The Role of Cryo-CMOS in Quantum Computers

Edoardo Charbon

EPFL, Lausanne, Switzerland

LBL– Berkeley, February 21st, 2019

Outline

- Introduction
- The quantum bit
- Quantum computer architecture
- Cryogenic electronics & cryo-CMOS
  - Models
  - Reconfigurable Hardware
  - ASICs
- Current & future challenges
- Conclusions

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Introduction

Quantum Computing

A computation is a physical process. It may be performed by a piece of electronics or on an abacus, or in your brain, but it is a process that takes place in nature and as such it is subject to the laws of physics.

Quantum computers are machines that rely on characteristically quantum phenomena, such as quantum interference and quantum entanglement in order to perform computation.

– Artur Ekert

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– Artur Ekert

Overarching goal

Solve intractable problems with massive speedup in computation…

…using the superposition and entanglement, two of the cornerstones quantum mechanics

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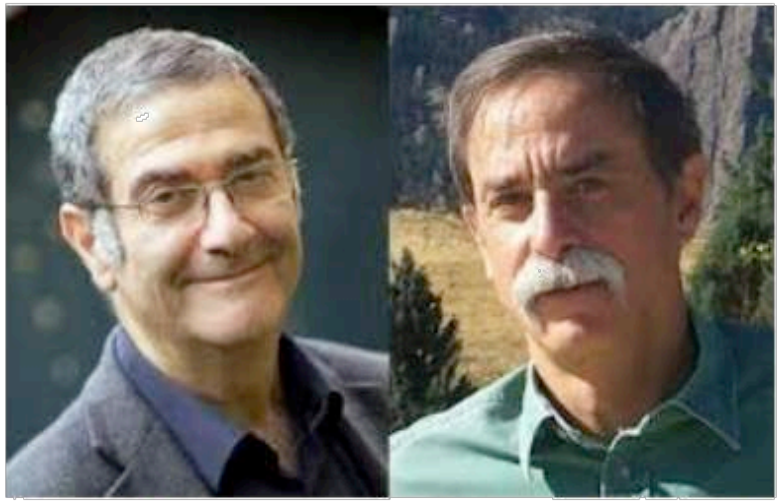
The 2012 Nobel Prize



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

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The Quantum Hype

Google

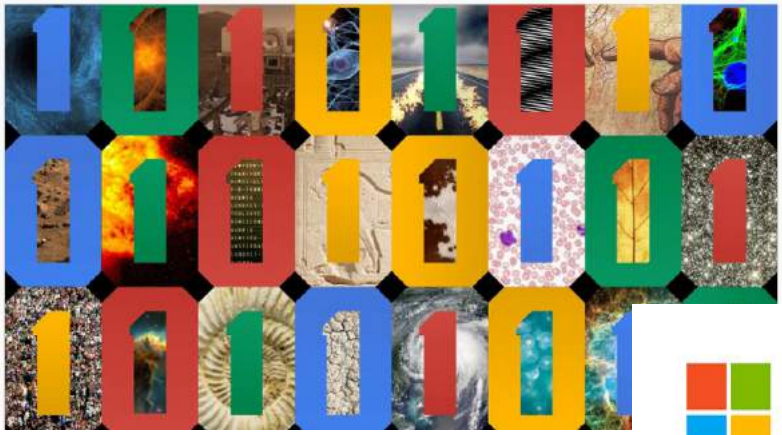
TC News Startups Mobile Gadgets Enterprise Social Trending Apple Google Facel

Google AI quantum computing

Google Partners With UCSB To Build Quantum Processors For Artificial Intelligence

Posted Sep 2, 2014 by Frederic Lardinois (@fredericl)

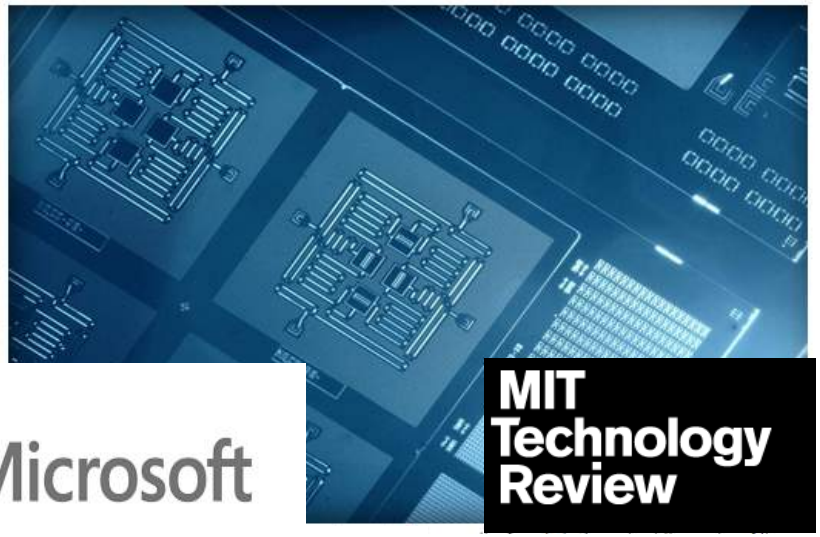
2,888 SHARES



IBM Shows Off a Quantum Computing Chip

A new superconducting chip made by IBM demonstrates a technique crucial to the development of quantum computers.

By Tom Simonite on April 29, 2015



MIT Technology Review

Microsoft

QuArC at Microsoft Research
Station Q @ UCSB

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Quantum Technologies Maturing:
The Intel Involvement

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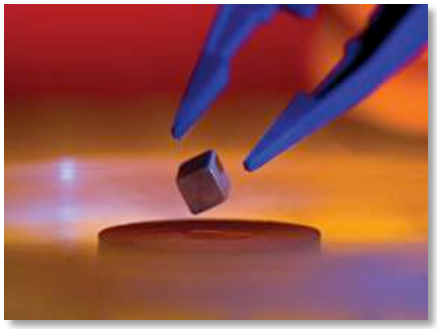
The Promise of Quantum Computing



Energy

Room-temperature superconductivity

Health

Quantum chemistry

Internet Security

Source: L. Vandersypen, ISSCC 2017

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The Quantum Bit

a.k.a. qubit

Definition

- 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> and |1>

- Superposition of states is represented by

$$|\psi\rangle = \alpha_0 |0\rangle + \alpha_1 |1\rangle$$

$\alpha_0, \alpha_1 \in C$

α_i is a probability amplitude

$|\alpha_0|^2 + |\alpha_1|^2 = 1$

$|\alpha_i|^2$ Is the probability of finding the qubit in state $|i\rangle$ when you measure it.

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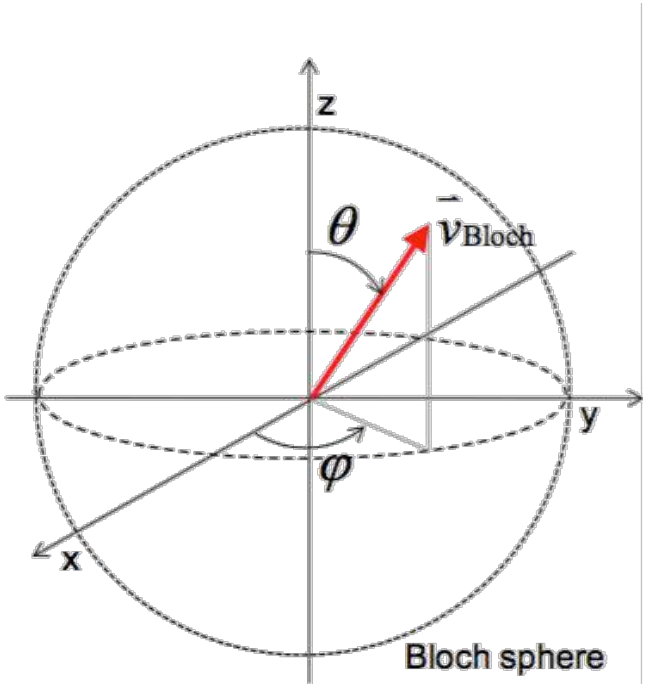
Bloch Sphere

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

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

θ is polar angle

φ is azimuthal angle



- A single qubit is represented in three dimensions
- X,Y,Z axes represent possible projections for qubit readout
- The x-y plane is important – see its importance later

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The Power of Superposition

1 qubit……2 states
2 qubits……4 states

N qubits……2^N states

40 qubits: 10^{12} parallel operations
300 qubits: more than the atoms in the universe

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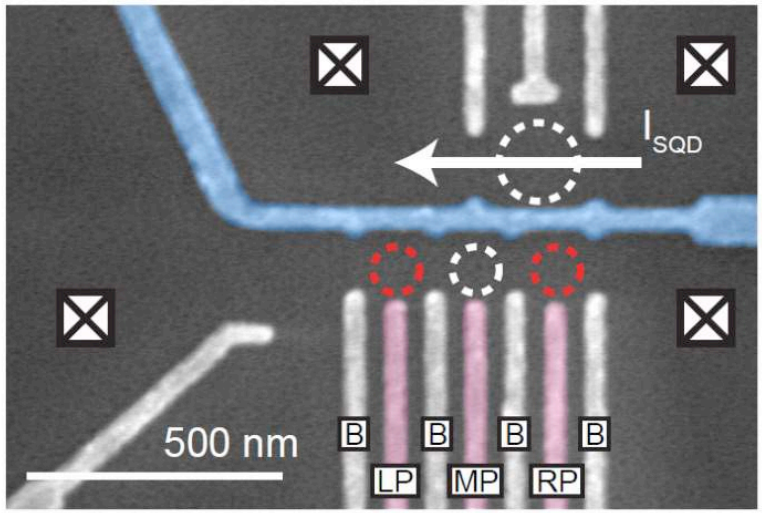
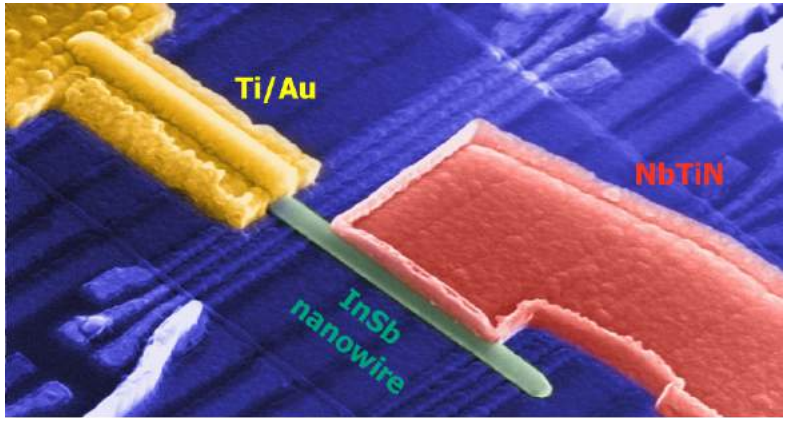
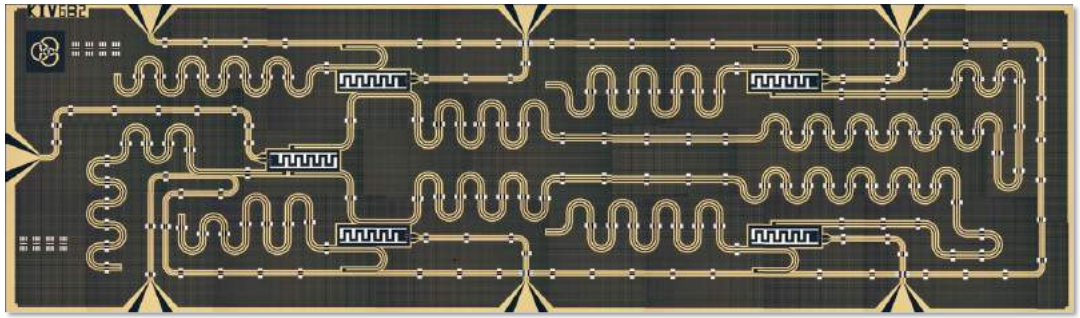
Qubits



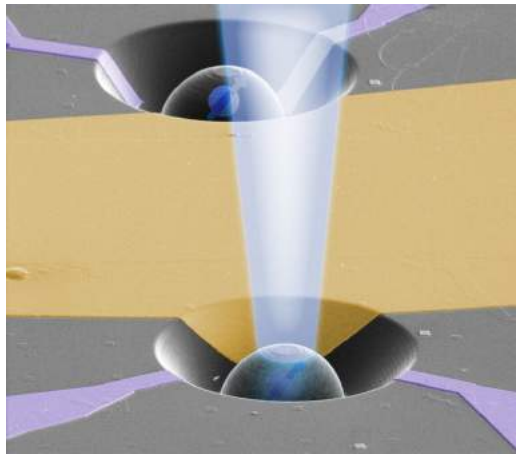
Semiconductor quantum dots



Semiconductor-superconductor hybrids



Superconducting circuits



Impurities in diamond or silicon

Source: L. Vandersypen, 2017

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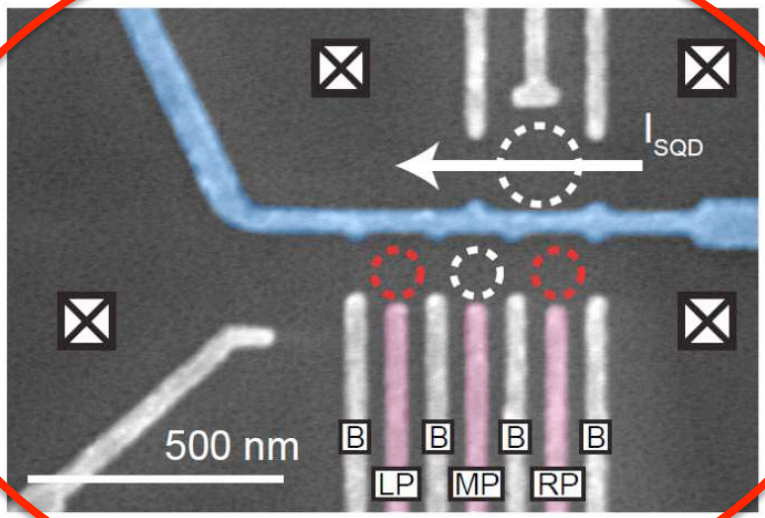
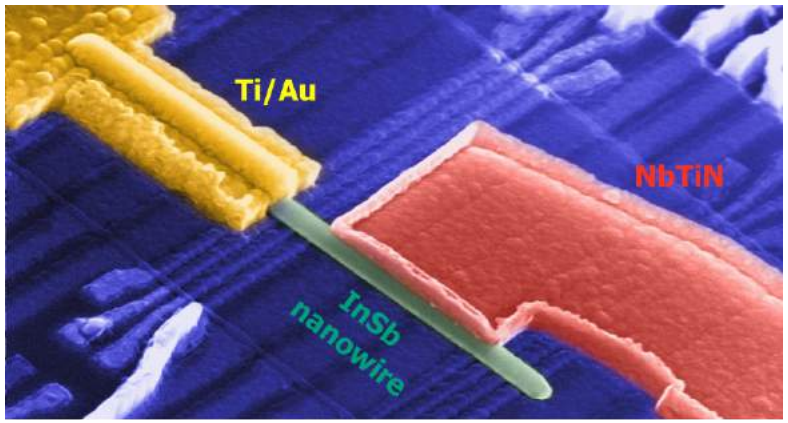
Qubits



Semiconductor quantum dots



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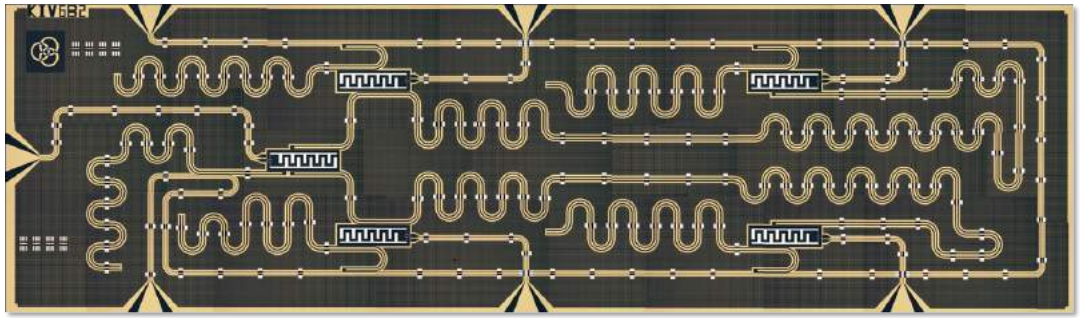
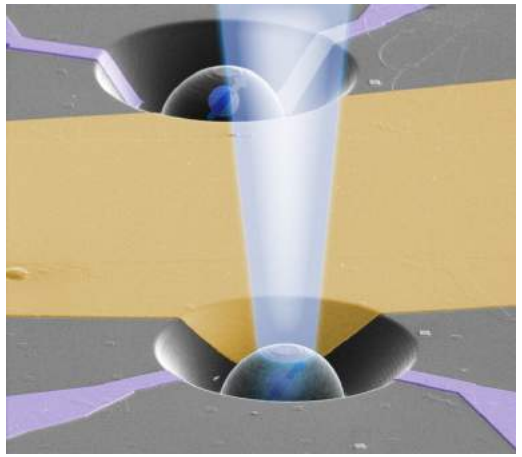


Superconducting circuits



Impurities in diamond or silicon

Source: L. Vandersypen, 2017

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Salient Properties of Qubits

- Coherence time…… µs – ms
- Fidelity of operations…… 99-99.999%
- Miniaturization capability …… nm – mm
- Scalability…… 10^6 – 10^9
- Requires correction

- Differentiating factor between technologies: **scalability** to large arrays, implying requirements on
  - Size/pitch of qubits
  - Yield
  - Reliability
  - Coherence
  - Control

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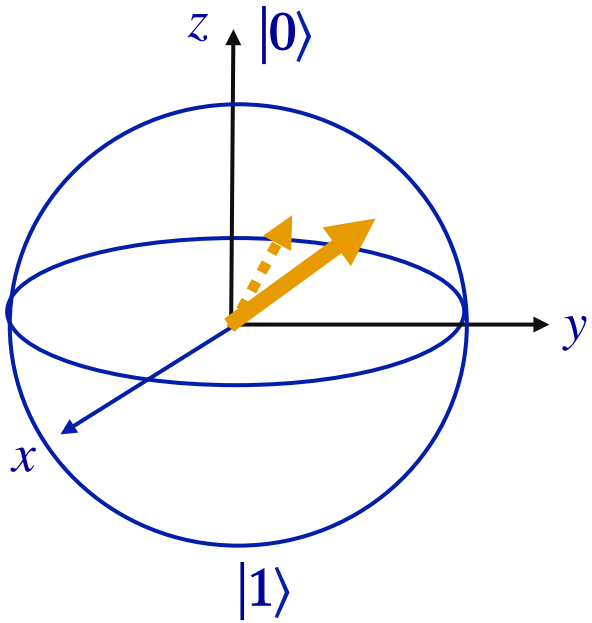
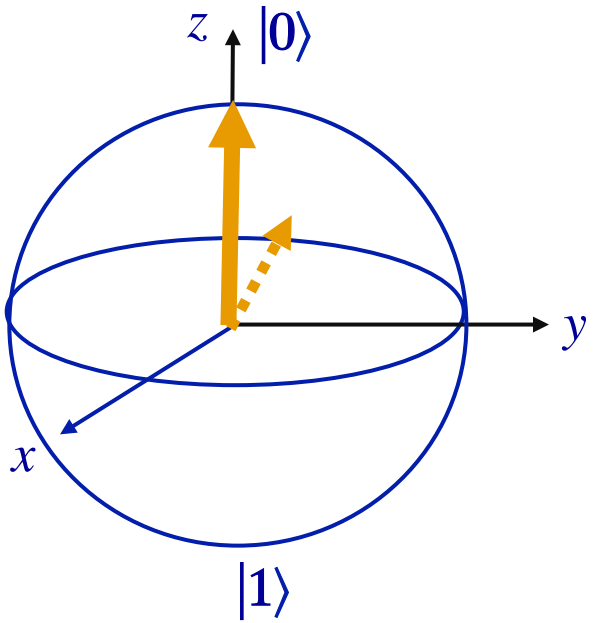
Qubits are Fragile

- Environment can cause decoherence due to dephasing and relaxation
- Fidelity

Dephasing



Relaxation



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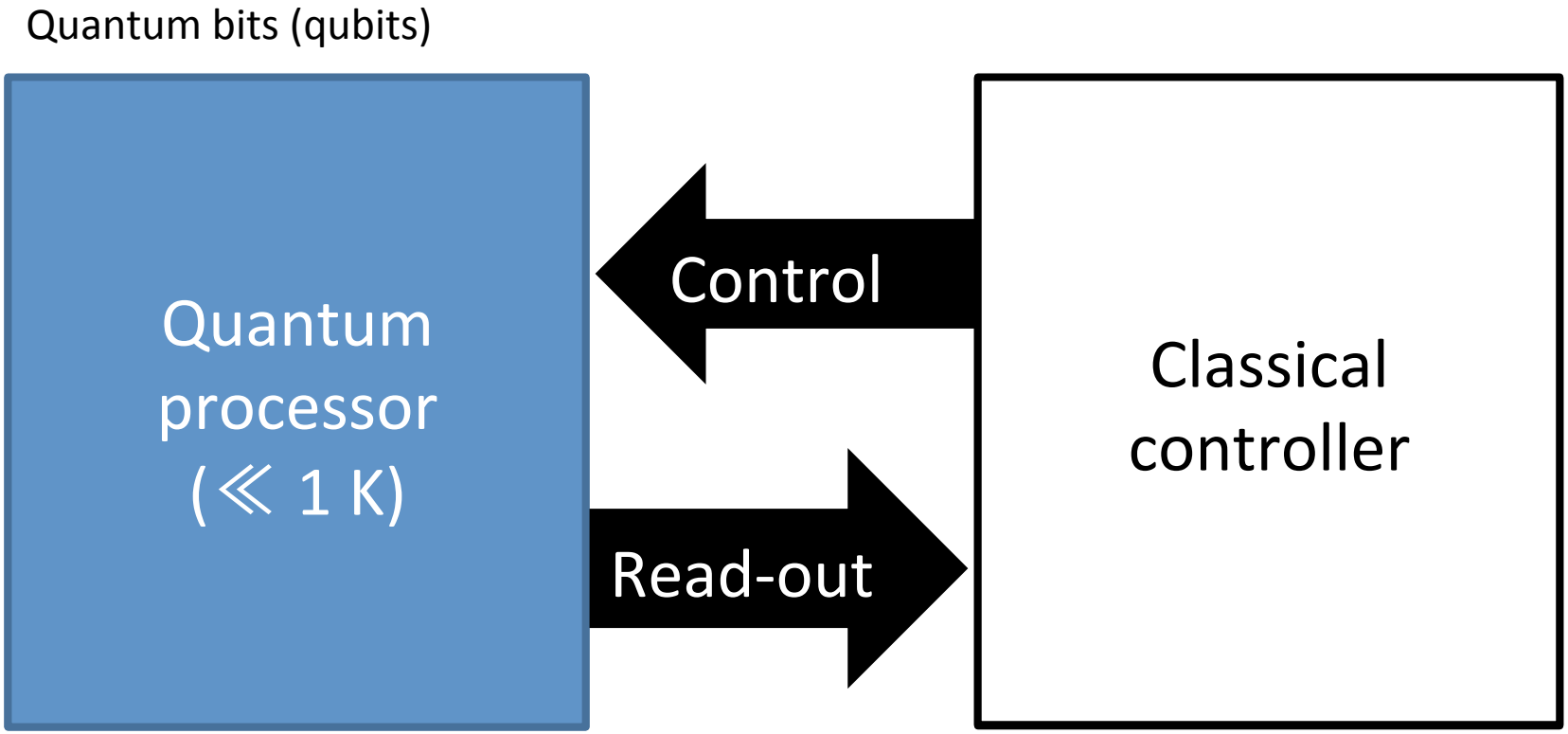
Interfacing Qubits with Classical World



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

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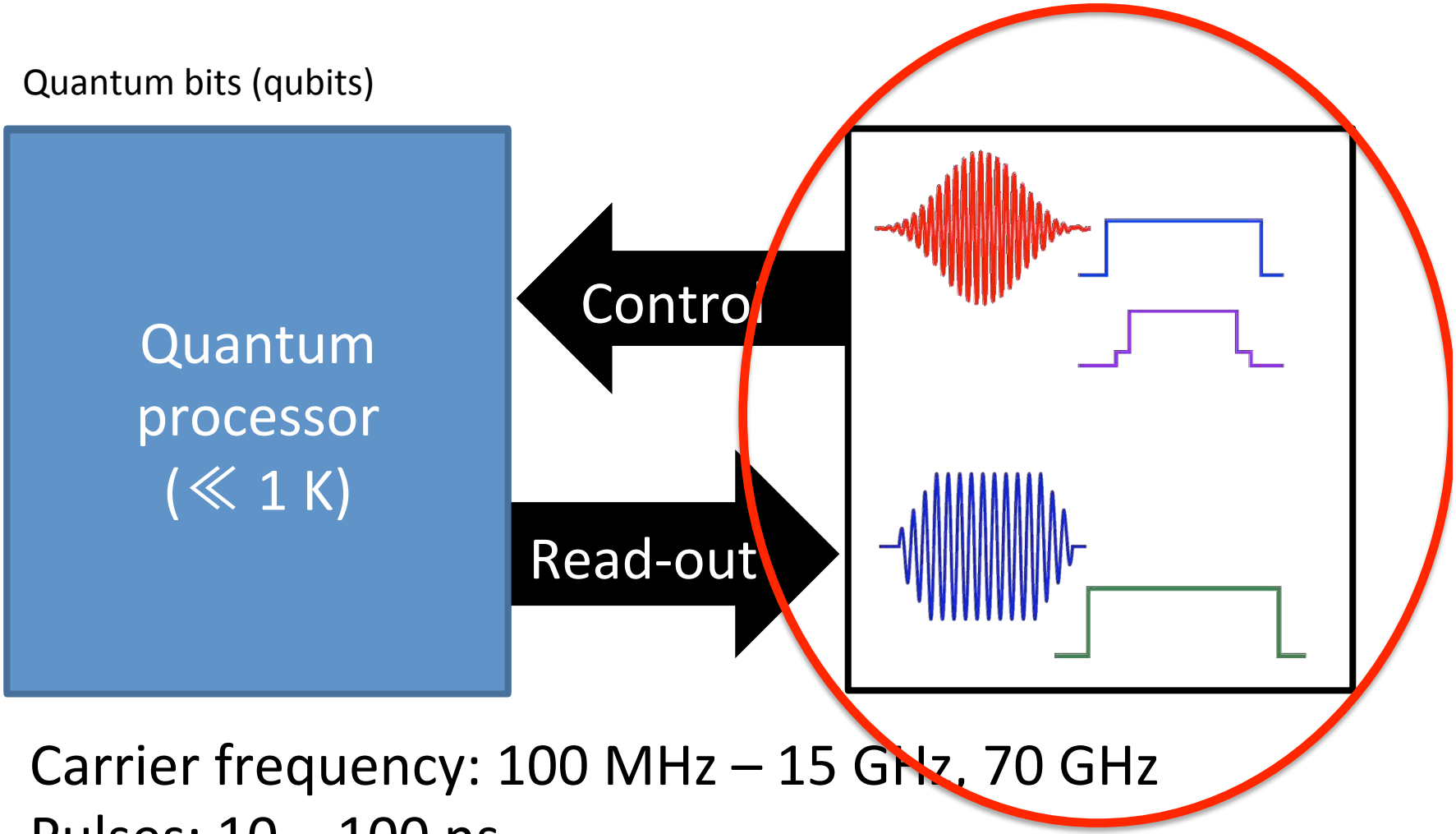
Interfacing Qubits with Classical World



- Carrier frequency: 100 MHz – 15 GHz, 70 GHz
- Pulses: 10 – 100 ns
- Readout techniques for spin qubits: **ESR, EDSR**

ESR: Electron spin resonance – EDSR: Electric dipole spin resonance

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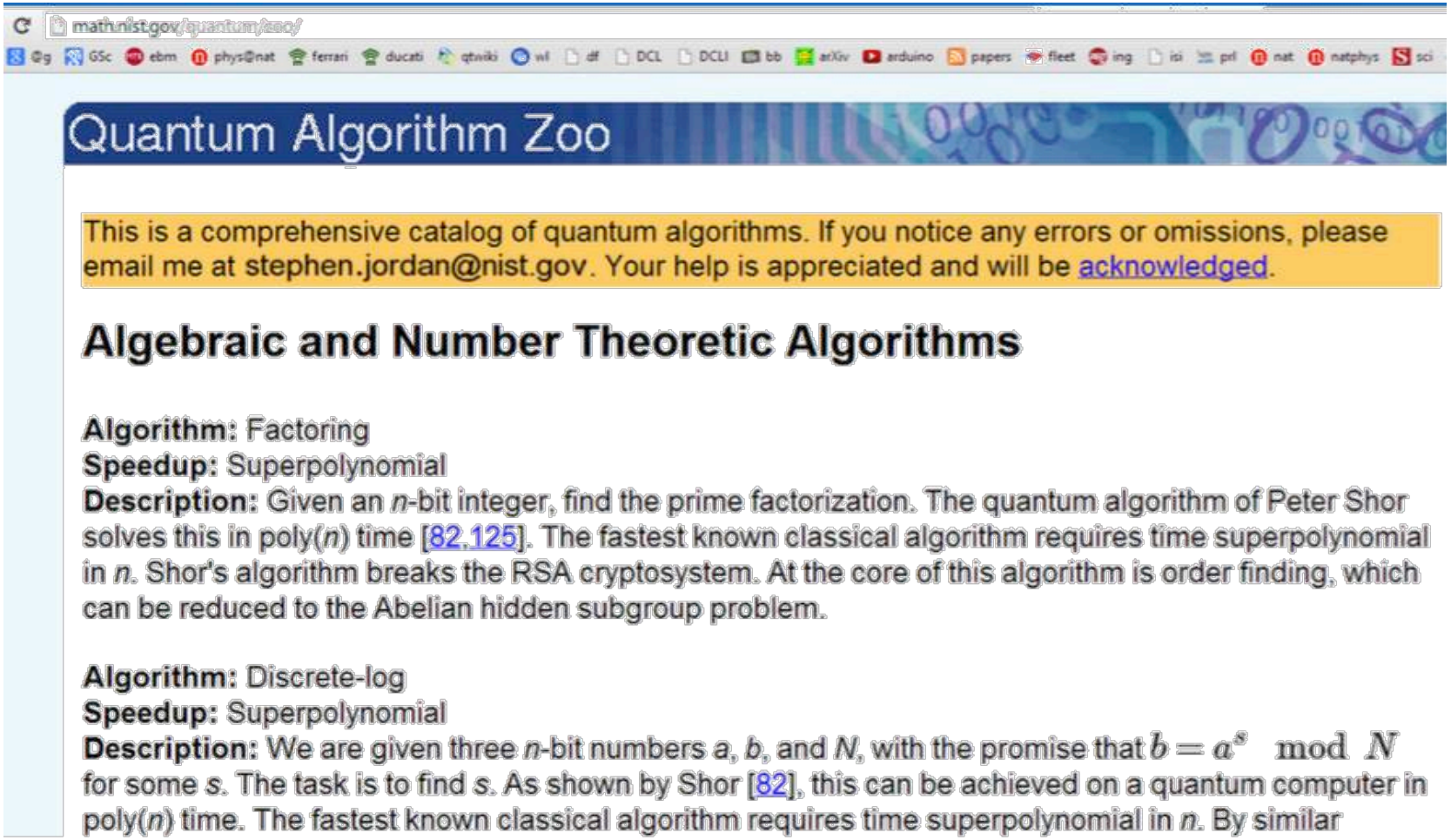
Status of Quantum Algorithms



math.nist.gov/quantum/zoo/

Quantum Algorithm Zoo

This is a comprehensive catalog of quantum algorithms. If you notice any errors or omissions, please email me at stephen.jordan@nist.gov. Your help is appreciated and will be acknowledged.

Algebraic and Number Theoretic Algorithms

Algorithm: Factoring
Speedup: Superpolynomial
Description: Given an n-bit integer, find the prime factorization. The quantum algorithm of Peter Shor solves this in poly(n) time [82,125]. The fastest known classical algorithm requires time superpolynomial in n. Shor's algorithm breaks the RSA cryptosystem. At the core of this algorithm is order finding, which can be reduced to the Abelian hidden subgroup problem.

Algorithm: Discrete-log
Speedup: Superpolynomial
Description: We are given three n-bit numbers a, b, and N, with the promise that $b = a^s \mod N$ for some s. The task is to find s. As shown by Shor [82], this can be achieved on a quantum computer in poly(n) time. The fastest known classical algorithm requires time superpolynomial in n. By similar

~50 algorithms with quantum speedup, but most people know 2.

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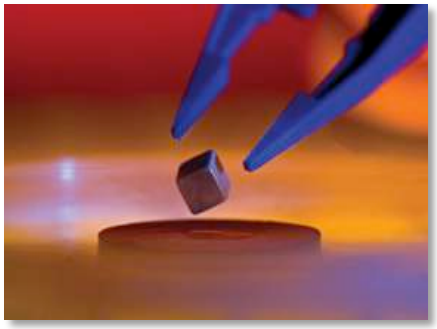
How Many Qubits Do We Need?



Energy

Room-temperature superconductivity

Perhaps millions?

Health

Quantum chemistry

> 200 logical qubits

Internet Security

> 2000 logical qubits

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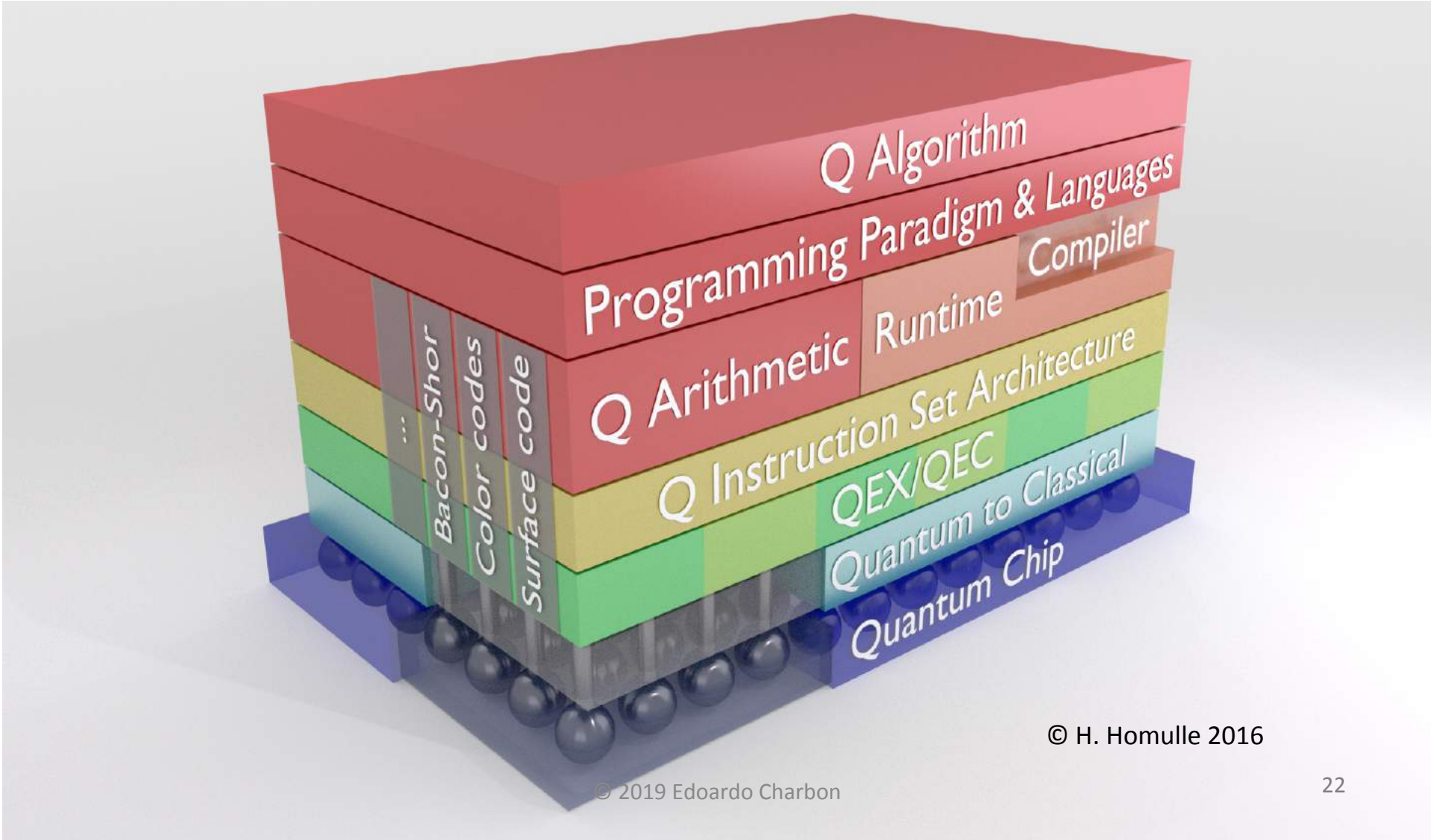
Quantum Computing Stack



© H. Homulle 2016

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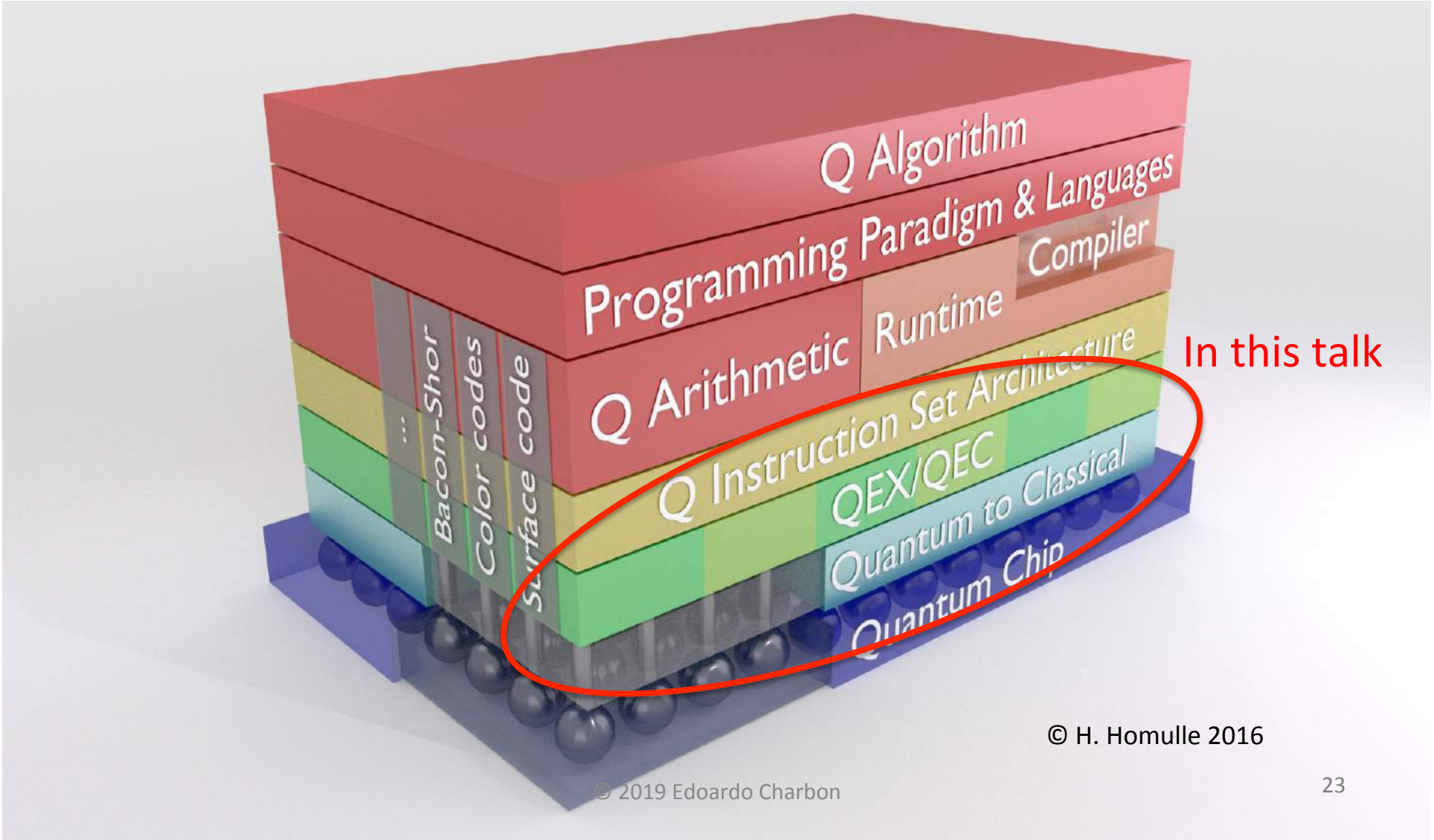
Quantum Computing Stack



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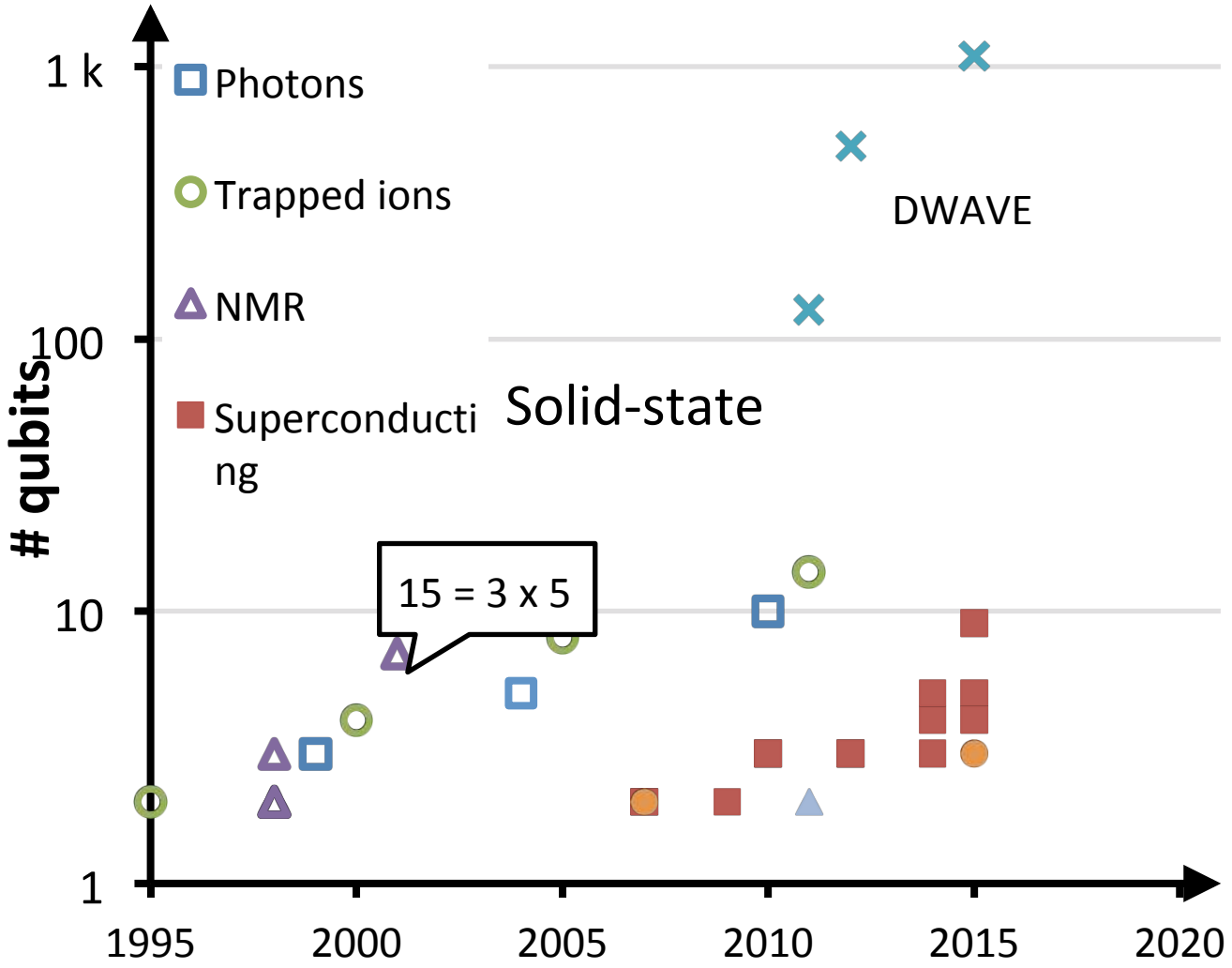
Status of Qubits



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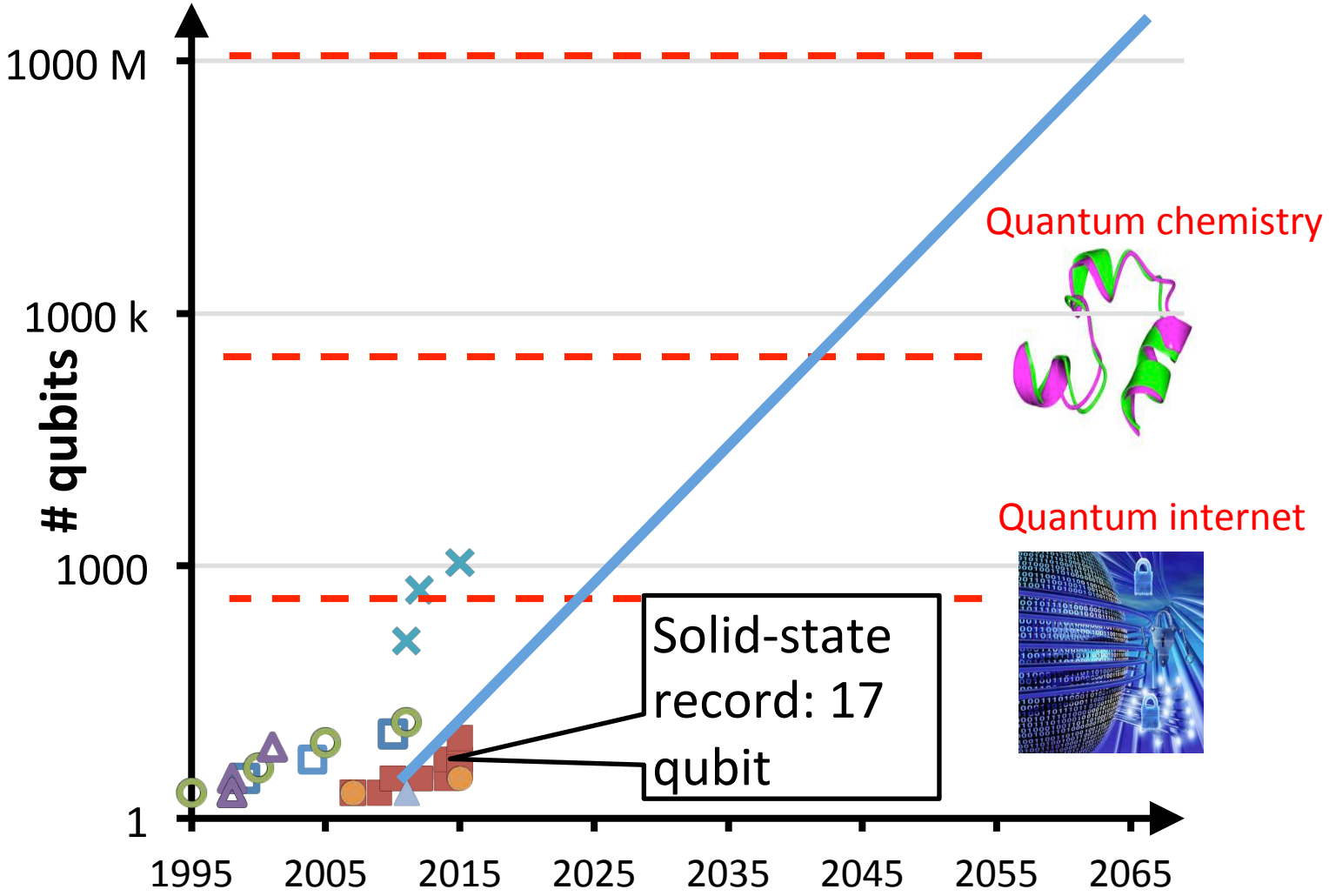
Scaling Up



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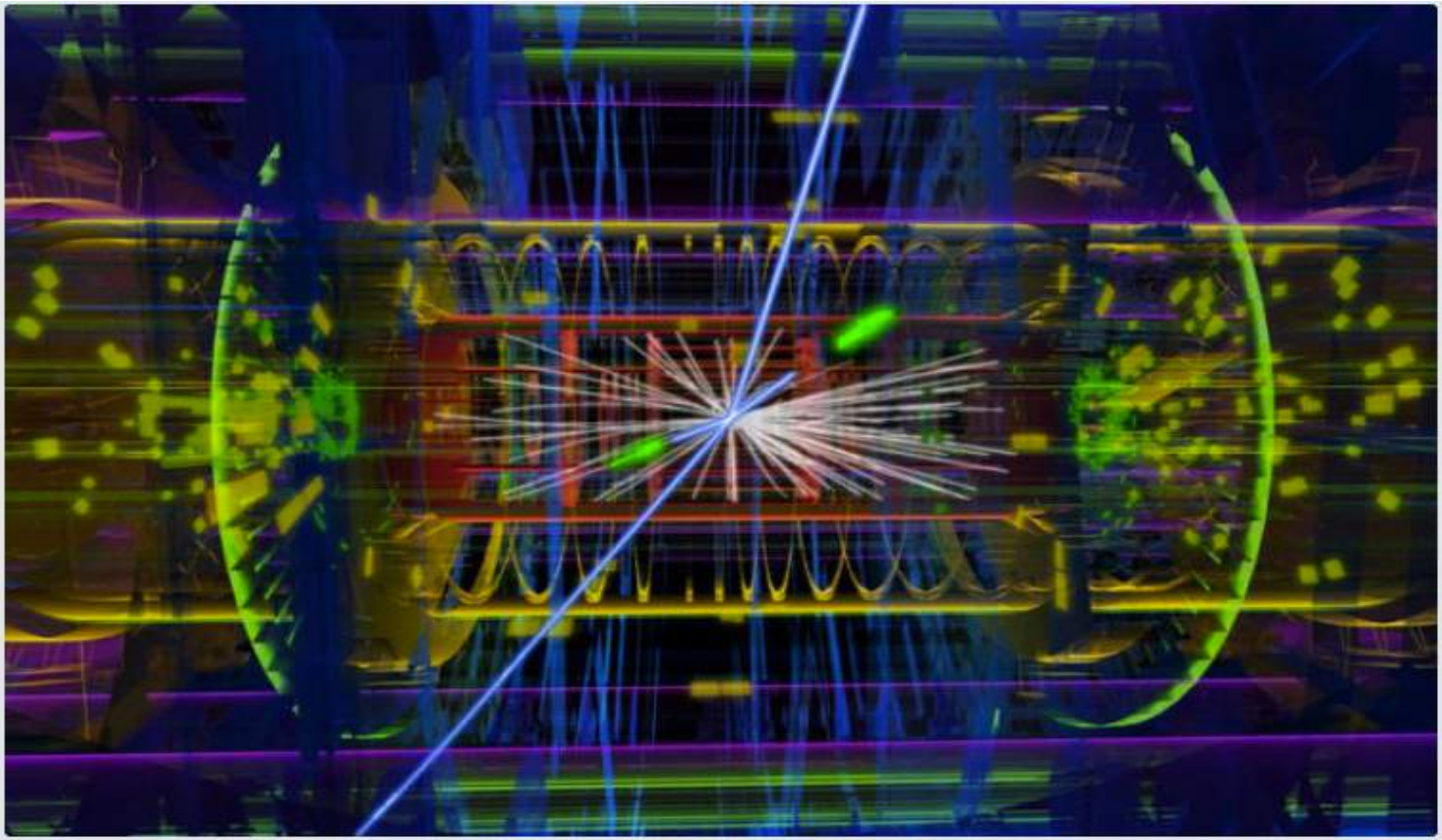
Recent News



OCT 26, 2017

Ars Technica: Higgs Boson Uncovered By Quantum Algorithm On D-Wave Machine

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D-Wave

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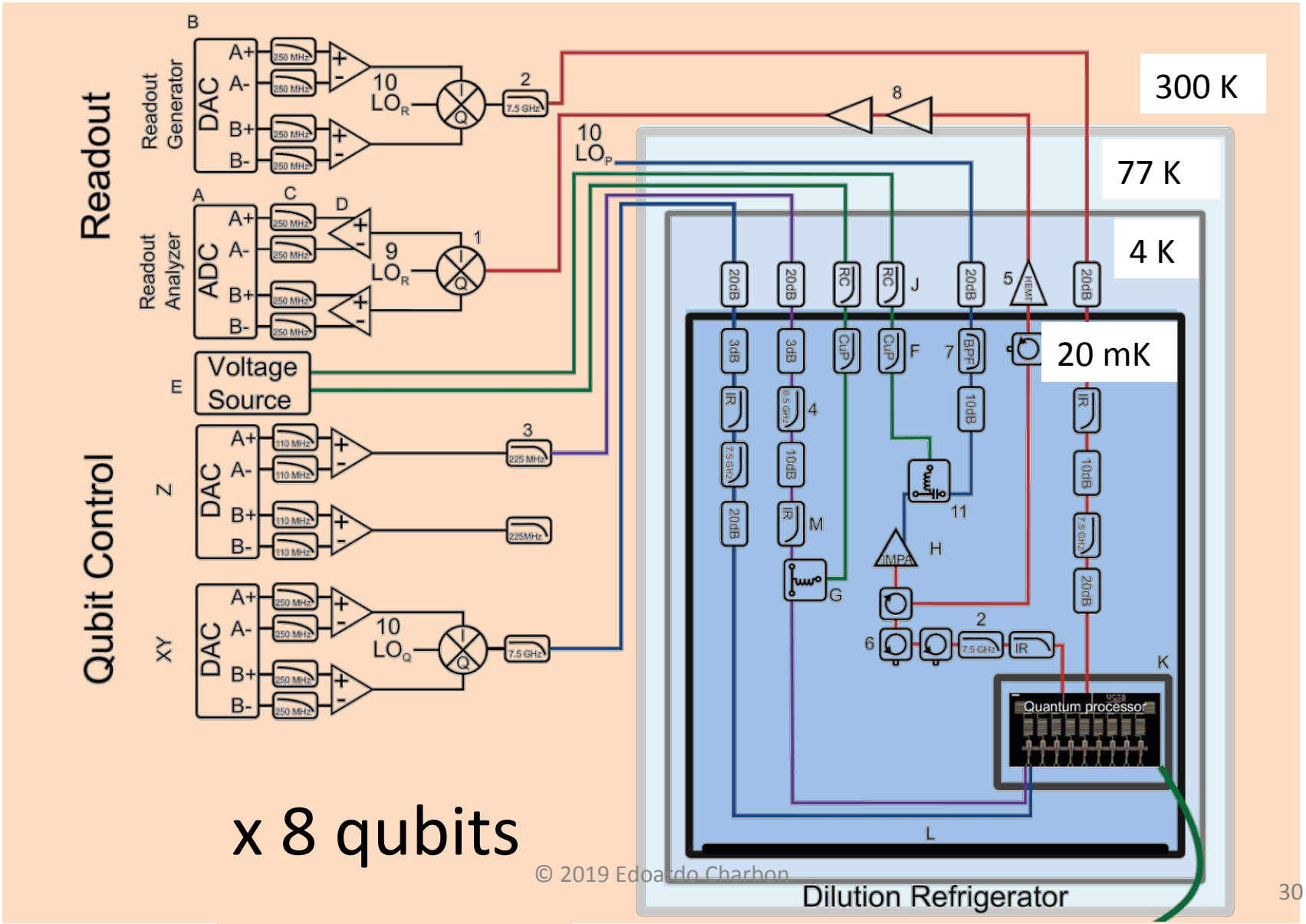
Quantum Computer Architecture

A Real-life Quantum Computer



x 8 qubits

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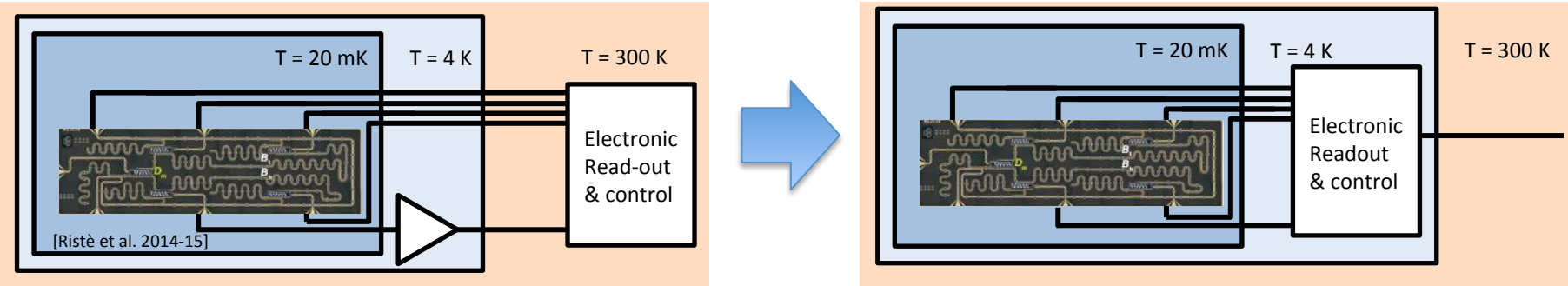
Possible Solutions

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



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

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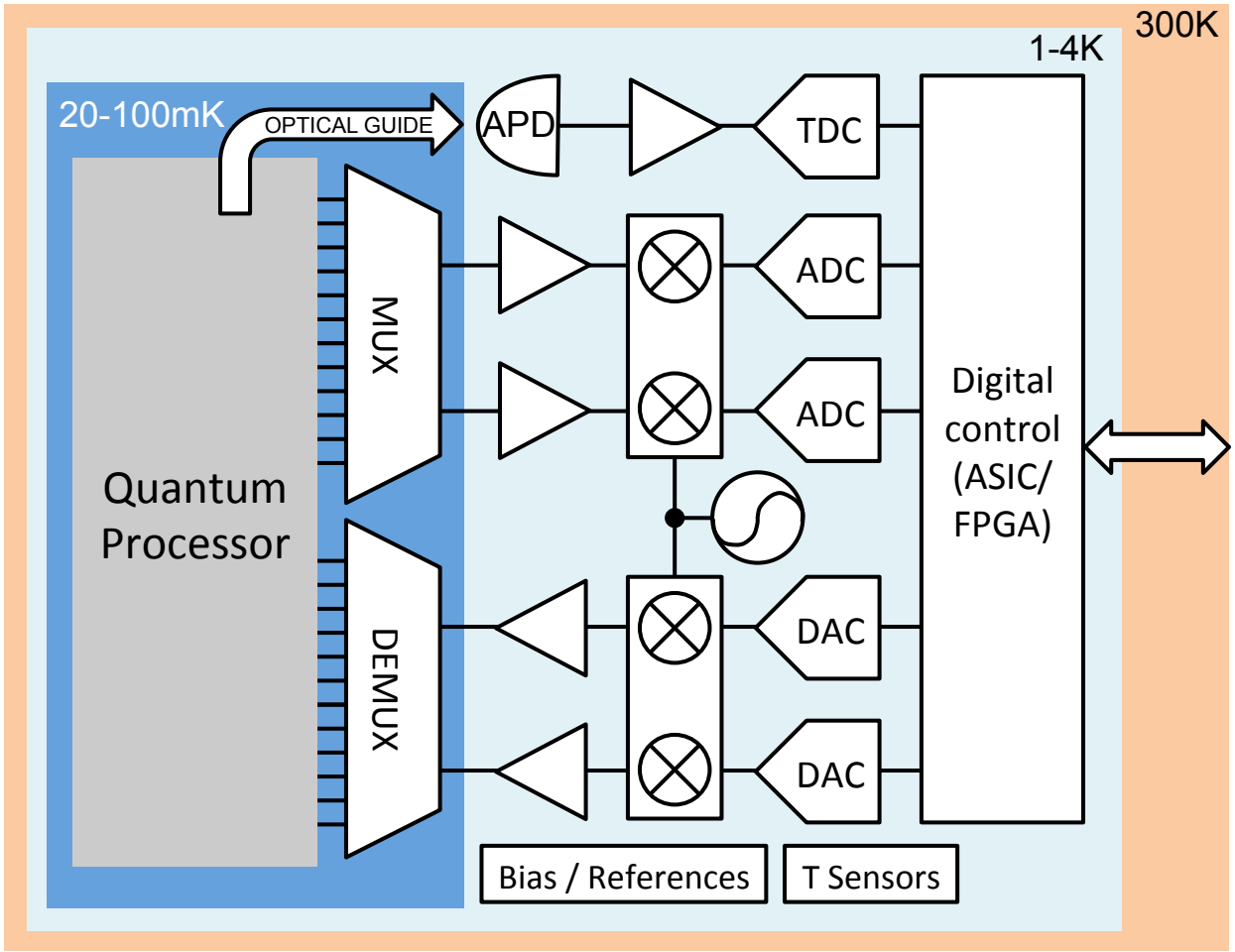
Electronic Readout & Control



E. Charbon *et al.*, *IEDM* 2016

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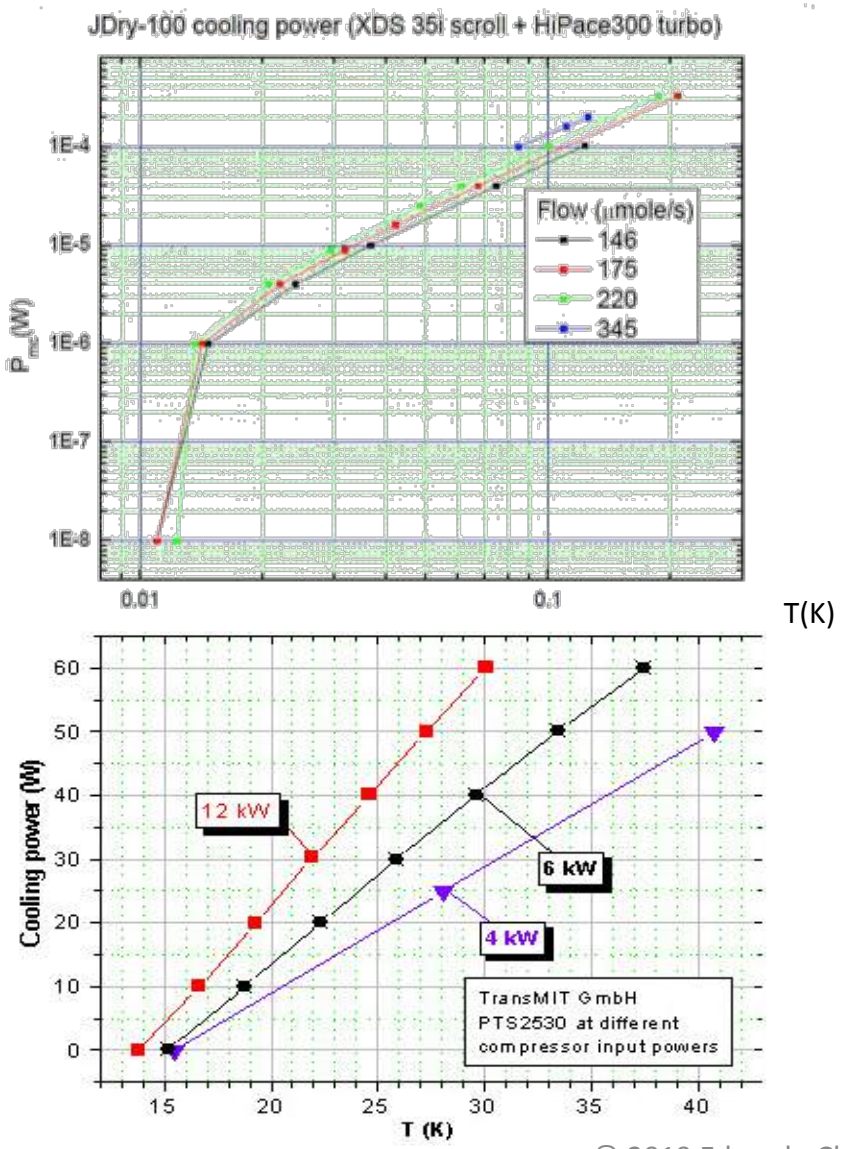
Cooling Power Issue



300 K

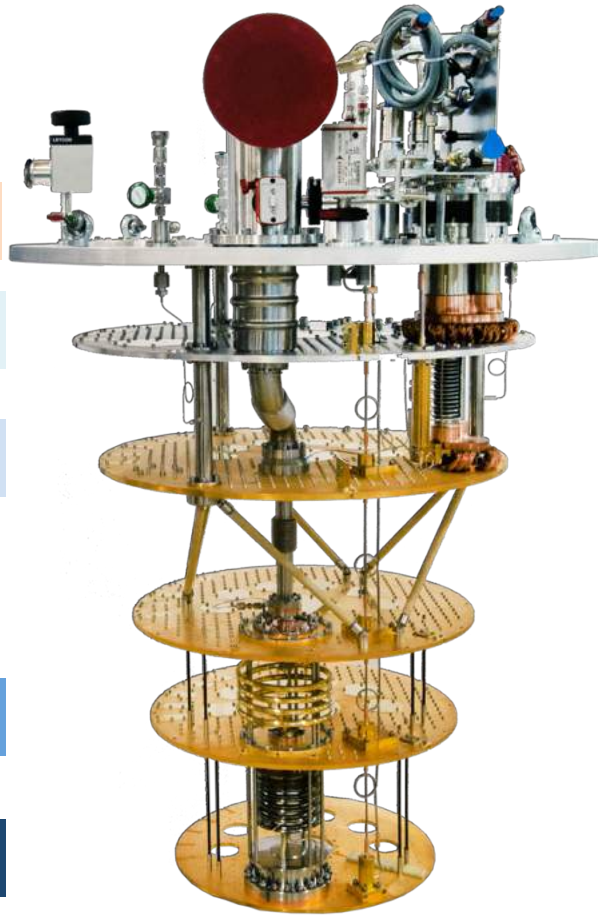
70 K

4 K

100 mK

20 mK

Dilution refrigerator



Courtesy: Oxford instruments

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Scalability Issue

- Noise budget…….< 0.1nV/√Hz
- Power budget (for scalability)…….<< 2mW/qubit
- Physical dimensions (for scalability)……. 30nm
- Bandwidth (for multiplexing)……. 1-12GHz
- Kick-back avoidance

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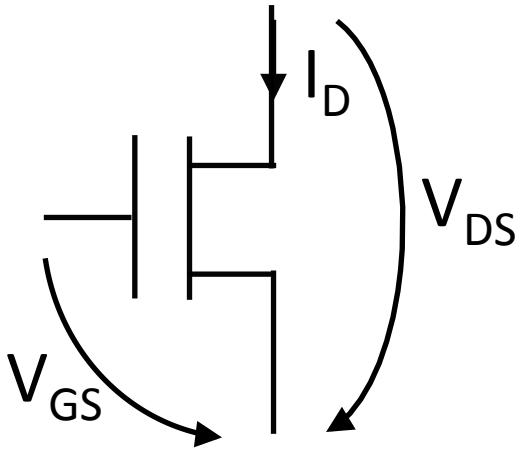
Cryogenic Electronics

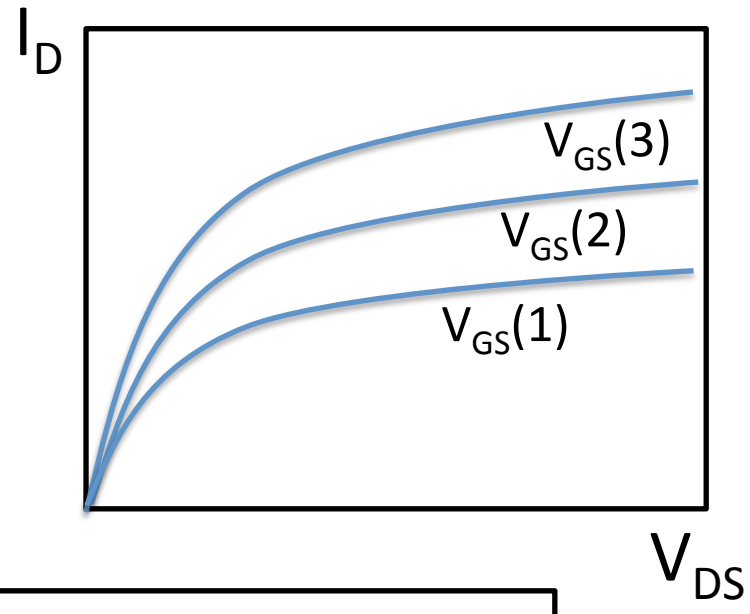
Cryogenic Electronics

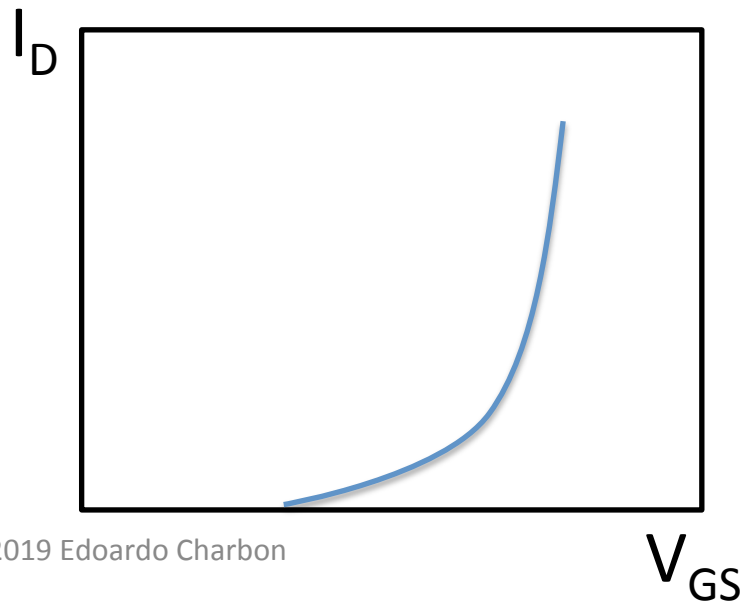
Cryo-CMOS Technologies

The First Thing is Modeling

- MOSFET







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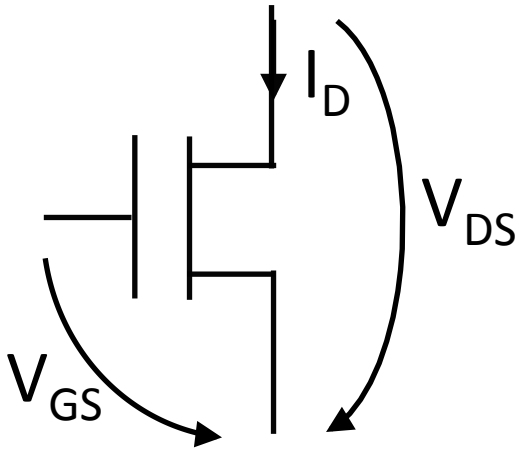
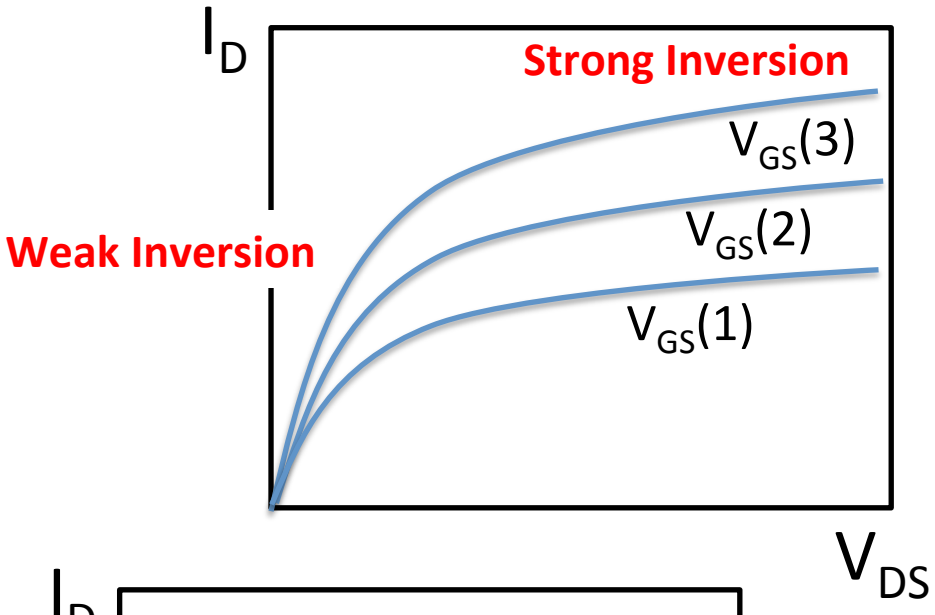
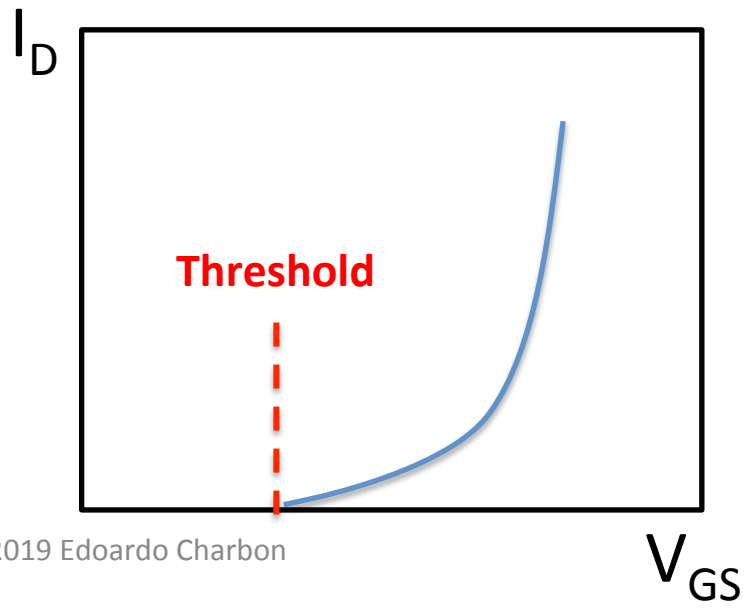
The First Thing is Modeling

- MOSFET







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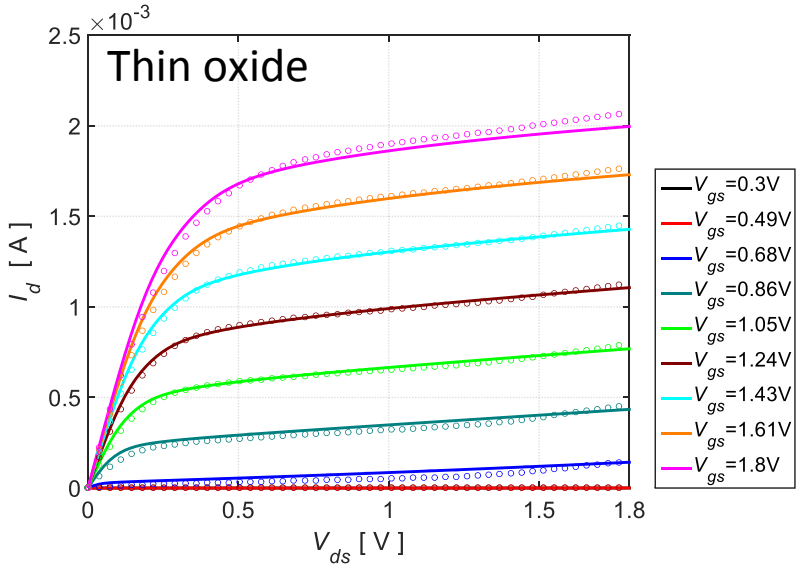
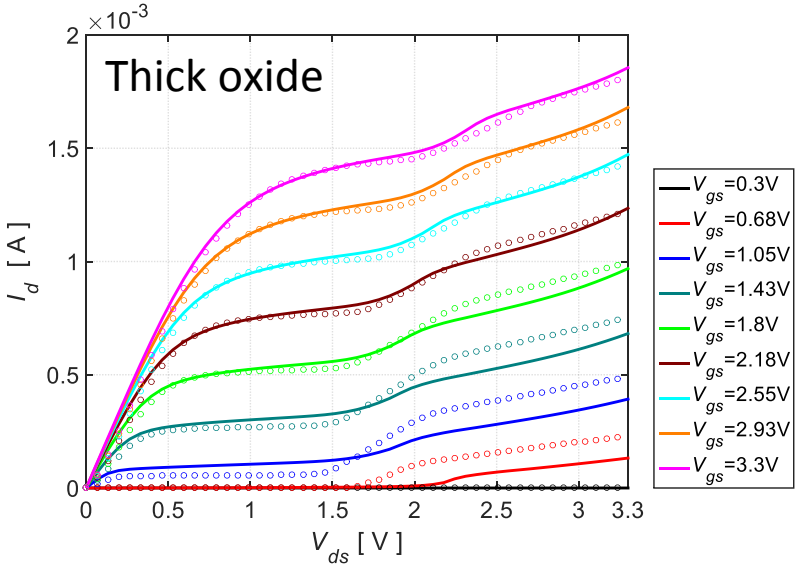
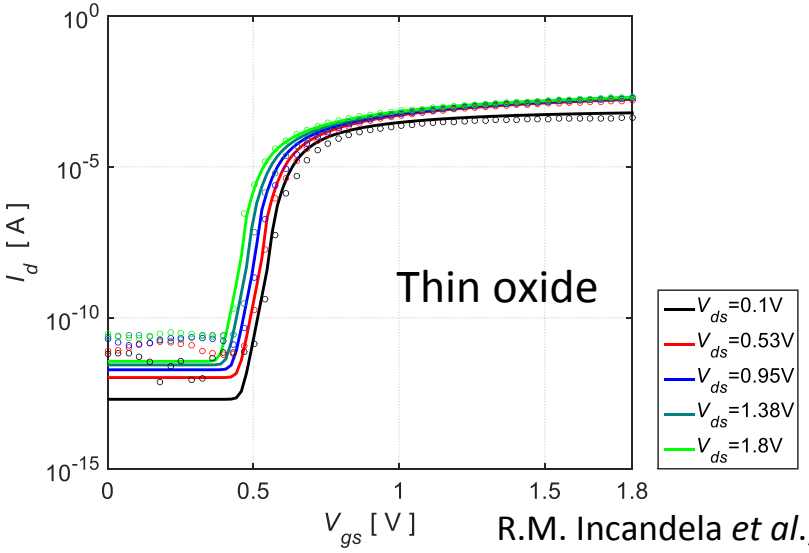
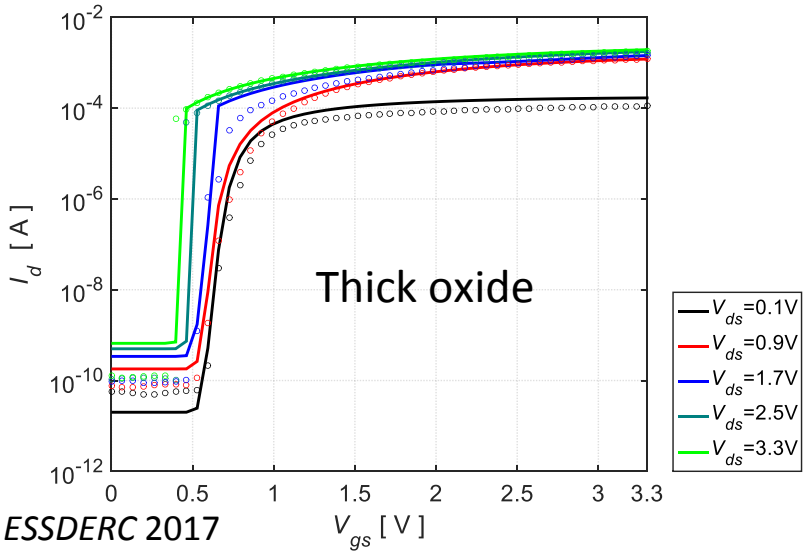
Device Modeling (160nm)



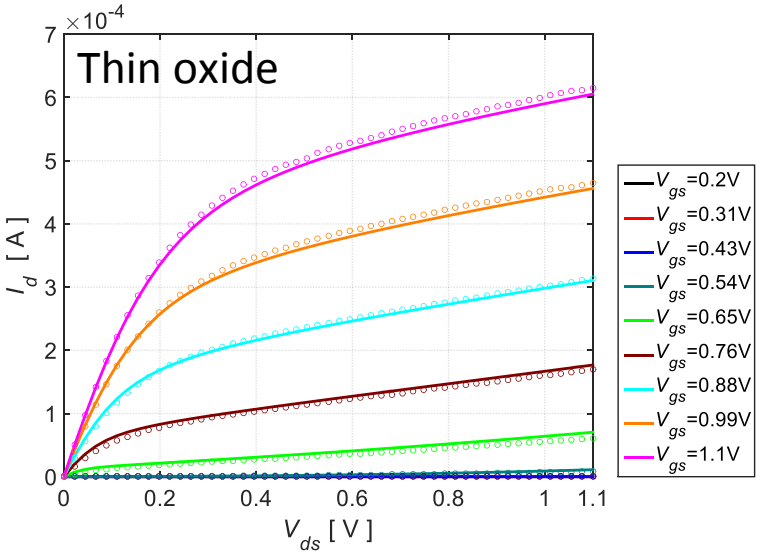


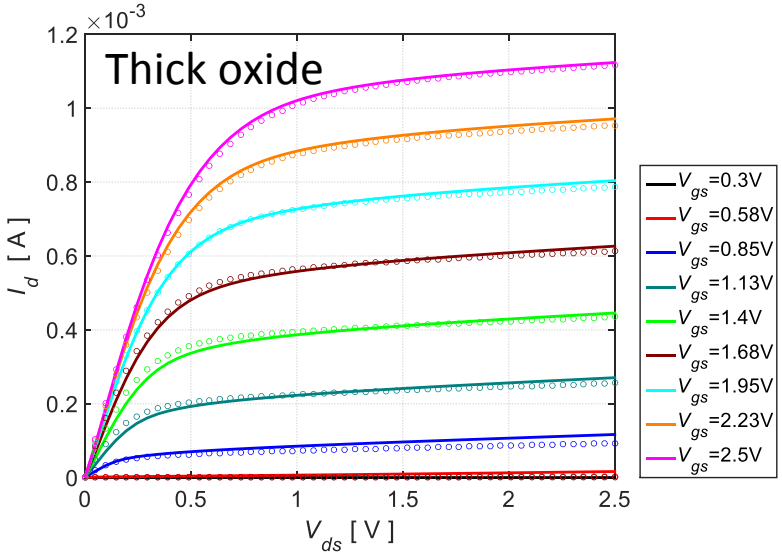


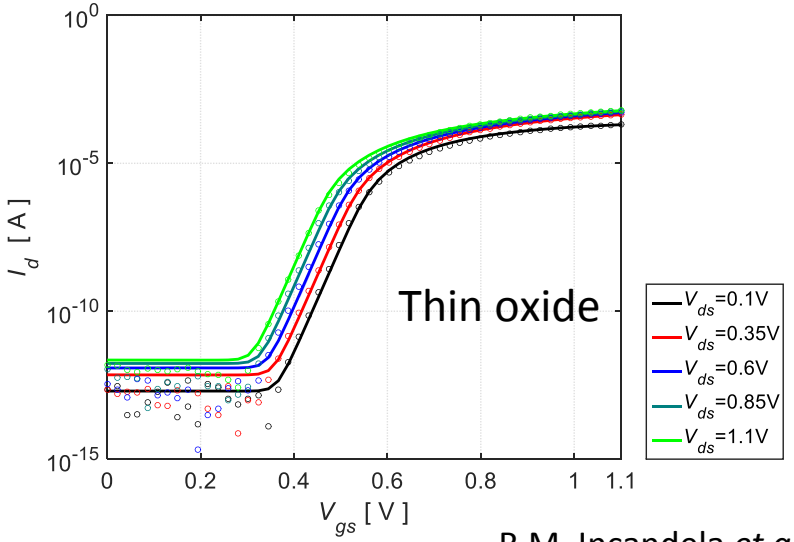


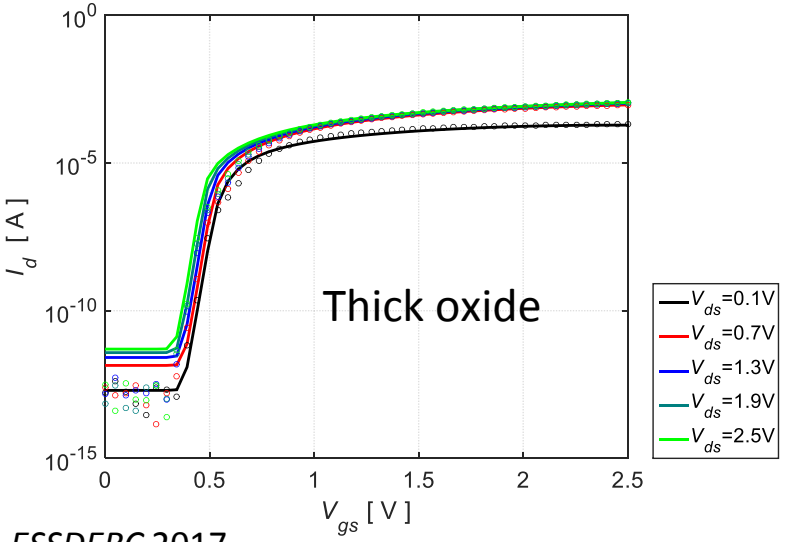
R.M. Incandela *et al.*, *ESSDERC* 2017
R.M. Incandela *et al.*, *J. of EDS 2018*

Device Modeling (40nm)





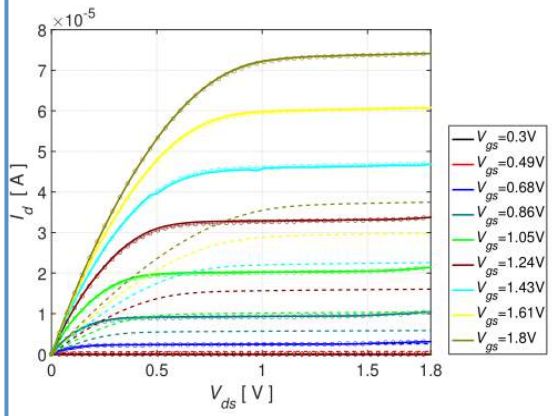
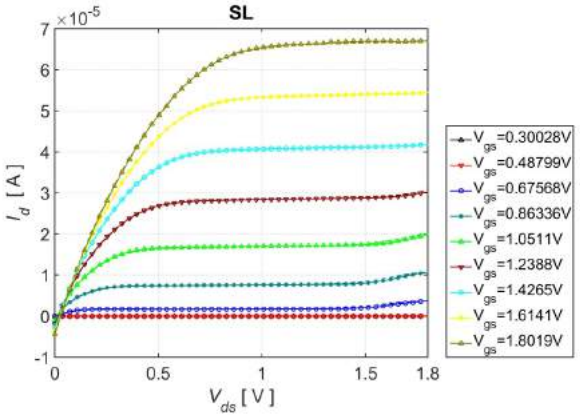
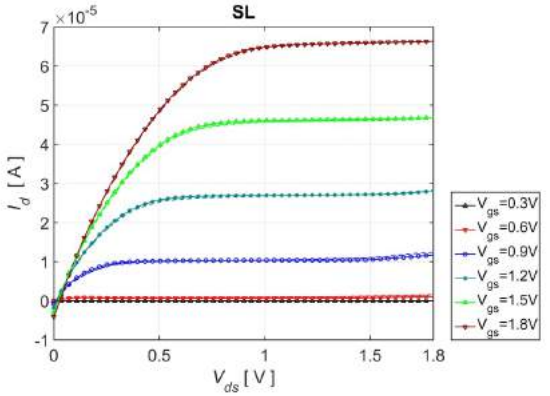
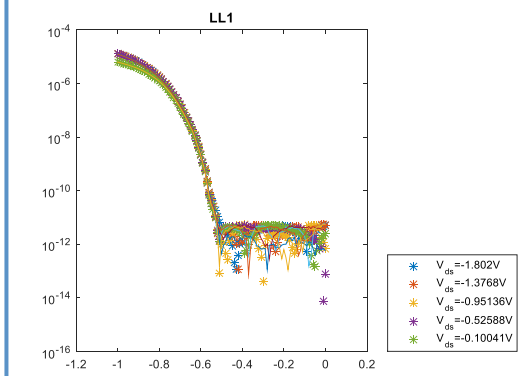
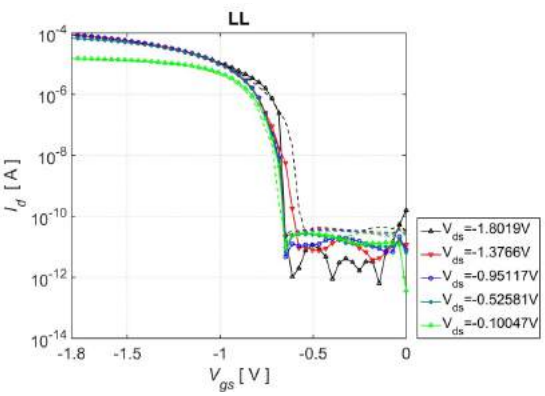
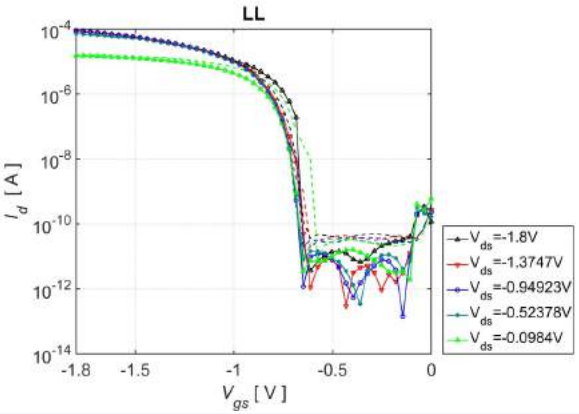




R.M. Incandela *et al.*, *ESSDERC* 2017
R.M. Incandela *et al.*, *J. of EDS 2018*

Towards mK

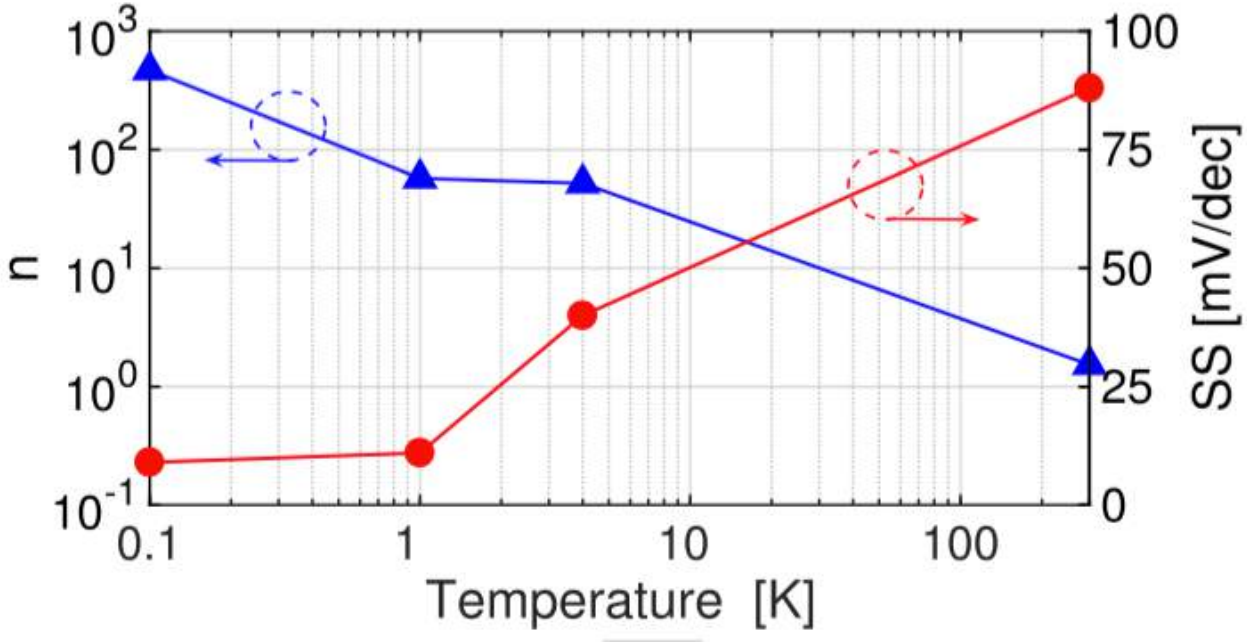
- Full functionality at 1 K and 100 mK
- More hysteresis at subthreshold region

	4K*	1K	100mK
NMOS			
PMOS			

*The transistors measured at 4K is different from that at 1K and 100mK

Subthreshold slope in mK regimes

PMOS W/L = 2.32µm / 1.6µm



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

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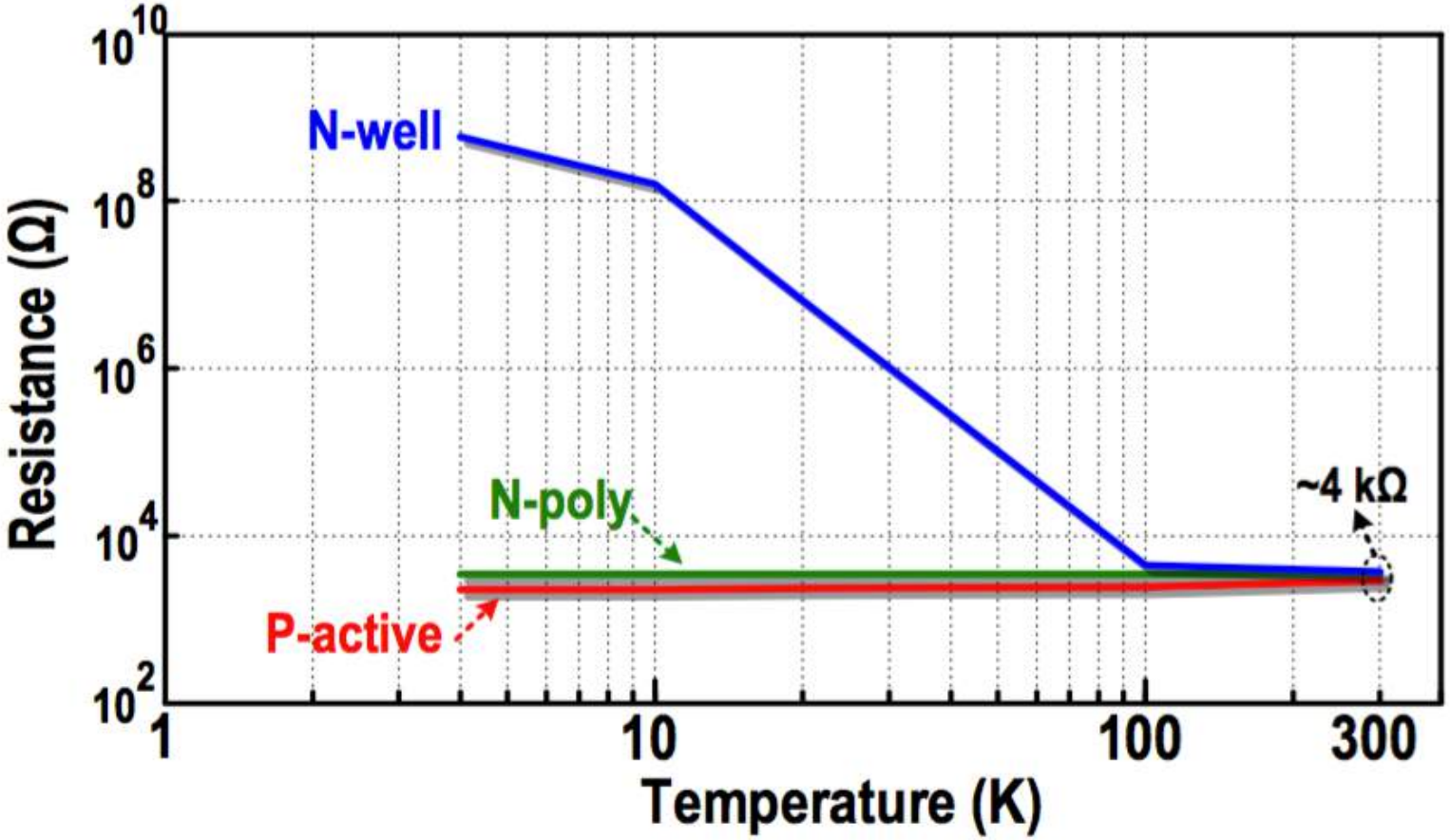
Substrate resistivity



Patra *et al.*, *JSSC* 2018

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Cryo-CMOS Modeling

IEEE Journal of the Electron Device Society

Characterization and Compact Modeling of Nanometer CMOS Transistors at Deep-Cryogenic Temperatures

Rosario M. Incandela, *Student, IEEE,* Lin Song, Harald Homulle, Edoardo Charbon, *Fellow, IEEE,* Andrei Vladimirescu, *Fellow, IEEE,* and Fabio Sebastiano, *Senior Member, IEEE*

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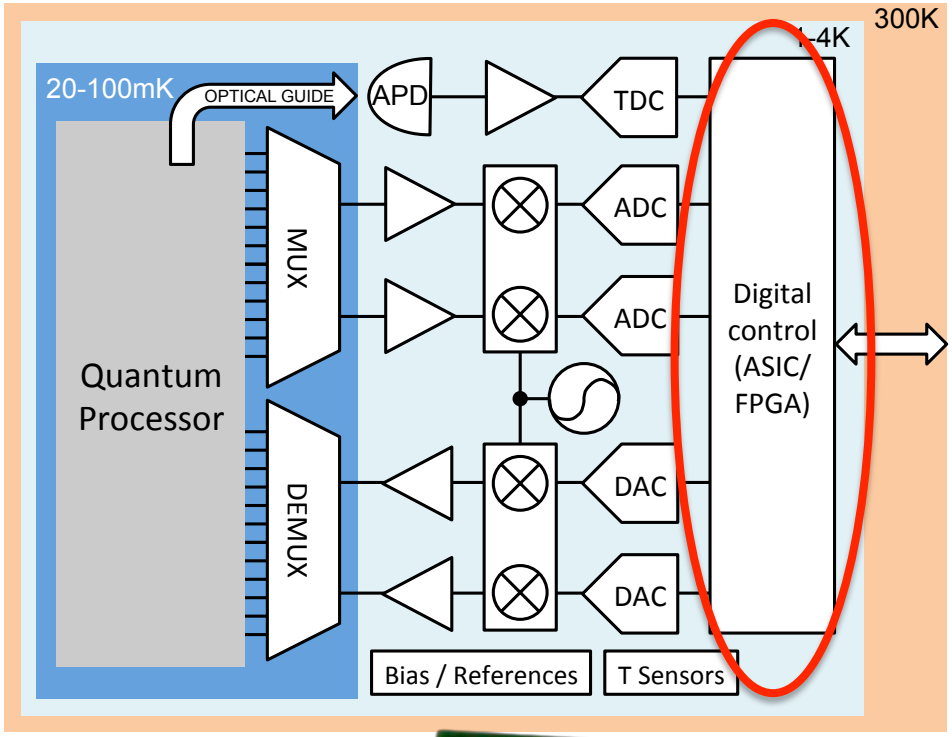
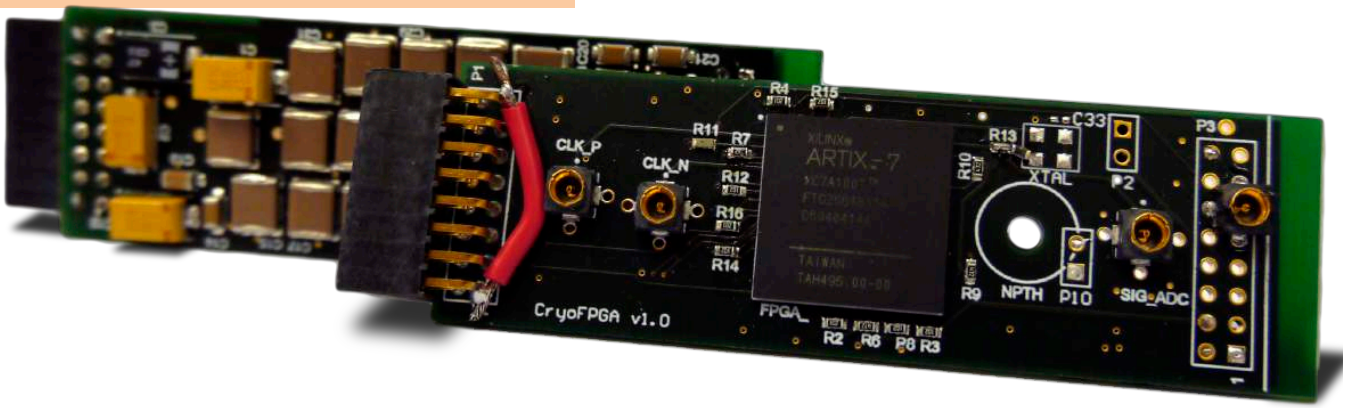
Cryogenic Reconfigurable Hardware

Cryo-FPGAs





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Cryo-FPGAs

CryoCMOS Hardware Technology
A Classical Infrastructure for a Scalable Quantum Computer

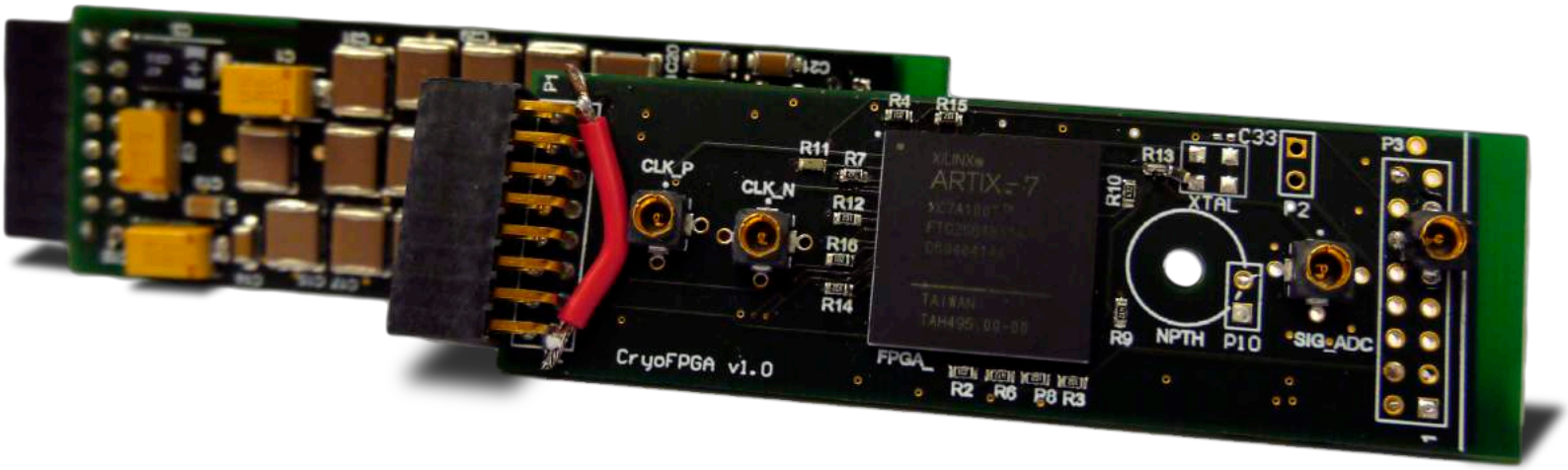
ACM Frontiers in Computing, Como 2016

Harald Homulle[1], Stefan Visser[1], Bishnu Patra[1], Giorgio Ferrari[2], Enrico Prati[3],
Carmen G. Almudéver[1], Koen Bertels[1], Fabio Sebastiano[1], Edoardo Charbon[1]

[1]QuTech, Delft University of Technology, Delft, The Netherlands

[2]Politecnico di Milano, Milano, Italy, [3]Consiglio Nazionale delle Ricerche, Milano, Italy

{h.a.r.homulle, f.sebastiano, e.charbon}@tudelft.nl



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FPGA functionality

- All FPGA components are working in the cryogenic environment down to 4K
- No modifications required

Component	Functional	Behavior
IOs	✓	
LVDS	✓	
LUTs	✓	Delay change < 5%
CARRY4	✓	Delay change < 2%
BRAM	✓	No corruption (800 kB)
MMCM	✓	Jitter reduction of roughly 20%
PLL	✓	Jitter reduction of roughly 20%
IDELAYE2	✓	Delay change of up to 30%
DSP48E1	✓	No corruption over 400 operations

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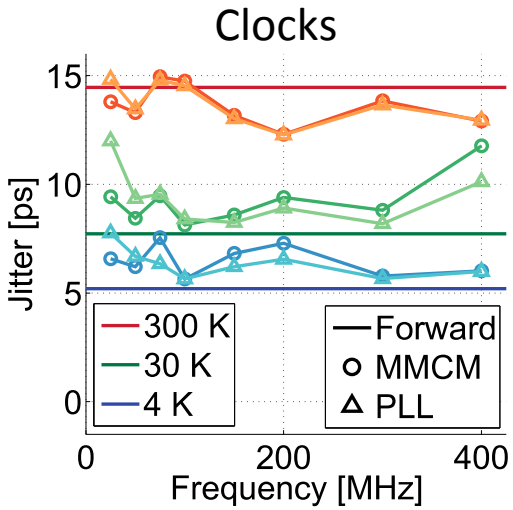
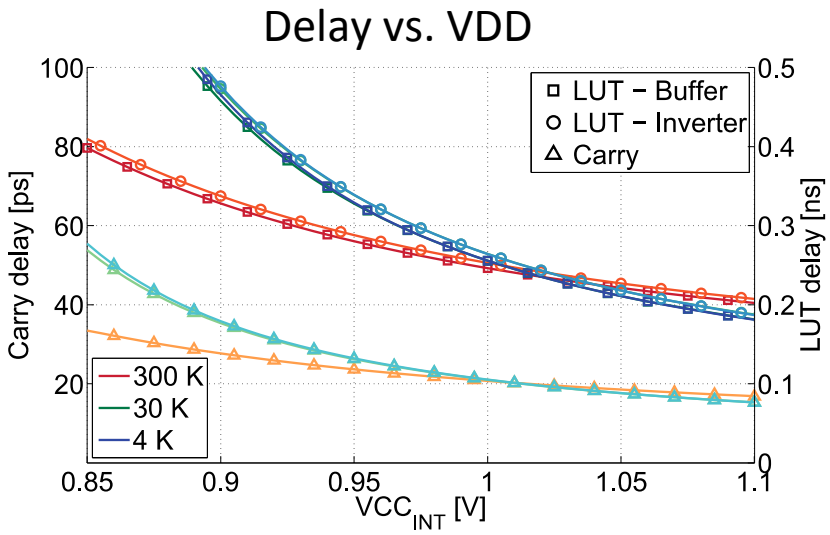
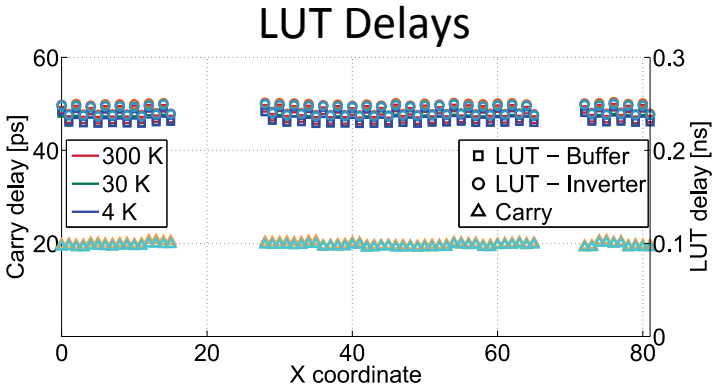
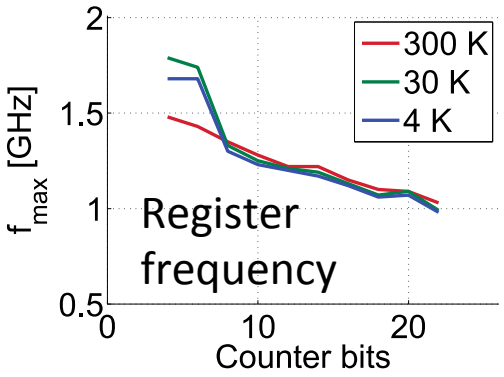
FPGA Performance

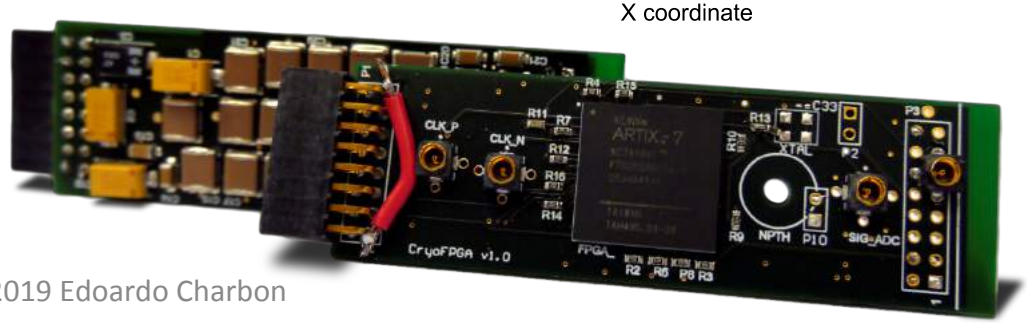
Specs:
Carry: 20 vs. 8.4 ps at 300 K
LUTs: 238 vs 235 ps at 300 K
Speed-up 2.4 vs 10.8% toward 300 K











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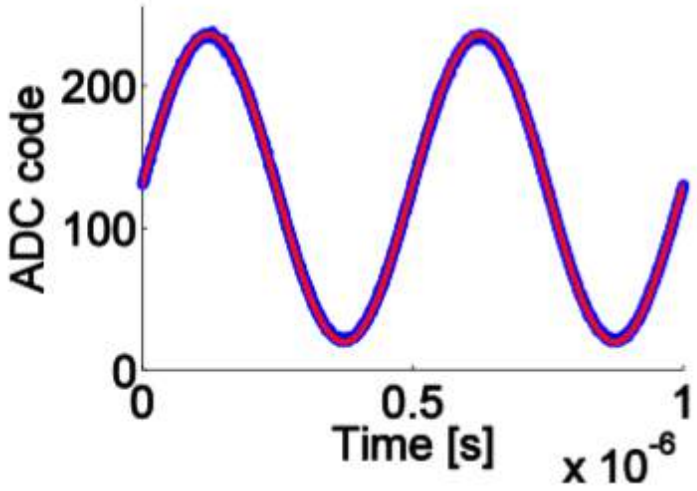
ADC on FPGA (1.2GSa/s)

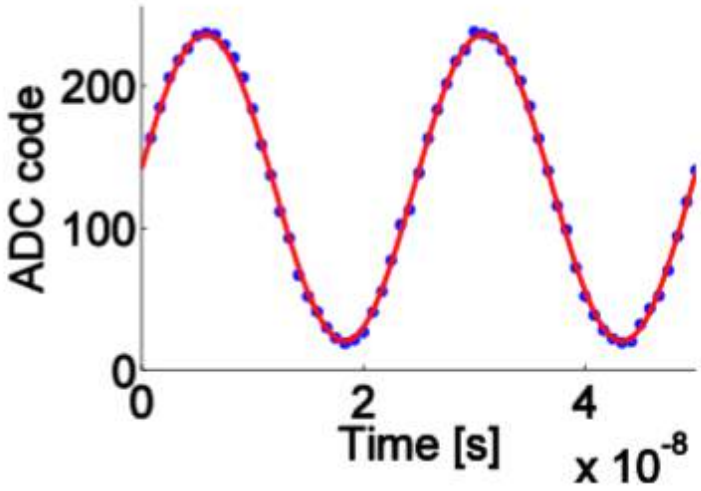
Signal bandwidth: 2 MHz

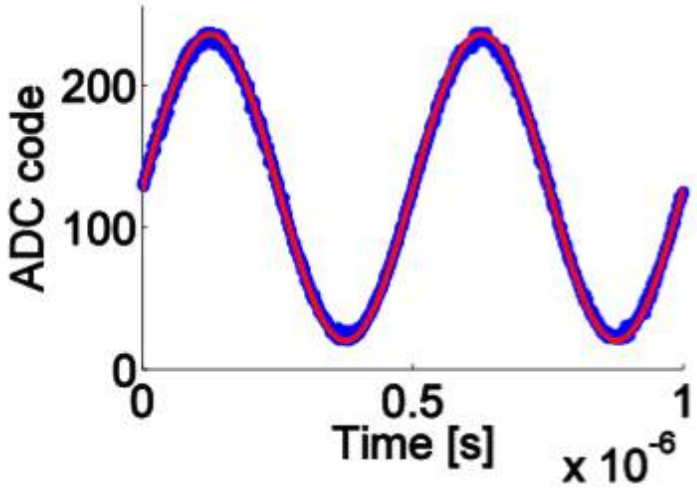
Signal bandwidth: 40 MHz

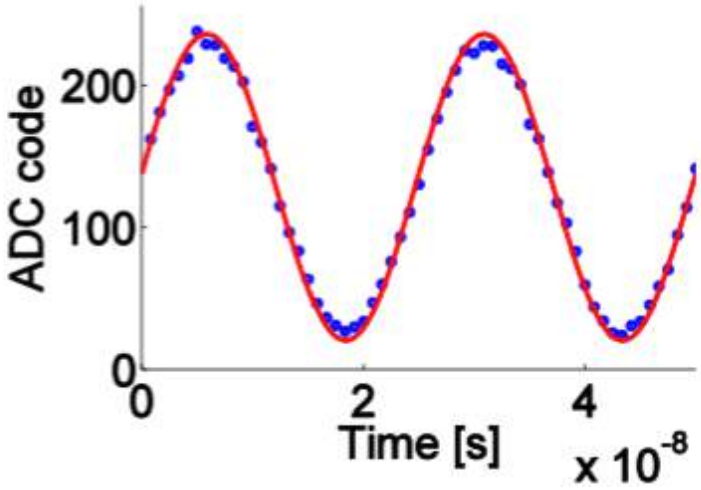
300K

15K









H. Homulle *et al.*, TCAS I, 63(11), 1854-1865, 2016

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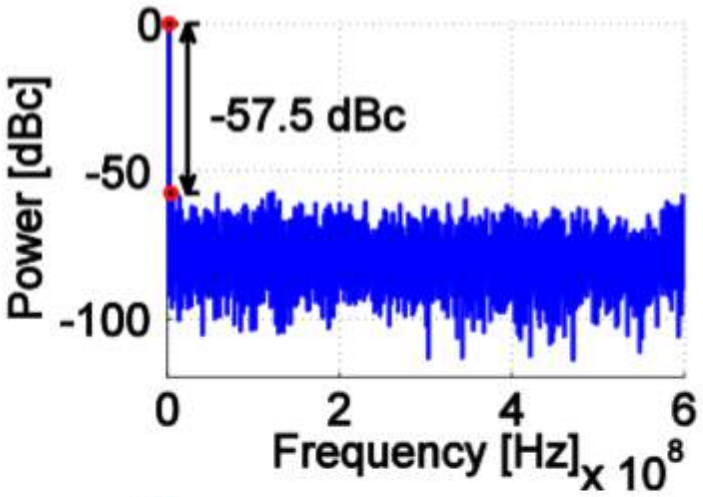
ADC on FPGA

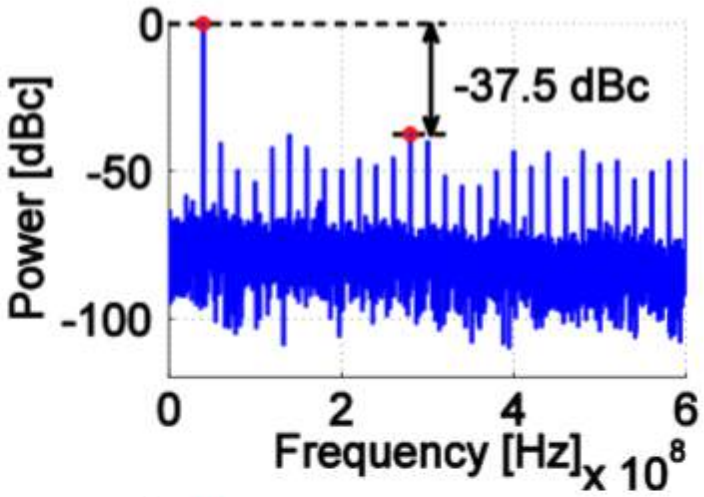
Signal bandwidth: 2 MHz

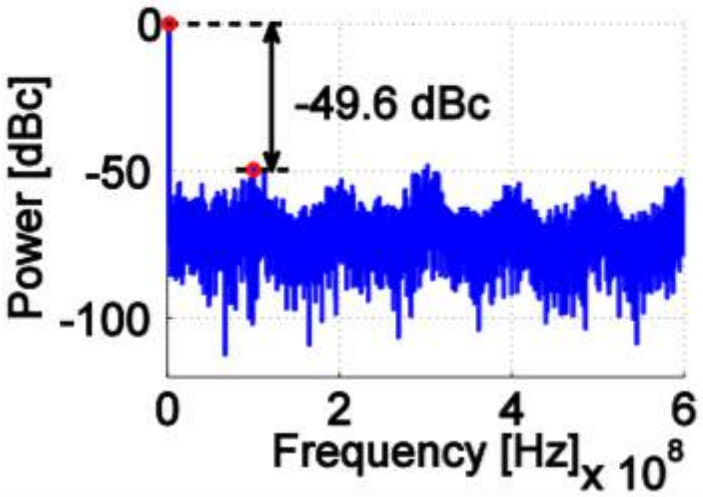
Signal bandwidth: 40 MHz

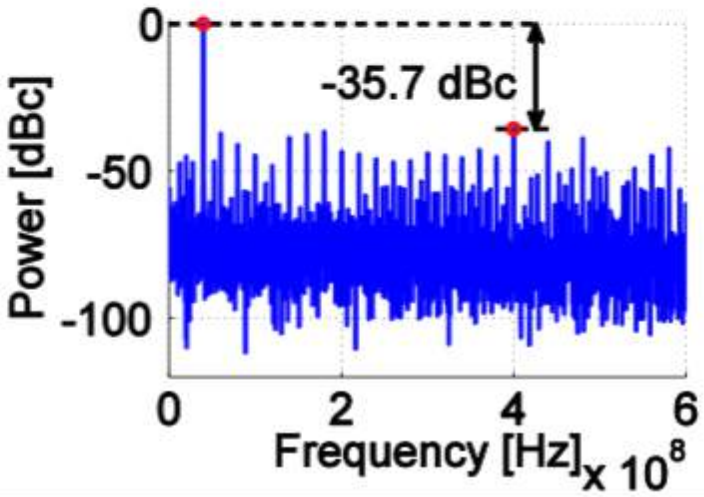
300K

15K









H. Homulle *et al.*, TCAS I, 63(11), 1854-1865, 2016

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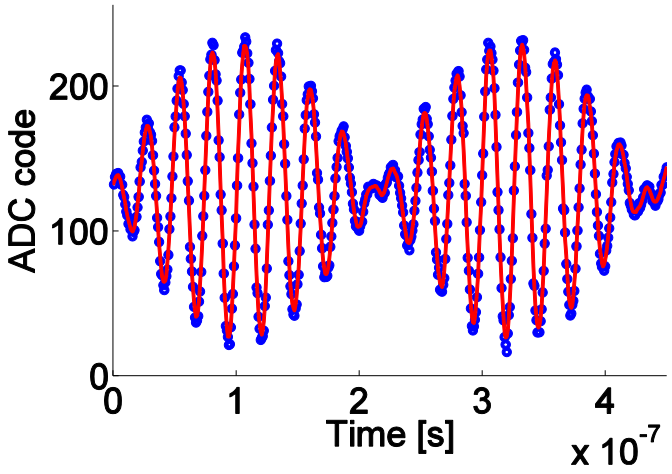
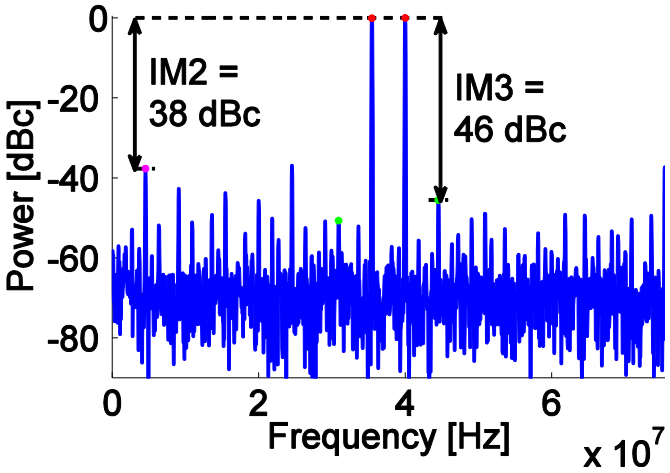
Distortion (IM2, IM3)

- Two tones: ≈ 36 / 41 MHz
  - IM2 = 38 dB
  - IM3 = 46 dB
- Many secondary harmonics
- Interference with 100 MHz (sampling tone)





H. Homulle *et al.*, TCAS I, 63(11), 1854-1865, 2016

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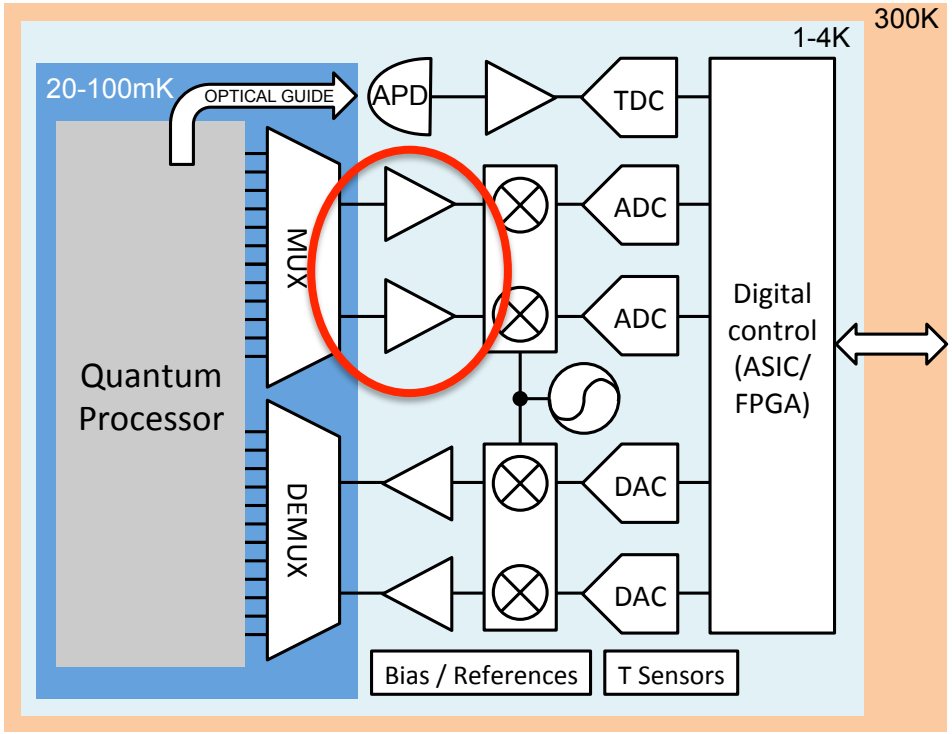
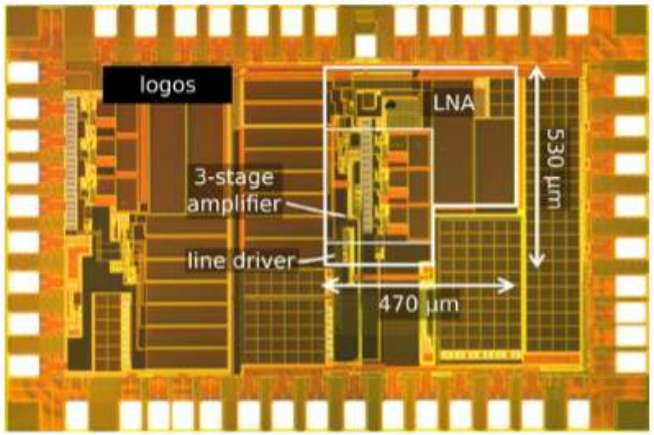
Cryogenic ASICs

Low Noise Amplifiers (Cryo-LNAs)





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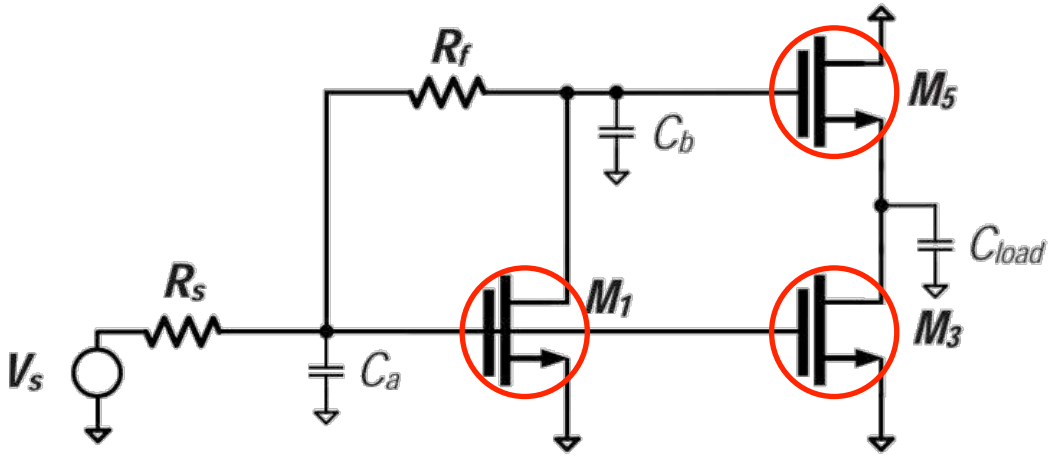
Cryo-LNA



F. Bruccoleri *et al.*, *JSSC* 2004

- Standard 160nm CMOS
- 500 MHz Bandwidth
- 0.1dB Noise figure
- 7K noise-equivalent temperature

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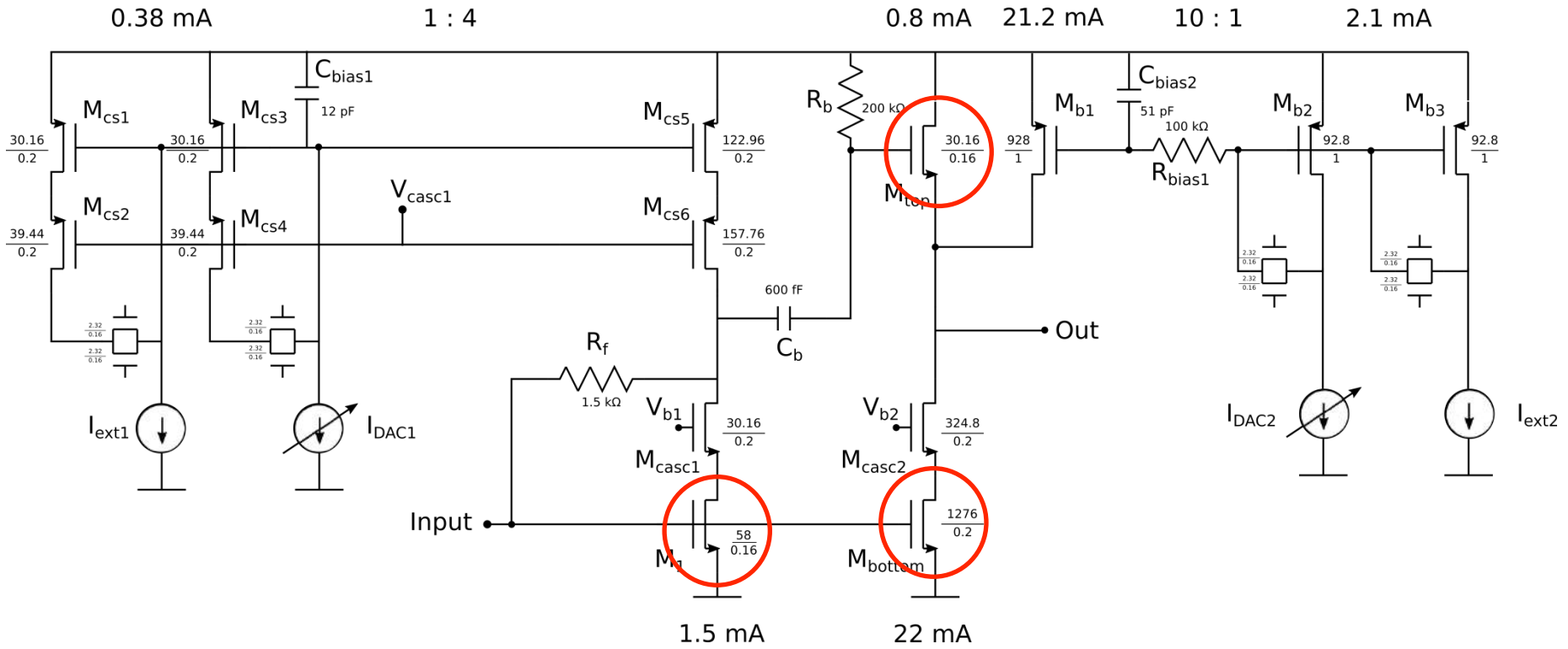
Cryo-LNA



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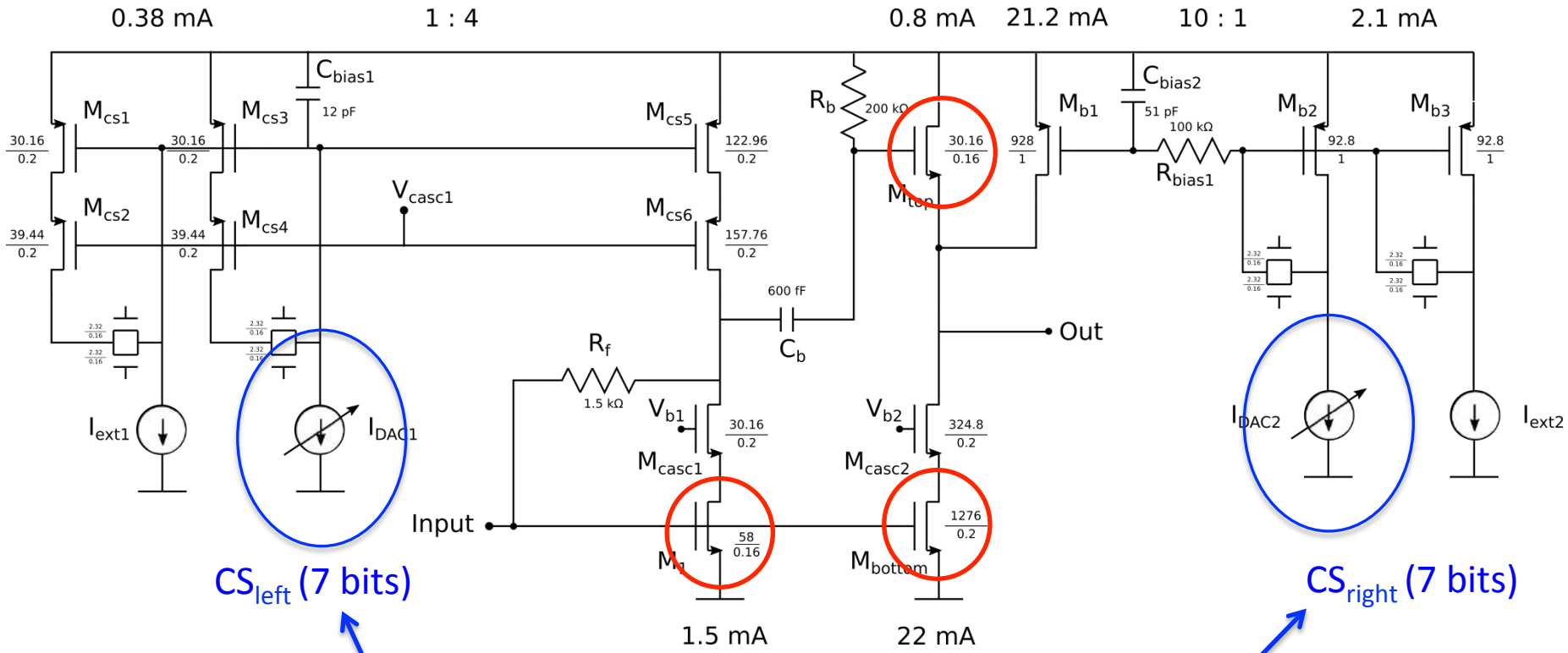
Cryo-LNA



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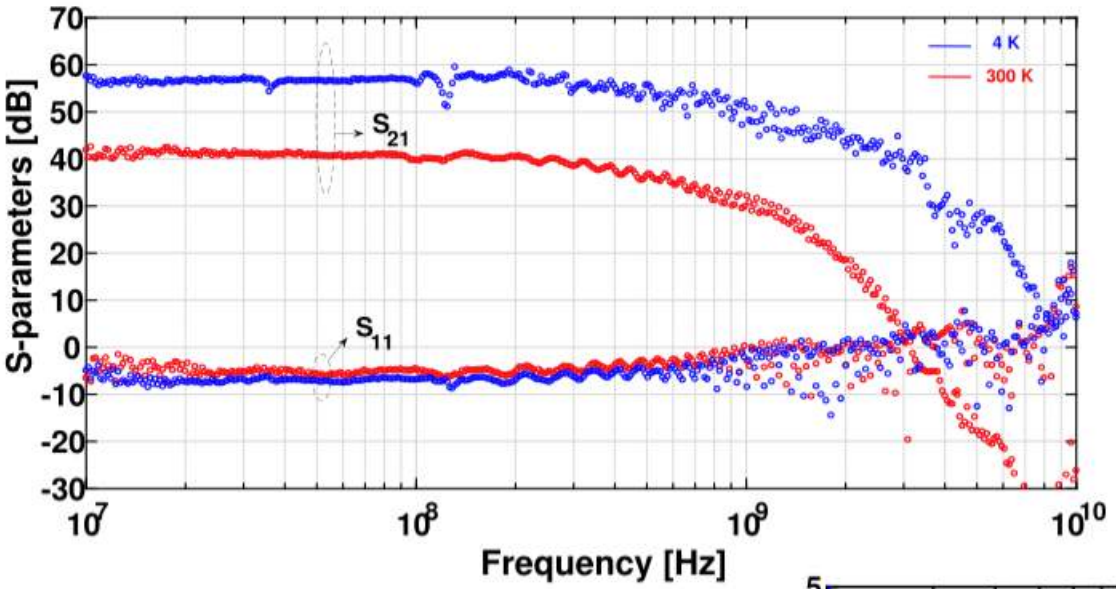
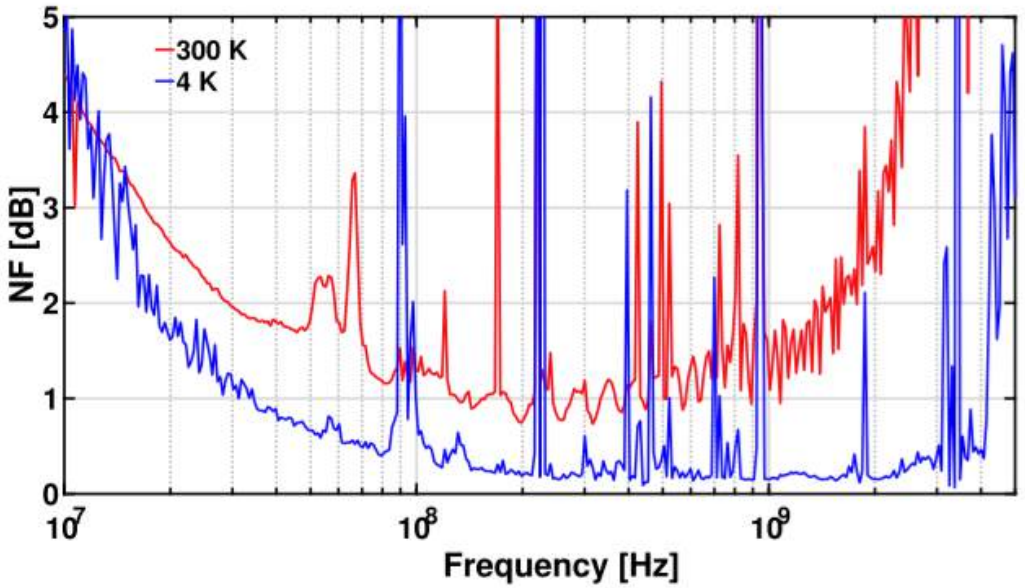
Gain and Noise



Gain

Noise Figure



B. Patra, R.M. Incandela *et al.*, *JSSC* 2018

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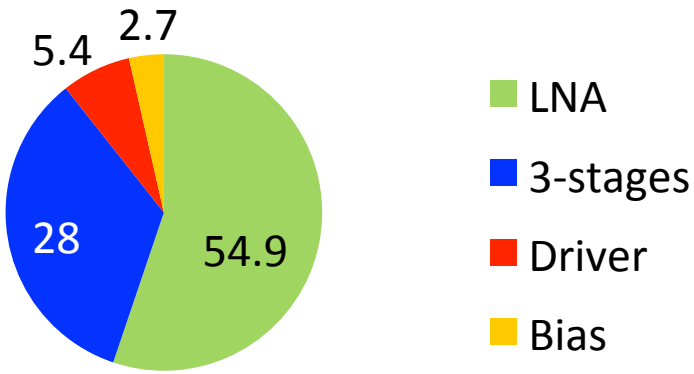
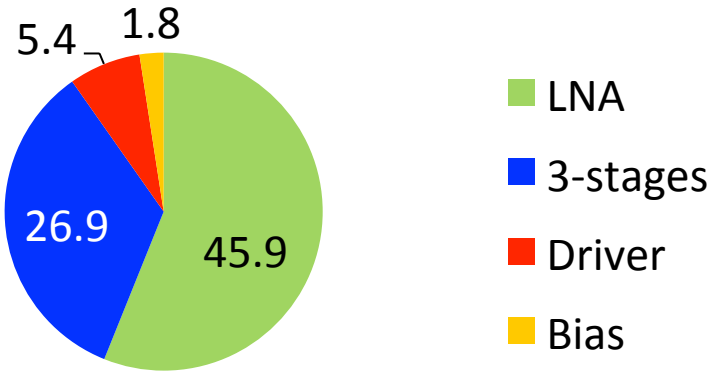
Power

Power consumption at 4 K [mW]



Measured: **91mW**

Power consumption at 300 K [mW]



Measured: **80mW**

Sharing 25 20MHz-channels (one channel per qubit)

=

3.6mW per qubit

Rosario Incandela

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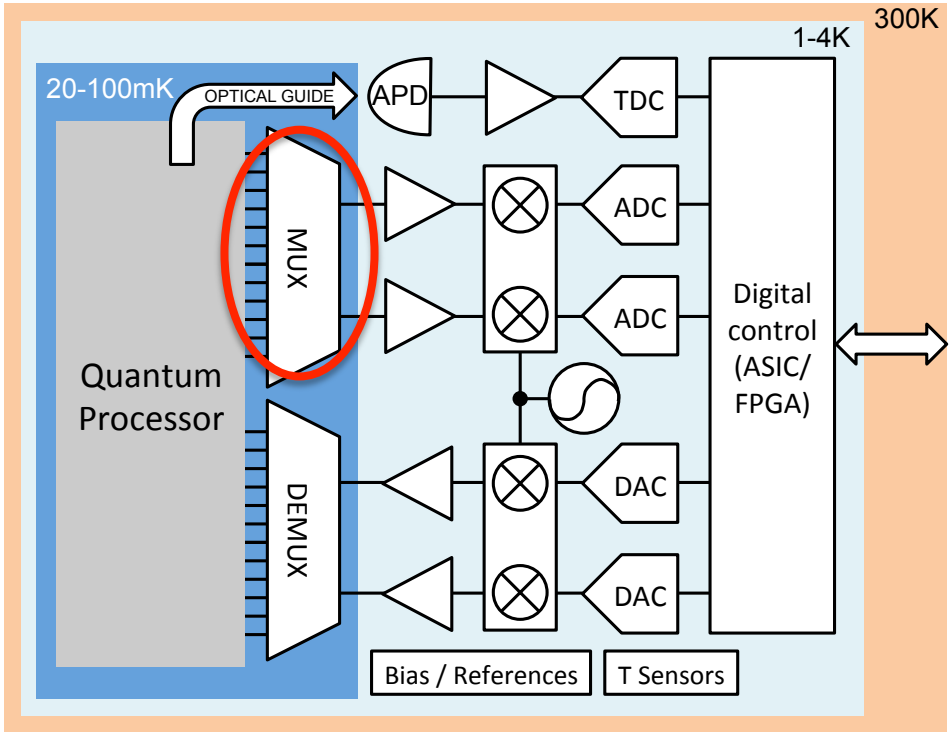
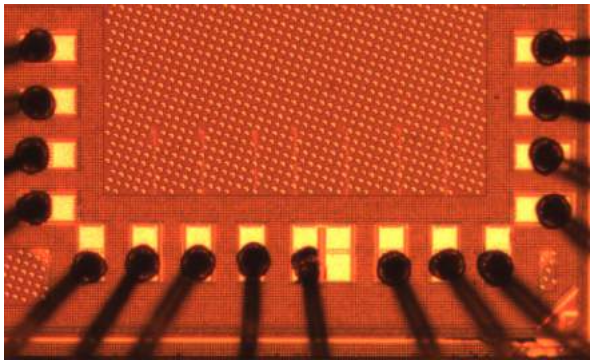
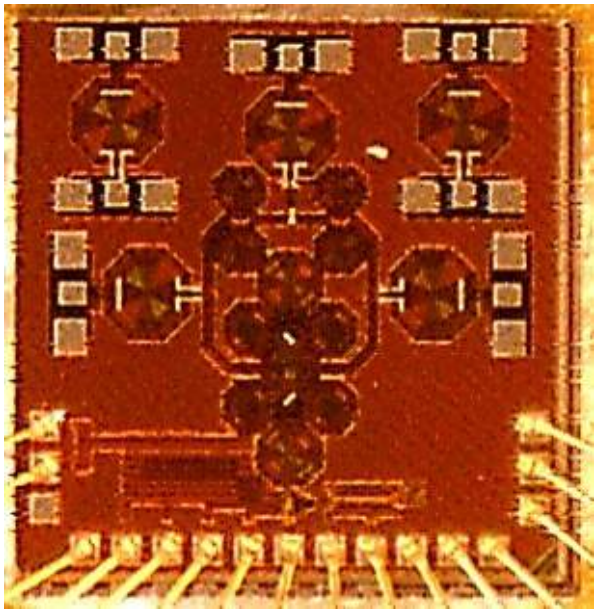
CMOS Passive Circulators & Multiplexers







A. Ruffino *et al.*, RFIC 2019

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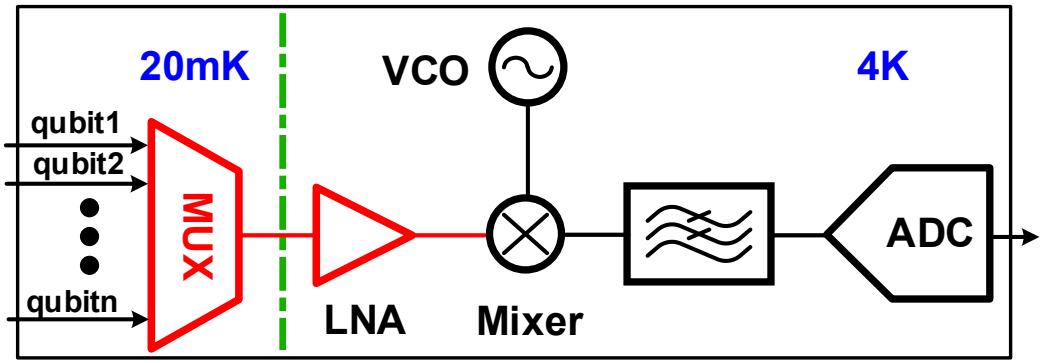
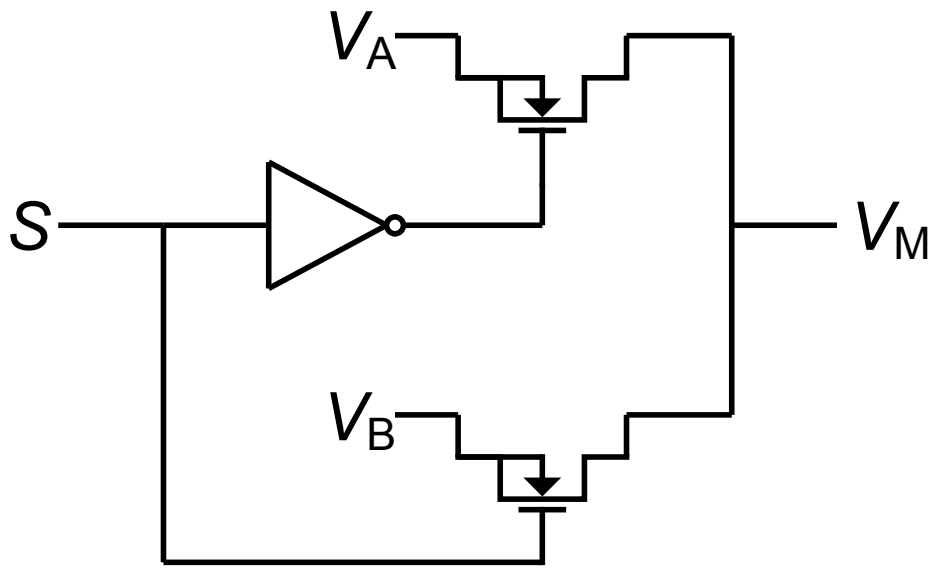
Multiplexers





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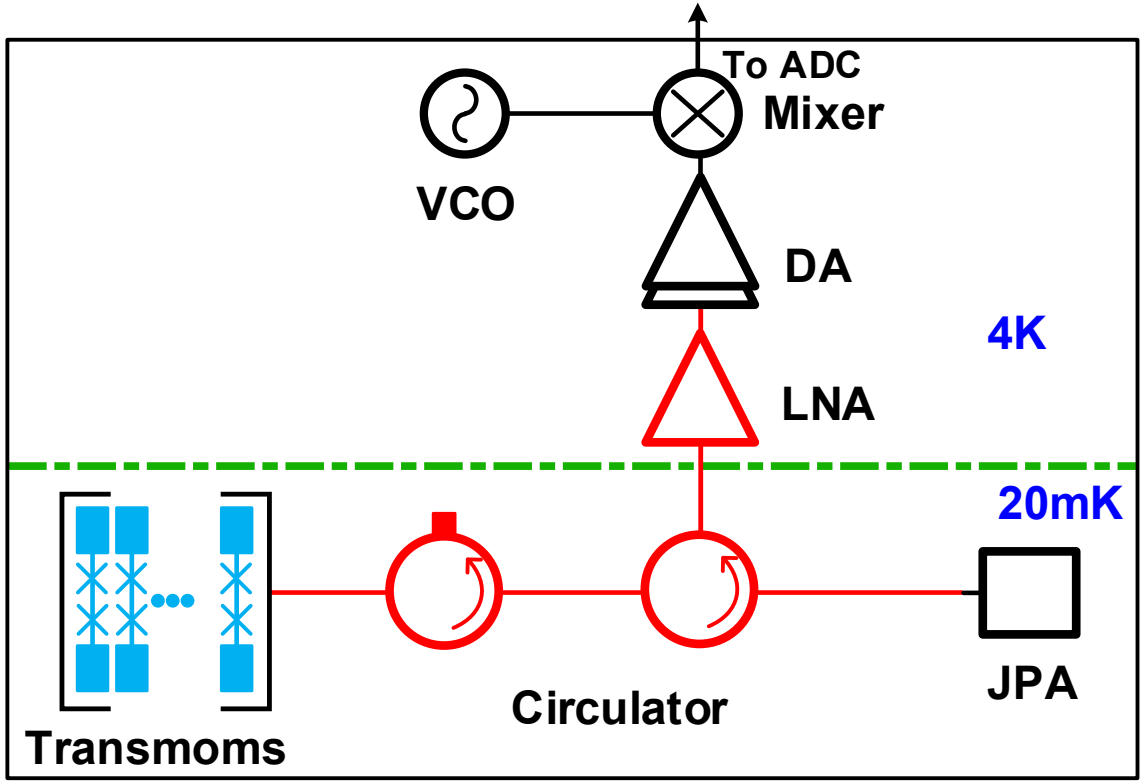
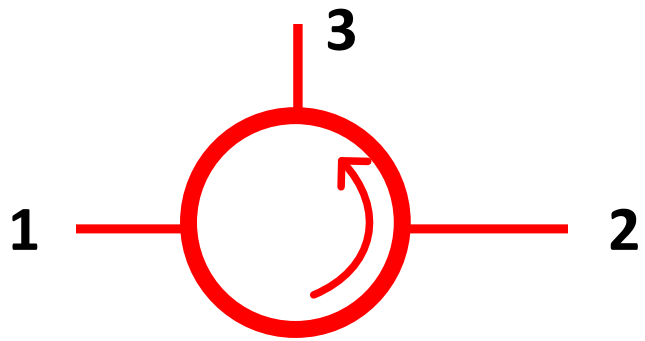
Circulators





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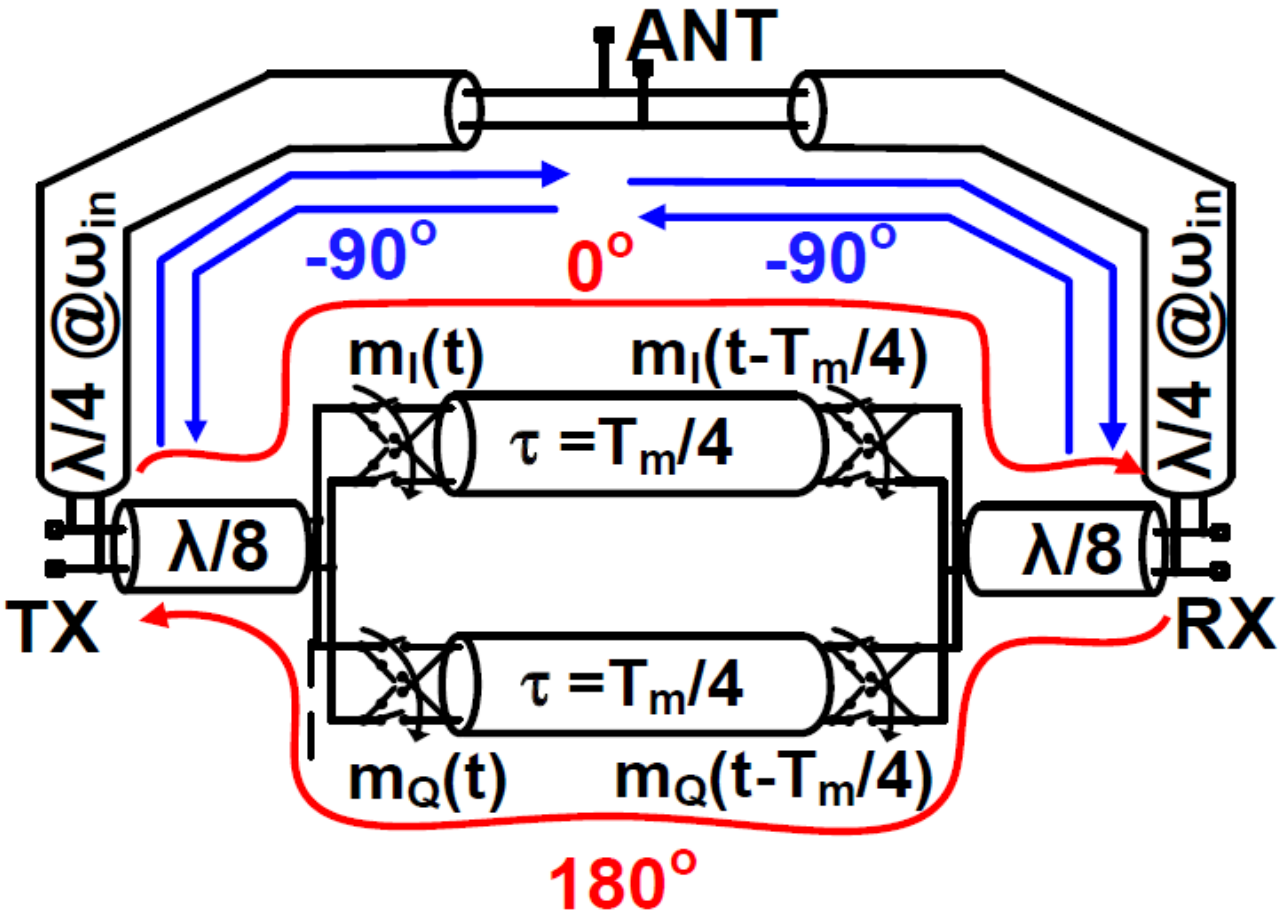
Transmission Line Circulator



S-parameters at $\omega_{in} = 3\omega_m$

$$S = \begin{bmatrix} 0 & 0 & -1 \\ -j & 0 & 0 \\ 0 & -j & 0 \end{bmatrix}$$

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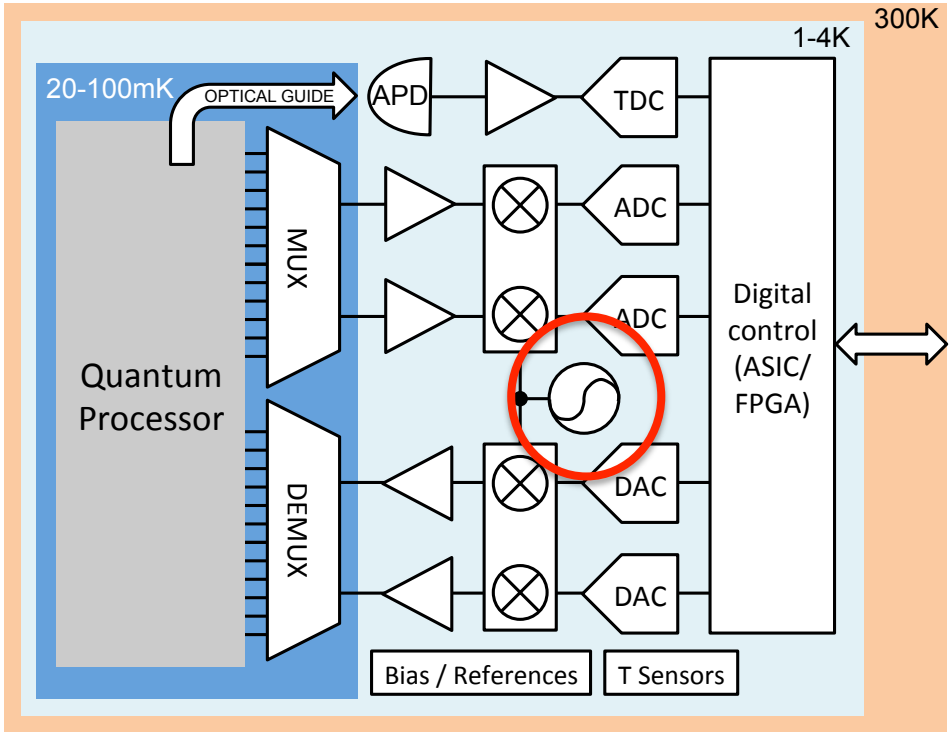
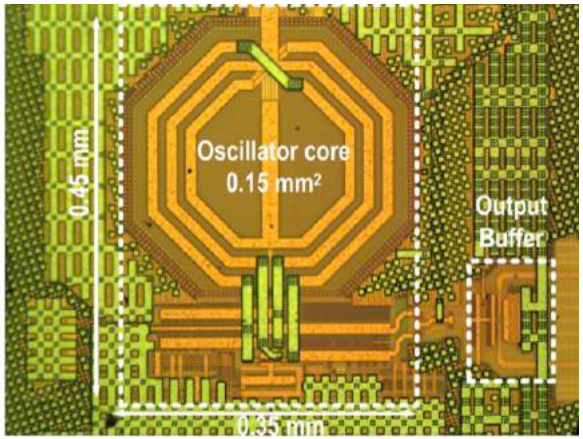
Cryo-Oscillators





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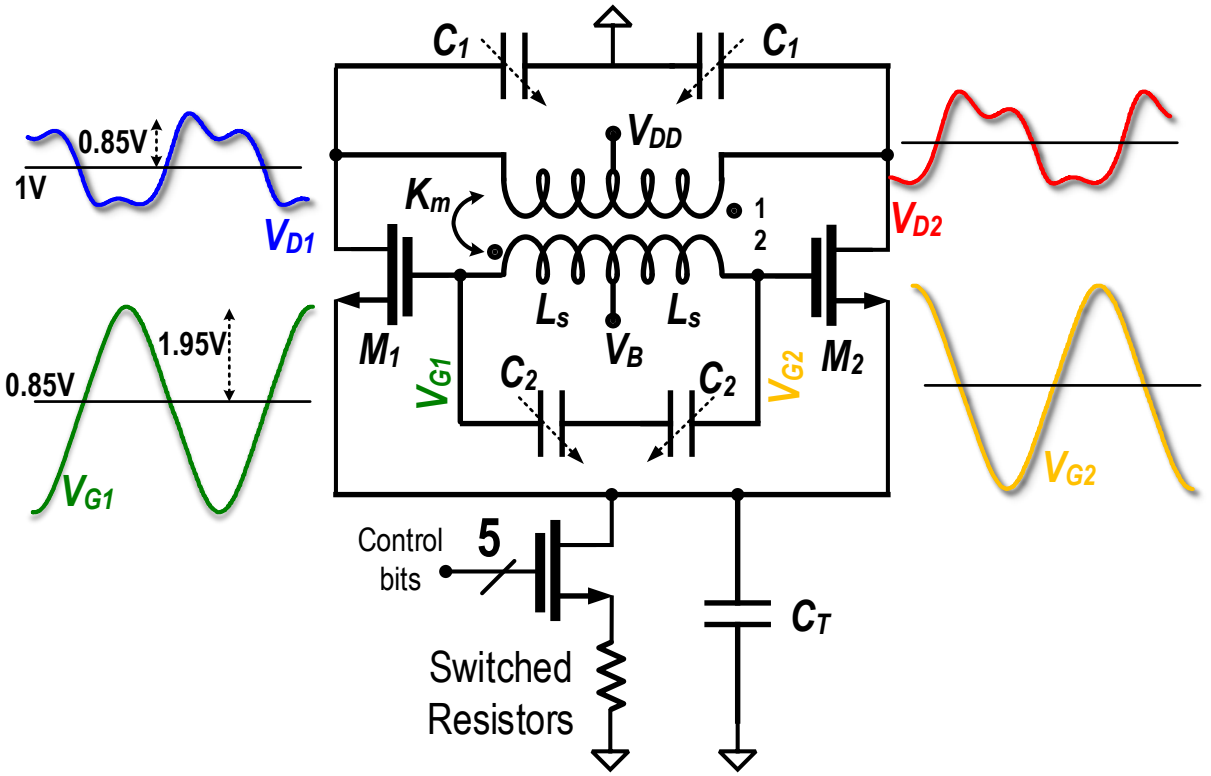
Cryo-Oscillator (Class F)



M. Shahmohammadi, *ISSCC* 2015

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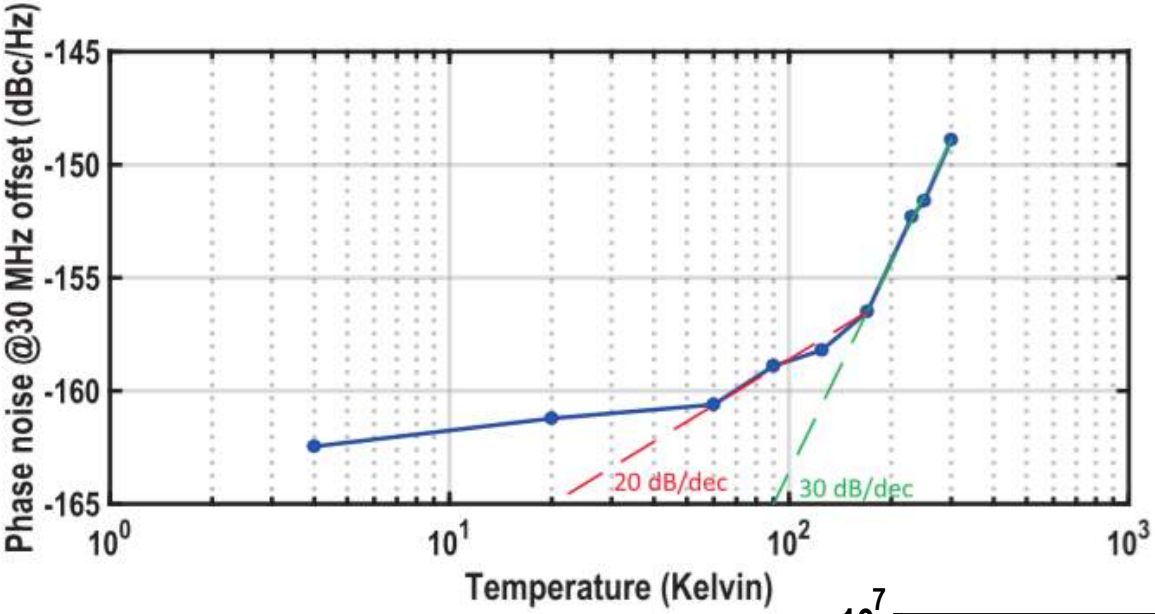
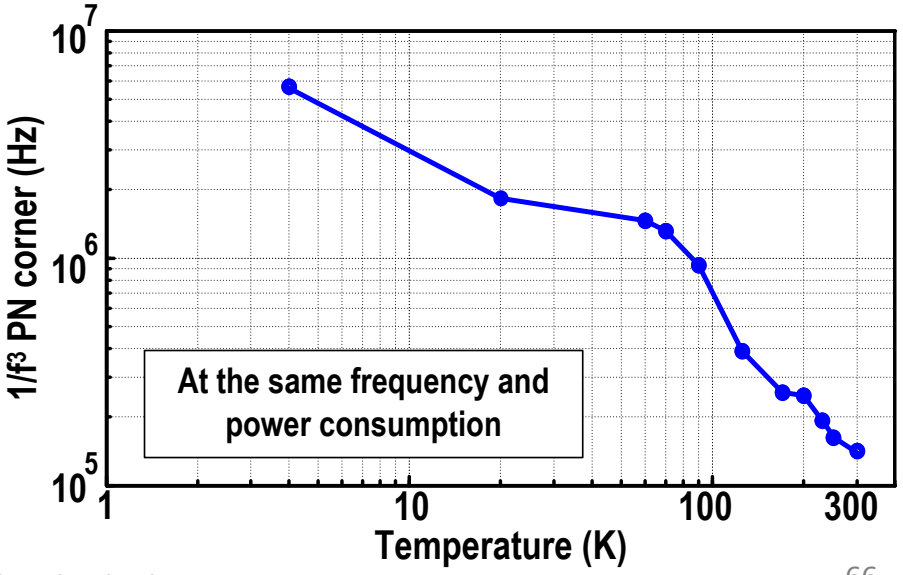
Measured Phase Noise



$1/f^2$ part of PN (thermal noise)

B. Patra et al, *JSSC* 2017



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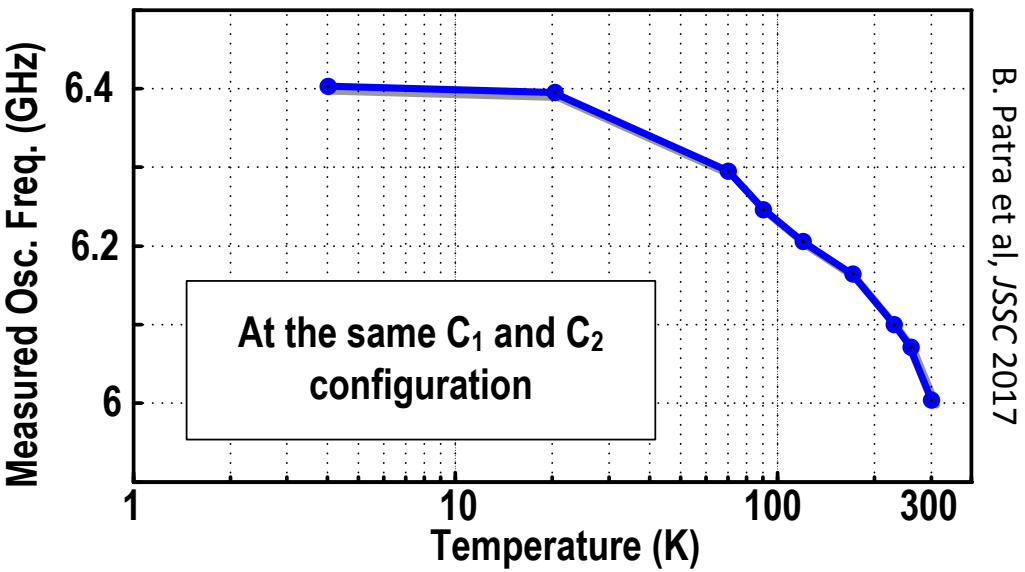
Frequency Stability



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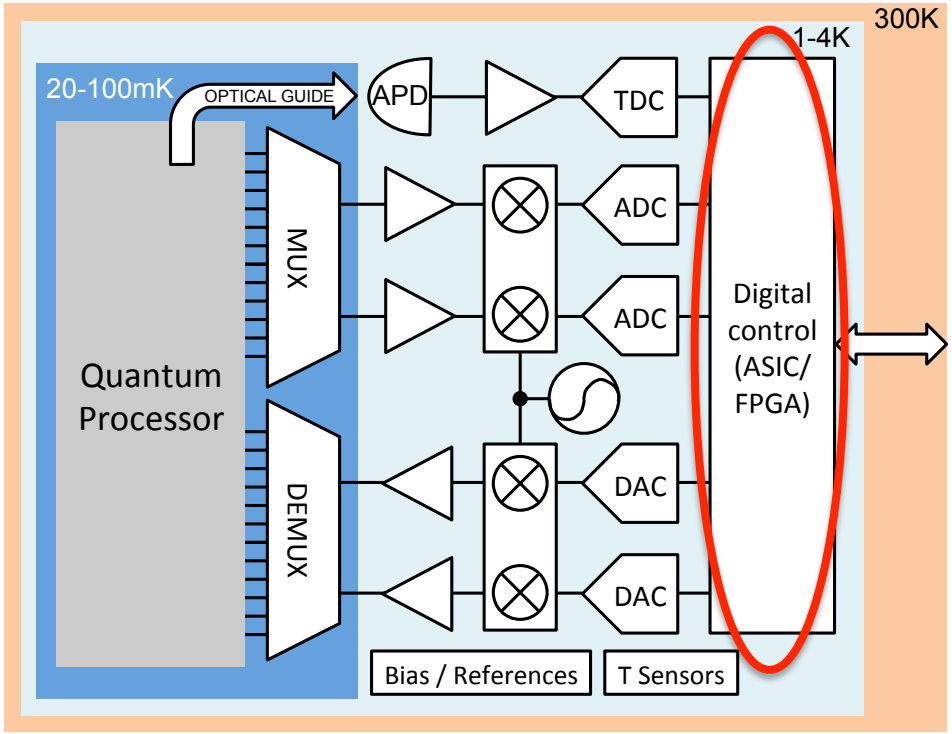
Cryo-Logic



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Ultra-Low Voltage Library ‘cooLib’

- Digital library optimized for 4K
- Ultra low voltage operation (100s mV)
- Sub-threshold bias of N/P MOS
- Resilient to latchup and hysteresis-free
- Several logic families (static and dynamic CMOS)
- Compatible with commercial P&R tools

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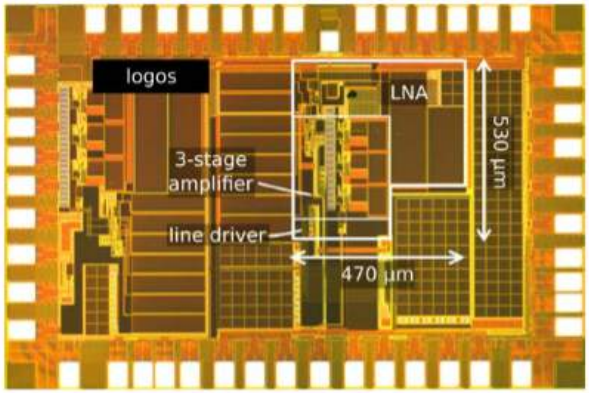
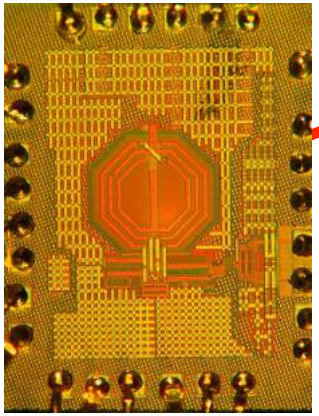
In Summa



IEEE ISSCC 2017

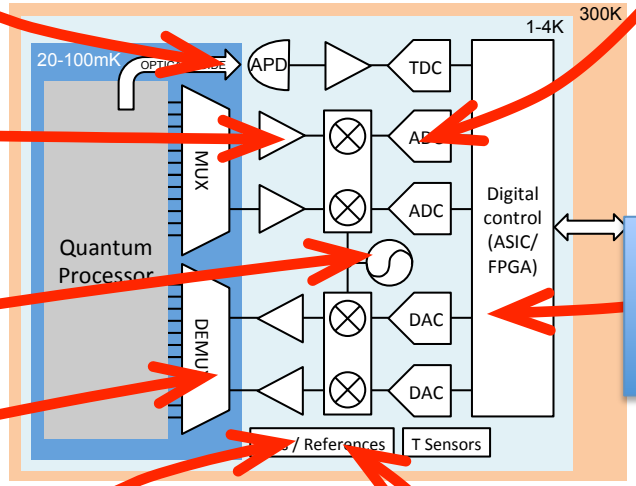


IEEE ISSCC 2017

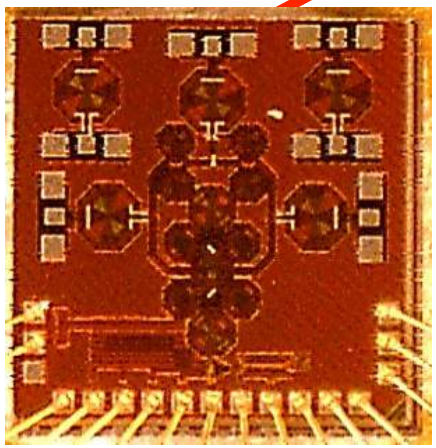
IEEE IEDM 2016

III-V SPAD
By Tosi et al.
Our version to be published

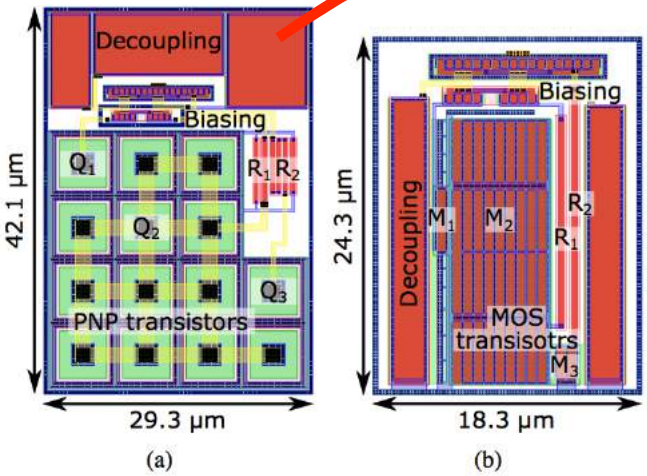
IEEE IEDM 2016



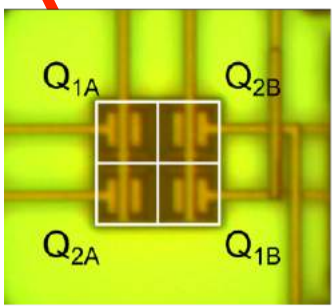
CooLib



IEEE RFIC 2019



Cryo-Bandgap: BJTs (a), DTMOS (b)
SSC-L 2018, Cryogenics, 2018



IEEE Sensors 2016

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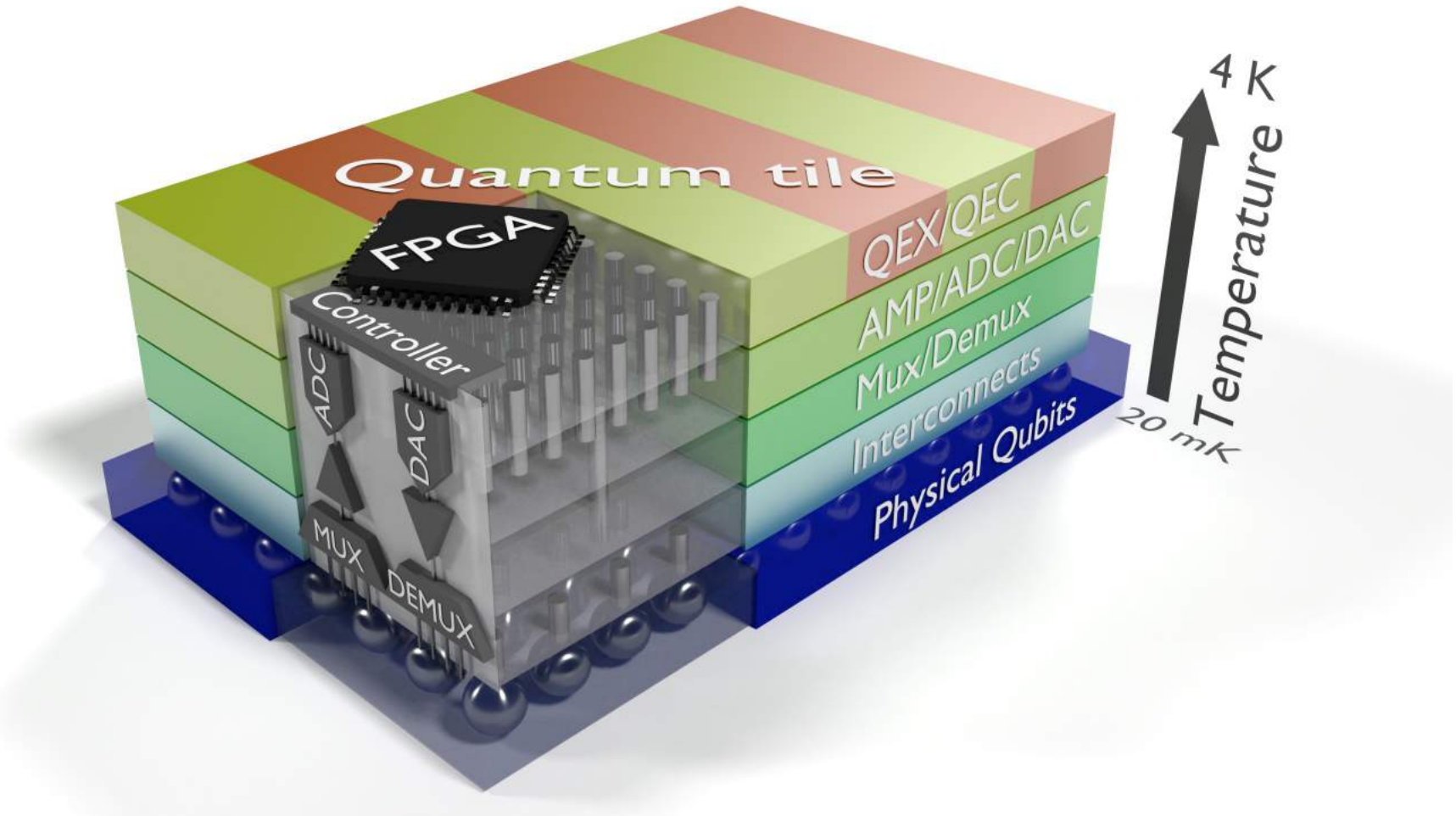
Quantum Computing Stack



Cryo-CMOS Circuits and Systems

IEEE JOURNAL OF SOLID-STATE CIRCUITS

Cryo-CMOS Circuits and Systems for Quantum Computing Applications

Bishnu Patra, *Student Member, IEEE*, Rosario M. Incandela, *Student Member, IEEE*, Jeroen P. G. van Dijk, Harald A. R. Homulle, Lin Song, Mina Shahmohammadi, *Member, IEEE*, Robert Bogdan Staszewski, *Fellow, IEEE*, Andrei Vladimirescu, *Fellow, IEEE*, Masoud Babaie, *Member, IEEE*, Fabio Sebastiano, *Senior Member, IEEE*, and Edoardo Charbon, *Fellow, IEEE*

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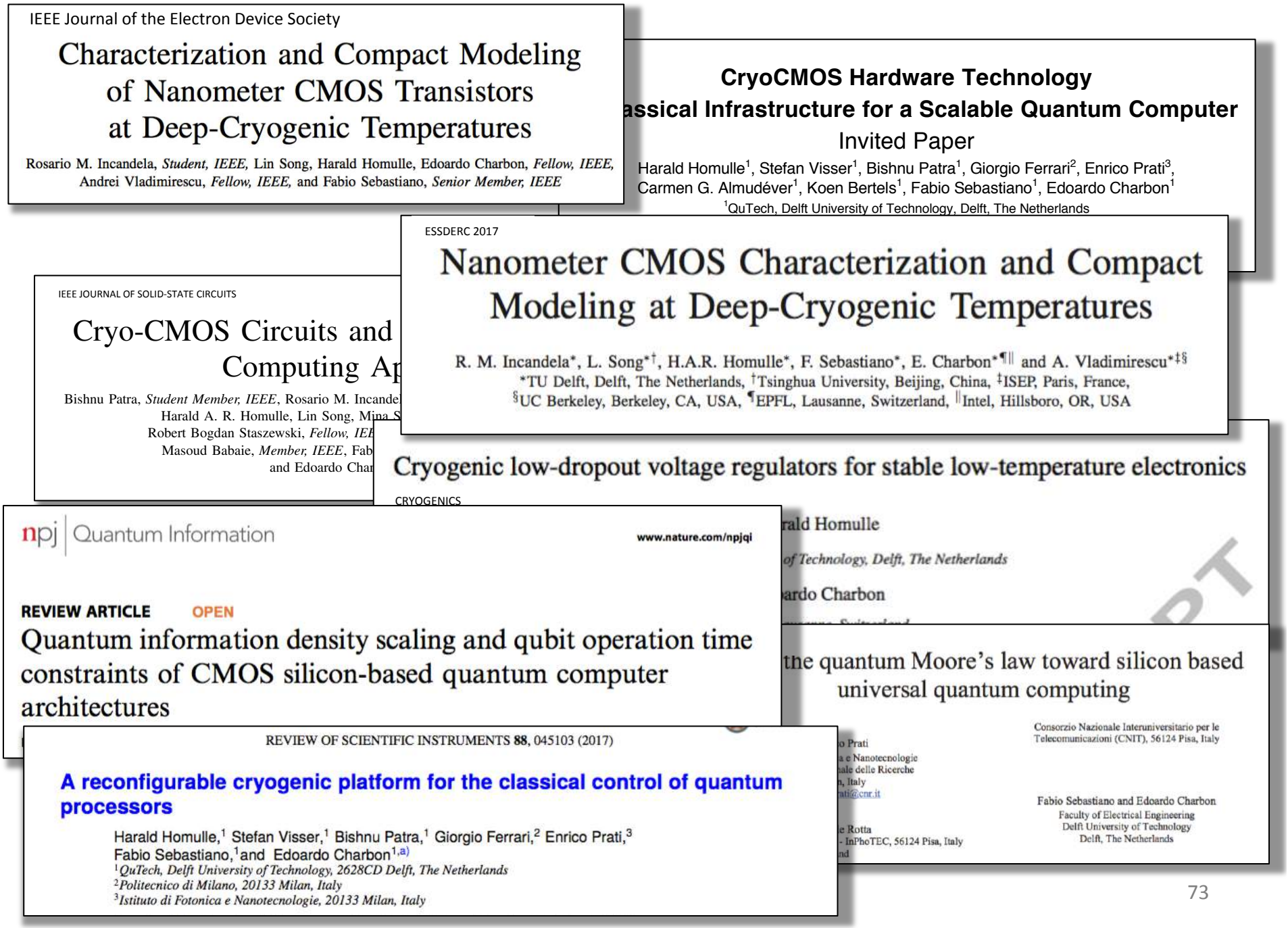

IEEE Journal of the Electron Device Society

Characterization and Compact Modeling of Nanometer CMOS Transistors at Deep-Cryogenic Temperatures

Rosario M. Incandela, *Student, IEEE,* Lin Song, Harald Homulle, Edoardo Charbon, *Fellow, IEEE,* Andrei Vladimirescu, *Fellow, IEEE,* and Fabio Sebastiano, *Senior Member, IEEE*

CryoCMOS Hardware Technology

assical Infrastructure for a Scalable Quantum Computer

Invited Paper

Harald Homulle[1], Stefan Visser[1], Bishnu Patra[1], Giorgio Ferrari[2], Enrico Prati[3], Carmen G. Almudéver[1], Koen Bertels[1], Fabio Sebastiano[1], Edoardo Charbon[1]

[1]QuTech, Delft University of Technology, Delft, The Netherlands

ESSDERC 2017

Nanometer CMOS Characterization and Compact Modeling at Deep-Cryogenic Temperatures

R. M. Incandela*, L. Song*†, H.A.R. Homulle*, F. Sebastiano*, E. Charbon*¶‖ and A. Vladimirescu*‡§

*TU Delft, Delft, The Netherlands, †Tsinghua University, Beijing, China, ‡ISEP, Paris, France, §UC Berkeley, Berkeley, CA, USA, ¶EPFL, Lausanne, Switzerland, ‖Intel, Hillsboro, OR, USA

IEEE JOURNAL OF SOLID-STATE CIRCUITS

Cryo-CMOS Circuits and

Computing Ap

Bishnu Patra, *Student Member, IEEE*, Rosario M. Incande

Harald A. R. Homulle, Lin Song, Mina S

Robert Bogdan Staszewski, *Fellow, IEE*

Masoud Babaie, *Member, IEEE*, Fab

and Edoardo Char

Cryogenic low-dropout voltage regulators for stable low-temperature electronics

CRYOGENICS

rald Homulle

of Technology, Delft, The Netherlands

ardo Charbon

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REVIEW ARTICLE OPEN

Quantum information density scaling and qubit operation time constraints of CMOS silicon-based quantum computer architectures

the quantum Moore's law toward silicon based universal quantum computing

Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT), 56124 Pisa, Italy

o Prati

a e Nanotecnologie

ale delle Ricerche

n, Italy

ati@cnr.it

e Rotta

- InPhoTEC, 56124 Pisa, Italy

nd

Fabio Sebastiano and Edoardo Charbon

Faculty of Electrical Engineering

Delft University of Technology

Delft, The Netherlands

REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 045103 (2017)

A reconfigurable cryogenic platform for the classical control of quantum processors

Harald Homulle,[1] Stefan Visser,[1] Bishnu Patra,[1] Giorgio Ferrari,[2] Enrico Prati,[3] Fabio Sebastiano,[1] and Edoardo Charbon[1,a)]

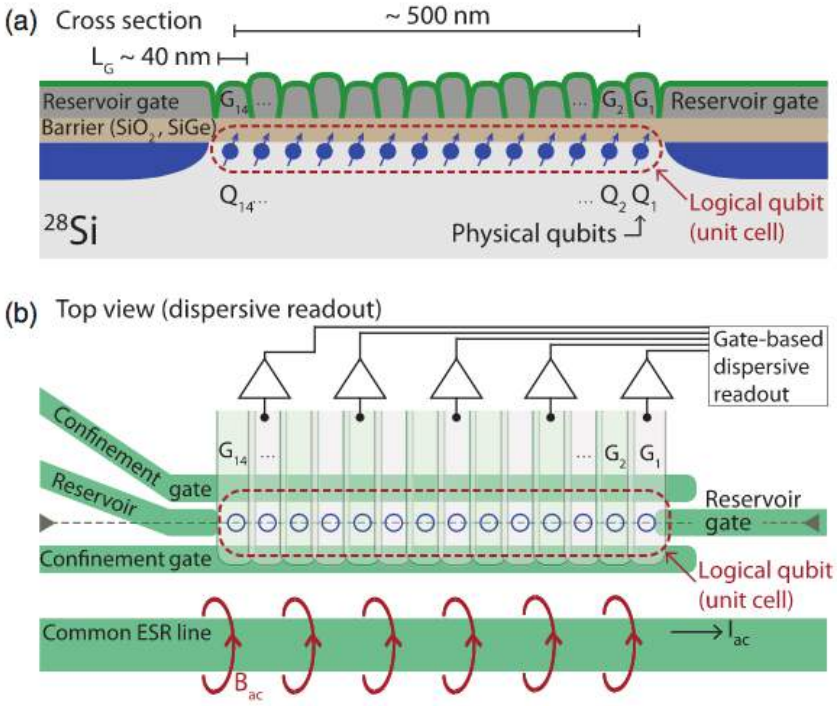
[1]*QuTech, Delft University of Technology, 2628CD Delft, The Netherlands*

[2]*Politecnico di Milano, 20133 Milan, Italy*

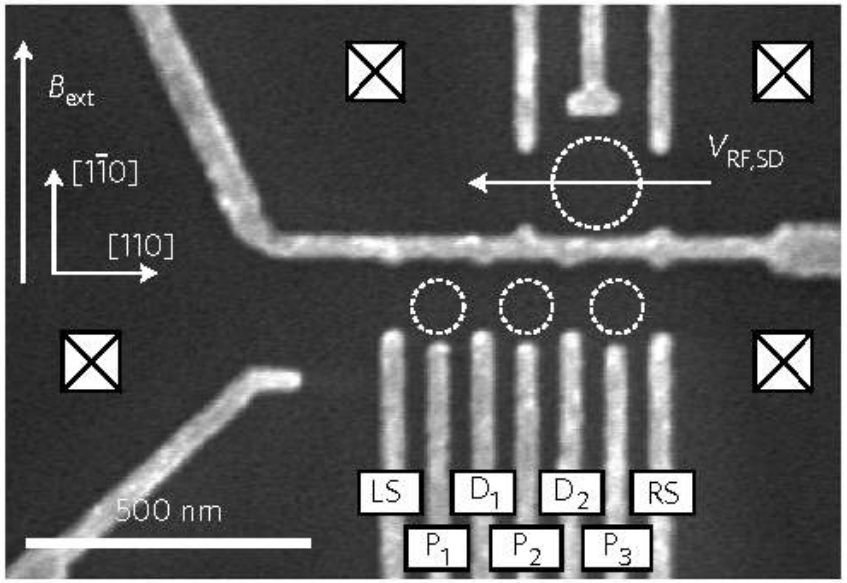
[3]*Istituto di Fotonica e Nanotecnologie, 20133 Milan, Italy*

Current & Future Challenges

Realizations of 1D Qubit Arrangements



Jones *et al*, PRX 8, 021058 (2018)



Baart *et al*, Nat Nano (2017)

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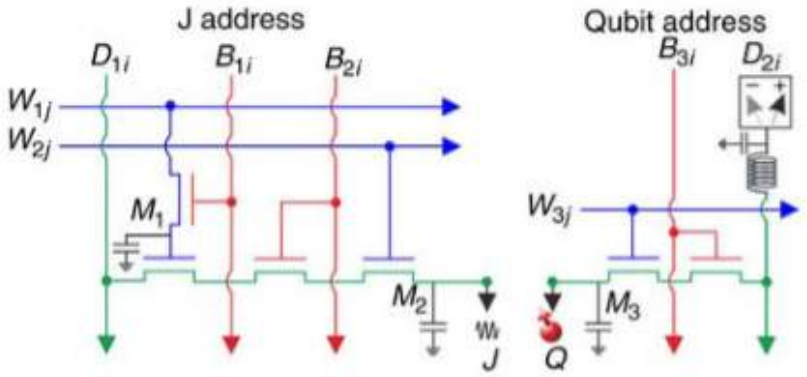
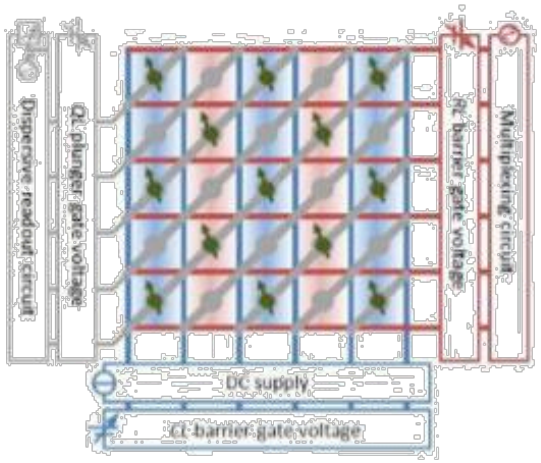
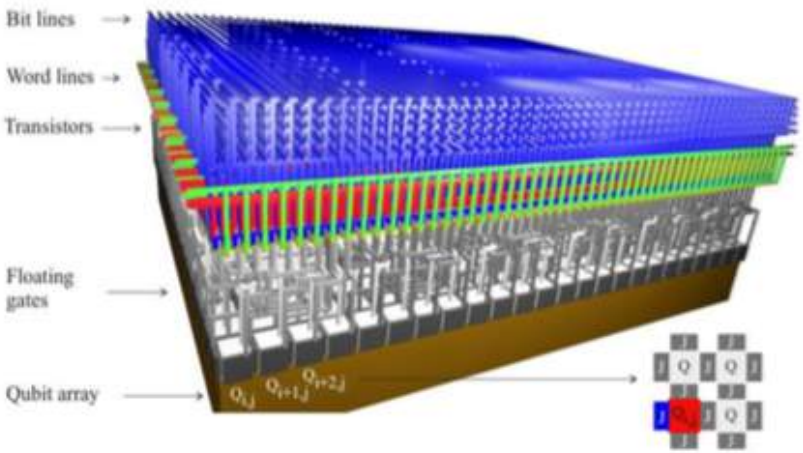
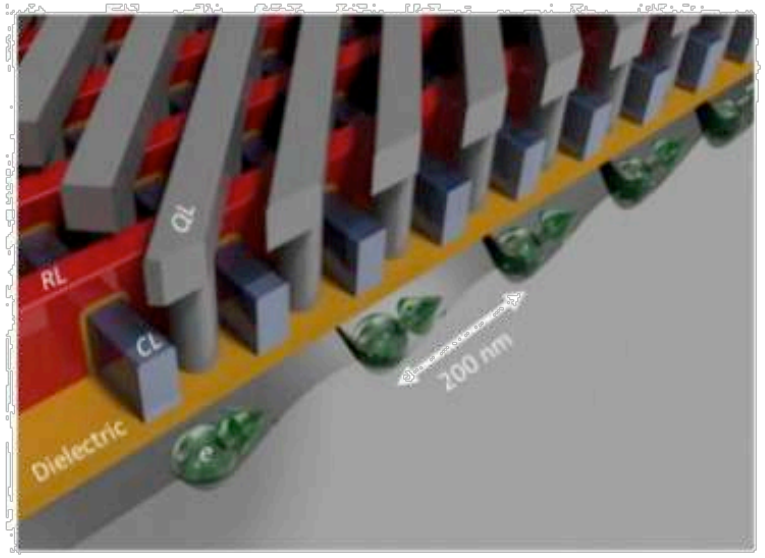
Proposals for Scalable Fault-Tolerant 2D Qubit Arrangements







M. Veldhorst *et al. (UNSW), Nature Comm.* (2017)



R. Li et al., arXiv 1711.03807 (2017)

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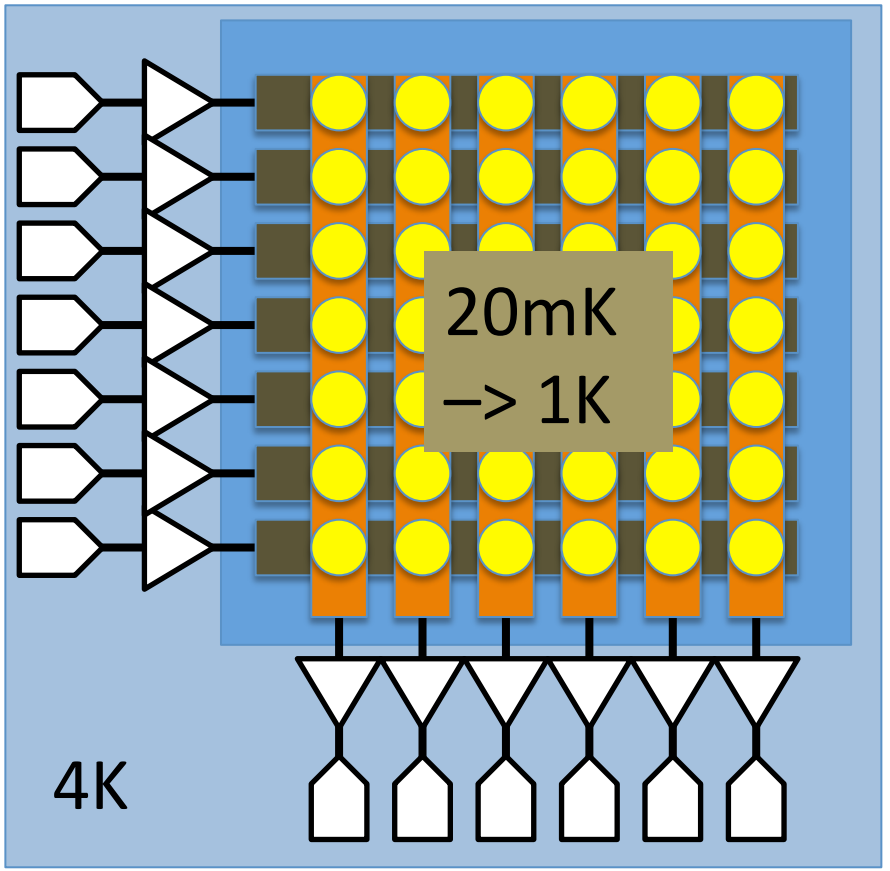
Platforms for the 2D Approach

- **Single-shot dispersive readout** just achieved by several groups: could be the core of column readouts
- Use ***imaging sensor*** readout as inspiration
- Use tunneling barriers as selectors
- (limited) use of 3D stacking
- Ideally bring qubits to 1-4K, make them CMOS-compatible



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H. Homulle *et al.*, QuRO interface
Silicon Quantum Electronics Workshop, 2018

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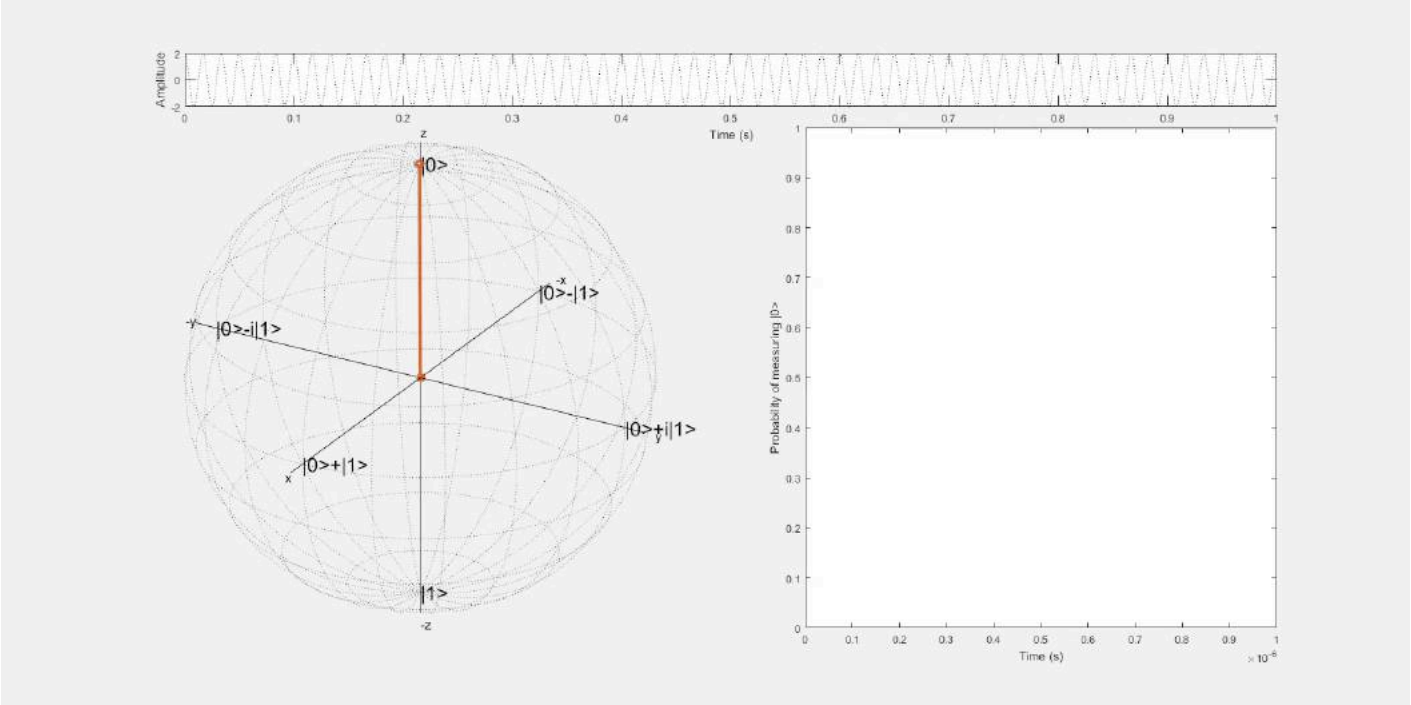
System-Level Modeling – *SPINE*



JPG van Dijk *et al.*, arXiv:1803.06176 (2018)

- SPINE: Spin Emulator
- Simulation from Hamiltonian to SPICE
- Whatif analysis to trade off specifications

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General Specifications

- Target fidelity: 99.99% for 1…10 MHz operation
- Analog:

Error Source	*Type*	*Value*	*Contribution*
Microwave frequency	inaccuracy	35.4 kHz	1-F = 12.5 ppm
(nominally 10 GHz)	noise	35.4 kHz_{rms}	1-F = 12.5 ppm
Microwave phase	Inaccuracy	0.20 °	1-F = 12.5 ppm
	noise	0.20 °	1-F = 12.5 ppm
Microwave amplitude	inaccuracy	38.3 µV	1-F = 12.5 ppm
(nominally 17 mV, -53 dB)	noise	38.3 μV_{rms}	1-F = 12.5 ppm
Microwave duration	inaccuracy	113 ps	1-F = 12.5 ppm
(nominally 50 ns)	noise	113 ps_{rms}	1-F = 12.5 ppm
			F = 99.99%

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			F = 99.99%

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Tradeoffs

1-qubit gate:
Oscillator phase noise
Timing accuracy
…

Fidelity
(99.9%)

2-qubit gate:
Voltage drift
Timing jitter
…

Power
(~ 1 mW/qubit)

Qubit read-out:
Amplitude noise
…

- Fidelity is usually expressed as a percentage, ofter referred to as x9's (e.g. 5 9's = 99.999%)
- Higher fidelity usually requires high power, which is budgeted, espcially at low temperatures (e.g. µW of thermal absorption at mK, while W at 4K)

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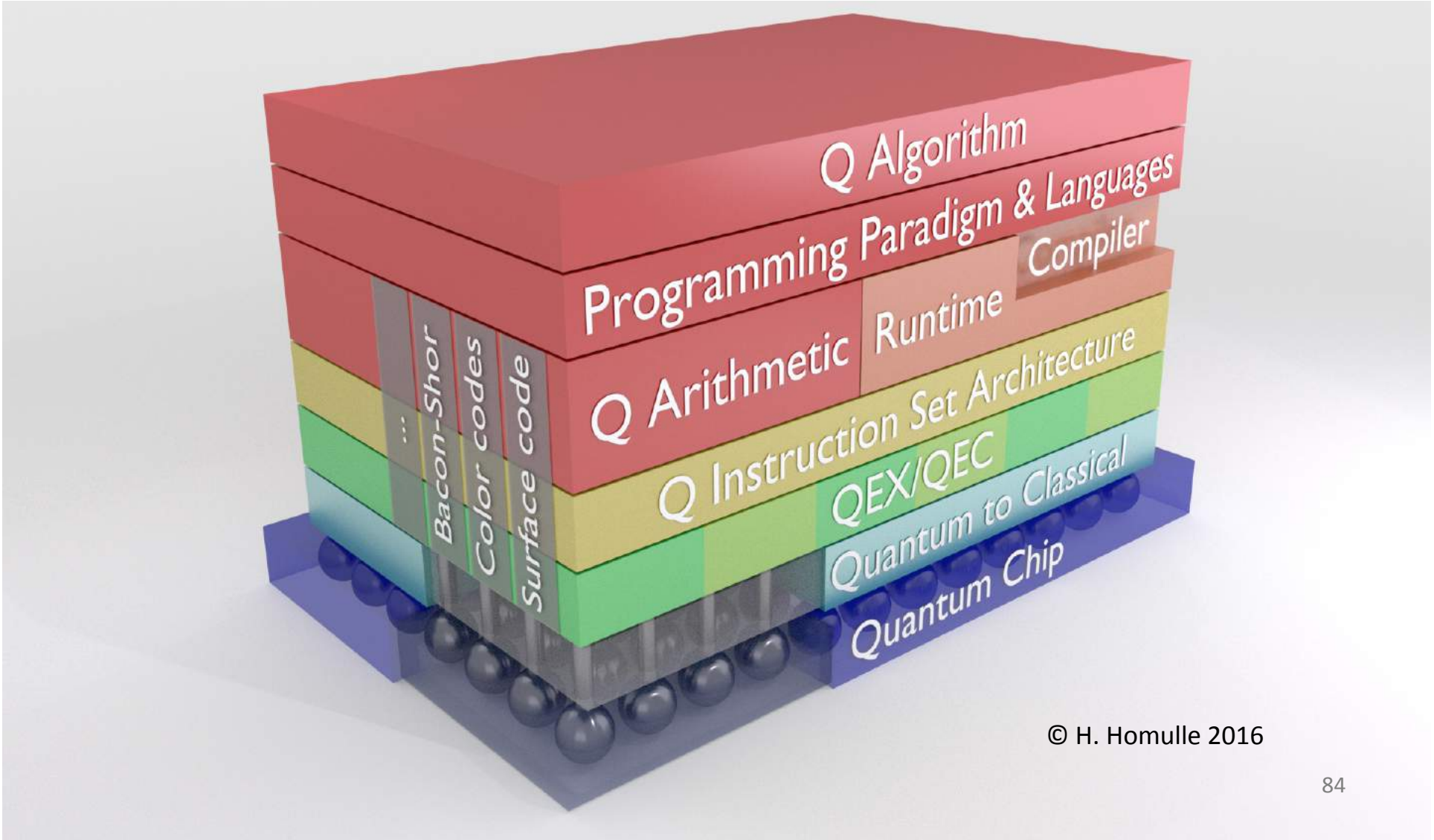
Conclusions

Putting things in context



© H. Homulle 2016

Take-home Messages

- A quantum computer is a new computing paradigm and as such it holds the promise to handle today's intractable problems
- A qubit is fragile and thus needs to be constantly corrected to extend its coherence and to maintain fidelity
- Cryogenic electronics for quantum computing ensures compactness and scalability to much larger quantum processors

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Acknowledgements

Intel Corp.
Swiss National Science Foundation
European Space Agency
FP6 and FP7
NCCR-MICS
NOW-STW
EC Funded MOS-QUITO

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http://aqua.epfl.ch

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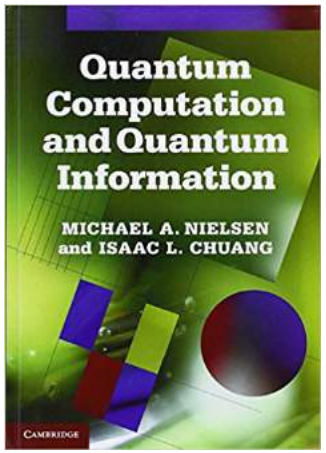

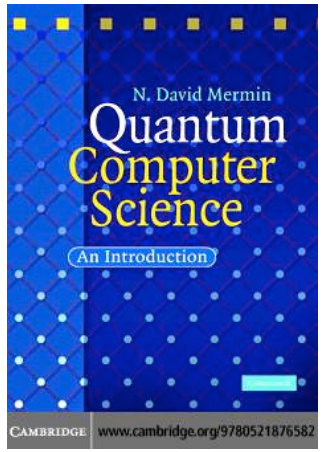

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