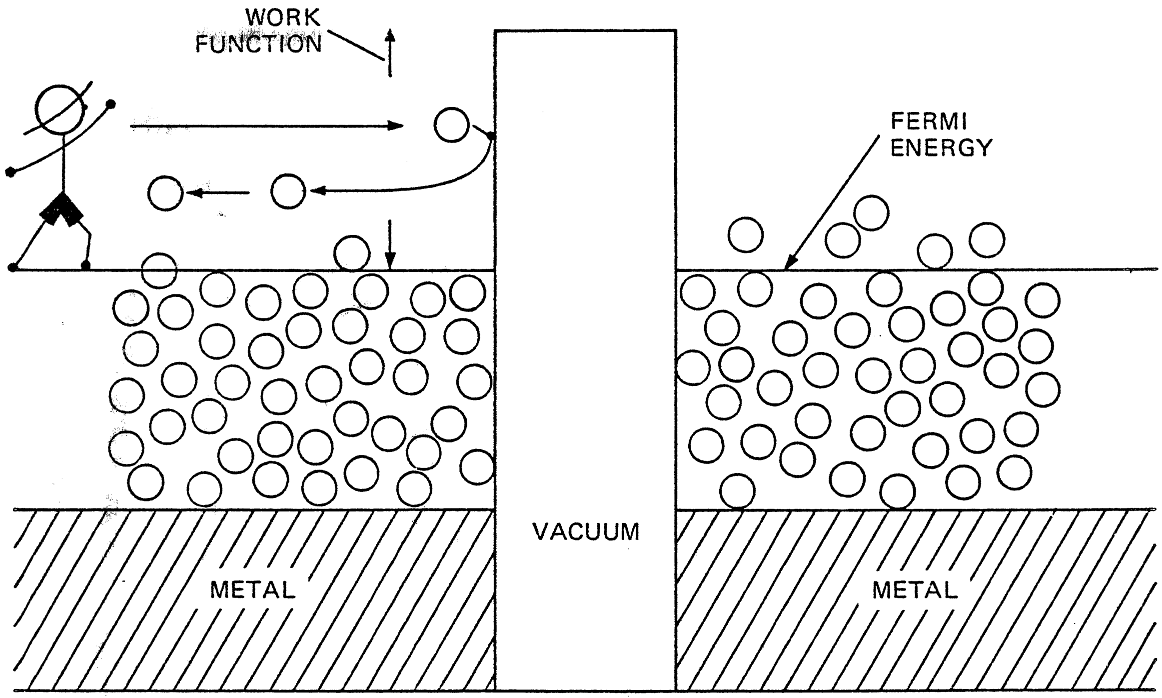
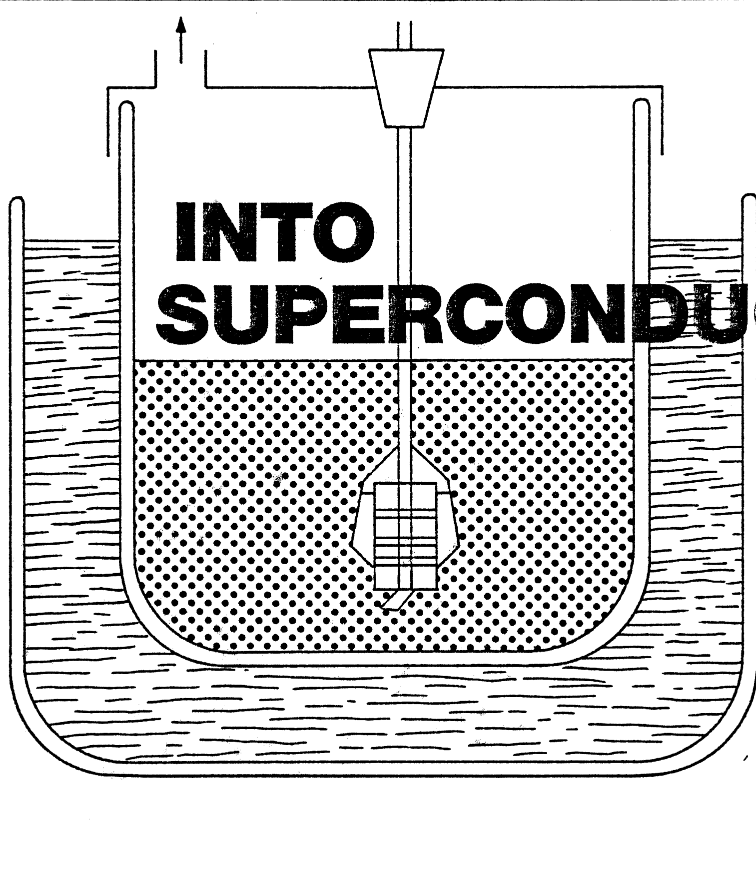
3

DISCOVERY OF ELECTRON TUNNELING



INTO SUPERCONDUCTORS



A NOTE ON THE NOBEL PRIZE FOR TUNNELING

The 1973 Nobel Prize for Physics was shared by three physicists for their work on tunneling effects. One half of the prize was shared by Leo Esaki and Ivar Giaever for their pioneer experimental work on single-particle tunneling (Esaki in semiconductors and Giaever in superconductors); the other half went to Brian Josephson for his theory of 'Josephson Tunneling,' which is the subject of Chapter 2 of the Gamma Volume of *Adventures in Experimental Physics.*

Tunneling is a pure quantum mechanical effect in which a particle penetrates a barrier that according to classical physics should be impenetrable.

Josephson tunneling is the tunneling of *correlated* electron pairs ('Cooper' pairs), while 'ordinary' or single-particle tunneling is the passage of *uncorrelated* single electrons through *insulator* barriers. (There is also the tunneling of both kinds through metal barriers, but its mechanism is quite different in detail and not within the scope of this chapter.)

While Josephson tunneling can occur only between two superconductors (which must be at very low temperatures), single-electron tunneling can take place at any temperature, provided the barrier is thin enough. Since, in the latter, each electron is not correlated with any other electron, the system manifests a normal resistance as opposed to Josephson tunneling where there is zero resistance.

There is also a quantitative difference in the insulator barrier thickness between the two types of tunneling: Josephson tunneling requires much thinner barriers, typically 10Å, whereas single-particle tunneling occurs through thicknesses of several hundred Å.

There are some interesting parallels as well as contrasts in the way in which the two effects were discovered.

Prior to the experiments of Giaever it did not occur to many theorists that the superconducting energy gap would be observable by means of single-particle tunneling. The observation was made by an experimentalist who was guided by his own intuitive predictions and indeed proved them to be correct.

Josephson predicted the Cooper pair tunneling and worked out its complete theory while a graduate student in *experimental* physics in Cambridge, England; yet, his attempts to verify it in the laboratory were not successful at the time, and thus it was not believed.

While working for the Sony Corporation in Tokyo during 1956-8, Leo Esaki developed the *tunnel diode* (also known as the *Esaki diode*), which enables electrical current to pass through normally impassable electronic barriers. This device exhibits negative resistance: above a critical value, an increase in voltage results in a decrease in current. This feature makes the tunnel diode an amplifier of electrical signals.

Tunnel Effect

The tunnel effect in semiconductors and insulators is a special case of the general quantum-mechanical phenomenon of the passage of particles through potential barriers. Classically, a particle can never cross a region of space where there is a potential barrier whose height V_0 exceeds the particle's total energy E, because its kinetic energy inside the barrier would be negative. However, when the wave aspect of the particle is taken into consideration, there exist, in the barrier, solutions of Schrödinger's equation which decay exponentially with depth of penetration. The particle has thus a finite probability of being found on the far side of the barrier, as if it had 'tunneled' through the potential mountain.

Probably the best known case of tunnel effect is the passage of α-particles through the potential barrier surrounding atomic nuclei. But the effect occurs very widely: for instance, in nuclear reactions, in many molecular phenomena, in field emissions from metals, etc.

In semiconductors and insulators, one means by 'tunnel effect' the internal field emission first considered by Zener in 1934 to explain dielectric breakdown in dielectrics (though it is now known that ordinary breakdown occurs generally through different mechanisms). For an electron in an insulator, the gap between the conduction band and the valence band behaves as a potential barrier. The width of the barrier is determined by the magnitude of the field. There is thus a finite probability for the electron, without changing its energy, to tunnel across the forbidden gap into the empty conduction band. This process creates an electron-hole pair.

[Based on Encyclopaedic Dictionary of Physics (Pergamon Press, 1962).]

Esaki completed his research, which subsequently stimulated great advances in the area of tunneling in semiconductors, while doing doctoral studies at the University of Tokyo, which he completed in 1959. The text of Esaki's Nobel lecture on tunneling is reproduced as Explanatory Physics Notes p. 154.

Ivar Giaever's contribution was, as he put it, to "marry tunneling to superconductivity." Using a sandwich consisting of an insulated piece of superconducting metal and a normal one, he achieved new tunneling effects that led to greater understanding of superconductivity.

Giaever's experiments concerned the energies that electrons could have in superconductors. A few years before them, John Bardeen, Leon Cooper and John Robert Schrieffer had published their (BCS) theory of superconductivity, for which they themselves received the Nobel Prize in 1972. A striking characteristic of this theory was the prediction that when a metal becomes superconducting there will be a range of energy in which no electrons can exist; that is, a forbidden gap. Giaever found that the tunneling at certain applied voltages decreased or disappeared when he cooled his samples through the superconducting transition temperature. This disappearance of current was explained by the forbidden gap of the BCS theory, which prevents electrons from tunneling into the superconductor. Thus, Giaever provided support for the BCS theory and was able to study the superconducting gap of many materials in detail.

BCS THEORY OF SUPERCONDUCTIVITY

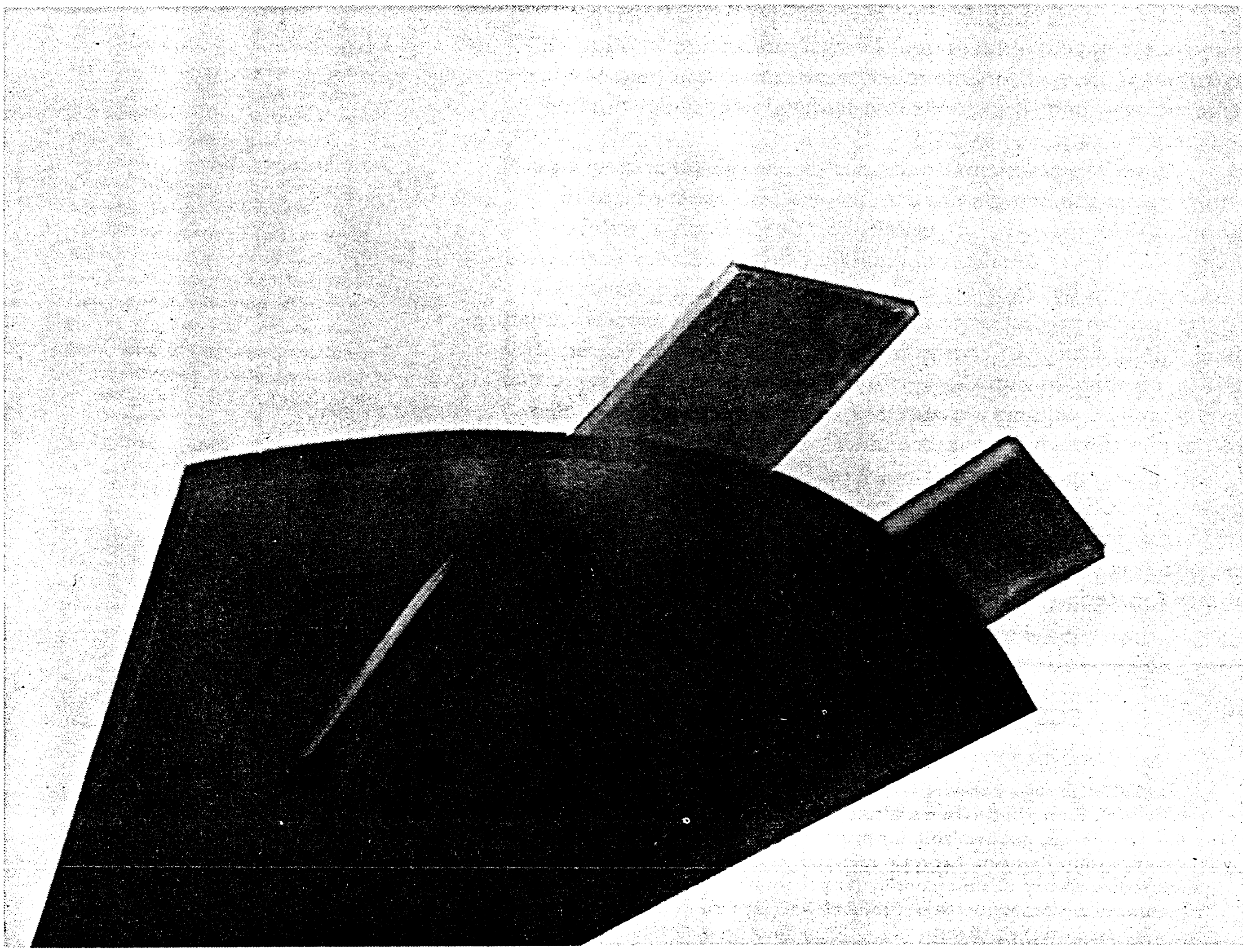
Although superconductivity was first observed in 1911 by the Dutch physicist H. Kamerlingh Onnes, a successful theoretical explanation of this phenomenon was not available for nearly half a century. In 1957, American physicists John Bardeen, Leon Cooper and John Schrieffer introduced a microscopic theory of superconductivity,* which explains superconducting phenomena as consequences of fundamental physical laws. All later theoretical work is based on their theory.

Certain materials become superconductors below a critical temperature, usually several degrees Kelvin. The key to the BCS theory is that at this critical temperature and below, electrons of equal but opposite momenta and opposed spins are paired. These pairs are able to maintain themselves against thermal excitation in a state of lower energy than a randomly chosen pair of electrons of uncorrelated momenta. The members of a pair need not be spatially close to one another and in fact may be separated by a distance several thousand times the distance between two lattice sites. The paired electrons have a definite momentum (zero if there is no current, a common finite value if there is a current). By the uncertainty principle, their center-of-mass cannot be localized to any particular region of the metallic volume. Since the motion of all pairs of electrons in a superconductor is correlated, the pairs are able to move without momentum change (without resistance).

For an excellent description of the BCS theory and its predictions, see the 1972 Nobel Prize Lectures by Bardeen, Cooper, and Schrieffer**.

* Bardeen, J., Cooper, L., and Schrieffer, J., *Phys. Rev.* **108**, 1175(1957).

** Schrieffer, J. Robert, "Macroscopic Quantum Phenomena from Pairing in Superconductors," *Phys. Today* 26,23(July 1973); Cooper, Leon, N., "Microscopic Quantum Interference in the Theory of Superconductivity," *Phys. Today* 26,31 (July 1973); Bardeen, John, "Electron-Phonon Interactions and Superconductivity," *Phys. Today* 26,41 (July 1973); copyright 1972 by the Nobel Foundation.
See also: *Superconductivity,* edit. by Parks, R. D., (Marcel Dekker, Inc., N.Y. 1969).



The heart of the equipment used by Ivar Giaever in the experiments described in the Discovery Story. The fan-shaped plate is a mask upon which glass slides are placed, inside an evacuated bell jar. With slots cut in it, this mask permitted Giaever to deposit thin strips of aluminum on the slides during his investigation of 'tunneling' in superconductors. [From: *R & D Review*, Corporate Research and Development, General Electric Company, Schenectady, New York, 1974.]

Ivar Giaever,
at the General Electric Research and Development Center (Schenectady, New York, 1974). The bell jar in his hands was used to create a vacuum in which he performed his key experiments on tunneling in 1960.

One Researcher's Personal Account*

by
Ivar Giaever

IN my laboratory notebook dated May 2, 1960 is the entry: "Friday, April 22, I performed the following experiment aimed at measuring the forbidden gap in a superconductor." This was obviously an extraordinary event not only because I rarely write in my notebook, but because the success of that experiment is the reason I have the great honor and pleasure of addressing you today. I shall try in this lecture, as best I can, to recollect some of the events and thoughts that led to this notebook entry, though it is difficult to describe what now appears to me as fortuitous. I hope that this personal and subjective recollection will be more interesting to you than a strictly technical lecture, particularly since there are now so

* *From: Nobel Lecture, 1973.*

1. Burstein, E., and Lundqvist, S., Eds. *Tunneling Phenomena in Solids* (Plenum, New York, 1969); Parks, R. D., Ed. *Superconductivity* (Dekker, New York, 1969).

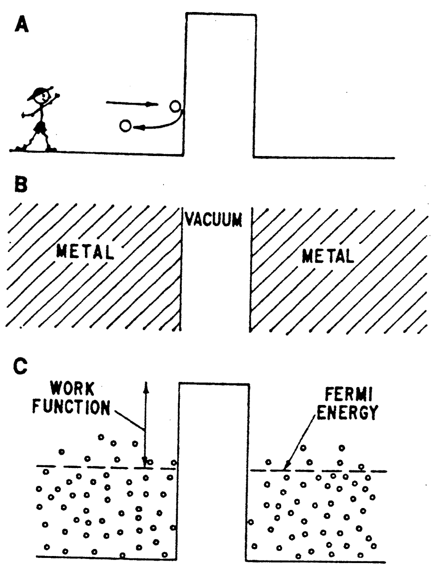


Fig. 1. (A) *If a man throws a ball against a wall, the ball bounces back. According to the laws of physics, the ball can penetrate or tunnel through the wall, but the chance is infinitesimally small because the ball is a macroscopic object.* (B) *Two metals separated by a vacuum will approximate the situation in* (A). *The electrons in the metals are the 'balls,' and the vacuum represents the wall.* (C) *A pictorial energy diagram of the two metals. The electrons do not have enough energy to escape into the vacuum. The two metals can, however, exchange electrons by tunneling. If the metals are spaced close together, the probability for tunneling is large because the electron is a submicroscopic particle.*

many good review articles dealing with superconductive tunneling[1].

A recent headline in an Oslo paper read approximately as follows: "Master in billiards and bridge, almost flunked physics—gets Nobel Prize." The paper refers to my student days in Trondheim. I have to admit that the reporting is reasonably accurate; therefore, I shall not attempt a "cover-up," but confess that I almost flunked in mathematics as well. In those days I was not very interested in mechanical engineering and school in general, but I did manage to graduate with an average degree in 1952.

When I was 28 years old, I found myself in Schenectady, New York, where I discovered that it was possible for some people to make a good living as physicists. I had worked on various company assignments in applied mathematics and had developed the feeling that the mathematics was much more advanced than the actual knowledge of the physical systems to which we applied it. Thus, I thought perhaps I should learn some physics and, even though I was still an engineer, I was given the opportunity to try it at the General Electric Research Laboratory.

The assignment I was given was to work with thin films and to me films meant photography. However, I was fortunate to be associated with John Fisher who obviously had other things in mind. Fisher had started out as a mechanical engineer as well but had later turned his attention toward theoretical physics. He had the notion that useful electronic devices could be made with the use of thin-film technology, and before long I was working with metal films separated by thin insulating layers trying to do tunneling experiments. I have no doubt that Fisher knew about Leo Esaki's tunneling experiments at that time, but I certainly did not. The concept that a particle can go through a barrier seemed sort of strange to me, just struggling with quantum mechanics at Rensselaer Polytechnic Institute (R.P.I.) in Troy, New York, where I took formal courses in physics. To an engineer it sounds rather strange that if you throw a tennis ball against a wall enough times, it will eventually go through without damaging either the wall or itself. That must be the hard way to a Nobel Prize! The trick, of course, is to use very tiny balls, and lots of them. Thus if we could place two metals very close together without making a short, the electrons in the metals can be considered as the balls and the wall is represented by the spacing between the metals. These concepts are shown in Fig. 1. Although classical mechanics correctly predicts the behavior of large objects such as tennis balls, to predict the behavior of small objects such as electrons we must use quantum mechanics. Physical insight relates to everyday experiences with large objects; thus we should not be too surprised that electrons sometimes behave in strange and unexpected ways.

Neither Fisher nor I had much background in experimental physics, none to be exact, and we made several false starts. To be able to measure a tunneling current, the two metals must be spaced no more than about 100 angstroms apart, and we decided early in the game not to attempt to use air or a vacuum between the two metals because of problems with vibration. After all, we both had training in mechanical engineering! We tried instead to keep the two metals apart by using a variety of thin insulators made from Langmuir films and from Formvar. Invariably, these films had pinholes and the mercury counter electrode which we used would short the films. Thus we spent some time measuring very interesting but always nonreproducible current-voltage characteristics which we referred to as miracles since each occurred only once. After a few months we hit on the correct idea: to use evaporated metal films and to separate them by a naturally grown oxide layer.

To carry out our ideas we needed an evaporator; thus I purchased my first piece of experimental equipment. While waiting for the evaporator to arrive, I worred a lot—I was afraid I would become tied to this expensive machine and get stuck in experimental physics. My plans at that time were to switch into theory as soon as I had acquired enough knowledge. The premonition was correct; I did get stuck with the evaporator, not because it was expensive but because it fascinated me. Figure 2 shows a schematic diagram of an evaporator. To prepare a tunnel junction we first evaporated a strip of aluminum onto a glass slide. This film was removed from the vacuum system and heated to oxidize the surface rapidly. Several cross strips of aluminum were then deposited over the first film, making several junctions at the same time. The steps in the sample preparation are illustrated in Fig. 3. This procedure solved two problems: first, there were no pinholes in the oxide because it is self-healing, and second, we got rid of mechanical problems that arose with the mercury counter electrode.

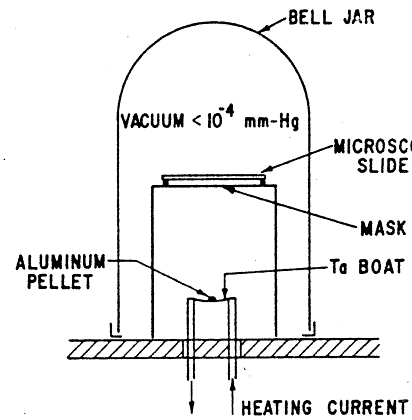


Fig. 2. *A schematic drawing of a vacuum system for depositing metal films. For example, if aluminum is heated resistively in a tantalum boat, the aluminum first melts, then boils and evaporates. The aluminum vapor will solidify on any cold substrate placed in the vapor stream. The most common substrates are ordinary microscope glass slides. Patterns can be formed on the slides by suitably shielding them with a metal mask.*

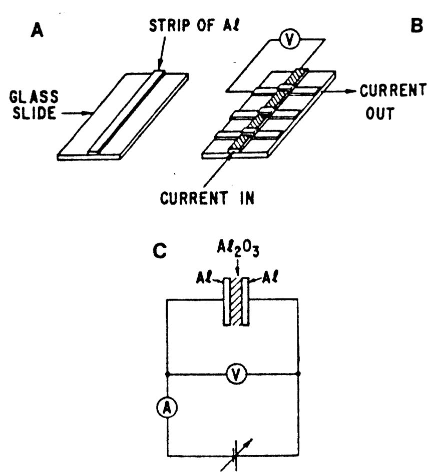


Fig. 3. (A) *A microscope glass slide with a vapor-deposited aluminum strip down the middle. As soon as the aluminum film is exposed to air, a protective insulating oxide forms on the surface. The thickness of the oxide depends upon such factors as time, temperature, and humidity.* (B) *After a suitable oxide has formed, cross strips of aluminum are evaporated over the first film, sandwiching the oxide between the two metal films. Current is passed along one aluminum film up through the oxide and out through the other film, while the voltage drop is monitored across the oxide.* (C) *A schematic circuit diagram. We are measuring the current-voltage characteristics of the capacitor-like arrangement formed by the two aluminum films and the oxide. When the oxide thickness is less than 50 Å or so, an appreciable d-c current will flow through the oxide.*

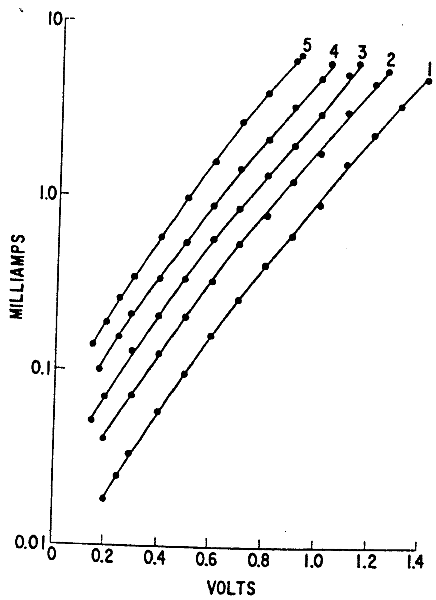


Fig. 4. *Current-voltage characteristics of five different tunnel junctions, all with the same thickness but with five different areas. The current is proportional to the area of the junction. This was one of the first clues that we were dealing with tunneling rather than shorts. In the early experiments we used a relatively thick oxide, thus very little current would flow at low voltages.*

By about April 1959, we had performed several successful tunneling experiments. The current-voltage characteristics of our samples were reasonably reproducible and conformed well to theory. A typical result is shown in Fig. 4. Several checks were carried out, such as varying the area and the oxide thickness of the junction as well as changing the temperature. Everything looked OK, and I even gave a seminar at the GE Laboratory. By this time, I had solved Schrödinger's equation enough times to believe that electrons sometimes behave as waves, and I did not worry much about that part anymore.

However, there were many real physicists at the Laboratory, and they properly questioned my experiment. How did I know I did not have metallic shorts? Ionic current? Semiconduction rather than tunneling? Of course, I did not know, and even though theory and experiments agreed well, doubts about the validity were always in my mind. I spent a lot of time inventing impossible schemes such as a tunnel triode or a cold cathode, both to try to prove conclusively that I was dealing with tunneling and to perhaps make my work useful. It was rather strange for me at that time to get paid for doing what I considered having fun, and my conscience bothered me. But as with quantum mechanics, you get used to it, and now I often argue the opposite point; we should pay more people to do pure research.

I continued to try out my ideas on John Fisher who was now looking into the problems of fundamental particles with his characteristic optimism and enthusiasm. In addition, I received more and more advice and guidance from Charles Bean and Walter Harrison, both physicists with the uncanny ability of making things clear as long as a piece of chalk and a blackboard were available. I continued to take formal courses at R.P.I., and one day in a solid-state physics course taught by Professor Huntington we got to superconductivity. Well, I didn't believe that the resistance drops to exactly zero—but what really caught my attention was the mention of the energy gap in a superconductor, central to the new Bardeen-Cooper-Schrieffer (BCS) theory (see box p. 131). If the theory was any good and if my

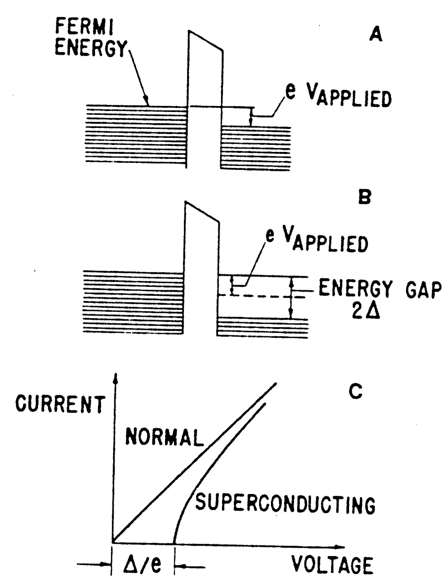


Fig. 5. (A) *An energy diagram of two metals separated by a barrier. The Fermi energies in the two metals are at different levels because of the voltage difference applied between the metals. Only the electrons from the metal on the left in the energy range $e \cdot V_{app}$ can make a transition to the metal on the right, because only these electrons face empty energy states. The Pauli principle allows only one electron in each quantum state.* **(B)** *The metal on the right is now superconducting, and an energy gap 2 Δ has opened up in the electron spectrum. No single electron in a superconductor can have an energy such that it will appear inside the gap. The electrons from the metal on the left can still tunnel through the barrier, but they cannot enter into the metal on the right as long as the applied voltage is less than Δ/e, because the electrons either face a filled state or a forbidden energy range. When the applied voltage exceeds Δ/e, current will begin to flow.* **(C)** *A schematic current-voltage characteristic. When both metals are in the normal state, the current is simply proportional to the voltage. When one metal is superconducting, the current-voltage characteristic is drastically altered. The exact shape of the curve depends on the electronic energy spectrum in the superconductor.*

tunneling experiments were any good, it was obvious to me that by combining the two some pretty interesting things should happen, as illustrated in Fig. 5. When I got back to the GE Laboratory, I tried this simple idea out on my friends, and as I remember it did not look as good to them. The energy gap was really a many-body effect and could not be interpreted literally the way I had done. But even though there was considerable skepticism, everyone urged me to go ahead and make a try. Then I realized that I did not know what the size of the gap was in units I understood—electron volts. This was easily solved by my usual method of first asking Bean and then Harrison and, when they agreed on a few millielectron volts, I was happy because that is in an easily measured voltage range.

I had never done an experiment requiring low temperatures and liquid helium—that seemed like complicated business. However, one great advantage of being associated with a large laboratory like General Electric is that almost in any field, there are always people around who are knowledgable and, better still, they are willing to lend you a hand. In my case, all I had to do was go to the end of the hall where Warren DeSorbo was already doing experiments with superconductors. I no longer remember how long it took me to set up the helium Dewars I borrowed, but probably no longer than a day or two. People unfamiliar with low-temperature work believe that the whole field of low temperature is pretty esoteric, but all it really requires is access to liquid helium, which was readily available at the Laboratory. The experimental setup is shown in Fig. 6. Then I made my samples using the familiar aluminum-aluminum oxide, but I put lead strips on top. Both lead and aluminum are superconductors; lead is superconducting at 7.2°K, and thus all you need to make it superconducting is liquid helium which boils at 4.2°K. Aluminum becomes superconducting only below 1.2°K, and to reach this temperature a more complicated experimental setup is required.

The first two experiments I tried were failures because I used oxide layers that were too thick. I did not get enough current through the thick oxide to measure it reliably with the instruments I used, which were simply a standard voltmeter and a standard ammeter. It is strange to think about that now, only 13 years later, when the Laboratory is full of sophisticated x-y recorders. Of course, we had plenty of oscilloscopes at that time, but I was not very familiar with their use. In the third attempt instead of deliberately oxidizing the first aluminum strip, I simply exposed it to air for only a few minutes and then put it back in the evaporator to deposit the cross strips of lead. In this way the oxide was no more than about 30 angstroms thick, and I could readily measure the current-voltage characteristic with the available equipment. To me the greatest moment in an experiment is always just before I learn whether the particular idea is a good or a bad one. Thus even a failure is exciting, and most of my ideas have of course been wrong. But this time it worked! The current-voltage characteristic changed markedly when the lead changed from the normal state to the superconducting state, as shown in Fig. 7. That was exciting! I imme-

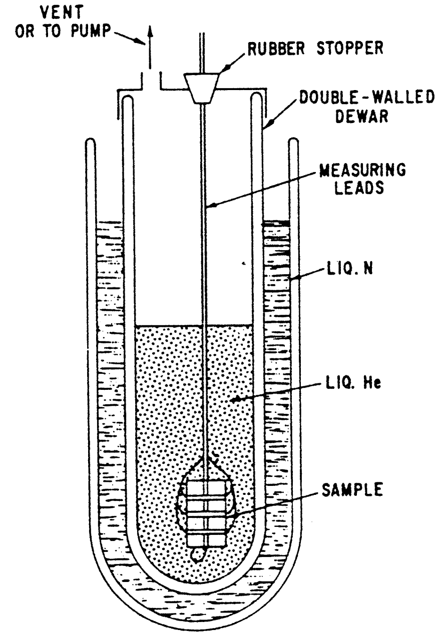


Fig. 6. *A standard experimental arrangement used for low-temperature experiments. It consists of two Dewars, the outer one containing liquid nitrogen and the inner one, liquid helium. Helium boils at 4.2° K at atmospheric pressure. The temperature can be lowered to about 1° K by reducing the pressure. The sample simply hangs into the liquid helium supported by the measuring leads.*

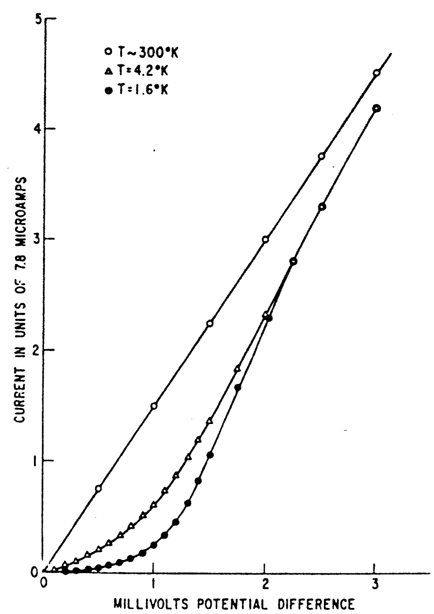


Fig. 7. *The current-voltage characteristic of an aluminum-aluminum oxide-lead sample. As soon as the lead becomes superconducting, the current ceases to be proportional to the voltage. The large change between 4.2° and 1.6° K is due to the change in the energy gap with temperature. Some current also flows at voltages less than Δ/e because of thermally excited electrons in the conductors.*

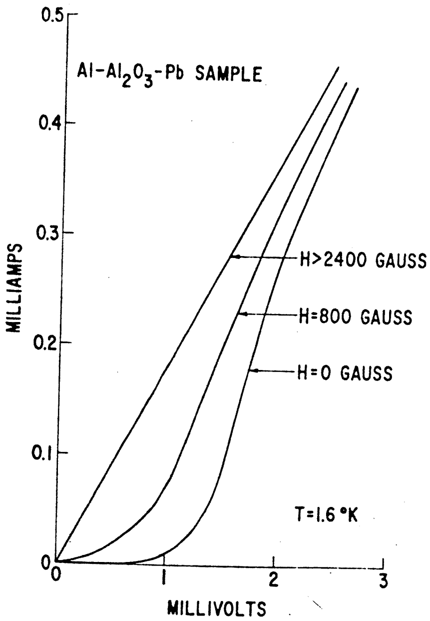


Fig. 8. *The current-voltage characteristic at 1.6° K as a function of the applied magnetic field. At 2400 gauss the films are normal, but at 0 gauss the lead film is superconducting. The reason for the change in the characteristics between 800 gauss and 0 gauss is that thin films have an energy gap that is a function of the magnetic field.*

diately repeated the experiment using a different sample—same results! Another sample—still the same results. Everything looked good! But how to make certain? It was well-known that superconductivity is destroyed by a magnetic field, but my simple setup of Dewars made that experiment impossible. This time I had to go all the way across the hall where Israel Jacobs was studying magnetism at low temperatures. Again I was lucky enough to go right into an experimental rig where both the temperature and the magnetic field could be controlled, and I could quickly do all the proper experiments. The basic result is shown in Fig. 8. Everything held together, and the whole group, as I remember it, was very excited. In particular, I can remember Bean enthusiastically spreading the news up and down the halls in our Laboratory, and also patiently explaining to me the significance of the experiment.

I was, of course, not the first person to measure the energy gap in a superconductor, and I soon became aware of the nice experiments done by M. Tinkham[2] and his students, using infrared transmission. I can remember that I was worried that the size of the gap that I measured did not quite agree with those previous measurements. Bean set me straight with words to the effect that from then on other people would have to agree with me; my experiment would set the standard, and I felt pleased and like a physicist for the first time.

That was a very exciting time in my life; we had several great ideas to improve and extend the experiment to all sorts of materials such as normal metals, magnetic materials, and semiconductors. I remember many informal discussions over coffee about what to try next, and a photograph of one of these sessions, taken in 1960, is shown in Fig. 9. To be honest, the picture was staged. We weren't

Fig. 9. *Informal discussion over a cup of coffee. From left to right: Ivar Giaever, Walter Harrison, Charles Bean, and John Fisher.*

2. Tinkham, M., "Absorption of Electromagnetic Radiation in Superconductors," *Physica* 24, Supplement S35 (Sept., 1958); Ginsberg, D. M. and Tinkham, M., *Phys. Rev.* 118, 990 (1960).

normally so dressed up, and rarely did I find myself in charge at the blackboard! Most of the ideas we had did not work very well, and Harrison soon published a theory showing that life is really complicated after all. But the superconducting experiment was charmed and always worked. It looked like the tunneling probability was directly proportional to the density of states in a superconductor. Now if this were strictly true, it did not take much imagination to realize that tunneling between two superconductors should display a negative resistance characteristic, as illustrated in Fig. 10. A negative resistance characteristic meant, of course, amplifiers, oscillators, and other devices. But nobody around me had

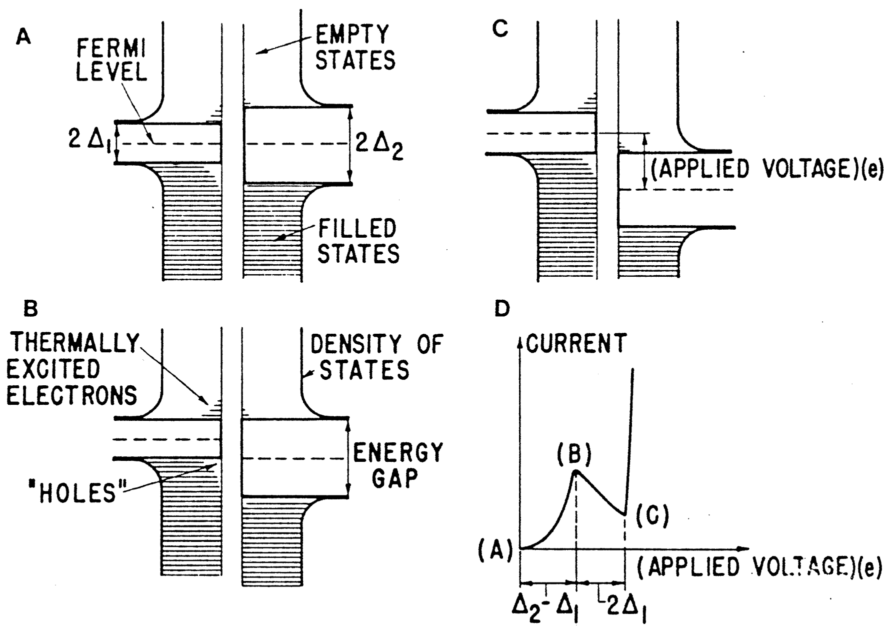


Fig. 10. *Tunneling between two superconductors with different energy gaps at a temperature above 0° K.* (A) *No voltage is applied between the two conductors.* (B) *As a voltage is applied, it becomes energetically possible for more and more of the thermally excited electrons to flow from the superconductor with the smaller gap into the superconductor with the larger gap. At the voltage shown, all the excited electrons can find empty states on the right.* (C) *As the voltage is further increased, no more electrons come into play and, since the number of states the electrons can tunnel into decreases, the current will decrease as the voltage is increased. When the voltage is increased sufficiently, the electrons below the gap in the superconductor on the left face empty states on the right and a rapid increase in current will occur.* (D) *A schematic picture of the expected current-voltage characteristic.*

facilities to pump on the helium sufficiently to make aluminum become superconducting. This time I had to leave the building and reactivate an old low-temperature setup in an adjacent building. Sure enough, as soon as the aluminum went superconducting, a negative resistance appeared and, indeed, the notion that the tunneling probability was directly proportional to the density of states was experimentally correct. A typical characteristic is shown in Fig. 11.

Now things looked very good because all sorts of electronic devices could be made using this effect but, of course, they would be operative only at low temperatures. We should remember that the semiconducting devices were not so advanced in 1960, and we thought that the superconducting junction would have a good chance of competing with, for example, the Esaki diode. The basic question I faced was which way to go: engineering or science? I decided that I should do the science first and received full support from my immediate manager, Roland Schmitt.

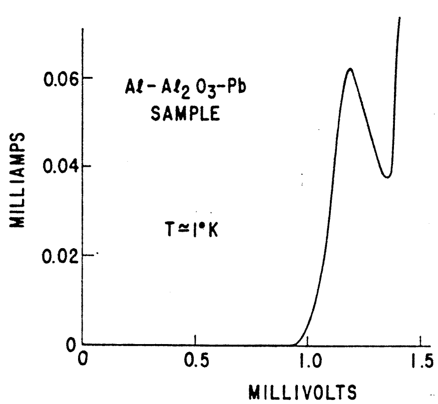


Fig. 11. *A negative resistance characteristic obtained experimentally in tunneling between two different superconductors.*

Cont. p. 141.

ENERGY GAP IN SUPERCONDUCTORS MEASURED BY ELECTRON TUNNELING

Ivar Giaever
General Electric Research Laboratory, Schenectady, New York
(Received July 5, 1960)

If a potential difference is applied to two metals separated by a thin insulating film, a current will flow because of the ability of electrons to penetrate a potential barrier. The fact that for low fields the tunneling current is proportional to the applied voltage[1] suggested that low-voltage tunneling experiments could reveal something of the electronic structure of superconductors.

Aluminum/aluminum oxide/lead sandwiches were prepared by vapor-depositing aluminum on glass slides in vacuum, oxidizing the aluminum in air for a few minutes at room temperature, and then vapor-depositing lead over the aluminum oxide. The oxide layer separating aluminum and lead is thought to be about 15-20A thick.

At liquid helium temperature, in the presence of a magnetic field applied parallel to the film and sufficiently strong to keep the lead in the normal state, the tunnel current is linear in the voltage. However, when the magnetic field is removed, and lead becomes superconducting, the tunnel current is very much reduced at low voltages as shown in Fig. 1. There is no influence of polarity, identical results being obtained with both directions of current flow.

The slope dI/dV of the curve in Fig. 1 where $H=0$, $T=1.6°K$, divided by dI/dV for normal lead, is plotted in Fig. 2. On the naive picture that tunneling is proportional to density of states,[2] this curve expresses the density of states in superconducting lead relative to the density of states when lead is in its normal state, as a function of energy measured from the Fermi energy. It seems clear that the density of states at the Fermi level is drastically changed when a metal becomes a superconductor, the change being symmetric with respect to the Fermi level. The curve resembles the Bardeen-Cooper-Schrieffer[3] density of states for quasi-particle excitations. There is a broadening of the peak that decreases with decreasing temperature.

An approximate measure of half the energy gap

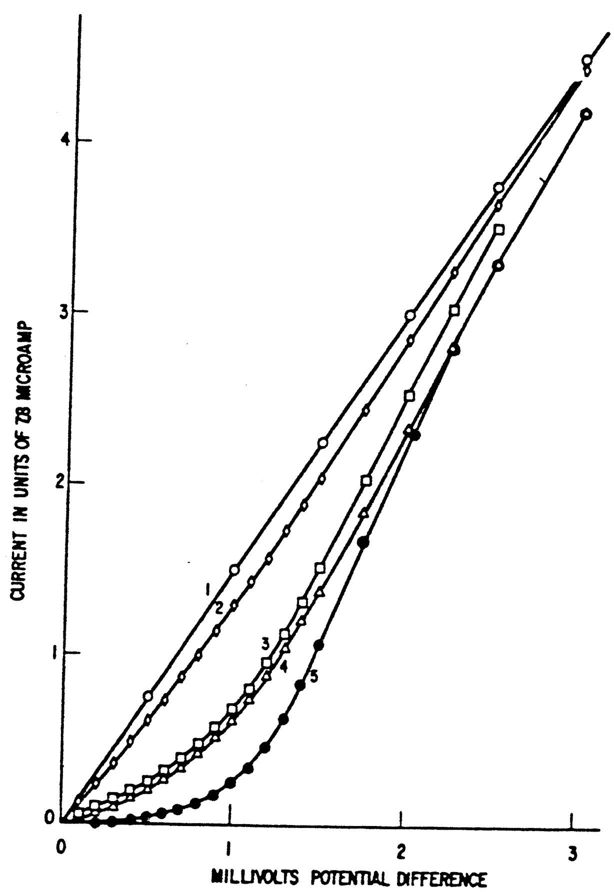


FIG. 1. Tunnel current between Al and Pb through Al_2O_3 film as a function of voltage. (1) $T=4.2°K$ and $1.6°K$, $H=2.7$ koe (Pb normal). (2) $T=4.2°K$, $H=0.8$ koe. (3) $T=1.6°K$, $H=0.8$ koe. (4) $T=4.2°K$, $H=0$ (Pb superconducting). (5) $T=1.6°K$, $H=0$ (Pb superconducting).

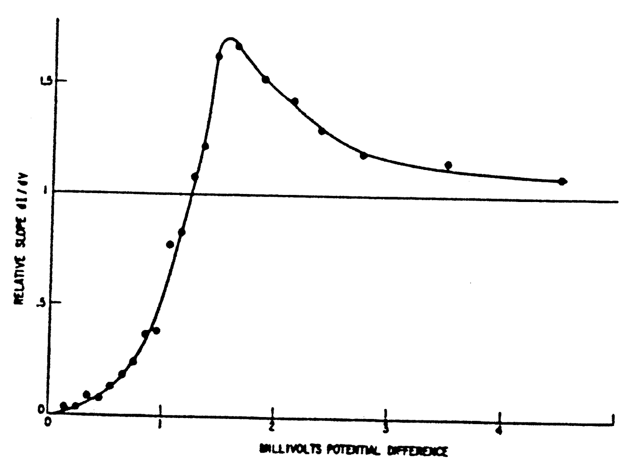


FIG. 2. From Fig. 1, slope dI/dV of curve 5 relative to slope of curve 1.

is given by the point at which the relative slope $dI/dV = 1$. On this basis the gap width for lead is $(4.2 \pm 0.1)kT_C$.

The experiment has been repeated with tin and indium giving entirely similar results; the gap in each case is approximately $4kT_C$. These results are of a preliminary nature, and experiments at lower temperatures will make them more precise.

I wish to thank C. P. Bean and J. C. Fisher for their interest and encouragement, and P. E. Lawrence for his help in performing the experiments.

[1] J. C. Fisher and I. Giaever (to be published).

[2] W. A. Harrison (private communication) has pointed out that the tunnel current is not proportional to the density of states except in the limiting case of a low density of states.

[3] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).

Cont. from p. 139

In retrospect, I realize how tempting it must have been for Schmitt to encourage other people to work in the new area, and for the much more experienced physicists around me to do so as well. Instead, at the right time, Schmitt provided me with a co-worker, Karl Megerle, who joined our Laboratory as a Research Training Fellow. Megerle[3] and I worked well together, and before long we published a paper dealing with most of the basic effects[3].

As always in physics, it is important to extend experiments to a higher energy, a greater magnetic field or, in our case, to a lower temperature. Therefore, we joined forces with Howard Hart, who had just completed a helium-3 refrigerator that was capable of getting down to about 0.3°K. At the same time, Megerle finished a lock-in amplifier which we could use to measure directly the derivative of the current with respect to the voltage. That was really a nice-looking machine with a magnet rotating past a pickup coil at 8 cycles per second but, of course, vastly inferior to the modern lock-in amplifier. We had known for some time that there were anomalies in the current-voltage characteristics of lead, and now we finally pinned them down by finding some extra wiggles in the derivative curve. This is shown in Fig. 12. That made us happy because all that the tunneling experiments had done up till then was to confirm the BCS theory, and that is not what an experimentalist would really like to do. The dream is to show that a famous theory is incorrect, and now we had finally poked a hole in the theory. We speculated at the time that these wiggles were somehow associated with the phonons thought to be the cause of the attractive electron-electron interaction in a superconductor. As often happens, the theorists turned the tables on us and cleverly used these wiggles to properly extend the theory and to prove that the BCS theory was indeed correct. Professor Bardeen gave a detailed account of this in his most recent Nobel Prize lecture[4].

I have, so far, talked mainly about what went on at General Electric at that time; sometimes it is difficult for me to realize that Schenectady is not the center of the world. Several other people began to do tunneling work, and to mention just a few: J. M. Rowell[5] and W. L. McMillan were really the ones who unraveled the phonon

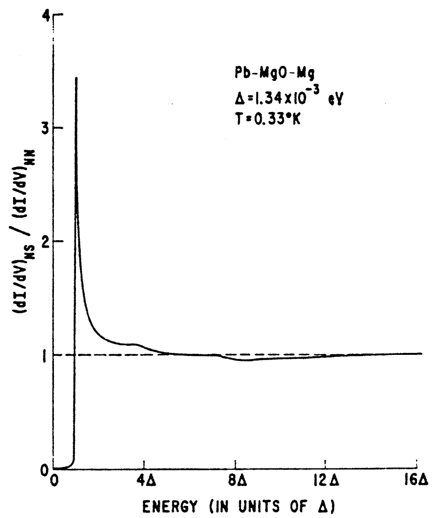


Fig. 12. *A normalized derivative of the current with respect to the voltage of a lead junction in a lead-magnesium oxidemagnesium sample at 0.33 °K. The simple BCS theory predicts that the derivative should approach unity asymptotically as the energy increases. Instead, several wiggles are observed in the range between 4 △ and 8 △. These wiggles are related to the phonon spectrum in lead.*

3. Giaever, I., Megerle, K., *Phys. Rev.* 122, 1101 (1961) reproduced p. 143.)
4. Bardeen, J., "Electron-Phonon Interactions and Superconductivity," *Phys. Today* 26, 41 (July 1973).
5. Rowell, J. M., Chynoweth, A. G., Phillips, J. C., *Phys. Rev. Lett.* 9, 59 (1962); Rowell, J. M., Anderson, P. W., Thomas, D. E., *Phys. Rev. Lett.* 10, 334 (1963).

Lock-In Amplifier

One of the most useful techniques for the extration of a signal from noise, even of the same bandwidth, is the use of a *lock-in amplifier,* which is sensitive only to signals at or near a given frequency. This frequency is determined by a control signal applied independently. The lock-in amplifier is also phase sensitive, hence this technique is also known as *phase sensitive detection or phase discrimination.* It carries the requirement that the signal be repetitive, as in signal averaging. One is thus able to 'lock-in' on a particular signal of interest, amplifying only that signal without amplifying noise or extraneous signals. [See: Diefenderfer A. J., *Principles of Electronic Instrumentation* (W. B. Saunders Co., 1972)].

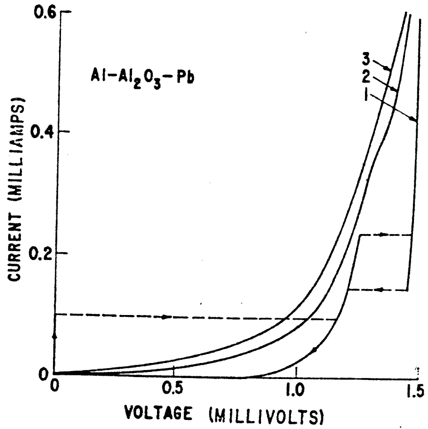


Fig. 13. *Effect of trapped magnetic field on a tunneling characteristic. Curve 1 is a virgin curve, curve 3 is the case for a moderate magnetic field, and in curve 2 the magnetic field has been removed. In curve 1 we also have a small resistance-less current which we interpreted as caused by metallic shorts. In retrospect, it was actually due to the Josephson effect.*

structure in a superconductor; W. J. Tomasch[6], of course, insisted on discovering his own effect; S. Shapiro[7] and colleagues did tunneling between two superconductors at the same time we did; and J. Bardeen, and later M. H. Cohen[8] and his co-workers, took care of most of the theory.

Meanwhile, back at R.P.I., I had finished my course work and decided to do a theoretical thesis on ordered-disordered alloys with Professor Huntington, because tunneling in a superconductor was for the most part understood. Then someone made me aware of a short paper by Brian Josephson[9] in *Physics Letters*—what did I think? Well, I did not understand the paper, but shortly after this I had the chance to meet Josephson at Cambridge and I came away impressed. One of the effects Josephson predicted was that it should be possible to pass a supercurrent with zero voltage drop through the oxide barrier when the metals on both sides were superconducting; this is now called the d-c Josephson effect.

We had observed this behavior many times; as a matter of fact, it is difficult not to see this current when junctions are made of tin-tin oxide-tin or lead-lead oxide-lead. The early tunnel junctions were usually made with aluminum oxide which generally is thicker, and therefore thermal fluctuations suppress the d-c current. In our first paper Megerle and I included a curve, which is shown in Fig. 13, demonstrating such a supercurrent and that it depended strongly on a magnetic field. However, I had a ready-made explanation for this supercurrent—it came from a metallic short or bridge. I was puzzled at the time because of the sensitivity to the magnetic field, which is unexpected for a small bridge, but no one knew how a bridge 20 angstroms long and 20 angstroms wide could behave anyway. If I have learned anything as a scientist, it is that one should not make things complicated when a simple explanation will do. Thus all the samples we made showing the Josephson effect were discarded as having shorts. This time I was too simple-minded! I have been asked many times since then if I feel bad for missing the effect. The answer is clearly no, because, to make an experimental discovery, it is not enough to observe something; one must also realize the significance of the observation, and in this instance I was not even close. Even after I learned about the d-c Josephson effect, I felt that it could not be distinguished from real shorts; therefore, I erroneously believed that only the observation of the so-called a-c effect would prove or disprove Josephson's theory.

In conclusion, I hope that this rather personal account may provide some slight insight into the nature of scientific discovery. My own beliefs are that the road to a scientific discovery is seldom direct, and that it does not necessarily require great expertise. In fact, I am convinced that often a newcomer to a field has a great advantage because he is ignorant and does not know all the complicated reasons why a particular experiment should not be attempted. However, it is essential to be able to get advice and help from experts in the various sciences when you need it. For me the most important ingredients were that I was at the right place at the right time and that I found so many friends both inside and outside General Electric who unselfishly supported me. □

6. Joseph, A. S. and Tomasch, W. J., *Phys. Rev. Lett.* 12, 219 (1964); Tomasch, W. J. and Joseph, A. S., *Phys. Rev. Lett.* 12, 148 (1964).
7. Nicol, J., Shapiro, S., and Smith, P. H., *Phys. Rev. Lett.* 5, 461 (1960); Smith, P. H., Shapiro, S., Miles, J. L., and Nicol, J., *Phys. Rev. Lett.* 6, 686 (1960).
8. Bardeen, J., *Phys. Rev. Lett.* 6, 57 (1961); Cohen, M. H., Falicov, L. M., Phillips, J. C., *Phys. Rev. Lett.* 8, 316 (1962).
9. Josephson, B. D., *Phys. Lett.* 1, 251 (1962).

Reprinted from THE PHYSICAL REVIEW, Vol. 122, No. 4, 1101–1111, May 15, 1961
Printed in U. S. A.

Study of Superconductors by Electron Tunneling

IVAR GIAEVER AND KARL MEGERLE
General Electric Research Laboratory, Schenectady, New York

(Received January 3, 1961)

If a small potential difference is applied between two metals separated by a thin insulating film, a current will flow due to the quantum mechanical tunnel effect. For both metals in the normal state the current-voltage characteristic is linear, for one of the metals in the superconducting state the current voltage characteristic becomes nonlinear, and for both metals in the superconductive state even a negative-resistance region is obtained. From these changes in the current voltage characteristics, the change in the electron density of states when a metal goes from its normal to its superconductive state can be inferred. By using this technique we have found the energy gap in metal films 1000–3000 A thick at 1°K to be $2\epsilon_{Pb}=(2.68\pm0.06)\times10^{-3}$ ev, $2\epsilon_{Sn}=(1.11\pm0.03)\times10^{-3}$ ev, $2\epsilon_{In}=(1.05\pm0.03)\times10^{-3}$ ev, and $2\epsilon_{Al}=(0.32\pm0.03)\times10^{-3}$ ev.

The variation of the gap width with temperature is found to agree closely with the Bardeen-Cooper-Schrieffer theory. Furthermore, the energy gap in these films has been found to depend upon the applied magnetic field, decreasing with increasing field.

INTRODUCTION

THE existence of an energy gap in superconductors is well documented experimentally, and is firmly grounded in the theory of superconductivity of Bardeen, Cooper, and Schrieffer.[1] Experimental evidence for the existence of a gap and, indirectly, its width, can be obtained from measurements of specific heat, thermal conductivity, nuclear relaxation, ultrasonic attenuation, and electromagnetic absorption.[2] In general, the width of the gap is inferred from the variation of one of the above parameters and, with the exception of electromagnetic absorption, represents only an indirect measurement.

This paper describes a method for investigating the energy gap and density of electron states in superconductors by means of electron tunneling through thin insulating films. It represents an entirely new approach to the problem and results in clear, unambiguous measurements of the energy gap. Some preliminary results, employing this method, have already been published.[3–6]

The samples used in this experiment consist of a thin insulating oxide layer sandwiched between two evaporated metal films. Experimentally, the electron tunneling current through the insulating oxide layer is observed as a function of the voltage applied between the two metal films. Because of their small physical size, the samples are well suited for standard low-temperature techniques.

If a *small* potential difference is applied to the two metals in their normal, nonsuperconducting state, the tunneling current through the insulating film will vary linearly with applied voltage, as long as the density of electron states in the two metals is constant over the applied voltage range.[7] On the other hand, if the density of electron states varies rapidly in this voltage range, as it does in superconductors, the current-voltage characteristics will be nonlinear. It appears that this nonlinearity is simply correlated with the variation in the density of electron states. In particular, no electrons can flow into the energy region of the gap in superconductors.

By this method we have measured the energy gap in lead, tin, indium, and aluminum. The variation of the energy gap as a function of temperature[6] and magnetic field has also been investigated.

APPARATUS

The apparatus which is shown in Fig. 1 consists basically of a liquid helium Dewar with provisions for

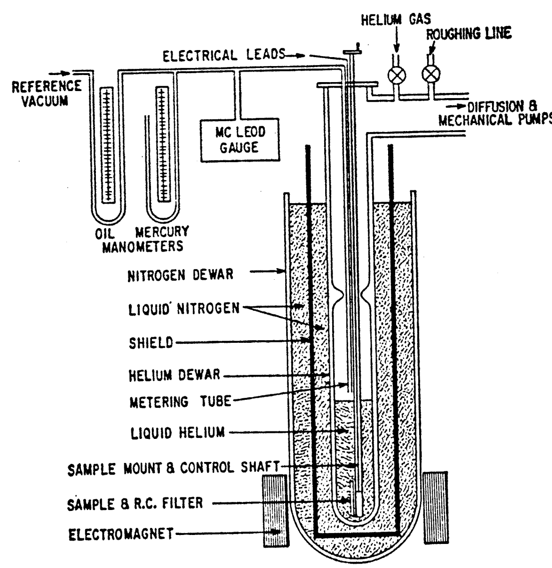


FIG. 1. A schematic drawing of the apparatus. The shield can be removed when studies are made using a magnetic field.

[1] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. 108, 1175 (1957).
[2] M. A. Biondi, A. T. Forrester, M. P. Garfunkel, and C. B. Satterthwaite, Revs. Modern Phys. 30, 1109 (1958).
[3] I. Giaever, Phys. Rev. Letters 5, 147 (1960).
[4] I. Giaever, Phys. Rev. Letters 5, 464 (1960).
[5] J. Nicol, S. Shapiro, and P. H. Smith, Phys. Rev. Letters 5, 461 (1960).
[6] I. Giaever, Proceedings of the Seventh International Conference on Low-Temperature Physics, Toronto, 1960 (to be published).
[7] J. C. Fisher and I. Giaever, J. Appl. Phys. 32, 172 (1961).

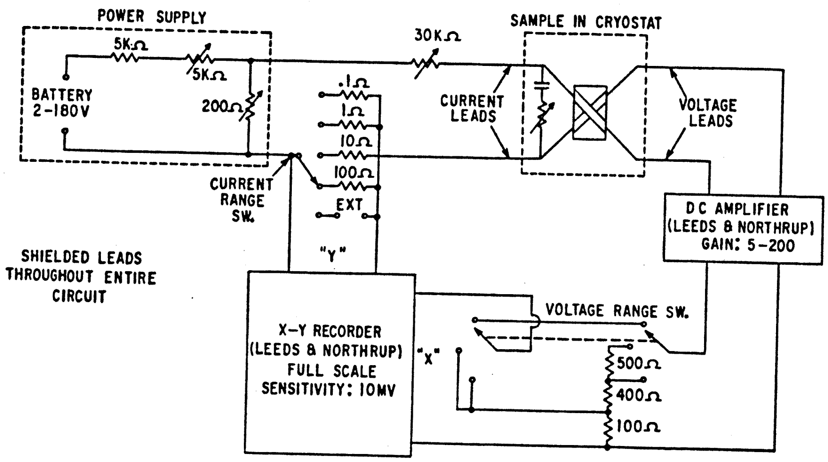


FIG. 2. Circuit diagram of the measuring circuit.

pumping on the helium, and an outer Dewar containing liquid nitrogen which acts as a radiation shield for the helium. The helium Dewar has a constriction in its diameter to minimize creep losses of the superfluid helium when the temperature is below the λ point.

Temperatures are measured by means of the helium vapor pressure. A metering tube which extends to within a few inches of the liquid helium level is connected to both oil and mercury manometers and to a McLeod gauge. The system is capable of attaining a temperature of about 0.9°K. Due to the low heat leakage, this temperature can be maintained for approximately six hours, which is adequate for making numerous measurements.

The electrical circuitry is shown in Fig. 2. To trace out the current-voltage characteristics, a Leeds and Northrup X-Y recorder and matching Leeds and Northrup dc amplifier are used in conjunction with external shunts and multipliers to extend the range of the instruments. These instruments contain chopper-stabilized amplifiers and, therefore, have virtually no drift. To accommodate various sample resistances and to obtain the necessary detail in the current-voltage curves, the current scale can be decade switched over a full-scale sensitivity from 100 ma to 1 μa and the voltage scale from 100 mv to 50 μv.

The emf source can be used as either a high- or low-impedance source, by suitable adjustment of the two variable resistors and the applied battery voltage. The high capacitance of the sample in conjunction with considerable lead inductance gives rise to very troublesome high-frequency oscillations whenever the sample is biased into its negative-resistance region. By placing an adjustable high-pass filter in parallel with the sample, the high-frequency oscillations can be eliminated or at least greatly reduced. The high-pass filter consists of a capacitor large in comparison to the sample capacitance and a variable resistor in series, and is in close proximity to the sample to minimize lead inductance. The oscillations are reduced by matching the variable resistance to the negative resistance of the sample. The variable resistor is a Bourns Trimpot which is mounted on the end of a $\frac{1}{4}\times 0.008$ in. stainless steel tube. Concentric with this tube is a $\frac{1}{8}\times 0.008$ in. stainless steel tube which engages the adjustment screw of the resistor and passes through an O-ring seal in the Dewar cover plate, to permit external adjustments.

The electrical connections into the Dewar, consisting of current and voltage leads, are brought out through the cover plate and are sealed in place with Apiezon wax to achieve a tight seal. In order to minimize heat leaks, four 3-mil Formex-covered copper wires are used inside the cryostat. To minimize induced noise, the entire electrical circuitry outside the Dewar is shielded. The sample and leads within the Dewar can be shielded by a copper-clad soft iron shield which sits in the liquid nitrogen, surrounding the helium Dewar. This shield is not used for measurements made with an externally applied magnetic field.

Since the voltages applied to the sample are very small, induced voltages caused by ever-present fluctuating stray fields remain a difficult problem even after careful shielding. The slow response time of the recording apparatus causes the readings to be averaged over the fluctuations resulting from induced voltages. Due to the nonlinear characteristics of our samples, this averaging tends to smooth out the current-voltage curves and results in lost detail. The difficulty is virtually eliminated by including a resistance in series with the current loop, and making this resistance as large as practical. The large resistance in series with the sample resistance acts as a voltage divider for induced noise, so that only a small amount of noise appears across the sample. This large series resistance effectively increases the emf source impedance and cannot be used when investigating the negative-resistance region of the sample. It has, however, been retained for measurements outside the negative resistance region on most samples.

The sample is mounted directly on the variable resistor which is a part of the high-pass filter. This insures mechanical rigidity and reproducible, accurate positioning for measurements involving magnetic fields.

When the sample is subjected to a magnetic field, it is aligned so that the field vector is in the plane of both films, parallel to the long dimension of the aluminum film, and normal to the long dimension of the other metal film.

SAMPLE PREPARATION

The sample consists of two metal films separated by a thin insulating layer. Aluminum/aluminum oxide/metal sandwiches are prepared by vapor-depositing aluminum on microscope glass slides in vacuum, oxidizing the aluminum, and then vapor-depositing a metal over the aluminum oxide. First the microscope slide is cut to size, $\frac{1}{2}\times 3$ in., so as to fit through the constriction in the helium Dewar. Next, indium is smeared onto the four corners of the glass slide to provide contacts between the evaporated metal strips and external leads. The glass slide with indium contacts is then washed with Alconox detergent, rinsed with distilled water and ethanol, and dried with dry nitrogen gas.

Next, the glass slide is mounted in the evaporator so that it can be positioned behind suitable masks in vacuum. The evaporations are made from tantalum strips approximately $\frac{3}{8}\times 1\frac{1}{2}\times 0.005$ in., which have previously been charged and heated in vacuum so that the charge wets the tantalum strip. The evaporations are made at a starting pressure of 5×10^{-5} mm Hg, or less.

Preparation of the metal/insulator/metal sandwich proceeds in three distinct steps, as shown in Fig. 3, during which the substrate is at room temperature.

First, a layer of aluminum is evaporated onto the glass slide between two contacts. This strip is 1 mm wide and 1000–3000 A thick. Next, the aluminum is oxidized either at atmospheric pressure or some reduced pressure. Finally, a layer of Al, Pb, In, or Sn, of dimensions similar to the aluminum strip, is evaporated over the aluminum oxide layer between the remaining two contacts.

The thickness of the Al_2O_3 insulating layer between the metal strips is subject to a number of variables. The pressure and time dependence of oxidation rate has been extensively investigated and is well documented in the literature.[8] Atmospheric humidity or residual H_2O vapor in the vacuum system also affects the oxidation rate. We have found that an increase in the amount of water effects a more rapid oxide growth rate. The oxide thickness is also contingent upon the evaporation rate and evaporation temperature of the metal layer deposited over the oxide layer. Presumably, metals which require higher temperatures for evaporation must give up more energy to the oxide film; i.e., the atoms penetrate further into the oxide, thereby effectively reducing the thickness of the oxide layer. Another parameter is oxidation temperature, elevated temperatures promoting an increase in the oxidation rate. A final variable is introduced by the evaporation rate of the aluminum layer, which influences its surface characteristics. We have noted that the oxide grows more slowly and reaches a thinner limiting value on films which were evaporated with a high deposition rate (approximately 1000 A/sec).

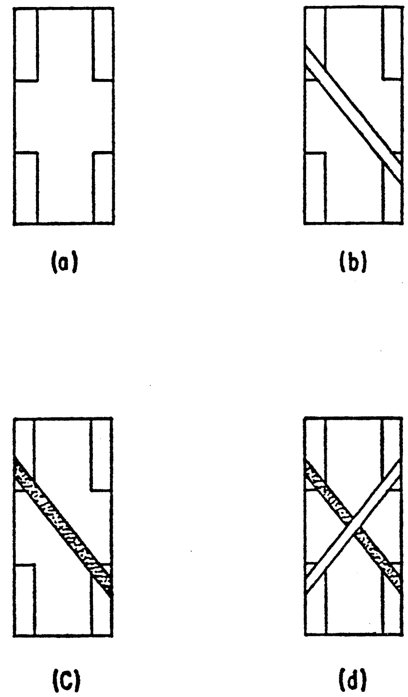


FIG. 3. Sample preparation. (a) Glass slide with indium contacts. (b) An aluminum strip has been deposited across the contacts. (c) The aluminum strip has been oxidized. (d) A lead film has been deposited across the aluminum film, forming an Al-Al_2O_3-Pb sandwich.

TABLE I. Approximate relationship between oxidation time and film resistance for Al-Al_2O_3-Pb sandwiches.

Time	Temperature	Pressure	Resistance (ohm/mm^2)
24 hr	100°C	atmospheric	10^5-10^7
24 hr	room	atmospheric	10^3-10^5
10 min	room	atmospheric	$10-10^3$
2 min	room	atmospheric	$1-10^2$
10 min	room	200μ Hg	10^1-10^{-1}
10 min	room	50μ Hg	$10^{-2}-10^{-1}$

By controlling these parameters to some extent, the resistance of a 1-mm^2 junction can be made to vary between 10^{-2} and 10^7 ohm. Typical oxidation conditions for an Al-Al_2O_3-Pb sandwich are given in Table I. (The resistance variations are probably due to the effect of humidity and the surface characteristics of the aluminum layer.)

It is possible to measure indirectly the thickness of the oxide layer by measuring the capacitance of the junction and then calculating the thickness.[7]

MODEL

The concept that particles can penetrate energy barriers is as old as quantum mechanics. In nuclear

[8] D. D. Eley and P. R. Wilkinson, *Structure and Properties of Thin Films* (John Wiley & Sons, Inc., New York, 1959), p. 508.

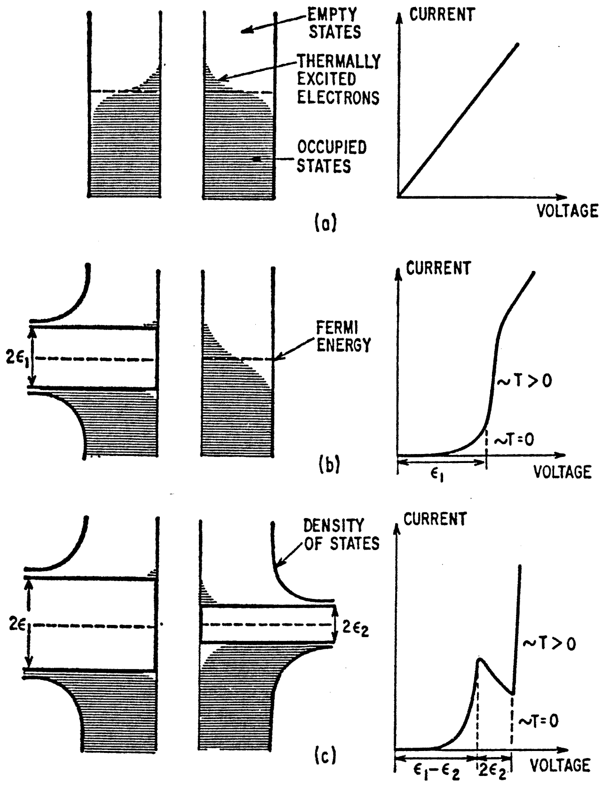


FIG. 4. Energy diagram displaying the density of states and the current-voltage characteristics for the three cases. (a) Both metals in the normal state. (b) One metal in the normal state and one in the superconducting state. (c) Both metals in the superconducting state.

physics, for example, the theory of α decay depends upon this tunnel effect. It has long been known that an electric current can flow between two metals separated by a thin insulating film because of the quantum-mechanical tunnel effect. Theoretical calculations were first made by Sommerfeld and Bethe[9] for a small potential difference applied between the two metals. These calculations were later extended by Holm.[10] An important result of these calculations is that for small voltages across the insulating film the tunnel current through the film is proportional to voltage. Holm *et al.*[11] furnished early experimental evidence for the tunneling effect, a work which was extended by Dietrich[12] and later by Fisher and Giaever.[7] The experiment of tunneling into superconductors[3] furnishes unquestionable evidence that this conduction mechanism is responsible for practically the whole current flow. In the following discussion we shall treat only the low-voltage region where the current flowing through the insulating film is proportional to the voltage across the film, provided both superconductors are in the normal state.

In Fig. 4(a) we show a simple model of two metals separated by a thin insulating film, the insulating film is pictured as a potential barrier. In Fig. 4(b) is shown the case when one of the two metals is in the superconducting state. Note how the electron density of states has changed, leaving an energy gap centered at the Fermi level as postulated by Bardeen, Cooper, and Schrieffer.[1] This particular model of a superconductor is a one-particle approximation, and it gives a surprisingly accurate picture of the experiments. In Fig. 4(c) both the metals are pictured in the superconducting state.

First we shall discuss qualitatively these three different cases, and later quantitatively calculate the current when both metals are in the normal state, and when only one of the metals is in the normal state.

The transmission coefficient of a quantum particle through a potential barrier depends exponentially upon the thickness of the barrier and upon the square root of the height of the barrier. For small voltages applied between the two metals neither the barrier thickness nor the barrier height is altered significantly. The current will then be proportional to the applied voltage, because the number of electrons which can flow increases proportionally to the voltage. The temperature effect will be very small, as the electron distribution is equal on either side of the barrier with metals in the normal state and in addition, kT is much smaller than the barrier height.

When one of the metals is in the superconducting state the situation is radically different. At absolute zero temperature, no current can flow until the applied voltage corresponds to half the energy gap. Assuming that the current is proportional to the density of states, the current will increase rapidly with voltage at first, and then will asymptotically approach the current-voltage characteristic found when both metals were in the normal state. At a temperature different from zero we will have a small current flow even at the lowest voltages. But since the two sides of the barrier now look different, the current will depend strongly upon temperature.

When both metals are in the superconducting state, the situation is again different. At absolute zero no current can flow until the applied voltage corresponds to half the sum of the two energy gaps. At a finite temperature, a current again will flow at the smallest applied voltages. The current will increase with voltage until a voltage equal to approximately half the difference of the two energy gaps is applied. When the voltage is increased further it is possible for only the same number of electrons to tunnel, but since the electrons will face a less favorable (lower) density of states, the current will actually decrease with increasing voltage. Finally, when a voltage equal to half the sum of the two gaps is applied the current will again increase rapidly with voltage and approach asymptotically the

[9] A. Sommerfeld and H. Bethe, *Handbuch der Physik*, edited by S. Flügge (Verlag Julius Springer, Berlin, 1933), Vol. 24, Part 2, p. 333.

[10] R. Holm, J. Appl. Phys. **22**, 569 (1951).

[11] R. Holm, *Electric Contacts* (Hugo Geber, Stockholm, Sweden, 1946).

[12] J. Dietrich, Z. Physik **132**, 231 (1952).

current-voltage characteristics obtained when both metals were normal.

Since we regard the distributions of holes and electrons in the metals in both the normal and superconducting state as symmetric about the Fermi level, no rectification effects are expected.

If we regard the tunneling through the insulating layer as an ordinary quantum-mechanical transition, the transition probability from an occupied state $\mathbf{k}$ on the left side of the barrier to a state $\mathbf{k}'$ on the right side can be written:

$$P_{\mathbf{k}\rightarrow\mathbf{k}'}=(2\pi/\hbar)|M|^2n'(1-f'), \qquad (4.1)$$

where n' is the density of states on the right side and f' the probability that the state $\mathbf{k}'$ is occupied. $|M|^2$ is the matrix element for the transition and we assume $|M|^2$ vanishes unless the components of $\mathbf{k}$ and $\mathbf{k}'$ transverse to the boundary are equal; that is, specular transmission and then n' is the density of states on the right for fixed wave number components parallel to the boundary. This is a convenient though not an essential assumption.

To calculate the current from left to right we sum over occupied states on the left and obtain

$$i=(4\pi e/\hbar)\textstyle\sum_{k_t}\sum_{k_x}|M|^2n'f(1-f'), \qquad (4.2)$$

where k_t is the component of wave number transverse to the barrier, k_x the component perpendicular to the barrier, e the electron charge, and f the probability that state $\mathbf{k}$ is occupied.

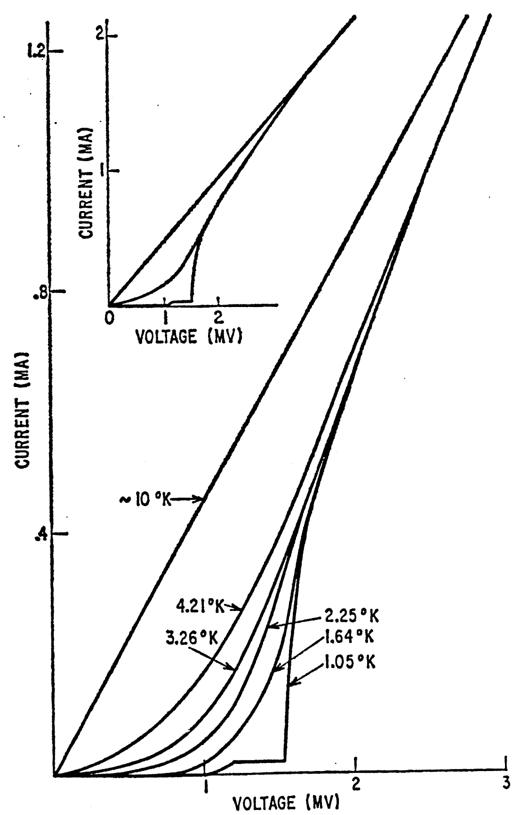


FIG. 5. Current-voltage characteristics of an Al-Al_2O_3-Pb sandwich at various temperatures.

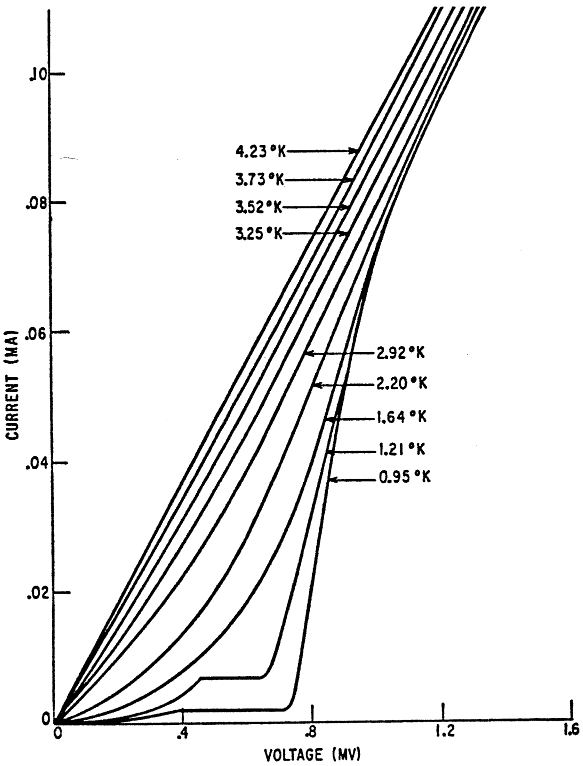


FIG. 6. Current-voltage characteristics of an Al-Al_2O_3-Sn sandwich at various temperatures.

By converting the sum over k_x to an integral over energy with fixed k_t we get

$$i=A\sum_{k_t}\int_{-\infty}^{\infty}|M|^2nn'f(1-f')dE, \qquad (4.3)$$

where A is a constant, n the density of states at the left side of the barrier (for fixed k_t), and E the energy measured from the Fermi energy.

By subtracting a similar expression for the current flowing from right to left, we get the net current flow:

$$I=A\sum_{k_t}\int_{-\infty}^{\infty}|M|^2n'n(f-f')dE. \qquad (4.4)$$

To fit the experimental results it is necessary to assume that $|M|^2\approx$constant. Bardeen,[13] using a many-particle point of view in connection with the WKB method, finds it plausible that $|M|^2$ is a constant over the energy values of interest. On assuming a constant $|M|^2$ and spherical symmetry of the dependence of energy on wave number, n' and n which are one dimensional densities of states are proportional to the total densities of states, and we may therefore sum over k_t directly and take $|M|^2$ out of the integral. We are

[13] J. Bardeen, Phys. Rev. Letters 6, 57 (1961).

left with

$$I=A'\int_{-\infty}^{\infty} n'n\{f(E)-f(E+eV)\}dE, \qquad (4.5)$$

where A' is a constant and eV is the difference between the two Fermi levels. (V is the applied voltage.)

For the current between two normal metals we obtain at absolute zero and for small applied voltages:

$$I_{NN}=A'n'(E_F)n(E_F)eV, \qquad (4.6)$$

i.e., the current is proportional to voltage.

For a superconductor we may take the density of states from the Bardeen-Cooper-Schrieffer theory:

$$n_s=n\frac{E}{(E^2-\epsilon^2)^{\frac{1}{2}}}, \qquad (4.7)$$

where E is measured from the Fermi energy, and ϵ is half the energy gap. Thus the current between one metal in the normal state and one metal in the superconducting state can be written:

$$I_{NS}=A'n'(E_F)n(E_F)\int_{-\infty}^{\infty}\frac{|E|}{(E^2-\epsilon^2)^{\frac{1}{2}}} \times[f(E)-f(E+eV)]dE. \qquad (4.8)$$

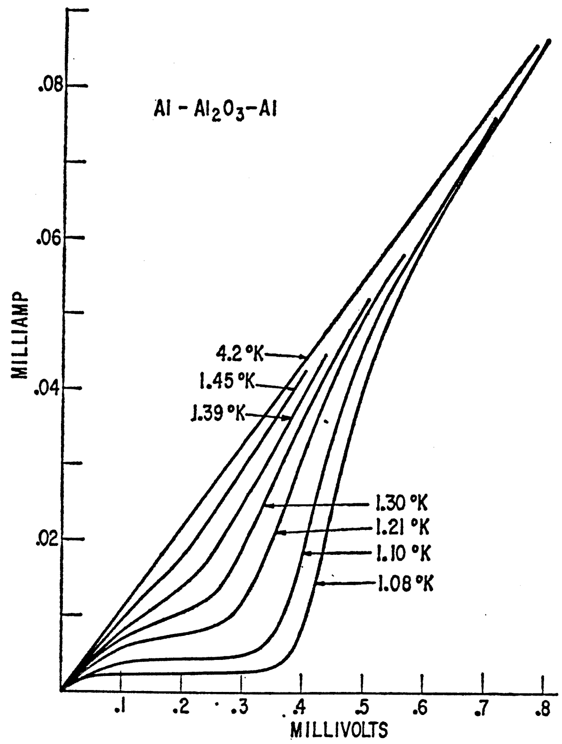


FIG. 8. Current-voltage characteristics of an Al-Al_2O_3-Al sandwich at various temperatures.

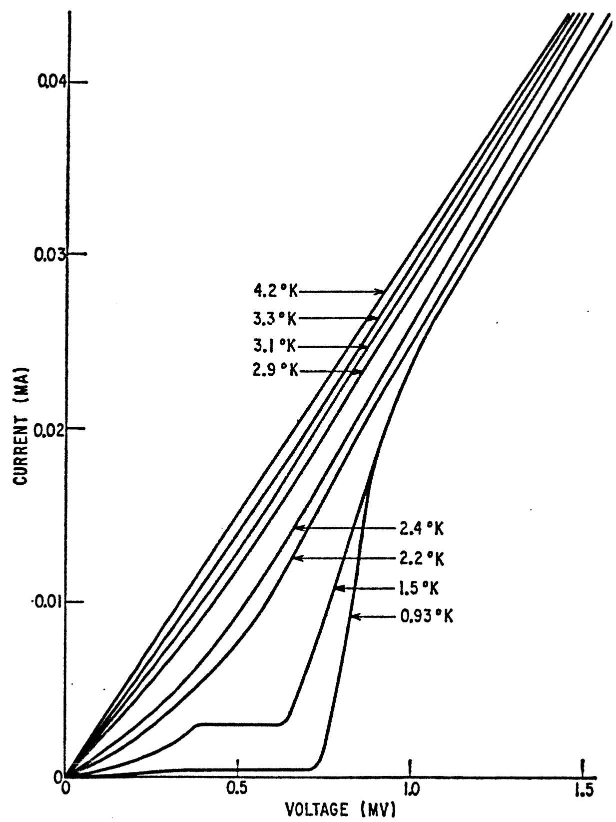


FIG. 7. Current-voltage characteristics of an Al-Al_2O_3-In sandwich at various temperatures.

For small applied voltages such that $eV<\epsilon$ we may evaluate the above integral, as shown in Appendix I, and obtain:

$$I_{NS}=2C_{NN}\frac{\epsilon}{e}\sum_{m=1}^{\infty}(-1)^{m+1}K_1\left(m\frac{\epsilon}{kT}\right)\sinh\left(m\frac{eV}{kT}\right), \qquad (4.9)$$

where C_{NN} is the conductance when both metals are in the normal state, K_1 is the first order of the modified Bessel function of the second kind, e the electron charge, k the Boltzmann constant, T the temperature, and m an integer. Evaluation of (4.9) for special cases is given in Sec. (c) below. Calculations of the current for $eV>\epsilon$ and for tunneling between two superconductors, require more extensive computation.

Finally, it should be mentioned here that we have treated the insulating layer as if it were a vacuum. However, since the insulator has both a conduction band and a valence band, we could possibly also get a "hole" current. In this particular case this is of little importance as we are mostly interested in the current ratio I_{NS}/I_{NN} rather than the absolute values of current.

EXPERIMENTAL RESULTS

(a) Energy Gaps

We report on four different combinations of superconductors namely Al-Al_2O_3-Pb, Al-Al_2O_3-Sn, Al-Al_2O_3-In,

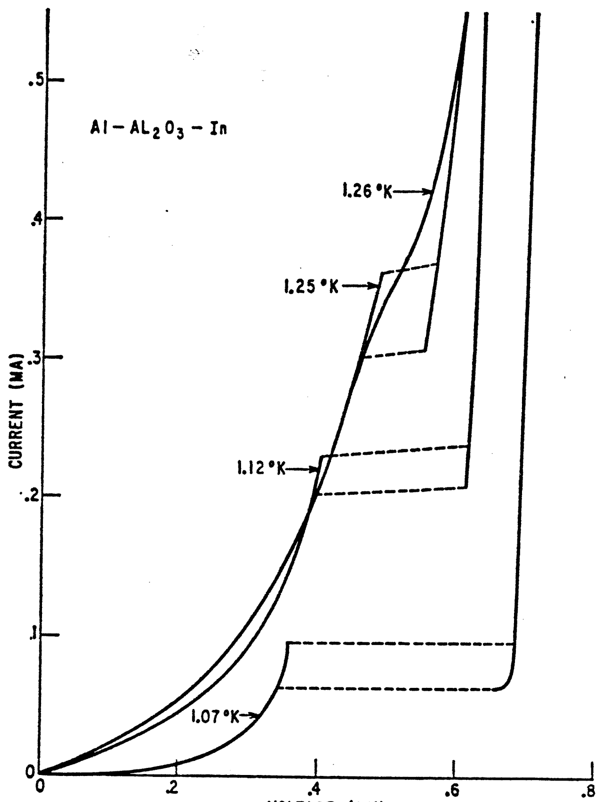


FIG. 9. Detailed current-voltage characteristics of an Al-Al_2O_3-In sandwich, showing the change of energy gap in Al as a function of temperature.

and Al-Al_2O_3-Al. The current-voltage characteristics at various temperatures for these four systems are shown in Figs. 5, 6, 7 and 8, respectively. As seen, the general behavior of the current-voltage characteristics is as predicted from the model. The negative resistance regions are not very apparent on these curves due to the current scale chosen. When the energy gaps on either side of the barrier are equal, as is the case for the Al-Al_2O_3-Al sandwich, a negative resistance region should be observable as well at sufficiently low temperatures. We did not observe this, however, due to temperature limitations in the experimental setup. Note in particular the insert on Fig. 5, showing that for larger voltages the current-voltage characteristics are independent of whether the metals are in the normal or superconducting states. This fact strongly supports the assumption that the tunnel current between superconductors is proportional to the density of states.

From these curves we find the energy gaps at approximately 1°K:

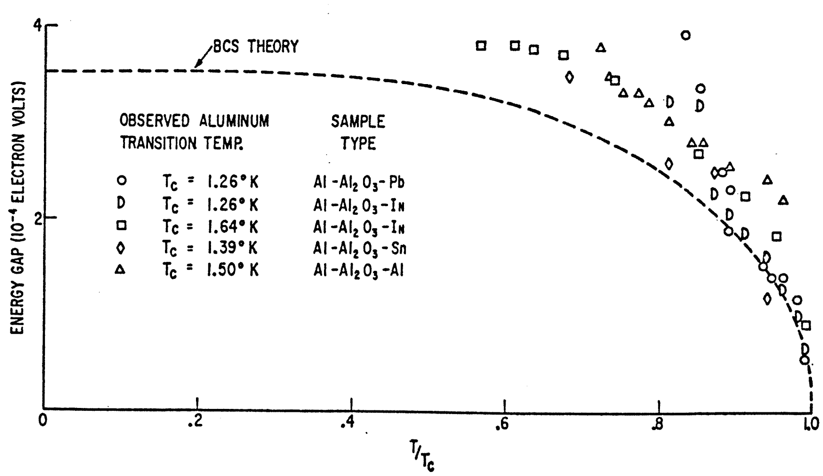
$$2\epsilon_{Pb} = (2.68\pm0.06)\times10^{-3}\text{ ev} = (4.33\pm0.10)kT_c,$$
$$2\epsilon_{Sn} = (1.11\pm0.03)\times10^{-3}\text{ ev} = (3.46\pm0.10)kT_c,$$
$$2\epsilon_{In} = (1.05\pm0.03)\times10^{-3}\text{ ev} = (3.63\pm0.10)kT_c,$$
$$2\epsilon_{Al} = (0.32\pm0.03)\times10^{-3}\text{ ev} = (3.20\pm0.30)kT_c.$$

While the energy gaps in Pb, Sn, and In will not change significantly between 1° and 0°K, this is not true for Al, because of its low transition temperature. It should be noted that the transition temperature for the aluminum films varied from sample to sample, was always greater than the bulk transition temperature, and increased with decreasing thickness of the aluminum films. The highest transition temperature observed for Al was 1.8°K. In calculating the energy gaps in terms of kT_c the bulk transition temperature has been used for all films. One reason for this choice is that the observed energy gap in the aluminum films at 1°K is approximately 0.32×10^{-3} ev, regardless of the transition temperatures observed. This experimental result may be due to the broad transition region usually observed in evaporated films.

(b) Variation of the Energy Gap with Temperature

In Fig. 9 we show detailed current-voltage characteristics for an Al-Al_2O_3-In sandwich as a function of temperature. Because the curves are traced out using a constant current source rather than a constant voltage source, the negative resistance region appears as a hysteresis loop. The width of this loop corresponds ap-

FIG. 10. The energy gap as a function of reduced temperature for several aluminum films, compared with the Bardeen-Cooper-Schrieffer theory.



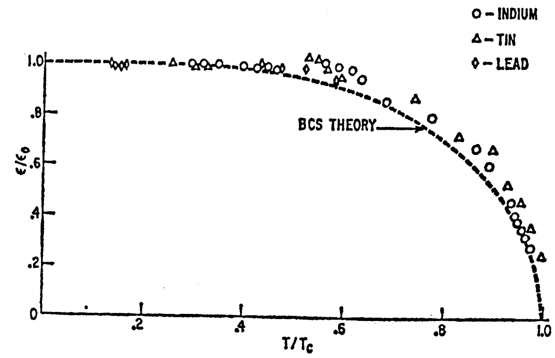


FIG. 11. The energy gap of Pb, Sn, and In films as a function of reduced temperature, compared with the Bardeen-Cooper-Schrieffer theory.

proximately to the full gap width in aluminum, and we can clearly see the variation of gap width with temperature. In Fig. 10 we have plotted the variation of the gap width as a function of reduced temperature for several different samples. For this figure we have used the observed value of the transition temperature T_c. As seen from the figure, the energy gap at $T=0$ does not appear to be very sensitive to the variations in the transition temperature actually observed for the aluminum films. One reason for this could be that the whole area of the aluminum film does not become superconducting at the same temperature, due to localized stresses or impurities. The best estimate of the energy gap for aluminum at absolute zero is

$$2\epsilon_{Al} = (4.2\pm0.6)kT_c = (0.42\pm0.06)\times10^{-3} \text{ ev},$$

where T_c is taken as the bulk value.

It is possible to observe directly the variation of the energy gap in aluminum over the entire applicable temperature range. The energy gap in indium, tin, and lead can also be observed directly in the temperature range in which aluminum is superconducting. At higher temperatures the gap in lead, tin, and indium is not directly observable; however, we are able to calculate the gap width for all temperatures. By letting $V\rightarrow0$ in Eq. (4.9), we may write:

$$\frac{I_{NS}}{I_{NN}} = 2\sum_{m=1}^{\infty}(-1)^{m+1}m\frac{\epsilon}{kT}K_1\left(m\frac{\epsilon}{kT}\right). \qquad (5.1)$$

The quality I_{NS}/I_{NN} as $V\rightarrow0$ is easily obtained from the experimental results and we may then calculate ϵ from Eq. (5.1). The results are shown in Fig. 11 and are in good agreement with the theory. It should be pointed out that the values of the energy gap, calculated in this way, are in agreement with the directly observed values in the temperature range where both of these measurements can be made. This is most gratifying since these measurements are independent of each other, one being defined at absolute zero, and the other arising solely from the temperature-dependence of the current. The calculated values of the energy gap may appear somewhat too large at low temperatures for some samples due to noise in the measuring circuit.

(c) Calculated versus Measured Current

For tunneling between a metal in the normal state and a metal in the superconducting state, we again use Eq. (4.9) and restrict the calculations to the region where $\epsilon > eV$. In Fig. 12, we compare the calculated values of current with the experimental results obtained on an Al-Al_2O_3-Pb sandwich at various temperatures. The agreement is very good using only two terms of the series in Eq. (4.9). Note in particular that for $\epsilon \gg kT$ and for large voltages such that $\sinh(eV/kT)\approx\frac{1}{2}\exp(eV/kT)$, we may write

$$\ln I_{NS} = \frac{1}{kT}eV + \alpha(\epsilon,T), \qquad (5.2)$$

where α is some function of ϵ and T, independent of V. Thus we can determine the temperature directly from the slope when we plot $\ln I_{NS}$ versus V.

(d) Variation of the Energy Gap with Magnetic Field

By subjecting these samples to a magnetic field parallel to the plane of the metal films, we have found that the energy gap is a function of the applied field. In Fig. 13 we show some detailed results obtained on an Al-Al_2O_3-Pb sandwich. These results are summarized in

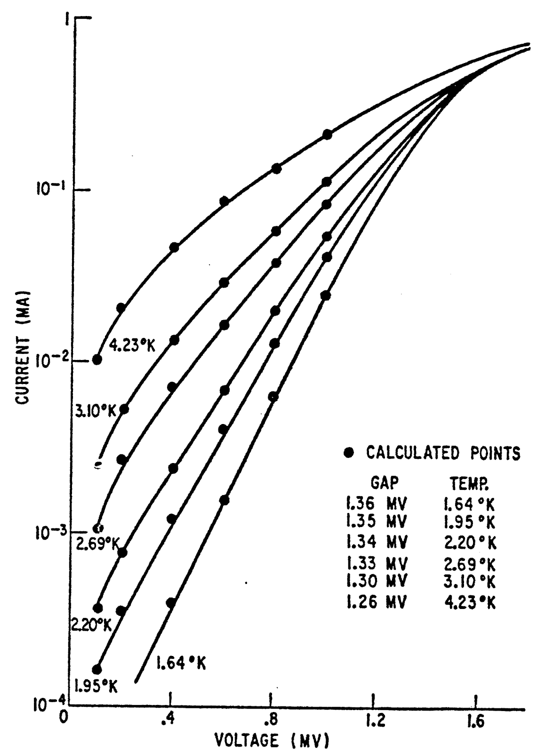


FIG. 12. Observed current-voltage characteristics for an Al-Al_2O_3-Pb sandwich at various temperatures, versus calculated values using the Bardeen-Cooper-Schrieffer density of states.

Fig. 14 where the gap width for aluminum is shown as a function of magnetic field. This curve does not agree with the observed fact that for bulk materials the transition between the normal and superconducting state is a first-order transition. A first-order transition would require a discontinuous change in gap width at the critical field. While this discrepancy may arise from the possibility that the transition is not of first order in a thin film, we believe it more likely that the surface roughness of the film will cause the magnetic field to be nonuniform. This nonuniformity will tend to smear the discontinuous change in gap that we expect at the critical field.

To make sure that the change in the current-voltage characteristics is due to a change in the energy gap, rather than being due to the aluminum film going into the intermediate state, we also investigated the effect of the magnetic field on the energy gap of lead. In Fig. 15 we plot current versus voltage for an Al-Al_2O_3-Pb sandwich at various magnetic fields. If we deal with the intermediate state in lead, then the observed current should be the sum of a current varying linearly with voltage and a current varying exponentially with voltage. This is clearly not so. On the other hand, a good fit to these curves can be obtained by using the expression derived for the tunnel current between one normal and one superconducting member with a varying gap for different field strengths. To obtain a good fit, it is necessary to use a rather large gap. This is probably due to noise in the measuring circuit or possibly a non-uniform energy gap in lead. It should be mentioned, although no detailed investigation has been made by us, that for thinner films much higher fields are needed to observe the change in the energy gap.

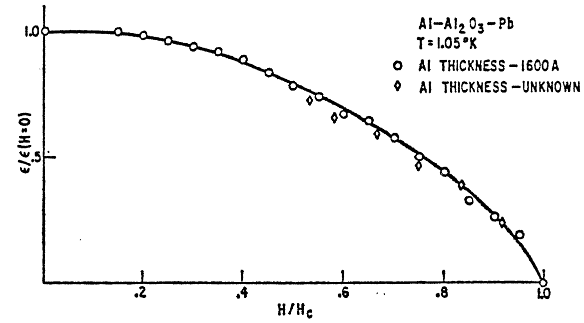


FIG. 14. Apparent variation of the energy gap in an aluminum film as a function of the applied magnetic field.

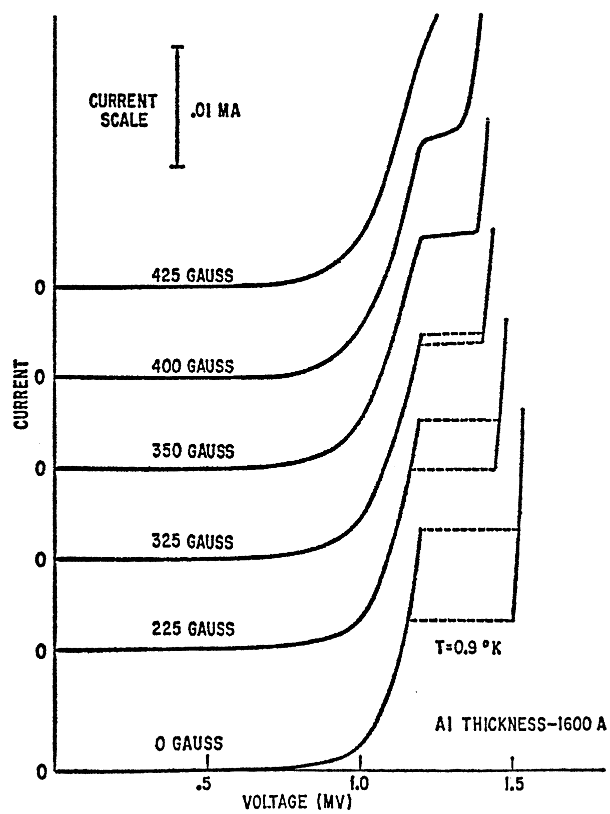


FIG. 13. Detailed current-voltage characteristics of an Al-Al_2O_3-Pb sandwich, showing a change in the energy gap of aluminum as a function of the applied magnetic field.

(e) Density of States

The good agreement between the experimental and calculated currents, using the density of states from the

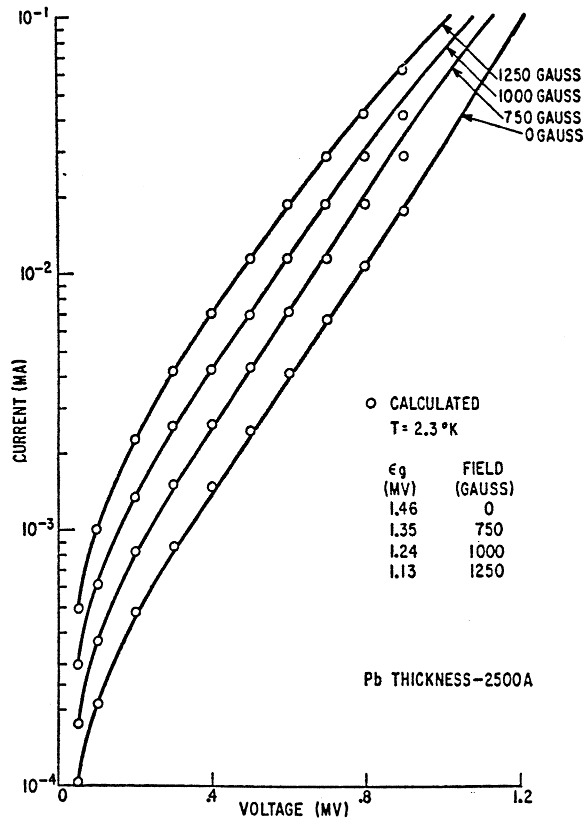


FIG. 15. The change in the current-voltage characteristics of an Al-Al_2O_3-Pb sandwich as a function of the magnetic field, demonstrating that the observed change cannot be due to the lead film being in the intermediate state.

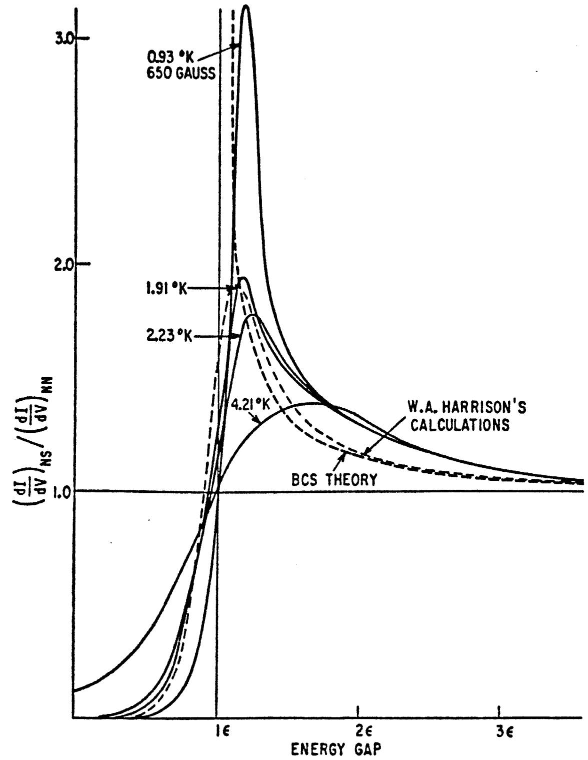


Fig. 16. The relative conductance for an $Al\text{-}Al_2O_3\text{-}Pb$ sandwich, i.e., the conductance of the sandwich when the lead film is in the superconducting state, divided by the conductance when the lead film is in the normal state, plotted against energy, and compared with the Bardeen-Cooper-Schrieffer density of states. This density of states is used by W. Harrison in his calculations, with $\epsilon/kT=10$.

Bardeen-Cooper-Schrieffer theory, is a great triumph for this theory. In deriving Eq. (4.9), we have integrated over the density of states so that the current is relatively insensitive to small variations in the density of states. Under the assumption that the current is proportional to the density of states, we should get the relative change in the density of states directly by plotting the conductance when one of the metals is superconductive $(dI/dV)_{NS}$ divided by the conductance when both metals are normal $(dI/dV)_{NN}$ against energy. In Fig. 16 we show these results, obtained from an $Al\text{-}Al_2O_3\text{-}Pb$ sandwich at four different temperatures. Note that at the lowest temperature we have kept the aluminum normal by applying a magnetic field and this again smears the energy gap in lead, making it difficult to assign a specific value to the gap. We see that in spite of the kT smearing, the density of states strongly resembles the theoretical density of states.

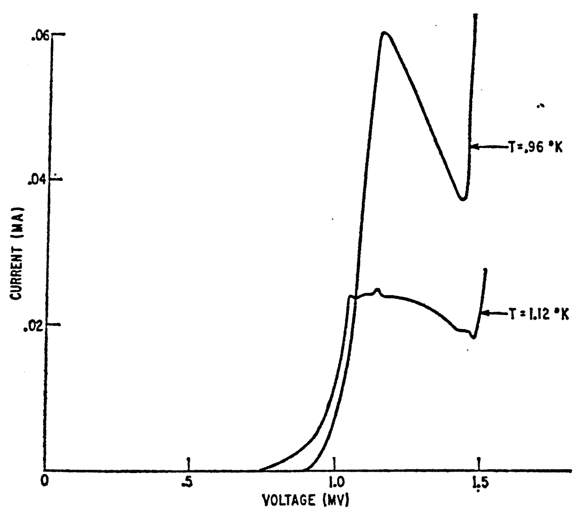


Fig. 17. The negative-resistance region traced out for two different $Al\text{-}Al_2O_3\text{-}Pb$ sandwiches. We believe the wiggles in the lower curve are due to oscillations in the circuit.

(f) Negative-Resistance Region

In spite of the damping RC network used in parallel with the sample, we found it difficult to eliminate self-induced oscillations in the negative-resistance region. In Fig. 17 we show two attempts to trace out the negative resistance region. We believe that induced noise in the measuring circuit is the limiting factor in tracing out the negative-resistance region, as literally microvolts of induced noise will smear out the curves.

(g) Effect of Metal Bridges and Trapped Flux

In Fig. 18 we show the effect of a metal bridge short-circuiting the sample. The bridge is initially superconducting so that no voltage can be applied across the sample. Then, at a certain current density the bridge becomes normal, but now its resistance is too large to appreciably affect the tunnel current. When the voltage

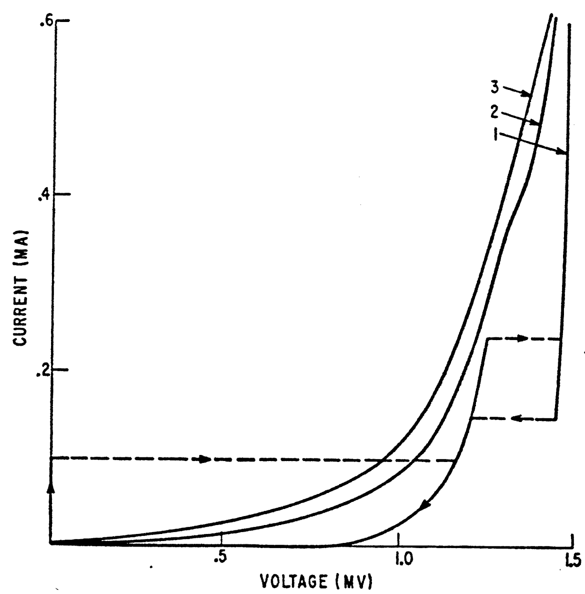


Fig. 18. The effect of trapped flux on the current-voltage characteristic of an $Al\text{-}Al_2O_3\text{-}Pb$ sandwich. (1) The sample with no field applied; (2) the external field removed, showing the effect of the trapped flux. The figure also shows the effect of a metal bridge across the insulating film; (3) with a magnetic field applied normal to the surface of the films.

is again reduced, the bridge remains normal at a lower current density due to Joule heating.

In Fig. 18 we also show the effect of trapped flux, when the magnetic field purposely has been applied normal to the films. The trapped flux has a large effect upon the current-voltage characteristics, and this technique may possibly be helpful in studying the intermediate state.

(h) Other System

All the experiments we report on have been done by using Al_2O_3 as the insulating layer; however, the experiments may be done by using other insulating layers as well. For example, we have observed tunneling through tantalum and niobium oxides. In these experiments we used bulk specimens of tantalum and niobium; however, we did not observe any evidence for an energy gap in any of these materials. We believe the reason for this is that due to impurities, the surfaces of these materials did not become superconducting. Another superconductor used by us is lanthanum, in which we have observed evidence for an energy gap.

SUMMARY

The method of studying superconductors by electron tunneling has been very successful, and the results are in good agreement with the Bardeen-Cooper-Schrieffer theory. We have directly verified the change of energy gap with temperature. Also, we have shown that for thin films the energy gap is a function of the magnetic field.

ACKNOWLEDGMENTS

We are grateful for the generous and unselfish help received from all members of the Physical Metallurgy Section. We wish to extend special thanks to C. P. Bean, J. C. Fisher, W. A. Harrison, and R. W. Schmitt for their encouragement and interest. Our thanks also to M. V. Doyle for help in performing some of the experiments and L. B. Nesbitt for advice concerning cryogenics.

APPENDIX I

To evaluate the expression:

$$I_{NS}=A'n'(E_F)n(E_F)\int_{-\infty}^{\infty}\frac{|E|}{(E^2-\epsilon^2)^{\frac{1}{2}}}\times[f(E)-f(E+eV)]dE, \quad (A.1)$$

we introduce the conductance C_{NN} when both metals are normal, i.e.,

$$\frac{I_{NN}}{V}=C_{NN}=A'n'(E_F)n(E_F)e, \quad (A.2)$$

and split the integral into two parts:

$$I_{NS}=\frac{C_{NN}}{e}\int_{+\epsilon}^{\infty}\frac{E}{(E^2-\epsilon^2)^{\frac{1}{2}}}\{f(E)-f(E+eV)\}dE - \frac{C_{NN}}{e}\int_{-\infty}^{-\epsilon}\frac{E}{(E^2-\epsilon^2)^{\frac{1}{2}}}\{f(E)-f(E+eV)\}dE. \quad (A.3)$$

By introducing $x+\epsilon=E$ in the first integral and $x+\epsilon=-E$ in the second integral, we get

$$I_{NS}=\frac{C_{NN}}{e}\int_{0}^{\infty}\frac{x+\epsilon}{[(x+2\epsilon)x]^{\frac{1}{2}}}[f(x+\epsilon)-f(x+\epsilon+eV)]dx + \frac{C_{NN}}{e}\int_{\infty}^{0}\frac{x+\epsilon}{[(x+2\epsilon)x]^{\frac{1}{2}}}\times\{f[-(x+\epsilon)]-f[eV-(x+\epsilon)]\}dx, \quad (A.4)$$

and because the Fermi function is an even function, i.e. $f(-\xi)=1-f(\xi)$

$$I_{NS}=\frac{C_{NN}}{e}\int_{0}^{\infty}\frac{x+\epsilon}{[(x+2\epsilon)x]^{\frac{1}{2}}}\times[f(x+\epsilon-eV)-f(x+\epsilon+eV)]dx. \quad (A.5)$$

By expanding the Fermi function in a series valid for $\epsilon>eV$, we obtain

$$I_{NS}=2\frac{C_{NN}}{e}\sum_m(-1)^{m+1}e^{-m(\epsilon/kT)}\sinh(meV/kT)\times\int_0^{\infty}\frac{x+\epsilon}{[(x+2\epsilon)x]^{\frac{1}{2}}}e^{-m(x/kT)}dx. \quad (A.6)$$

The last integral is of a known Laplace-integral form [A. Erdélyi, *Table of Integral Transforms* (McGraw-Hill Book Company, Inc., 1954)], and we obtain

$$I_{NS}=2C_{NN}\frac{\epsilon}{e}\sum_m(-1)^{m+1}K_1(m\epsilon/kT)\sinh(meV/kT), \quad (A.7)$$

where K_1 is the first-order modified Bessel function of the second kind.

APPENDIX II

Note added in proof. It is of interest to compare the values of the energy gaps obtained by using electron tunneling to previous direct measurements of the energy gap (Table II).

TABLE II.

		Energy gap in units of kT_c	
Superconductor	Tunneling measurements	Richards and Tinkham[a]	Ginsburg and Tinkham[b]
Indium	3.63±0.1	4.1±0.2	3.9±0.3
Tin	3.46±0.1	3.6±0.2	3.3±0.2
Lead	4.33±0.1	4.1±0.2	4.0±0.5

[a] P. L. Richard and M. Tinkham, Phys. Rev. 119, 581 (1960).
[b] D. M. Ginsburg and M. Tinkham, Phys. Rev. 118, 990 (1960).

IVAR GIAEVER: A SCIENTIFIC AUTOBIOGRAPHY*

I was born in Bergen on the west coast of Norway, in 1929, but I only lived there for a year. We moved to a community known as Toten, which is about two hours by car north of Oslo, and I grew up there in the "inland" of Norway. It's very difficult to live *inland* in Norway. This is farm country, so I grew up on a farm. My father was a pharmacist, as was my grandfather. I went to public school in Toten, but there were no high schools there. So when I was 14 or 15, I had to move away from home in order to attend high school in a city across a lake from us. It wasn't very far away, but I lived there and went home on weekends.

It's difficult to describe how I became interested in engineering. I *wasn't* really very interested in mechanical engineering, the field in which I majored. The problem was that in Norway at that time the schools were in short supply. For the first seven years, everybody went to school. I think there were about 25 people in my elementary class, and only three or four went on to secondary school. Only the people with the best grades could get in. Then, in secondary school there were perhaps 25 people in a class, and only three or four went on to high school. And so we went to high school, and only two or three went on to college.

I *was* interested in electrical engineering or electronics at that time, but I couldn't get into either of those fields because my grades weren't good enough. I applied for chemical engineering but they wouldn't accept me either, because of my grades. Finally I was accepted in mechanical engineering, which was my last choice. I wasn't very interested in that, but that's the way the ball bounces.

After graduation from college, which closely followed my marriage, I spent a required year in military service. When I was discharged, I found it easy to get a job as an engineer, but impossible to find an apartment for my family, which now included a young son. For a while I worked as a patent examiner in Oslo, answering every advertisement in the newspapers that held out the promise of an apartment, without getting a single reply. Finally, we decided to move to the United States or Canada.

I had four good friends from college who had moved to the United States, and they were writing me letters about the streets being "paved with gold." The reason we eventually left for Canada was because when you went to the American Embassy and said you wanted to go to the United States, they would give you some forms to fill out and tell you that it would probably take about a year and a half to get a visa. When I went to the Canadian Embassy, they said "You're an engineer . . . that's great. In a month and a half we'll have a visa ready for you."

When we arrived in Toronto, I simply could not get a job. All we were allowed to take out of Norway was $100 each. My wife knew some people in Toronto, so we did not starve, but there were absolutely no jobs. We had arrived just before Christmas 1954, and everyone said,"Merry Christmas—and come back in April." Employment, at least at that time, was very seasonal. IBM would not even let me fill out an application form.

I walked into the reception room of Canadian General Electric in Toronto, sort of a big hall, and told the receptionist that I wanted to apply for a job. I didn't speak English very well. The girl told me to go up some stairs and take the first door on the left, or right, whatever it was she said. I did what I thought she had said, opened the door, and found myself back out on the street.

* Based on extemporaneous, autobiographical comments of I. Giaever, in an interview with the *R&D Review*, General Electric Company, 1974.

At the author's request, his comments are reproduced in their original conversational form.

So I walked away, thinking maybe she had done this on purpose, but after I had gone a few hundred yards I thought, "My God, she couldn't have been that cruel," right? So I went back in and told her I had lost my way, and this time she took me by the hand to the Employment Office. There they said they were very sorry but there were no jobs since I was not a Canadian citizen, but I could fill out a form if I wanted to. So I filled one out and I left, not expecting to hear from them again.

I finally got a job as a draftsman in an architect's firm through the help of a fellow Norwegian who worked there. After several months, with the job market livening up with the coming of spring, I received a telegram from Canadian General Electric offering me a job, which I accepted.

When I joined CGE, I had the opportunity to take an engineering course that the company offered. Actually, it was a series of three courses called the "A,B, and C" courses.

As you may have gathered, I had been a somewhat indifferent student in Norway, but in Canada I realized that this was my last chance—if I wanted to get somewhere I would have to buckle down. So I worked hard on the A course and I learned a lot. Each week we would be given an engineering problem and we would have to work out all the different aspects of it. It was far more demanding than school problems, where you know you are working on a certain chapter in the textbook so you know what techniques you are expected to use to solve them. When the course was over, I wanted to go on to take the other two parts—B and C—but they weren't available in Canada. I had also heard that salaries were higher in the U.S., so I started to work on being transferred.

After transferring to the General Electric Company in Schenectady, New York, I was given a series of assignments as an applied mathematician in various parts of the sprawling Schenectady plant. At the same time, I was taking the engineering courses that had drawn me to the Research Laboratory (as it was then known) and I found that I liked the atmosphere and was stimulated by the mathematicians, scientists, and engineers with whom I worked. In 1958, with my courses completed, I joined the staff.

Before I actually started to work at the lab, I took a leave of absence for two months and went to Norway on a sort of vacation. The people at the lab had said that I would be working in the area of thin films. Knowing nothing of the current research in physics, I thought that would have something to do with photography, so while I was in Norway I went to the library and took out a big book on films and photography.

When I got back to the lab I began to work closely with Dr. John Fisher, who had encouraged me earlier when I first decided that I wanted to come to the lab. He set me straight on what thin films were and put me in touch with other people on the staff who were working in that area. I really don't know how I got onto the concept of tunneling. I didn't know about tunneling—that's a quantum mechanical concept, and I hadn't had any quantum mechanics, so obviously it must have been due to John. But I do remember that after a short time I started measuring d.c. currents across a capacitor, and that's really what tunneling is. I'm sure that John knew about Esaki's experiments—Esaki had done tunneling in semiconductors. I hadn't been at G.E. more than maybe half a year before I started to do experiments in tunneling.

When I started tunneling work, John and I did a whole series of experiments designed to show that electrons can travel from one metal to another and I became convinced that we had really observed it. I gave a talk at the lab describing what we had seen. It was very well received, but it was clear to me that many people were properly skeptical. It's easy to measure a current between two metals separated by an insulator, but you don't know whether you have a tunneling current or whether you have a short circuit—there can be all sorts of things that can go wrong with the experiment. How can you *really* convince people that you're dealing with tunneling? I looked around for ways of proving this conclusively, but there were all kinds of experimental difficulties and none of them worked very well.

But at the same time, I had started at Renssalaer Polytechnic Institute to get a Ph.D. in physics. I was taking a solid state physics course, and we got to superconductivity. One day in Professor Hill Huntington's class, the new BCS theory of superconductivity came up that dealt with an "energy gap" in a superconductor. It was obvious to me, right away, that if I could tunnel into a superconductor having an energy gap I should see a large effect from that energy gap. I knew I had found the experiment I had been looking for. That I knew I could do—there would be no experimental difficulties except for cooling things down, but I knew I could do that.

I talked to some of the fellows at G.E., and they said, "Great. It won't work, but it's a great idea. Superconductivity is much more complicated than this simple energy-gap picture." But they all said go ahead, and within a week I had done it. That's the experiment that led to it all.

The tunneling experiments I did wouldn't have gotten anywhere if it hadn't been for the superconductivity experiment. But because I happened to have the right background when I heard about the superconductivity theory—that made the difference.

By 1969 I had stopped doing superconductivity and, in 1970, I received a Guggenheim Fellowship which took care of half my needs while General Electric supplied the other half, and I went to Cambridge University for a year on sabbatical. I didn't really have it clear in my mind what I should do when I went there. I thought I should do some tunneling work, but when I got there I realized that wouldn't be the thing to do, since it would be much more difficult doing an experiment there than it would be here, so why waste the time? So finally I decided to learn some biology.

I chose biology because Charlie Bean, my friend and co-worker, had switched a few years before from physics to biology, and secondly because—rightly or wrongly—I was tired of working in the field of solid state physics.

By then, everything appeared to be calculable. Solid state physics had reached the point where I thought applied mathematics was, when I entered physics. It has become a more mature science, and therefore the problems are harder both to identify and to solve. There are a lot of experiments that can be done, of course, in order to elucidate the physics, but as I see it, there are no great unsolved problems on which I can have an impact. I don't mean to say that there are not going to be any inventions in solid state physics, or that it is not going to have large commercial impact. It has simply lost some of its appeal, possibly because of the great sophistication required in instrumentation.

Things are very different in biology. There are enormous numbers of problems waiting to be solved. Take memory, for example. There's a mechanism there, but nobody knows what it is. Some people say that memory is superconductive, some say it deals with protein molecules, and others say you have electrical impulses going back and forth all the time, but the fact is that the explanation is completely unknown. Something makes you remember and it somehow must be something involving chemistry or physics, but nobody knows what it is. So if you want to make an impact, solve the problem of memory. I don't say that it's an easy problem to solve, but it's an easy problem to *identify*. You can work towards that goal.

Moreover, in biology you can still succeed in doing things with very simple means, whereas in most solid state physics problems you need sophisticated equipment before you can start. I like doing very simple experiments, and since solid state physics has matured that becomes more and more difficult.

Perhaps I should add just one more thing. When I came to G.E., I was 29 years old, and I talked to John Fisher. He is very enthusiastic and I talked to him about everything. I told him I was really too old to do something in physics, because people normally do their best work in physics when they are much younger, but I would like to learn.

"No," John said, "that is not the reason. People do their good work when they are learning. You are 29 years old and you are going to learn something and then you'll do good work. When you know it all, then you become stale. Then it's time to switch your field."

You don't know it all, of course, but you may think you do. When you have to learn something you get all sorts of ideas. It's an exhilarating experience, even though the ideas you get are most often incorrect.

Now, just because this mode of working fits me, it does not mean that everybody should do it. Fortunately, we are all sorts of people, who depend on each other and contribute to each other's work. I have certainly benefitted a lot from other people's work or advice, and I hope to contribute a little, too. □