GENERAL ELECTRIC

Research Laboratory

TUNNEL DIODES

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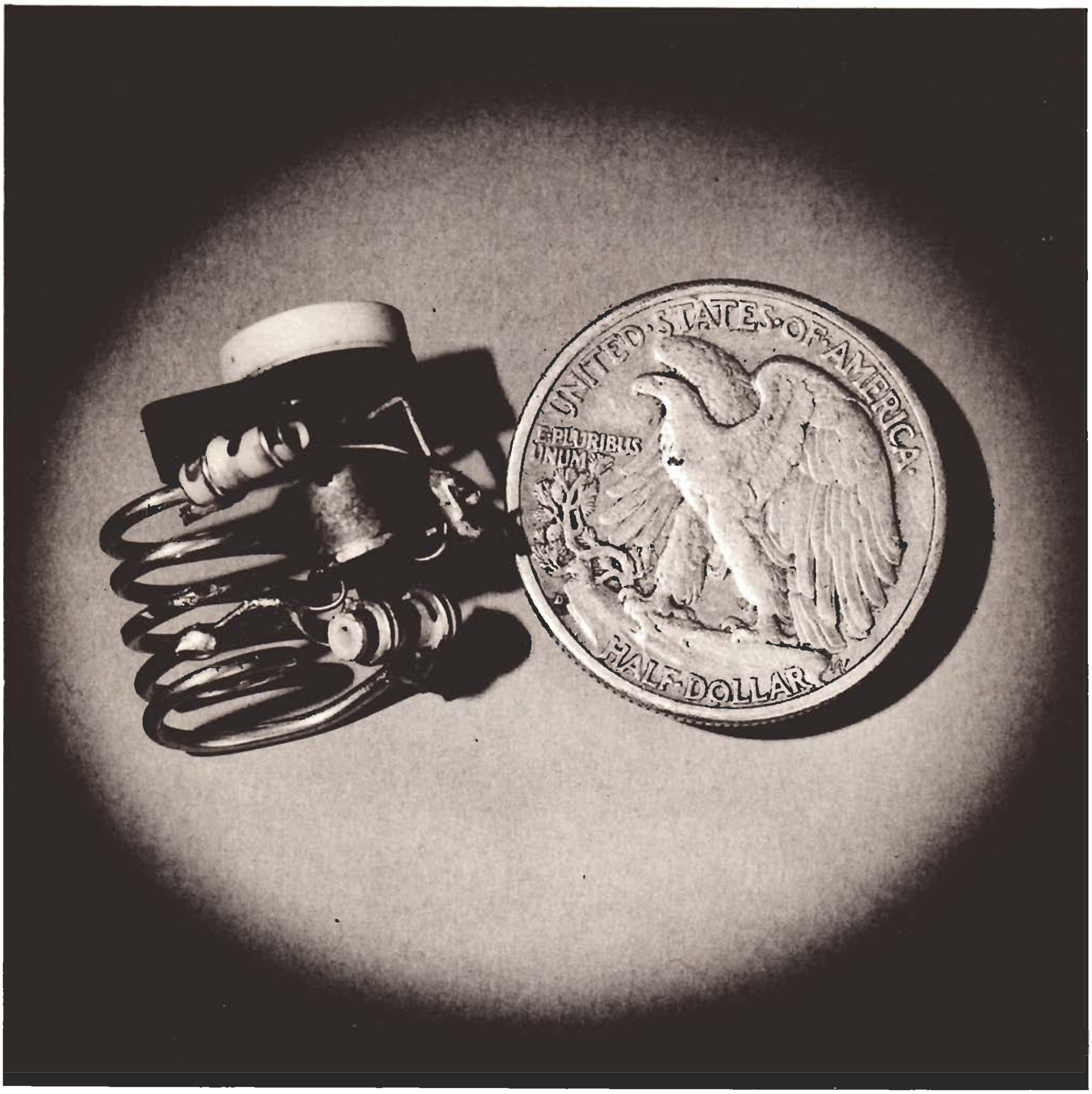

A complete tunnel diode transmitter is compared in size with a 50-cent piece. The transmitter consists of one variable and two fixed ceramic capacitors, a coil that tunes to the operating frequency — which may be higher than one kilomegacycle per second — and the tunnel diode itself, located inside the "can" in the center of the device. Progress in development of new devices using tunnel diodes, and new scientific understanding of the diode itself, was reported by the General Electric Research Laboratory on July 23, 1959.

TUNNEL DIODES

The newest "baby" in the fast-growing family of electronic devices -- the "tunnel diode"* -- is coming of age, the General Electric Company revealed today. The new device, little over a year old, is both better understood and closer to commercial application as a result of an intensive research program, according to Dr. Guy Suits, General Electric vice president and director of research.

The tunnel diode, first reported in 1958 by Japanese scientist Leo Esaki, is first cousin to a transistor, but operates on a different principle and offers advantages that the transistor does not. Before long it should find its way into high-speed computers, television sets, communication equipment, nuclear controls, satellites and space vehicles, Suits predicted.

"Because we were convinced that the tunnel diode could lead to revolutionary changes in the electronics industry, we launched a concentrated research program on the subject," Suits said. "This has resulted in important new scientific understanding of the device, which has led to vastly improved tunnel diodes, as well as a number of significant improvements in the field of applications.

"Further advances in the design and application of tunnel diodes can be expected, and it is probable that transistors and other solid-state devices will also benefit from the new knowledge."

The improved tunnel diodes are still in the experimental stage, and are not yet commercially available. However, to spur progress in circuit design, General Electric's Semiconductor Products Department now has plans to offer limited quantities of experimental samples for such use within the next few months. All of the research was financed by the General Electric Company itself, Dr. Suits stated.

One of the most significant advances in scientific understanding of the device originated with some observations of mysterious "wiggles" in

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*Press release of July 23, 1959.

performance curves. These were first noted by Drs. Nick Holonyak, Jr., and Arnold Lesk at GE's Advanced Semiconductor Laboratory, in Syracuse, N. Y. A theory that successfully explained the puzzling effect was subsequently worked out at the General Electric Research Laboratory in Schenectady, N. Y., by Drs. Jerome J. Tiemann, Robert N. Hall, and Henry Ehrenreich.

The tunnel diode takes its name from the physical phenomenon that makes it possible: "quantum-mechanical tunneling." The term is used to describe the manner in which the electrical charges move through the device. Such motion takes place with the speed of light, in contrast to the relatively slow motion of electrical charge carriers in transistors.

The high speeds at which electrical charges travel in the tunnel diode make it possible for the device to operate at extremely high frequencies. Oscillation frequencies higher than 2000 megacycles have already been obtained, matching advanced transistor performance, and frequencies of more than 10,000 megacycles are expected in the near future.

The device's high-speed response also suggests applications in computers. When used as switches, tunnel diodes have functioned in a fraction of a milli-microsecond -- from 10 to 100 times as fast as the fastest transistor.

The device also resists the damaging effects of nuclear radiation. Because it is less dependent on the structural perfection of its crystal than is the transistor, it is much less affected by the damage that radiation can do to such crystal structures. In this respect it outranks transistors by more than 1000 to 1. Semiconductors that have been used by GE scientists for making tunnel diodes include silicon, germanium, gallium arsenide, gallium antimonide, and indium antimonide.

The tunnel diode is smaller than a transistor and, because of a simpler structure, ultimately will be a small fraction of its present size. It also is little affected by environmental conditions. Silicon tunnel diodes made by General Electric work at temperatures as high as 650°F; conventional silicon diodes will not operate above 400°F.

As an electrical circuit element, the tunnel diode exhibits a unique combination of electrical properties including what is called a "negative resistance" over part of its operating voltage range. These characteristics allow it to be used in a wide variety of applications, such as an amplifier, a generator of radio-frequency power, and a switching device. The simplicity of this device makes possible the development of "integrated circuits," in which entire circuits for some applications may be formed on a single semiconductor structure. It is superior to vacuum tubes and transistors for applications in low-noise amplifiers and mixers for high frequencies. Many parametric amplifier jobs, for example, could be performed more easily by tunnel diodes.

Technical Information Sheet
TUNNEL DIODES

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Technical Information Sheet

1. Background Information on Tunnel Diodes

A. Functioning

The tunnel diode is a revolutionary new semiconductor device. Although it can perform many of the functions of conventional devices, its principles of operation are entirely different from the operating principles of other semiconductor devices and vacuum tubes.

Such conventional amplifying devices as transistors and vacuum tubes depend on emitting a charge carrier into a region where its motion can be influenced by a signal electrode, and on subsequently collecting the charge carrier on an output electrode. The speed of this conventional amplification process is limited by the time it takes a charge carrier, having left the emitter, to traverse the control region, and appear on the collector.

This time is generally quite long compared, for example, to the time it takes for a signal to travel an equivalent length along a copper wire. The reason is that, in the wire, the signal is carried by the electric field of all of the electrons in the wire, rather than by the motion of a particular group of electrons. Each electron in the wire moves only a microscopic distance, and those coming out the other end are not the same ones that went in as signal. The signal in a tunnel diode moves with the same rapidity as does a signal traveling along a copper wire. It is for this reason that the diode has such a short response time.

The difference between the tunnel diode and the copper wire, of course, is that the copper wire cannot amplify. The wire has a positive resistance: that is, an increase in the voltage results in an increase in the current. In the tunnel diode, an increase in the voltage can result in a decrease in the current. That is, it has a negative resistance. It is for this reason that the tunnel diode can act as an amplifier and perform its many other functions. Instead of absorbing the signal as a resistor does, it increases it.

B. Physical Description of a Tunnel Diode Junction

A semiconductor has a forbidden region where there are no states available for its electrons. This region is called the band gap. The states below this gap (which comprise the valence band) are almost all filled. The states above it (the conduction band) are almost all empty. The number of empty states in the valence band, or electrons in the conduction band, can be controlled by adding either acceptor impurities or donor impurities to the semiconductor crystal. Each acceptor impurity takes one electron out of the valence band, and each donor gives one electron to the conduction band. In this way p-type (empty states in valence band) and n-type (electrons in conduction band) regions can be built into a crystal. The surface where two of these regions touch each other is called a p-n junction.

Figures 1 and 2 represent the conduction and valence bands in the vicinity of a junction at different values of applied bias. One can see that as the bias is increased the bands which overlap each other at zero bias become uncrossed. Since tunneling is represented by a horizontal transition on this picture, the current decreases as the bands become uncrossed.

C. The Tunnel Effect

The tunnel diode takes its name from the tunnel effect -- a process wherein a particle (obeying the laws of the quantum theory) can disappear from one side of a potential barrier and appear instantaneously on the other side, even though it does not have enough energy to surmount the barrier. It is as though the particle can "tunnel" underneath the barrier.

In the case of the tunnel diode, the barrier is the space charge depletion region of a p-n junction. This is the same barrier which prevents the current from flowing in the reverse direction in the case of the ordinary rectifier diode. In the tunnel diode, this barrier is made extremely thin (less than a millionth of an inch) -- so thin, in fact, that penetration by means of the tunnel effect becomes possible. This gives rise to an additional current in the diode at very small forward bias which disappears when the bias is increased. It is this additional current, called the Esaki current in honor of the scientist who first observed it, that produces the negative resistance in a tunnel diode.

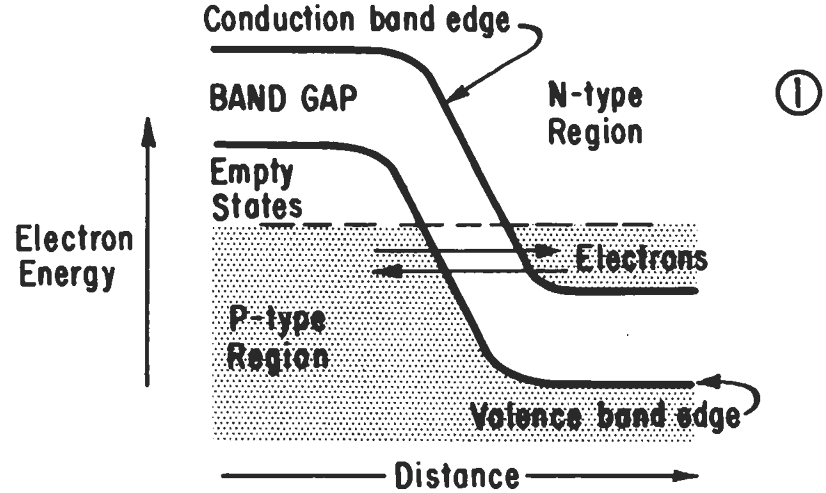
The origin of the Esaki current can be qualitatively understood by considering the changes in the characteristics of a conventional p-n junction diode as one goes to higher and higher concentrations of free carriers in the semiconductor crystal. As one increases the density of the charge carriers, the reverse breakdown voltage decreases. One might think that there would be a limiting case when the reverse breakdown voltage was reduced to zero. This is not correct, however; the limit is determined by the solubility of the impurities which determine the carrier concentrations. Experiments have shown that one can dope many semiconductor materials more heavily than is needed to reduce the breakdown voltage to zero. If one does dope more heavily, the diode can still be in reverse breakdown condition at a slight forward bias.

When a larger forward voltage is applied, the diode goes out of the reverse breakdown condition, and the current falls to a small level. The reverse breakdown current that flows with a forward applied bias is the Esaki current.

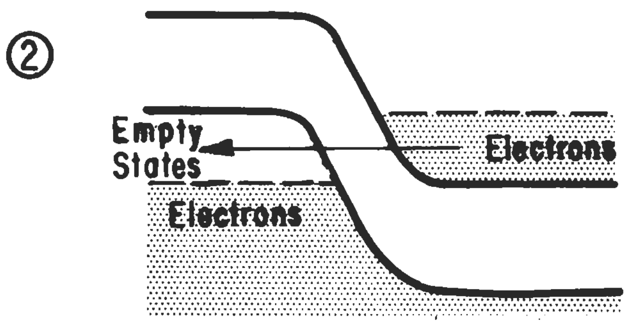
FIGURE 1

TUNNEL DIODE JUNCTION
AT VARIOUS BIAS CONDITIONS

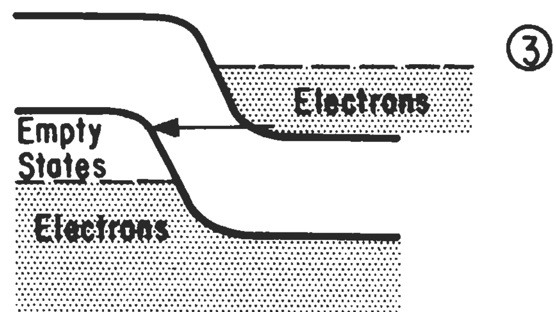
(The numbered diagrams below correspond to the numbered points on the current-voltage curve, Figure 2.)



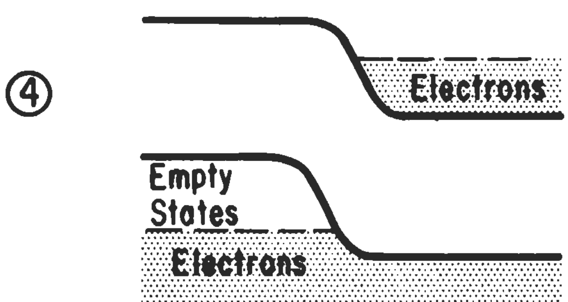
Electrons at same level on both sides of junction. No net current.



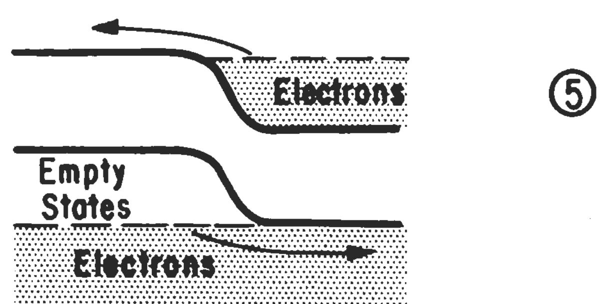
Electrons on right side are raised until they are opposite empty states on left side. Strong current flows from right to left.



Electrons on right raised still farther. Some are opposite "forbidden band gap," some opposite empty states. Current decreases.



Electrons all are opposite forbidden gap. Very small current.



Electrons raised until they spill over barrier. Current increases.

2. Contributions of General Electric Research to the Knowledge of Tunnel Diodes

Through studies of tunnel diodes made from many different materials

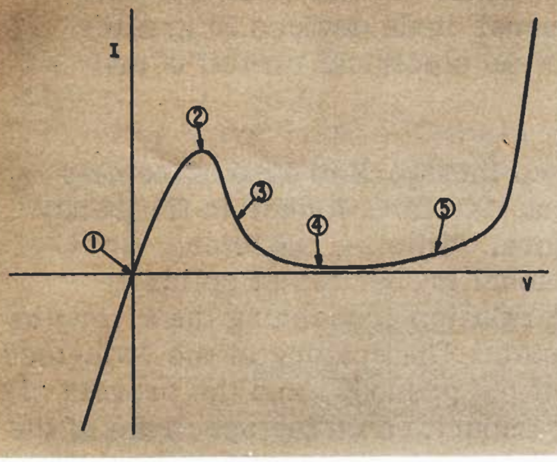


FIGURE 2

CURRENT-VOLTAGE CURVE

For description of numbered points, see Fig. 1.

in many different ways, General Electric scientists gained new knowledge of the operation of the device. This additional insight led to the solution of most of the problems associated with the tunnel diode. As a result, it was possible to develop an improved tunnel diode which, because of its vastly superior electrical characteristics, is a versatile and useful new component. The availability of these improved experimental tunnel diodes, in turn, made further research possible, and it was the research on these improved diodes that led to a major scientific discovery, which has explained the most puzzling aspect of the tunneling process.

One of the unanswered questions regarding the operation of the tunnel diode was that the tunneling process seemed to occur equally well in materials with indirect band gaps and in materials with direct band gaps. An indirect band gap is one where the minimum energy state in the conduction band occurs at a different value of momentum from that of the maximum energy state in the valence band. In other words, an electron would have different momentum after tunneling than it had before tunneling. This would seem to violate the classical laws of the conservation of momentum. It would appear, therefore, that the tunneling process was in some way more complicated than the simple concept formerly held.

Additional evidence that the tunneling process was more complicated was uncovered by General Electric scientists. This evidence involved the appearance of some mysterious "wiggles" in the current-voltage characteristics which were measured on tunnel diodes made from silicon cooled to very low temperatures. Acting on the hunch that these "wiggles" were related in some way to the conservation of momentum problem, further experiments were performed, and the hunch was proven correct.

The "wiggles" correspond to tunneling processes which are assisted by an ultrasonic vibration of the crystal. These vibrations of the crystal, called phonons, turned out to have exactly the right frequency for momentum conservation.

The identification of this process has enabled the General Electric scientists to analyze the performance of the tunnel diode devices in greater detail, and to further increase their usefulness as electrical circuit components.

From the point of view of basic science this work is also extremely important. The ultrasonic vibrations are about 100 times higher in frequency than any coherent vibrations produced heretofore. This is, therefore, an important new tool for investigating the vibrational properties of solids. Measuring the size of the "wiggles" yields information concerning the strengths of the electron-phonon interactions of the crystal. The spacing of the "wiggles" yields information regarding the frequencies of the phonons, and the breadth of the "wiggles" discloses some of the effects of impurities on the spectrum of the phonons.

One can expect that improvements in conventional semiconductor devices, as well as in tunnel diodes, will result from these discoveries and from the new research that they will make possible.

3. Comparison with Other Electronic Devices

A. For Communication Applications

In the field of communication, tunnel diodes compete with transistors, parametric amplifiers, vacuum triodes, magnetrons, klystrons, traveling wave tubes, and masers. The pertinent characteristics for comparison in this field are maximum oscillation frequency, minimum power requirements, and low noise amplification.

MAXIMUM OSCILLATION FREQUENCY

(In Kilomegacycles)

Tunnel Diode - 2 kMc (10 + kMc in a few years; 100 + kMc is conceivable)
Transistor - 2 kMc
Parametric Amplifier - 6 kMc
Vacuum Triode - 10 kMc
Maser - 10 kMc
Close Space Triode - 10 kMc
Traveling Wave Tube - 60 kMc
Klystron - 75 kMc
Magnetron - 100 kMc

MINIMUM POWER REQUIREMENTS

Tunnel Diode - one-millionth of a watt
Transistor - one-thousandth of a watt

MINIMUM POWER REQUIREMENTS (continued)

Vacuum Triode - one-tenth of a watt
Klystron - 10 watts
Traveling Wave Tube - 10 watts
Parametric Amplifier - 10 watts
Magnetron - 20 watts
Maser - 400 watts

LOW NOISE AMPLIFICATION

Noise Temperatures (at a frequency of 1000 megacycles)
Noise Temperature (proportional to noise level)

Maser* - 20°K
Parametric Amplifier* - 35°K at room temperature; 20°K when cooled with liquid nitrogen
Tunnel Diode* - 100°K to 300°K
Traveling Wave Tube - 300°K
Klystron - 300°K
Vacuum Triode - 900°K
Transistor - 3000°K

B. For Computer Applications

In this area the tunnel diode competes with transistors. The diode is at least 100 times faster than today's transistors, and can be made to use only about 1/100 as much power. Moreover, the tunnel diode is insensitive to temperature changes, in contrast to the transistor. The improved stability of the tunnel diode may make it possible to take short cuts in circuitry without sacrificing reliability.

APPLICATIONS

Radio transmission

The tunnel diode will have important applications whenever small size, light weight, low battery drain or extreme stability and ruggedness are needed. Some examples are:

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*Note: In the area of low noise amplification, only parametric amplifiers and masers compete closely with tunnel diodes. The tunnel diode is the only one of these three devices capable of operating directly from a battery. The parametric amplifier and the maser require an additional source of radio frequency power, and the maser requires an additional cryostat for cooling, and a magnet for bias.

1. Personal communications transmitters
2. Remote telemetry where power requirements are stringent, such as in weather balloons.
3. Satellite communications
4. Medical research and diagnosis. A small pill-sized transmitter can relay information about its surroundings within a living organism to the outside world without the encumbrance of wires

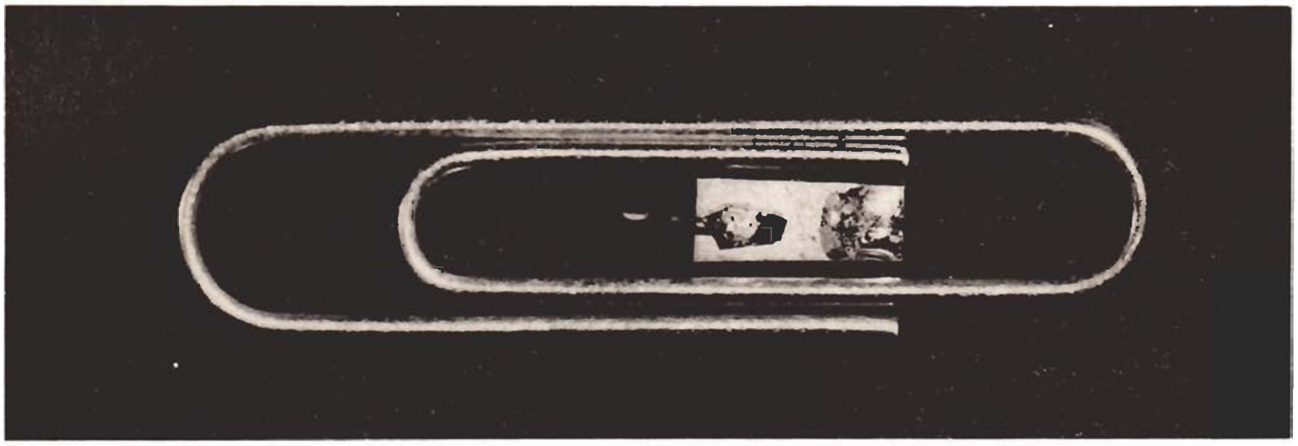
Radio reception

The tunnel diode will have application whenever simplicity, low noise, low power requirements or high frequencies are important, namely:

1. Personal communication
2. Television receivers (especially if UHF is included)
3. FM receivers
4. Detectors for broadcast and shortwave receivers
5. Special low noise receivers for high frequency (Example: radar for commercial airlines and military)

Amplifiers

The tunnel diode will have application whenever environment makes conventional devices inefficient or inoperative.



Nestled inside a paper clip, with room to spare, a tunnel diode is shown in close-up view. The connecting wire (left end) leads into an alloy, which is soldered to a germanium crystal (dark area). The crystal is soldered to a rectangular metal plate, which constitutes the other connection. (Discoloration at right end of plate is left-over solder from previous experiments.)

1. Atomic power. The tunnel diode provides a radiation resistant amplifier for relaying measurements inside atomic reactors. This may eventually make reactors that are better controlled and safer to operate.
2. Low noise pre-amplifiers for high frequency radio purposes.
3. Control devices for rockets and nose cones where high temperature operation is needed.

Computers

The tunnel diode will find its way into the computer field first because of its high speed. Other considerations are the high and low temperature operation. Radiation tolerance, the low cost per unit, stability and rugged reliability. Low power.

General purpose control

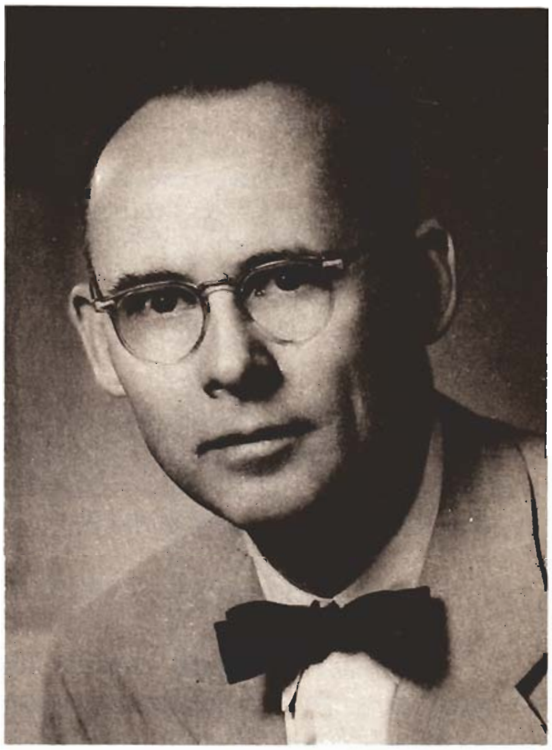
The tunnel diode can act as a current switch. It can be used both as a warning device that switches a control current when a particular thermal or electrical situation is encountered, or it can be used as a control device that switches the current being delivered to some other unit.

1. Thermostats
2. Protective devices for motors or other equipment.
3. Current flow indicators.

D. C. to A. C. conversion

The tunnel diode is important as a d. c. $\longrightarrow$ a. c. converter, because its operation voltage is so low. For this reason it matches the output of thermocouples, thermionic converters and solar cells.

TUNNEL DIODES



DR. MALCOLM H. HEBB
Manager
General Physics Research Dept.

The tunnel diode is the most important advance in semiconductor devices since the transistor. When we in General Electric first recognized its significance we embarked on a three-pronged attack: (1) improvement of the tunnel diode itself; (2) application in novel ways for useful purposes, and (3) fundamental understanding of its performance and characteristics.

We are now in a position to report that we have tremendously improved tunnel diodes and have greatly increased their versatility. Our achievement can be attributed to the fortunate way in which the three elements of our attack interacted with and supported one another. Improvements in tunnel diodes suggested new applications, and new applications demanded even better diodes. More importantly, the improved diodes made possible measurements of more fundamental significance and led to a better scientific knowledge of how the new, formerly mysterious, devices actually worked. This new knowledge, in turn, led to the vastly superior tunnel diodes that we will tell you about today.

In our Laboratory the first to appreciate the tunnel diode was Dr. Robert N. Hall. He interested Dr. Jerome J. Tiemann who started work on it. Soon many others added their efforts, not only in the Research Laboratory at Schenectady, and in the Advanced Semiconductor Laboratory at Syracuse, but also at other locations in the General Electric Company. From the beginning the torchbearers have been Hall and Tiemann.

The tunnel diode was first announced in 1958 by the Japanese scientist, Leo Esaki. Its principle of operation, which was partially interpreted by Esaki, is radically different from that of transistors, rectifiers, ordinary diodes, and other semiconductor devices. The potentialities of the tunnel diode were not generally recognized at first, and no great notice was taken of Esaki's announcement. Moreover, much of the behavior of the tunnel diode was simply not understood.

The name "tunnel diode" comes from the physical phenomenon of "quantum-mechanical tunneling," by which electrons are able to get across the junction region of the diode. In the transistor one has a simple picture of an electron starting from the emitter and diffusing across the base region to the collector. In the tunnel diode, on the other hand, there is no such classical picture. One must somehow imagine that the electron can "jump" from one side of the junction to the other without being in between. While the ordinary motion of electrons in semiconductors is relatively slow, electrons tunnel across the diode at the ultimate speed -- the speed of light. This is one of the reasons that there is so much interest in the tunnel diode: because it functions at the speed of light, it can be the ultimate in fast-acting or high-frequency devices.

The objective of the General Electric scientists who have been mentioned was to lay the foundation for the practical application of the tunnel diode. It was first necessary to explore many different ways of making tunnel diodes and to discover how to improve their characteristics.

One of the more important characteristics of these versatile devices is the negative resistance region of the current-voltage curve. The negative part of the curve should be as steep as possible for best performance in oscillators and amplifiers. The ratio of currents at the peak and valley should be large in order to minimize power requirements. For microwave frequencies, the capacitive reactance of the diode must be kept small in relation to the negative resistance. For application as a detector, the curvature of the current-voltage characteristic should be high. All of these properties can be attained by the fabrication of the tunnel diode and the elements of which it is made.

The second line of activity that we have pursued is the incorporation of tunnel diodes in novel circuits to perform different functions. These have included oscillators, amplifiers, mixers, detectors, computer elements, and temperature and voltage sensors. This is an extremely exciting area to think about, since it gives a glimpse of the many applications for the future.

But the third area of our work is perhaps the <u>most</u> important for the future. The basic phenomenon of tunneling has been known for a long time and is well understood. However, its existence in semiconductors is comparatively new, and the behavior of the tunnel diode, as I have said, was a puzzle. Past experience has shown that we are never able to realize the full potentialities of any physical phenomenon until we understand it quite thoroughly. It was therefore a significant part of our objective to unravel and interpret the measurements on tunnel diodes in a fundamental way. I am happy to report that we have made progress in this direction.

The first break came when our scientists, while experimenting with tunnel diodes at the temperature of liquid helium, found some pronounced differences between the current-voltage characteristic at this temperature and the current-voltage characteristic at high temperatures. An unexpected result such as this is a challenge but also an opportunity for, if it can be explained, it will give additional insight into what is going on. After considerable conjectures and attempted verification, the correct explanation was evolved, and proven. The new feature which our scientists uncovered were cusps in the current-voltage curves. Their explanation of these new features can be summarized in the following way. Whenever an electron "tunnels" in the diode it must generate a little sound wave or vibration of the semiconductor crystal, called a phonon. Since this requires extra energy, the current increases suddenly when the voltage is able to provide the energy for the phonon. This is the most direct demonstration so far, of the interaction between electrons and phonons. For example, the voltage at which the cusps occur gives the energy of the phonon directly, and the size of the current increase is related to the strength of the interaction between the phonons and electrons.

This knowledge is likely to have repercussions on many areas of solid state physics and will, with little doubt, lead to improvements in other semiconductor devices.

Applications of TUNNEL DIODES

DR. JEROME J. TIEMANN
General Physics Research Dept.

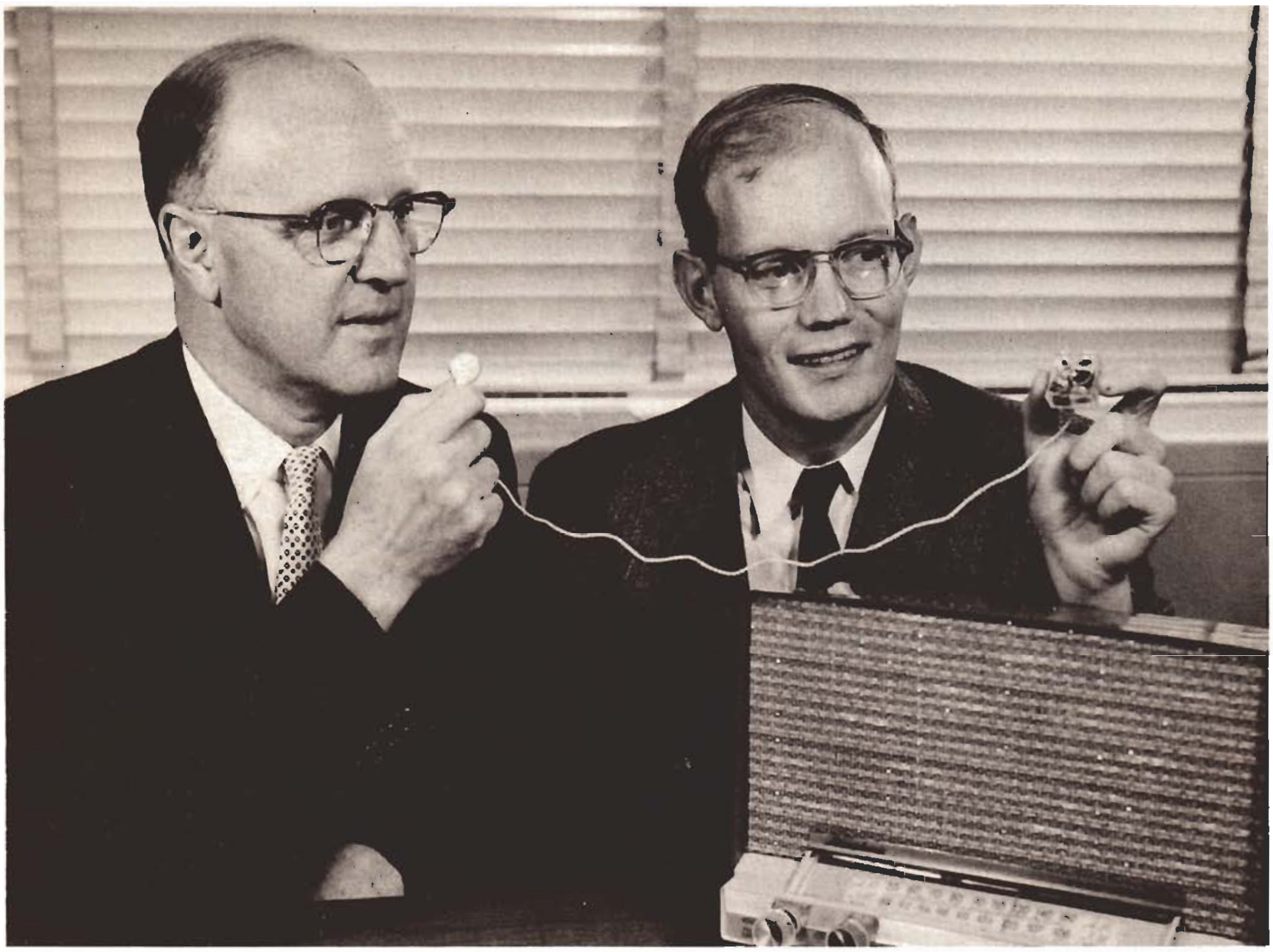
Dr. Hebb has told you a little about the possible applications of the improved tunnel diodes made by my colleagues and myself. I would like to elaborate a bit on this subject, and demonstrate a few selected applications. Most of what I will say is in the technical information sheet, but I would like to tell you which aspects of the tunnel diode are the most important ones for the various fields of application.

Generally speaking, the important properties of tunnel diodes from the electronic-circuit point of view are:

1. Extreme speed (high frequency)
2. Stable characteristics that are insensitive to temperature changes
3. Modest power supply requirements
4. Ability to operate in a wide variety of critical environments
5. Low noise level
6. Simplicity - light weight - small size

These features indicate that the tunnel diode will find many applications in a large number of fields.

One of the most important of these fields will be high-speed digital computers. The reason the tunnel diode is important in this field is its high



Vest-pocket transmitter, making use of a tunnel diode, is demonstrated by Dr. Guy Suits, Vice President and Director of Research, and Dr. Jerome J. Tiemann.

speed of response when made to operate as a switch. The tunnel diode switches either on or off in a fraction of a millimicrosecond. (A millimicrosecond is one billionth of a second.)

The first demonstration I would like to show you is a scale-of-two binary counter cell. This is a bistable, flip-flop circuit that changes its state upon receipt of an appropriate input pulse.

The important thing here is not that one can do what you have seen in any particularly convenient way with tunnel diodes. What is important is that the switching can occur so fast after the input pulse has been received. When you see this circuit up close later on you will notice some relays, which are needed to boost the voltage up to where the indicator lights can operate. The low output voltage of the tunnel diode may therefore appear to be an inconvenience -- and, in some respects, it is. This, however, may turn out to be a blessing in disguise.

I say this because the low voltage means that tunnel diodes do not generate much heat, and one of the most difficult problems which plagues computer engineers is how to get rid of all the heat. As people try to pack more and more computer in a smaller and smaller space, the problem of heat dissipation becomes ever more severe. The tunnel diode may offer some help in this respect, since it can be made to consume far less power even than a transistor -- which in turn uses much less than a vacuum tube.

Another field of application is radio communication. Here the tunnel diode is important, first because of its high-frequency potential and excellent stability, and also because of its ability to operate in critical environments with modest power supply requirements. As an extra bonus, it turns out that the tunnel diode has excellent low-noise properties. At present it is surpassed in this respect only by the maser -- which requires bulky refrigeration equipment -- and by the parametric amplifier -- which requires a high-frequency oscillator (generally a klystron) in order to operate. In contrast, the tunnel diode needs only a simple direct-current supply.

Because of the auxiliary equipment needed for an amplifier employing parametric diodes or masers, the over-all power consumed by these systems is over a million times as much as would be required by the tunnel diode stage. Even after one has added in the power required by subsequent stages in a receiver, which would be common to any system, the simplicity of the tunnel diode may prove to be such an advantage that it will find use in airborne or satellite communications equipment despite its slightly noisier performance.

There are four demonstrations for you to see which relate to this field: an FM receiver, to demonstrate radio reception; a small FM transmitter, to demonstrate radio transmission; a microwave oscillator to demonstrate the high-frequency potential, and a crystal controlled oscillator which can operate equally well in a high temperature oven or immersed in liquid air.

The FM receiver circuit is interesting in that it shows how the tunnel diode's characteristics can be exploited -- through novel circuit design -- to produce a variety of functions from one diode that would require a large number of conventional components to duplicate. The important idea here is that the tunnel diode is a new and different component with a unique combination of electrical properties. It happens that these characteristics make it the proverbial square peg for quite a number of square holes. Tunnel diodes will also find application as local oscillators for superheterodyne receivers, as amplifying mixers and detectors, and in low-noise preamplifiers for high-frequency receivers.

H. B. FANCHER
General Manager
Semiconductor Products Dept.

TUNNEL DIODES...their implications

Assessing a new electronic component and especially one as new as the tunnel diode is never an easy job. You always run the risk that later your profound words of wisdom may come back to haunt you.

However, in this case I think we are on pretty safe ground--the tunnel diode is a remarkable device as you have heard and seen demonstrated. Its impact will depend on the ingenuity of the circuit designers to utilize its unique characteristics.

The scientific work performed in the Research Laboratory and the Advanced Semiconductor Laboratory has rapidly transformed an interesting scientific phenomenon into a distinct commercial probability.

A new active electronic component is more than just another piece of hardware. It gives the designer the freedom to improve existing equipment, devise new equipments and thereby generate a lot of new businesses. This, as you know, is the history of the effects of the invention and practical reduction to practice of transistors.

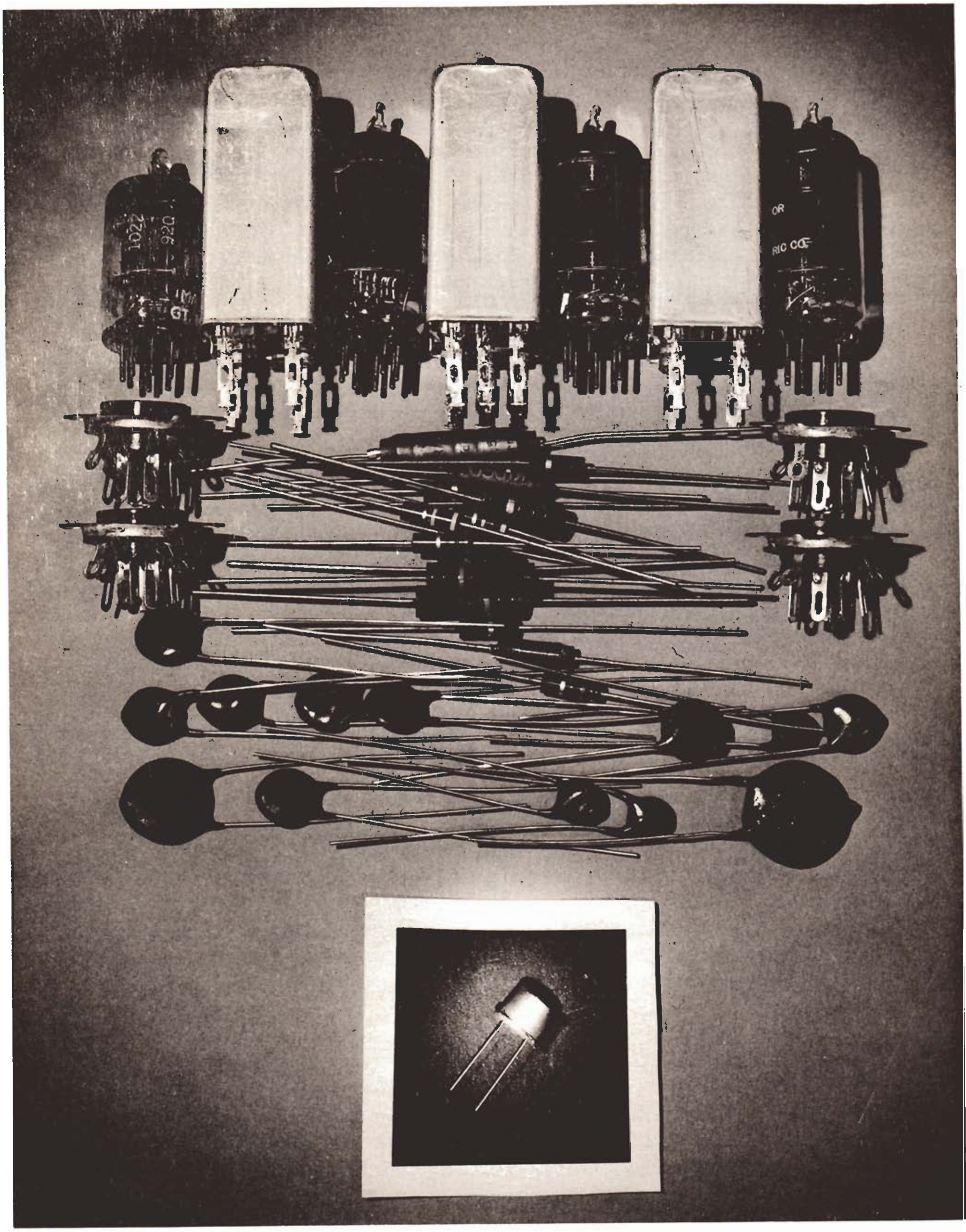
The basic building blocks of electronic equipment, such as transistors and tubes, determine not only whether the equipment is large or small but even as importantly what it will do and how reliably it will operate. To improve equipment you can shuffle the components that make it up but you are limited by the building blocks you have available as to possible improvements. The limitations of the components are transferred directly as limitations of the equipment itself. Add a new building block like the tunnel diode and you open the door not only to significant improvements in size and capability; you also can devise wholly new equipments.

This it seems to me is the significance of the tunnel diode and the work our scientists have performed in gaining the basic understanding of its operation and in now transforming it into a practical and useful device.

Let us take a look at the tunnel diode from an equipment viewpoint. First of all we do not see it primarily displacing transistors or other active components in circuits. True in some instances it may do this, but broadly tunnel diodes should improve the functional worth of other active components by working with them. In addition we believe tunnel diodes together with other semiconductor devices will make possible the practical design of equipment now either impossible or impractical. As an example, cryotrons are very fast computer elements, but they only perform at temperatures close to absolute zero. They need a small amplifying component to work with them. For practical use this amplifier must work along side the cryotron and in the same very low temperature environment. The tunnel diode appears to fulfill this need.

Secondly to the equipment designer, tunnel diodes have a lot to offer. In addition to working well at the temperature of liquid helium, (only a few degrees above absolute zero,) they also perform virtually unchanged at the freezing point of water, at room temperature and at 600 degrees Fahrenheit. As far as I know, this temperature range is unprecedented in electronic devices. They have other important attributes too. They are unaffected by extremely high levels of fast neutron irradiation. Gamma rays don't bother them either. They also switch currents very fast. In addition they work at very low voltages, yet have been made to handle as high as five amperes of current. They also are extremely fast pulse generators. All of these features are desirable in separate devices. In one device they are phenomenal.

However, with all this there still could be more. We are not sure yet of the full implications of the applications work we have carried on so far. Results to date are promising and certainly assure us of many areas where tunnel diodes will be practical.



Like transistors, the many uses for tunnel diodes can not be satisfied by a single unit. Already we can see a variety of separate types of tunnel diode for such applications as oscillators, mixers, amplifiers, switches, drivers, and detectors. We envision a whole family of tunnel diodes just like our present-day families of transistors and rectifiers.

But probably the two largest applications will be in the communications field, (everything from broadcast receivers to two-way radios to high frequency satellite transmitters,) and in the computer field for logic circuits.

In high frequency communications equipment, one tunnel diode can perform several functions as Dr. Tiemann has illustrated. In places like earth satellites and guided missiles where space is very dear, such a miniature active component is very desirable because it increases the work output load ratio so that more vital information can be transmitted.

In computers, together with transistors, tunnel diodes offer the opportunity for much higher speed operation; and today speed is a bottleneck in complex data handling requirements.

From an electronic component manufacturer's viewpoint, the tunnel diode is appealing primarily because it looks as if it offers us the opportunity of giving the equipment designer what he is always seeking -- a small, highly reliable and versatile active element for his circuits at a reasonable price. Compared to transistors and rectifiers it appears that tunnel diodes will be relatively simple to manufacture since, for one thing they are not as sensitive to surface variations.

As equipment requirements have demanded higher frequency performance from transistors the device structures are becoming more and more complex and difficult to manufacture. The tunnel diode offers the opportunity of extending the frequency range of solid state components without a corresponding increase in the complexity of the structure.

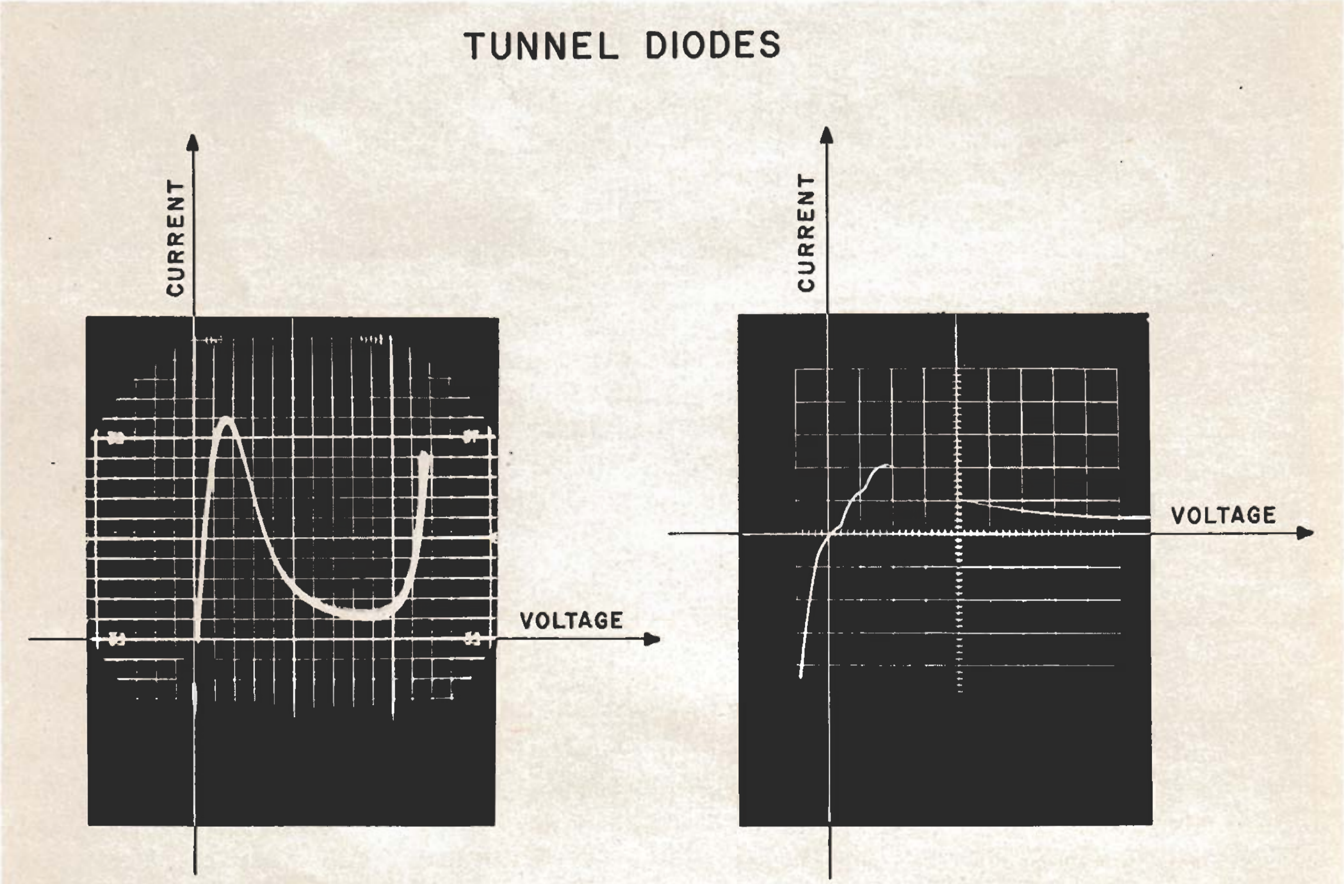
Tunnel diodes are now beginning to move out of the research area and into an advanced development phase.

Tunnel diode (in can, at bottom of photo) can perform simultaneously the following functions that are necessary in an FM receiver: amplification, oscillation, conversion, limiting, detection, and automatic frequency control. If an FM receiver were rebuilt using a tunnel diode, all of the conventional components shown in the photo could be omitted, although with some sacrifices in performance. Such performance limitations reflect the present state of the art and not the inherent capabilities of the tunnel diode.

We at General Electric will be offering limited experimental samples for use outside the Company for circuit and other applications development work within the next few months. They will be available sometime in September at a charge of approximately $75.00 each. This will permit the circuit development work so necessary to the practical reduction to equipment design to proceed rapidly. Since these samples will be handmade in advanced development, the initial price will be fairly high in relation to their selling price when we are in production.

However, the research job is far from complete and major efforts in this area must and will continue.

In the future wholly new solid state devices and improved present ones may result from the better understanding of the quantum mechanical tunneling effect described by Dr. Hebb. We in the product end of the business are looking forward to his and his associates' continuing achievements in giving us the fundamental knowledge we need for expanding and improving the uses of electronics.



NORMAL CHARACTERISTICS

CHARACTERISTICS SHOWING WIGGLES

One of the puzzles in the tunneling process which piqued the curiosity of General Electric research scientists and led to the major scientific discovery were mysterious "wiggles" in the performance curve of tunnel diodes. The "wiggles," it was found, prove that ultrasonic vibrations of the crystal are involved in the tunneling process. The sound waves generated are one hundred times higher in frequency than have ever been produced before. This is an important new tool in investigating the vibration properties of solids. Improvements both in tunnel diodes and other solid state devices are expected to result from this discovery. The size of the "wiggles" tells the strength of the electron-phonon interaction. The spacing of the "wiggles" tells the frequency of the vibrations.

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