Scanning the Issue

Special Issue on Applications of Superconductivity

The purpose of this special issue is to give an assessment of the existing and potential applications of superconductivity. The last special issue of the PROCEEDINGS OF THE IEEE on superconductivity was in October 1989; the field has changed dramatically since that time, both in electronics and large-scale applications.

I. HISTORY OF SUPERCONDUCTIVITY

The phenomenon of zero resistance at low cryogenic temperatures was discovered in 1911 by Prof. H. K. Onnes in the Netherlands in the course of studying the low-temperature properties of metals. He tried and failed to make an electromagnet of lead wire, and it was not until 1961 that the method to make superconducting materials for successful high-field magnets was discovered. Meanwhile, in 1933, another important property of superconductors was discovered experimentally by W. Meissner and R. Ochsenfeld; they found that superconductors have the tendency to exclude magnetic field. A certain class of superconductors, called Type I, can almost completely exclude magnetic field and, therefore, have almost perfect diamagnetic properties.

Guided by the zero resistance and diamagnetism, a theory was developed by F. London and H. London. Even today, the London theory is used extensively in applied superconductor electronics where magnetic fields are weak. This theory assumed a function $\Psi(r)$ representing the superconducting electron fluid that can be thought of as a single giant quantum mechanical wave function that extends throughout the superconductor. It also revealed that magnetic flux is quantized inside superconducting loops. It was later shown that the quantum of magnetic field has the value $\Phi_0 = 2e/h$, where e is the electron charge and h is Planck's constant.

In 1950, G. L. Ginzburg and L. Landau published a theory that was also phenomenologically based but, unlike the London theory, is useful for situations with strong magnetic fields, such as in the large-scale applications.

The concept of electron pairing was introduced in 1956 by L. N. Cooper. The electrons are paired in "momentum space," and are known as Cooper pairs. In 1957, J. Bardeen, J. R. Schrieffer, and L. N. Cooper (BCS) published a microscopic theory of superconductors based on the concept of electron pairing in momentum space. It had been 46 years between the original experimental demonstration of superconductivity and a first-principles theory. With this new understanding, B. Josephson developed a theory for quantum mechanical tunneling between superconductors, in which electron pairs can pass through a thin insulator from one superconductor to the other, even with zero applied voltage. The so-called Josephson effects, combined with low electromagnetic loss, underlie today's electronic applications.

During the period up to 1973, numerous metallic materials were found to have superconducting transition temperatures T_c up to 23.2 K. Today these materials are referred to as low-temperature superconductors (LTSs). In 1986, certain oxide-based materials were shown by J. G. Bednorz and K. A. Müller to be superconducting up to appreciably higher temperatures, with T_cs up to 35 K. This was quickly followed by demonstrations early in 1987 of materials with T_cs of about 90 K, for which cheap and easily available liquid nitrogen could serve as the refrigerant, since it boils at 77 K at sea level. The materials with T_cs above 23 K are collectively called high-temperature superconductors (HTSs). Materials research on HTSs since 1987 has led to excellent thin films suitable for filter applications and to wires that are becoming increasingly useful for large-scale applications. Only small circuits using HTS Josephson junctions have been made. More research is needed to find a way to make sufficiently controllable junctions for complex circuits.

This special issue is divided into two parts, electronics and large-scale applications. Since the phenomena of superconductivity are not familiar to many of the readers, we will give some introduction.

II. ELECTRONICS

A. *Superconductor Phenomena for Electronics Applications*

Although there were some programs in electronic applications of superconductivity that predated the discovery of the Josephson tunneling in 1963, this new development produced a major burst of activity in both analog and digital circuits. We give here a brief introduction to Josephson junctions. The physical structure of a Josephson junction is a trilayer made of two superconductors separated by a weak

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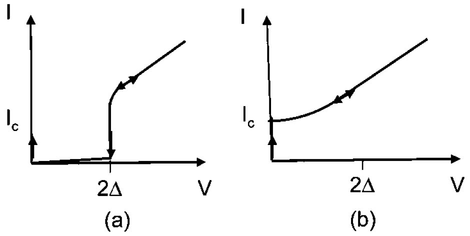

Fig. 1. (a) Hysteretic *I–V* characteristic of an insulating-barrier Josephson junction. (b) Nonhysteretic *I–V* characteristic of a conducting-barrier Josephson junction.

connection that allows overlap of the electron-pair quantum mechanical wave functions in the two superconductors. The most common form is composed of two thin films separated by a thin (typically 1 nm) insulator. The most highly developed type employs niobium films with a layer of aluminum oxide between them. The fabrication starts with a deposition of a base niobium film of about 100–150-nm thickness. While still in a vacuum chamber, an 8-nm layer of aluminum is deposited and then partially oxidized to form a 1-nm layer of aluminum oxide. Then, the niobium counter-electrode of about 60-nm thickness is deposited to complete the trilayer, which is subsequently etched to form individual junctions with linear dimensions typically of 1–3 μm. The *I–V* characteristic of such a junction is shown in Fig. 1(a). If a dc current is supplied to the junction and slowly raised from zero, it follows a path up the zero-voltage axis as shown by arrows. One result of the Josephson theory is that electron pairs can tunnel through the insulator barrier with zero voltage across the junction until a certain current called the critical current (I_c) is reached. Depending on the application, I_c may be as small as 1 μA or as large as a few milliamperes; the current is determined by the thickness of the oxide and the area of the junction. If the current is further increased, the electron-pair current cannot be sustained and further increases of the current must be carried by single electrons with a voltage across the junction. This is shown as the other branch of the *I–V* characteristic located at and beyond the voltage 2Δ (about 2.8 mV). The quantity Δ is referred to as the energy gap of the superconductor, and 2Δ is the energy required to break apart an electron pair. Upon lowering the current, a path down along the single-electron part of the characteristic is followed. This kind of characteristic is referred to as hysteretic, since the current lowering path is different from the current raising path.

If the layer between the superconductor films is a conductor rather than an insulator, the resulting *I–V* characteristic can be that shown in Fig. 1(b). This type of characteristic is required for many applications; but the tunnel junction technology is so much more highly developed than that for conducting barrier junctions, it is usual today to obtain the *I–V* characteristic in Fig. 1(b) by connecting an external shunt resistor across the tunnel junction. This type of *I–V* characteristic is referred to as nonhysteretic, since raising and lowering the current follows the same path, as seen by the arrows in Fig. 1(b).

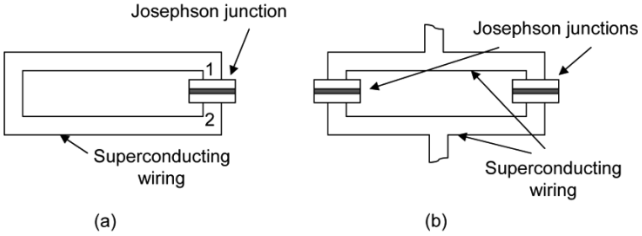

Fig. 2. (a) One-junction (RF) SQUID. (b) Two-junction (dc) SQUID.

The current state of the technology is that the vast majority of Josephson junctions are made with niobium, the transition temperature of which is 9.2 K. The temperature dependence of the junction properties dictates that operation should be less than one-half to two-thirds of T_c, so operation with liquid helium, which boils at sea level at 4.2 K, is appropriate. Similar junctions can also be made using niobium nitride (or niobium titanium nitride) electrodes; its higher T_c allows operation at 8–10 K. This represents a significant advantage with regard to the refrigeration, but the technology is not so highly developed. It also has been possible to make Josephson junctions using the complex HTS materials, and *I–V* characteristics of the type in Fig. 1(b) have resulted. The control of critical currents is not as good as those made with LTS materials. Small HTS digital circuits have been demonstrated, but the spread of I_c values is still too great to make successful complex circuits.

Another component that plays an important role in electronics applications is the superconducting quantum interference device (SQUID). It consists of a loop of superconductor, usually a thin film, intercepted by one or more Josephson junctions as shown in Fig. 2. We mentioned earlier that the electrons form pairs in the superconducting state and the paired state can be represented by a constant-amplitude phase-coherent wave function that extends throughout the superconducting body. This wave function can be visualized as being like and electromagnetic wave in a waveguide. The phase at point 1 in Fig. 2(a) is related to the phase at point 2, and the difference of the two phases depends on the magnetic field linking the loop. The difference of phase across the Josephson junction determines the current through it. The two-junction SQUID in Fig. 2(b) is a more common form; the principle is similar to that just described for the one-junction SQUID. Such SQUIDs play roles as temporary data storage devices in digital circuits and as sensitive magnetic field detectors in magnetometer applications.

B. Applications

We open the issue with integrated circuit fabrication, the foundation for progress in electronics applications. The first paper, “Superconductor Integrated Circuit Fabrication Technology,” by L. A. Abelson and G. L. Kerber, gives a review of fabrication processes in use in several laboratories and an in-depth analysis of the process used at Northrop Grumman Space Technology. They developed a highly optimized process for the niobium tunnel junction technology using statistical techniques employed in semiconductor IC process lines. The authors include a discussion of the state of NbN junction development, as well the prospects for higher temperature materials.

SQUID devices have long been the best technology for detection of extremely weak magnetic fields, down to 11 orders of magnitude below the earth's magnetic field. The sensitivities are even sufficient to observe fields generated by the human brain that are measured outside the skull. This forms the basis of one of the present important applications, magnetoencephlography. The paper "Superconducting Quantum Interference Devices: State-of-the-Art and Applications," by R. Kleiner, D. Koelle, F. Ludwig, and J. Clarke, gives an outline of the theory, fabrication, device properties, and performance of SQUIDs and reviews applications in science, engineering, and medicine.

The early Josephson digital applications from about 1967 to 1990 used the two states of a Josephson junction represented by points in Fig. 1(a) on the zero-voltage axis and on the single-electron branch to represent zero and one, but these so-called voltage-state circuits have been mostly replaced by ones based on the manipulation of single quanta of magnetic flux. The project at IBM in the early period, and those in Japan, mainly in the 1980s, employed voltage-state circuits. The prevalence of single-flux quantum circuits grew during the 1990s. Several families of single-flux-quantum circuits have been invented; the most highly developed and widespread logic family is called RSFQ, for Rapid Single-Flux Quantum logic. Simple RSFQ circuits have been operated at several hundred gigahertz and numerous larger circuits have been operated at several tens of gigahertz. These circuits not only offer ultrahigh throughput but also extremely low on-chip power dissipation. This performance is tantalizing for ultrahigh performance routers and computer systems. In this special issue, the paper "Superconducting Digital Electronics," by H. Hayakawa, N. Yoshikawa, S. Yorozu, and A. Fujimaki, reviews the design techniques and tools for digital integrated circuits and the applications of single-flux-quantum circuits in proposed large-scale systems.

A key component of a high-speed communications system is the analog-to-digital (A/D) converter. They appear in many systems; a new thrust is to perform the A/D conversion closer to the antenna at RF frequencies and then to process the signals digitally. This requires ultrafast sampling and large dynamic range. The single-flux quantum circuits allow extremely fast switching, natural quantization, quantum accuracy, and low noise, all at low power. The two classes of A/D converter, Nyquist sampling and oversampling, are discussed in the paper "Superconductor Analog-to-Digital Converters," by O. A. Mukhanov, D. Gupta, A. M. Kadin, and V. K. Semenov.

Today, the main role of HTS materials in electronics applications is as thin-film microwave filters that are used in cellular base station receivers. HTS filters with many poles and low losses make feasible filters with very sharp band edges and low insertion loss. The use of HTS materials allows operation in the 60–80 K range and the cooling can be accomplished by a very compact refrigerator. This superconductor electronics application can make significant system improvements and comprises one of the largest commercial markets. The filter fabrication, their characteristics, and the packaging into a commercial unit are covered in the paper in this special issue entitled "Superconducting Microwave Filter Systems for Cellular Telephone Base Stations," by R. Simon, R. B. Hammond, S. J. Berkowitz, and B. A. Willemsen.

One application that employs junctions having the same construction as the Josephson tunnel junction but does not use the Josephson effect is millimeter-wave detection and mixing. In this application, the Josephson current must be suppressed to avoid noise degradation and the device is called a superconductor–insulator–superconductor (SIS) junction. The extremely sharp discontinuity of the *I–V* characteristic at the voltage 2Δ originally attracted attention for mixing and detection because, in classical devices, the sensitivity increases with curvature of the *I–V* characteristic at the operating point. A quantum mechanical theory was developed and it was found that mixers of this kind also have gain, unlike classical mixers. Recent developments in superconducting bolometers have heightened their usefulness at millimeter and submillimeter wavelengths. The cosmological motivation for interest in radiation at these wavelengths, the physics of the devices, and array technology are among the topics discussed in the paper in this special issue called "Superconducting Detectors and Mixers for Millimeter and Submillimeter Astrophysics," by J. Zmuidzinas and P. L. Richards.

One of the long-standing applications of the Josephson effect makes use of the fact that RF current at a frequency $f_J = (2e/h)$ V flows through a junction with a dc voltage V applied across it. Because there is a relationship between voltage and frequency involving only fundamental constants, and frequency can be measured with great precision, the Josephson device has been used as a voltage standard since 1972. There have been major advances in the technology since then and, today, the Josephson junction is the basis for primary volt standards around the world. Recent research has been directed toward using ideas from digital signal processing with single-flux quantum pulses to develop an ac volt standard. The current status of volt standards and a review of the concepts underlying dc and ac Josephson volt standards are presented by S. P. Benz and C. A. Hamilton in "Application of the Josephson Effect to Voltage Metrology" in this issue.

Quantum computing is an active current research topic for which superconducting devices are contenders. A fundamental requirement for gates comprising a quantum computer is that they must be able to remain in a preset quantum state long enough for a computation to be made. It is generally agreed that in order to scale up to the large numbers of gates needed for significant computation, solid-state devices of some kind must be used. In order for the state of a quantum gate to remain coherent for a long enough time, noise must be kept to a minimum so experiments are being done at temperatures in the millikelvin range. Deep cryogenic temperatures are needed so the use of superconductivity is natural. K. K. Berggren surveys the current work and the challenges in "Quantum Computing with Superconductors" in this issue.

III. LARGE-SCALE APPLICATIONS

A. Superconducting Phenomenon for Large-Scale Applications

A second type of superconductor, one that remains superconducting even as magnetic field penetrates the bulk of the material, was reported in the same year as the publication of the BCS theory (1957). This type of material is generally referred to as a type II material. Perhaps the simplest type II material is pure niobium. Though wires made of pure niobium can support a transport current in a magnetic field, their current carrying capacity is negligible for most practical applications because the magnetic flux freely penetrates the pure material at any location. When the current is high enough, the Lorentz force between it and the flux causes the flux to move across the superconductor and thereby induce a voltage drop along the superconductor. Practical superconductors for large-scale applications are type II materials with the feature that the magnetic flux is pinned within the atomic structure. These sources of pinning are referred to as pinning centers, and they can be part of the inherent structure of the material, as in the case of the compound Nb_3Sn or in irregularities in material distribution in alloys such as Nb–Ti. In addition, artificial pinning centers can be added to some superconductors to improve their performance.

The effect of the pinning centers is to allow a material to carry a significant current at an elevated magnetic field. Taking Nb–Ti as an example, a great deal of this material was produced for high-energy physics detectors in the late 1960s. That material could support a current of about 700 A/mm^2 in a field of 5 T at a temperature of 4.2 K. Today the conductors made with the same material can support over 3000 A/mm^2. Most of the improvement is because the pinning centers are more effective. It is significant that at zero current the critical field and critical temperature of Nb-Ti have not changed at all in this same period.

In addition to having pinning centers, most superconducting materials for large-scale applications must be subdivided into filaments which are stable against thermal variations and subsequent thermal runaway or "quench." The most frequently used approach is to embed small-diameter filaments of superconductor in a normal conductor such as copper (for LTS materials) or silver (for HTS materials) and to make a conductor of one or more strands of the resulting wire. Fig. 3 shows a Rutherford cable (named after Rutherford Laboratory in the United Kingdom, where the structure was first developed) that was part of the prototyping effort for the superconducting supercollider in the late 1980s.

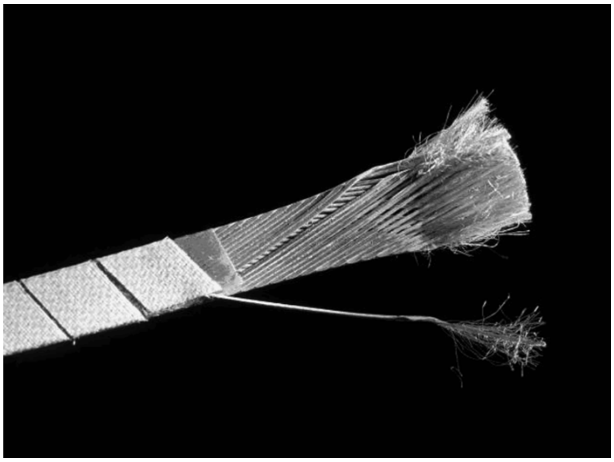

Fig. 3. Sample of SSC prototype cable consisting of 30 wires of 0.8-mm diameter. Each wire or strand is made of copper with approximately 2000 Nb–Ti filaments, each with a diameter of about 5 μm. The tiny filaments are shown at the ends of the wires where the copper has been etched away. Two types of insulation are wrapped on the cable. They not only electrically insulate the cable, but they are devised to allow helium to penetrate the conductor to limit local temperature variations.

B. Applications

Prior to 1960, superconductors were for the most part a laboratory curiosity. The discovery at the beginning of that decade of Nb_3Sn and Nb-Ti with transition temperatures of 18 and 9 K, respectively, and with the ability to sustain high current densities in high magnetic fields enabled the construction of dc magnets with fields of 10 T and greater. Wires made from these materials have been chosen for virtually all superconducting magnets up to the beginning of the 21st century. In 1987, however, the prospects for new and potentially better materials appeared with the discovery of a family of layered cuprate superconductors with transition temperatures reaching nearly 135 K. Ideally, such materials would allow magnet operation in liquid nitrogen rather than liquid helium. Unfortunately, fabricating practical conductors from these materials has proved to be a significant challenge. More recently, another superconductor, MgB_2, was found with an intermediate transition temperature of 39 K. It seems to be more amenable to wire fabrication than the cuprates, but will require cooling well below the temperature of liquid nitrogen.

The first large-scale paper, "Superconducting Materials for Large-Scale Applications," by R. M. Scanlan, A. P. Malozemoff, and D. C. Larbalestier, presents several aspects of conductors made of all these superconductors. It addresses the inherent characteristics of the superconductors themselves, and then describes the fabrication procedures used to achieve significant current-carrying capabilities in wires and tapes and explains how the end use of the applications affects design choices in materials and conductor design.

From the original discovery of superconductivity, there have been dreams of improving the operation of electric power equipment by the use of a lossless material to conduct electricity. Thus, it is no surprise to hear that the Korean initiative in superconductivity for power applications is named "Dream of Advanced Power System by Applied Superconductivity Technologies" (DAPAS). The need for liquid helium for Nb-Ti and Nb_3Sn was a limitation for superconducting technologies prior to the discovery of the high-temperature, cuprate superconductors. The paper

"Electric Power Applications of Superconductivity," by W. V. Hassenzahl, D. Hazelton, B. Johnson, P. Komarek, M. Noe, and C. Reis, discusses the rationale for the development of superconducting systems for electric power, such as improved efficiency, smaller size, and reduced weight. Several studies mentioned in the paper address the ways in which superconducting power components can also contribute to improved power quality and increased system reliability. It describes historical developments and the technology status of four superconducting power applications: cables, superconducting magnetic energy storage (SMES), fault-current limiters, and transformers. One conclusion is that superconducting technologies will first enter the market as: 1) upgrade replacements based on better performance in an envelope defined by the size and weight of existing devices and 2) in locations where their specialized performance will provide a functional solution unavailable with conventional devices.

In addition to the references in this paper, there are ancillary issues that have been addressed by organizations such as the International Energy Agency, which is concerned with the extensive CO_2 savings that are possible with HTS superconducting devices, and the potential market size. Dr. Wolsky of Argonne National Laboratory is preparing a paper on this topic.

Perhaps the most familiar large-scale application of superconductors is in the production of magnetic fields. The paper "Superconducting Magnets and Their Applications," by S. A. Gourlay, G. L. Sabbi, F. Kircher, N. Martovetsky, and D. Ketchen, describes several of the most significant of these applications. Technologies described include magnets for accelerators that have circumferences of 10s of kilometers, detector magnets that are tens of meters in circumference, containment magnets for fusion research, and magnets for levitation. The field is much greater than can be described in the available space. For example, many of the hospitals in industrialized countries have magnetic resonance imaging devices, which use magnets that are large enough for patient access and produce fields of 0.5 to 3 T. Other magnets not described are used for the separation of impurities in a variety of industrial processes. In addition, many research laboratories now use small superconducting magnets that deliver fields of up to 16 T for measurements of a variety of physical characteristics.

All but a tiny fraction of the electricity used today is produced by rotating electrical machines (generators) that convert mechanical energy into electrical energy. Somewhat over 50% of that electrical energy is converted back into mechanical energy by other rotating machines (motors). The total electricity generating capacity in the United States is about 9×10^{10} W and, on the average, these plants operate 50% of the time. In addition, there are generators and motors on ships, automobiles, airplanes, etc. Design improvements and material developments during the past century allowed rotating machines to increase in power capacity, size, and efficiency. Characteristics of practical superconductors, such as increased current density and the production of magnetic fields higher than possible in iron-based machines will allow further improvements of rotating electrical machinery. Specific areas where we can expect improvements are higher efficiency and smaller and more compact devices.

The paper "Development Status of Rotating Machines Employing Superconducting Field Windings," by S. S. Kalsi, K. Weeber, H. Takesue, C. Lewis, H. W Neumueller, and R. D. Blaugher, reviews the present status of one class of rotating machines, those that use superconducting field windings. These windings are part of the rotor and carry a dc current that produces a magnetic field that also rotates. As with conventional rotating electrical machinery, these devices can be designed to be generators or motors, and in some cases both. Many challenges still exist before this technology will be commercially widespread. The two most significant are cost and the issues associated with penetration of a new technology into one that seems to function quite well. There are however, several model demonstrations in place and others planned for the near future.

In addition to the machines described in this paper, there are other types of rotating machines and superconductivity can provide advantages to some of them as well. In particular, a superconducting homopolar motor, which has stationary field coils, will have weight and size advantages compared to the devices described in this paper. However, their use is somewhat restricted because they use direct current and operate at relatively low voltage. Thus, either ac must be converted to dc or the generator must be relatively close. One case of interest is onboard ships where they can operate at low revolutions per minute and provide direct drive to propellers, thereby avoiding a complicated and heavy gearbox.

Superconductors are generally chosen for electrical power devices because they can sustain higher current densities or have lower losses than equivalent devices that use conventional conductors. The paper "Applications of Bulk High-Temperature Superconductors," by J. R. Hull and M. Murakami, discusses bulk superconductors that instead of being fabricated in the form of wires, are either large, single-grain blocks or are sintered structures. These materials can operate in three distinct modes: they exclude flux, they trap flux, or they carry a current in much the same way as a superconducting wire or tape. It is only with the advent of high-temperature superconductors, however, that flux trapping or flux exclusion has become a practical component of several applications. In particular, bulk superconductors in combination with permanent magnets provide bearings for rotating machines with lower losses than any other technology. In addition, their nonlinear properties may provide the key to limiting fault currents in the ever-expanding electrical grid.

IV. REFRIGERATION

A key component of any electronic or large-scale application of superconductivity is the cryocooler that removes heat at the cryogenic operating temperature. In a paper in this issue entitled "Refrigeration for Superconductors," R. Radebaugh discusses the operating principles and availability of various kinds of cryocoolers for the range of cryogenic temperatures used or proposed for superconductor applications. Important aspects such as efficiency, reliability, cost, size, and mass of the available cryocoolers are surveyed. Continual improvements of reliability, efficiency, and size of cryocoolers will encourage acceptability of superconductor applications in the coming years.

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He has been on the faculty in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley, since 1961, where he initiated research in applications of superconductivity in 1968. He is currently a Professor in the Graduate School. He was one of the founding Scientific Advisory Board Members of the superconductor startup Conductus, Inc., which is now a part of Superconductor Technologies, Inc. He is Coauthor of two textbooks, *Principles of Superconductive Devices and Circuits* (with C. W. Turner) and *Fields and Waves in Communication Electronics* (with S. Ramo and J. R. Whinnery) and has published more than 200 papers in the research literature, with most on superconductor electronics. He is currently on the Editorial Board of the *IEICE Transactions on Electronics*. His current research interests focus on advanced Josephson devices and multigigahertz digital superconductor circuits, including hybrids with cryogenic semiconductor components.

Dr. Van Duzer is a Member of the U.S. National Academy of Engineering. He was awarded the Berkeley Citation and the IEEE/CSC Award for Significant and Continuing Contributions to Applied Superconductivity. The best paper award for the IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY has been designated the Van Duzer Award by the IEEE Council on Superconductivity. He was the first Distinguished Lecturer for the IEEE Council on Superconductivity. He was the Guest Editor of special issues of the PROCEEDINGS OF THE IEEE in 1973 and 1989 and of the IEEE TRANSACTIONS ON ELECTRON DEVICES in 1980. He was founding Editor-in-Chief of the IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY in 1991. He is currently on the Editorial Boards of the PROCEEDINGS OF THE IEEE and the IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, and is on the organizing boards of several conferences.

William V. Hassenzahl (Member, IEEE) was born in Fort Smith, AR, on July 11, 1940. He received the B.S. degree in physics and electrical engineering from the California Institute of Technology, Pasadena, in 1962 and the M.S. and Ph.D. degrees in physics from the University of Illinois, Urbana-Champaign, in 1967.

He was with the Lawrence Berkeley National and the Lawrence Livermore National Laboratories from 1980 to 1993 and with the Los Alamos Scientific Laboratory from 1967 to 1980. He is currently the President of Advanced Energy Analysis, Piedmont, CA, a consulting firm in the areas of electric power and applied physics. His publications include over 200 technical papers and two books on energy storage. He has participated in the development of several superconducting magnets and other superconducting systems, and he is active in the research on medical systems using superconductivity. He was recently the Editor of a series of articles on the applications of superconductivity in the *Power Engineering Review*.

Dr. Hassenzahl is a Member of the IEEE Council on Superconductivity, where he represents the Power Engineering Society. He is a Member of several IEEE societies. He is a Chairman of the Board of Directors of the Electricity Storage Association.