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Applications of HTS

Summary

The extremely low resistance nature of Ambature's a-axis architected superconducting materials lends itself to a broad range of applications. From augmentations to developing entirely new systems, high-temperature superconductors provide a new platform to develop the next generation of technology. Quantum computers, magnetic resonance imaging, and cell phone base stations are particularly important advancements, but improvements can also be found in power generation, energy storage, microelectronics, and a wide range of sensor-based applications. Before describing these applications in detail, it is important to discuss some background information about superconductors and the semiconductors they replace in certain scenarios.

Semiconductors

A semiconductor is a material that can act as both a conductor of electricity or an insulator, depending on how it is altered or "doped". Beginning with this simple concept, years of development have produced complex systems on a chip (SoC's) such as the electronics currently driving your devices (Figure 1). Most semiconductor development has occurred in silicon transistor switches, specifically in metal oxide semiconductor field effect transistors (MOSFETs). You can see in Figure 1 that MOSFETs make up submodules like "logic gates". Logic gates operate on input bits (1's and 0's) and produce output bits according to the type of logic gate (OR, AND, NOR, NAND, etc.). Huge arrays of logic gates are grouped by function into "chiplets" that are applied to specific jobs within the device such as computation (cores), short-term storage (memory), and signalling (I/O). Chiplets are packaged into one component using various die-to-die interconnects, which helps reduce waste relative to "monolithic integration", the traditional method of creating SoC's. If one "core" chiplet does not meet specifications, then it can be replaced without replacing the remaining chiplets. Simple components, like cameras and microphones, are still based on monolithic integration, where the entire SoC must be discarded if it does not meet specifications. Ultimately, our complex devices can be broken down to millions of transistors connected with metal interconnects.

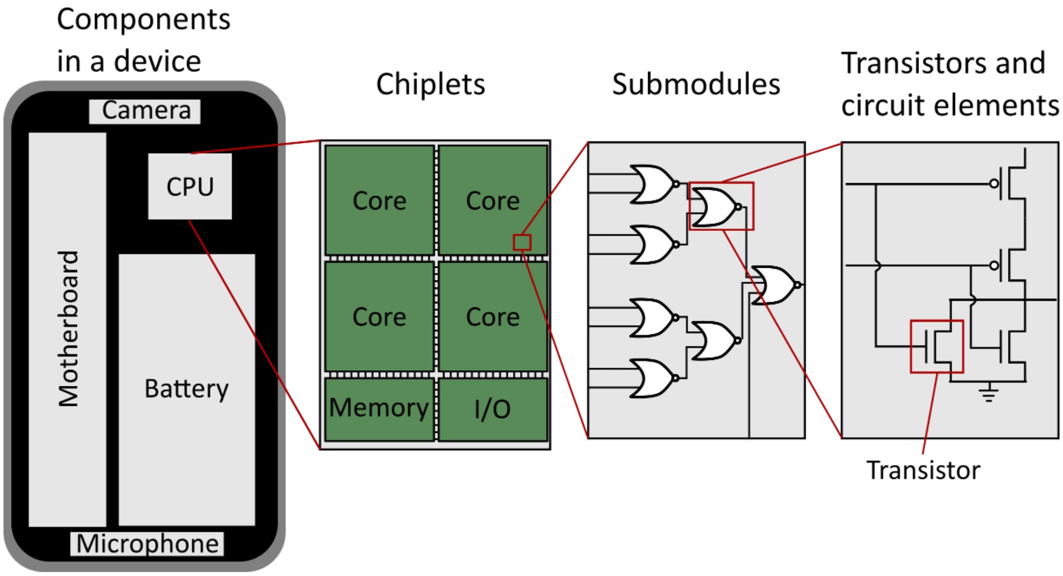

Figure 1: Breaking down a typical device into its components, chiplets, submodules, and circuit elements (transistors).

Superconductors

Superconductors are materials that have zero electrical resistance, and therefore no heat is generated when current flows. This happens because electrons pair up into "Cooper pairs" and are less able to be slowed (resisted) as they transit through the superconductive material. Superconductivity requires very low temperatures to convince the Cooper pairs to form. Low-temperature superconductors (LTS) like niobium or aluminum need to be cooled near absolute zero (0 K, -273 °C, -459 °F), while high-temperature superconductors (HTS) can be as warm as 100 K (-173 °C, -280 °F). Often HTS are ceramic materials with a preferential direction for current flow. Ambature has demonstrated control over these preferential directions. We are the only company in the world that has optimized high-temperature superconductors for their specific applications and maximized the potential benefit according to a chosen preferential current direction.

It is well known that advancements can be made on the zero-resistance principle alone. Metal interconnects, capacitors, inductors, and antennas are common circuit elements that can be converted to superconductors for less wasted heat and less latency. Circuits can operate up to an order of magnitude faster and use approximately 30% of the power all while improving signal quality. Superconductors also have natural properties that allow them to create excellent filters with a high quality factor ("Q-factor"), applicable for example to 5G base stations. In this case, superconductors improve the sensitivity and allow for 50% more channels, which alleviates some of the present concerns of bottlenecking in receiver networks.

Semiconductors & Superconductors

Semiconducting and superconducting materials can be integrated to achieve various best-of-both-worlds technologies. They can be merged following the chiplet configuration or monolithic integration as discussed above. Beyond waste reduction, chiplets enable the development of more flexible SoC's. For example, a laptop CPU might require six cores and one I/O chiplet, while a server CPU will need many more cores and I/O chiplets. Identical core and I/O chiplets are used for both applications, however, the number of each will vary depending on the requirements. This also means that it is relatively straightforward to integrate superconducting and semiconducting chiplets because the two materials are kept separate (Figure 2). Each chiplet is formed separately with their own fabrication methods and then bonded using a series of electrical interconnects. Monolithic integration is when superconducting and semiconducting elements are close together or in direct contact at the submodule or circuit element level. Forming both elements next to each other on the same substrate requires clever growth, fabrication, and cooling solutions, but can provide unique functionality to IC technology. Initial stages of development may focus on either of the two SoC configurations or a combination of both.

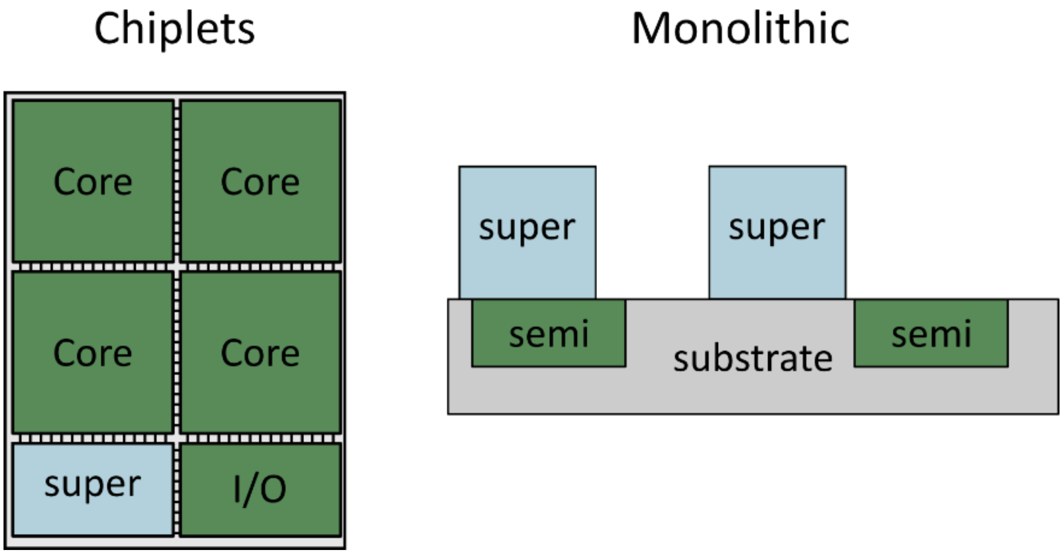

Figure 2: Integration of superconducting and semiconducting elements. Chiplets (left) are shown top down in plan view. Monolithic (right) is shown in cross section and the scale is much smaller. Chiplet SoC's are bonded to a common die to electrically connect the two materials. Monolithic SoC's require superconductors and semiconductors to be formed on the same platform by careful fabrication and design. A recent Google patent application that combines the classical and quantum approaches states that the combination of the two could lead to substantial savings in energy consumption [1].

Josephson Junctions

Much in the same way that transistors are a direct result of the material properties of semiconductors, Josephson junctions (JJs) are superconducting devices based on quantum tunnelling. Brian Josephson received the Nobel Prize in Physics in 1973 for his work predicting the Josephson Effect occurring in a Josephson junction. The JJ is a key element in many applications including superconducting electronics and integrated circuits, improved sensors, and quantum computers. A JJ consists of two superconducting layers separated by a thin insulating layer (Figure 3). When connected in a circuit, supercurrent can flow in the JJ from one superconducting layer, through the insulating layer, to the next superconducting layer via tunneling. Even though there is a layer of insulating material, supercurrent flows through the device unimpeded. This is called the DC Josephson effect. Once a critical current is reached (I_c), a gigahertz-frequency oscillating voltage appears across the junction. This behaviour is functionally quite different from that of a semiconductor transistor, as shown in Figure 3. A JJ has two regions of operation, one where supercurrent flows through the device and one where an oscillating voltage appears across the terminals. In comparison, transistors (MOSFETs) are a three-terminal device where a voltage on the “gate” controls how current flows through the substrate from “source” to “drain”. It has two regions of operation like the JJ, but the two regions in a MOSFET are simply ON and OFF like a switch. There are many types of transistors, but none of them operate like a JJ, including the current industry standard “finFETs”. A JJ’s unique functionality comes from the properties of the superconducting layers.

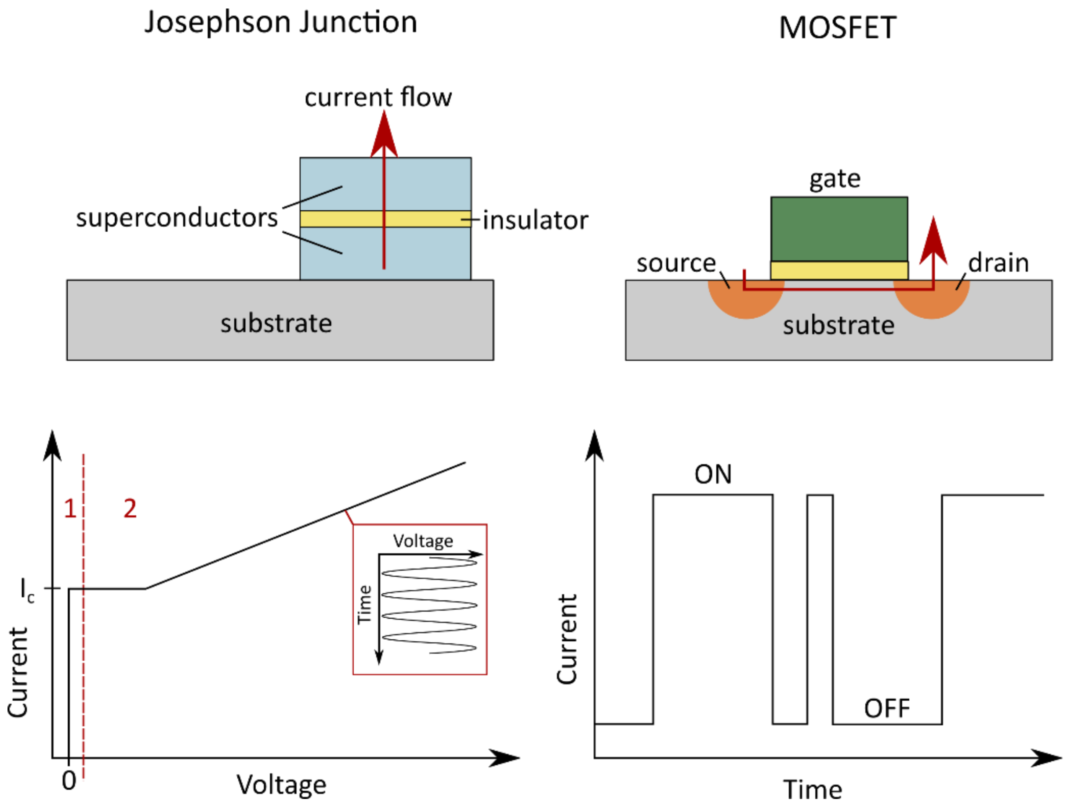

Figure 3: The top two images are cross sections of a Josephson junction and a MOSFET. The red arrows show the current path through each device. Two plots on the bottom identify the characteristic current responses for each device. JJs have a critical current (I_c) beyond which their voltage begins to oscillate with time. MOSFETs turn ON and OFF according to the gate voltage, and the plot shows the current through the MOSFET changing as the gate voltage changes with time.

JJs are not functionally equivalent to transistors but, with some clever engineering, JJ chiplets and submodules can replace semiconductor chiplets to the benefit of an entire device. Extremely low resistance clock and logic submodules can be made from JJs, which produce much less heat and operate faster and more accurately than their transistor counterparts. Although chiplet replacement is possible, it is unlikely that entire devices will consist of superconductors in the near future. Instead, JJs and transistors must exist in synergy to allow for a new degree of technological optimization and advancement. It is expected that the synergy of JJs with conventional MOSFETs will augment the functionality of the processor architecture.

One of the most important applications of JJs is in quantum computing. Up to this point in the memo, computations have been discussed in a classical sense (bits), but quantum computers are an important next step for several industries today. They will allow for quantum encryption, faster drug/vaccine design, disaster prediction, and many other applications that current computers are not capable of handling. JJs are essential to quantum computing because they create and manipulate quantum bits (qubits). Unlike conventional bits that can be either 1 or 0, qubits can be 1 or 0 or anything in between. Using a concept called “superposition”, all qubit states are represented by a combination of 1 and 0 states. Qubits create unlimited combinations that, in practice, can rapidly outpace classical bits in specific tasks. JJs are also important in submodules that manipulate qubits such as amplifiers, switches, etc.

Moreover, JJs can be connected in a loop to form a superconducting quantum interference device (SQUID). A SQUID is a powerful quantum device that can measure magnetic flux at the finest possible increments (flux quanta). SQUID sensors are ~1000x more sensitive than conventional devices. This is particularly beneficial in magnetic resonance imaging (MRI) applications, where low noise, high sensitivity electromagnetic sensors detect minor changes in energy from rotating protons in the patient. An MRI based on SQUID technology would be smaller, cheaper, and have better resolution than current systems. It is even possible to create a portable MRI with this technology.

There are two main avenues for Ambature’s superconducting technology platform that controls the direction and vector of current flow. The first includes applications relying on the material properties of Ambature’s high-temperature superconductors. These are mostly monolithic augmentations of semiconductor SoC’s that ultimately improve device characteristics but do not change the functionality of the SoC. In some cases, like cell phone base stations, entire filter submodules can be replaced with superconductors. Goldman Sachs has reported that electrical resistance results in 50% reduced speed in a typical cell phone base station. The second includes applications relying on Josephson junction devices themselves. Due to the unique functionality of JJs, these applications will typically require development on the chiplet scale. Such is the case for quantum computing or SQUID array sensors.

In summary, the properties of lower or zero electrical resistance, enhanced sensing capability, and ease of fabrication can significantly improve the performance and cost of many existing devices, as well as permit new devices that do not currently exist. Ambature’s current technology roadmap focus is summarized below.

References

[1] USPTO Patent Application Publication (2020/0257644), “Chips including classical and quantum computing processors”

Technology Roadmap

Application	Description
Advanced Semiconductors	Ambature's HTS can be used in advanced ICs to deliver more data with more efficient power, faster clock speeds, and greater density.
Artificial Intelligence & Machine Learning	Ambature's HTS sensor technology can enhance the collection of larger data blocks. For example: implementing enhanced software-defined radio front-ends with more sensitive, wider dynamic range inputs. Ambature's JJs can be used for faster processing of data and to reduce latency in responses.
Antennas	Ambature's antennas can help to reduce resistance losses and allow for smaller, more efficient antennas.
Autonomous Vehicles	Ambature's sensors and JJs can enable faster response times and decision making by reducing latency from many signal/data inputs. For example: radar and lidar.
Data Centers	Ambature's JJ technology can help to manage power consumption and heat dissipation in data management while reducing the largest cost in data centers—electricity usage. Ambature's JJs can also provide for faster computing and communication networks.
Electric Vehicles	Size, weight, and power concerns consume the engineers of electric vehicle manufacturers. In particular, battery terminal resistances need to be reduced. HTS can offer solutions for more electrical efficiency throughout the vehicle and longer driving distances.
HTS Filters	Thin film HTS filters offer proven superiority in wireless communications applications. They offer ultra-high selectivity and can be programmed. As thin film devices, they can be integrated into hand-held devices. The ultimate goal is the generation of less parasitic heat from power amplifiers and converters and better Q-factors.
Imaging Devices	Ambature's JJ technology and SQUID detectors can be utilized as a highly sensitive RF receiver in a low-B-field embodiment of point-of-care MRIs. The combination of a better SNR and faster signal processing can lead to smaller portable diagnostic devices, even as surveillance tools against future pandemics.

Application	Description
Sensors	Ambature’s HTS technology offers ultra-high signal sensitivity and wide dynamic range sensors. MEMS and SQUIDs can be used in many architectures, including edge sensors, SDR architectures and a variety of advanced receivers.
Smart Cities	Ambature’s JJs and sensor/SQUID applications can be used to form orders-of-magnitude better sensors.
Software-Defined Radio	Up to 60 dB SNR improvements are possible, enabling superior spur-free dynamic range (SFDR).
Quantum Communication	Ambature’s JJs can be used in applications such as cryptography, cybersecurity, and the quantum internet.
Quantum Computing	Ambature’s JJs can be used to form qubits for quantum computing as well as enhanced classical computing to get data in and results out of the qubit.
Quantum Sensing/Imaging	Ambature’s JJs and SQUID applications can be used for precision sensing in mining, medical, infrastructure, and military applications.