel with 150 dB dynamic range to meet the requirements of ADAS and surround-view cameras [2].

The third application for sensors in the automotive space is in-cabin DMS, which use sensors to monitor the driver's behavior and alter the safety settings accordingly. Time-of-flight (ToF) technology may be used to create a 3D map of the cabin. Overall, however, it is beneficial to use global shutter pixels that are concurrently capable of depth sensing [8].

In conclusion, the automotive image sensor market requires a wide portfolio of solutions to improve driving safety. We reviewed some of the existing solutions available by onsemi and others and discussed their merits, challenges, and future trends.

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Recent Evolution of CMOS Image Sensor Pixel Technology

Bumsuk Kim, Hyuncheol Kim, Hye Yeon Park, DongHyun Kim, Jonghoon Park, Kyungho Lee
System LSI Division, Samsung Electronics, Hwaseong-si, Gyeonggi-do, Republic of Korea

The image sensor has evolved from its initial purpose of recording light by replacing film to pursuing image quality similar to that of the human eye by increasing resolution and performance. As it gradually evolved into a data and information collection device, it has expanded to various applications, not only cameras, but also automobiles and robots.

Over the past 20 years, pixel size has been reduced by a factor of 1/10 and pixel area by a factor of 1/100 to increase resolution. As a result, technological innovations have been made to improve pixel performance. The dominant factors affecting pixel performance vary depending on the ambient light conditions, with noise and sensitivity being important in extreme low light (<1 lux), sensitivity and crosstalk in low light (1 lux ~ 100 lux) regions, and full well capacity (FWC) and crosstalk in high light regions.

To simultaneously ensure sensitivity and crosstalk, the pixel structure has evolved into the combination of BSI and FDTI structures, and technologies have been developed to ensure an equivalent or higher FWC even with smaller pixel sizes. The advantages of the FDTI structure have made it possible to increase the PD capacitance per unit area. Furthermore, in order to implement PDAF pixel such as dual pixel and quad pixel in FDTI, a novel pixel structure that shares individual PDs was devised. The inner DTI structure, called DTI center-cut (DCC), can secure high FWC without nonlinearity. In addition, the DCC structure enables FD merging, reducing FD capacitance and achieving 2.5 times larger maximum conversion gain and dark random noise of sub 1.0e-. It also helped improve sensitivity by removing DTI from the microlens focusing part.

In the FDTI pixel structure, the vertical transfer gate (VTG), which allows easy transfer of PD electrons in the deep bulk region, has evolved into a dual VTG structure, enabling FWC of 10ke- in 0.6um FDTI pixels. In order to overcome the size limitations of the SF transistors, a quarter-ring structure or 3D bending SF was introduced to effectively improve RTS noise and temporal noise.

The direction of increasing the pixel's FWC and reducing RN ultimately leads to an increase in dynamic range. The dynamic range per unit area of the FDTI pixel is secured at over 80 dB and is constantly challenging higher limits.

Technologies have been developed to maximize sensitivity while maintaining crosstalk in FDTI-based fine pixels. The low RI optical grid, which replaced the metal grid, significantly reduced optical loss around the color filter, improving sensitivity. And by compressing the optical system using microlenses made of high-refractive materials and thin color filter technology, performance sacrifices in small pixels were reduced.

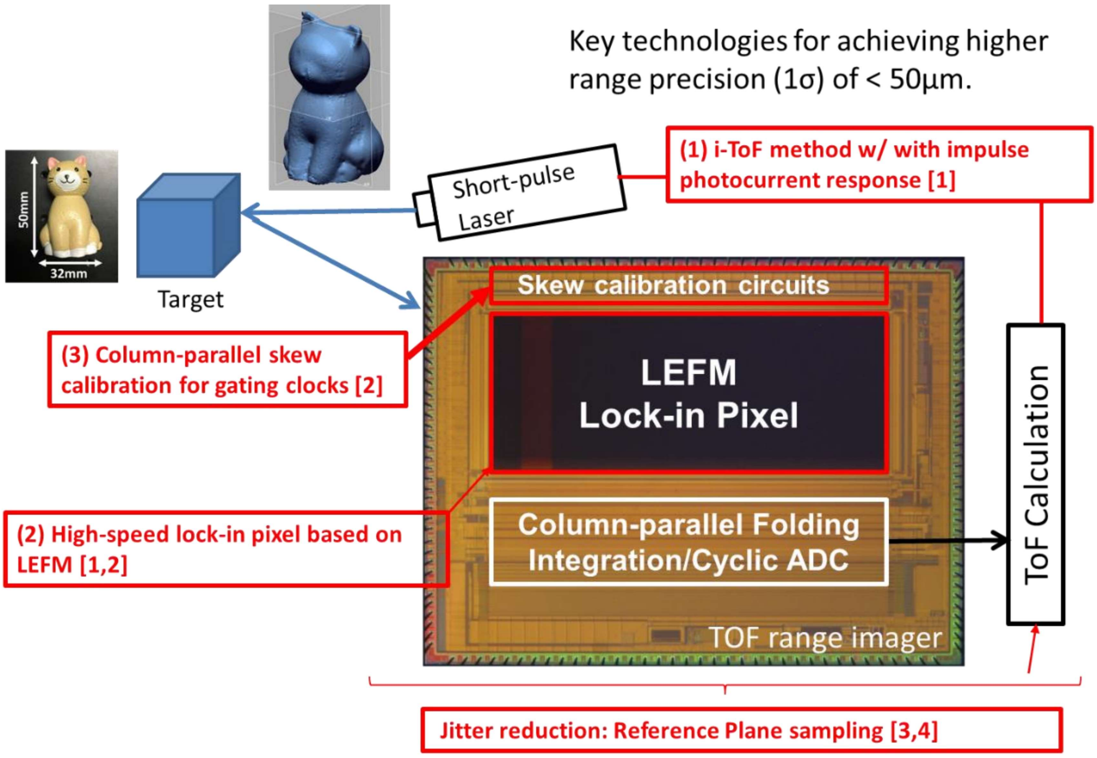
To fundamentally overcome the limitations of pixel optical performance, a novel technology has been developed to control the optical path for each wavelength with a high-refractive nano-photonics structure. The NanoPrism technology based on nano-photonics attracts light from neighboring different color pixels, increasing the effective pixel size and improving the sensor's light efficiency by 30%.

In summary, an FDTI-based DCC structure was developed to reduce dark temporal noise while securing high pixel FWC, which is suitable for high-resolution CIS with fine pixels. To improve low-light image quality, we have developed techniques to reduce optical loss and optical compression techniques using high-refractive materials. As pixel technology approaches its limitations, nano-photonics technology such as NanoPrism can be an alternative that transcends the limitations.

High precision ToF image sensor and system for 3D scanning application.

Keita Yasutomi, Shizuoka University
Email: yasutomi.keita@shizuoka.ac.jp

This talk discusses a time-of-flight range imager and system that enables high range precision of <50 µm. The key technologies include an indirect ToF measurement technique with an impulse photocurrent response, a high-speed lock-in pixel based on a lateral electric field charge modulator, and skew calibration of the gating clocks between the pixels. In addition, jitter reduction techniques for both the light trigger and gating clock, which are important for achieving higher range precision of <100 µm, are also introduced.



Reference

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Title: High-definition SPAD image sensors for computer vision applications

Author: Kazuhiro Morimoto (Canon Inc.)

Abstract:

In computer vision applications, concept of sensor fusion relies on integration of multiple cameras and sensors monitoring different physical parameters to achieve robust perception and recognition. Fusing output of those cameras and sensors suffers from mismatched field-of-view and frame timing. Spatial and temporal image alignment is necessary to avoid the impact of those mismatches, whereby complex post-processing increases computational cost and latency. Recently, monocular implementation of a novel image sensor with multiple sensing modalities has been investigated to eliminate the image alignment process.

We present a 5μm-pitch, 3D-backilluminated 1 megapixel time-gated single-photon avalanche diode (SPAD) image sensor with 2D interactive gating network. The newly developed SPAD image sensor enables multiple sensing modalities in a monocular configuration. 2D global shutter imaging with zero parasitic light sensitivity is achieved at 1,310fps with 4bit depth readout. Combining with a dedicated post-processing realizes event-based vision sensing with 0.76ms temporal resolution under scene illuminance as low as 0.02lux. Synchronous operation with laser pulse emission ensures range gated imaging, where the camera can selectively capture target objects that are located within a specific distance range. For extended capability for outdoor sensing, 2D interactive gating network architecture, in conjunction with 1.85ns minimum gate length, provides a unique solution for strong ambient light suppression based on full-resolution coincidence detection. The proposed SPAD image sensor is promising for image alignment-free sensor fusion in computer vision applications, covering from extremely low light to daylight scenarios.

Single Photon Avalanche Diode Sensor Technologies for Pixel Size Shrinkage, Photon Detection Efficiency Enhancement and 3.36-µm-pitch Photon-counting Architecture

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I. Introduction

Single photon avalanche diode (SPAD) pixels have been developed for time of flight (ToF) image sensors [1] and photon-counting image sensors [2] through the exploitation of their single photon sensitivity and sub-nanosecond-level timing resolution. Recently, back-illuminated SPAD stacked with a pixel- front-end (PFE) circuit via Cu–Cu connection has been proposed, which allows the SPAD pixel fill factor and photon detection efficiency (PDE) to be increased by reducing the SPAD pixel size and integrating more advanced PFE circuits.

II. Pixel size shrinkage

S. Shimada and Y. Fujisaki have attempted to decrease the SPAD pixel size to 6 [3], 3, and 2.5 µm [4] while enhancing the PDE [5]. The peak PDE was increased to 82.5 %, the PDE at a wavelength of 940 nm exceeded 26.5 %, and the dark count rate (DCR) was 2.2 cps at room temperature under 3.3 µm pixels and 3 V of excess bias. The high PDE was achieved by implementing a gapless on-chip lens (OCL) and a pyramid surface for diffraction (PSD) structure. The sufficiently low DCR was achieved by optimizing the multiplication layout design to increase avalanche guard ring width (Fig.1 (a) and (b)). The small SPAD improve the robustness of depth sensing against ambient light by decreasing the count loss under a high incident optical power.

III. PDE enhancement

The PDE at a wavelength of 940 nm was further enhanced to 36.5 % for a 6-µm-pitch pixel by implementing a shallow trench for diffraction (STD) on the front side of Si surface, a 2 × 2 OCL, an optimized PSD, and optimized FTI (Fig. 1(c)) [5]. The optimized PSD and STD can increase the optical path in the SPAD pixel. The 2 × 2 OCL enhances the effect of the STD as its layout is highly compatible with the STD layout. The optimized FTI can reduce light absorption on the FTI interface, thus enhancing the PDE by more than 5 %.

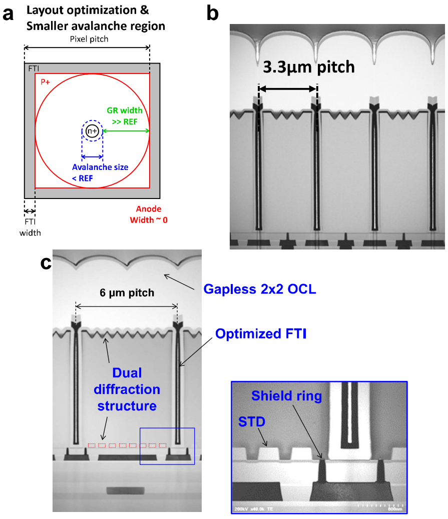

Fig. 1 (a) Concept of the layout optimization less than 3.3-µm-pitch pixel and (b) the fabricated SPAD pixel. (c) Fabricated SPAD pixel with the PDE enhancement technologies.

IV. High-resolution photon counting

High-resolution and high-dynamic-range (DR) photon-counting image sensors have been reported by reducing the SPAD pixel size and power consumption. T. Takatsuka reduced the pixel pitch to 3.36 µm using only an 8-bit in-pixel counter by employing clustered multicycle clocked recharging (CMCR), intermediate most-significant-bit read out (MSB-Read), and amplitude limitation achieved using a clipping transistor (Fig. 2) [6]. The CMCR can limit the maximum number of counting photons with nonlinear counting response, thus increasing the DR while reducing power consumption. The MSB-Read expands the counter bit by detecting the number of in-pixel counter saturation and then storing the number in the SRAM outside the pixel array. This can increase the signal to noise ration (SNR) to more than 30 dB under bright light. The clipping transistor limits the amplitude to less than 0.8 V by maintaining the SPAD bias voltage at approximately 3 V. Most PFE circuits can be constructed using low-voltage transistors with the amplitude limitation and a minimized circuit area via the 22-nm-node logic process. The 3.36-µm-pitch photon-counting image sensor indicated a 120-dB DR under a frame rate of 150 fps as well as 104 mW of power consumption under a frame rate of 60 fps.

V. Conclusion

3 - 6 µm pitch SPAD pixels have been reported with the high PDE and a low DCR. Additionally, the 3.36-µm-pitch photon-counting image sensor has been achieved with competitive characteristics.

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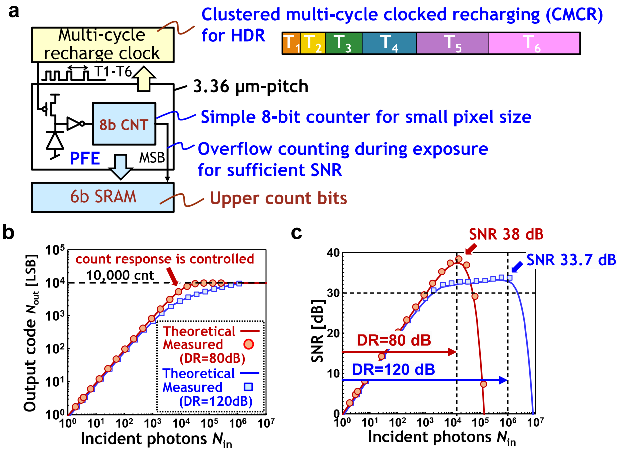


Fig. 3. (a) Concept of the 3.36-µm-pitch photon counting image sensor and measurement results of (b) counting response and (c) SNR.

SWIR Single-Photon Detection with Ge-on-Si Technology

Abstract: Ge-based photoreceivers, widely applied in Si photonics for high-speed optical communication, have recently adventured into the territory of shortwave infrared (SWIR) sensing and imaging with active light source. Here, I review the history and key milestones including the recent demonstrations of SWIR lock-in detection with Ge-in-Si and SWIR single-photon detection with Ge-on-Si, all at room temperature.

Neil Na, PhD

CTO, Artilux Inc.

From SPADs to Smart Sensors: ToF System Innovation and AI Enable Endless Applications

As reliance on sensing for various applications grows, Time-of-Flight (ToF) systems have become increasingly essential in overcoming related challenges. This sector has experienced significant advancements, contributing to a broad range of applications, and transforming how we interact with the environment.

In this talk, we will present advancements in system development optimization for direct Time-of-Flight (ToF) technology. Our discussion will cover a range of topics, including 3DSPAD technology, system optimization such as embedded high voltage generation, illumination type and dimension, meta-surface optics, and artificial intelligence (AI) processing.

These advancements are supported by ST's capability to co-design complete system solutions tailored for ultra high-volume production, alongside a truly unique and comprehensive ecosystem for AI products. This ecosystem facilitates the creation of easy-to-develop applications based on analytic or compact AI/classifier processing of ST's direct ToF multimodal output information.

All of this is achieved with a commitment to sustainability, creating new use cases and optimizing power consumption. Examples include Human Presence Detection, enhancing user experiences with Head Orientation and Hand Gesture Recognition, Floor Material Sensing for robotics, and enabling groundbreaking applications such as an Air Quality Index (AQI) monitoring solution developed in partnership with an external company.

Laurent Plaza

ToF & ALS Product Line Mgr. | Imaging sub-group, STMicroelectronics

Laurent Plaza leads STMicroelectronics' Time-of-Flight (ToF) and Ambient Light Sensing Product Line, overseeing product portfolios for the Personal Electronics and Industrial segments. With over 24 years of experience in the Imaging industry, Laurent has been a key contributor to the creation and expansion of ST FlightSense products, including SPAD-based dToF and fast-photodiode iToF systems. These technologies have been integrated into over 220 phones, 200 laptops, and numerous other devices, positioning STMicroelectronics as the world's leading ToF supplier with over 2 billion units shipped.

Laurent holds a Master's degree in Microelectronics & Robotics from Ecole Polytechnique Universitaire de Montpellier. Early in his career, he developed an AI-based face identification system before transitioning to roles in Imaging products application and marketing. He successfully launched the CIS die business in Taiwan and worked on cutting-edge Image Signal Processors (ISP) and RGB cameras, including large pixel high dynamic range sensors. Laurent has since driven the ToF product line, working closely with R&D teams to develop groundbreaking products and innovative use-cases.

Olivier Lemarchand

Imaging Innovative Application Manager | Imaging sub-group, STMicroelectronics

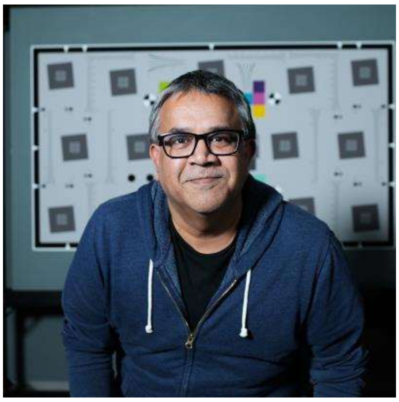
Olivier Lemarchand spearheaded the development of AI-driven turnkey solutions at STMicroelectronics, revolutionizing Time-of-Flight sensors into intelligent sensors for end customers. With over 20 years of experience in the imaging industry, Olivier pioneered the Human Presence Detection solution for the Personal Computer market. His innovative use of STMicroelectronics' low-resolution dToF sensors has established the company as the global leader in this field.

Olivier holds an engineering degree in Electronics and Telecommunication from ENSEIRB-MATMECA in Bordeaux, France. Early in his career, he specialized in developing image processing algorithms for cameras. He then transitioned to deploying cutting-edge solutions with dToF sensors, including Human Presence Detection, Hand Gesture Detection, Human Head Orientation, and Body Posture Detection, all powered by Artificial Intelligence.

Depth Sensing Technologies, Cameras and Sensors for VR and AR

Harish Venkataraman

Depth Cameras Tech Lead, Reality Labs, Meta Inc.



Short Bio: — Harish holds multiple degrees in the fields of physics, computer science and engineering. Beginning at Texas Instruments, he advanced to Director of Design in the High Volume Linear Org where his team led sensor designs in the field of Touch Sensing for consumer electronics. Transitioning to Apple in 2014, he contributed significantly to the development of inertial sensors before switching gears and joining the Camera Team. Over the next 6 years, he specialized in the field of 2D and 3D Cameras as a key contributor to features like Face ID and the Lidar Scanner for iPhones. Currently, Harish serves as Depth Cameras Tech Lead at Meta Inc. focusing on identifying and integrating depth sensing technologies for AR and VR applications.

Content Framework:

- Introduction to Depth Sensing
- Tree of Light (Intro to technologies)
- Passive Stereo
- Active Stereo
- Camera & Image Sensor requirements for Stereo
- Structured Light
- Improved Structured Light
- Camera & Image Sensor Requirements for Structured Light
- Indirect Time of Flight
- Camera & Image Sensor Requirements for iToF
- Direct Time of Flight
- SPAD sensor as a detector
- Depth Technologies Example Applications
- What do Depth and RGB Cameras enable in AR and VR Applications
- Summary