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RESEARCH AND DEVELOPMENT OF SUPERCONDUCTIVITY IN THE U.S.A.

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INTRODUCTION

It is a great honor for me to be invited to give this address at the 25th anniversary lecture of the Metal Mining Agency of Japan. I wish to thank the President, Dr. Junichiro Sato, for his kind invitation. I am also grateful to the Japan Economic Foundation for their generous sponsorship of my visit to Japan.

The recent discovery by Bednorz and Müller of superconductivity at about 30K in a ceramic sample containing lanthanum, barium, copper and oxygen and the subsequent identification of the superconducting phase as La$_{2-x}$Ba$_x$CuO$_{4-y}$ by Tanaka and coworkers at the University of Tokyo created an unprecedented storm of activity in the physics, chemistry, and materials science communities. Very soon afterwards, Chu and coworkers at the University of Texas discovered superconductivity at about 95K in YBa$_2$Cu$_3$O$_{7-\delta}$. In January of this year Maeda and his group at the National Research Institute for Metals discovered superconductivity up to 105K in Bi-Sr-Ca-Cu-O, and the following month the present record of 125K was established in Tl-Ba-Ca-Cu-O. These high-\(T_c\) superconductors are being studied by thousands of scientists around the world, and many years of exciting basic research undoubtedly lie ahead. Even the basic mechanism for the formation of Cooper pairs...
which give rise to superconductivity in these materials is not understood at all, and much theoretical effort is needed to explain the origins of high-$T_c$ superconductivity.

At the earliest stages of the breakthroughs in superconductivity there was a great deal of publicity in the news media. Much of the attention was directed towards perceived applications of the new materials -- from ultrafast computers and ultrasensitive detectors of magnetic fields to levitated cars and loss-free transmission of electrical power. In this address, I have decided to focus my attention on the present and potential applications of superconductors -- both the classic "low-$T_c$" superconductors such as niobium and its alloys and the new high-$T_c$ materials. This discussions falls naturally into two broad areas: "large scale" applications such as large magnets and power generators, and "small scale" applications such as ultrasensitive detectors of electromagnetic radiation and of tiny magnetic fields. I shall talk about these two areas in turn.

**LARGE SCALE APPLICATIONS**

The single most important breakthrough for large scale applications was the discovery of Type II superconductivity in 1960. The two most useful of these materials are NbTi and Nb$_3$Sn, and their important properties are summarized in Table I.\(^1\) A very successful industry has been built on NbTi; Nb$_3$Sn is much more difficult to handle, and finds limited application. All of the applications of these materials involve operation at liquid $^4$He temperatures, usually at the boiling point of liquid $^4$He, 4.2K. In the case of YBa$_2$Cu$_3$O$_{7-\delta}$ (see Table I), the transition temperature and
critical field are obviously much higher than in the Nb-based materials, but the critical current density of bulk, ceramic material is much lower, perhaps $10^2$-$10^3$ A/cm$^2$. Furthermore, the materials are very brittle, and producing wires that can be wound into magnets is not straightforward. Of course, strenuous efforts are being made in the U.S., Japan and many other countries to develop materials that have both higher ductility and higher critical current densities, and one can hope for great progress to be made in the next few years.

I will now give a brief overview of some of the large scale superconducting systems that have been built and operated in the U.S. From a commercial point of view, by far the most important and successful application has been the use of NbTi magnets in magnetic resonance imaging (MRI). Peak magnetic fields are below 2.5T, and the required critical current density is low, so that NbTi at 4.2K can easily serve as the wire. At this point more than 1000 medical MRI systems have been installed worldwide in hospitals and clinics. It is expected about about 500 more will be added in 1988. In these systems, by an ingenious combination of scanning magnetic field gradients and radio frequency excitation one can obtain a nuclear magnetic resonance image of almost any portion of the human body. This noninvasive technique has become a very powerful diagnostic tool for pathologies ranging from multiple sclerosis to torn knee ligaments.

Current production MRI magnets are horizontal solenoids with an inner diameter of 1 m, an outer diameter of 2 m and a length of 3 m. They consume typically 0.25 liters/hour of liquid $^4$He and 1 liter/hour of liquid $N_2$. The helium is replenished every 4 weeks and the nitrogen every 2 weeks. Some systems involve a small, closed-cycle refrigerator
that eliminates the need for liquid N$_2$, and reduces the liquid $^4$He consumption to 0.1 liters/hour or less. Many MRI systems are operated as "Mobile Imaging Centers". These vans travel between several hospitals or clinics each of which is too small to support a system of its own. These systems have proved to be exceedingly reliable in practice.

The next most important application of low-$T_c$ superconductors has been in particle accelerators, notably in the Tevatron at the Fermi National Laboratory. This facility contains over 1000 superconducting magnets, and has operated successfully since 1983. The magnets are cooled by liquid $^4$He produced by an array of closed cycle refrigerators. The proposed Superconducting Super Collider (SSC) will employ about 10,000 superconducting magnets, operated at 4.35K, and is designed to produce 20 TeV protons. The ring, more than 80 km in circumference, is to be divided into 10 segments, each serviced by a refrigerator with a capacity of about 7.5 kW at 4.35K; an eleventh refrigerator services the injector. Two types of magnet are involved: dipole magnets to guide the protons in the required orbit, and quadrupole magnets to focus them. The design for the dipole magnets specifies a field of 6.6 tesla, produced by 6.5 kA in a NbTi coil. Each magnet is 17 m long. The heat leak into the 17 m-long magnet is very low, less than 0.2 W. If the SSC is ever built, it will be by far the largest cryogenic installation in the world.

Another very large scale prototype set of magnets has been built by Westinghouse. These magnets are for plasma fusion research at Oakridge National Laboratory, and each has an aperture of approximately 3 m × 2.5 m. Five of these were wound from NbTi and one
from Nb$_3$Sn; the latter has been tested to 8.8 tesla.\textsuperscript{4} Westinghouse has also produced a demonstration 10 MVA electrical power generator with a superconducting rotor using NbTi wire. This generator functioned perfectly the first time it was operated.\textsuperscript{4} These two very different systems illustrate the highly developed state of the art of low-$T_c$ superconducting coils.

A quite different application\textsuperscript{2} is the use of a superconducting magnet in a processing plant in Georgia for the magnetic separation (that is, purification) of Kaolin clay for the paper industry. This system has been very successful, and a second system is now on order.

One other potentially important application of superconducting magnets is in high-speed levitated trains. Although there was much interest in the subject in the U.S. during the 1970's, there is currently no work in this field. To my knowledge, the only existing prototype train of this kind is in Japan.

In any of these applications, high-$T_c$ superconducting wire could be substituted for NbTi or Nb$_3$Sn provided that such wire can be fabricated and provided it has a sufficiently high critical current density. Both of these barriers look formidable at present. For example, a panel chaired by Albert Narath of AT&T Bell Laboratories to study the application of high-$T_c$ superconductivity to the SSC reckoned under optimistic conditions "it would take 4 years to develop processes to make continuous lengths of 5-10 $\mu$m diameter superconducting wire with appropriate mechanical properties. Another 8 years would be needed to develop winding techniques for building prototype magnets."\textsuperscript{5}

Furthermore, one should not overestimate the cost savings: refrigeration accounts for only a small fraction of the total cost.
Part of the savings of operating at 77K rather than at 4.35K might be offset by the loss of the cryopumping effect of the $^4$He-cooled line, so that larger vacuum pumps would be needed. Thus, one may summarize by saying that if one could use liquid N$_2$-cooling rather than liquid He-cooling in any of the large scale applications one obviously would do so, but the cost savings are likely to be a relatively small percentage of the total cost. The decision to build any of these large systems is unlikely to depend on whether one uses liquid N$_2$ or liquid He. Of course, superconductors with $T_c > 400K$ (say) that could be operated at room temperature would change one's thinking entirely!

**SMALL SCALE APPLICATIONS**

In the second half of this address I shall make some remarks about superconducting electronics. This field started in the early 1960's, having received a considerable boost from the advent of Josephson tunneling. At this stage of development, a small number of devices have emerged that are better than the competing technologies, and that are used very successfully in an intriguing number of applications ranging from radio astronomy to the measurement of tiny magnetic fields emanating from the human brain.

I begin with some comments on the Josephson effect. A Josephson tunnel junction consists of two superconductors separated by an insulating barrier [Fig. 1(a)]. A practical Josephson tunnel junction using conventional superconductors is shown in Fig. 1(b). A thin film of a superconducting material, for example niobium, is deposited on an insulating substrate and an oxide layer typically 20-30 A thick is grown on it. This barrier may be formed in several ways, for example,
by thermal oxidation of the superconductor or by the deposition and subsequent oxidation of aluminum. A second superconducting film is deposited to cross the first film, thus forming the tunnel junction. Modern photolithographic techniques are routinely used to produce junctions 1-2 μm across, the area of the junction often being defined by a window in a thick insulating layer such as SiO. Electron-beam lithography can produce junctions with areas as small as 10^{-2} μm² or even less. A very high degree of reproducibility and reliability has been achieved in the fabrication of junctions from niobium, particularly in Japan.

When the junction is cooled well below the transition temperature of the superconductors, one obtains the current-voltage (I-V) characteristic illustrated in Fig. 1(c). As the current is increased from zero, initially no voltage appears: this is the dc Josephson effect. When I exceeds the critical current, I₀, however, the voltage switches abruptly to approximately 2Δ/e, where Δ is the energy gap. As we increase and subsequently decrease the current a hysteretic I-V characteristic is traced out. This hysteretic behavior forms the basis of computer memory and logic devices, but must be eliminated for certain other devices, notably SQUIDs. The nonhysteretic characteristic shown in Fig. 1(d) is obtained by shunting the junction with a thin normal film of sufficiently low resistance.

Unfortunately, it is not trivial to extend the existing Josephson junction technology to a material such as YBCO. One problem is the difficulty of maintaining the integrity of a thin insulating barrier during the processing of the counter-electrode at (say) 650°C. A second problem is the fact that the surface layers of YBCO appear to be
nonsuperconducting. Substantial efforts are already underway to attempt to circumvent these problems.

Finally, Fig. 1(e) shows a quite different type of junction, the Anderson-Dayem bridge. The bridge is itself superconducting, but with a sufficiently small cross-section that it can sustain only a tiny supercurrent. This structure exhibits Josephson-like behavior with an I-V characteristic something like that in Fig. 1(d) provided the length of the bridge is no greater than the coherence length $\xi$, which is, roughly speaking, the spatial extent of a Cooper pair. In a low temperature superconductor such as Nb $\xi$ is of the order of 100 nm, a dimension that can be achieved with modern lithographic techniques. In YBCO, on the other hand, $\xi$ is estimated to be rather less than or somewhat greater than 1 nm, depending on the crystalline orientation, and it has (so far) been impracticable to produce structures of this size.

Oversimplifying somewhat, we can conveniently divide the field of small scale electronics into three broad categories, indicated schematically in Fig. 2.6 First, the input signal and its accompanying noise are fed into an analog detector: this signal could be anything from the 100 GHz signal from a radiotelescope to the 1 Hz signal from a human brain. The second stage of processing generally also involves analog devices: for example, the bandwidth of the amplified signal might be narrowed to reduce the noise. Finally, most systems today involve digital processing to produce the data in which we are interested. Substantial effort has been expended to develop logic and memory devices based on Josephson tunnel junctions for superconducting computers and, indeed, a cross-sectional module of a computer was
successfully demonstrated at IBM about 5 years ago. At present, however, the only substantial effort on 4.2K devices is in Japan.

Generally speaking, the important superconducting detectors are successful because they have lower noise than competing devices, and this advantage arises, at least in part, because they operate at low temperatures, say 4.2K. Operating the same devices at a higher temperature, say 77K, inevitably means that the noise will be increased. Thus, one can never expect the performance of superconducting detectors at 77K to match that at 4.2K, although a given device may still be useful if it is the quietest available at 77K. On the other hand, when one considers analog (or indeed digital) processing devices, the increase in noise does not necessarily degrade the performance.

The three most important devices in Fig. 2 are, in my view, the standard volt, the SIS mixer, and the Superconducting QUantum Interference Device (SQUID), and I will say a little about each.

The Josephson standard volt was one of the earliest applications of Josephson tunneling, and is the means by which most national standards laboratories maintain the volt. The principle is simple: when a high capacitance Josephson tunnel junction is irradiated with microwaves of frequency f, constant-voltage current steps are induced at voltages \( V = \frac{n \hbar f}{2e} \), where \( n \) is an integer, \( \hbar \) is Planck's constant and \( e \) is the electronic charge. For example, a frequency of 96 GHz corresponds to about 200 \( \mu V \) for \( n = 1 \). To facilitate comparison with other voltage standards, the modern Josephson standard, developed at NBS Boulder, PTB Berlin, and ETL Japan, consists of 1500 to 2000 junctions in series to produce a standard volt of around 1 volt. Since one can readily
determine frequency to extremely high accuracy, the Josephson junction provides a straightforward means of producing an accurate volt in any laboratory. Of course, the procedure would be simplified if the device were to operate at 77K. Again, there is a pressing need for a Josephson tunnel junction; nonhysteretic junctions could possibly be used, but their operation in an array would not be easy.

One of the major success stories of superconducting electronics is the SIS (superconductor-insulator-superconductor) tunnel junction mixer. Mixers of this kind are installed as receivers on a number of radio telescopes, working mostly at frequencies around 100 GHz, and are typically used to observe molecular lines.

A mixer combines a weak signal at frequency $f_s$ with the output from a local oscillator at frequency $f_{LO}$ to produce sum and difference frequencies $f_s \pm f_{LO}$. The difference frequency $f_s - f_{LO}$ is subsequently amplified by an intermediate frequency amplifier. The mixing process requires a sharp nonlinearity in the current-voltage characteristic, which in the case of the SIS mixer is found at the sharp rise in the current at a voltage $2\Delta/e$ [see Fig. 1(c)]. (In the SIS mixer, the Josephson current is suppressed with a magnetic field.) Carefully implemented, SIS mixers have useful levels of gain, and at 36 GHz have exhibited noise levels within a factor of 2 of the quantum limit. At frequencies up to several hundred gigahertz this mixer is the most sensitive detector available, and its continued success when operated at liquid $^4$He temperatures seems assured.

The most obvious problem in fabricating an SIS mixer from YBCO is the need for a tunnel junction with an exceedingly sharp rise in current at $V = 2\Delta/e$ [see Fig. 1(c)] combined with very low current
leakage at lower voltages. Given the difficulties with making any kind of high-$T_C$ tunnel junction, suitable junctions are unlikely to be available soon.

The most widely used superconducting device and one that has been commercially available for many years is the SQUID. The two varieties, dc and rf, are shown in Fig. 3. Of the two, the dc SQUID is more highly developed and more sensitive, while the rf SQUID is more widely used, largely because it has been commercially available for almost two decades. When the dc SQUID is biased with a constant current $I$, the voltage $V$ across it oscillates as a function of the applied flux $\phi$ with period $\phi_0 = h/2e = 2 \times 10^{-15}$ Wb. Using niobium-based thin-film technology several groups have produced relatively sophisticated devices, usually involving a thin-film "washer" design. An insulating layer is deposited over the SQUID, followed by a multiturn spiral coil of superconducting film through which the input current passes. This coil is coupled to the circuitry appropriate for a given application.

The rf SQUID [Fig. 3(b)] is coupled to a tuned circuit excited by a rf current, typically at 20 MHz; the amplitude of the rf voltage $V_{rf}$ is periodic in $\phi$. Commercially available rf SQUIDs consist of a toroidal body machined from niobium, inside which is a single Josephson junction. The input coil, wound from niobium wire, is placed in the toroidal cavity.

Both types of SQUID are flux-to-voltage transducers, producing an output voltage in response to a magnetic flux $\phi$. One usually operates them in a feedback circuit that produces an equal and opposite flux to cancel any applied flux, thereby linearizing the response of the SQUID.
and enabling one to detect changes in flux much less than $\phi_0$.

To assess the impact of higher operating temperatures on SQUIDs we need to characterize their resolution. The simplest way is in terms of the equivalent flux noise, which represents the smallest change in magnetic flux the SQUID can resolve. For example, the best dc SQUIDs in the liquid $^4$He temperature range can resolve a few $\mu\phi_0$ Hz$^{-1/2}$ at frequencies above the $1/f$ (flicker) noise region where the noise is white. A more useful means of characterizing the resolution is in terms of the flux noise energy per unit bandwidth, $\varepsilon = \langle \phi^2_N(f) \rangle / 2L$, where $\langle \phi^2_N(f) \rangle$ is the mean square flux noise per unit bandwidth and $L$ is the inductance of the SQUID. At 4.2 typical state-of-the-art thin film dc SQUIDs have noise energies in the range $(1-5) \times 10^{-32}$ JHz$^{-1}$ (or, 100-500 $\mu$), although values as low as a few $\mu$ have been achieved. Typical commercial dc SQUIDs, on the other hand, have noise energies around $10^{-30}$ JHz$^{-1}$ (10,000 $\mu$). Commercially available rf SQUIDs are somewhat less sensitive, with noise energies of about $10^{-29}$ JHz$^{-1}$ (100,000 $\mu$).

There are well developed theories for white noise in both the dc and rf SQUID, which enable one to predict the noise at 77K. Roughly speaking, the noise energy in the dc SQUID scales as the temperature, $T$, and that in the rf SQUID as $T^{4/3}$. Thus, we expect the noise in the dc SQUID to increase by a factor of about 18 in going from 4.2K to 77K, and that in the rf SQUID by about 50.

Both rf and dc SQUIDs were produced remarkably quickly after the discovery of superconductivity in YBCO in the U.S., Japan, and Europe. For example, Zimmerman and coworkers at the National Bureau of Standards in Boulder, Colorado produced the "break junction" SQUID. A
cylindrical pellet of YBCO with a hole drilled through and a slot cut part way along a radius as indicated was glued into an aluminum holder, and the whole assembly cooled to 77K. A taper pin was forced into the slot in the mount, thereby causing the YBCO to break in the region of the cut; when the pin was withdrawn slightly, the YBCO surfaces on the two sides of the crack were brought into contact, producing a junction. This technique allows one to break the YBCO under a liquid, and to bring together two uncontaminated surfaces. The rf SQUID so formed was coupled to a resonant circuit and operated in the usual way, with an output that oscillated smoothly as a function of magnetic field. The best magnetic flux resolution quoted (at 75K) is $4.5 \times 10^{-4}$ $\Phi_0$Hz$^{-1/2}$; using the estimated inductance of 0.25 nH, we find a noise energy of $1.6 \times 10^{-27}$ JHz$^{-1}$.

The first high-$T_c$ thin film dc SQUID was developed by Koch and coworkers$^{10}$ at IBM. YBCO films were evaporated onto MgO or sapphire substrates, and covered with a 0.5 $\mu$m-thick Au film which was patterned to leave covered the portions of the YBCO that were to remain superconducting. The films were ion-implanted with O$_2$ or As so that the unprotected regions of YBCO became insulating at low temperatures; the gold mask was removed by ion-milling. The two bridges so formed were 17 $\mu$m wide, and the loop was 40 $\mu$m x 40 $\mu$m, giving an estimated inductance of 80 pH. The critical current varied from about 150 $\mu$A at 4.2K to about 10 $\mu$A at 60K. It appears likely that the junctions were formed between superconducting grains in the bridges. Modulation of the critical current of the SQUID by an external magnetic field was observed at temperatures up to 68K; at 40K the measured flux noise was less than 1 m$\Phi_0$Hz$^{-1/2}$ at 100 Hz, limited by noise in the amplifier.
coupled to the SQUID. The corresponding noise energy was $2.5 \times 10^{-26}$ JHz$^{-1}$. A similar dc SQUID was subsequently operated at Hitachi, in Japan by Nakane and coworkers.\textsuperscript{11}

Over the past two decades, SQUIDs at liquid $^4$He temperatures have been put to an amazingly wide range of applications, including (i) laboratory-based instrumentation, for example, voltmeters with sensitivities as high as $10^{-15}$ volts, and radiofrequency amplifiers for detecting magnetic resonance; (ii) the detection of magnetic signals from human subjects, for example, spontaneous or evoked brain activity; (iii) geophysics, for example, magnetotellurics, electromagnetic sounding, paleomagnetism, tectonomagnetism, and internal ocean waves; (iv) "exotic instruments", for example, gravity wave detectors, and monopole detectors.

The likely impact of 77K operation on the various applications of SQUIDs varies considerably. For example, one could imagine a sensitive voltmeter able to operate at 77K rather than at 4.2K would greatly enhance its usefulness. Similarly, geophysical devices which usually operate in remote areas would be much easier to deploy in liquid N$_2$ (or Ne) cryostats than they are in liquid $^4$He cryostats. On the other hand, the SQUID used in the transducer of a gravity wave detector should ideally be quantum limited, and cooled down to millikelvin temperatures rather than warmed up to 77K. In the case of biomagnetic sensors, currently the largest commercial market for SQUIDs, the cost of the cryogenics is a relatively small fraction of the capital and operating costs, and the advantages of operating at high temperatures with a less sensitive device may not be so obvious. Perhaps a high-$T_c$ flux transformer could be used with a 4.2K SQUID, thus bringing the
pick-up loop(s) closer to the skull of the subject. But these applications are merely extensions of 4.2K technology: much more intriguing is the possibility of hitherto unknown applications of SQUIDs made possible by the relative ease of operation at 77K.

Finally, it is exceedingly important to realize that the new materials have not in themselves given us concepts for new devices. I believe personally that they will, that the vastly greater numbers of scientists now involved in this field will invent new devices: for example, we can now think seriously of making superconductor-semiconductor hybrid circuits. It is the excitement of this potential for changing the world of electronics that will keep many scientists and engineers very busy for many years to come.

In preparing this review, I have been helped by many people. I wish particularly to thank M. R. Beasley, D. B. Crum, F. Bedard, J. K. Hulm, R. H. Koch, P. L. Richards, and R. E. Schwall. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
Table I. Critical temperature \( (T_c) \), critical field \( (H_{c2}) \), critical current density \( (J_c) \), and mechanical properties of NbTi, Nb\(_3\)Sn and YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\). (Source: ref. 1.)

<table>
<thead>
<tr>
<th>Material</th>
<th>( T_c )(K)</th>
<th>( H_{c2} )(T)</th>
<th>( J_c )(A/cm(^2))</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>9.6</td>
<td>6</td>
<td>( 10^5 )</td>
<td>ductile, high strength</td>
</tr>
<tr>
<td>Nb(_3)Sn</td>
<td>18</td>
<td>11</td>
<td>( 2 \times 10^5 )</td>
<td>brittle, weak</td>
</tr>
<tr>
<td>YBa(_2)Cu(<em>3)O(</em>{7-\delta}) (bulk)</td>
<td>95</td>
<td>18</td>
<td>( 10^2)–( 10^3 )</td>
<td>extremely brittle</td>
</tr>
</tbody>
</table>
References


Figure Captions

Fig. 1 (a) Schematic representation of Josephson tunnel junction showing two superconductors separated by an insulating barrier. Passage of a current $I$ through the junction involves the quantum mechanical tunneling of Cooper pairs through the barrier. When the current exceeds the critical current $I_0$ of the junction, a voltage $V$ appears. (b) Practical cross-strip tunnel junction. A thin-film of (conventional) superconductor is oxidized (shading), and a second film deposited over the oxide layer. When the junction is cooled below the superconducting transition temperature, the current-voltage (I-V) characteristic shown in (c) is obtained as the current is increased from zero to a maximum value and then reduced to zero again. The hysteresis evident in (c) can be eliminated by means of a thin film of normal metal connecting the two superconducting films to provide a shunt conductance in parallel with the tunnel junction: the resulting nonhysteretic I-V characteristic is shown in (d). The Anderson-Dayem bridge is shown in (e). The thin film is necked down to produce a very narrow channel connecting the two superconductors.

Fig. 2 Superconducting electronics divided, somewhat arbitrarily, into three broad categories: for the detection of an incoming signal, for the analog processing of the amplified signal, and for the subsequent digital processing. Representative examples of each category are listed. (From ref. 6.)

Fig. 3 (a) dc SQUID: two Josephson tunnel junctions (x) connected in parallel on a superconducting loop of inductance $L$. The SQUID
is biased with a current $I$ to produce a voltage $V$. As the magnetic flux $\phi$ is changed, the voltage oscillates with a period of one flux quantum, $\phi_0$. (b) rf SQUID: a single Josephson junction incorporated into a superconducting loop with inductance $L$. The loop is inductively coupled to the inductor of a resonant circuit excited at its resonant frequency (typically 20 MHz) with a radiofrequency current. As the flux $\phi$ in the loop is changed, the amplitude of the radiofrequency voltage $V_{rf}$ is modulated with a period $\phi_0$. 
Fig. 1
Fig. 2
Fig. 3