ASTRONOMICAL APPLICABILITY OF COLLOIDAL QUANTUM DOT SHORT-WAVE INFRARED IMAGE SENSOR WITH SCALABLE PIXEL PITCH DOWN TO SUB-2 MICRON

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IMEC: INDEPENDENT R&D HUB

SEMICONDUCTOR SCALING AND NANOELECTRONICS
FOUNDED 1984
HQ IN LEUVEN, BELGIUM
4500 PEOPLE OF 97 NATIONALITIES
>600 PARTNERS
70% OF BUDGET FROM INDUSTRY
BSI CIS
High-sensitivity

Special epitaxial layers
High Near-Infrared sensitivity

Spectral filters (VIS to IR)
Interferential hyperspectral filters

TFPD sensors
Thin-Film PhotoDetector for hi-res/low-cost infrared

SWIR ToF
Components for LiDAR

Fast ADC design IP
High-speed custom chip

Drivers + readout design IP
High-speed custom chip

NIR SPADs
High-sensitive SPADS for dToF

Burst / gated pixel
High-speed custom chip

III-V wafer reconstitution
High-resolution SWIR chip

Die stitching
High-resolution custom chip

CCD-in-CMOS
High-speed, low power
Drag button to views of the Eagle Nebula, 7,000 light years from Earth

Telescopes cover different parts of the electromagnetic spectrum

JAMES WEBB
Observations in the near and mid-infrared

Webb

Ultraviolet  Visible  Infrared  Radio

HUBBLE
Observations in ultraviolet, visible and near-infrared

Source: Esa
TFPD (THIN-FILM PHOTODETECTOR) OPPORTUNITY

### CIS
- **visible**
  - ✓ high maturity
  - ✓ high throughput
    - >6B units/year!
    - substrate: 200-300 mm
  - ✓ low cost
    - single $ per camera
  - ✗ no SWIR EQE
    - 0% in SWIR
  - ✓ small pixel pitch
    - SotA CIS 0.56 µm

### TFPD
- **Y-X-UV-Vis–IR**
  - » new technology
  - » **potentially** high throughput
    - monolithic wafer-level flow
    - target substrate: 200/300 mm
  - » **potentially low cost**
    - target: 10$ – 100$ (with volume)
  - ✓ good SWIR EQE
    - ~60%
  - ✓ small pixel pitch
    - <2 µm

### III-V / II-VI / hybrid
- **IR**
  - ✓ high maturity
  - ✗ low throughput
    - ~10K units/year
    - substrate: 3-4 inch + flip-chip
  - ✗ high cost
    - several K$ per camera
  - ✓ high SWIR EQE
    - 80-90%
  - ✗ large pixel pitch
    - SotA InGaAs 5 µm

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Images of OPD, QDPD, CMOS ROIC, and InGaAs PD are presented.
QD ULTRA-SPECTRALITY
FROM Y-RAY TO LONG-WAVE INFRARED

Ultra-spectrality can be realized by printing different thickness of QD for corresponding color unit pixel

Radiation Spectrum

High energy photon to electrons

Nat. Photon. 16, 14–26 (2022)

Thicker PD detects high-energy photons

Mater. Adv., 2021, 2, 6744–6767

J. Park (Ed.) Photodiodes - World Activities in 2011
PROCESS DEVELOPMENT
QUANTUM DOT IMAGE SENSOR
“MONOLITHIC HYBRID” INTEGRATION

→ customizable spectrum
  e.g. EQE peak at 1450 or 1550 nm

→ customizable readout
  e.g. 2 µm pixel and 4K resolution
QUANTUM DOT PHOTODIODE
CAPTURING Λ > 1400 NM IN A 300 NM THICK FILM

QD absorber

5 nm

photodiode stack

Top Transparent Contact
HTL
Photo active layer
ETL
Bottom Reflective Contact

200 nm
QD IMAGE SENSOR
SPECTRUM CAN BE CUSTOMIZED WITH TUNING OF THE STACK
Pixelation - Wafer Level TFPD Stack Patterning

TFPD stack pixilation demonstrated at wafer level

*More details to be shared during VLSI 2022
QD image sensor

Readout can be customized for a certain form factor

Size of a VGA array
(640x480 px)

CIS monolithic
pixel pitch:
0.56 µm (SotA)

QD monolithic
pixel pitch:
1.82 µm (imec SotA)

InGaAs flip-chip
pixel pitch:
15 µm (SotA 5 µm)

Full-WF Single Chip:
Sensor Area 20,000 mm²,
6 Gigapixel (8 inch WF)
Image Sensor Design and Characterization
Customer ROIC designs

- Custom readouts and camera build

- Pixel architecture study for scaling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>gen1 (2020)</th>
<th>gen2 (2021)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel pitch</td>
<td>5</td>
<td>1.82</td>
<td>µm</td>
</tr>
<tr>
<td>Resolution</td>
<td>768x512</td>
<td>128x128</td>
<td>px</td>
</tr>
<tr>
<td>DR</td>
<td>84</td>
<td>63</td>
<td>dB</td>
</tr>
<tr>
<td>FWC</td>
<td>470</td>
<td>16.8</td>
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<tr>
<td>J0</td>
<td>0.3</td>
<td>0.2</td>
<td>µA/cm²</td>
</tr>
<tr>
<td>RN</td>
<td>33</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>PRNU</td>
<td>1.3</td>
<td>1.8</td>
<td></td>
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<tr>
<td>λ_PEAK</td>
<td>1400</td>
<td>1450</td>
<td>nm</td>
</tr>
<tr>
<td>EQE</td>
<td>13</td>
<td>40</td>
<td>%</td>
</tr>
</tbody>
</table>

- pixel < 2 µm: enabler for compact (yet hi-res) sensors
- pixel ≥ 5 µm: good for low-light applications

J. Lee et al., IEDM paper 16.5 (2020) DOI: 10.1109/IEDM13553.2020.9372018
V. Pejović et al., IEEE TED (2021) DOI: 10.1109/TED.2021.3093081

Pixel structure study for scaling

- 3T
- CTIA

- Good
- Not good (constant biasing for amp.)

- Stable
- Low voltage

- Good for large pixel size
- Additional noise source (amplifier)

- Variable ➔ Linearity
- High voltage ➔ Dark current

- Good for scaled pixel size
- Good for large pixel size

- Power consumption
- Good

- Dark current
- Stable

- PD bias
- Variable
- High voltage

- Read Noise (RN)
- Good for scaled pixel size

- 3T CTIA
- Pixel Structure PD + 3 transistors (RST, SEL, SF) PD + Amp. with feedback cap. + Buffer and switch

- Readout and camera build

- Gen1
- Gen2
- Gen3

- J. Lee et al., IEDM paper 16.5 (2020) DOI: 10.1109/IEDM13553.2020.9372018
- V. Pejović et al., IEEE TED (2021) DOI: 10.1109/TED.2021.3093081

- 5 µm
- 2.1 µm
- 1.82 µm

- Gen2

- Customer readouts and camera build

- Pixel structure study for scaling

- 3T
- CTIA

- Good
- Not good (constant biasing for amp.)

- Stable
- Low voltage

- Good for large pixel size
- Additional noise source (amplifier)

- Read Noise (RN)
- Good for large pixel size

- 3T CTIA
- Pixel Structure PD + 3 transistors (RST, SEL, SF) PD + Amp. with feedback cap. + Buffer and switch

- Power consumption
- Good

- Dark current
- Stable

- PD bias
- Variable
- High voltage

- Conversion gain
- Good for scaled pixel size
- Good for large pixel size

- Read Noise (RN)
- Good for scaled pixel size

- Good for large pixel size

- Additional noise source (amplifier)
High quality imaging in SWIR
Small pixel size $\rightarrow$ compact form factor + more details

Resolution chart image acquired with imec PbS QD1450 sensor

5 µm*  2.5 µm

*SotA for InGaAs imagers

Credit: CSA
TRANSPORT LAYER CONDUCTIVITY VS. BLOOMING

Less conductive (Less laterally mobile), Less Blooming

Blooming Characterization

No inter-pixel potential difference

Neighbouring pixel saturated

How to suppress X-talk of QD Imager

1. Spectral: Uniform QD size distribution
2. Optical: PD Full Pixelation
3. Electrical: Pixelation, Resistive TL

ACTIVATION ENERGY OF 0.41 EV FOUND

MULTIPLE PEAKS SEEN FROM 0.23 EV TO 0.43 EV (MID-BANDGAP ENERGY)
TFPD image sensor validation

What have we tested?

**Benchmarking**
Validation of the imec camera against an off-the-shelf InGaAs

**Security/surveillance** (see through sunglasses)

**Wafer inspection** (detection of voids after bonding)

**Real-time Demo** (Future Summits 2022)

**Food sorting** (stones among coffee beans)

**Lens-free imaging** (e.g. microscopy)
Where is the industry currently?
First products are already coming to market!
(and new players entering)

<table>
<thead>
<tr>
<th>Company</th>
<th>Spectral range: up to 2000 nm</th>
<th>Array size: 640 × 512 px</th>
<th>Pixel pitch: 20 µm</th>
</tr>
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<tbody>
<tr>
<td>Emberion (Finland)</td>
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<tr>
<td>www emberion.com</td>
<td></td>
<td></td>
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<tr>
<td>SWIR Vision Systems (USA)</td>
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<tr>
<td>www swirvisionsystems.com</td>
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<tr>
<td>qurv (Spain)</td>
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<tr>
<td>www qurv tech</td>
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<td>ST Microelectronics (France)</td>
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<tr>
<td>www st com</td>
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<td></td>
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<tr>
<td>Pixel pitch: 1.62 µm</td>
<td></td>
<td></td>
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<tr>
<td>Wafer size: 300 mm</td>
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</table>
TFPD IMAGE SENSORS
R&D program at imec – technology building blocks

**TRL**

1st results on SWIR InAs QDs

```
<table>
<thead>
<tr>
<th>Ext. quantum efficiency (%)</th>
<th>QD absorbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 V</td>
<td>10</td>
</tr>
<tr>
<td>3 V</td>
<td>8</td>
</tr>
<tr>
<td>2 V</td>
<td>6</td>
</tr>
</tbody>
</table>
```

“what’s next?”

**MRL**

QD stack pixelation on 200 mm wafers

```
PbS CQD
CMOS-TFPD interface
5 μm
```

“how to manufacture?”

**Validation**

Modular camera enabling field testing at end users

“what are the specs?”
QD SENSORS FOR ASTRONOMICAL IR IMAGING

Highly Scalable IR Image Sensor

- Astronomical IR Image Sensor: Observing deeper and older universe
- QD Imager is enabling more scalable astronomical imaging
  - Large pixel number, WF-lv sensing area, High-resolution, Ultra-spectral imager
- Imec QD Imager has shown
  - QD Synthesis to PD stack development
  - Wafer-level process development
  - Imager design and deep-analysis
- Imec has been leading QD Imager innovation at the forefront.
IMEC QD IMAGE SENSOR TRACK RECORD

Press:
- Promotional video: vimeo.com/653649418
- IMVE magazine, 18th Feb 2021, URL: bit.ly/3e4VUUr
- Press release (SWIR pixel pitch state-of-the-art: 1.82 µm), 9th Dec 2020, URL: bit.ly/3oypX9y

Publications:
- V. Pejović et al. IEEE Transactions on Electron Devices (2021), DOI: 10.1109/TED.2021.3133191
- J.H. Kim et al. IISW 2021, paper R40
- V. Pejović et al. IEEE Electron Device Letters 42/8 (2021), DOI: 10.1109/LED.2021.3093081
- P.E. Malinowski et al. Proc. SPIE 11765 (2021), DOI: 10.1117/12.2584144
- Y. Li et al., SEMI – CSTIC, Symposium IV, Session V (2021)
- Z. Lin et al., Proc. SPIE 11632 (2021), DOI: 10.1117/12.2578857
- J. Lee et al., IEDM 2020, paper 16.5 (2020), DOI: 10.1109/IEDM13553.2020.9372018
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- P.E. Malinowski et al. Sensors 17/2867 (2017), DOI:10.3390/s17122867
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