Roadmapping Cryogenic Electronics and Quantum Information Processing

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In IRDS 2017, Cryogenic Electronics organized as one of two emerging application areas within the Beyond CMOS International Focus Team (IFT). Coverage included superconductor electronics, cryogenic semiconductor electronics, and cryogenic quantum computing. The team formed wrote a section for the 2017 Beyond CMOS that was much more comprehensive than requested. In the process we determined that cryogenic electronics has significant markets and would benefit from technology roadmapping to coordinate market development. This document briefly states the case to establish a separate IRDS IFT for Cryogenic Electronics and Quantum Information Processing.

The International Roadmap for Devices and Systems (IRDS) through the work of roadmap teams closely aligned with the advancement of the devices and systems industries. International Focus Teams (IFTs) collaborate in the development of a roadmap.

In 2017, Cryogenic Electronics organized as one of two emerging application areas within the Beyond CMOS IFT. Tasked with writing a 3 to 5 page status summary for cryogenic electronics, we formed an international team of 21 people to cover superconductor electronics, cryogenic semiconductor electronics, and cryogenic quantum computing. The Cryogenic Electronics section in the 2017 Beyond CMOS report has 10 pages of text, 6 pages of references, and 6 spreadsheet tables.

Indications that a separate IFT is needed emerged during the process of preparing the 2017 report.

- Applications and drivers are somewhat different
- Existing markets are larger and more diverse than realized
- Devices are fundamentally different
- Circuit utility is less driven by device scaling
- Metrics and benchmarks have not been tracked by others
- Growing acceptance that superconductor and quantum computing will happen
- European quantum technologies roadmap reports have been published since 2005, but other regional roadmapping efforts have been intermittent and there has been no international roadmap

Details are provided in the Cryogenic Electronics section in the 2017 Beyond CMOS report.

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With the reorganization of ITRS as IRDS under IEEE, there is no longer a limitation to semiconductors. Areas covered by cryogenic electronics are (1) not covered by other IRDS IFTs, and (2) in need of technology roadmaps. We therefore urge the establishment of a separate IFT for Cryogenic Electronics and Quantum Information Processing.

Vision for a Technology Roadmap

Superconductor electronics (SCE) based on Josephson junctions (JJs) offers several options in the Beyond Moore's law timeframe. Digital superconductor electronics based on single flux quantum (SFQ) logic is currently available commercially in several logic families at an integration level up to about one million devices per chip (gray in Figure 1).

Superconductor electronics is already used in exotic systems (green in Figure 1) with niche applications such as voltage standards and sensor arrays, an area we project to develop further.

Superconductor electronics has been seen as an option for supercomputers since its inception in the 1960s, although the term "supercomputer" has broadened to include data centers (orange in Figure 1). Superconductor electronics is currently getting substantial support from IARPA in the US Government.

Quantum information processing (QIP) is a rapidly evolving area that includes areas such as quantum computing and quantum artificial intelligence (blue in Figure 1). Quantum computers have been seen as ultra-powerful computers in limited domains since the 1994 discovery of Shor's algorithm for factoring numbers. Machine learning algorithms have been demonstrated recently on quantum computers, generating a lot of excitement because of their wide applicability.

The US Superconductor Electronics Workshop held in November 2017 and attended by Paulo Gargini included multiple sessions on roadmapping superconductor technologies. The general consensus was that current SCE technology, at a million devices per chip, is ready for additional scale-up. However, it is not possible to scale instantly from a million devices per chip to the billions required to compete with CMOS directly, so the proposed roadmap focuses on the intermediate steps in the short term that leverage technology's unique strengths (tilted gray ovals in Figure 1).

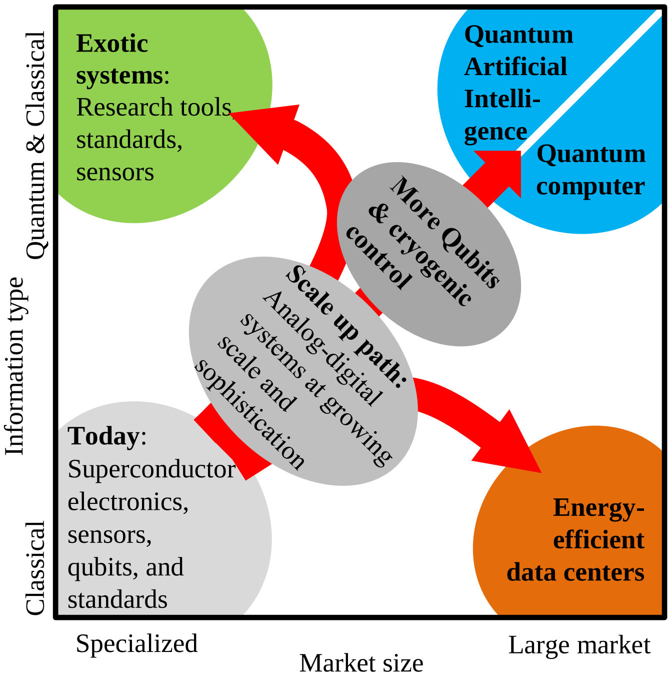

Figure 1. Top-level structure for a superconductor electronics and quantum information processing roadmap.

Signal processors are one intermediate step, specifically sensor-processor combinations that may run at extremely high speed or low power. Applications requiring cryogenic operation are especially suitable.

Quantum computer control electronics is a second area. While qubits are an active and highly specialized research area, each qubit must be controlled by classical electronics equivalent to many gates. However, most qubits operate near absolute zero, creating a requirement for support electronics that is extremely energy efficient at millikelvin (mK) operating temperatures to avoid unacceptable cooling load.

Superconductor Electronics

What makes superconductor electronics different? The following is an excerpt from the Cryogenic Electronics section in the 2017 Beyond CMOS report.

Figure 2 compares superconductor technologies (RQL and AQFP) with several of the most promising beyond CMOS technologies. Superconducting devices (AQFP, RQL) have open circles for 4 K operation and a solid symbol at 1,000 W/W (300 K/4 K) with whiskers showing a range for refrigeration cost from 400 to 10,000 W/W. Dashed lines show constant energy-delay products.

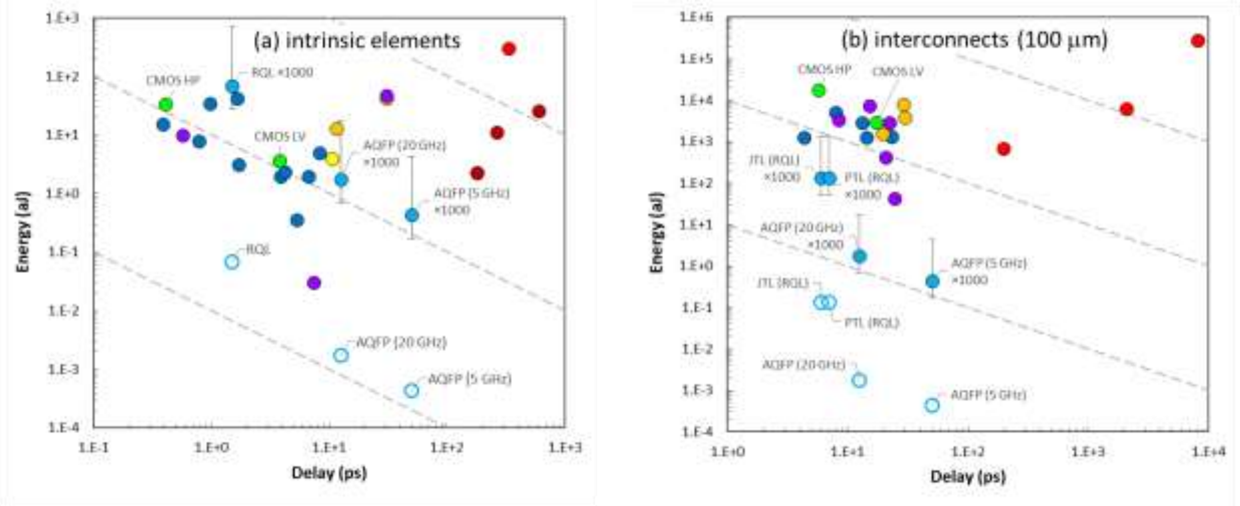

Figure 2. Energy versus Delay for (a) Intrinsic Elements and (b) Interconnects of 100 µm Length

Superconductor circuits switch magnetic flux using Josephson junctions and store flux in inductors. This is very different from semiconductor circuits, which switch electric charge using transistors and store charge in capacitors. A superconducting loop with inductance L and circulating current I stores magnetic flux $\Phi = LI$. Unlike a loop made with normal, resistive material, the current can circulate for as long as it stays superconducting. The behavior is analogous to an ideal capacitor, but the loop stores magnetic flux instead of charge.

Only discrete values of magnetic flux are possible in a superconducting loop due to the quantum nature of the superconducting state. A simple description is that the superconducting state is associated with a wave function and that the phase change around a loop must be $2\pi n$, where n is the number of flux quanta in the loop. The value of the magnetic flux quantum is $\Phi_0 = 2.07$ fWb. Expressed in practical units, 1 fWb is equivalent to 1 mA·pH or 1 mV·ps. Phase differences between points within superconductor circuits can be produced by magnetic flux, electric currents, and certain devices. Superconductor phase engineering is an important part of SCE circuit design without analogy in CMOS circuit design.

Single flux quantum (SFQ) digital logic represents digital ‘1’ and ‘0’ by the presence, absence, or location of magnetic flux quanta within a circuit element.

Josephson junctions (JJs) are devices used for switching or their nonlinear behavior. Physically, JJs are 2-terminal devices made like a thin-film capacitor with superconducting plates or contacts. Quantum tunneling of Cooper pairs through the thin barrier layer allows a supercurrent to flow between the contacts with zero voltage drop.

Cryogenic Electronic Systems

Cryogenic and quantum systems require components operating near absolute zero temperature, making just about every aspect of the design exotic. The architecture of these quantum–classical hybrid computers is zeroing in on the structure shown in Figure 3. The qubits (quantum bits) must be kept at a temperature of approximately 15 mK. They need support from classical, i.e. non quantum, electronics. The main options include Josephson junctions operating at temperatures around the boiling point of liquid helium, ~ 4 K, and specialized transistors often cryoelectronics. The electronics must have extremely low energy dissipation, because the external refrigeration will consume large multiple of the energy released by the cold electronics. Logic-gate circuits based on Josephson junctions are available that perform the logic functions for error correction as well as the gate microwave signals required to control qubits.

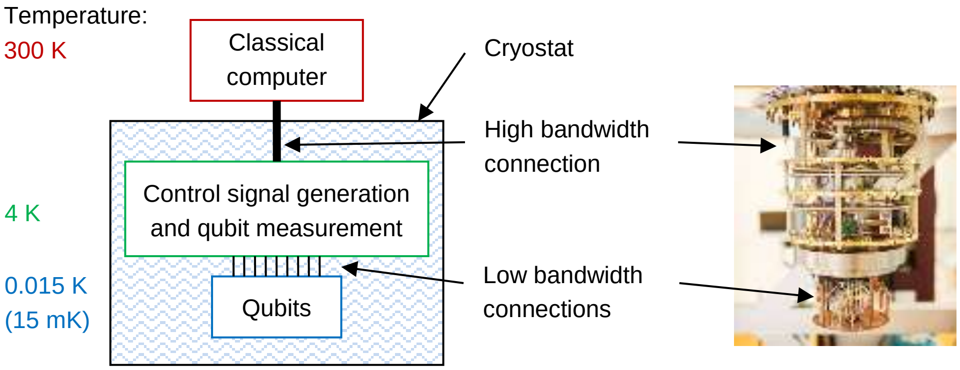

Figure 3. General structure of a quantum computer system. The user interacts with the classical computer. If the problem requires optimization, the classical computer translates the user’s problem into a standard form for a quantum computer. The classical computer then creates control signals for qubits (quantum bits) located in a cryogenic environment and receives data from measurements of the qubits.

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