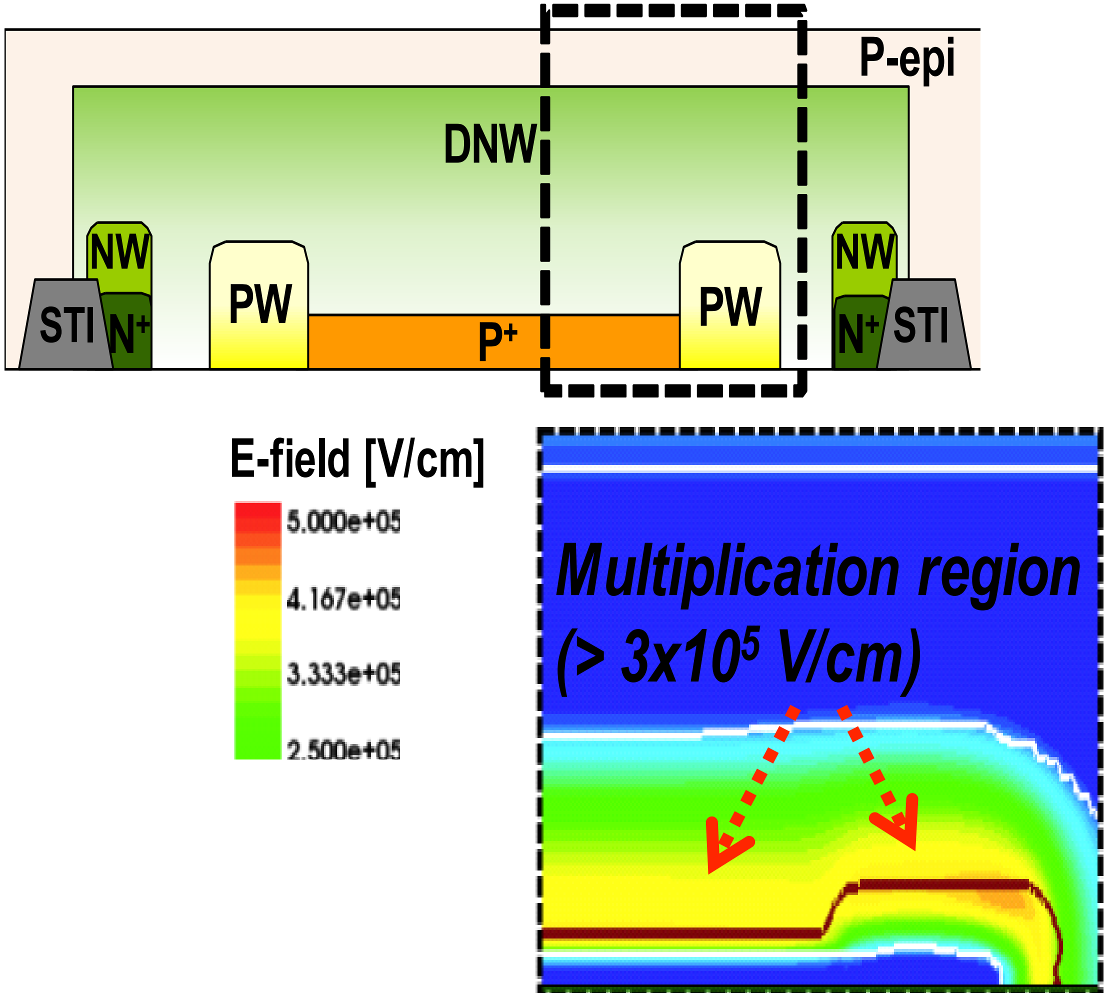
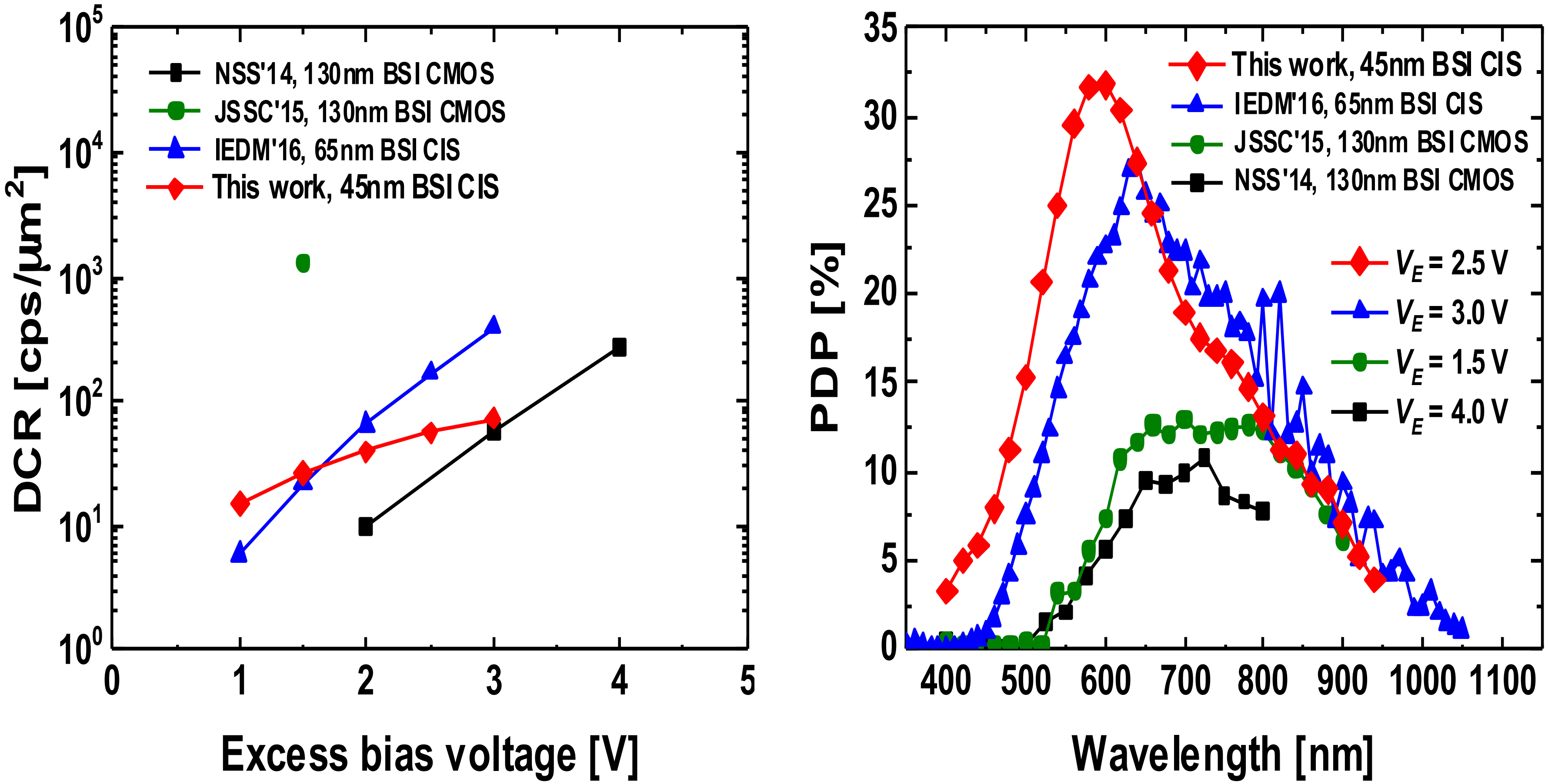
# Electrical Microlenses



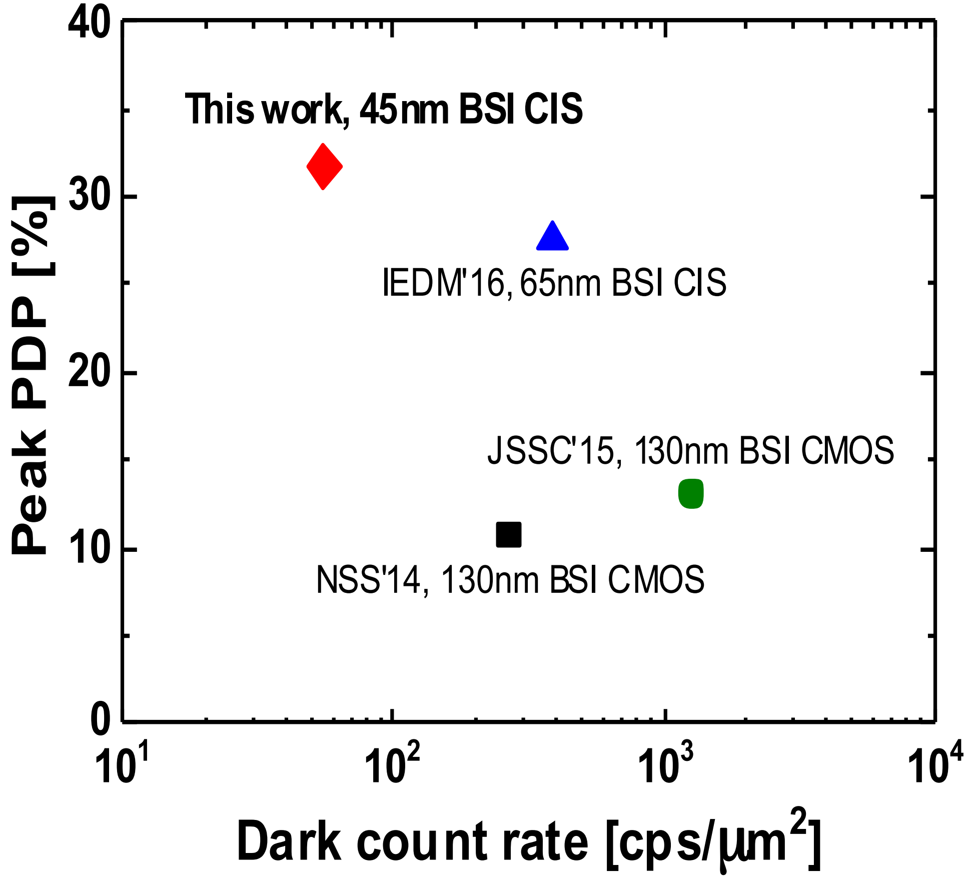

*E-field profile*

- **Extended multiplication region below GR**
  **➔ *Larger FF***

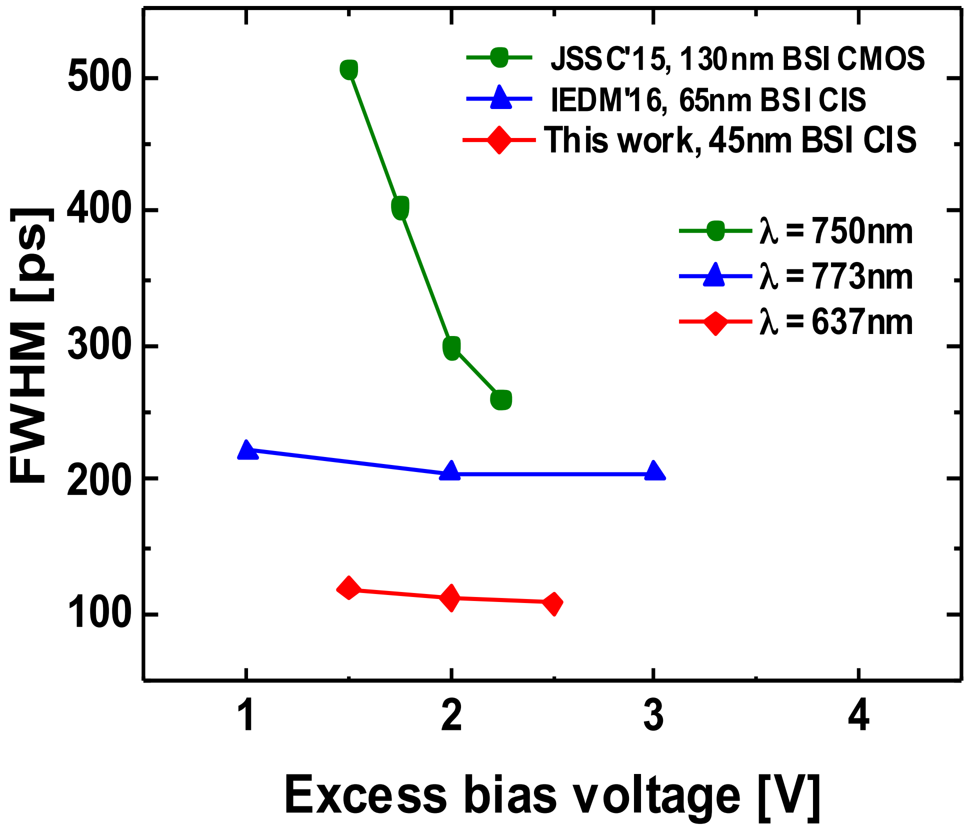
# 3D-Stacked BSI Comparison: DCR & PDP



# 3D-Stacked BSI Comparison: DCR & PDP



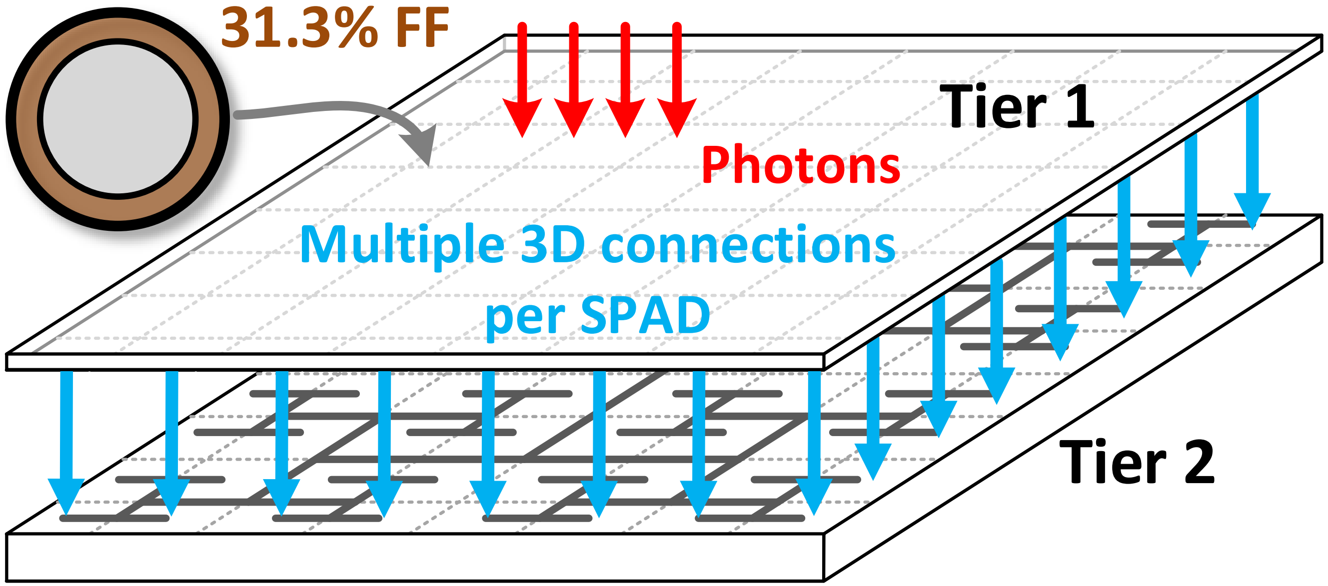
# 3D-Stacked BSI Comparison: Timing Jitter



# 3D-Stacked BSI State-of-the-art

| | NSS'14 | JSSC'15 | IEDM'16 | This work |
|---|---|---|---|---|
| **Technology (Top/Bottom)** | 130nm CMOS<br>130nm CMOS | 130nm CMOS<br>130nm CMOS | 65nm CIS<br>40nm CMOS | **45nm CIS<br>65nm CMOS** |
| **Junction \| GR** | $P^+$/NW \| PW GR | NLDD/PW \| NW GR | PW/DNW \| Virtual GR | **$P^+$/DNW \| PW GR** |
| **Active area** | 28.3 $\mu m^2$ | 28 $\mu m^2$ | 27.6 $\mu m^2$ | **122.7 $\mu m^2$** |
| **Fill factor** | n.a. | 23.3 % | 45 % | **up to 60.5 %** |
| **$V_B + V_E$** | 12.3 V + 4 V | 16.5 V + 1.5 V | 12.0 V + 3 V | **28.5 V + 2.5 V** |
| **DCR** | 7.5 kcps<br>265.3 cps/$\mu m^2$ | 35 kcps<br>1250 cps/$\mu m^2$ | 10.8 kcps<br>391.4 cps/$\mu m^2$ | **6.8 kcps<br>55.4 cps/$\mu m^2$** |
| **PDP peak (@λ)** | 11 % (@725nm) | 13 % (@700nm) | 27.5 % (@640nm) | **31.8 % (@600nm)** |
| **PDP @450nm** | 0.3 % | 0.3 % | 0.9 % | **6.9 %** |
| **FWHM (@λ)** | n.a. | 505 ps (@750nm) | 205 ps (@773nm) | **107.7 ps (@637nm)** |

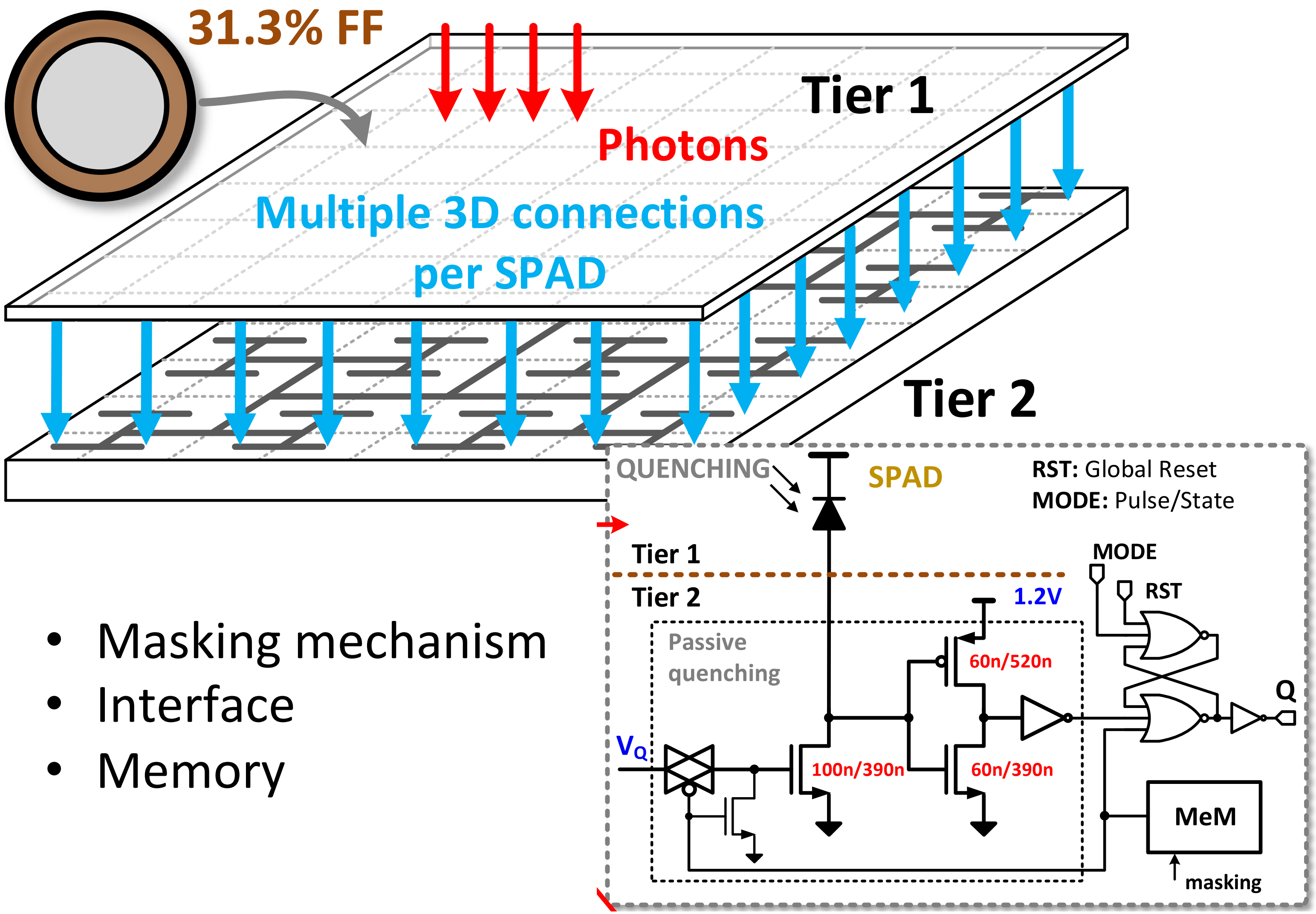
# Case Study: LiDAR Sensor




M.J. Lee, A.R. Ximenes, P. Padmanabhan, Y. Yamashita, D.N. Yaung, E. Charbon, IEDM 2017

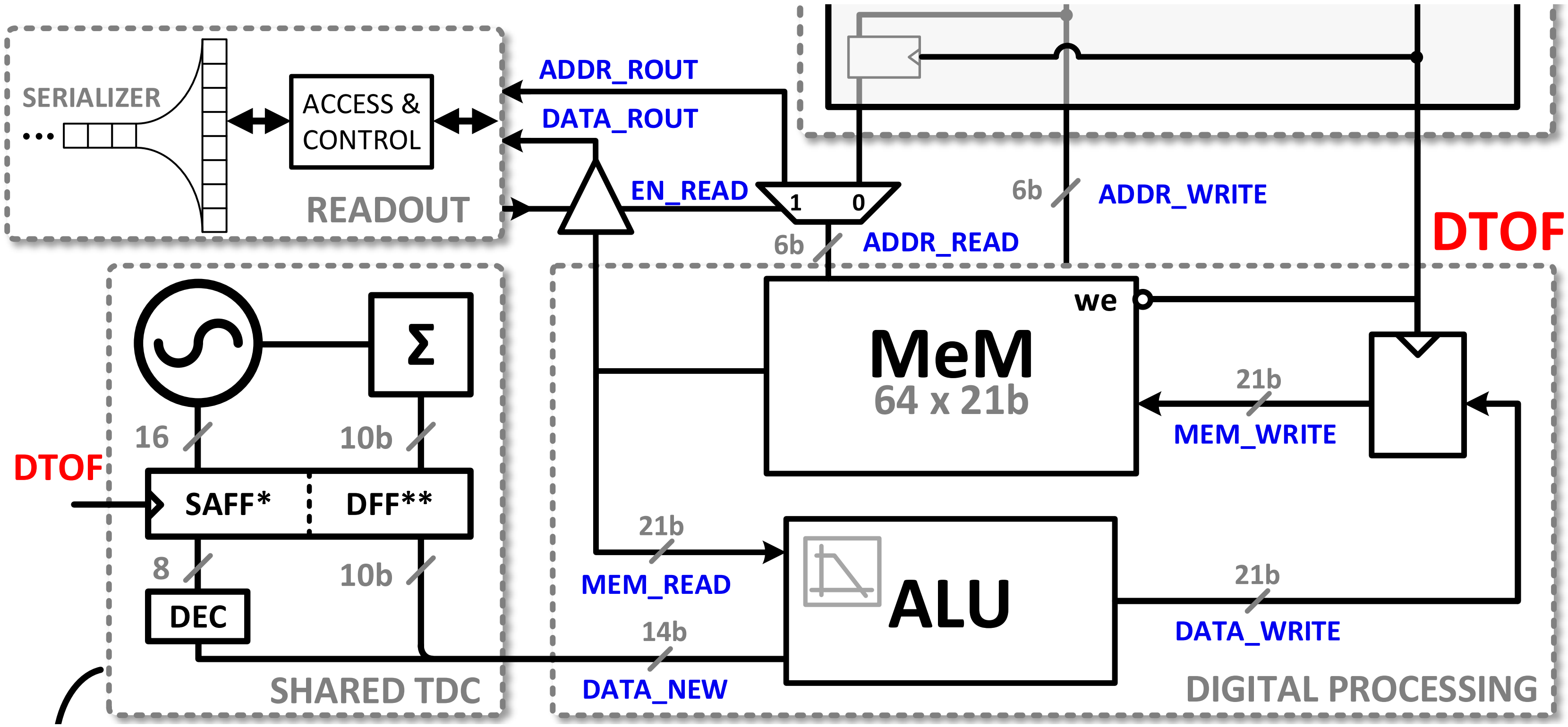
- Tier 1: SPADs + microlenses
- Tier 2: quenching, recharge, TDCs, multi-core, memories, communication unit, I/O

# Case Study: LiDAR Sensor



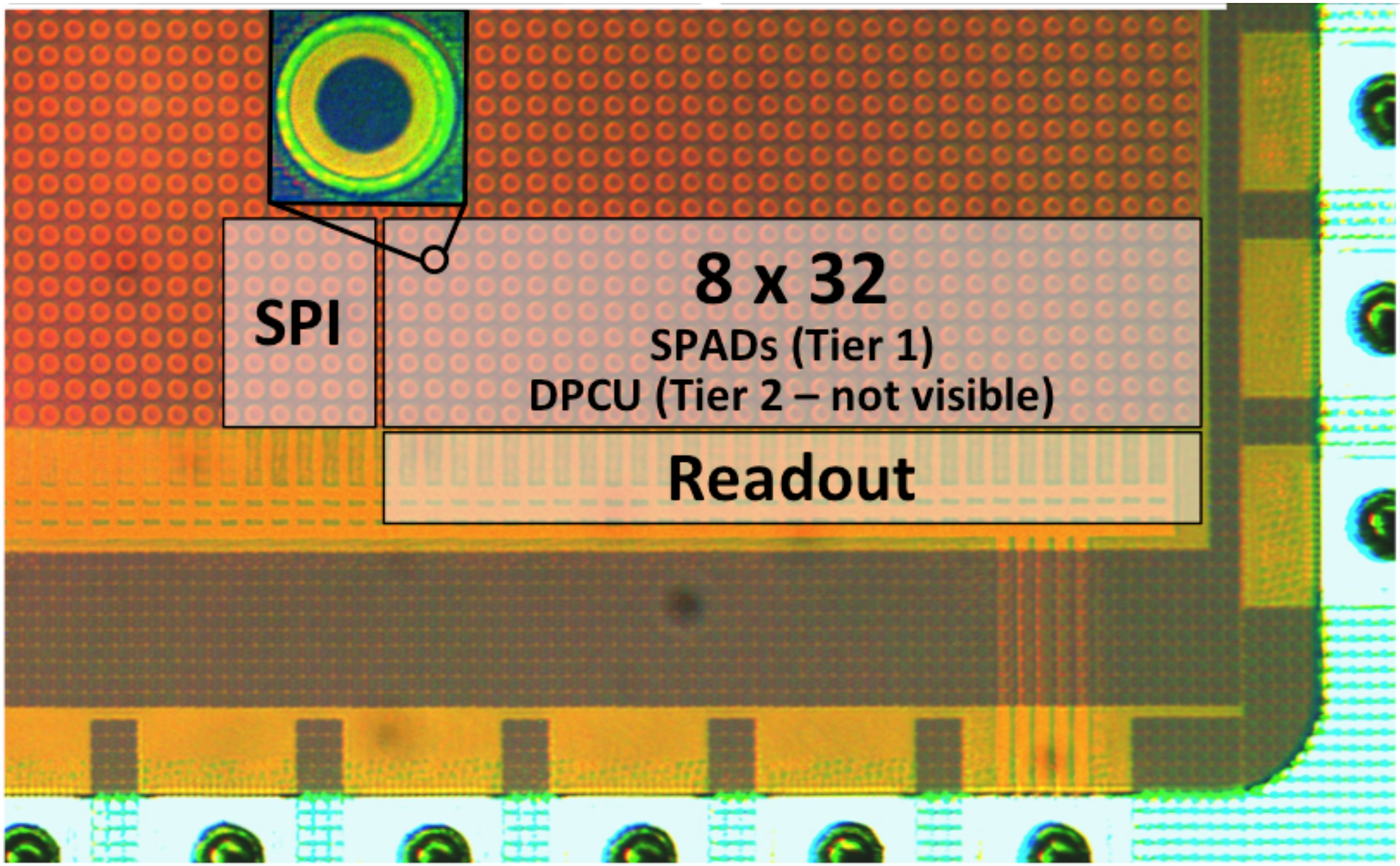

- Masking mechanism
- Interface
- Memory

# Case Study: LiDAR Sensor

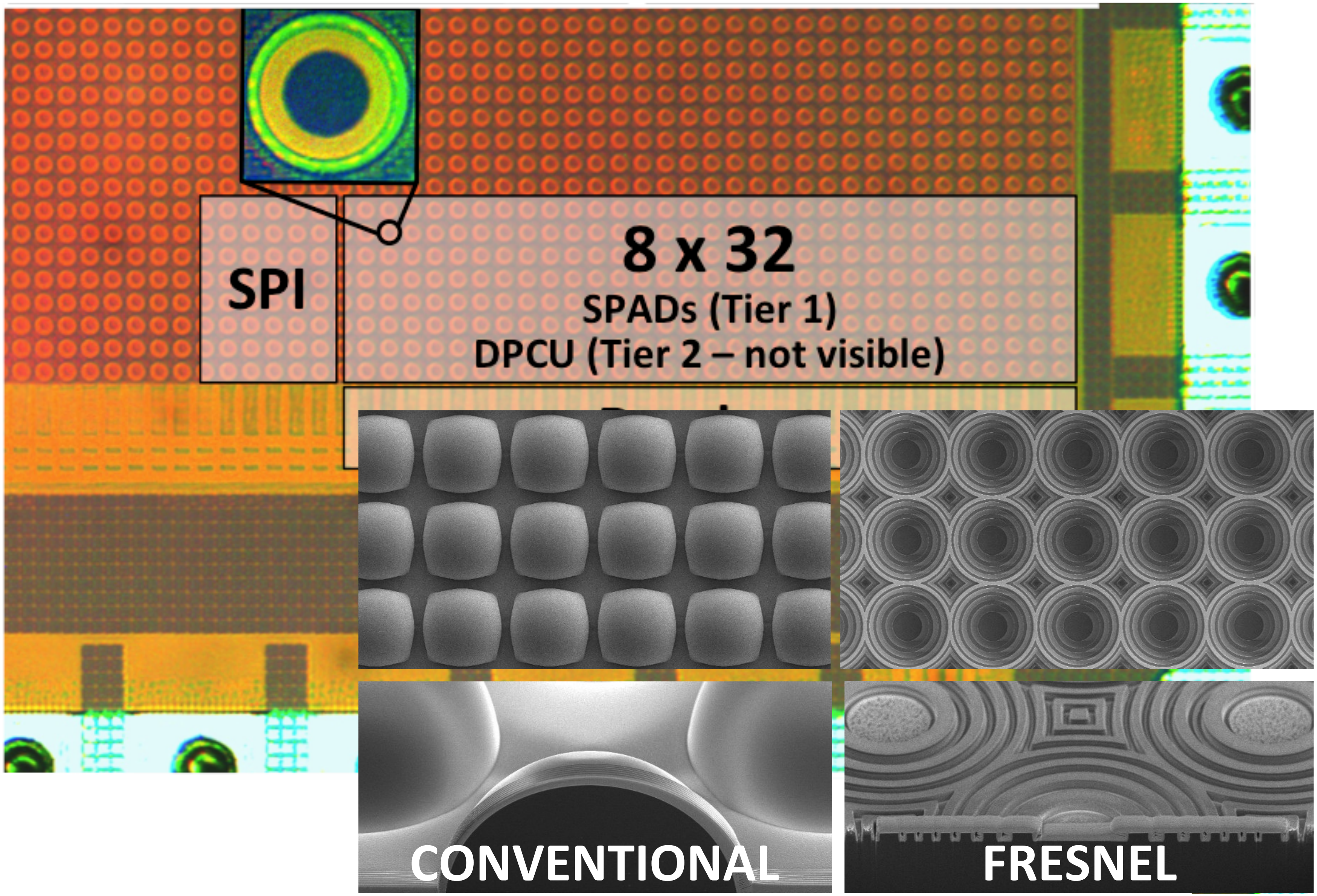



A.R. Ximenes, P. Padmanabhan, M.J. Lee, Y. Yamashita, D.N. Yaung, E. Charbon, ISSCC 2018

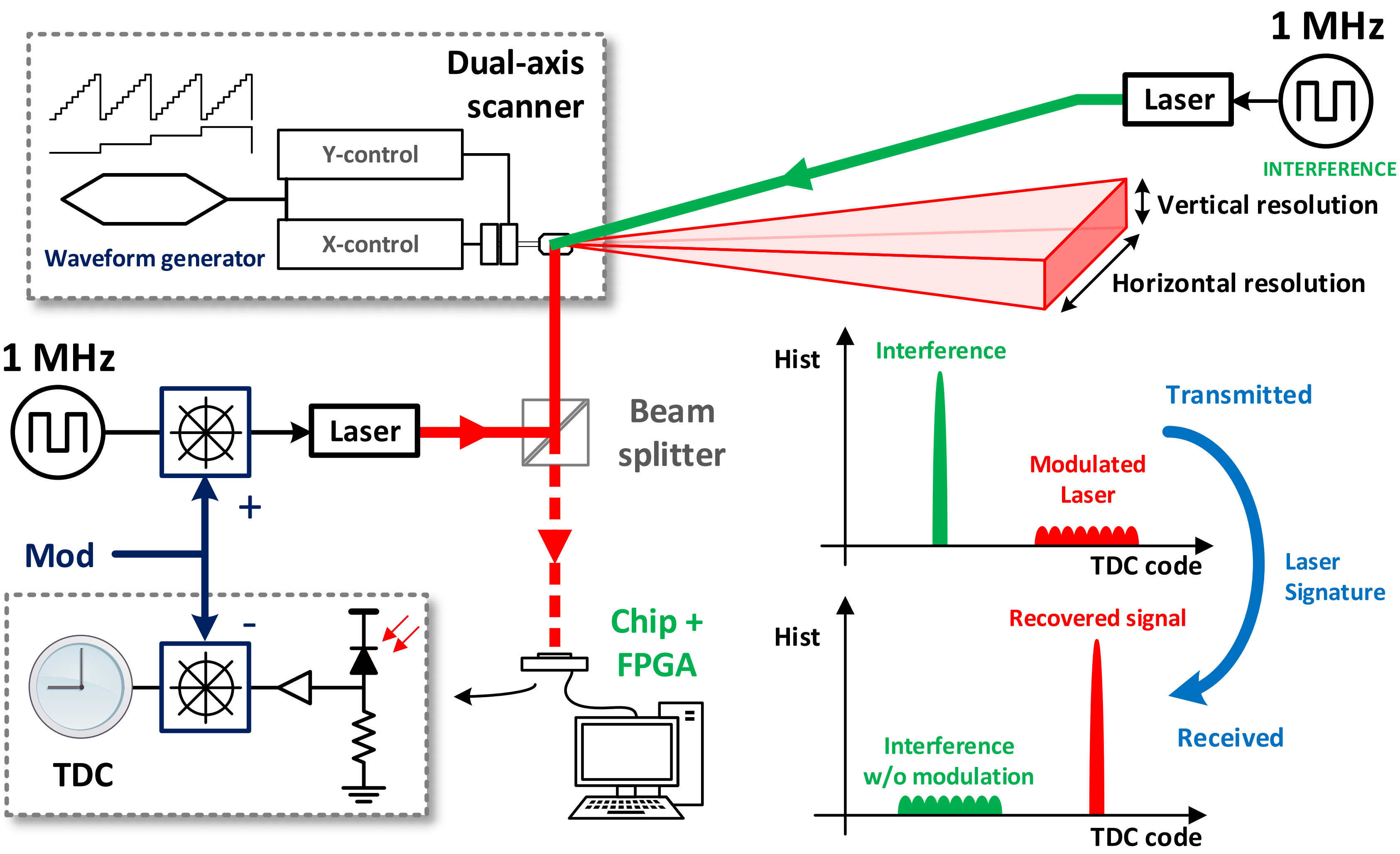
# 3D-Stacked Chip Micrograph



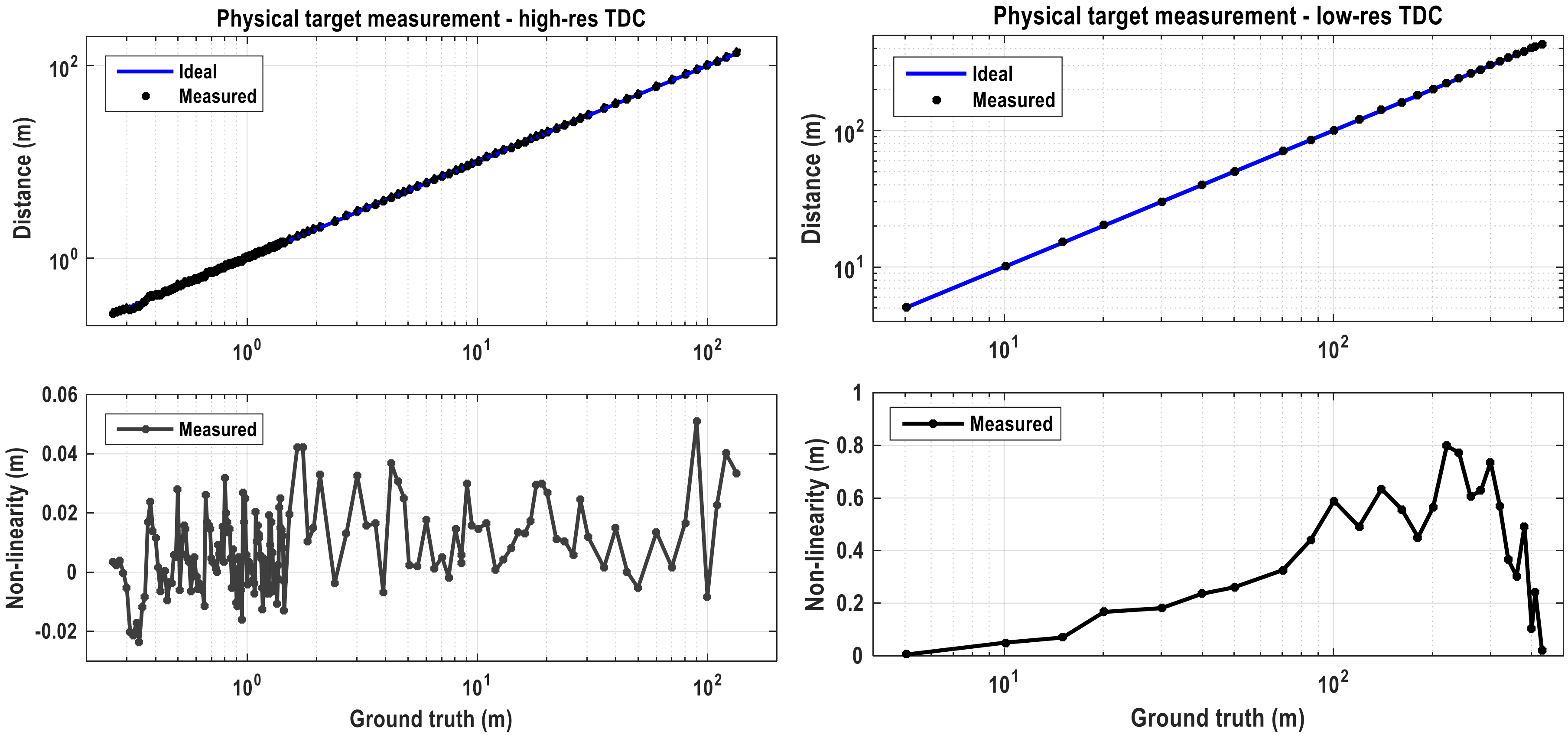
# 3D-Stacked Chip Micrograph



# The LiDAR System

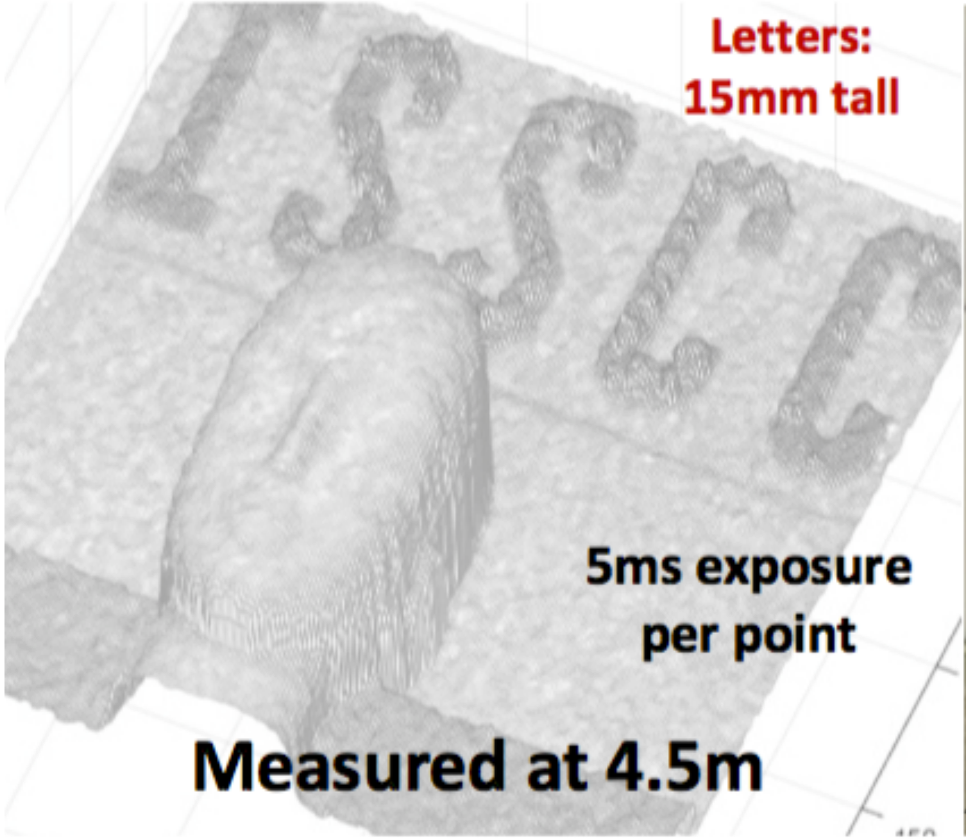


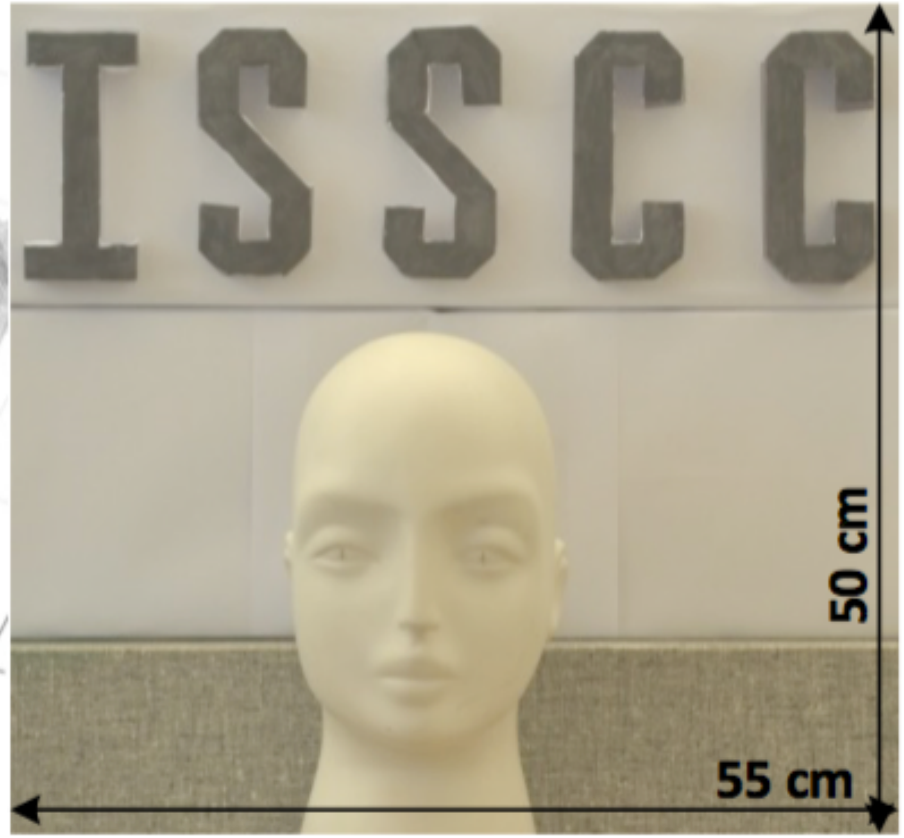
# Distance Measurements



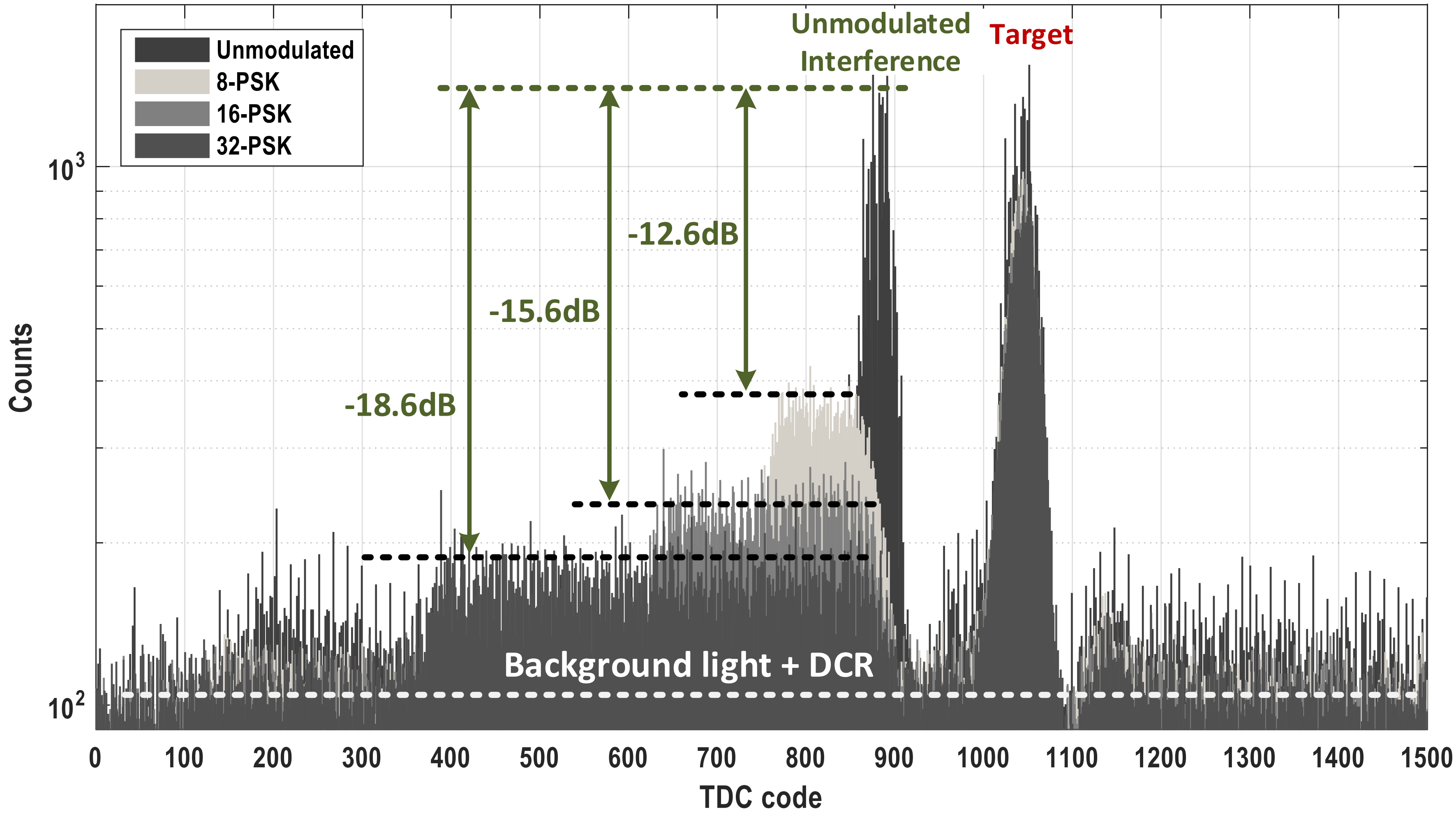

A.R. Ximenes, P. Padmanabhan, M.J. Lee, Y. Yamashita, D.N. Yaung, E. Charbon, ISSCC 2018

# 256x256 3D Image Reconstruction



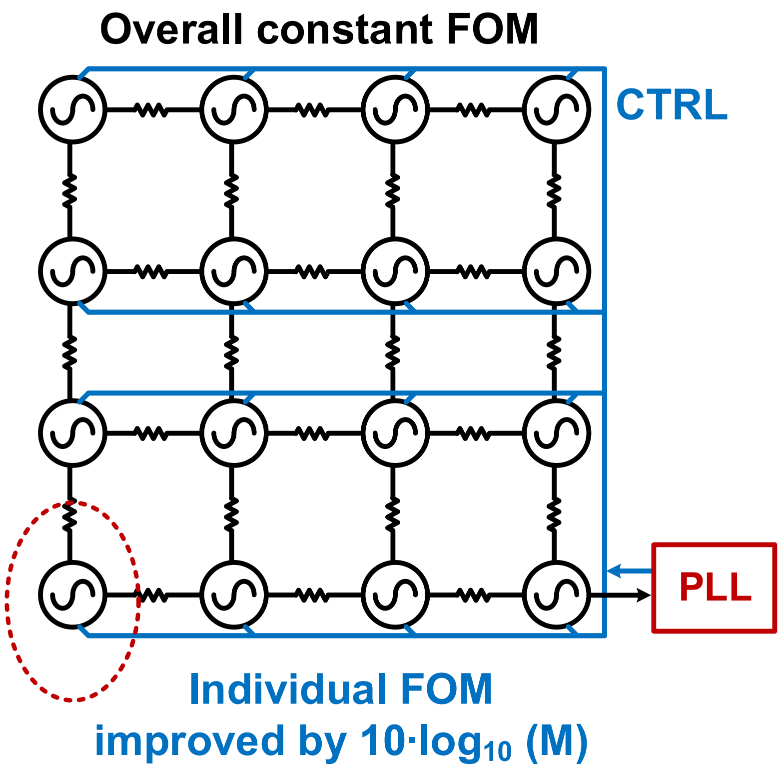



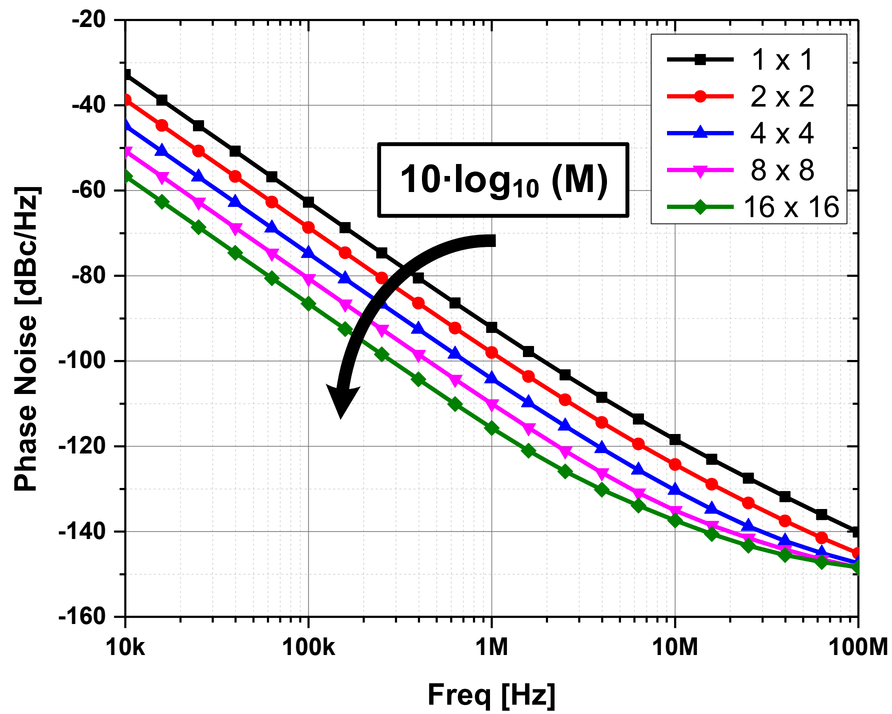
# Interference Suppression



# Large Array Synchronization

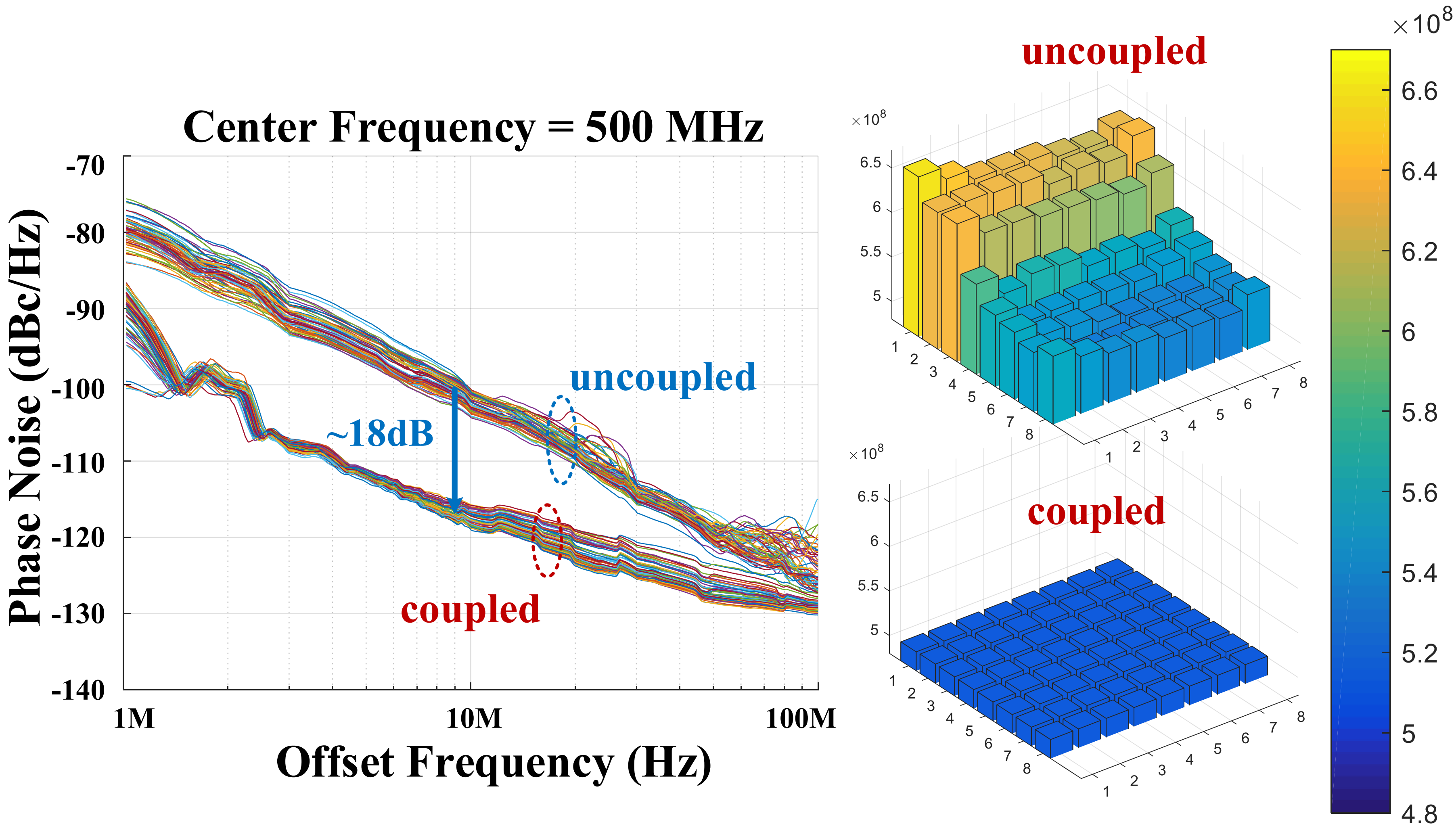
- Use injection locking for coupling VCOs
- The PLL only forces the desired frequency on the VCOs



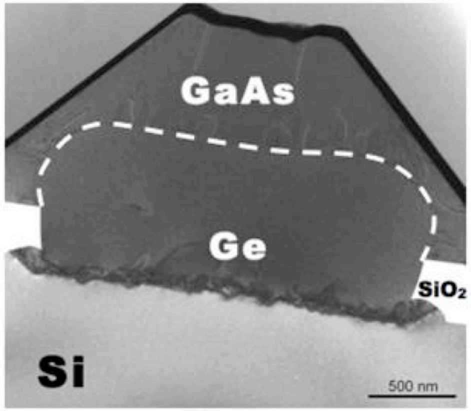

A.R. Ximenes, P. Padmanabhan, et al., IISW 2018

# Mutual Coupling Measurements

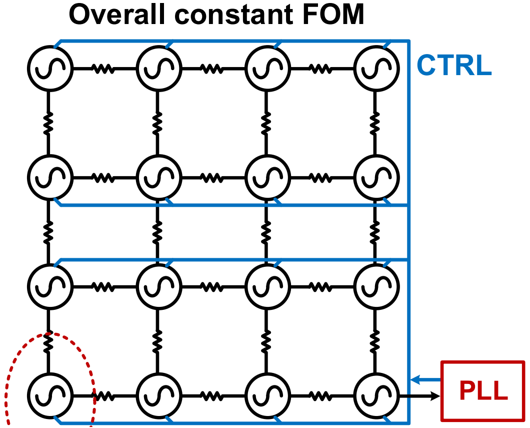


# Perspectives for 2020

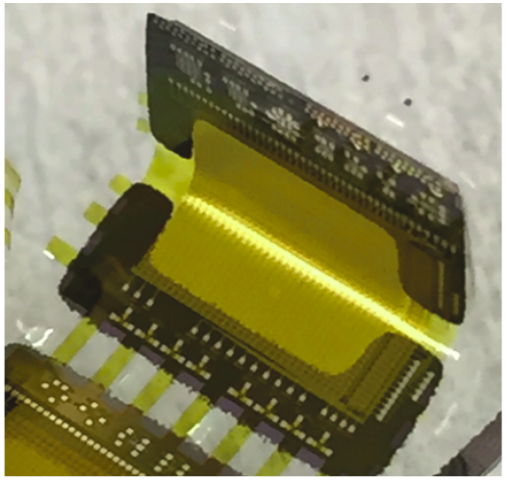
- Sub-65nm CMOS
- Large, scalable designs (Lego™ approach)
- Backside illumination (BSI) 3D IC
- New Materials (InP, GaAs, Ge, polymers)
- Small pixels, low noise, μlenses

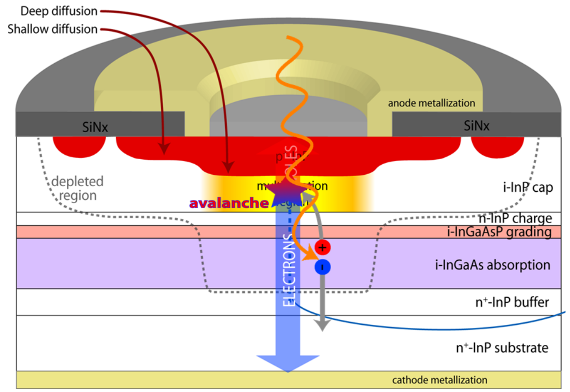


Sammak, Aminian, Charbon, Nanver, IEDM11



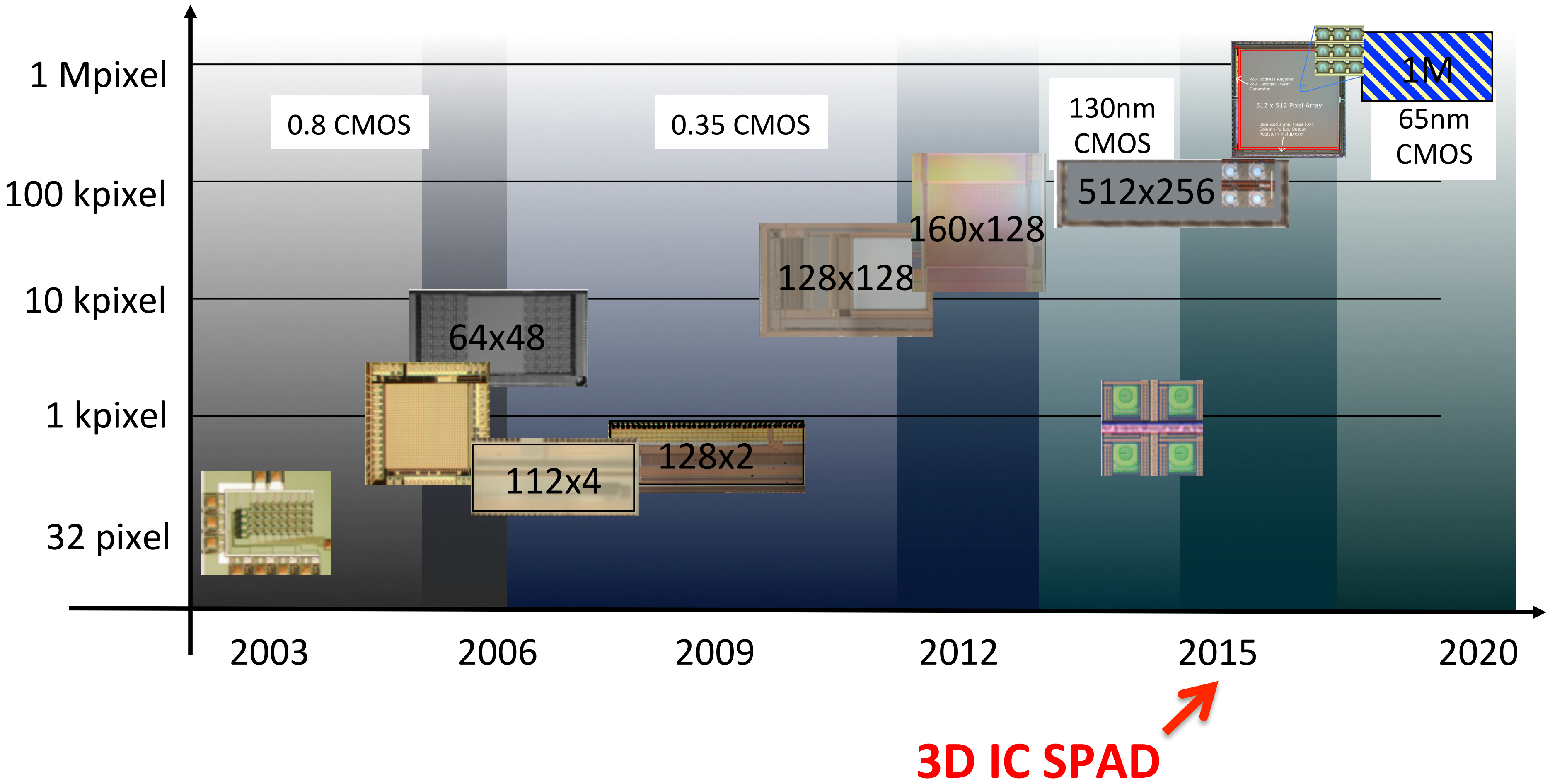
Ximenes, Padmanabhan, Charbon, IISW, 2017


Sun, Ishihara, Charbon, IISW, 2017



Tosi et al, 2012

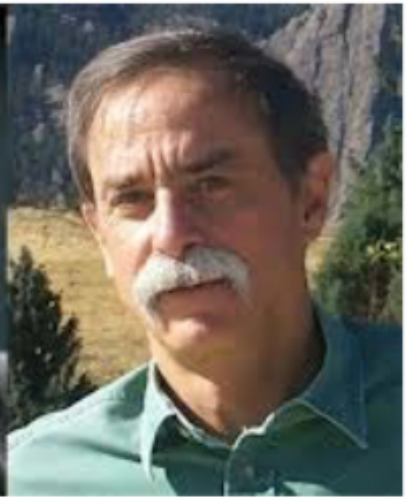
# Moore’s Law for SPADs



# SPADs in
# Quantum Computing

# Quantum Computing

Serge Haroche



David Wineland

2012 Physics Nobel Prize

*Both Laureates work in the field of quantum optics studying the fundamental interaction between light and matter, a field which has seen considerable progress since the mid-1980s. Their ground-breaking methods have enabled this field of research to take the very first steps towards building a new type of super fast computer based on quantum physics. Perhaps the quantum computer will change our everyday lives in this century in the same radical way as the classical computer did in the last century.*

–Announcement 2012 Nobel Prize

# From bits to qubits

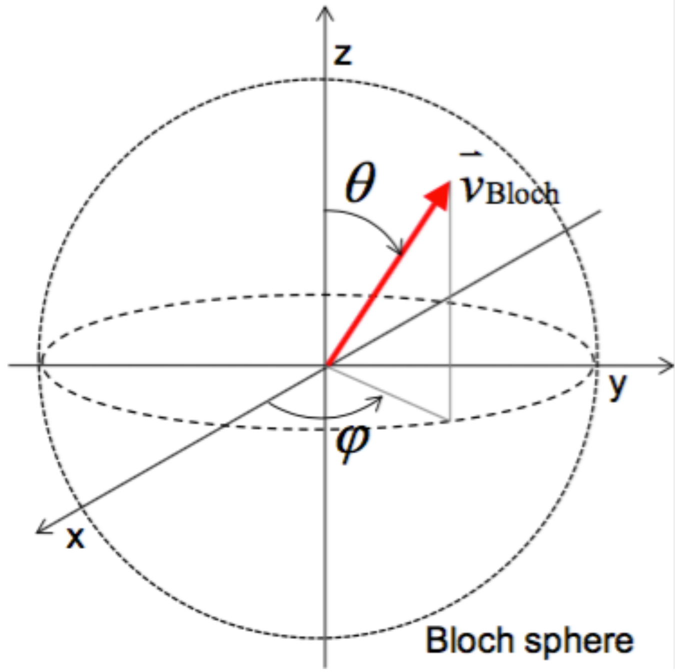
- A quantum bit or qubit is a quantum system in which the Boolean states 0 and 1 are represented by a pair of mutually orthogonal quantum states labeled as $|0\rangle, |1\rangle$
- Quantum properties: **superposition** and **entanglement**

- $\alpha_0, \alpha_1 \in C$
- $|\alpha_0|^2 + |\alpha_1|^2 = 1$

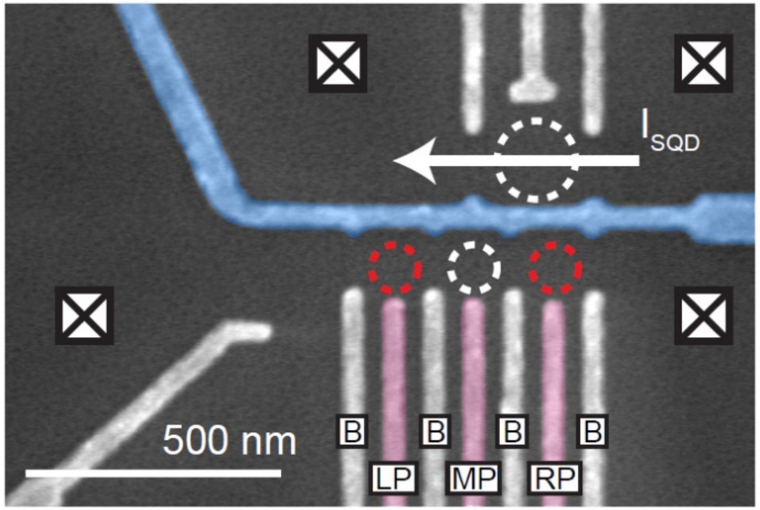
$$|\psi\rangle = e^{i\delta}\left(\cos(\theta/2)|0\rangle + e^{i\varphi}\sin(\theta/2)|1\rangle\right)$$

$\theta$ is polar angle

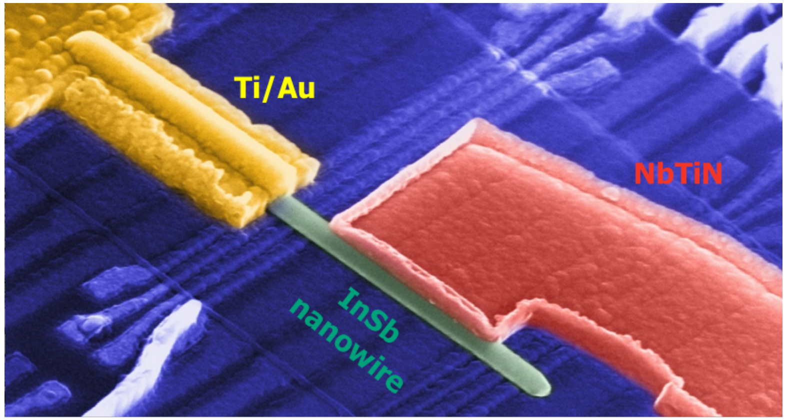
$\varphi$ is azimuthal angle



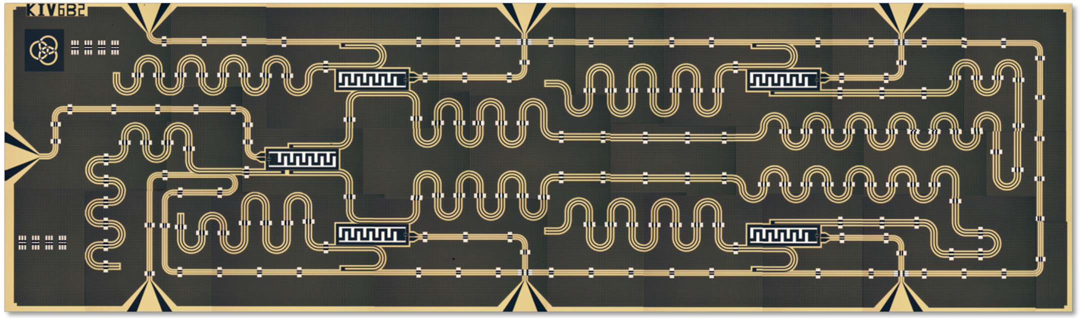
# Qbits on a Chip



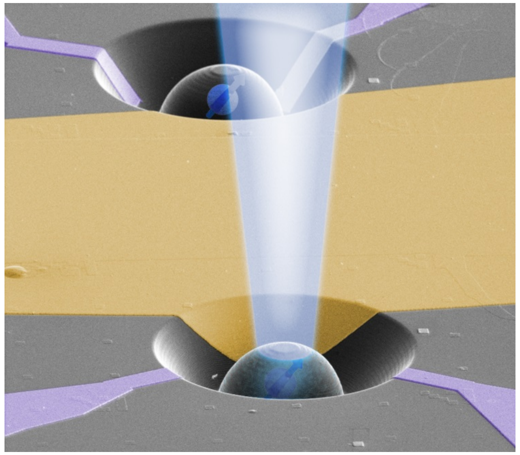

Semiconductor quantum dots




Semiconductor-superconductor hybrids



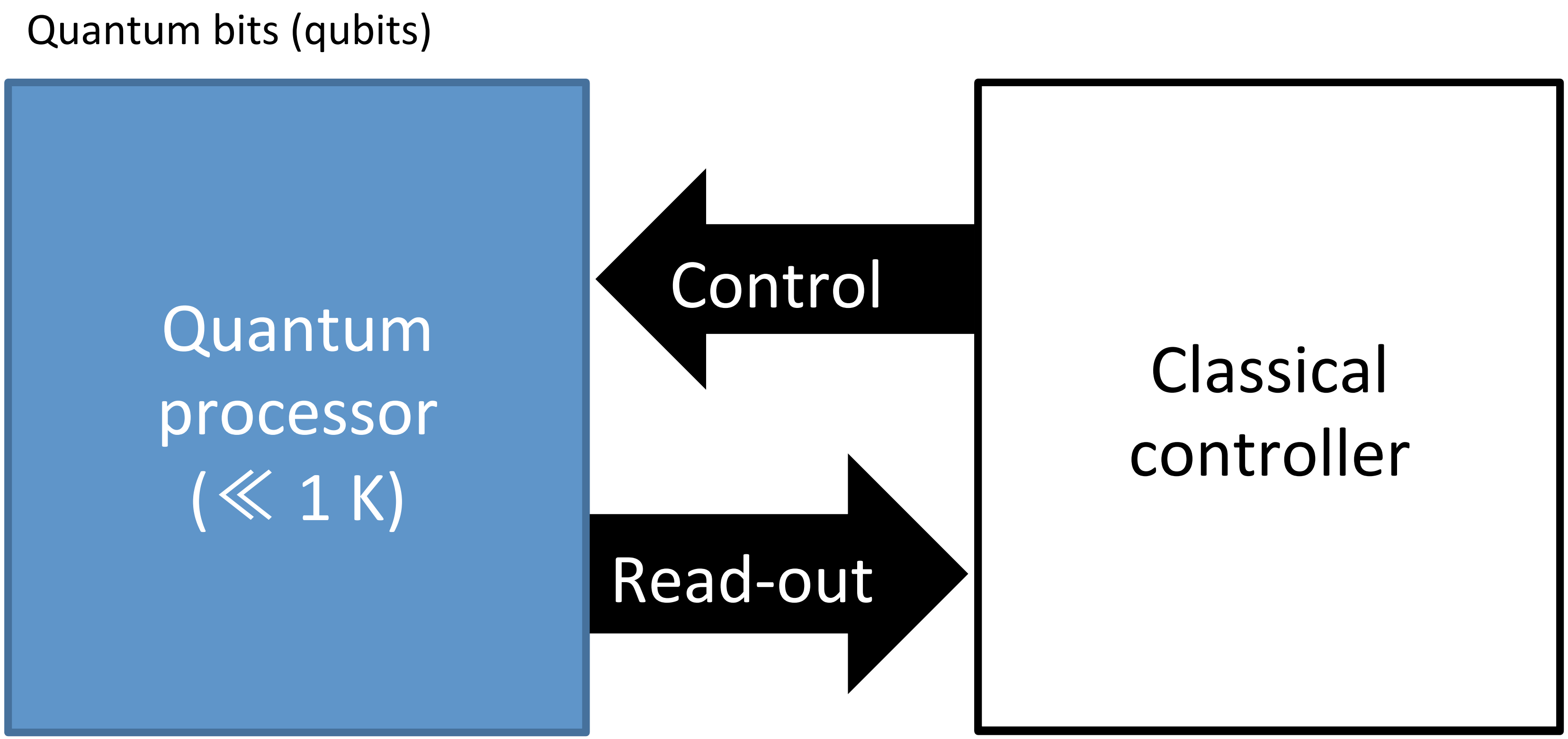
Superconducting circuits



Impurities in diamond or silicon

Source: L. Vandersypen, 2017

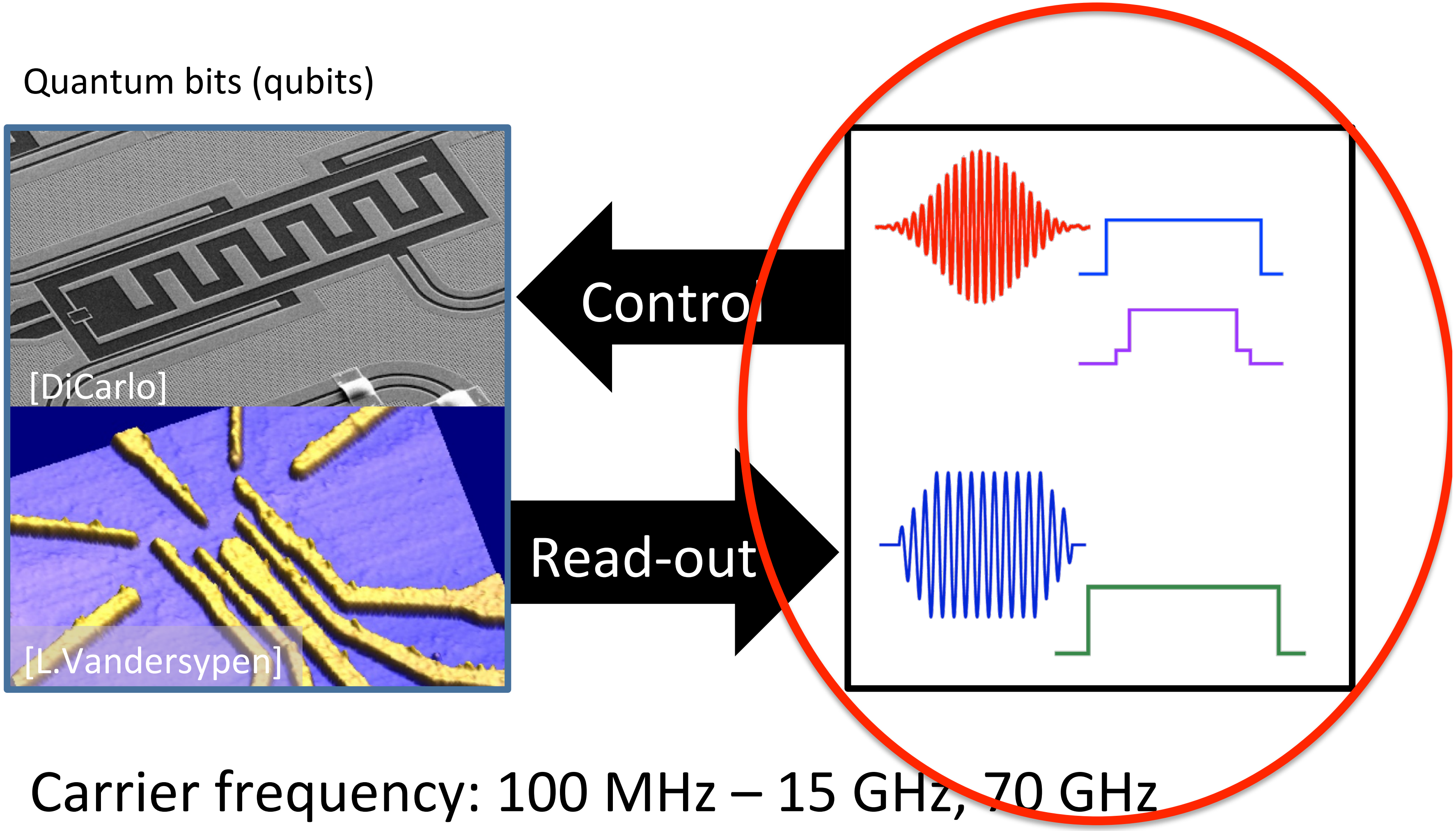
# Quantum Computer Architecture




- Carrier frequency: 100 MHz – 15 GHz, 70 GHz
- Pulses: 10 – 100 ns

# Quantum Computer Architecture

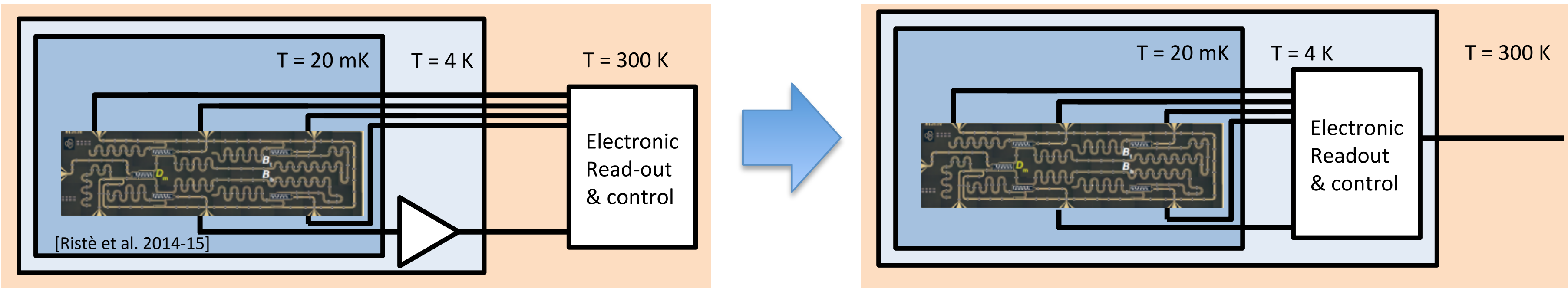
Quantum bits (qubits)




- Carrier frequency: 100 MHz – 15 GHz, 70 GHz
- Pulses: 10 – 100 ns

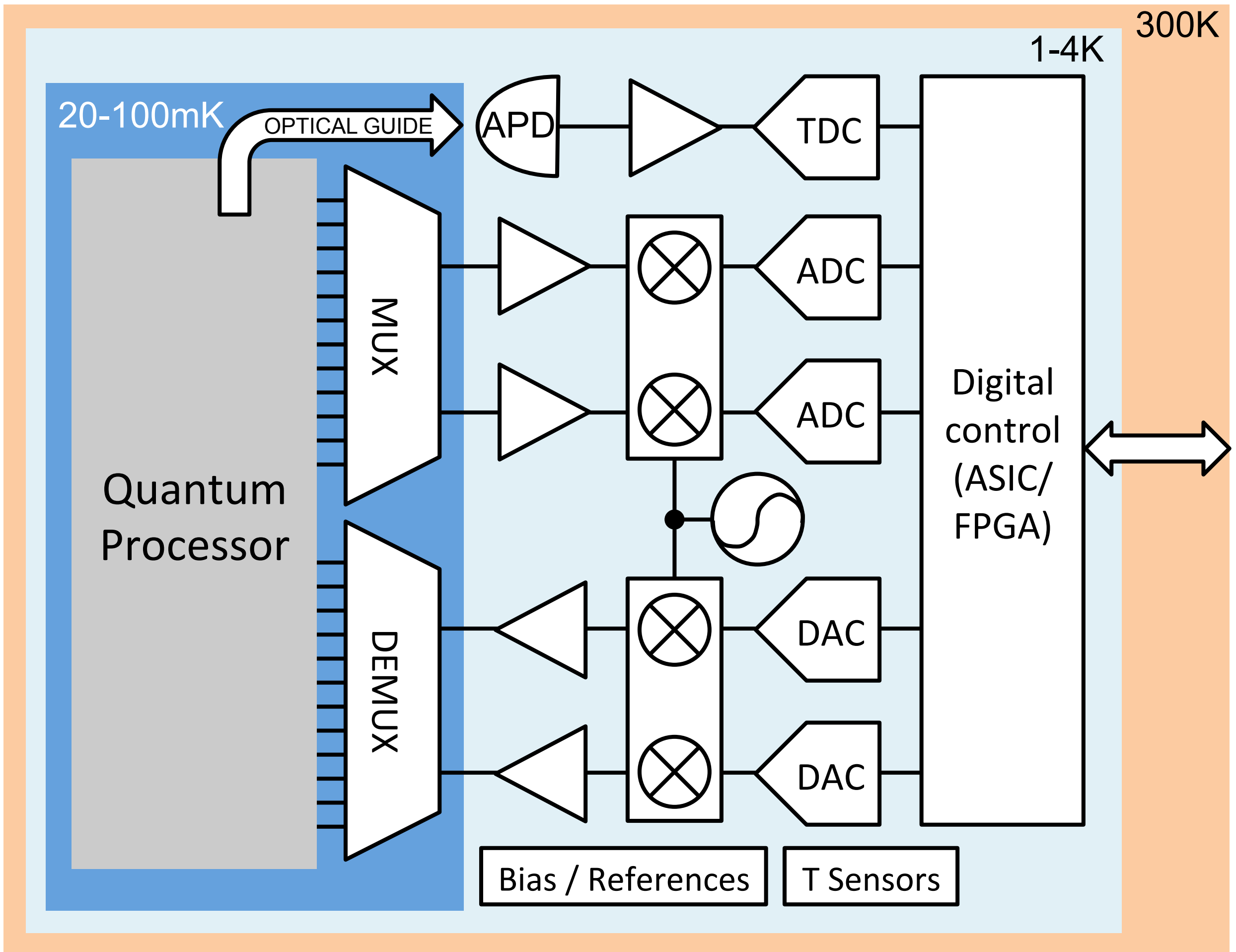
# Possible Solutions

- **Proposed solution**
  - Electronics at 4 K
  - Only connections to 4 K to 20 mK are needed




- **Ultimate solution**
  - Qubits at 4 K
  - Monolithic integration

# Electronic Readout & Control

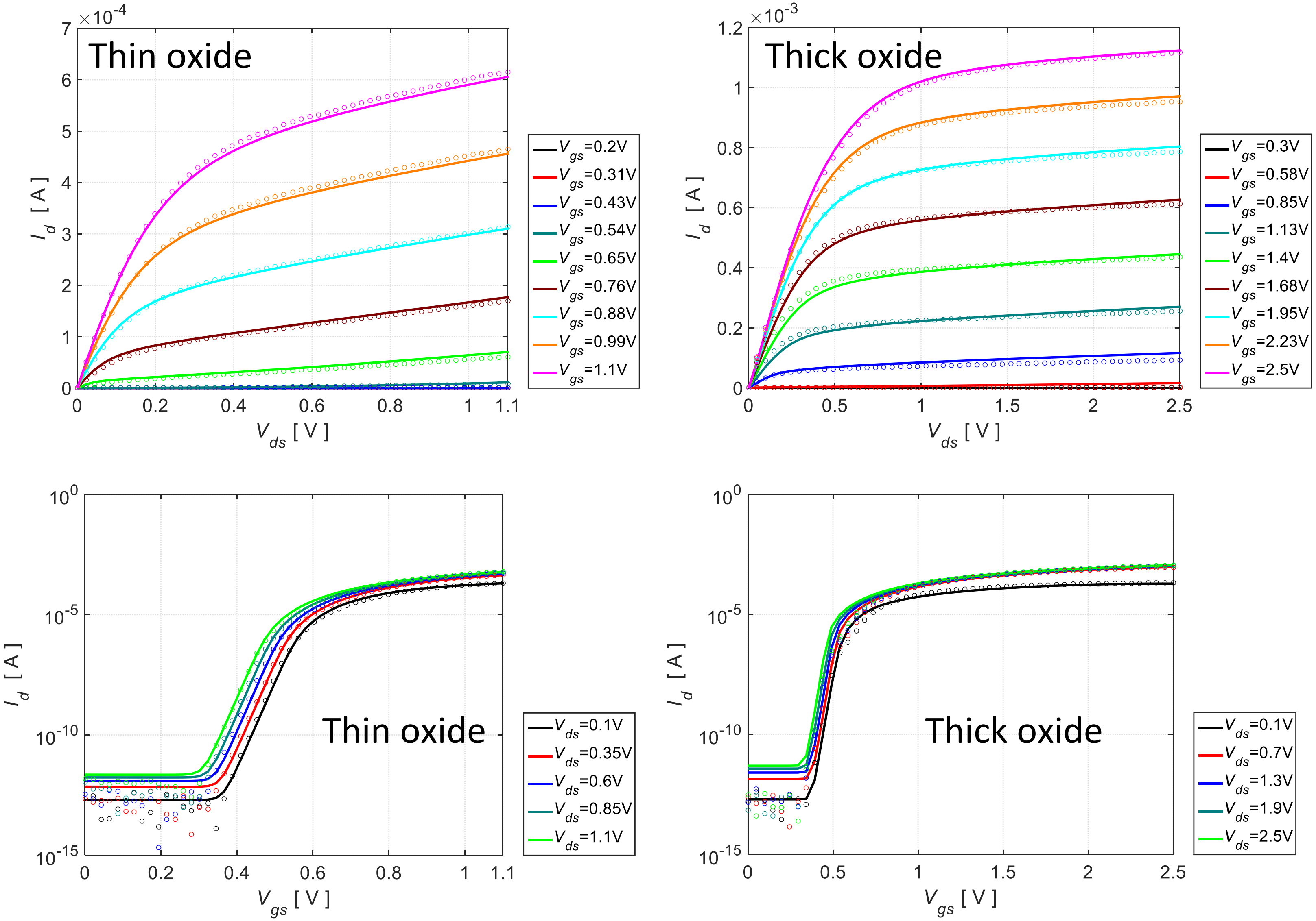



E. Charbon et al., *IEDM* 2016

# Cryogenic Electronics

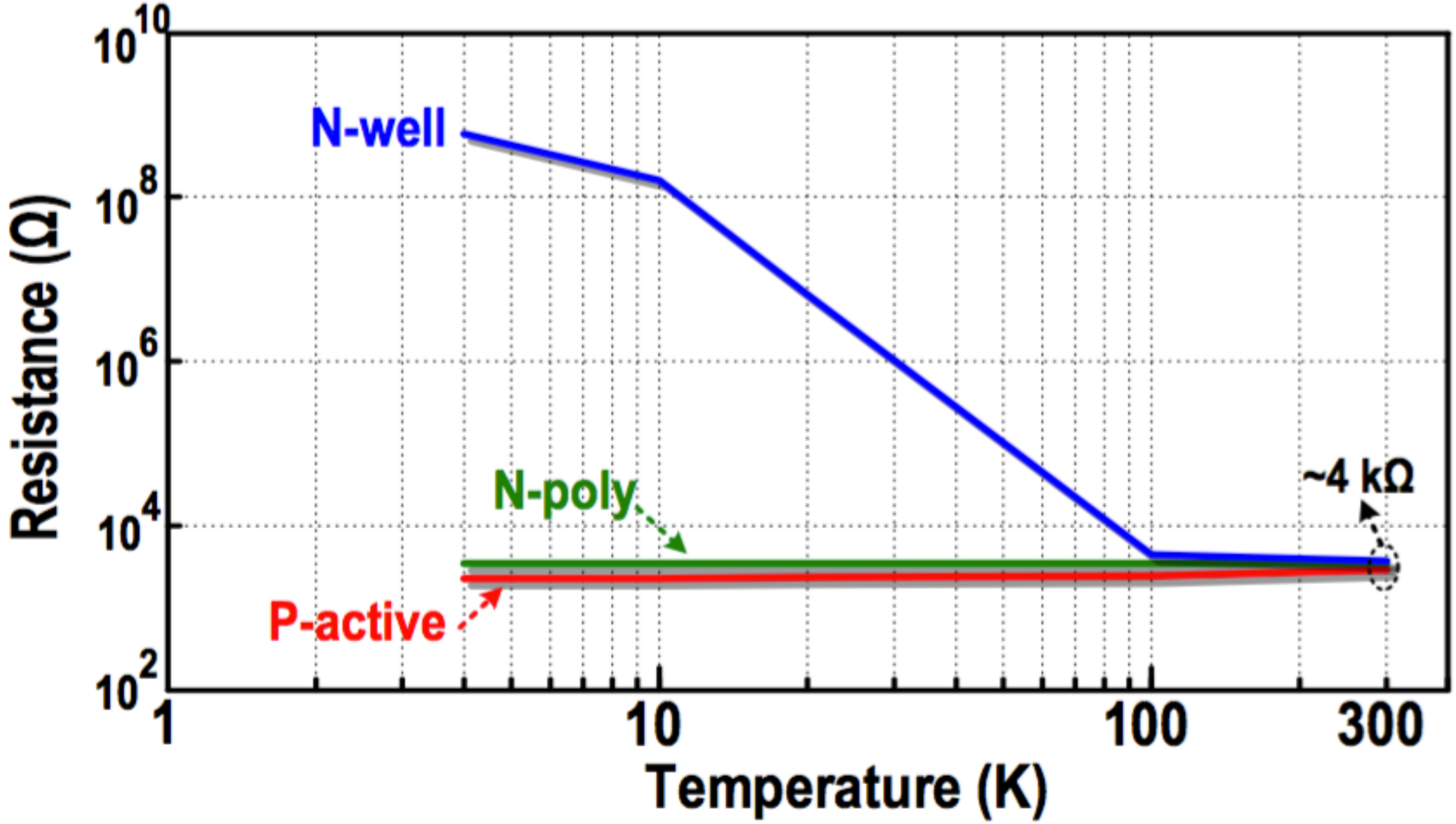
# Cryo-CMOS Technologies

# 40nm MOS at 4K



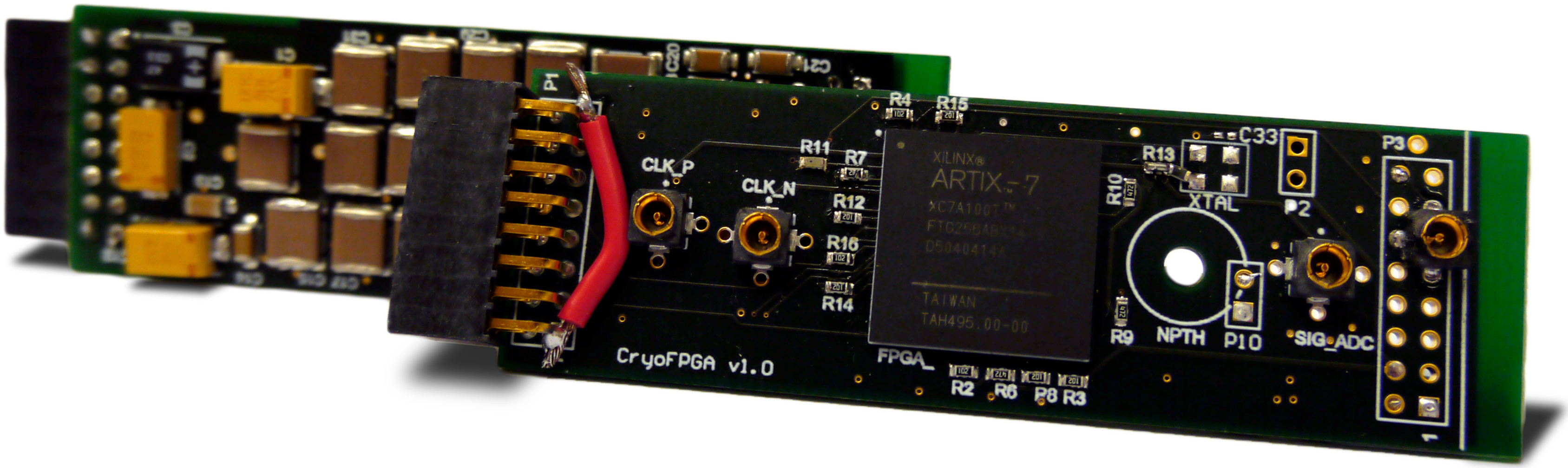

R.M. Incandela et al., *ESSDERC* 2017, Journal of EDS 2018

# Substrate resistivity




B. Patra et al., *JSSC* 2018

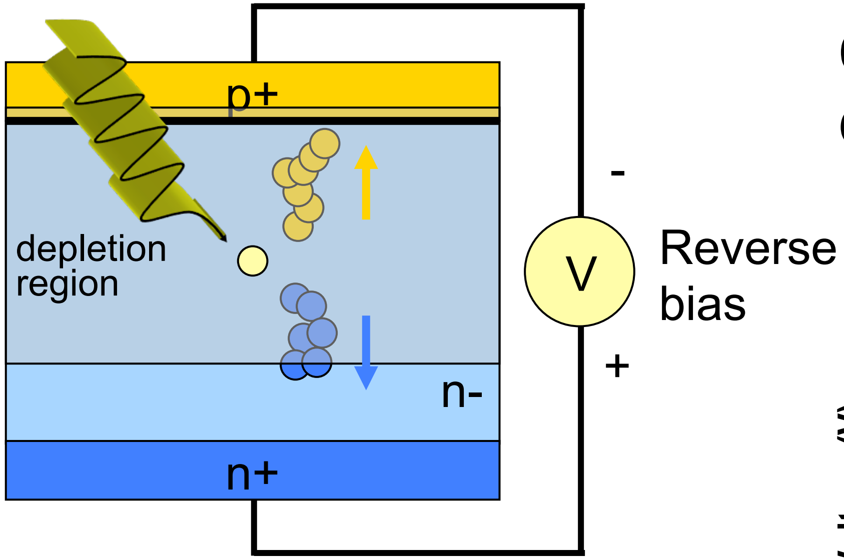
# Cryo-FPGAs




Harald Homulle

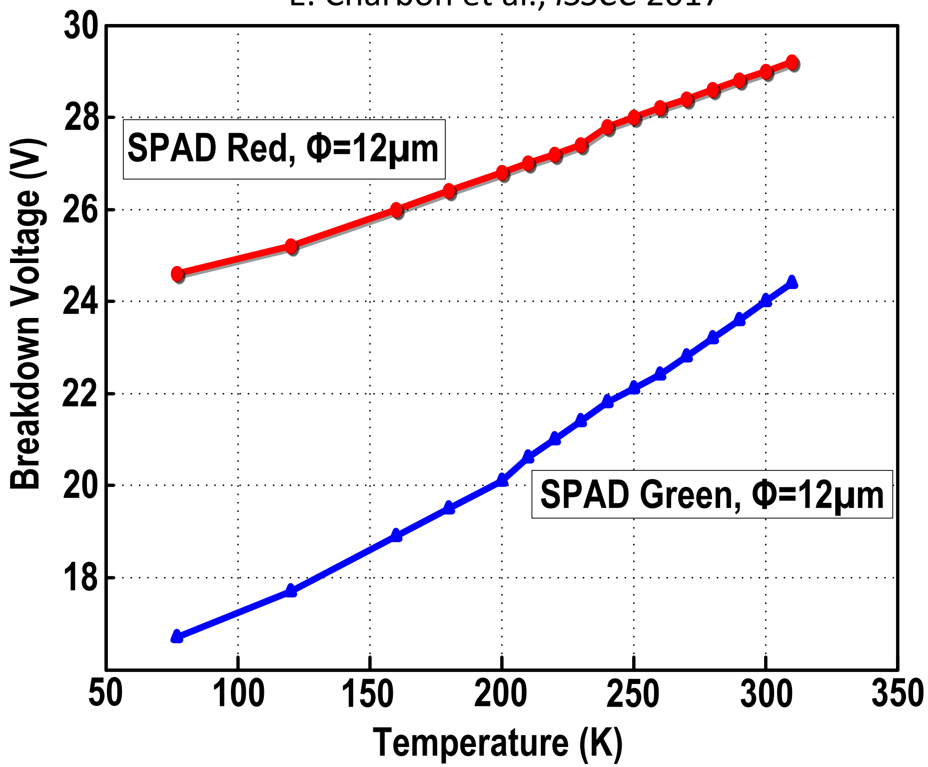
- Artix-7 full operation down to 4K
- Other FPGAs only limited to 30K

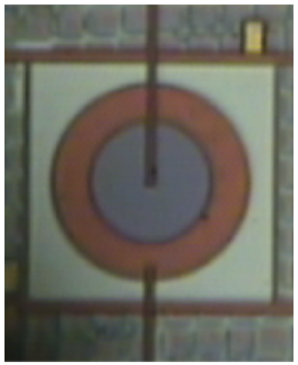
# Cryo-SPADs

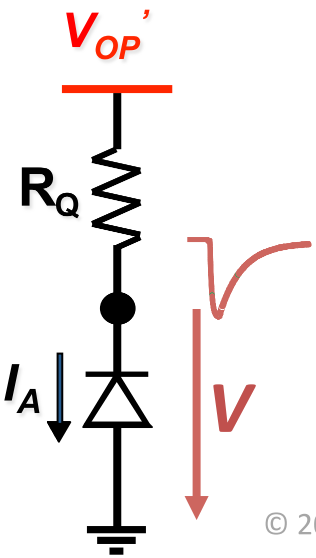



Operation in proportional and Geiger mode (SPAD)

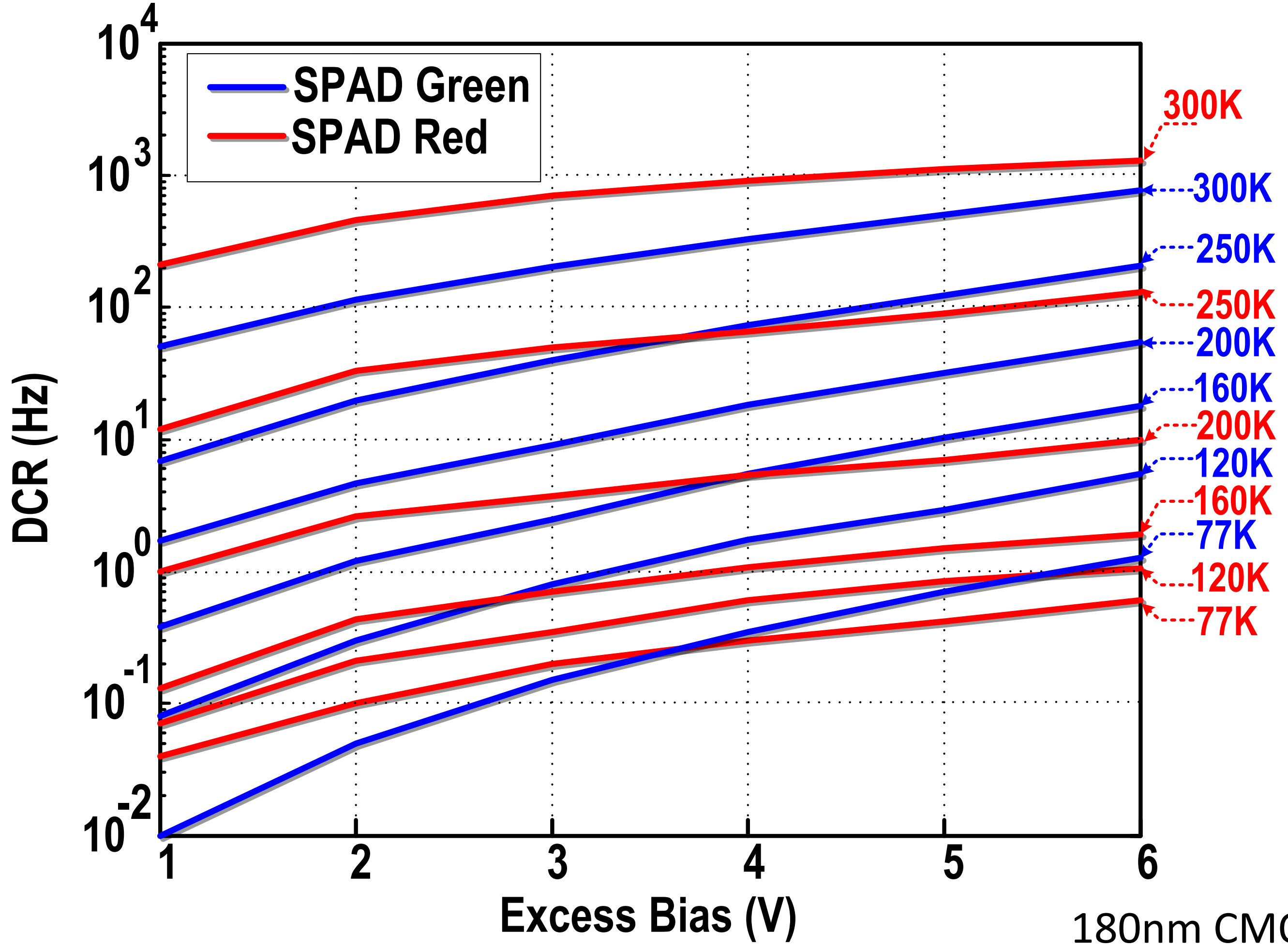
E. Charbon et al., *ISSCC* 2017





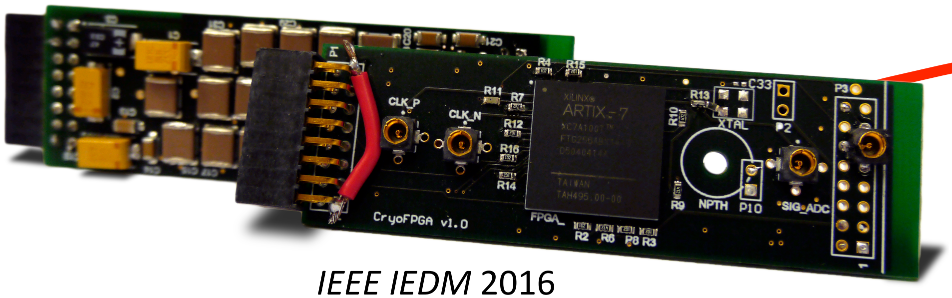
# Cryo-SPADs



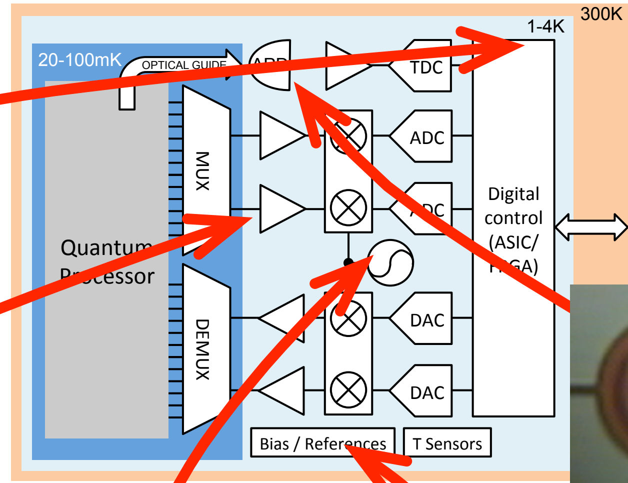

180nm CMOS bulk

B. Patra et al., *JSSC* 2018

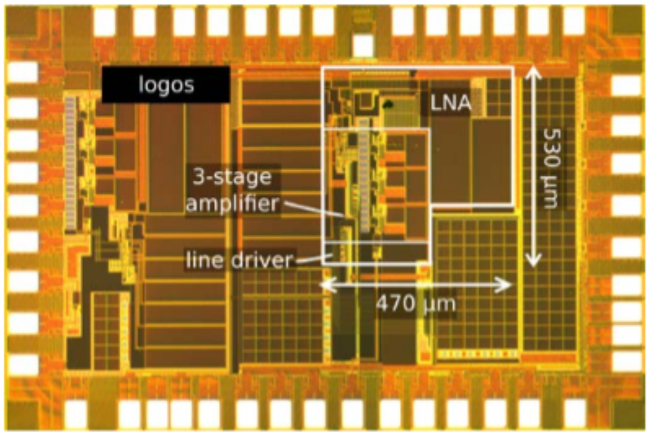
# Building up



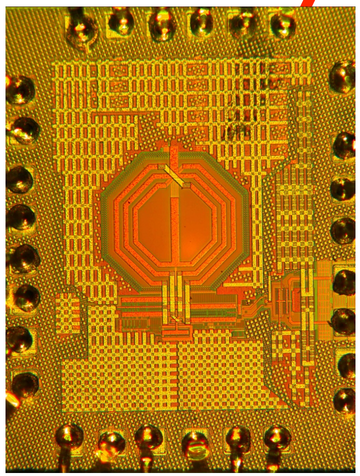

*IEEE IEDM* 2016



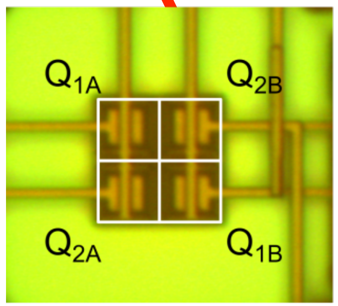

*IEEE IEDM* 2016
IEEE JSS




IEEE ISSCC 2017
IEEE JSSC 2018



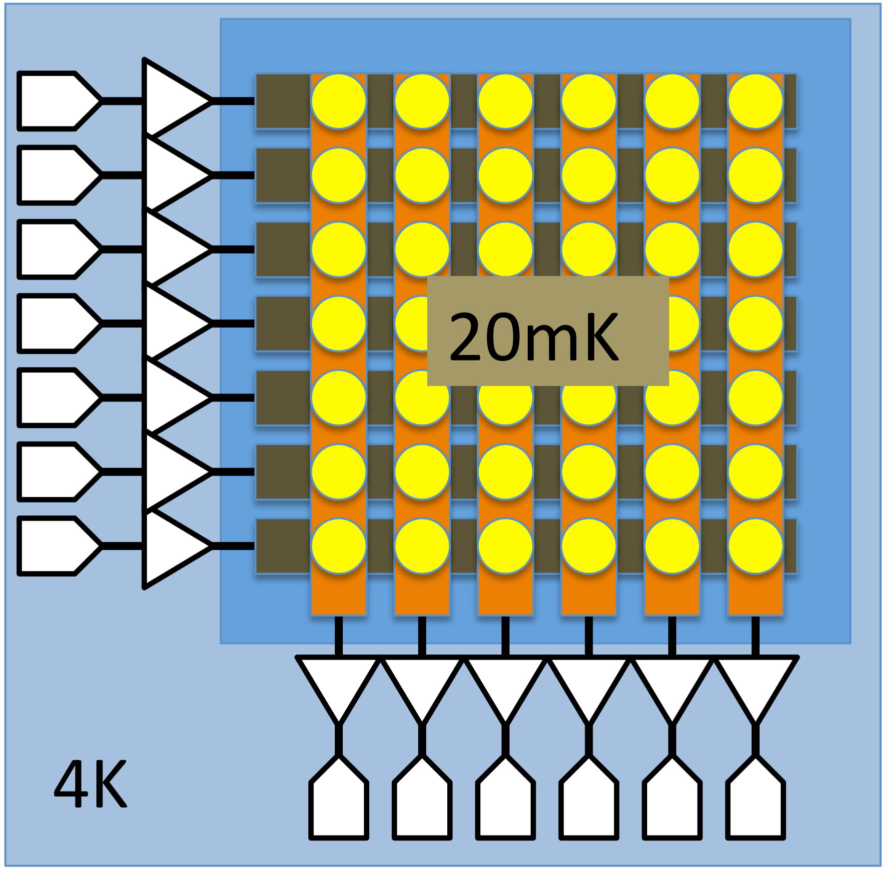
IEEE ISSCC 2017
IEEE JSSC 2018



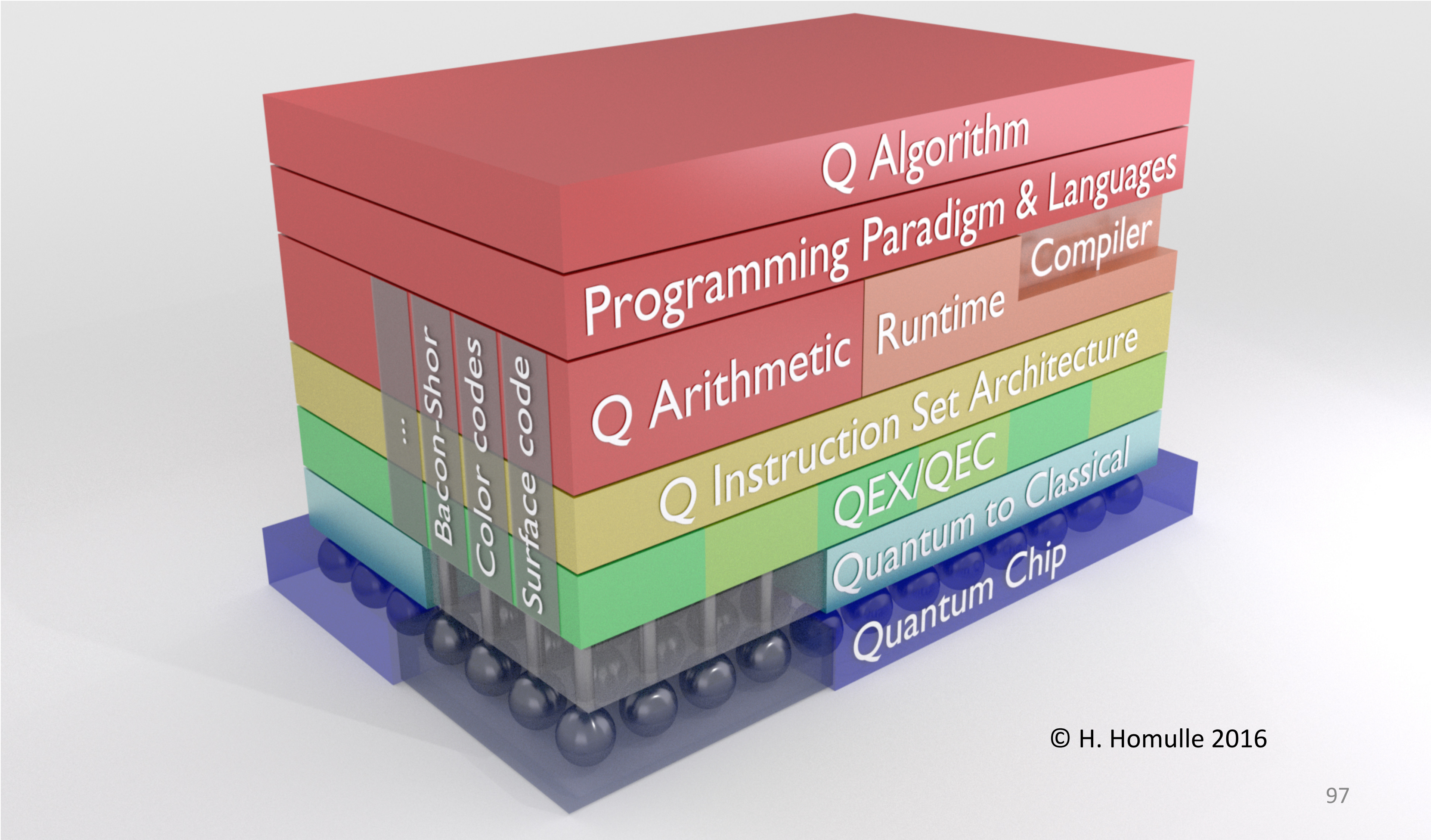

IEEE Sensors 2016

# 2D readout and control

- Use ***imaging sensor*** readout as inspiration
- Reduce number of transistors (ideally to zero)
- Use tunneling barriers as selectors
- (limited) use of 3D stacking



# Putting things in context



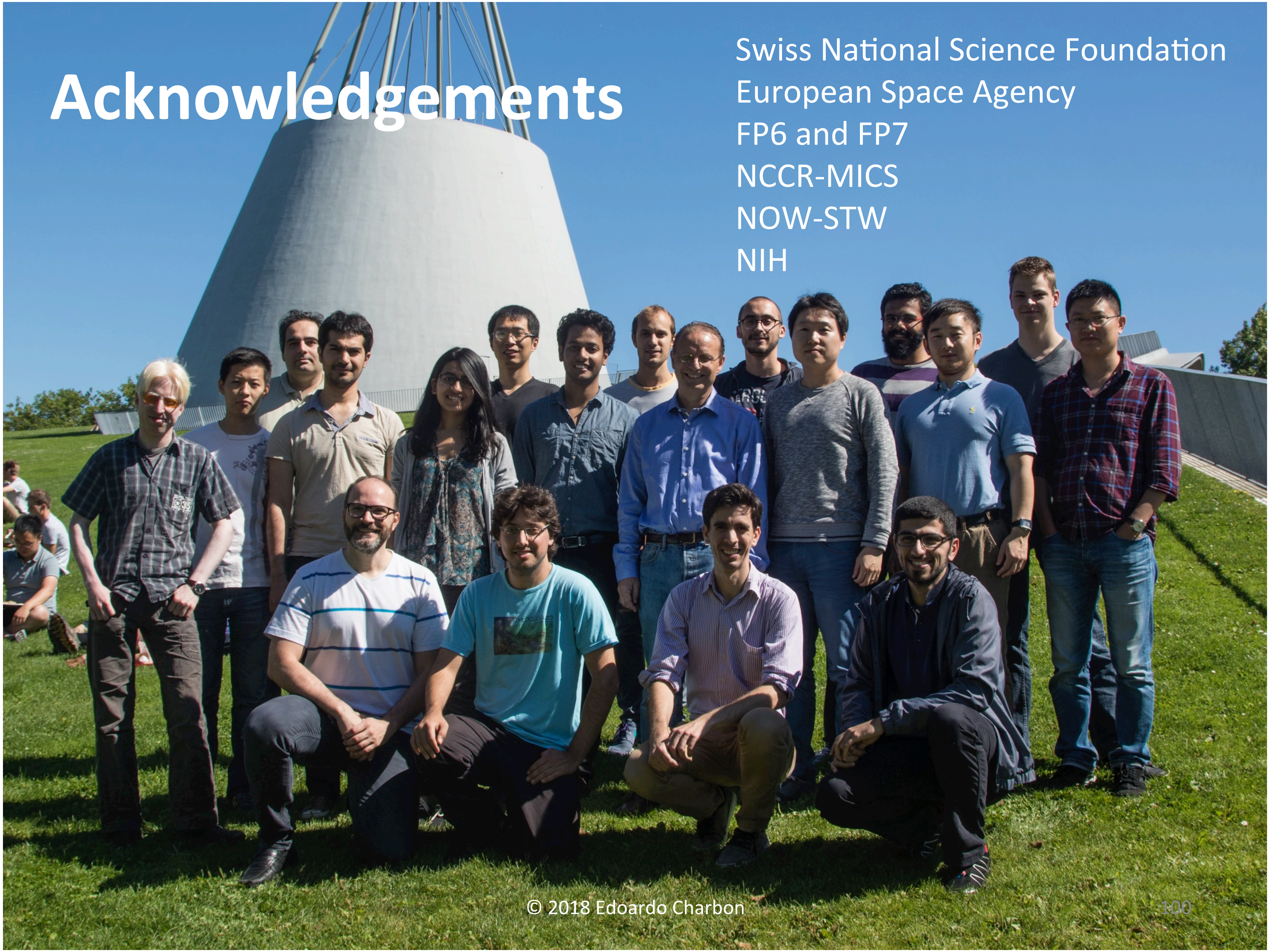
# Conclusions

# Take-home Messages

- SPADs are quantum devices and that they can be used for quantum applications
- Modularity is an important ingredient to large photonic systems and even the technology of a cellphone camera will do
- One can actually make a product (and money) out of SPADs
- Quantum Computing will need cryo-SPADs and 3D ICs

# Acknowledgements

Swiss National Science Foundation
European Space Agency
FP6 and FP7
NCCR-MICS
NOW-STW
NIH



**http://aqua.epfl.ch**

# Selected Literature

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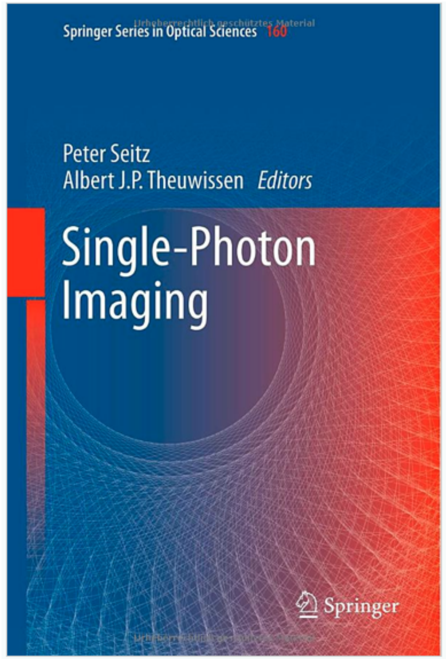


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