3D Imaging & Sensing
From enhanced photography to an enabling technology for AR and VR

February 2020
YOLE DEVELOPPEMENT

3 domains of expertise

**Photonics & Sensing**
- Photonics
- Lighting
- Imaging
- Sensing & Actuating
- Display

**Semiconductor & Software**
- Semiconductor Packaging and Substrates
- Semiconductor Manufacturing
- Memory
- Computing and Software

**Power & Wireless**
- RF Devices & Technologies
- Compound Semiconductors & Emerging Materials
- Power Electronics
- Batteries & Energy Management

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1. Application trend 4-16 – 15min
2. Market forecast 17-21 – 8min
3. Company ecosystem 22-26 – 8min
4. Technology trend 27-31 – 8min
I - Application trend
WHAT ARE WE TALKING ABOUT?

From imaging to sensing

- **Imaging**
  - Stereo images
  - 360° images
  - Image processing/enhancement
  - Holographic images

- **Sensing**
  - Facial recognition in mobile
  - Mapping in GIS
  - Detection in automotive
  - ADAS in automotive
  - Detection in AR/VR
  - Obstacle avoidance in drone
  - Object recognition in industrial
  - People counting in surveillance

3D imaging for display and 3D sensing for recognition/detection.
3D imaging & sensing cover a wide range of modality.

<table>
<thead>
<tr>
<th>Modality</th>
<th>3D sensor type</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Ray CT</td>
<td>CT scanner, flat panel CT, cone beam CT</td>
</tr>
<tr>
<td>Optical 3D</td>
<td>Structure from motion, stereo cameras, projection based cameras, time of flight cameras</td>
</tr>
<tr>
<td>Optical CT</td>
<td>Spectral domain OCT, swept source OCT</td>
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<tr>
<td>Lidar</td>
<td>Lidar, solid state Lidar, MEMS Lidar, Flash Lidar</td>
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<tr>
<td>Radar</td>
<td>Synthetic aperture radars</td>
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<tr>
<td>Ultrasound</td>
<td>Phased arrays</td>
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Covered by this presentation
USE OF MACHINE VISION TECHNOLOGY

Vision sensing technology is transforming all markets

Image generation is less often intended for human usage.
Machines have a greater requirement for sensory input for autonomy & interaction.
3D imagers & sensors are a key part of this technology revolution.

Robotics and immersive technologies are transforming the imaging landscape.
WHAT ARE WE TALKING ABOUT?

3D imaging & sensing from sub-components to camera modules

Minimum resolution for imaging
50 pixel x 50 pixel arrays

Analysis from component point of view.

VCSEL
Emitter
Receiver
Sensor array
Lens
Camera module
Semiconductor & Other Sub-components

Semiconductor level
Module level
Assembly
Systems

Wafers & raw material

Courtesy of Sony

Courtesy of Sunny Optical

Courtesy of OPPO

Courtesy of Sony Optical

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Structured Light approach has been chosen as a starting point for the 3D imaging era. The front 3D module could evolve toward ToF technology in the future, showing more reliability in direct sunlight and lower computational requirements.

ToF technology is used in REAR side in 2019 for photograph enhance. It developed more applications such like AR game, 3D measurement etc.. It has some advantage such like longer work distance, smaller size and less cost etc., it will grow fast and eventually will encroach the mobile 3D market more in future.
MOBILE MARKET TREND

Proliferation of cameras in mobile - historical

**Smartphones:** Main camera size stops shrinking, and a front-facing camera is added

**Dual & Triple rear:** improved photography zoom and wide angle lenses

**Camera phones:** Innovation from Sharp in June 2000

- 1st camera: 20 x 10mm², $20
- 2nd camera: 10 x 10mm², $10
- 3rd camera: 5 x 5mm², $5
- 4th camera: 1 x 1mm², $1

The “selfie trend”: front-facing camera size increases

**Sensing module:** 3D front & rear – under display FP

**Market size**

- Rear camera modules: $20B
- Front camera module: $10B
- Sensing module: $5B
- Yole Développement © Oct. 2019

Yole Développement © Oct. 2019

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Mobile drivers are sometime pulling in different directions.

MOBILE MARKET TREND
CMOS image sensor - market drivers

3 Drivers

Image quality
Leading smartphone cameras are expected to deliver « DSLR-like » image quality
→ Indoor and nighttime conditions
→ High-resolution photography and video (4k)
→ High-speed AF and OIS
→ Zoom capability
→ Slow motion

User interface
Beyond the touchscreen, smartphone makers want to improve the user experience:
→ Removal of the physical button
→ Biometric unlocking (3D sensing or underdisplay fingerprint cameras)
→ Virtual reality interactions

Aesthetics
Thin form-factor and borderless screens have become mandatory
→ Lower F# optics (high CRA)
→ Multiple camera approaches
→ Front-side camera conundrum

Mobile drivers are sometime pulling in different directions.
MOBILE MARKET TREND
CMOS image sensor - market drivers

Mobile drivers are sometime pulling in different directions.

- Image quality
- User interface
- Aesthetics

Proliferation of cameras
3D sensing & biometry
Edge to edge displays visible attribute

Front 3D ✓
Rear 3D

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Mobile 3D Camera Implementations

Use-cases and opportunities for the **front** 3D camera:

- **Easy unlocking**
- **Security** (Facial recognition)
- **Morphing** (Augmented reality)
- **Gaming** (Avatar)
- **Enhanced video call**
- **Holographic displays**

Use-cases and opportunities for the **rear** 3D camera:

- **Better photography**
- **Augmented reality**
- **Gaming**
- **Commercial**
- **3D print**
- **Other?**

Market is expending thanks to Apple

Market had a good start with Huawei

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MOBILE APPLICATION – FRONT 3D IMAGING & SENSING
Password to facial payment（1/3）

Evolution of payments.

Password payment

Fingerprint payment

With 3D imaging and sensing, the payment can use facial recognition to replace the password and fingerprint.

Facial recognition payment
✓ Easy use
✓ Most security
✓ Non-contact

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MOBILE APPLICATION – FRONT 3D IMAGING & SENSING

From animoji to morphing  (2/3)

Whatever animoji or morphing, it relies on the 3D imaging.

With 3D sensing, facial expression is uploaded to the app and then itself modified using a digital avatar.

This has significant implications on Vblog, video call and video app, enhance the video effect.

Note: The 3D module is used to make the original calibration then the tracking of the face is done through the 2D camera. The 3D module is too power consuming to be used to track the face all the time.
Photography enhance is a key applications for rear 3D in the phone.

MOBILE APPLICATION – REAR 3D IMAGING & SENSING

Body/Face shaper

Bokeh

Image render
MOBILE APPLICATION – REAR 3D IMAGING & SENSING

3D commercial applications are everywhere.

- EC site buyer
- Cloth fitting
- AR Advertisement
- City navigation
- Object measurement
2 – Market Forecast
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3D Sensing and Imaging - 2019-2025 Market Forecast (in $M)

2019

$5B

Defense & aerospace
- $259M (5%)
- $1,041M (21%)

Industrial
- $877M (17%)

Medical
- $854M (17%)

Automotive
- $2,017M (40%)

Mobile & consumer
- $2,017M (40%)

$2,017M (40%)

CAGR2019-2025
+20%

$334M (2%)

$1,197M (8%)

$1,710M (11%)

$3,673M (25%)

$8,165M (54%)

2025

$15B

3D Imaging & Sensing is still a major consumer application.
MOBILE MARKET TREND

3D camera adoption scenario

The original adoption scenario was coined on similar smartphone hardware adoption curves (FP, IMU combos)

In 2017 Apple started to attach a front 3D camera for face unlock

In 2019 Huawei switched the adoption from the front to the rear

Overall the 3D sensing forecast remains more or less on track, the ratios rear and front are totally reversed.

2015-2025 Penetration scenario of 3D cameras in Smartphones (in %)

- All 3D Forecast 2019
- Front 3D camera
- Rear 3D camera
- Front 3D 2018 Forecast
- Rear 3D 2018 Forecast
From OPPO, Vivo, Huawei and then Samsung, Android makers quickly adopted ToF as its 3D rear camera, and the volume and revenue increased accordingly. Yole expect that ToF will surpass structured light in the next 1-2 years.

Rear 3D camera is rise rapidly.
MARKET & TECHNOLOGY ROADMAP

**FRONT**
- **2018**
  - Volume: 67 Mu
  - Technology: Structured Light

- **2019**
  - Volume: 93 Mu
  - Technology: QD Structured Light

- **2020**
  - Volume: 136 Mu
  - Technology: Indirect Time of Flight

- **2021**
  - Volume: 194 Mu
  - Technology: Direct Time of Flight

- **2022**
  - Volume: 238 Mu
  - Technology: Under display 3D ToF

**REAR**
- **2018**
  - Volume: 2 Mu
  - Technology: Structured Light

- **2019**
  - Volume: 71 Mu
  - Technology: Indirect Time of Flight

- **2020**
  - Volume: 175 Mu
  - Technology: QD Structured light

- **2021**
  - Volume: 356 Mu
  - Technology: Direct Time of Flight

- **2022**
  - Volume: 466 Mu
  - Technology: Under display 3D ToF

Rear 3D technology did start with ToF while Front 3D technology will transition to ToF.

3D sensing volume reaches 50% of mobile volume in 2022.

Front 3D would represent 1/6 of mobile volume.
Rear 3D would represent 1/3 of mobile volume.

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3 – Company Ecosystem
STM and Sony are sharing the market in almost equal proportions.

- ST Microelectronics has been Apple’s NIR sensor supplier since 2017, it’s big winner in the structure light market of mobile phone but it’s highly rely on it.
- Sony is supplying the ToF sensor to Android-based smartphone and quickly gained a large market share in 2019, it’s highly involved in Huawei and Samsung mobile supply chain and this relation is expected to continue.
- OVT got several design-win from Android comp. such like OPPO and Huawei for the structure light, however, due to these players are stagnant later in 2019, it’s growing slowly.
3D sensing is changing the ranking in the VCSEL market.

- AMS (Princeton Optronics) has been highly involved in Android-based smartphones and this trend is expected to continue in 2020.

- Finisar has been qualified by Apple and should grab some market share from Lumentum with the manufacture of VCSEL for the Face ID module. Moreover, II-VI is expected to be qualified by Android-based smartphone manufacturers, giving it the opportunity to enter the consumer market.

- Trumpf is highly involved in STMicroelectronics’ supply chain and this relation is expected to continue. Some design wins with Android-based smartphone manufacturers should complete its activity in the consumer market.
Structured Light

Emitter/VCSEL/Diffractive grating

Receiver/CIS Die

Module Maker

Apple iPhone Xs, Xr

Xiaomi Mi 8 Released May 2018.

Oppo Find X Released July 18, 2018.

Huawei Mate 20 Pro Released November 2018

Lumentum

Amur

Si augmented

Sharp

Foxconn

LG Innotek

Finisar

OmniVision

Sunny Optical Technology

LUX Visions

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3D Imaging and Sensing - Supply Chains

ToF
- Emitter/VCSEL
- Receiver/ToF Die
- Module Maker

Manufacturer
- Oppo R17 Pro
  - Released Aug 2018
- Vivo NEX Dual Display
  - Released Dec 2018
- LG G8 ThinQ
  - Released April 2019
- Samsung
  - Note 10+
    - Released Aug 2019
  - Huawei Mate 30 Pro
    - Released Oct 2019

Other Companies
- Lumentum
- ViaVI
- Sony
- Sunny Optical Technology
- Amur
- Panasonic
- OFL
- Infineon
- LG Innotek
- Trumpf
- Philips
- Vertilite
- Lux Visions

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4 – Technology trend
PIXEL SIZE ROADMAP

Pixels are shrinking with time

Depending on the technology, the potential for pixel shrink varies.

Hiding large digital part below the sensitive part of the pixel gives great size reduction potential

Direct ToF arrays will address lidar first

Indirect ToF arrays entry in mobile thanks to BSI technique

Quantum Dots Global Shutter could enter in size or cost critical applications
Sensitivity in the near-infrared spectrum is key for active imaging. The quantum dot option could help shrink current approaches.

Quantum dot and similar organic approaches

In February 2017 Invisage released a 1.1um GS sensor

Panasonic has developed a similar technology called OPF

Acquired in Nov. 2017
Apple notch halved or under display?

3D structured light approach will shrink down

All players remain, but silicon content may shrink
Wild guess roadmap

2018:
End of 2017: Apple introduces SL sensor on the front with great success

2019:
Huawei and Samsung introduce rear ToF sensor with great success

2020:
Apple is expected to refresh front SL and introduce rear ToF

2021:
Rear direct ToF introduction (Huawei?)

2022:
Front underdisplay ToF (LG?)

2024:
Next big hardware overall for Apple

2024e:
MOBILE 3D IMAGING & SENSING MARKET
Thank you
This presentation is based on 2 recently published Yole reports

3D Imaging & Sensing 2020

Status of the CIS Industry 2019
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- Semiconductor Packaging and Substrates
- Semiconductor Manufacturing
- Memory
- Computing and Software

**Photonics & Sensing**
- Photonics
- Lighting
- Imaging
- Sensing & Actuating
- Display

**Power & Wireless**
- RF Devices & Technologies
- Compound Semiconductors & Emerging Materials
- Power Electronics
- Batteries & Energy Management
4 BUSINESS MODELS

- **Consulting and Analysis**
  - Market data & research, marketing analysis
  - Technology analysis
  - Strategy consulting
  - Reverse engineering & costing
  - Patent analysis
  - Design and characterization of innovative optical systems
  - Financial services (due diligence, M&A with our partner)

- **Syndicated reports**
  - Market & technology reports
  - Patent investigation and patent infringement risk analysis
  - Teardowns & reverse costing analysis
  - Cost simulation tool

- **Monitors**
  - Monthly and quarterly update
  - Excel database covering supply, demand, and technology
  - Price, market, demand and production forecasts
  - Supplier market shares

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  - i-Micronews e-newsletter
  - Communication & webcast services
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Device manufacturers

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Our analysts provide market analysis, technology evaluation, and business plans along the entire supply chain.
We work across multiples industries to understand the impact of More-than-Moore technologies from device to system.
Over more than 20 years, Yole Développement has grown to become a group of companies. Together with System Plus Consulting and KnowMade, we now provide marketing, technology and strategy consulting, media and corporate finance services, reverse costing, structure, process and cost analysis services as well as intellectual property (IP) and patent analysis. Together, our group of companies is collaborating ever more closely. In 2020, we therefore will offer a collection of over 125 syndicated reports, 11 monitors and 160 teardowns. Combining the respective expertise and methodologies from the three companies, our products cover

- MEMS & Sensors
- RF devices & technologies
- Medical technologies
- Semiconductor Manufacturing
- Advanced packaging
- Memory
- Batteries and energy management

- Power electronics
- Compound semiconductors
- Solid state lighting
- Displays
- Computing & Software
- Imaging
- Photonics

Our team of analysts, including PhD and MBA qualified industry experts from Yole Développement, System Plus Consulting and KnowMade, collect and analyse information, identify trends, challenges, emerging markets, and competitive environments. They turn that information into results and give you a complete picture of your industry’s landscape. In the past 20 years, we have worked on more than 2,300 projects, interacting with technology professionals and high-level opinion makers from the main players in their industries and completed more than 5,000 interviews per year.

**WHAT TO EXPECT IN 2020?**

During 2019 we introduced new additions to our “monitor” product offering, which provides continual updates on your industry during the year, and we will be expanding this offering during 2020. In addition to the monitors, we also developed “teardown tracks” that provide you online visibility into the latest consumer technology product designs and the suppliers within them. In 2020, an automotive track will be launched, further expanding our research focused on emerging technologies. On our traditional report side of our business, the Yole Group continues our commitment to a new collection of reports addressing six key markets: Mobile & Consumer, Automotive & Transportation, Telecom & Infrastructure, Medical, Industrial, and Defense & Aerospace. Discover our 2020 program right now, and ensure you get a true vision.

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- RF GaN Market: Applications, Players, Technology, and Substrates 2020
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- SiC Diodes Comparison 2020
- SiC Transistors Comparison 2020
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- GaN-on-Si HEMT vs Superjunction MOSFET Comparison 2019

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- Power GaN 2019
- Power SiC: MOSFETs, SBDs and Modules 2019

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- DRAM Memory Comparison 2020
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- LPDDR4 Memory Comparison 2019

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- 5G Packaging Trends 2020: RF FE Modules & Base Stations
- Fan Out Packaging Technologies and Market 2020
- Status of the Advanced Packaging Industry 2020
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- Status of Advanced Substrates 2019

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- Fan Out Packaging Comparison 2020

## PATENT LANDSCAPE REPORT
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- Status of the Power Electronics Industry 2020
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- Discrete Power Device Packaging: Materials Market and Technology Trends 2019
- Power Management IC: Technology, Industry and Trends 2019
- Status of the Inverter Industry 2019

## STRUCTURE, PROCESS & COST REPORT
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- Si IGBT Comparison 2020
- Smartphone RF FEM Comparison 2020

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- 5G’s Impact on RF Front-End Module and Connectivity for Consumer Applications 2020
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- Status of the Thin-Film Integrated Passive Devices 2020
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- Epitaxy Growth Equipment for More than Moore 2020
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- Small Dimension Wafers Market 2020
- Nano-Imprint Technology Trends for Semiconductor Applications 2019

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- Wearables for Consumer and Medical Markets 2020
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- Piezoelectric Devices: From Bulk to Thin-Film 2019
- Uncooled Infrared Imagers and Detectors 2019

STRUCTURE, PROCESS & COST REPORT
- Automotive Inertial Sensors Comparison 2020
- Consumer Magnetic Sensor Comparison 2020
- MEMS Microphones Processes Comparison 2020
- Mobile Inertial Sensors comparison 2020
- Piezoelectric Material From Bulk to Thin Film – Comparison 2019
- Particle Sensor Comparison 2019

PATENT LANDSCAPE REPORT
- Circulating Tumor Cells Isolation 2020
- LiDAR 2020
- MEMS Foundries IP Portfolio 2020
- MEMS Sensors & Actuators: 2019 IP Trends and Prospective
- Microneedles for Biomedical Applications 2020
- Piezo MEMS 2020
- Nanopore Sequencing 2019
MARKET MONITORS

Advanced Packaging – NEW

This monitor will provide the evolution of the advanced packaging platforms. It will cover Fan-Out Wafer Level Packaging (WLP), Fan-Out Panel Level Packaging (PLP), Wafer-Level Chip Scale Packaging (WLCSP), Flip Chip packaging platforms, and 2.5D and 3D Through Silicon Via (TSV) integration. Starting from Q4 2019

Application Processor – NEW

The monitor examines and forecasts the application processor segment. It tracks processor revenue, units, and wafer volumes at both fabless chip designers and at the foundries themselves, sliced across various relevant parameters including process node, end product segment, core and IP type, etc. The monitor also examines the reported financials of players within the ecosystem. Starting from Q4 2019.

Compound Semiconductors – NEW

This monitor will describe how the compound semiconductor industry is evolving. It will offer a close look at GaAs, InP, SiC, GaN and other compounds of interest providing wafer volumes, revenues, application breakdowns and momentum. Starting from Q4 2019

CMOS Image Sensors – NEW

This monitor will provide the evolution of the imaging industry, with a close look at image sensor, camera module, lens and VCM. Volumes, revenues and momentum of companies like Sony, Samsung, Omnivision and ON Semiconductor will thus be analysed. Starting from Q3 2019

DRAM

This monitor analyzes the evolution of the DRAM market in terms of revenue, shipments, capex, and near-term price evolution, as well as demand per market segment (data centers, mobile, automotive, graphics, and PC), DRAM technology evolution, and detailed profiles of main suppliers. It also provides DRAM monthly pricing to track the price evolution of key components and packaged solutions.

NAND

This monitor provides all data related to NAND revenue per quarter, NAND shipments, pricing per NAND type, near and long-term revenue, market share per quarter, capex per company, and a market demand/ supply forecast, along with a complete analysis and details on the demand side, with a deep dive into client and enterprise SSD, data centers, mobile, automotive, PC, and more.
OUR 2020 MONITORS COLLECTION (2/2)

PATENT MONITORS

**GaN for Power & RF Electronics**

Wafers and epiwafers, GaN-on-SiC, silicon, sapphire or diamond, semiconductor devices such as transistors, and diodes, devices and applications including converters, rectifiers, switches, amplifiers, filters, and MMICs, packaging, modules and systems.

**RF Acoustic Wave Filters**

Including Surface Acoustic Wave (SAW), Temperature Compensated (TC)-SAW, Bulk Acoustic Wave- Free-standing Bulk Acoustic Resonator (BAWFBAR), BAWSolidly-Mounted Resonator (BAW-SMR), and Packaging.

**Microfluidics**

From components to chips and systems, including all applications.

**Solid-State Li-ion Batteries**

This monitoring service tracks patents related to electrodes, battery cells, battery packs/systems and electrolytes, including polymer, inorganic and inorganic/ polymer, inorganic materials, including argyrodites, Lithium Super Ionic CONductor, (LiSICONs), Thio-LiSICONs, sulfide glasses, oxide glasses, perovskites, anti-perovskites and garnets.

REVERSE TECHNOLOGY MONITOR

**Smartphones – NEW**

To stay updated on the latest components, packaging and silicon chip choices of the smartphone makers, System Plus Consulting has created its first Smartphone Reverse Technology monitor. This monitor will provide the design wins for the top smartphones OEM, the packaging evolution in term of type, footprint, pitch, as well as die area evolution per function, technology node, wafer size. It will offer a clear view of the technological strategy of the semiconductor companies leading the market and a direct comparison between OEM.
Our 160+ Tracks

Access anytime via our web portal new teardowns and updates, as our analysis progresses.

System Plus Consulting's teardown tracks uncover innovative design features and new semiconductor components to guide enterprises toward more streamlined solutions in future designs. We provide clients unmatched intelligence into 5 main tracks:

**Phones* - 440+ products already available**

**Apple**
- iPhone 11 Pro 512GB
- iPhone 11 Pro 256GB
- iPhone XR

**Oppo**
- OPPO Reno 5G
- OPPO K1
- OPPO R17 Pro

**Samsung**
- Samsung Galaxy A50 64GB Dual SIM
- Samsung Galaxy Fold
- Samsung Galaxy Xcover 4s

**Xiaomi**
- Xiaomi Mi Mix 3 5G 64GB
- Xiaomi Black Shark 2 128GB 8GB RAM
- Xiaomi Redmi Note 7 Pro

**Smart Home* - 90+ products already available**

**Amazon**
- Amazon Show 5
- Amazon Echo plus (2nd gen.)

**Google**
- Google Home Hub
- Google Clips

**Wearable* - 130+ products already available**

**Apple**
- Apple Airpods Pro w/Wireless charger
- Apple Watch 5

**Bose**
- Bose Frames

**Fitbit**
- Fitbit Charge 3
- Fitbit Versa
- Fitbit Flyer

**Connected Devices* - 110+ products already available**

**Microsoft**
- Microsoft Surface Go

**Samsung**
- Samsung Tab S5e

**Verizon**
- Verizon HUM x (Gen 1)

**Automotive**
First teardowns available from Q1 2020 (60+ in 2020)
To meet the growing demand for market, technological and business information, i-Micronews Media integrates several tools able to reach each individual contact within its network.

We will ensure your company benefits from this

**ONLINE**

i-Micronews e-newsletter
i-Micronews.com
FreeFullPDF.com

**ONSITE**

Events

**INPERSON**

Webcasts

<table>
<thead>
<tr>
<th>Brand visibility, networking opportunities</th>
</tr>
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<tbody>
<tr>
<td>Today’s technology makes it easy for us to communicate regularly, quickly, and inexpensively – but when understanding each other is critical, there is no substitute for meeting in-person. Events are the best way to exchange ideas with your customers, partners, prospects while increasing your brand/product visibility.</td>
</tr>
</tbody>
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| Targeted audience involvement equals clear, concise perception of your company’s message. |
| Webcasts are a smart, innovative way of communicating to a wider targeted audience. Webcasts create very useful, dynamic reference material for attendees and also for absentees, thanks to the recording technology. |

Unique, cost-effective ways to reach global audiences.

Online display advertising campaigns are great strategies for improving your product/brand visibility. They are also an efficient way to adapt with the demands of the times and to evolve an effective marketing plan and strategy.

| #15,100+ monthly unique visitors on i-Micronews.com |
| #10,900+ weekly readers of i-Micronews e-newsletter |
| #110 attendees on average |
| #14+ key events planned for 2020 on different topics |
| #280 registrants per webcast on average to gain new leads for your business |

Contact: Camille Veyrier (veyrier@yole.fr), Marketing & Communication Director
CONTACT INFORMATION

○ CONSULTING AND SPECIFIC ANALYSIS, REPORT BUSINESS
  • North America:
    • Steve LaFerriere, Senior Sales Director for Western US & Canada
      Email: laferriere@yole.fr - +1 310 600-8267
    • Chris Youman, Senior Sales Director for Eastern US & Canada
      Email: chris.youman@yole.fr - +1 919 607 9839
  • Japan & Rest of Asia:
    • Takashi Onozawa, General Manager, Asia Business Development
      (India & ROA)
      Email: onozawa@yole.fr - +81 34405-9204
    • Miho Ohtake, Account Manager (Japan)
      Email: ohtake@yole.fr - +81 3 4405 9204
    • Itsuyo Oshiba, Account Manager (Japan & Singapore)
      Email: oshiba@yole.fr - +81-80-3577-3042
    • Toru Hosaka, Business Development Manager (Japan)
      Email: toru.hosaka@yole.fr - +81 90 1775 3866
  • Korea: Peter Ok, Business Development Director
    Email: peter.ok@yole.fr - +82 10 4089 0233
  • Greater China: Mavis Wang, Director of Greater China Business
    Development
    Email: wang@yole.fr - +86 979 336 809 / +86 136 61566824
  • Europe & RoW: Lizzie Levenez, EMEA Business Development Manager
    Email: levenez@yole.fr - +49 15 123 544 182

○ FINANCIAL SERVICES (in partnership with Woodside Capital Partners)
  • Jean-Christophe Eloy, CEO & President
    Email: eloy@yole.fr - +33 4 72 83 01 80
  • Ivan Donaldson, VP of Financial Market Development
    Email: ivan.donaldson@yole.fr - +1 208 850 3914

○ CUSTOM PROJECT SERVICES
  • Jérome Azémar, Technical Project Development Director
    Email: azemar@yole.fr - +33 6 27 68 69 33

○ GENERAL
  • Camille Veyrier, Director, Marketing & Communication
    Email: veyrier@yole.fr - +33 472 83 01 01
  • Sandrine Leroy, Director, Public Relations
    Email: leroy@yole.fr - +33 4 72 83 01 89
  • Email: info@yole.fr - +33 4 72 83 01 80

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