Superconductor Electronics and Power Applications

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I. ESTABLISHING THE FOUNDATION BEFORE 1962

In the half century before 1962, experimental and theoretical developments laid the foundation for the following half century of innovations both in electronics and in power. Immediately after the discovery of superconductivity by H. Kamerlingh Onnes in 1911, he attempted to make use of its zero resistance to produce magnets. But the superconductivity was quenched by the fields produced by the magnets. It was found that this was characteristic of a class of materials later given the designation "type I"; an abrupt transition to the normal (resistive) state would occur at a value of current that depends on the material, the temperature, the configuration of the conductor, and the magnetic field. Type I and type II superconductors were defined by how the materials exhibited the magnetic fields associated with the currents. Type II materials could carry greater currents without quenching the superconductivity by allowing penetration of the magnetic flux into the superconductor while the current is flowing and by pinning the flux. Developing the right materials in sufficient quantities would be the key to magnet applications.

On the electronics side, a thin-film digital switch called a cryotron, based on the suppression of the zero-resistance currents by a magnetic field, was developed for computer applications. The zero resistance also suggested its use for high-quality-factor radio-frequency (RF) coils for communication applications. We will see below that the major strides in electronics applications awaited the discoveries related to superconducting tunnel junctions in the early 1960s.

Theoretical understanding of superconductivity would be critical to the development of applications. A phenomenological theory, the London theory, elaborated in the 1930s, proved powerful to explain the observed behavior of type I superconductors. One result was the prediction (and later observation) that magnetic flux is quantized in superconducting loops in units of $h/2e$, where e is the electron charge and h is Planck's constant. Subsequently, in the mid-1950s, Ginzburg and Landau developed theoretical foundations for type II superconductors. And in 1957, Bardeen, Cooper, and Schrieffer (BCS) devised a microscopic theory that explained the phenomenon of superconductivity from first principles. This was followed in 1961 by the theoretical discovery of the so-called Josephson effects in quantum tunneling between superconductors. The theoretical foundation was laid for the following half century of innovative applications.

II. REFLECTIONS ON THE PAST 50 YEARS OF R&D (SINCE 1962)

A. Electronics

Quickly after the first demonstration of the Josephson effects in

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superconductive quantum tunneling in 1963, RF detection and mixing was developed and advantageous sensitivity was seen. Superconducting tunnel junctions [superconductor–insulator–superconductor (SIS)] were seen to exhibit I–V characteristics with an extremely sharp curvature, thus making it a very sensitive microwave detector. Furthermore, it was shown that the associated quantum tunneling effects made it possible to realize a microwave mixer with gain, instead of the loss found in normal-state mixers. Subsequent work in this field showed that even a single photon could change the resistance of a superconductor thin film by enough to be detected. The related device is a bolometer called a transition-edge sensor (TES). Arrays of these devices are being made to map the RF sources in outer space, giving us a window on the early years of the universe.

The quantum behavior of currents in superconducting loops containing Josephson junctions led to the invention in the 1960s of the so-called superconducting quantum interference device (SQUID) as a highly sensitive detector of magnetic fields. SQUIDs have been employed in many applications including geophysical prospecting, fault detection in metal structures, and noncontact measurements of the electric currents in human hearts (magneto-cardiography) and brains (magneto-encephalography).

The National Institute of Standards and Technology (NIST) and other national standards laboratories have applied the quantum nature of superconducting currents to develop much more accurate standards. The best known is the volt standard, which employs the Josephson relation between frequency and voltage ($f = 2\,eV/h$) and the ability to measure frequency accurately. Other superconductive standards include current comparators, RF power meters, and thermometers.

The demonstration of the Josephson junction in 1964 was also followed by the realization that a junction's transition between the zero-voltage state and the voltage state (a few millivolts) is extremely fast. It was a superconducting switch far superior to the cryotron, mentioned above. This led to very large projects in the United States and Japan which were aimed toward developing a computer that would be faster than was expected using semiconductors. The most recent families of superconducting logic circuits employ the movement of single flux quanta. This work is still in progress, though the inexorable development of the complementary metal–oxide–semiconductor (CMOS) technology (Moore's law) has made it a much more competitive race than originally thought. Recent emphasis is on making computers that demand less wall power, which has become a very serious concern. Adequate memory for 4-K (kelvin) superconducting computers is a continuing problem; our laboratory is working to provide a solution by using a CMOS memory core with superconducting interface circuits.

In a major exciting development in 1986, radically new superconductors were discovered with transition temperatures well above the 23 K of the previously known metallic superconductors; these were called high-temperature superconductors (HTSs). Within a year, a material was found that even had a transition temperature of 90 K, above the boiling temperature of liquid nitrogen. Most superconducting electronics at that time was being done with niobium with a transition temperature of 9.2 K so higher operating temperatures with simpler, more efficient refrigeration caused great excitement. However, in time, it was realized that higher thermal noise would limit the useful operating temperature. The noise is a problem, but the main problem facing use of HTS in electronics has been the inability to make Josephson junctions with sufficiently controlled characteristics. This is probably attributable to the complexity of the multiple-element materials. After 25 years of research on HTS electronics, active superconductor applications are still being realized almost exclusively with niobium. Bright spots in this picture include the use of HTS films for microwave filters and some circuits needing only one or few Josephson junctions.

B. Power

The 1960s saw the beginning of the exploitation of new metallic superconductors [now called low-temperature superconductors (LTSs)] for power applications. Two type II materials, Nb–Ti and Nb_3Sn, were brought into practice in that period and have played a dominant role in power applications since then. Wires were made by embedding hundreds of parallel filaments of these materials in a matrix of copper. This conductive shunt serves as a current bypass if the limiting current in a filament is exceeded and the filament goes into the high-resistance normal state. The current bypass avoids catastrophic overheating failures. These composite wires are combined into a cable to carry the intended current capacity.

Early in the 50-year period that we are reviewing, there were already many developments employing these so-called LTSs. The applications included power transmission cables and magnets for many applications including magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR) spectrometers, energy storage, high-energy particle accelerators, train levitation, and industrial processing. Generators and motors, including motors for ship propulsion, were also demonstrated. Implementation was held back in some cases because of cost and the difficulty of refrigeration at 4 K.

The discoveries, starting in 1987, of high-temperature superconductors with transition temperatures of 90 K and above, have made a strong impact, especially on power applications. Power transmission projects can employ liquid nitrogen for cooling instead of the liquid helium used for LTS systems; this has greatly increased the feasibility of superconducting power transmission. Several test systems are being evaluated. Other system components, such as motors, generators, transformers, synchronous condensers, fault-current limiters, are being developed with HTS materials. Easier, more efficient refrigeration is a big factor in the acceptability of an application. But even after the introduction of HTS materials, some applications, such as particle accelerators, NMR, etc., continue using LTS materials.

III. THE NEXT 50 YEARS

A. Electronics

What does the future for superconductor electronics look like? Some superconductor applications, such as the volt standard and millimeter wave detection, are essentially without competition and can be expected to continue in place for the next 50 years. In other electronics applications, superconductor devices such as analog-to-digital (A/D) converters and digital radio have advantages and may be expected to continue to be developed over the coming decades. Research is continuing on superconducting digital computation using single (magnetic) flux quantum devices; superconductor processors have the potential for higher speed and lower power than semiconductor processors. The competition from room-temperature semiconductors may be weakening; the previously rapid increase of capability of semiconductor integrated circuits seen over the preceding decades expressed in Moore's law seems to be reaching its limits. Still, this contest must be played out. A particular issue is the need to provide sufficiently fast and low-power memory for the higher speed processors.

Major disadvantages for superconductor electronics include the need for refrigeration and the lack of foundries comparable with those for silicon devices. Also, the silicon industry is able to make small products that produce cash infusion for R&D and facilities; the need for refrigeration of superconducting devices precludes this source of income, and funding is limited predominantly to government sources.

SQUID systems for medical applications and mineral prospecting as well as cellular base station receivers show near-term commercial potential. But there are other applications that will continue to require government support, including national standards (e.g., the volt standard), radio astronomy, quantum communication and computation, high-performance large-scale computing, and military applications in radar and communications.

B. Power

What can we expect in the future of power applications of superconductivity? The LTSs, Nb–Ti and Nb_3Sn, are in a highly developed state and can be expected to continue to play important roles in high-power applications. And the field of HTS power devices, which started upon the discovery of the HTS materials in the late 1980s, has been developing strongly. These new materials offer help in meeting the need for greater efficiency, and new HTS components for the electric power grid, including electric generators, are being developed. There are also HTS opportunities in transportation such as more efficient motors and train levitation.

Some of these applications will lead to commercial products that can feed back funding for R&D. Motors and generators, fault current limiters in power systems, train levitation, and the materials for these applications show near-term potential for commerce. But there are other applications that will continue to require government support, including high-energy physics, high magnetic field research, power transmission, and military applications.

One captivating example of a large-scale application is the 370-mi/h superconducting levitated train that will carry passengers from Osaka to Tokyo in 67 min. It was initiated in 2011 by the Central Japan Railway as a privately funded project. The construction phase will start in 2014 and it should be finished by 2045.

IV. SUMMARY

We have seen that there are advantageous, unique applications of superconductivity that are already in use and others that will be realized in the coming years and decades. The quantum nature of superconductivity that fascinated many of us in the 1960s continues to lead to new inventions in electronics. And the remarkable current carrying properties of superconductors, including the *high-temperature* materials, will continue to lead to new, more efficient power applications. ■