Rebooting Computing, superconductor electronics, cryo CMOS, SFQ, FPGA, Beyond CMOS, superconducting FET, qubit, quantum control electronics, quantum computer

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Rebooting Computing

The National Quantum Initiative Will Also Benefit Classical Computers[1]

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The U. S. National Quantum Initiative puts quantum computer scale up into the same category as Moore's law. While the technical basis of semiconductor scale up is well known, the equivalent principle for quantum computers is still being developed. Let's explore the new ideas.

A regular, or classical, computer delivers value to the user based on the complexity of the calculation it performs. Classical computers are overwhelmingly based on transistors, and Moore's law showed how to make transistors cheaper, faster, and more energy efficient over time. While quantum computers are expected to be built mostly from classical devices as well, the value delivered to the user will depend on the qubits not the supporting devices. The point of this article is that shifting classical devices from the primary role to a supporting role will transform thinking about computers.

Let's introduce the new thinking by considering the central 3D structure of a quantum computer, which contains the qubits and a portion of the control system. While nobody knows which type of qubit will go into large-scale production, most candidate qubits require cryogenic operation.

Through-silicon vias (TSVs) are a current example of 3D technology. They are microscopic bumps that electrically and mechanically interconnect up to about a half-dozen integrated circuit die along their planar faces into a 3D module.

The first advance we're seeing is the extension of these approaches to multiple operating temperatures, such as room-temperature layers plus other layers at one or more cryogenic temperatures. The cryogenic layers allow a second extension to novel devices and circuits, including sensing devices that require low temperatures to function and computing devices to support them.

Logic performance and temperature

There was an extensive search for transistor replacement as a potential remedy to the so-called end of Moore's law, ultimately producing Figure 1's scatterplot of energy and delay

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for many candidate devices.[1] Focusing just on the top group for now, we see that the three data points with whiskers are Josephson junction-based reciprocal quantum logic (RQL) and adiabatic quantum flux parametron (AQFP) logic families. The dots for these cryogenic devices show the sum of device energy per operation plus the additional energy used by the cryogenic refrigerator to remove heat from 4 K to room temperature; the whisker shows the result over a refrigerator efficiency range. None of the devices in the top group stands out.

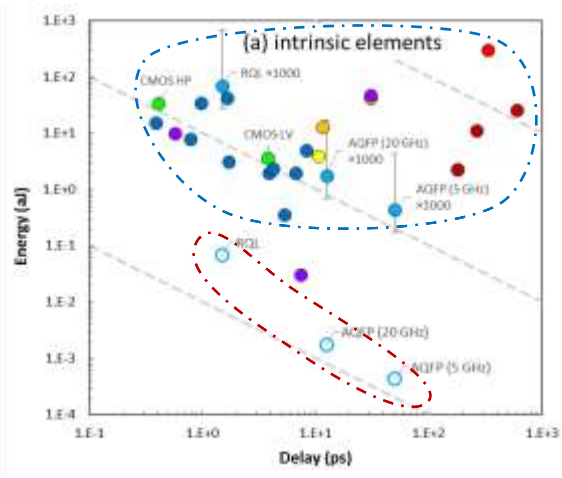

Figure 1. An energy-delay plot of a comprehensive set of logic devices at room temperature, including Josephson junctions operating at 4 K in three circuits (RQL and, at two speeds, AQFP). None of the devices stands out at room temperature because only the superconducting ones have refrigeration overhead. However, at 4 K, they all require refrigeration, causing the superconducting devices to stand out. (The outlier purple dot is a BisFET, which is too immature to be considered a serious contender.)

When low-temperature operation is required, all the devices in Figure 1 need refrigeration, and the method of tallying the energy cost of cryogenic refrigeration changes. In low-temperature operation, devices in both the upper and lower groups operate at temperature T and require a cryogenic refrigerator to remove heat to room temperature. A 100% Carnot-efficient refrigerator will multiply the heat by 300 K/T in the process of moving it to room the temperature (300 K) environment, and refrigerator inefficiency adds another multiple of 5×–20×. However, these factors are the same for all devices, so the best options will be the points closest to the origin of the graph, which are the cryogenic Josephson junction-based devices.

Different circuits become effective at low temperatures

Everybody wants to save energy, which is why wise engineers consider energy efficient light bulbs for their homes. However, once they see that the energy-efficient bulb costs ten times as much as an incandescent one, they do a calculation to see if it’s a good deal. If the increase in purchase price is greater than the energy savings over the bulb’s lifetime, it’s a bad deal. Energy-savings technology for computers, such as reversible and adiabatic logic, have been known for years. However, they trade energy efficiency during operation for more complex circuits that cost more to buy in the first place—leading to the same tradeoff as for light bulbs.

All other things being equal, you become more likely to choose the energy-efficient technology as the price of energy rises. Energy-efficient lights and reversible computers that are bad deals at room temperature become better deals at 4 K because of the effective 1,000× increase in energy cost—and are no-brainers for systems operating at millikelvins, such as quantum computers, where the effective cost rises 1 million times.

Adiabatic and reversible logic have been studied at room temperature for many years, and the plot in Figure 2 shows an example of the benefits when implemented with standard CMOS. The curves are the result of many simulations and show transistor power declining with clock period for both standard CMOS and a reversible logic family called 2LAL.[2] On the log-log scale, the power dissipation of CMOS declines with slope −1 (linear), while 2LAL has slope −2 (quadratic). This creates a widening advantage for 2LAL at lower clock frequencies, which eventually ends because of leakage current I_{off}. However, a 200-kHz microprocessor is not very useful even if it is energy efficient.

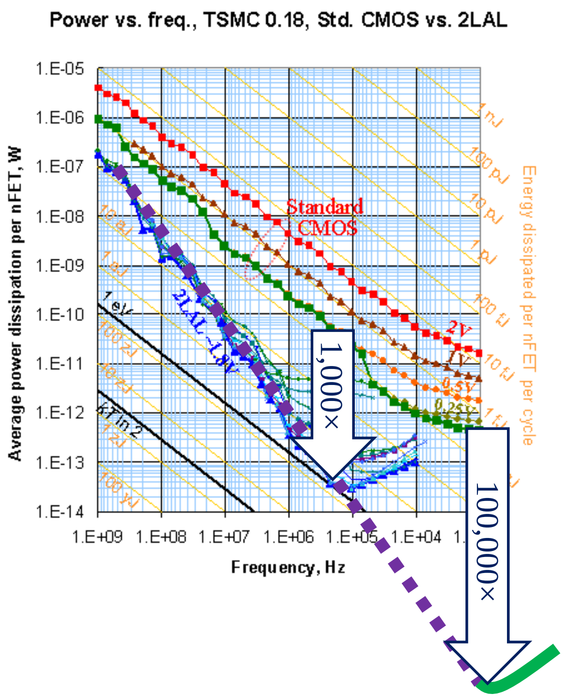

Figure 2. A comparison of circuit efficiency for standard CMOS (top line) and a reversible circuit 2LAL, showing a maximum advantage of 1,000× at 200 KHz. However, if the 2LAL is operated at 4 K, downward-sloping curves should extend further, leading to a possible 100,000× energy-efficiency improvement over room-temperature electronics. This may allow a transistorized 2LAL to compete with Josephson junctions in applications where speed is not essential. FET: field-effect transistor; freq.: frequency

What happens to reversible circuits at cryogenic temperatures? Studies of standard CMOS transistors operated at 4 K show a large reduction in leakage current[3] while other factors stay about the same. Although cryogenic 2LAL has not been systematically analyzed for this article, the qualitative result annotated on top of Figure 2's base graph is an extension of the region with downward slope –2 by an additional factor of perhaps 10,000× before leakage current I_{off} causes the upward sloping behavior. A review of the literature indicates that the advantage should increase a bit more below 4 K and then level off, but further work is indicated.

The exponential growth of Moore's law made semiconductors seem unbeatable for decades. However, recent changes in Moore's law have enabled superconductors to pull ahead for quantum computers. But wait! Now that we take time to think, semiconductors can play this new game, too, by switching from CMOS circuits to 2LAL or some other adiabatic form. If thinking hard can rejuvenate both semiconductors and superconductors, what could happen if we thought about using both at once?

Heterogeneous integration of semiconductors and superconductors

One of us saw a presentation at a recent conference reporting on the invention of a superconducting field-effect transistor.[4] It was kind of an odd device. The application of 90 V would switch it from a 0 Ω superconductor to a resistor of 50 Ω or so. Nobody had any idea what to do with it, but we'll suggest that it could interface between 2LAL and Josephson junction logic in a semiconductor-superconductor hybrid module.

Although the device was experimentally tested with 90 V swings, the authors claim that scaling could reduce the drive voltage to 2.5 V, a typical CMOS voltage swing. This could lead to a structure like the one shown in Figure 3, where CMOS voltage signals are converted to Josephson junction current signals.

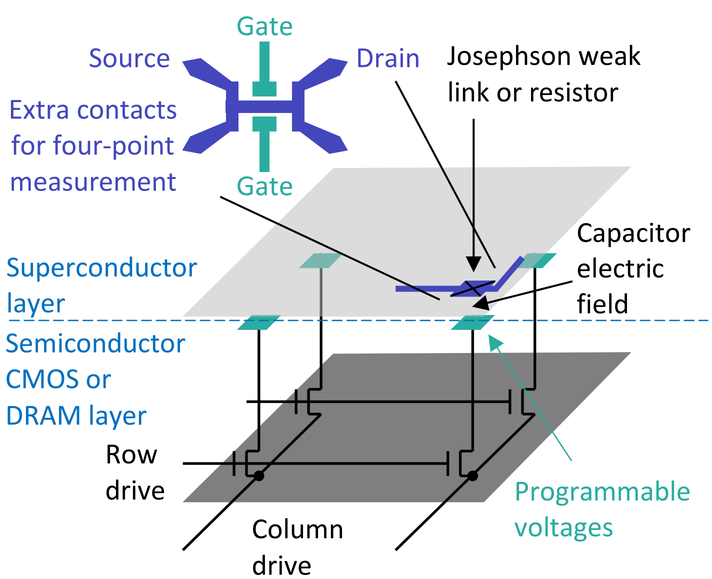

Figure 3. A possible semiconductor-superconductor hybrid. The semiconductor layer applies voltage-based signals to the gates of superconducting FETs, which translate the signals into a form readily used by superconducting circuits. The hybrid would be fabricated using a CMOS wafer as a base for depositing superconductor circuits, in lieu of today's method of using a blank silicon wafer as a base. DRAM: dynamic random-access memory.

The inset in Figure 3 shows a superconducting field-effect transistor FET.[4] Ignoring the green structures for the moment, the blue structure is a superconducting wire that will conduct current horizontally with zero resistance. However, a narrow superconducting wire conducts with zero resistance only up to a maximum current, called the *critical current*, above which the device becomes a resistor. A narrow wire of this type is called a weak link and is a type of a Josephson junction.

However, the critical current declines in the presence of an electric field, such as the field applied by the green capacitor plate in Figure 3 and the corresponding green structure in the inset. Because superconductor circuits are built from wires with zero resistance, voltages in a superconductor circuit almost always stay between ground and a few millivolts. Theory and experiment for the superconducting FET show that the weak link's critical current changes when the green structure applies a few volts or more, positive or negative, which is straightforward for transistorized electronics. Hence, the semiconductor layer would communicate with the superconducting layer through voltages that change critical currents.

Attempts to restore traditional computer performance growth rates, like Moore's law, have taken different directions recently. We've seen how several of these directions can be pursued at once to make a more audacious hybrid than has been seen before.

Running both semiconductors and superconductors at 4 K, with suitable circuits and an efficient, integrated interface between the two, yields a set of building blocks with a unique set of properties:

- Semiconductors: A large number of components are available per unit area, and the technology has achieved high maturity. Signals have 1 V to 2 V swings. However, achieving high energy efficiency requires progressively reducing the clock rate.
- Superconductors: Clock rate remains fast down to the lowest temperatures. These relatively immature devices have large features that would result in low device density. Signal voltages are around a millivolt, but there is a method for conversion from the 1 V to 2 V signals from semiconductors.

Is there any circuit in common use that could benefit from such an oddball combination of features? Our first thought is a superconducting field-programmable gate array (FPGA),[5] yet of a new design where the configuration logic is implemented with semiconductors. Because it runs on only power-up, it doesn't have to be fast. After the FPGA has been configured, the Josephson junction logic executes the user-defined logic at high speed.

The standard process for computer design is to create a Turing-complete processor out of universal gates, and then add I/O as an afterthought.

However, a quantum computer will have two types of universal gates, classical and quantum. Standard computer design would lead to a quantum computer system composed of a quantum processor connected to a classical control system via I/O. But this is not to be.

Qubits offer their exotic features only in specific environments, such as cryogenic temperatures, whereas classical electronics offers both density and performance only at room temperature. This article shows how the requirements of each intrude on the design space of the other, destroying the standard abstraction.

So "universal" Boolean logic gates actually have additional properties attached to them (i. e. density and performance at room temperature). The impact of these additional properties was invisible when we only had one example of them. However, mandates to scale up quantum computers force us to deal with quantum gates where the additional properties are incompatible. We must now learn to design with "generalized universal gates," after which we need to revise the standard process for computer design.

While quantum computing has the lion's share of public attention right now, the same technology could apply to cryogenic sensor systems that rely on quantum information and which may enable scientific breakthroughs.

Acknowledgments

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