Seminar at AGH University, Krakow, Poland

equal 1

Quantum Computer on a Chip

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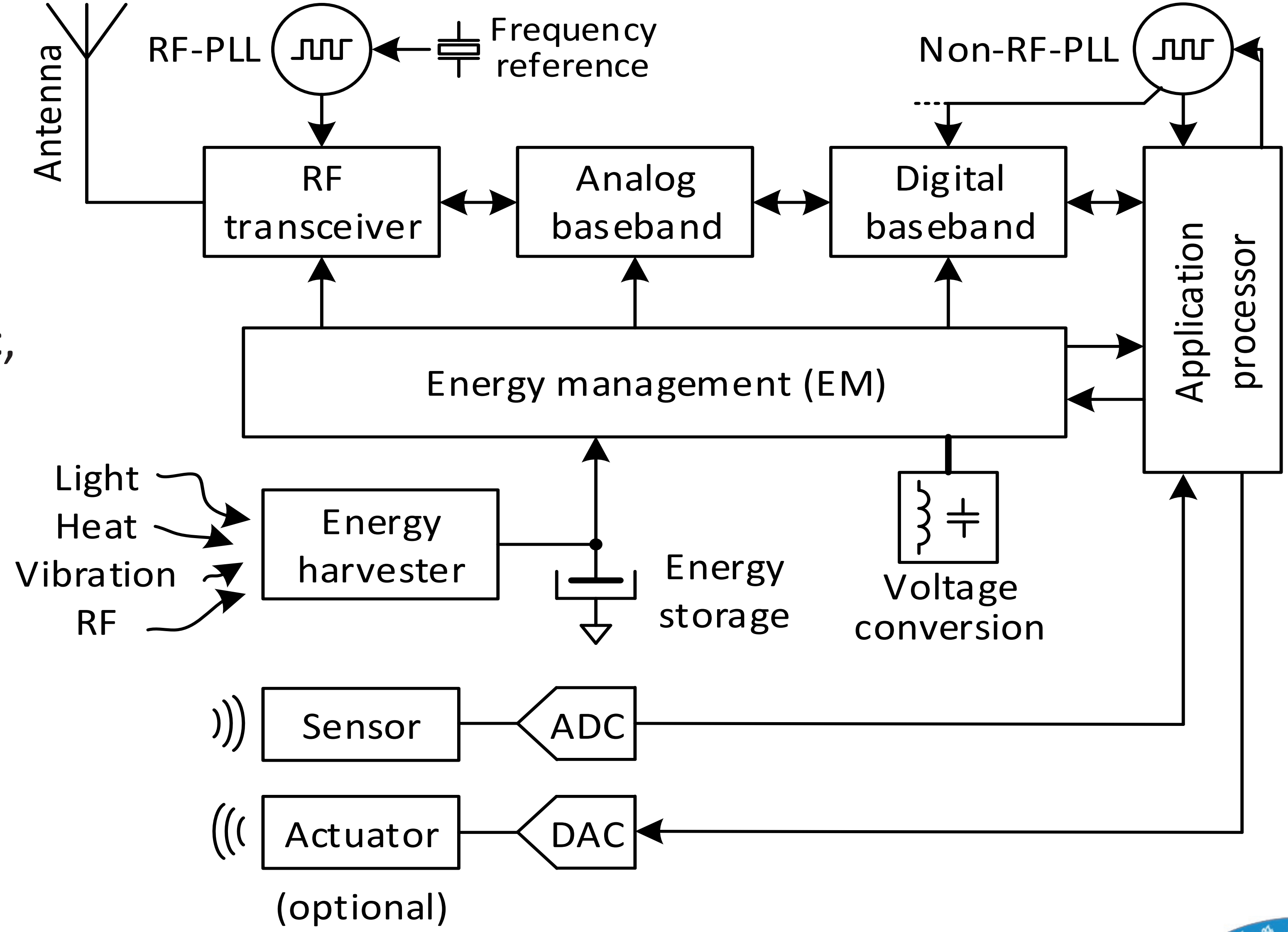
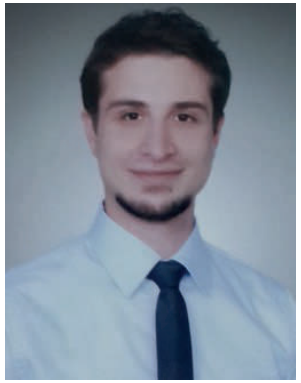
SFI Research Professorship grant: IoT SoC

- 5M euro for 5 years
  - 900k euro lab equipment
- 20 PhD students
- 1 Senior Research Fellow, 1 Senior Postdoc, 1 Junior Postdoc, 1 Technician



QC Research Team at UCD

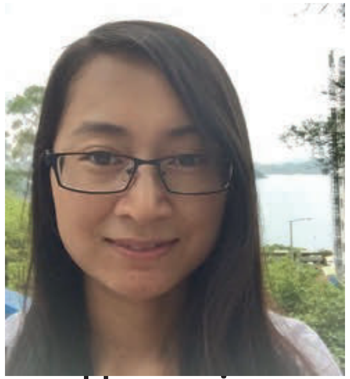


Dr. Cagri Cetintepe

- Antenna arrays & systems
- 5G IoT
- mmW power amplifier

Ali Esmailiyan

- <u>Bio-electronics</u>
- Charge-pump based ADC



Hongying Wang

- Level-crossing ADC
- Passive $\Sigma\Delta$ ADC

Dr. Panagiotis Giounanlis

(part-time)

Dr. Elena Blokina

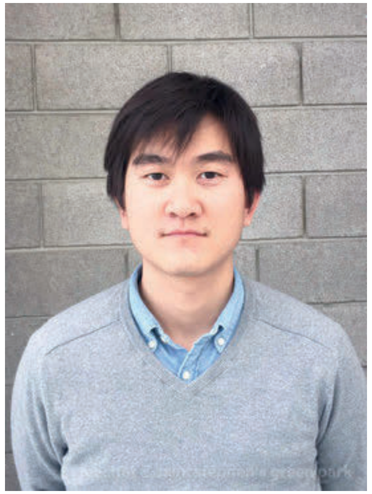
- MEMS
- Circuits theory
- Physical modeling

QC Research Team at UCD

(part-time)

Dr. Krzysztof Pomorski

- Physicist from AGH
- Josephson junctions



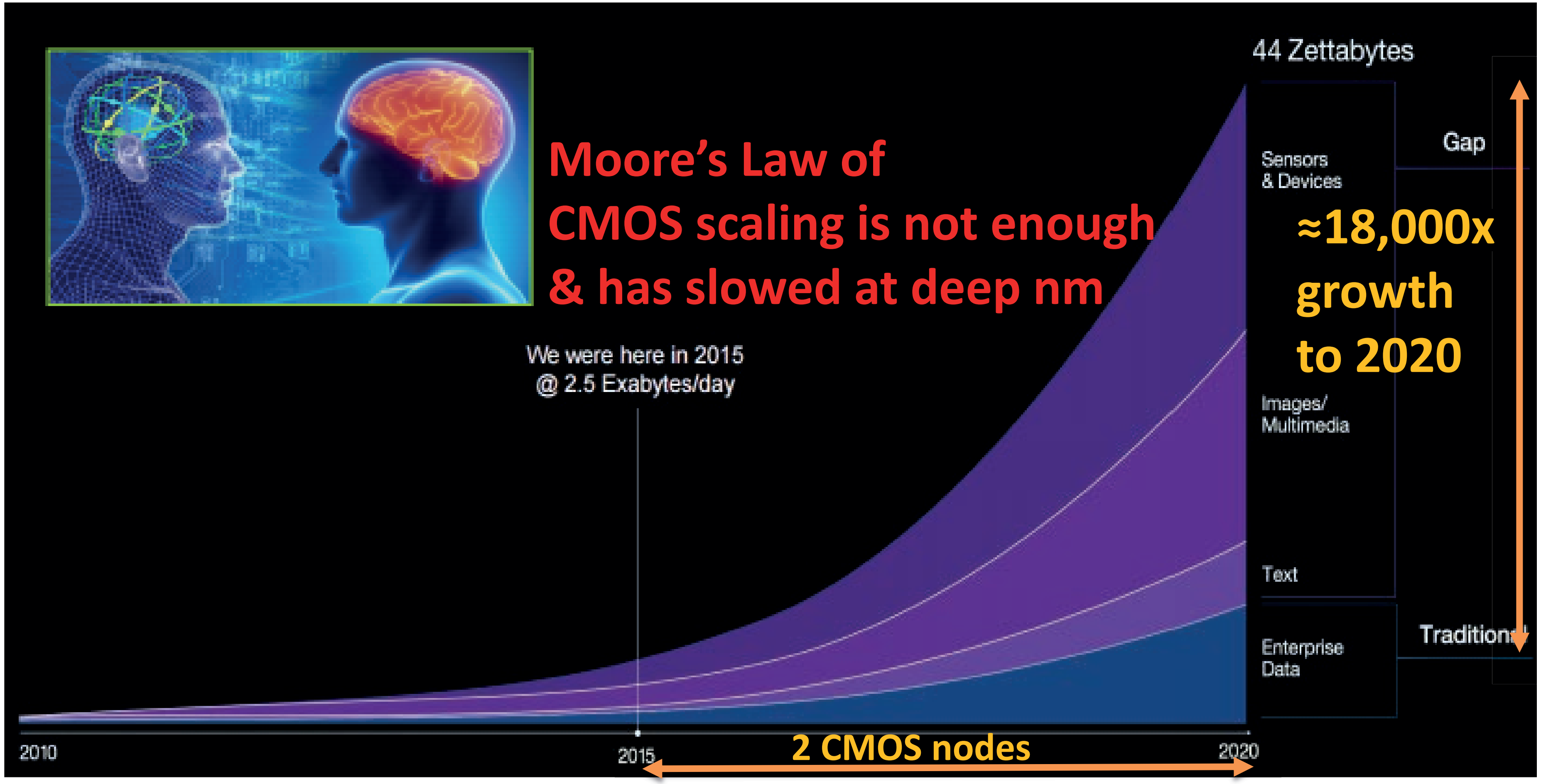
Dr. Teerachot Siriburnon

- Subsampling PLL
- ADPLL
- mmW PLL

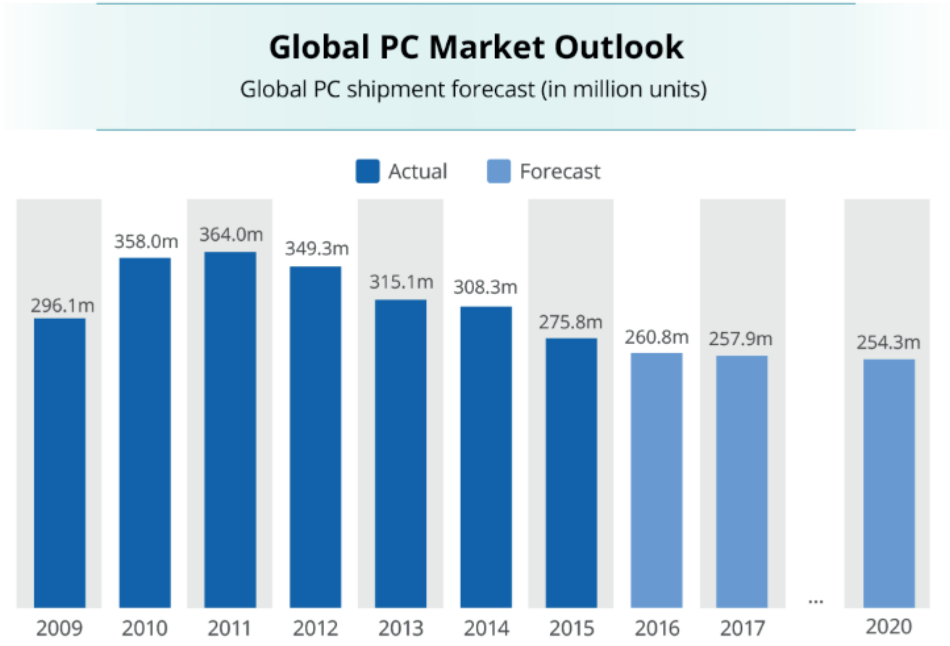
- **Plus a startup company in Silicon Valley ("Equal1" - 4 people with total relevant experience >100 years)**

Why Quantum Computing?

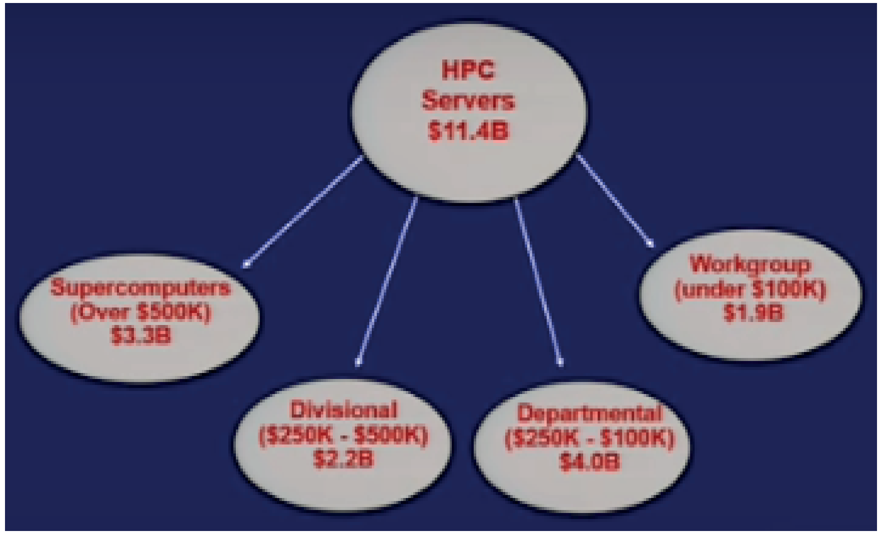
- Cognitive computing (see T.J.Watson presentation @ GTC2016)
- Machine learning will dominate the compute infrastructure

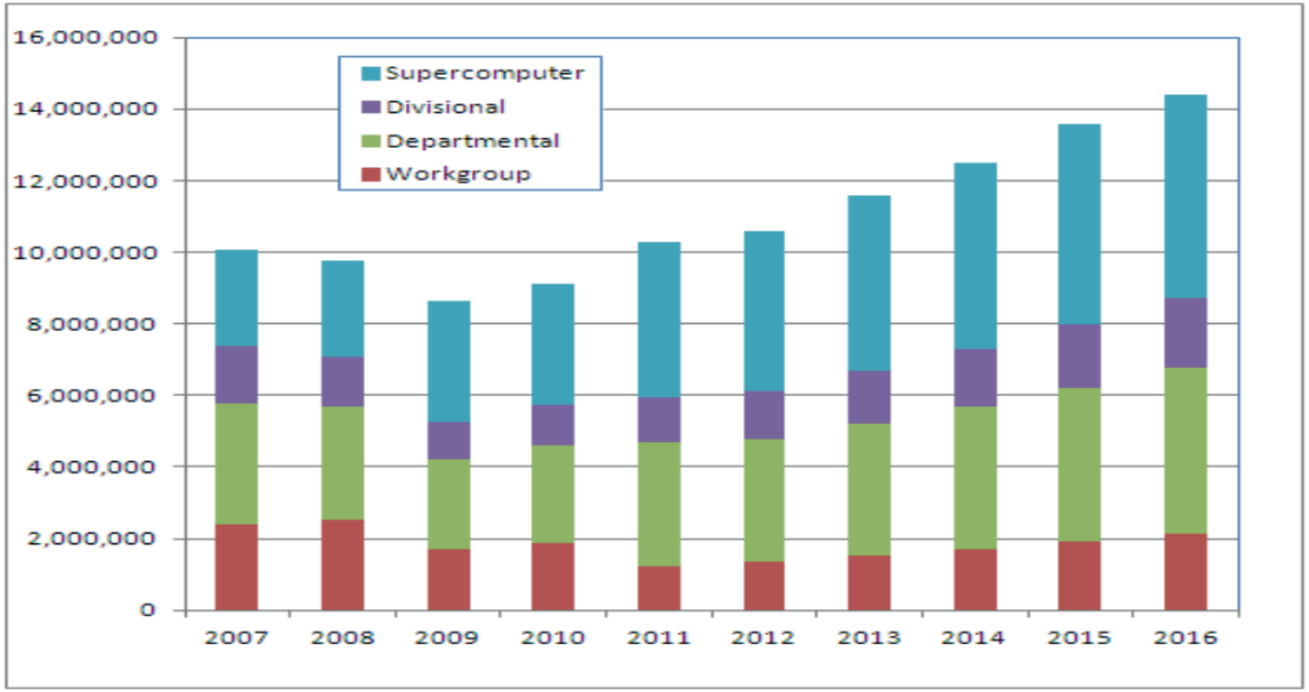


In declining PC market HPC Supercomputers Segment shines



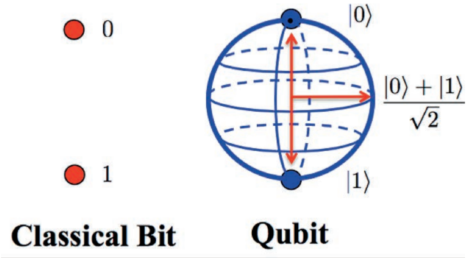
- PC market will stabilize
- Only another -8% decline till 2020
- HPC segment growing at 7% CAGR
- Quantum computers → supercomputers (over $500K) → @ $3.3B in 2015 & 10% CAGR





Quantum Computers (QC)

- QC can handle problems that are well beyond the reach of supercomputers
- Quantum bits ("qubits") can exist in both 0 and 1 simultaneously
  - Quantum superposition state



- Computing power doubles with each additional bit
- European Commission recently announced €1B to spur research in quantum computers (QC)
- State-of-the-art QCs are mainly based on entanglement of spin states of electrons or photons
  - require powerful superconducting magnets at ultra-low cryogenic temperatures of well below 100mK to maintain their spins and read/write through nuclear magnetic resonance (NMR)
- Our proposed practical approach to realizing qubits: an entanglement of electrostatic states of electrons

Quantum Computing Applications

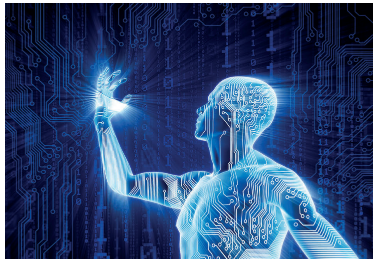
Searching 100+ Exabytes

Truly Safe Communications

Cloud Computing

Financial Institutions

Image Recognition



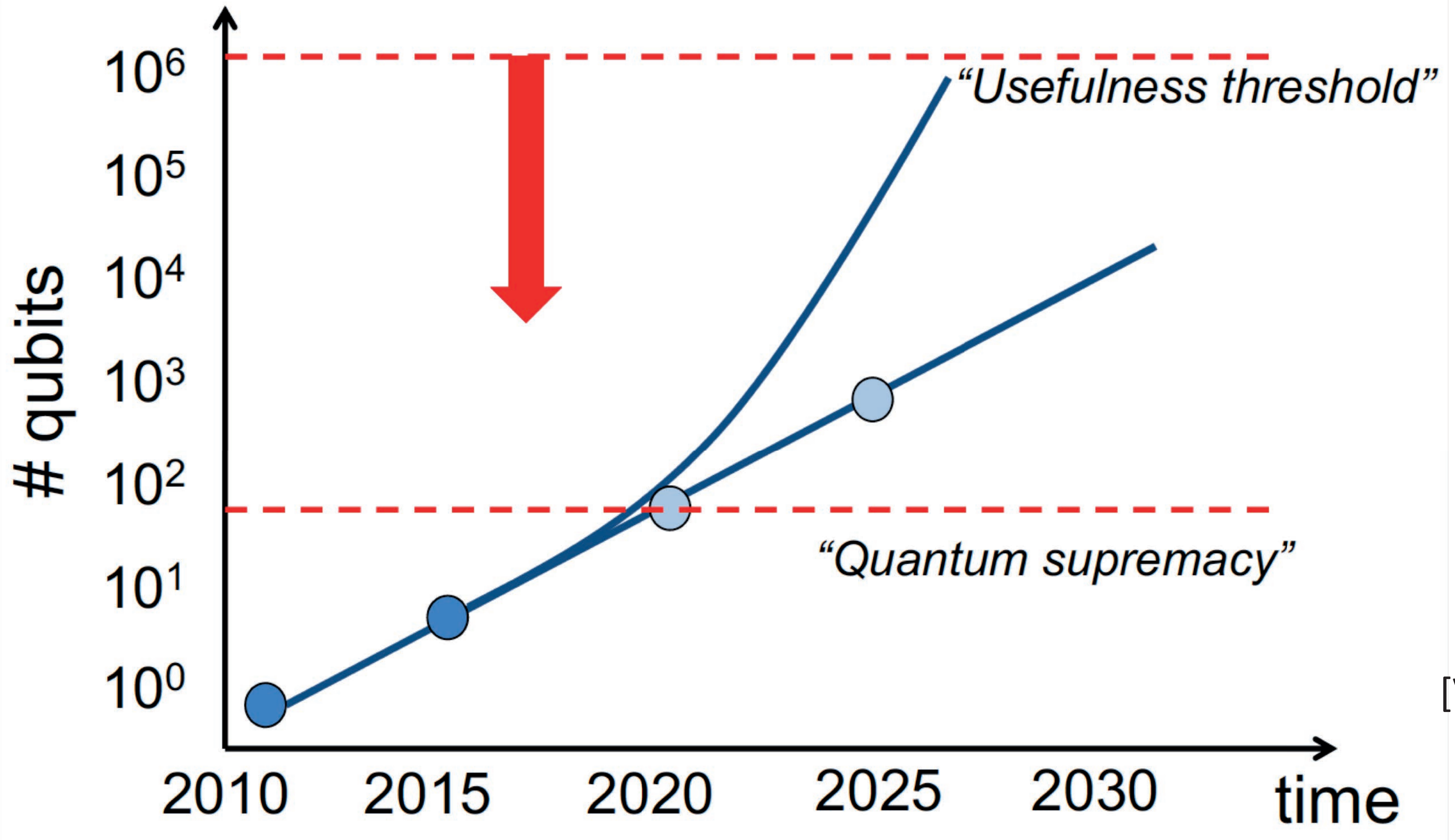
Artificial Intelligence

Why is it so difficult to built a QC?

- Three conditions must be satisfied:
  1. A collection of many two-state quantum mechanical systems (i.e., qubits) which do not decohere
  2. A method to interact with the qubits that generate universal quantum gates
  3. A measurement system
- None of these is easy!
  - Qubits are extremely fragile and can easily decohere by environmental fluctuations
  - The larger the quantum mechanical system, the more "classical" it becomes
  - Precision required to accurately alter the state of a single system at the quantum level
    - These systems are extremely microscopic (single atoms usually)!
- Qubit errors can be corrected

Quantum Scaling Progress

- Industry must team up with academia to speed up the QC development
- Radically new approaches needed



[Vandersypen, 2018]

Key industry players and their technology approaches

Universal Quantum Computers

Superconducting

- Google — University of California Santa Barbara — **72 Qubits**
- IBM, Raytheon — **16 Qubits**
- rigetti — **20 Qubits**
- intel — QuTech - University of Delft — **49 Qubits**

Trapped Ion

- IONQ
- University of Maryland
- University of Sussex

Compound Semi

- Microsoft — QuARC, University of Delft, Station Q
- NTT — Basic Research Lab

Foundry CMOS

- equal 1 — **64 Qubits, Scaling up to 1024**

Quantum Annealers Super Conductors

- D-Wave — The Quantum Computing Company™
- NASA
- Google
- Lockheed Martin

2048 Qubits
Entangle groups of 8

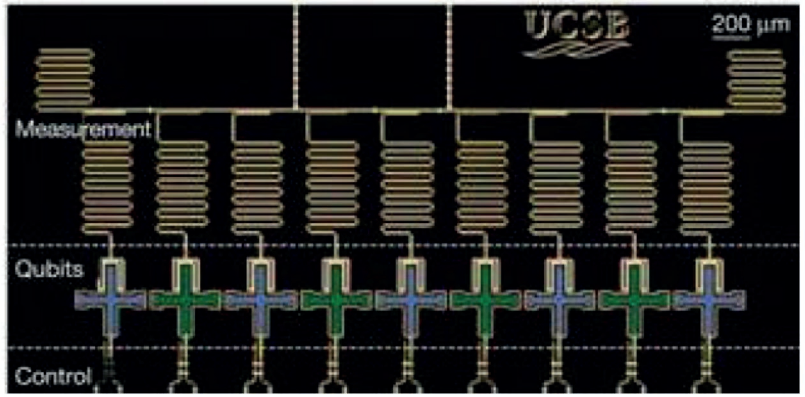
Quantum Simulators

- Google
- Microsoft
- Atos
- Fujitsu

QC Software

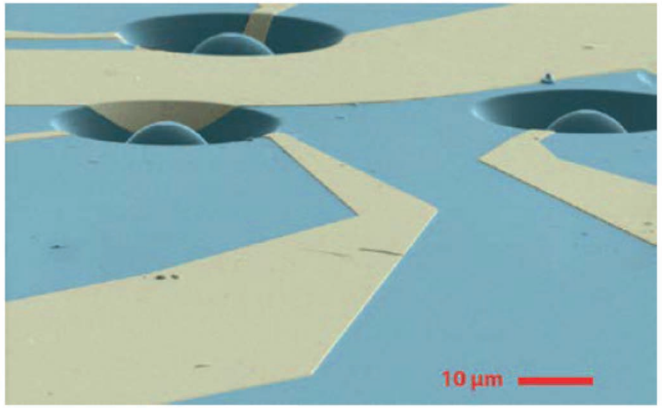
- 1QBit
- CQC — Cambridge Quantum Computing Limited

Current Quantum Processors



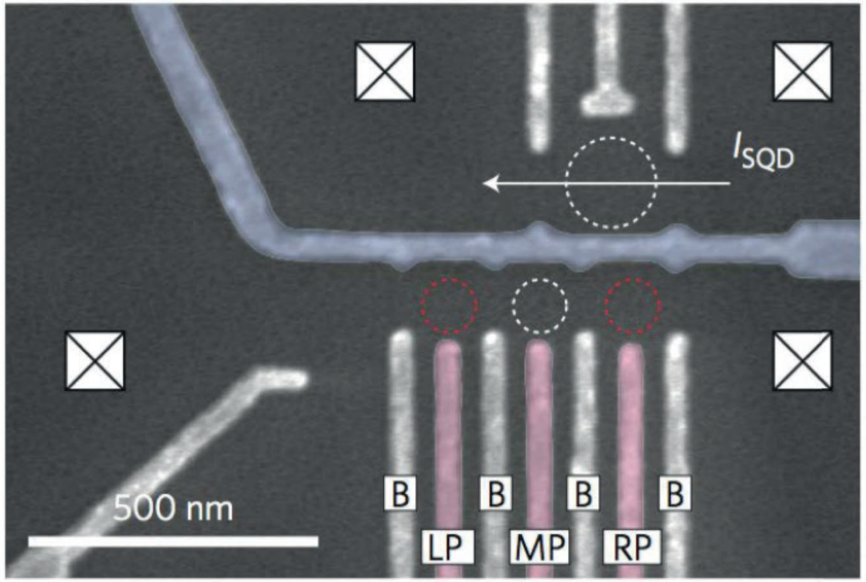
9-qubits transmon array

J. Kelly et al., *Nature* 2015



W.Pfaff et al., *Science* 2014

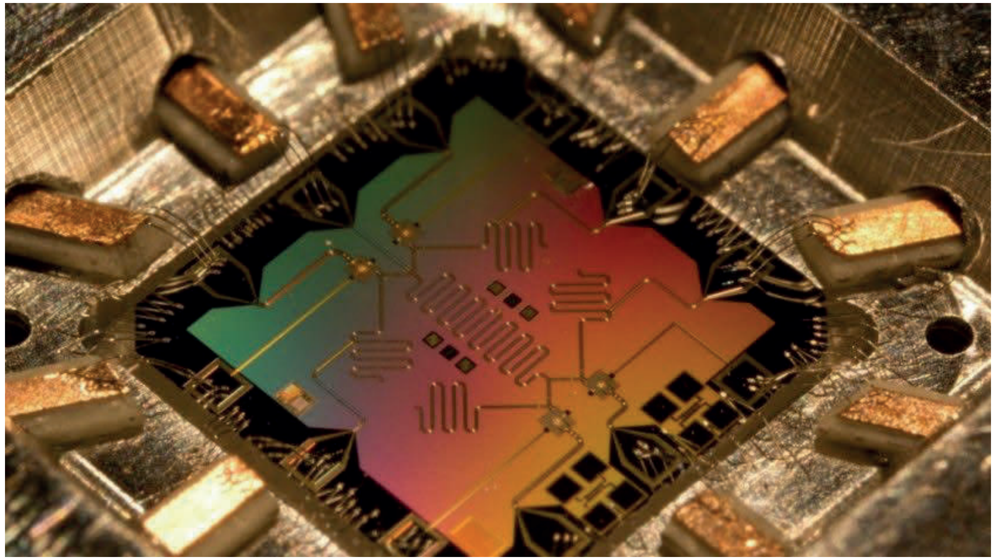
3 NV-center qubits [http://hansonlab.tudelft.nl/teleportation]

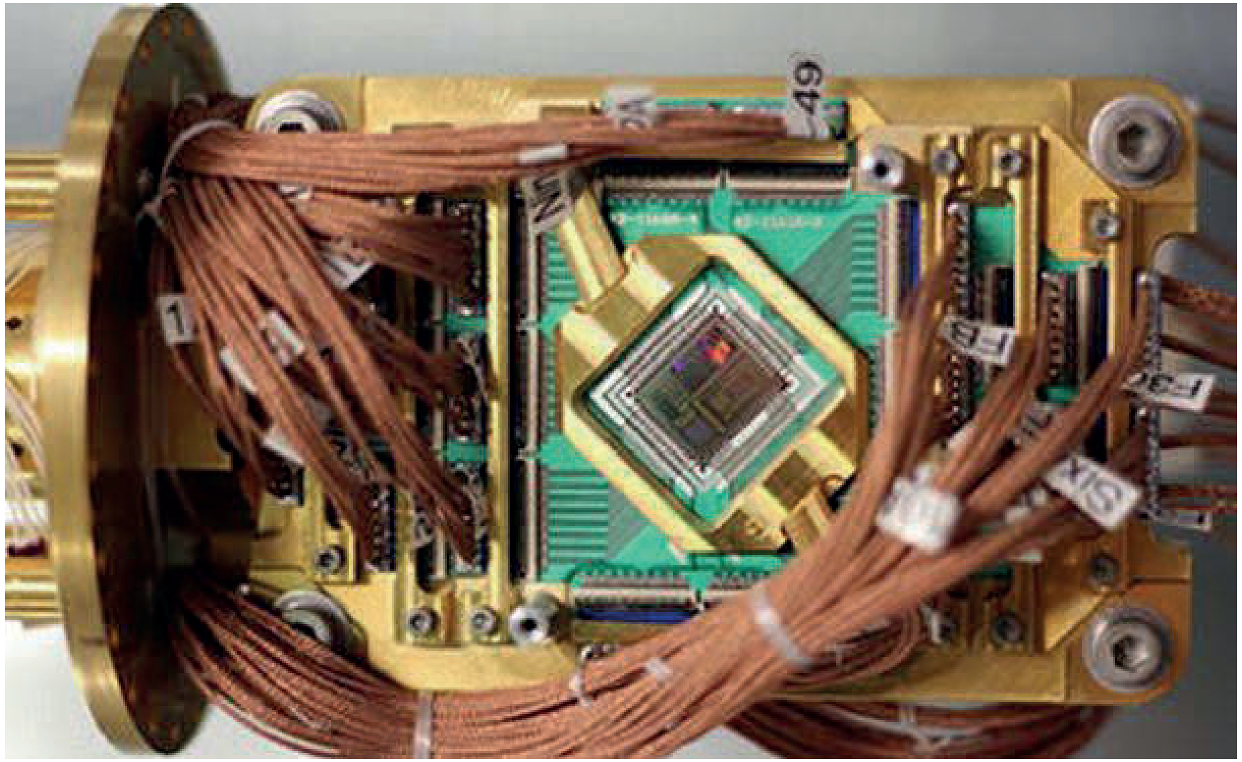


F.R. Braakman et al., *Nature Nanotechnology* 2013

3-quantum-dot array for spin qubits

Current Quantum Processors



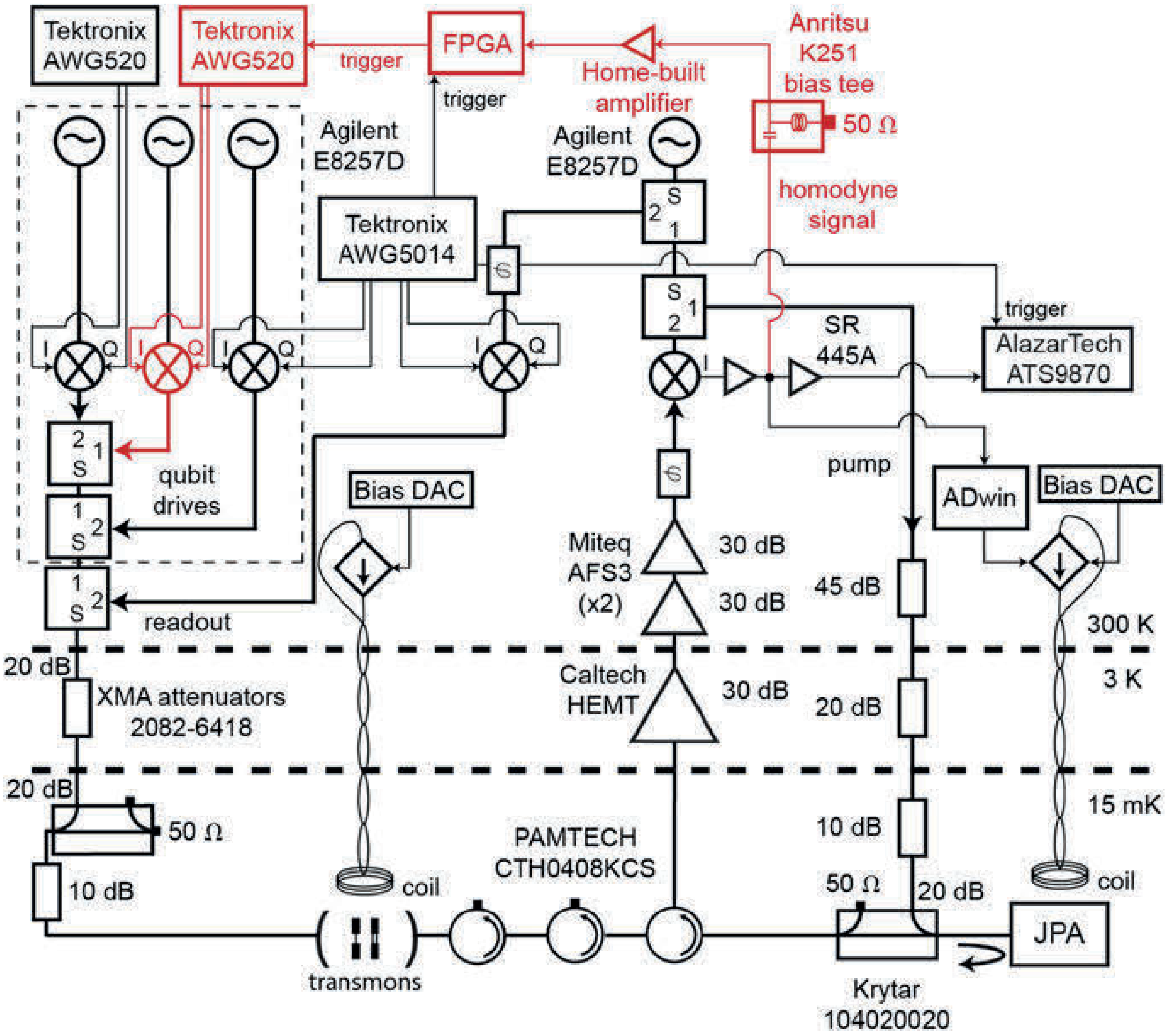


Current Paradigm of Quantum Computers

- IBM

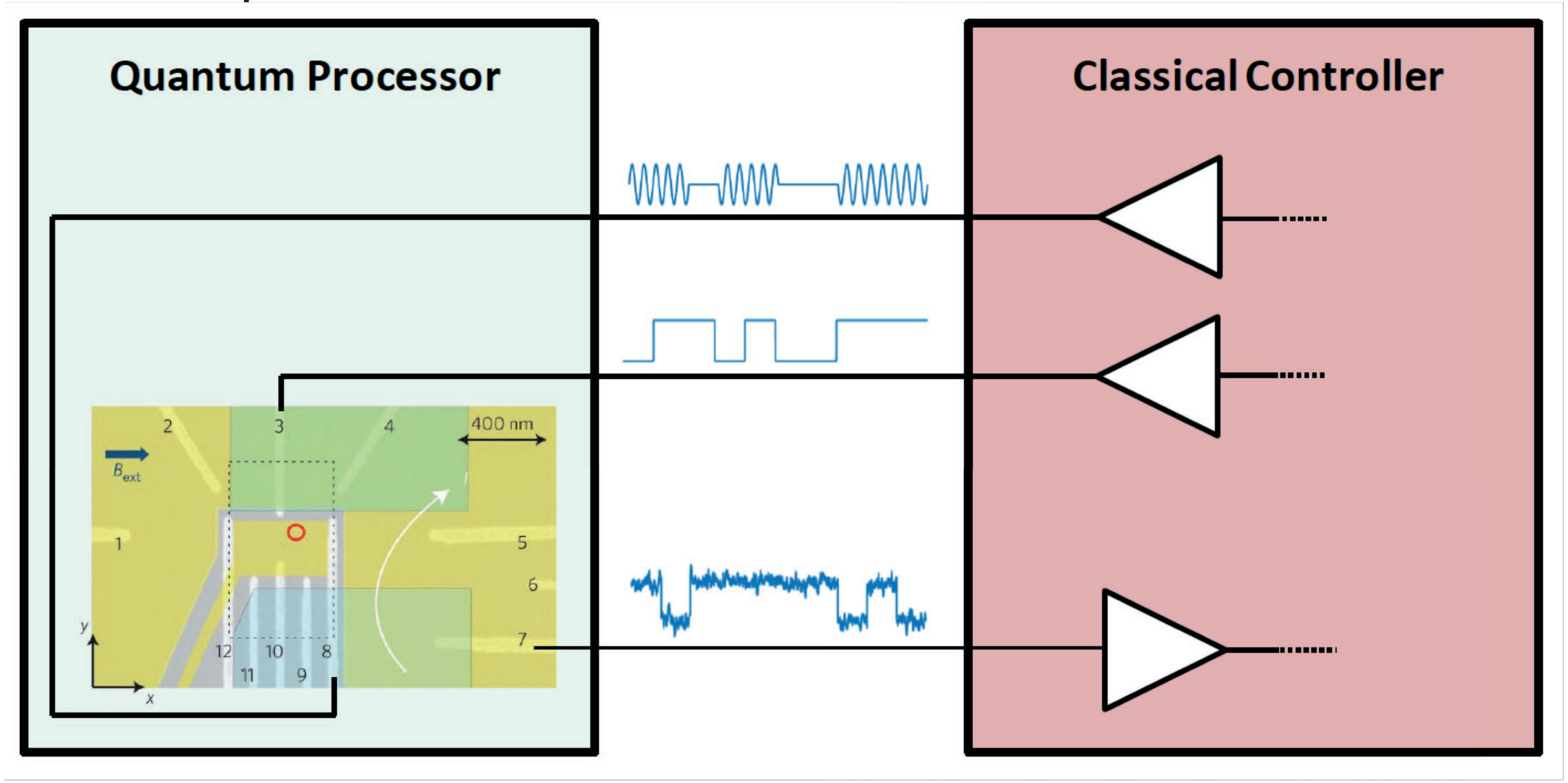
QC Setup

- Great for scientific experiments
  - but not scalable
- Use general-purpose test equipment, FPGA, bulky pieces:
  - Super-magnets
  - Microwave components



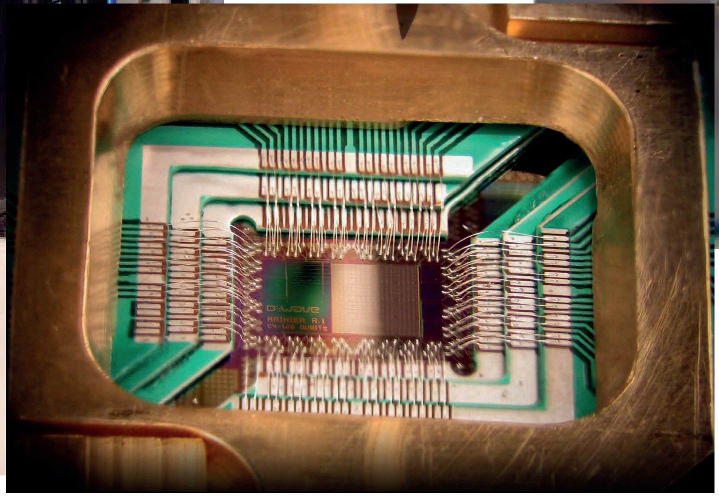
Current Paradigm of Quantum Computers

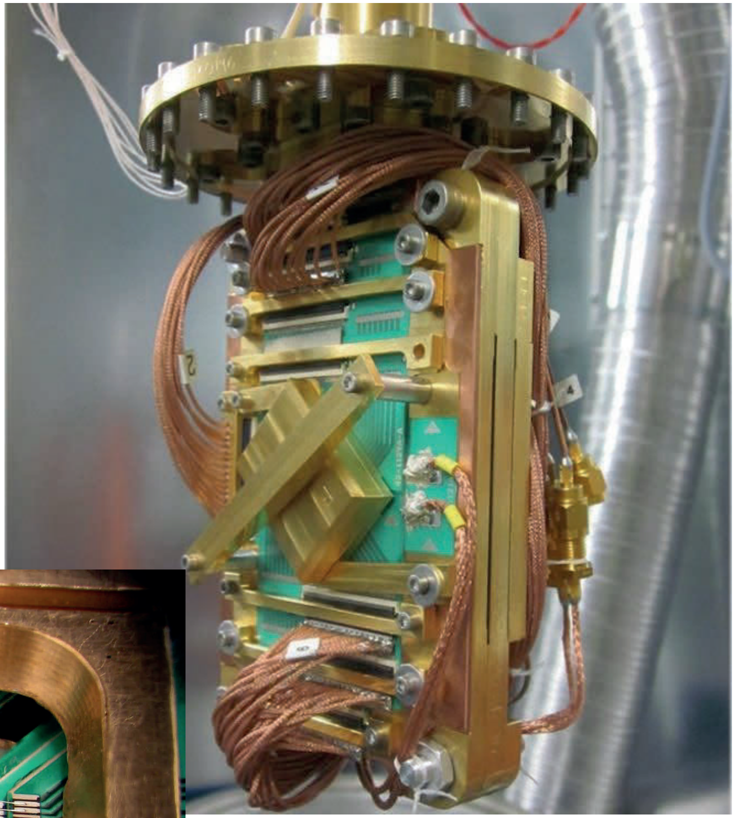
- Quantum - 15mK
- Classical – 300K
- A few dozen of qubits that are not scalable!



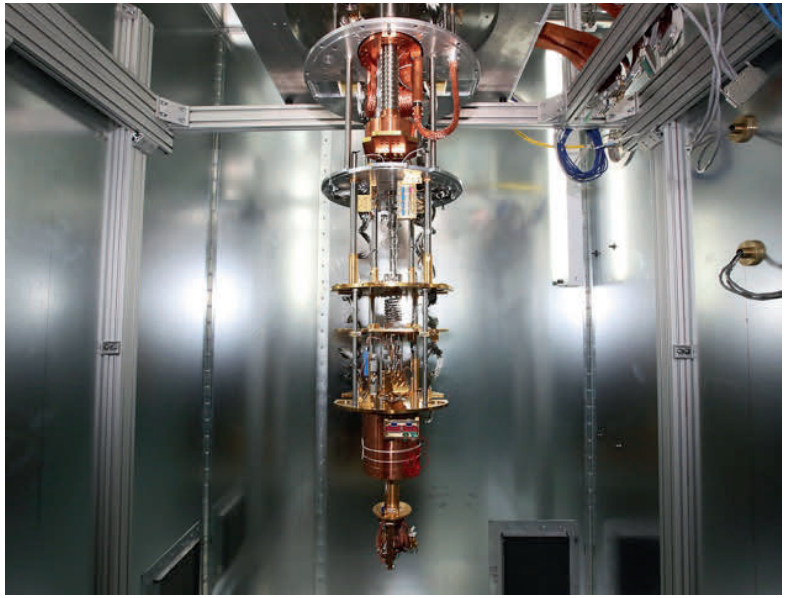
D-Wave Systems

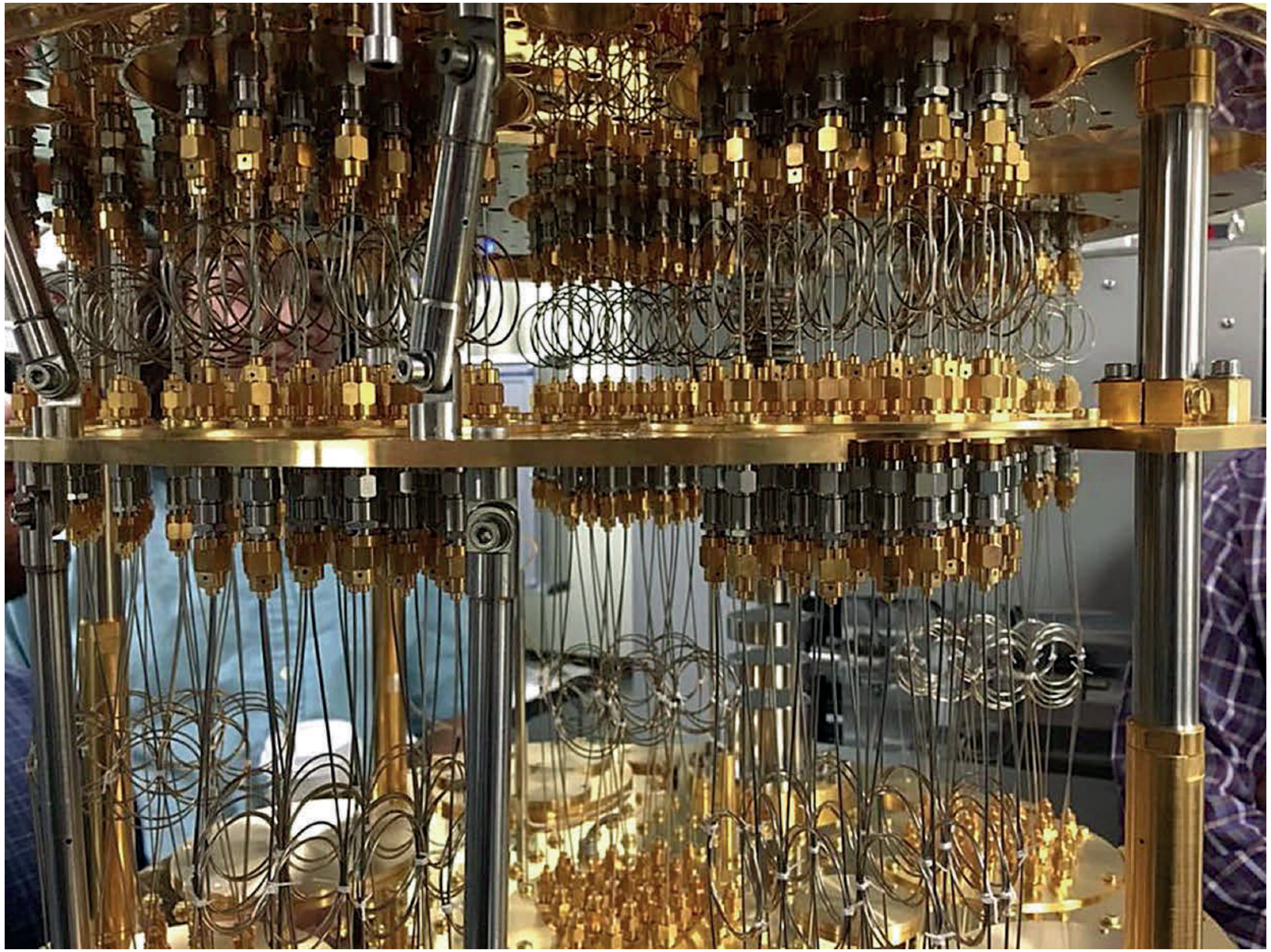
- First in the world to sell QC
- Uses quantum annealing in magnets
- Questions about speed-up…





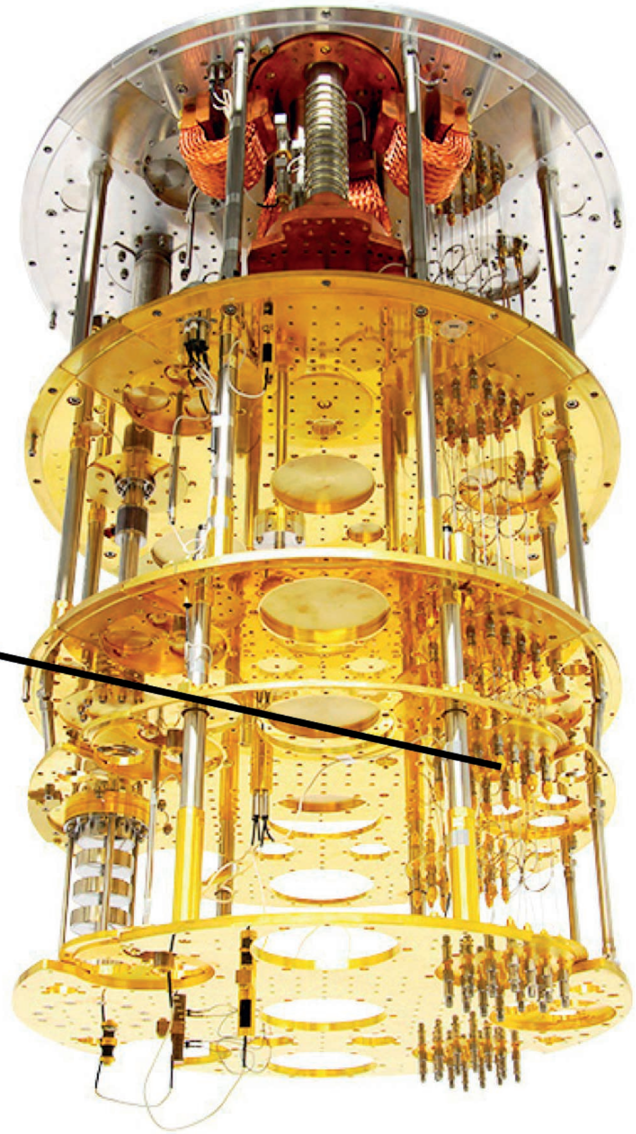
Cooling Issues





Cryogenic Cooling

- Helium-4 is the most abundant element in Universe
  - But not so on Earth
- Helium-4 can cool down to 4K
- Helium-3 required at <1K
  - Used for production of nuclear bombs



1st stage pulse tube head, 60 K

2nd stage pulse tube head, 4K, 2 W

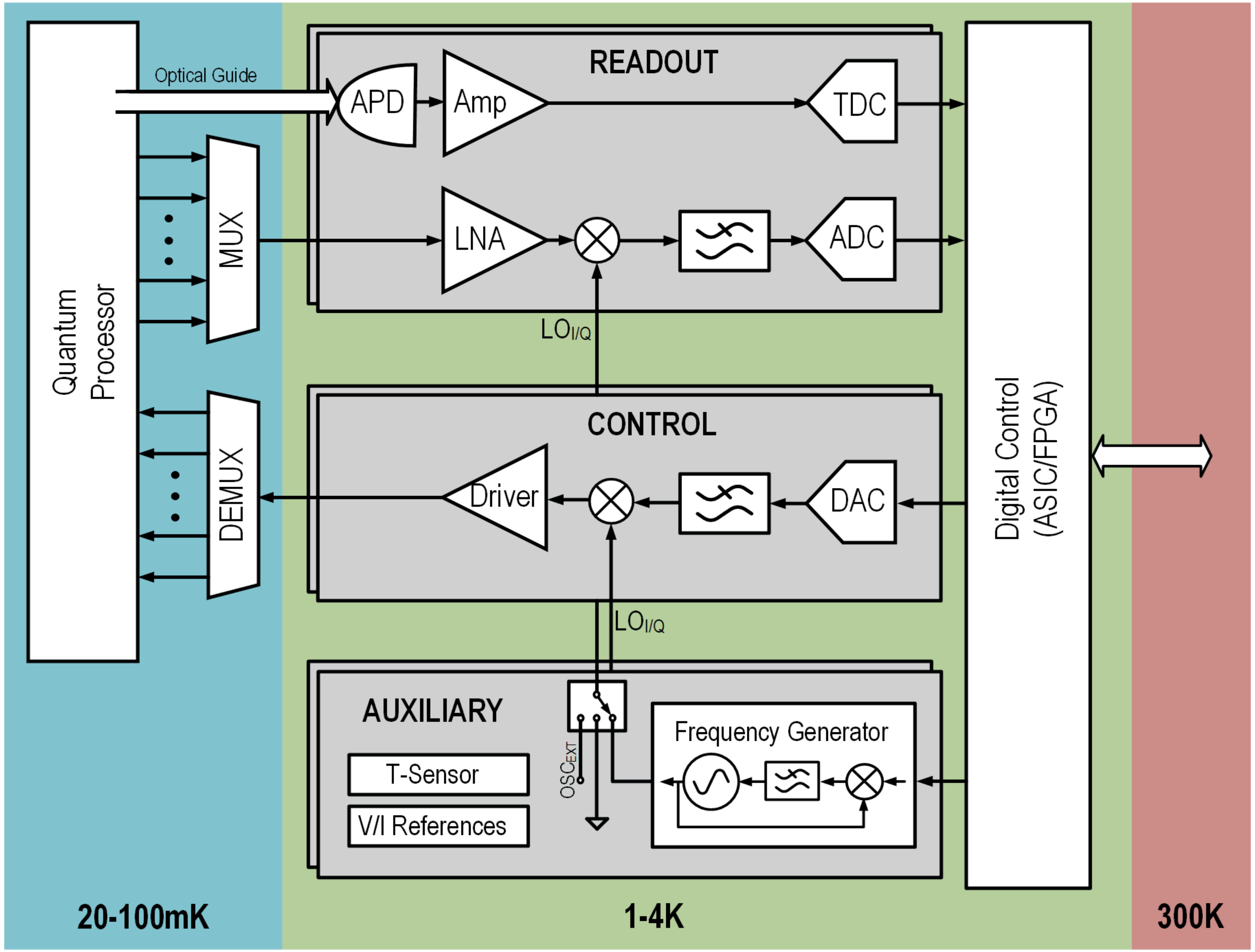
High-frequency lines

Still plate, 0.6 K

Mixing chamber plate
15 μW at 20 mK
0.5 mW at 100 mK

New Paradigm of Quantum Computers

- Quantum - 15mK
- Classical – 300K



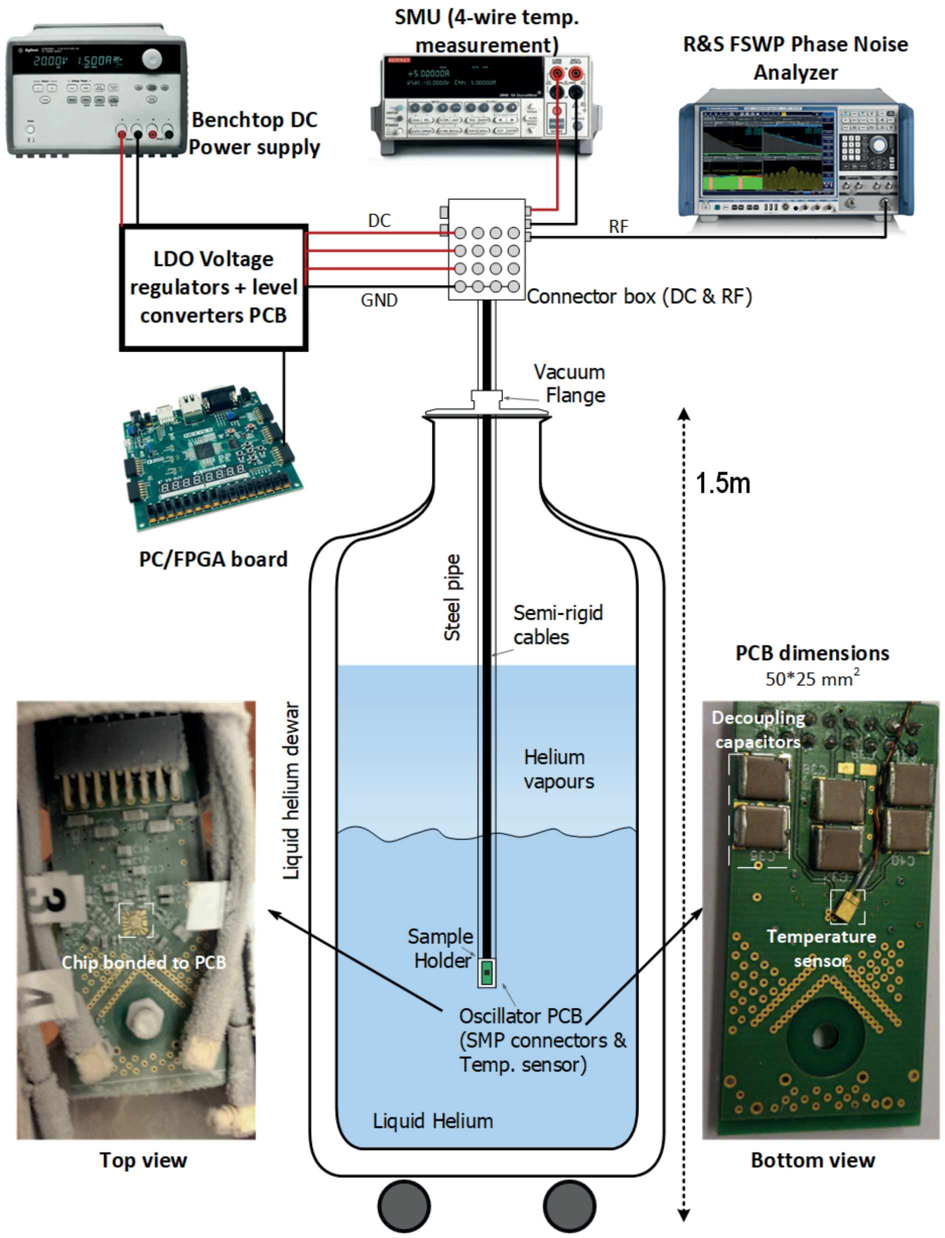
CMOS at Cryogenic Temperatures

- Some devices fail to work
- Some devices show degraded performance
- Some devices show improved performance
- Device models are not available
  – Pioneering work by Prof. Charbon at TU Delft/EPFL
  – MOS11 model at 4K

Cryo-CMOS Work at TU Delft

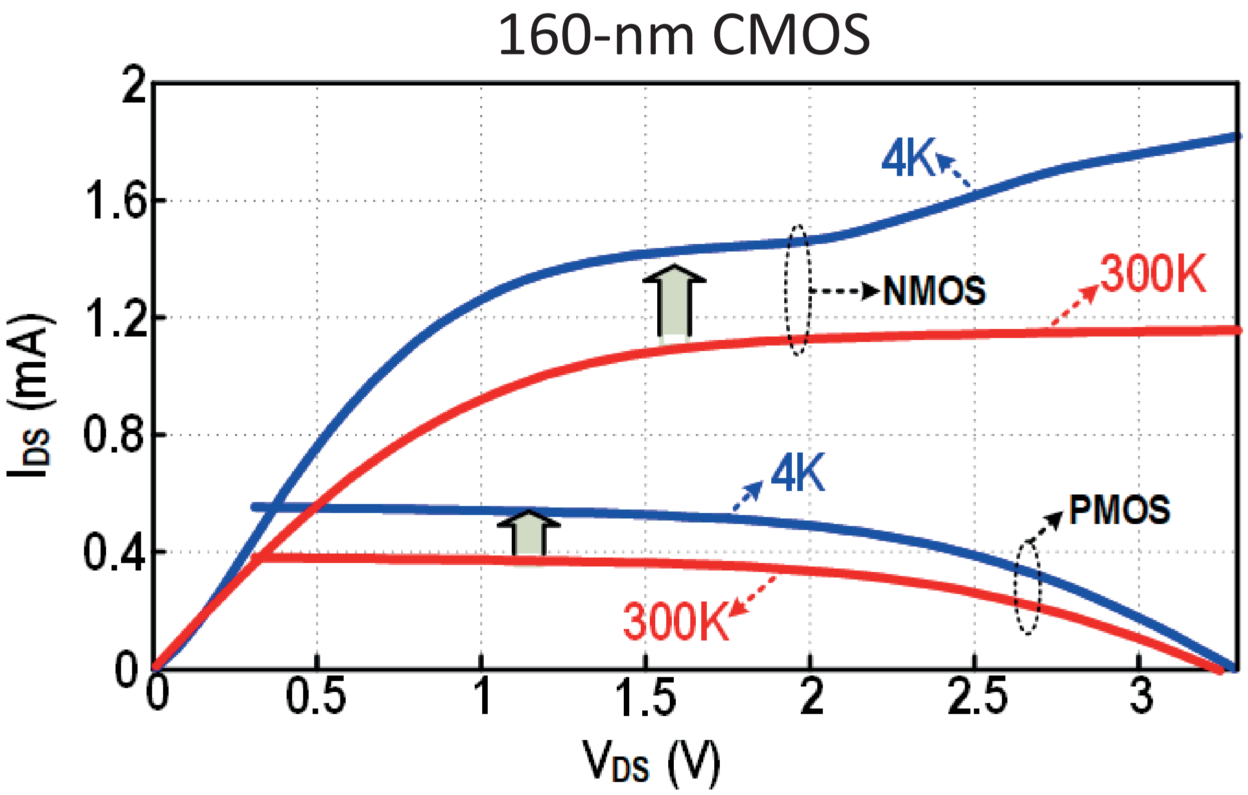
- [1] E. Charbon, F. Sebastiano, M. Babaie, A. Vladimirescu, M. Shahmohammadi, R. B. Staszewski, H. A.R. Homulle, B. Patra, J. P.G. van Dijk, R. M. Incandela, L. Song, and B. Valizadehpasha, “Cryo-CMOS circuits and systems for scalable quantum computing,” *Proc. of IEEE Solid-State Circuits Conf. (ISSCC)*, 7 Feb. 2017, sec. 15.5, pp. 264–265, San Francisco, CA, USA. DOI: 10.1109/ISSCC.2017.7870362
- [2] B. Patra, R. M. Incandela, J. P.G. van Dijk, H. A.R. Homulle, L. Song, M. Shahmohammadi, R. B. Staszewski, A. Vladimirescu, M. Babaie, F. Sebastiano, and E. Charbon, “Cryo-CMOS circuits and systems for quantum computing applications,” *IEEE Journal of Solid-State Circuits (JSSC)*, vol. 53, no. 1, pp. 309–321, Jan. 2018. DOI: 10.1109/JSSC.2017.2737549

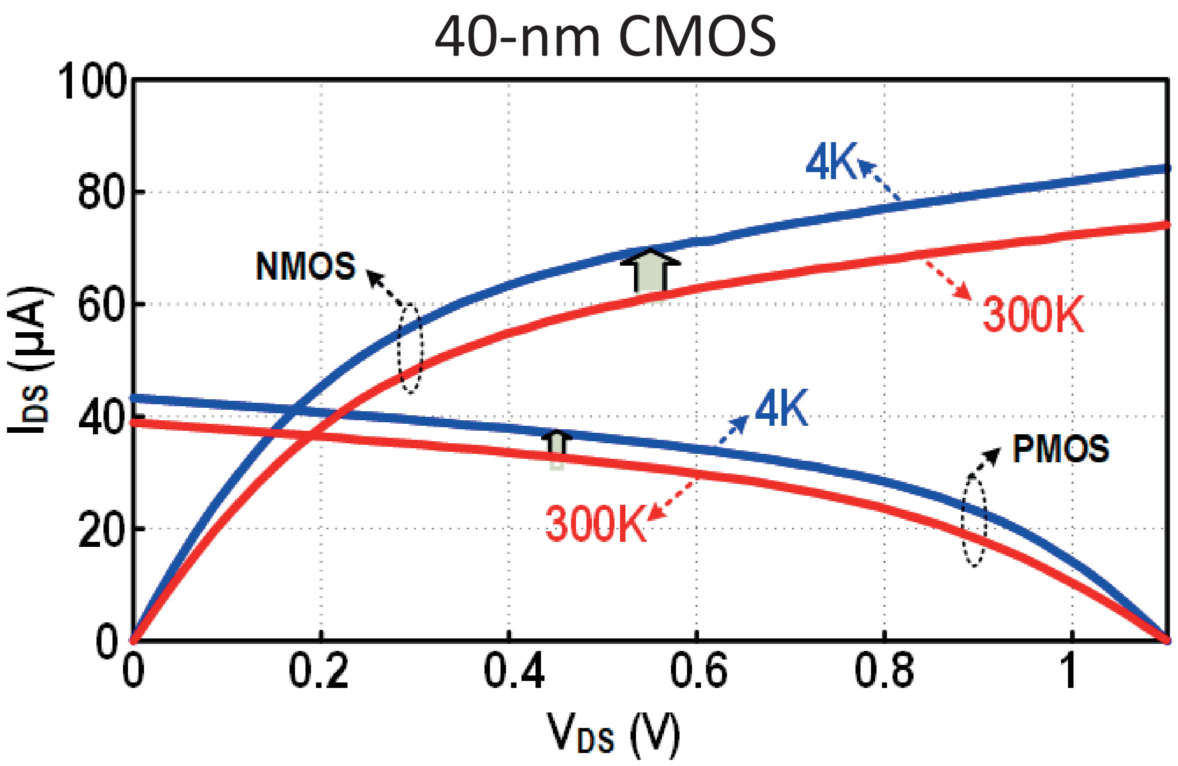
TU Delft Measurement Setup



CMOS Transistor Characteristics

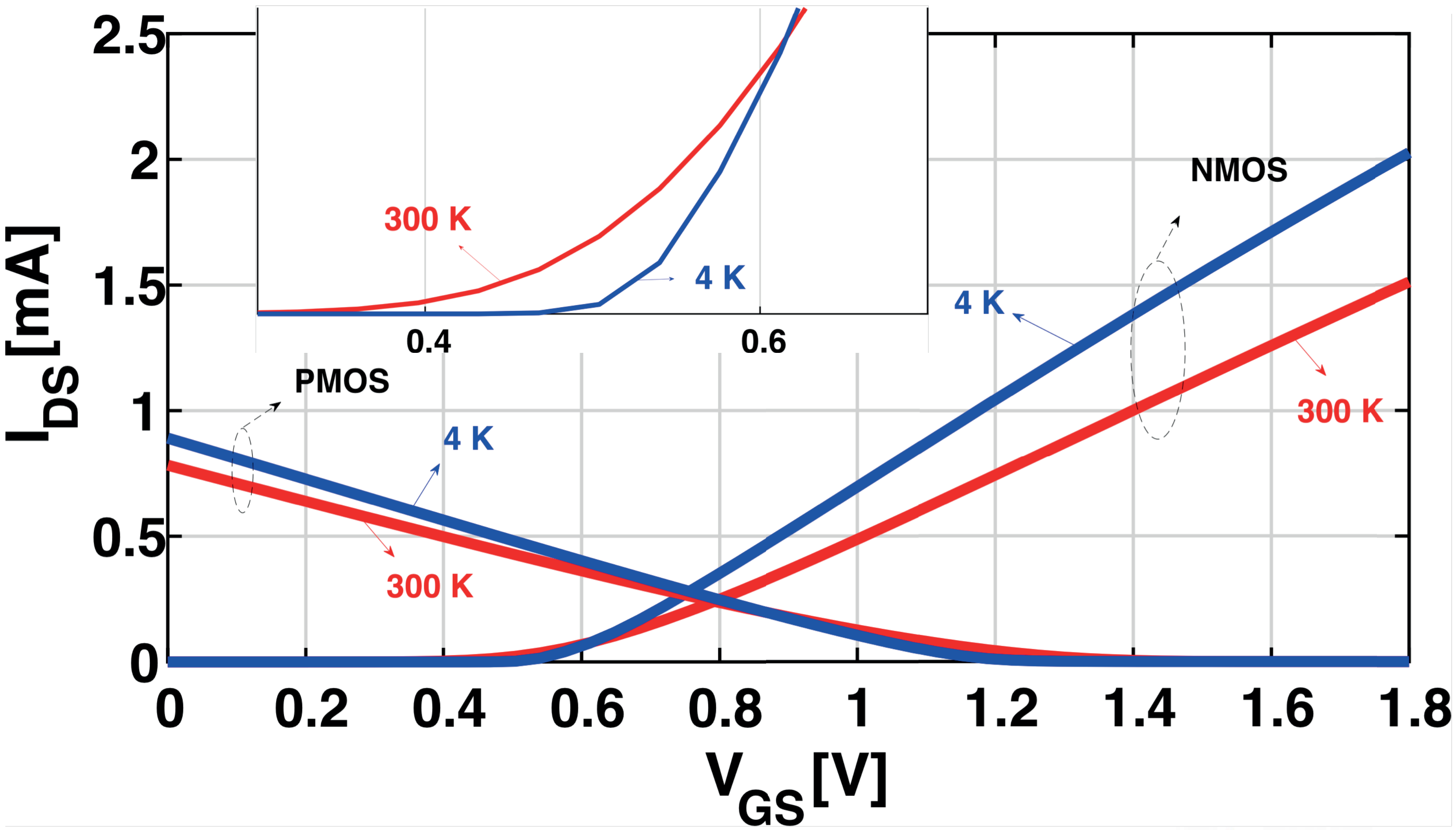
- Increased carrier mobility at cryo, but V_{th} increases
- ‘kink’ at higher V_{DS} with the older NMOS
  - Impact ionization at the drain?
  - Can be catastrophic in linear circuits





CMOS Transistor Characteristics

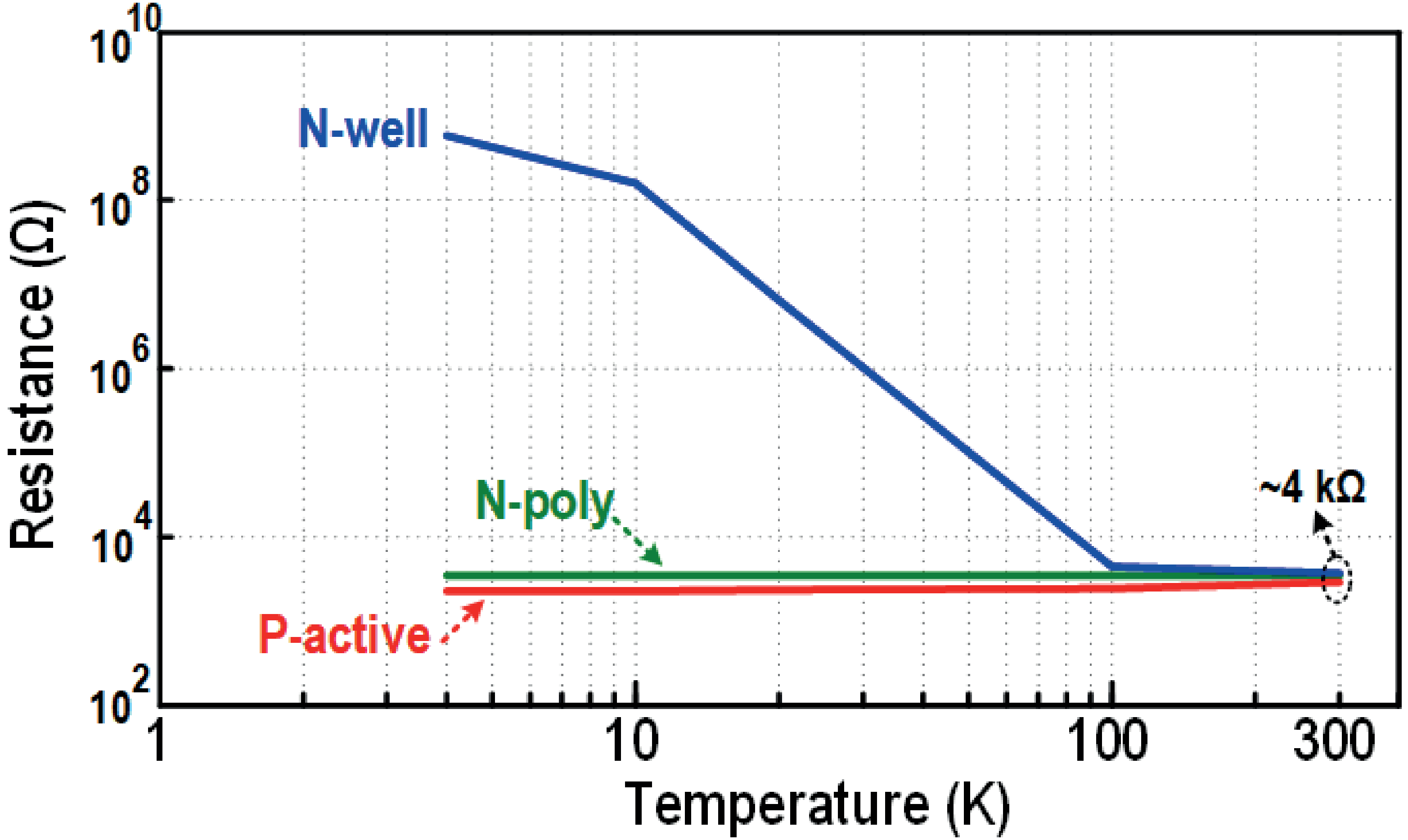
- Increased V_{th} at cryo



160-nm CMOS

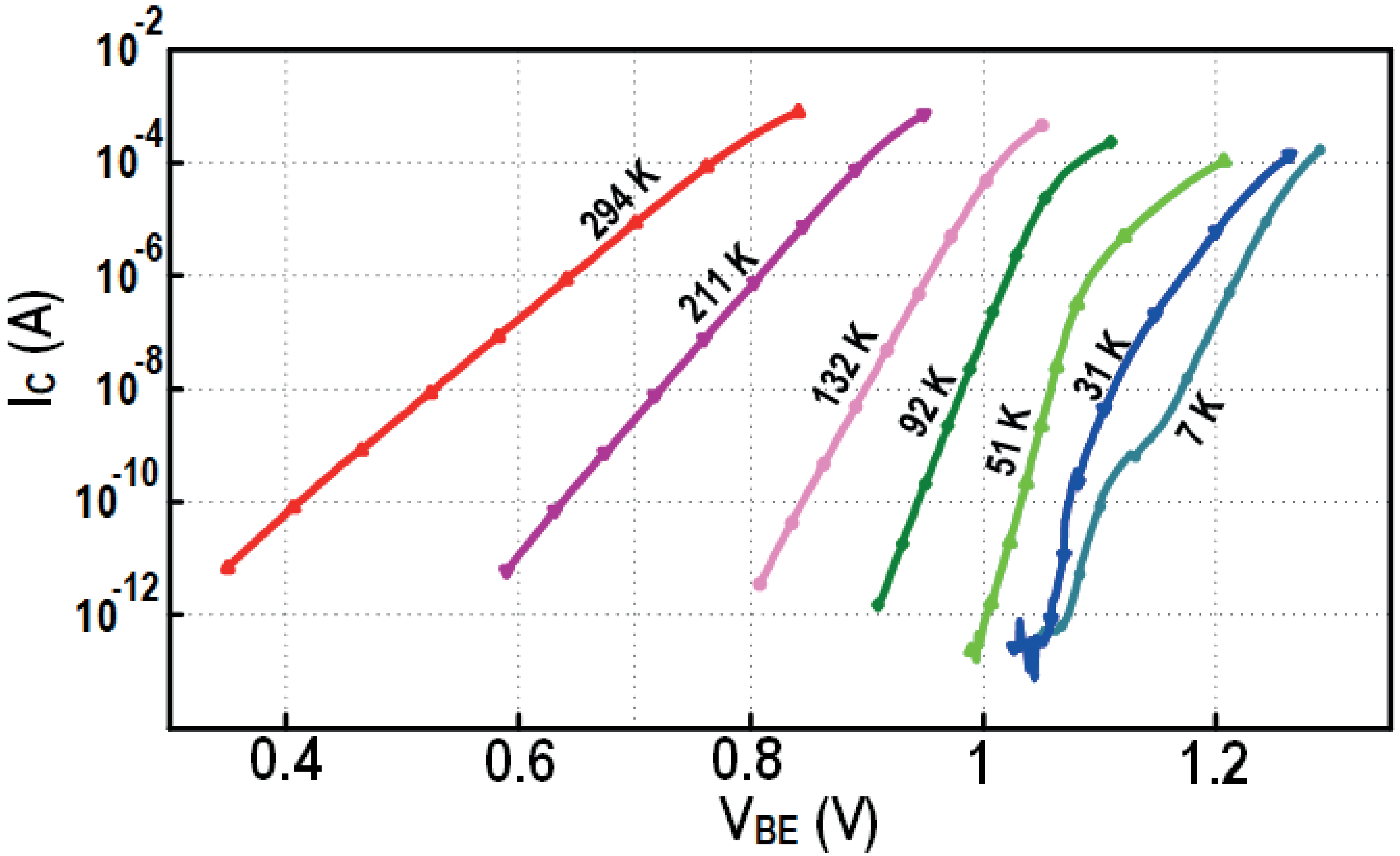
Resistor Characteristics

- N-well resistors fail due to carrier freeze-out



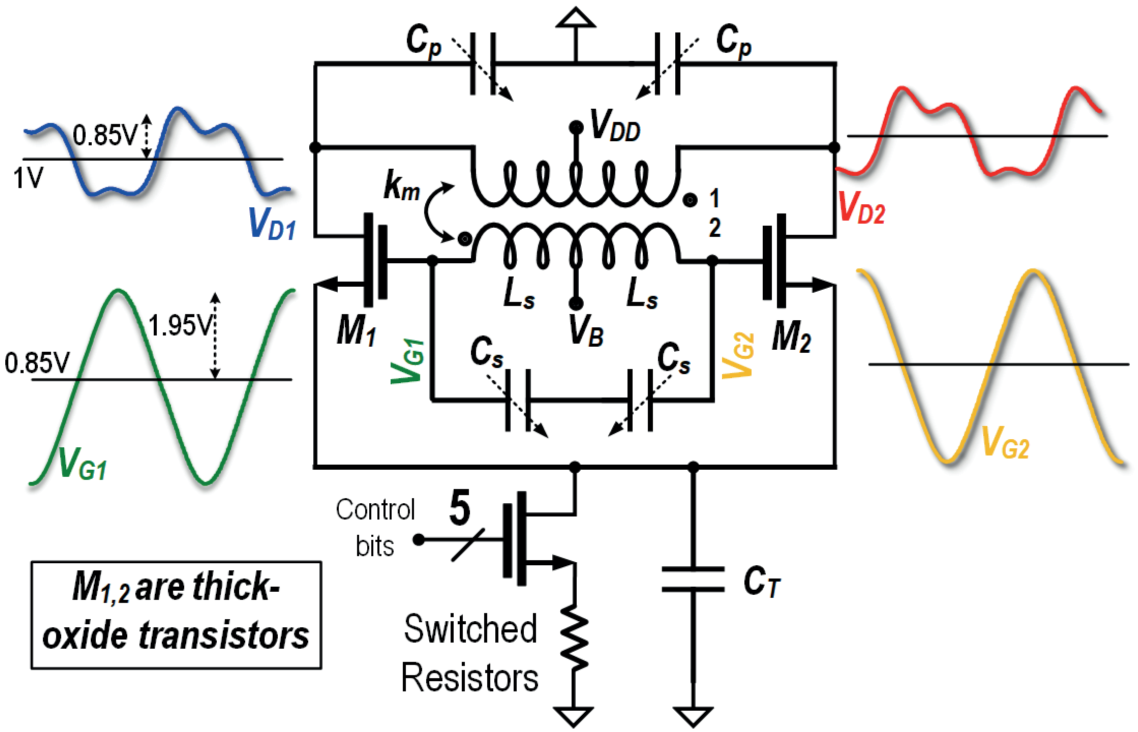
BJT Device Characteristics

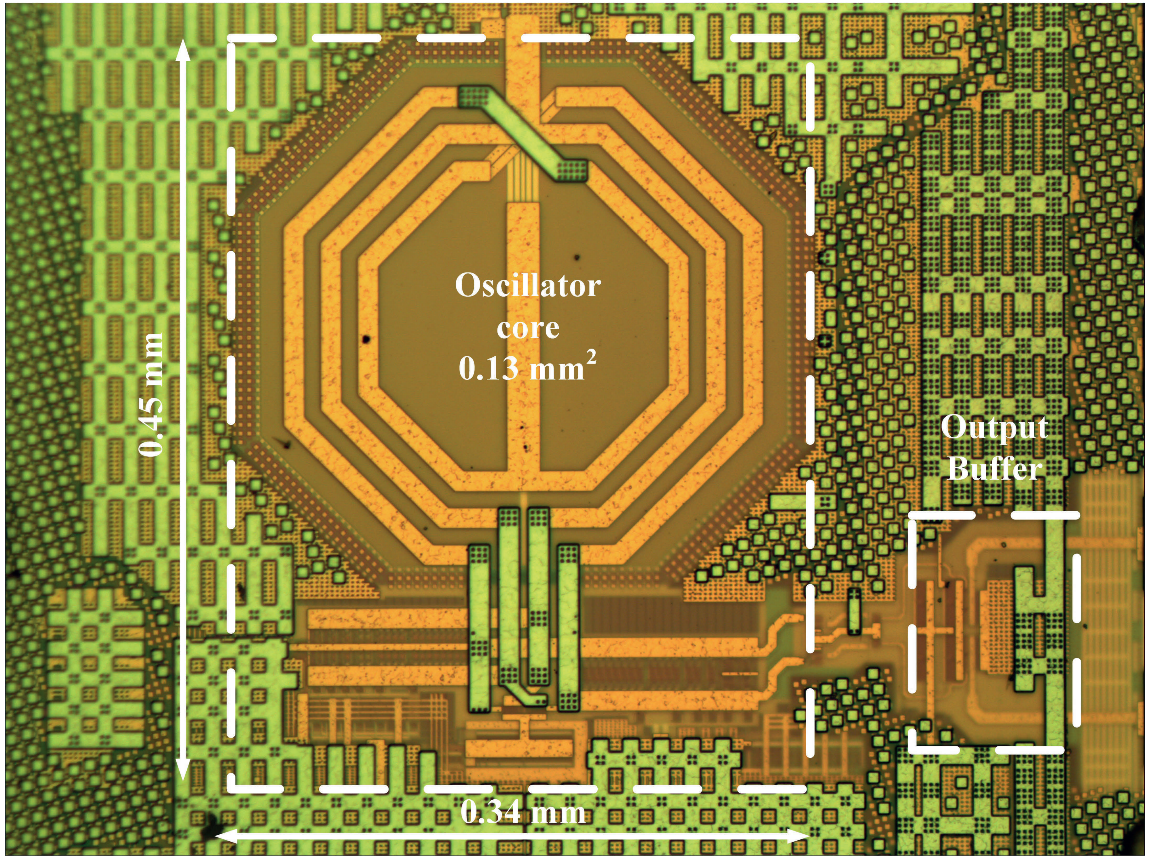
- Bipolar transistors typically used in bandgap references and temperature sensors
- BJTs cannot be reliably used at cryo
- Freeze-out in the base



Digitally Controlled Oscillator

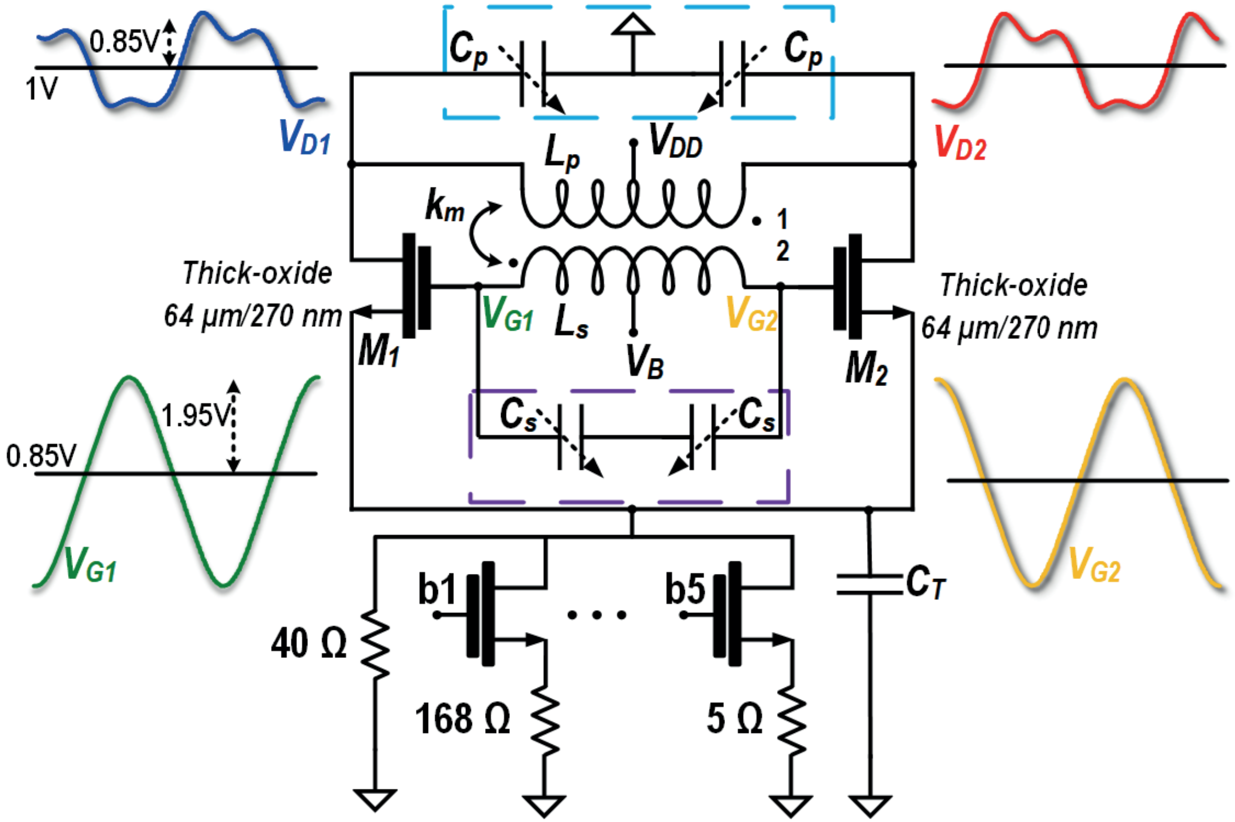
- Frequency noise spec: 1.9 kHz_{rms}
- Phase noise of -147 dBc/Hz at 10 MHz offset from 6 GHz carrier
- Class $F_{2,3}$ operation

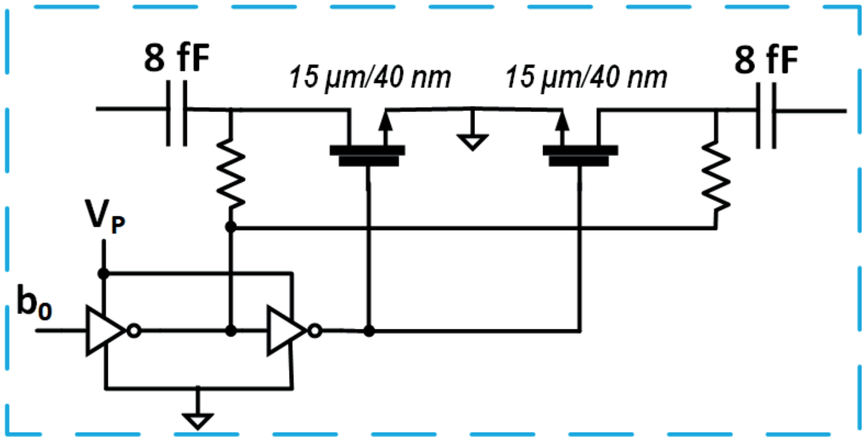


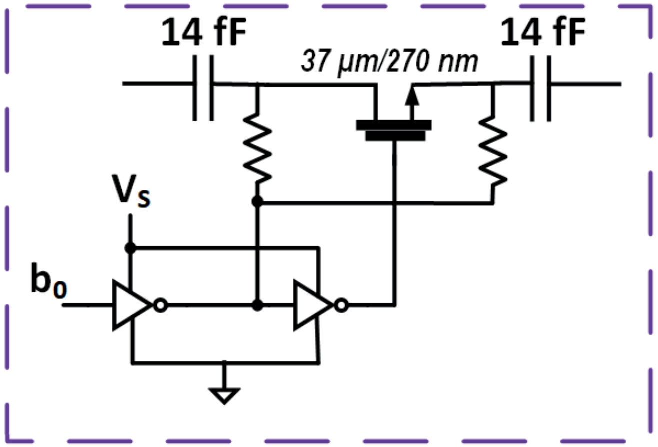


Digitally Controlled Oscillator – Switchable Caps

- Differential-mode and common-mode switchable capacitors

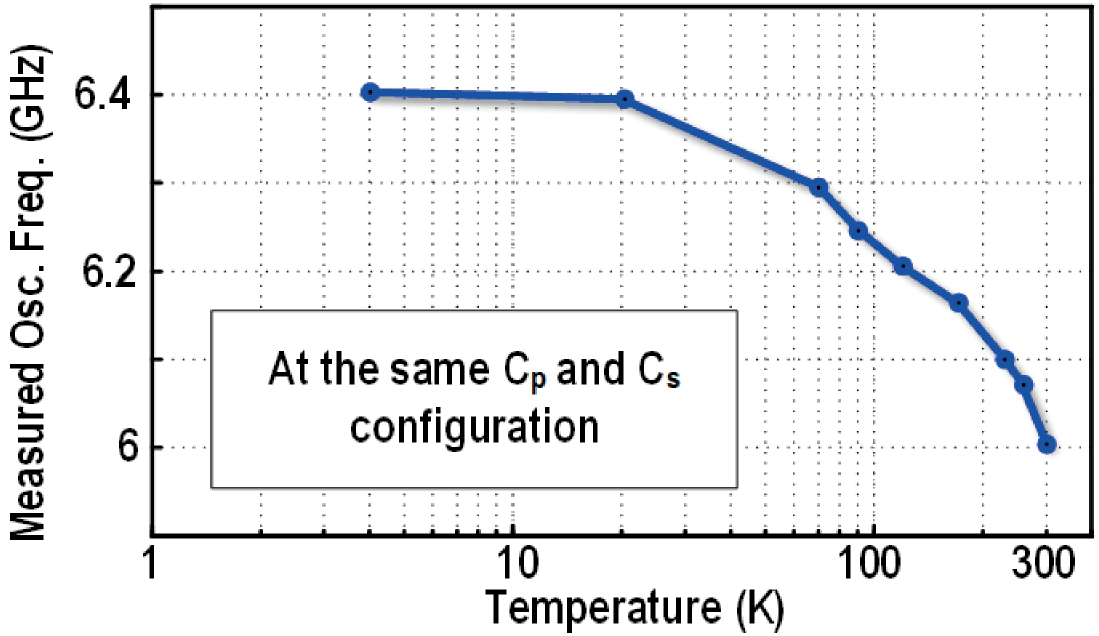


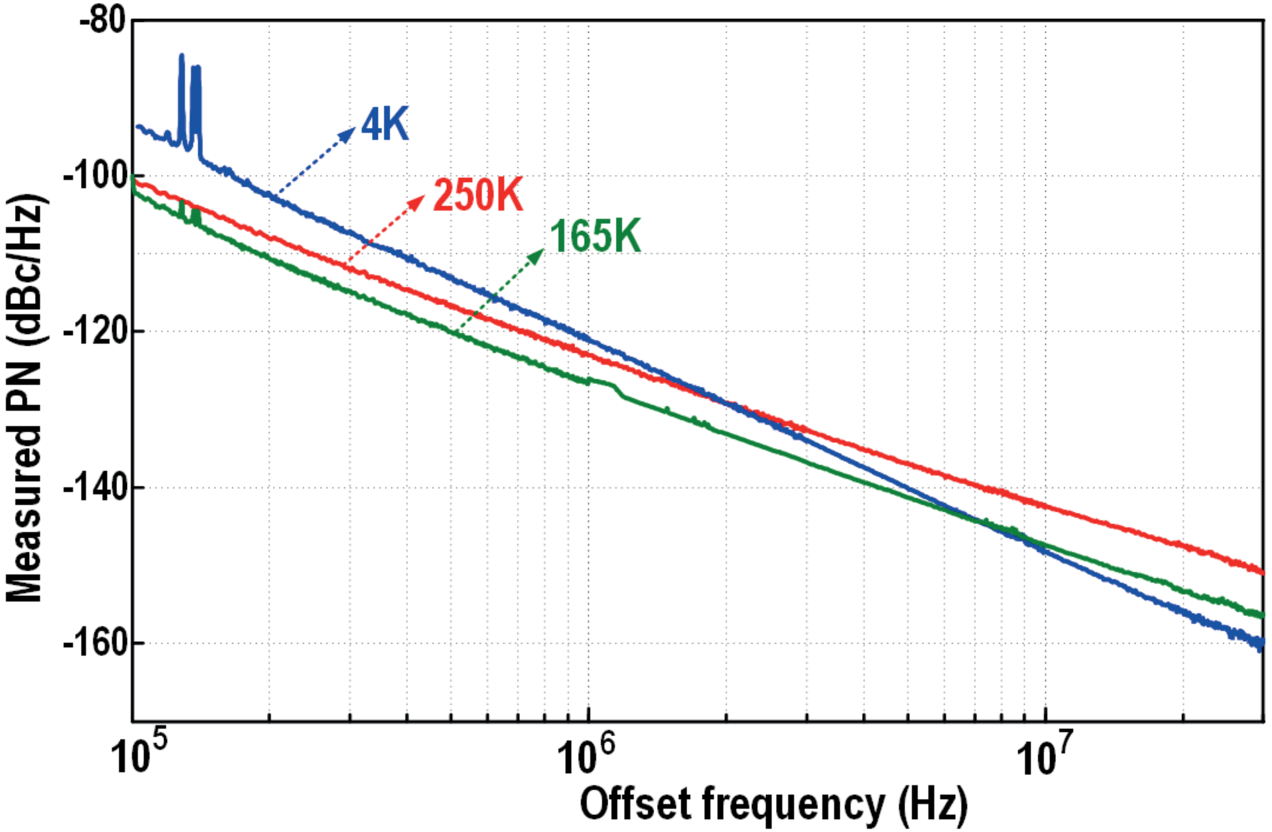




DCO Measurements

- Inductors shrink at lower temperatures
- Thermal noise decreases
- However, flicker noise increases



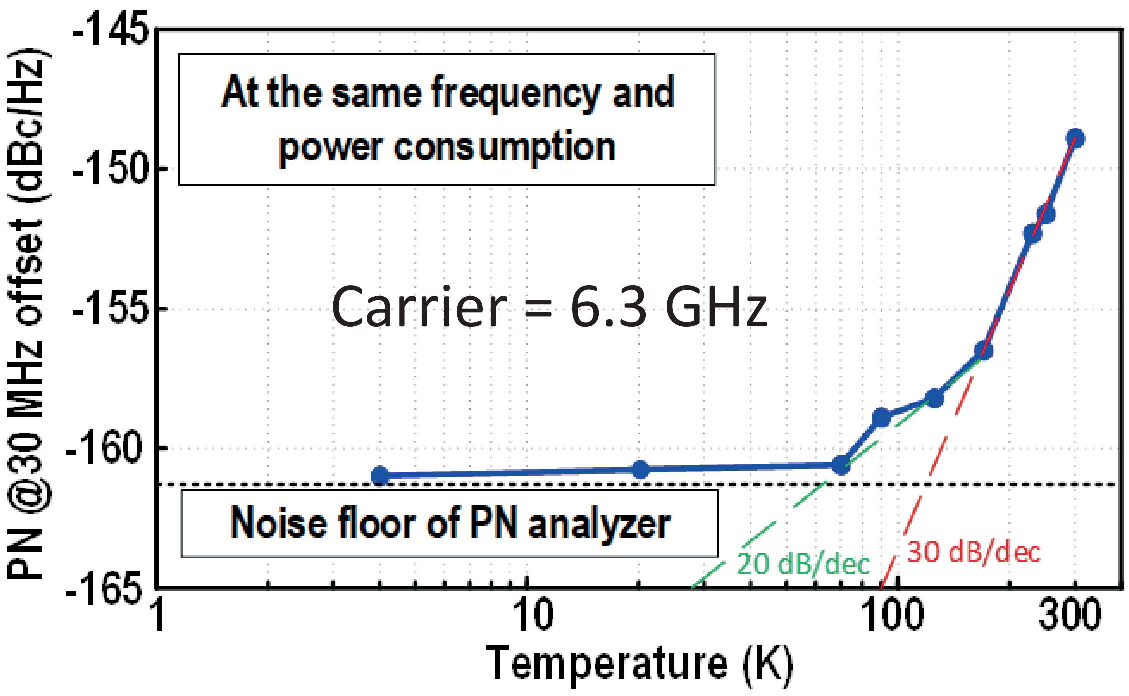


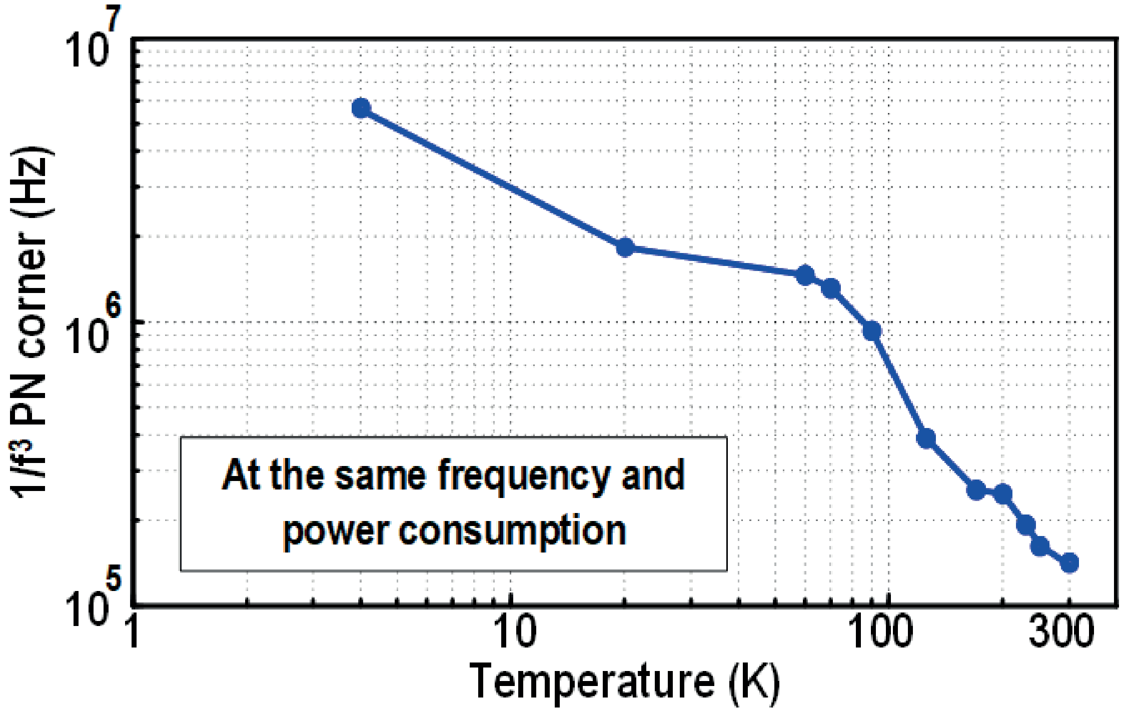
DCO Measurements – Phase Noise

- 10 dB/dec due to temperature reduction
  - $k_B T$
- 20 dB/dec due to quality factor enhancement
  - Substrate freeze out
- Below 70K: Increase in channel noise factor, γ

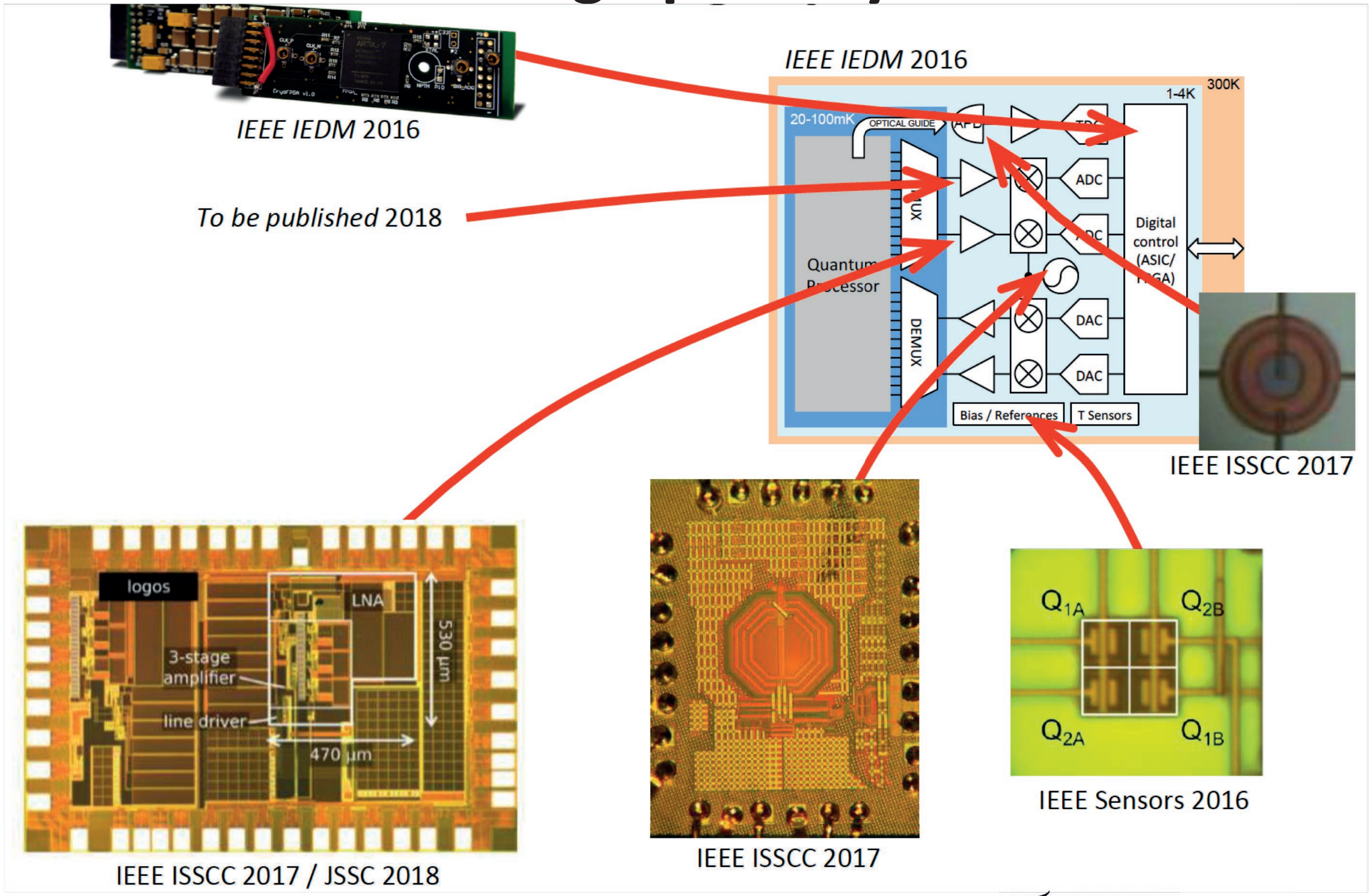
$$\mathcal{L}(\Delta\omega) = 10 \cdot \log_{10}\left(\frac{k_B T}{2} \cdot \frac{1}{Q^2 \cdot \alpha_V \cdot \alpha_I \cdot P_{dc}} \cdot \left(\frac{f_0}{\Delta f}\right)^2 \cdot (1+\gamma)\right)$$

Increased mismatch between two core transistors?





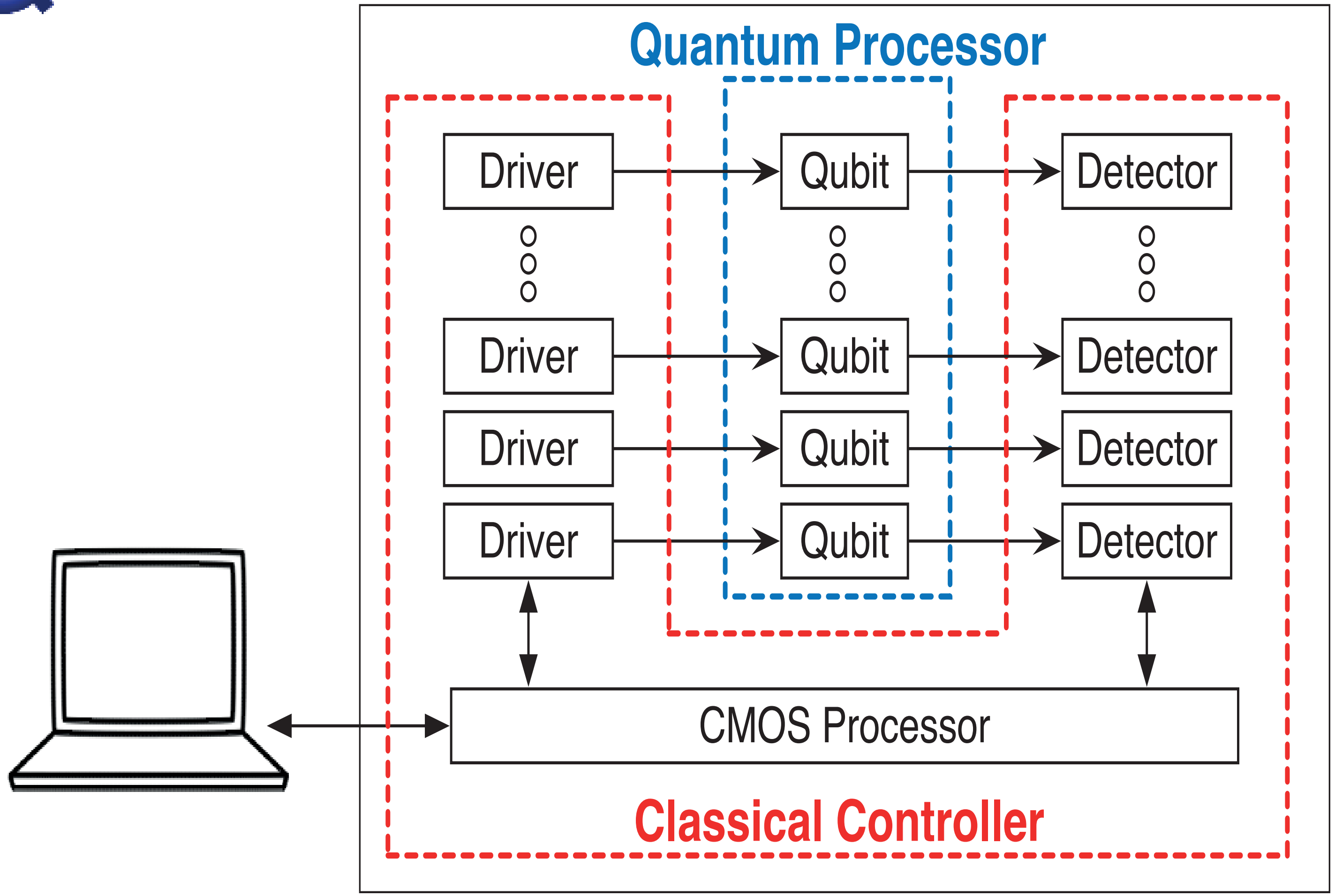
Building up the system



Why not use an advanced but standard CMOS?

- Used for mass-production of consumer electronics can now construct single-electron (SE) electrostatic structures with dimensions on the order of a few nanometres, which can attain controllable quantum dots for the creation of qubits
- Millions of qubits could be fabricated on a single small silicon die
- Their states can be individually controlled and measured by the on-die CMOS electronics, which is currently the biggest challenge in the spin-based qubits
- This has shown the urgent need to develop standard CMOS circuits operating at cryogenic temperatures (i.e., cryo-CMOS)

"Holy Grail" of Quantum Computing

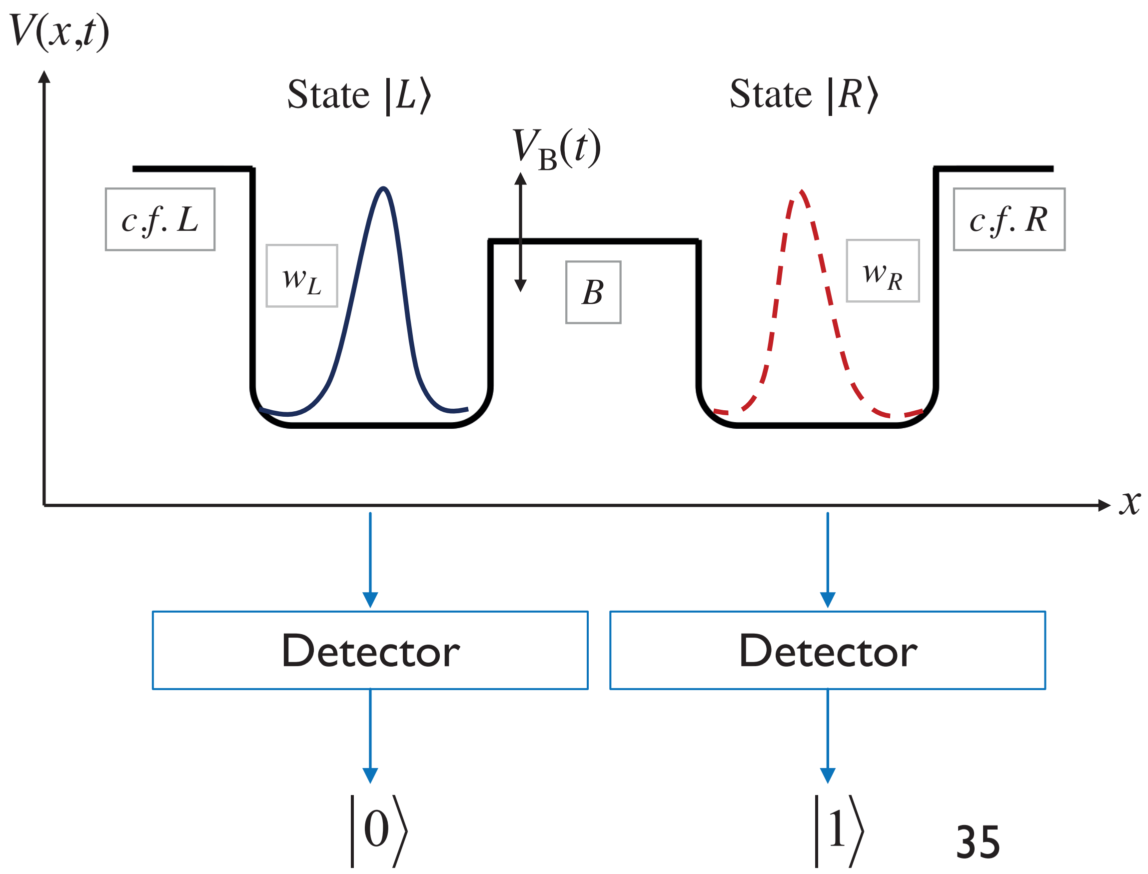


Single-Chip CMOS Quantum Computer (QCMOS)

Cryocooler by Montana Instruments

Qubits

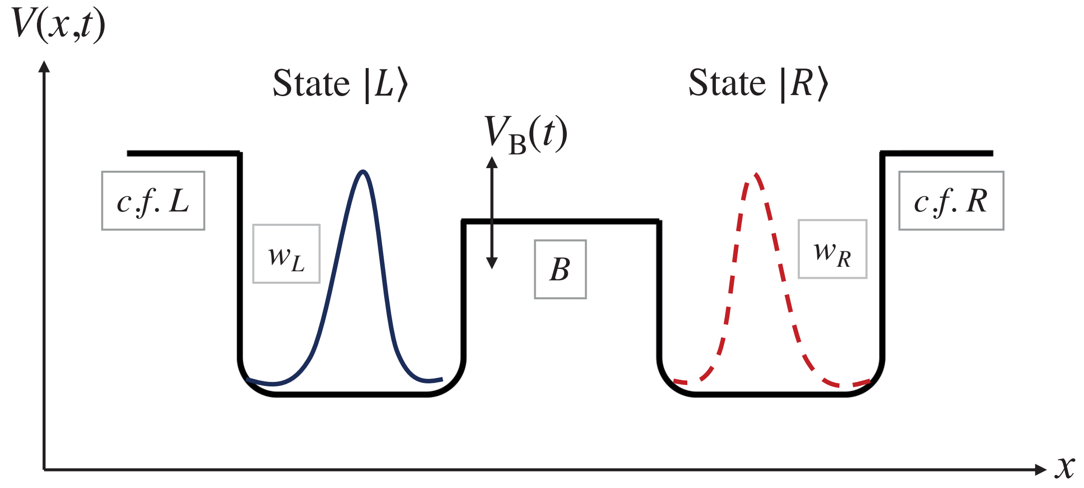
- More practical method to make a qubit (i.e., a two-state system) is two potential wells and one electron
  - Electron found in well "L" will be $|0\rangle$
  - Electron found in well "R" will be $|1\rangle$
- In general, we expect that the electron is neither in well L nor in well R – it is in quantum superposition
- Hence we have both attributes of a qubit: two states and superposition



Qubits

- Complex valued wave-function of an electron describes its probability density:

$$i\hbar \frac{\partial \left| \Psi(x,t) \right\rangle}{\partial t} = \left(\frac{\hbar}{2m} \frac{d^2}{dx^2} + V(x,t) \right) \left| \Psi(x,t) \right\rangle$$



- Time-independent problem:

$$\left(\frac{\hbar}{2m} \frac{d^2}{dx^2} + V(x,t) \right) \left| \psi(x) \right\rangle = E \cdot \left| \psi(x) \right\rangle$$

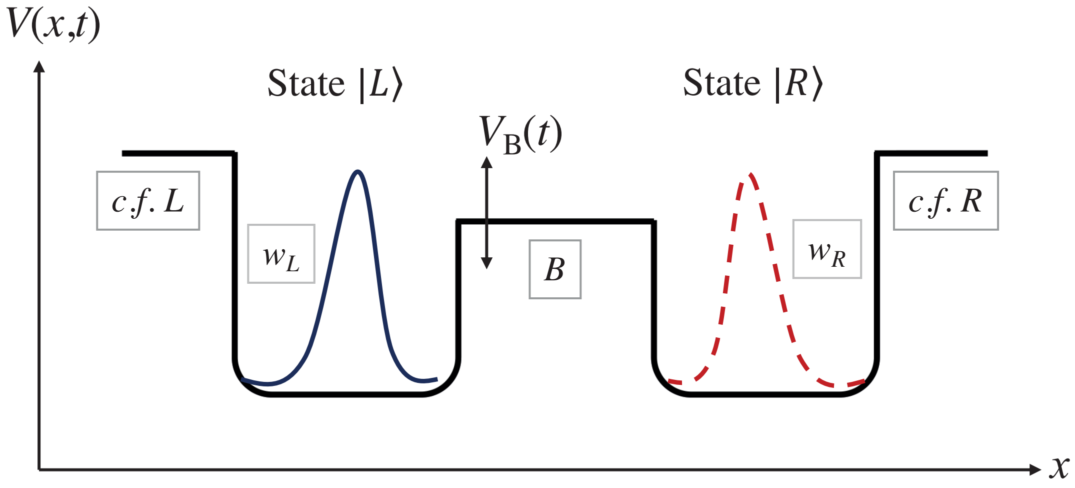
- Solved to find two lowest energy states E_1 and E_2 and correspondent eigen wave-functions ψ_1 and ψ_2

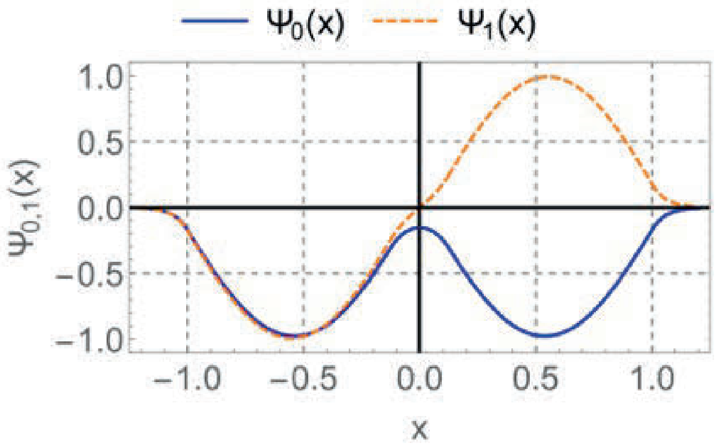
- Superposition of two states follows naturally from the equation:

$$\Psi(x,t) = a_1 e^{i\frac{E_1}{\hbar}t} \cdot \psi_1(x) + a_2 e^{i\frac{E_2}{\hbar}t} \cdot \psi_2(x)$$

Qubits

$$w(x,t) = \Psi\Psi^* = |a_1|^2 \cdot \psi_1^2 + |a_2|^2 \cdot \psi_2^2 + \boxed{a_1 a_2^* e^{i\left(\frac{E_2 - E_1}{\hbar}\right)t} \psi_1 \psi_2^*} + c.c.$$





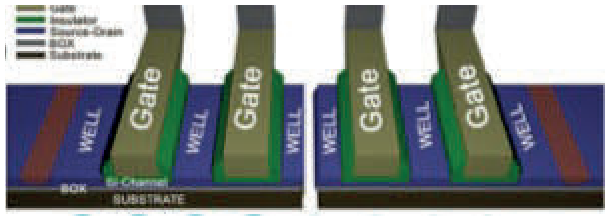
How to implement such a potential in CMOS?

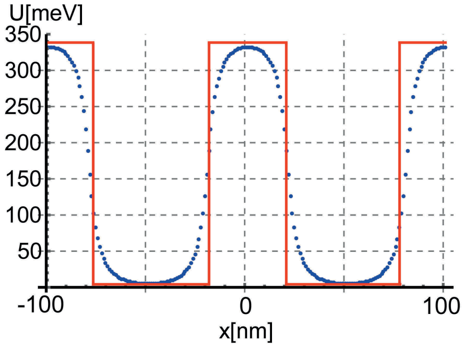
Semiconductor Qubits

Evaluation of geometry and potential function for Schrodinger equation

Numerical simulations with no approximations

Piecewise approximation and analytical solution





$$\left(\frac{\hbar}{2m}\frac{d^2}{dx^2}+V(x,t)\right)\left|\psi(x)\right\rangle = E\left|\psi(x)\right\rangle$$

$\left|\psi(x)\right\rangle$

Time dependent simulations

$$i\hbar\frac{\partial\left|\Psi(x,t)\right\rangle}{\partial t}=\left(\frac{\hbar}{2m}\frac{d^2}{dx^2}+V(x,t)\right)\left|\Psi(x,t)\right\rangle$$

$\left|\Psi(x,t)\right\rangle$ and $\hat{E}(t)$

Conclusions

- Quantum computing (QC) is a next step in the computing revolution
  - Real world is fundamentally quantum, hence quantum computing is needed to model it
- Quantum processor unit (QPU) operations right at (sub)atomic level
- QPU is faint and decoheres quickly
- Requires operation at cryogenic temperatures
- Current quantum computers are still in their infancy
- To build a practical QC:
  - First integrate all classical control/write/readout electronics at cryo
  - Ultimate goal: Single-chip QC at 4K cryo (cheap!)