The role of cryo-CMOS technology for scalable quantum systems

Edoardo Charbon

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Outline

• Quantum computing & qubits
• Architectures
• Cryogenic electronics
• Qubits and control
• Current & future challenges
Quantum Computing & Qubits
The Idea behind Quantum Computing

• Proposal by many, *in primis* Richard Feynman of using *entanglement* and *superposition* for computation
• Fundamentals and theory developed in the 1980-2000s

There is plenty of space at the bottom

- Richard Feynman
Decoherence theory reveals that the tiniest interaction with the environment, such as a single photon or gas molecule bouncing off the fallen card, transforms a coherent density matrix very rapidly into one that, for all practical purposes, represents classical probabilities such as those in a coin toss. The Schrödinger equation controls the entire process.

**IDEA:**
Tiny interactions with the surrounding environment rapidly dissipate the peculiar quantumness of superpositions.

**ADVANTAGES:**

**CAVEAT:**
Decoherence does not completely eliminate the need for an interpretation such as many-worlds or Copenhagen.

---

The uncertainty of a quantum superposition (left) is different from the uncertainty of classical probability, as occurs after a coin toss (right). A mathematical object called a density matrix illustrates the distinction. The wave function of the quantum card corresponds to a density matrix with four peaks. Two of these peaks represent the 50 percent probability of each outcome, face up or face down. The other two indicate that these two outcomes can still, in principle, interfere with each other. The quantum state is still “coherent.”

The density matrix of a coin toss has only the first two peaks, which conventionally means that the coin is really either face up or face down but that we just haven’t looked at it yet.
Decoherence theory reveals that the tiniest interaction with the environment, such as a single photon or gas molecule bouncing off the fallen card, transforms a coherent density matrix very rapidly into one that, for all practical purposes, represents classical probabilities such as those in a coin toss. The Schrödinger equation controls the entire process.

**DECOHERENCE:**

Tiny interactions with the surrounding environment rapidly dissipate the peculiar quantumness of superpositions.

**ADVANTAGES:**

Experimentally testable. Explains why the everyday world looks "classical" instead of quantum.

**CAVEAT:**

Decoherence does not completely eliminate the need for an interpretation such as many-worlds or Copenhagen.

**DECOHERENCE / CLASSICAL**

Interaction with Environment

![Diagram showing quantum superposition and classical probability]

The uncertainty of a quantum superposition (left) is different from the uncertainty of classical probability, as occurs after a coin toss (right). A mathematical object called a density matrix illustrates the distinction. The wave function of the quantum card corresponds to a density matrix with four peaks. Two of these peaks represent the 50 percent probability of each outcome, face up or face down. The other two indicate that these two outcomes can still, in principle, interfere with each other. The quantum state is still "coherent." The density matrix of a coin toss has only the first two peaks, which conventionally means that the coin is really either face up or face down but that we just haven't looked at it yet.

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**Entanglement**

**Definition:** two particles are entangled if the quantum state of one particle cannot be described independently from the quantum state of the other particle.

**Intuition:** measuring the quantum state of one particle implies knowledge of the quantum state (e.g. momentum, spin, polarization, etc.) of the other entangled particle using the same projection.
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, Institute for Advanced Study, Princeton, New Jersey

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

1.

A ny serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts whatever the meaning assigned to the term complete, the following requirement for a complete theory seems to be a necessary one: every element of the physical reality must have a counterpart in the physical theory. We shall call this the condition of completeness. The second question is thus easily answered, as soon as we are able to decide what are the elements of physical
The Second Quantum Revolution

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
Fastforward to the 2020s

- Big players and startups
- $140M in Canada alone (2018)
- Extrapolated to €1T worldwide for the next decade
The Promise of Quantum Computing

- **Energy**
  - Room-temperature superconductivity

- **Health**
  - Quantum chemistry

- **Internet Security**

Source: L. Vandersypen, ISSCC 2017

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Quantum Bit (Qubit)

\[ |\psi\rangle = \alpha_0 |0\rangle + \alpha_1 |1\rangle \]

- Superposition
- Entanglement
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
State-of-the-Art

- Ions, molecules, atoms, photons, ...
- 15 = 3 x 5
How Far Are We from Something Useful?

# qubits vs Year

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Quantum Supremacy or Quantum Advantage

Quantum supremacy is the potential ability of quantum computing devices to solve problems that classical computers practically cannot. [Wikipedia]

Google claims to have reached quantum supremacy (Financial Times)
Report on a an accepted paper to a peer-reviewed publication
Solid-state Qubit Implementations Today

- Based on superconducting qubits
- First multi-qubit chips announced
- Freely available qubits on line

Source: Tristan Meunier

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Solid-state Qubit Implementations Today

Semiconductor quantum dots

Superconducting circuits

Semiconductor-superconductor hybrids

Impurities in diamond or silicon

Source: L. Vandersypen, 2017

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Qubits are Fragile

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

Dephasing

Relaxation

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Qubit Transition from $|0\rangle$ to $|1\rangle$
Interfacing Qubits with Classical World

- Carrier frequency: 100 MHz – 15 GHz, 70 GHz
- Pulses: 10 – 100 ns
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
Status of Quantum Algorithms

Quantum Algorithm Zoo

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 $\text{poly}(n)$ 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 $\text{poly}(n)$ time. The fastest known classical algorithm requires time superpolynomial in $n$. By similar

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

In this talk
Architectures
A Real-life Quantum Computer

x 8 qubits
Today’s Solution

72 Qubit system with ~50% of room temperature cabling

Image: Google Bristlecone. Taken from: J.C. Bardin et al., "An Introduction to Quantum Computing for RFIC Engineers", RFIC Symposium 2019

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Proposed Solution

• 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
Cooling Power Issue

Dilution refrigerator

300 K
70 K
4 K
100 mK
20 mK

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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
Cryogenic Electronics

Cryo-CMOS Technologies
Modeling at Cryo-T
The First Thing is Modeling

- MOSFET

\[
\begin{align*}
I_D & = f(V_{DS}, V_{GS}) \\
V_{DS} & > 0 \\
V_{GS} & > 0
\end{align*}
\]

Strong Inversion

Weak Inversion

Threshold

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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

*The transistors measured at 4K is different from that at 1K and 40mK
How to Test on a Large Scale: Transistor Farms

Fig. 1. Die micrograph (left) with close-up of a W/L = 1.2 μm/0.4 μm matched pair (right).

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High-Level Modeling: SPINE (SPIN Emulator)

Objectives:
• Enable co-design qubit/electronics
• Derive specifications for Horse Ridge and other components
• Minimize power to achieve wanted fidelity

Circuit simulator

Electrical signals

Qubit simulator (Hamiltonian)

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SPINE

• Microwave Carrier: Keysight E8267D
  – 22.4 kHz resolution 1 mHz
  – \( \mathcal{L} \) (1 MHz) = -106 dBc/Hz >15 dB better
  – \( S_n = 7.12 \text{nV/\text{VHz}} \) 63 nV/\text{VHz}
  \( \rightarrow > 20 \text{ dB attenuation} \)

• Microwave Envelope: Tektronix 5014C
  – 8-bit resolution 14-bit
  – 140 MS/s 1.2 GS/s
  – 3.56 ns_{rms} 5.0 ps_{rms}
  – 40 dB SNR better

With SPINE we checked that these specs are enough
• Example of full simulation:
  – Sequence of rotations
  – Resulting RF signals
  – Qubit response, in terms of spin-up probability
• This involves spin emulation, M/S simulation, RF simulation

J. Van Dijk et al., DATE 2018
Cryogenic Reconfigurable Hardware
Cryo-FPGAs

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Cryo-FPGAs

CryoCMOS Hardware Technology
A Classical Infrastructure for a Scalable Quantum Computer

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Carmen G. Almudéver¹, Koen Bertels¹, Fabio Sebastiano¹, Edoardo Charbon¹

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FPGA functionality

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

<table>
<thead>
<tr>
<th>Component</th>
<th>Functional</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>IOs</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>LVDS</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>LUTs</td>
<td>✓</td>
<td>Delay change &lt; 5%</td>
</tr>
<tr>
<td>CARRY4</td>
<td>✓</td>
<td>Delay change &lt; 2%</td>
</tr>
<tr>
<td>BRAM</td>
<td>✓</td>
<td>No corruption (800 kB)</td>
</tr>
<tr>
<td>MMCM</td>
<td>✓</td>
<td>Jitter reduction of roughly 20%</td>
</tr>
<tr>
<td>PLL</td>
<td>✓</td>
<td>Jitter reduction of roughly 20%</td>
</tr>
<tr>
<td>IDELAYE2</td>
<td>✓</td>
<td>Delay change of up to 30%</td>
</tr>
<tr>
<td>DSP48E1</td>
<td>✓</td>
<td>No corruption over 400 operations</td>
</tr>
</tbody>
</table>

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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

Delay vs. VDD

Clocks

LUT Delays

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ADC on FPGA (1.2GSa/s)

Signal bandwidth: 2 MHz

Signal bandwidth: 40 MHz

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

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)
Cryogenic ASICs
Low Noise Amplifiers (Cryo-LNAs)
Cryo-LNA

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

F. Bruccoleri et al., JSSC 2004
Cryo-LNA

Tuning for input matching

Tuning for noise canceling

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Gain and Noise

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

Gain

- Gain = 59 dB

Noise Figure

- NET = 21 K
Power consumption at 4 K [mW]

- LNA: 54.9 mW
- 3-stages: 28 mW
- Driver: 2.7 mW
- Bias: 5.4 mW

Measured: 91 mW

Power consumption at 300 K [mW]

- LNA: 45.9 mW
- 3-stages: 26.9 mW
- Driver: 1.8 mW
- Bias: 5.4 mW

Measured: 80 mW

Sharing 150x 1MHz-channels (one channel per qubit) = 0.61 mW per qubit

Rosario Incandela

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### Can We Do Better?

<table>
<thead>
<tr>
<th>Amplifier Metrics</th>
<th>Cryogenic HEMT</th>
<th>JPA</th>
<th>TWPA 1.0</th>
<th>TWPA 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Dissipation</td>
<td>16 mW</td>
<td>100 pW</td>
<td>1 nW</td>
<td>5 nW</td>
</tr>
<tr>
<td>Bandwidth (&gt;15 dB gain)</td>
<td>11 GHz</td>
<td>100 - 200 MHz</td>
<td>6 GHz</td>
<td>5 GHz</td>
</tr>
<tr>
<td>1-dB Compression point</td>
<td>0 dBm (3 qubits)</td>
<td>-110 dBm (20-30 qubits)</td>
<td>-95 dBm (&gt; 100 qubits)</td>
<td>-85 dBm (&gt; 100 qubits)</td>
</tr>
<tr>
<td>Noise Temperature</td>
<td>5 K</td>
<td>400 mK</td>
<td>400 mK</td>
<td>400 mK</td>
</tr>
<tr>
<td>External Hardware</td>
<td>Isolator</td>
<td>Direct. Coupler, Circulator</td>
<td>Direct. Coupler</td>
<td>None</td>
</tr>
</tbody>
</table>

**Can We Do Better?**

Courtesy: David Hover and Greg Calusine, MIT Lincoln Laboratory
CMOS Passive Circulators & Multiplexers
Transmission Line Circulator

![Diagram of Transmission Line Circulator]

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

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

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Passive Circulator Architecture

- Non-reciprocal behavior due to staggered commutation
- Passive LC all-pass filters
- Passive mixers with non-overlapping I/Q phases
- On-chip LO divider and I/Q generation
- SPI control for tunability

$P_{DC} = 1.7 \text{ mW}$
$P_{AUX} = 8 \text{ mW}$
Passive Circulator Architecture
CMOS 40 nm Circulator Prototype

- TSMC CMOS 40 nm technology
- Tape-out, PCB design and measurements at 300 K and 4.2 K
- RF probing with LakeShore CPX probe station

A. Ruffino et al, RFIC 2019
Measured S-parameters (300K)

A. Ruffino et al, RFIC 2019
Measured S-parameters (4.2K)

A. Ruffino et al, RFIC 2019
Cryo-Oscillators
Cryo-Oscillator (Class F)

M. Shahmohammadi, ISSCC 2015

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Phase Noise

Measured PN (dBc/Hz)

Offset frequency (Hz)

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Sources of noise:
- Thermal noise
- Shot noise
- Impurities in copper
Frequency Stability

B. Patra et al, JSSC 2018
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
‘CooLib’ RISC-V Implementation

FEATURES
- RISC-V (picorv32, open-source) implemented using ‘CooLib’
- 8 Kb single-port SRAM from TSMC
- SRAM operates at nominal voltage, core at lower voltage
  - Interfacing by ‘CooLib’ level-shifters
- UART interface for serial in/output
- JTAG interface for SRAM write/read

Fully functional µP
Successfully Booted
LINUX at 4K

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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, Masoud Babaie, Member, IEEE, Edoardo Charbon, Fellow, IEEE, Robert Bogdan Staszewski, Fellow, IEEE, Andrei Vladimirescu, Fellow, IEEE, Mansou Rabah, Member, IEEE, Fabio Sebastiano, Senior Member, IEEE, and Edoardo Charbon, Fellow, IEEE
Qubits and Control (in the Fridge)
Step 1: Multiplexing Qubits

Two device gate maps measured in an interleaved manner

Approach can be applied down to 100nm scale

S Schaal et al., arXiv:1809.03894
Step 2: Reading Qubits

- Single-shot dispersive readout
- *Single electron transistor* readout
- (limited) use of 3D stacking
- Ideally bring qubits to 1-4K, make them CMOS-compatible

H. Homulle et al., QuRO interface
Silicon Quantum Electronics Workshop, 2018
Step 3: Controlling Qubits

- Lower Speed DAC + Mixer

Digital

\[ f_s = 2.5 \text{GHz} \]

Analog: noise/linearity specifications known + feasible
Controlling Qubits: Specs

- Target fidelity: 99.99% for 1...10 MHz operation

### Analog:

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Type</th>
<th>Value</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave frequency</td>
<td>inaccuracy</td>
<td>35.4 kHz</td>
<td>1-F = 12.5 ppm</td>
</tr>
<tr>
<td>(nominally 5...13 GHz)</td>
<td>noise</td>
<td>35.4 kHz_{rms}</td>
<td>1-F = 12.5 ppm</td>
</tr>
<tr>
<td>Microwave phase</td>
<td>Inaccuracy</td>
<td>0.20 °</td>
<td>1-F = 12.5 ppm</td>
</tr>
<tr>
<td></td>
<td>noise</td>
<td>0.20 °</td>
<td>1-F = 12.5 ppm</td>
</tr>
<tr>
<td>Microwave amplitude</td>
<td>inaccuracy</td>
<td>38.3 μV</td>
<td>1-F = 12.5 ppm</td>
</tr>
<tr>
<td>(nominally 17 mV, -53 dB)</td>
<td>noise</td>
<td>38.3 μV_{rms}</td>
<td>1-F = 12.5 ppm</td>
</tr>
<tr>
<td>Microwave duration</td>
<td>inaccuracy</td>
<td>113 ps</td>
<td>1-F = 12.5 ppm</td>
</tr>
<tr>
<td>(nominally 50 ns)</td>
<td>noise</td>
<td>113 ps_{rms}</td>
<td>1-F = 12.5 ppm</td>
</tr>
</tbody>
</table>

F = 99.99%

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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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SiMOS QD Qubit Operation at 1.5 Kelvin

Silicon quantum processor unit cell operation above one Kelvin

C. H. Yang,1,8 R. C. C. Leon,1 J. C. C. Hwang,1,† A. Saraiva,1 T. Tanttu,1 W. Huang,1 J. Camirand Lemyre,2 K. W. Chan,1,† K. Y. Tan,1,† F. E. Hudson,1 K. M. Itoh,3 A. Morello,1 M. Pioro-Ladrière,2,4 A. Laucht,1 and A. S. Dzurak1,§

⇒ 1.5 K performance comparable to natSi at 100 mK!

H. Yang et al., arXiv:1902.09126

Courtesy: A. Dzurak
Platforms for the 2D Approach

- Single-shot dispersive readout 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
Fidelity is usually expressed as a percentage, often referred to as x9’s (e.g. 5 9’s = 99.999%).

Higher fidelity usually requires high power, which is budgeted, especially at low temperatures (e.g. µW of thermal absorption at mK, while W at 4K).
Conclusions
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
Acknowledgements

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IceQubes: International Workshop on Cryogenic Electronics for Quantum Systems
2-5 June 2020, Neuchatel - Switzerland
http://aqua.epfl.ch
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• H. Ball, W. D. Oliver, and M. J. Biercuk, npj Quantum Information 2, 16033 EP (2016), review article.
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