Classic paper presentation

Electron tunneling and superconductivity

Nobel lecture, December 12, 1973

by

Ivar Giaever

Samapti Mondal
05.10.2024

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

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 that we applied it to. 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 lately turned his attention towards theoretical physics. He had the notion that useful electronic devices could be made using 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 in Troy, where I took formal courses in Physics. For 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 Figure 1. While classical mechanics correctly predicts the behavior of large

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 Å apart, and we decided early in the game not to attempt to use air or 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 non-reproducible 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 worried a lot-1 was afraid I would get stuck in experimental physics tied down to this expensive machine. My plans at the 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

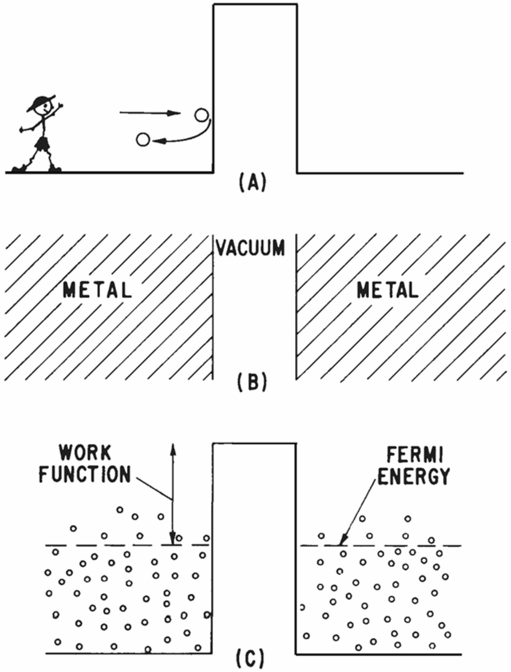


Fig. 1.
A. If a man throws a ball against a wall the ball bounces back. The laws of physics allow the ball to penetrate or tunnel through the wall but the chance is infinitesimally small because the ball is a macroscopic object. B. Two metals separated by a vacuum will approximate the above situation. The electrons in the metals are the "balls", 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 microscopic particle.

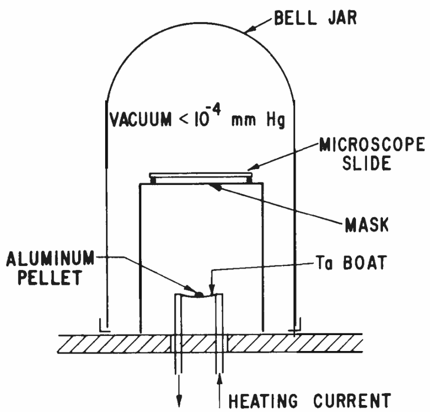


Fig. 2.
A schematic drawing of a vacuum system for depositing metal films. For example, if aluminum is heated resistively in a tantalum boat, the aluminum first melts, then boils and evaporates. The aluminum vapor will solidify on any cold substrate placed in the vapor stream. The most common substrates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

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 Figure 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.

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 Figure 4. Several checks were done, such as varying the area and the oxide

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 tunneling3 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 dealt 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 just like quan-

available. I continued to take formal courses at RPI, 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 theory. If the theory was any good and if my tunneling experiments were any good, it was obvious to me that by combining the two, some pretty interesting things should happen, as illustrated in Figure 5. When I got back to the GE Labo-

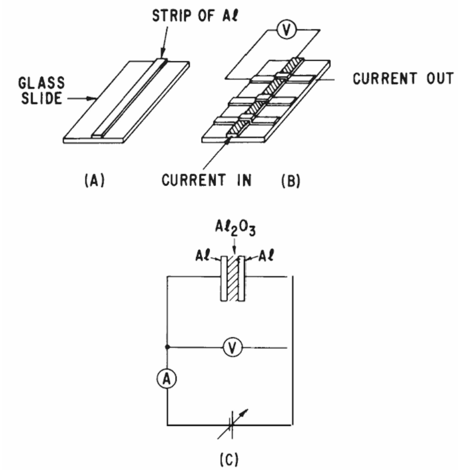


Fig. 3.
A. A microscope glass slide with a vapor deposited aluminum strip down the middle. As soon as the aluminum film is exposed to air, a protective insulating oxide forms on the surface. The thickness of the oxide depends upon such factors as time, temperature and humidity. B. After a suitable oxide 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 50Å or so, an appreciable dc current will flow through the oxide.

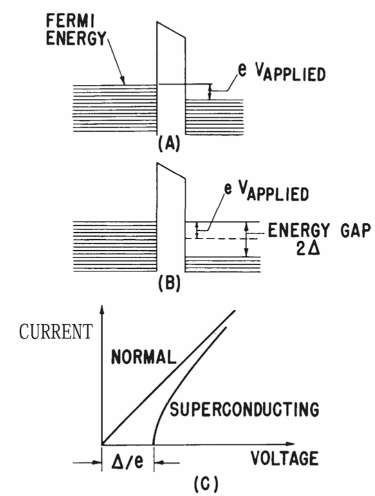


Fig. 5.
A. An energy diagram of two metals separated by a barrier. The Fermi energies in the two metals are at different levels because of the voltage difference applied between the metals. Only the left metal electrons in the energy range $e \cdot V_{App}$ can make a transition to the metal on the right, because only these electrons face empty energy states. The Pauli Principle allows only one electron in each quantum state. B. The right-hand metal is now superconducting, and an energy gap 2Δ 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.

mental setup is shown in Figure 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 which 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 very familiar with their use. In the third attempt rather than deliberately oxidizing the first aluminum strip, I simply exposed it to air for only a few minutes, and put it back in the evaporator to deposit the cross strips of lead. This way the oxide was no more than about 30Å 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 Figure 7. That was exciting! I immediately repeated the experiment using a different sample - 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 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 Figure 8. Every-

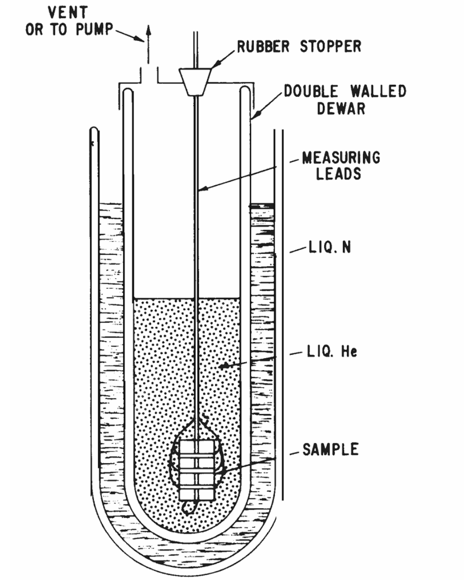


Fig. 6.
A standard experimental arrangement used for low temperature experiments. It consists of two dewars, the outer one contains liquid nitrogen, the inner one, liquid helium. Helium boils at 4.2" K at atmospheric pressure. The temperature can be lowered to about 1°K by reducing the pressure. The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

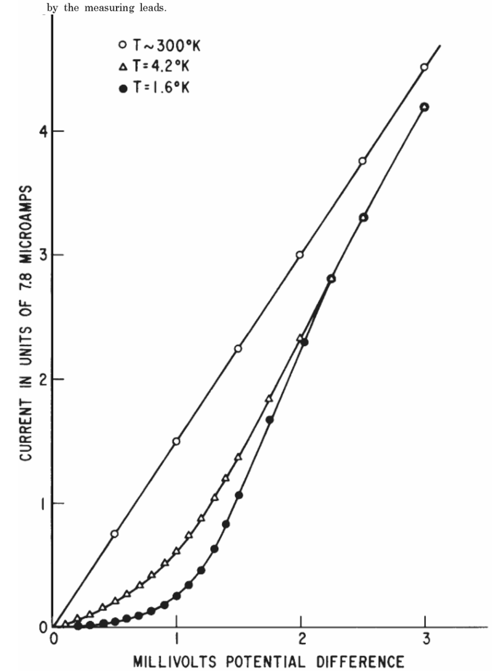


Fig. 7.
The current-voltage characteristic of an aluminum-aluminum oxide-lead sample. As soon as the lead becomes superconducting the current ceases to be proportional to the voltage. The large change between 4.2" K and 1.6" K is due to the change in the energy gap with temperature. Some current also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

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.

12. That made us happy because all that the tunneling experiments had done up till now 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 indeed was correct. Professor Bardeen gave a detailed account wide bridge would 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 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

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.

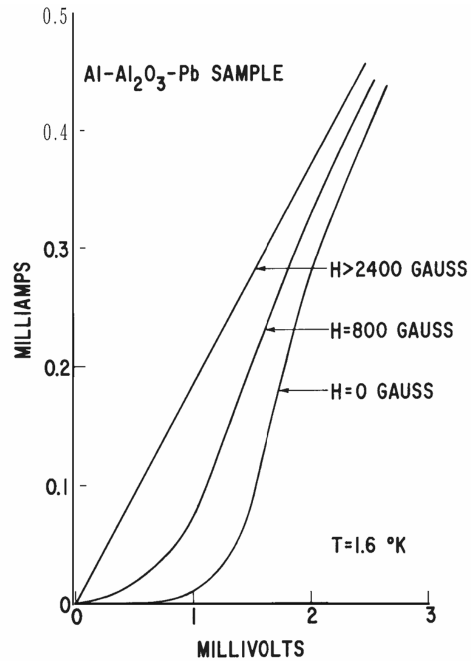
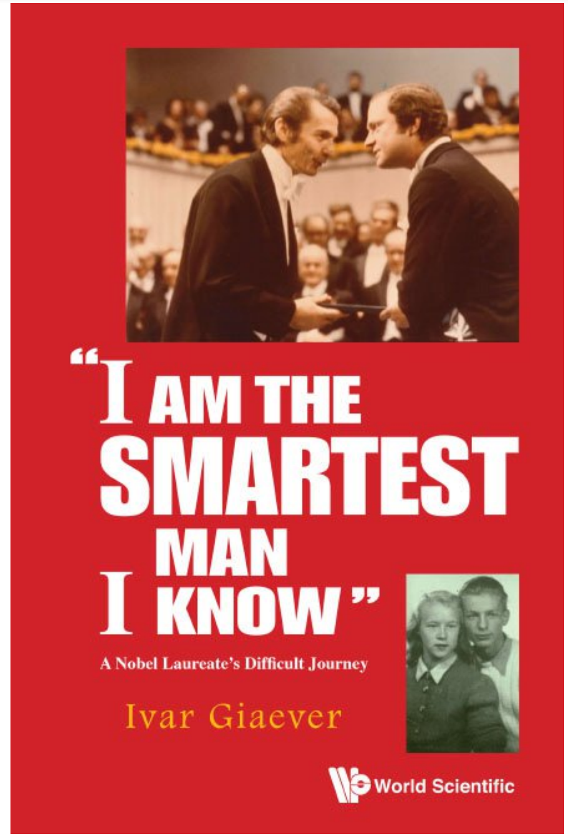


Fig. 8.
The current-voltage characteristic at 1.6” K as a function of the applied magnetic field. At 2 400 gauss the films are normal, at 0 gauss the lead film is superconducting. The reason for the change in the characteristics between 800 gauss and 0 gauss is that thin films have an energy gap that is a function of the magnetic field.

Biography

Giaever in 2010

Born	April 5, 1929 (age 95) Bergen, Norway
Nationality	Norway · United States
Alma mater	Norwegian University of Science and Technology Rensselaer Polytechnic Institute
Known for	Tunneling phenomena in superconductors
Awards	Oliver E. Buckley Condensed Matter Prize (1965) Nobel Prize in Physics (1973)
Scientific career	
Fields	Solid-state physics Biophysics



Thank you