THE FRANKLIN INSTITUTE

COMMITTEE ON SCIENCE AND THE ARTS

No. 3247.
(See 3210)

Subject THE STUART BALLANTINE MEDAL

Applicant

Address

Date of Application

Medalists
~~Inventor~~ Dr. John Bardeen and Dr. Walter H. Brattain

Address Bell Telephone Laboratories, Inc., Murray Hill, New Jersey.

COMMITTEE: 1951 - 1952

Dr. Winthrop R. Wright, *Chairman*	*MEETINGS:*
Dr. Charles B. Bazzoni	February 7, 1952
Mr. William G. Ellis	
Mr. Edward L. Forstall	
Dr. Albert F. Murray	

Report presented to General Committee:

February 13, 1952

Final Action:

March 12, 1952

Approved by Board of Managers
March 19, 1952.

Award Stuart Ballantine Medals

To John Bardeen
Walter H. Brattain

~~Reports~~ Report, ~~Medals~~ Medal, and Certificate ~~forwarded~~ presented *to ~~Inventor~~* Medalists

Medal Day, October 15, 1952.

THE FRANKLIN INSTITUTE OF THE STATE OF PENNSYLVANIA

FOR THE PROMOTION OF THE MECHANIC ARTS

Hall of the Institute,
Philadelphia, March 12, 1952.

Report No. 3247.

Investigating the Work of

John Bardeen, of Urbana, Illinois,

and

Walter H. Brattain, of Morristown, New Jersey.

THE FRANKLIN INSTITUTE OF THE STATE OF PENNSYLVANIA

FOR THE PROMOTION OF THE MECHANIC ARTS

Hall of the Institute,
Philadelphia, March 12, 1952.

Report No. 3247.

Investigating the Work of

Walter H. Brattain, of Morristown, New Jersey,

and

John Bardeen, of Urbana, Illinois.

Committee on Science and the Arts, The Franklin Institute

THE FRANKLIN INSTITUTE OF THE STATE OF PENNSYLVANIA

For the Promotion of the Mechanic Arts

- - - -

Hall of the Institute,

Philadelphia, March 12, 1952.

Committee on Science and the Arts Case No. 3247.

The Franklin Institute of the State of Pennsylvania, acting through its Committee on Science and the Arts, has considered carefully the work of those who have contributed greatly to the field of research in communication and reconnaissance, and has selected as recipients of the award of the Stuart Ballantine Medal for 1952 -

JOHN BARDEEN,
of Urbana, Illinois,
and
WALTER H. BRATTAIN,
of Morristown, New Jersey,

In recognition of their contributions to the theory of surface states in semi-conductors and of their invention of the Point Contact Transistor, a device foreshadowing a notable advance in the means of electromagnetic communication.

Committee on Science and the Arts, The Franklin Institute

The Transistor is a "three-electrode circuit element utilizing semi-conductive materials" which is capable of amplifying input current, input voltage, or input power and, hence, may be used in place of the more usual vacuum triode in amplifiers, oscillators and high speed switching circuits.

The Transistor is the invention of John Bardeen and Walter H. Brattain and was made while they were in the employ of the Bell Telephone Laboratories. Patent application was made on February 26, 1948 but this was abandoned in favor of an application filed on June 17, 1948. This latter application resulted in the issuance of United States Patent 2,524,035, dated October 3, 1950, to Bardeen and Brattain.

The discovery was set forth briefly by Bardeen and Brattain in a "Letter to the Editor" in the Physical Review of July 15, 1948 (Phys. Rev. 74, 230, 1948). In the issue dated April 15, 1949, there appeared a more complete discussion by the same two authors entitled "Physical Principles Involved in Transistor Action." (Phys. Rev. 75, 1208-1225, 1949.)

The last decade has seen a growing concern with the properties of the semi-conductors and the development of many devices which utilize these materials. The Bell Laboratories participated in this program, being active in both the experimental and the theoretical aspects. The discovery of the transistor is here presented in the light of the general growth of the "art."

The Fourth-Group Semi-conductors.

The three elements C, Si, and Ge are all of valence 4 and, in the solid state, each occurs in a crystal form in which any one atom falls at the center of a regular tetrahedron with its four nearest neighbors falling at the four vertices of the tetrahedron. The bond between any two atoms is of the covalent type, i.e., it is formed by the mutual action of two valence electrons, one from each atom. The core of the atom (i.e., the complete atom except for its valence electrons) is held in position in the crystal lattice. The valence electrons, in turn, are completely used up in forming the system of covalent bonds which bind the atoms in position. Hence, though the structure has both positive and negative components, there is no part of the system which is free to move under an externally applied electrical field and such crystals are essentially non-conductors. Carefully purified germanium, i.e., germanium in which the impurity content is only a part or two in a million, has a resistivity which exceeds that of copper by a factor of about 50,000. If, however, the impurity content is reduced to less than one part in a billion, the resistivity becomes about 30 million times that of copper.

The modern semi-conductor of the silicon or germanium type is presented diagramatically in Plates I and II. In Plate I there is shown a two-dimensional array of tetravalent Si atoms, the covalent bond structure being indicated by the four sets of double lines which radiate from each atom. There is also shown in the assemblage a single atom of arsenic which has replaced one of the silicon atoms in the crystal lattice. Arsenic belongs to the fifth group and hence each arsenic atom has five valence electrons. Four of these valence electrons go into the covalent bond system of the lattice. The fifth electron is not held in the lattice and may move to the left under the action of the electric field. This motion results in an electric current and hence enhances the conductivity or, conversely, reduces the resistivity. The resulting material is called an N-type semi-conductor in that each Group V atom in the lattice may furnish a negative carrier. The impurity atoms are correspondingly called donors, since each furnishes

Committee on Science and the Arts, The Franklin Institute

a conduction electron.

Plate II illustrates a semi-conductor where the impurity, boron, is a member of Group III. Each boron atom has only three valence electrons. Hence, when the boron atom enters the lattice, there is a lack of an electron in the covalent-bond structure. This gap is a defect or a "hole." By interchange of electrons between bonds, the "hole" may wander through the structure in the same way as a free positive electron would do. The actual displacement is one of interchange of electrons but the result is the same as if a fictitious positive carrier were present. Such semi-conductors are called P-type and the conductive process is called hole-conduction. The impurities are such as produce holes in the covalent bond system by accepting an electron each from the system and they are called acceptors.

<u>The Germanium Crystal Rectifier.</u>

The crystal rectifier shown in Plate III is strongly reminiscent of the cat-whisker detector used in the early days of radio. Silicon and germanium crystal rectifiers appeared in general use during the last World War, their development being the result of research carried on at many centers of research. A typical performance curve for a crystal of n-type germanium is shown on the same plate. It is noted that, for applied voltages in the "forward direction," i.e., with the point contact positive with respect to the base electrode, the current increases rapidly with the applied voltage. In the reverse direction the current increases much less rapidly and soon saturates. The rectifying effect is due to the lack of symmetry. As shown in the plate, there is a resemblance between the characteristics of the crystal rectifier and the vacuum tube diode. The inherent mechanism is, however, quite different.

Committee on Science and the Arts, The Franklin Institute

Committee on Science and the Arts, The Franklin Institute

It is evident, from the geometry, that the current density, for a given current through the rectifier, is much greater near the point contact than at any other place in the crystal. The explanation of the phenomenon is hence to be found in the conditions near the point contact. Experimental observations led to the conclusion that, when the point electrode is biased in the forward direction, it injects "hóles" into the semi-conductor and that these account for the observed excess of current over that attributable to the negative carriers already present in the n-type germanium. Bardeen was led to consider this problem theoretically and in 1947 he published a paper on "Surface States and Rectification at a Metal Semiconductor Contact" (Phys. Rev. 71, 717-727, 1947). Bardeen's theory led to a systematic attack upon surface phenomena in the semiconductors and, out of these experiments, came the invention of the Transistor.

The Type A Transistor.

The introduction by De Forest of a third electrode in the neighborhood of the filament of a vacuum-tube diode resulted in the triode, the progenitor of the great array of thermionic vacuum tubes which are now available. The primary function of the triode is emphasized by the word "valve", a common name for the device in British parlance. The third electrode, the grid, is essentially a control device which requires a small power input but which regulates a relatively large power output in the cathode-plate circuit. The control is made possible, in essence, through variations in the electrostatic field in the neighborhood of the cathode, the electrode at which the carriers are set free.

While the underlying mechanism of the crystal diode is quite different from that of the vacuum tube diode, the close resemblance of their current-voltage characteristics suggested to many investigators the possibility of a crystal triode with a performance characteristic similar to that of the vacuum tube triode. The difficulties may be illustrated by reconsideration of the two diodes shown in Plate III.

In the vacuum diode, electrons emitted by the filament build up a space charge in the neighborhood of the emitting surface which tends to limit the escape of electrons since, associated with a region containing such charges is an electrostatic field which acts as a barrier to escaping electrons. This field due to the space charge may, however, be neutralized by an externally applied field due to an array of conductors. In the diode this neutralizing field is supplied by the application of the proper potentials to filament and plate, the barrier field becoming less as the plate potential is raised with respect to the filament. For a given filament-plate potential, the net electrostatic field in the critical region may be varied by a potential difference applied between filament and a third electrode. In the usual tube this third electrode consists of a network of fine wires, located near the filament, which is called the control grid. Actually, control is possible even if the third electrode lies outside the evacuated tube in that the required electric field in the critical region is possible with a wide choice of geometry provided the proper potentials are used.

In the crystal rectifier of the type shown, the emitting electrode is the point contact which, with an n-type semi-conductor, "injects holes" into the region immediately surrounding it. In more general terms, the application of a potential difference between base and point modifies the potential distribution in the semi-conductor. This internal potential, however, may not be described in terms of the electrostatic fields of classical electrical theory but only in terms of quantum-mechanical states or levels and the control or modification of the

Committee on Science and the Arts, The Franklin Institute

situation by the application of the proper potential to an external electrode is not feasible in the same sense as suffices for the vacuum-diode.

In the course of a general research program centering on the surface properties of semi-conductors, particularly in those properties which might be associated with the existence of a barrier space-charge at the free surface of a semi-conductor, Bardeen and Brattain first observed the Transistor action. Plate IV is taken from their first comprehensive paper which was published in 1949.

The three electrodes are the base and two point contacts, the one called the emitter and the other the collector. The emitter is biased positively with respect to the base, i.e., in the forward direction corresponding to high conductivity. This circuit corresponds to the filament-grid circuit or input circuit in the vacuum triode. The point contact is made wedge-shaped, the area of contact being perhaps $10^{-6} cm^2$. The second point contact, the collector, is a similar wedge placed near the first, the linear separation of the two being of the order of 1/100th of a centimeter. The collector is biased negatively with respect to the base, i.e., in the reverse or low conductivity direction. This circuit corresponds to the filament-plate circuit or output circuit in the vacuum triode.

The currents in the two circuits are shown schematically in Plate V. In Figure a, the emitter is biased negatively (-0.25 volts) and the emitter current is zero. The collector is biased negatively (-25 volts) and the collector current of 0.8 ma. corresponds to saturation on the reverse portion of the diode characteristic of Plate III. In Figure b, the emitter bias has been made positive (0.14 volts) with a resulting current I_e of 0.4 ma. carried mostly by injected holes or positive carriers. These are deflected to the nearby collector and increase the collector current, in part directly to the extent of 0.4 ma. and in part indirectly through

Committee on Science and the Arts, The Franklin Institute

changing the surface states in the neighborhood of the collector, thus increasing the electron current by 0.6 ma. In Figure c, the emitter bias is greater (0.16 volts), the emitter current rises to 1.0 ma., and the collector current has risen to 28 ma.

As a first approximation, the behavior of a triode may be represented by a family of curves of the form $i_p = f\,(v_g, v_p)$ where, quite commonly, any one curve exhibits the plate current as a function of grid potential for a fixed value of the plate potential. The slope of any one of these curves corresponds to the partial derivative of f with respect to the grid potential and is known as the transconductance of the tube. If the curves are drawn so as to exhibit the plate current as a function of plate voltage for fixed grid potential, the slope of any curve is the reciprocal of the plate resistance. This simplicity results from the fact that the grid current is negligible to a first approximation.

In the transistor both currents and both voltages vary and the functional relations are more complex. The two voltages may be specified in terms of the two currents in the form

$$V_e = f_1\,(I_e, I_c)$$

$$V_c = f_2\,(I_e, I_c).$$

Plate VI exhibits measurements for an experimental transistor of the point contact variety (Type A). The collector voltage is plotted as a function of collector current, the emitter current being held constant. The slope of any one curve is that one of the four characteristic resistances of the Transistor which corresponds to plate resistance in a vacuum triode. The a.c. performance of the Transistor in a particular application may be computed, to a first approximation, on the basis of these four characteristic resistances.

Committee on Science and the Arts, The Franklin Institute

Committee on Science and the Arts, The Franklin Institute

Such a transistor may be used as a Class A amplifier, the base electrode being grounded. The input impedance is of the order of 500 ohms and the plate resistance about 20,000 ohms. The ratio of collector current to emitter current is about 2, there being some current amplification. The primary source of amplification, however, is due to the marked excess of output impedance over input impedance. For this transistor, the operating power gain may approach 20 db. and the corresponding power output 5 mw.

The above mode of operation of the Transistor is analogous to that for a triode with grounded grid. When the emitter is grounded, the performance resembles that of a triode with grounded cathode and, when the collector is grounded, the situation is like that of the triode used as a cathode follower.

The last four years have seen a great development in both the theory and the performance of transistors. The contact type transistor has been improved, partly by substituting single crystals for the polycrystalline plates used by Bardeen and Brattain and partly by modification of the contacts of the emitter and collector with the semi-conductor. The first transistors of this type were non-reproducible, their performance varied with aging and they had a temperature coefficient of about 1 per cent per degree centigrade. They are now produced with characteristics which vary from unit to unit to about the extent experienced with vacuum tubes, they are stable with respect to aging and the temperature coefficient has been reduced by a factor of four.

The most fruitful attack upon the problem, however, appears to be the junction type transistor due to W. Shockley. It was found that rectification was possible with single germanium or silicon crystals which had been so treated that one end of the crystal was of P-type and the other of N-type. With such crystals, the electrodes may be of large area in that the rectification takes place at the transition boundary in the crystal. The system is much simpler from the theoretical aspect than that of the point-type crystal rectifier and Shockley contributed much of the successful application of Fermi statistics to the problem.

The junction-type transistor is, in essence, a crystal having two such transition boundaries, e.g., a germanium crystal with each end of P-type and the center portion of N-type. The three electrodes are plates attached to these three portions. The emitter electrode is at one end and is biased, with respect to the center electrode, at a small positive potential for forward conduction at the nearer P-N boundary. The collector electrode is biased at a much higher potential negatively for reverse conduction at its P-N boundary. The relation of the underlying theory to the output performance of a junction-type transistor is clear and direct and the continued interplay of theory and experiment may be expected, with confidence, to yield transistors of still better performance.

The Morris Liebman Memorial Prize has recently been awarded to Shockley for his contribution to the development of transistors. It is believed that the work of Bardeen and Brattain and their invention of the contact-type Transistor is an important milestone in the history of electromagnetic communications which may be judged quite apart from the subsequent development of the art.

The Transistor has reached the stage of practical application. Phototransistors are now embodied in the new toll charge computers developed by the Bell Laboratories for the telephone industry. The Bell system has announced that large scale manufacture of transistors is under way but that applications in the transmitting circuits await the outcome of a test program which is to be started very shortly. It is understood that considerable application has been made by the armed services in devices used for both communication and reconnaissance but no details are available.

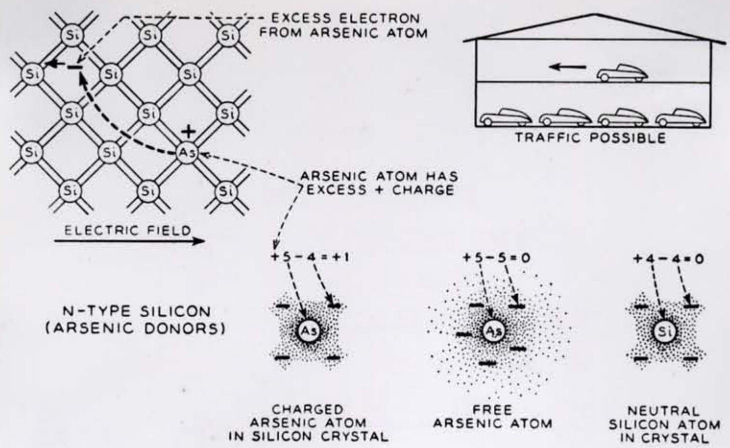
Committee on Science and the Arts, The Franklin Institute

In recognition of their contributions to the theory of surface states in semi-conductors and of their invention of the Point Contact Transistor, a device foreshadowing a notable advance in the means of electromagnetic communication, THE FRANKLIN INSTITUTE awards two STUART BALLANTINE MEDALS, one each to WALTER H. BRATTAIN, of Morristown, New Jersey, and JOHN BARDEEN, of Urbana, Illinois.

W. Wyman Rolph
President.

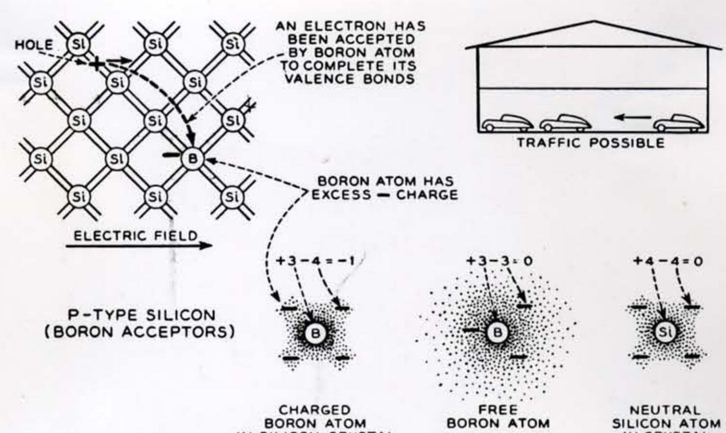
Henry B. Allen
Secretary.

Howard Stoertz
irman of the Committee on Science
and the Arts.



S. & A. Case No. 3247,
The Stuart Ballantine Medal.
Plate I.

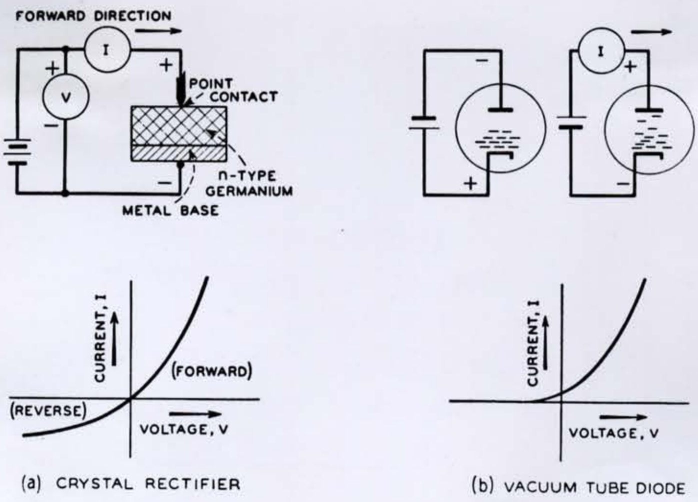
PLATE I.



S. & A. Case No. 3247,
The Stuart Ballantine Medal.
Plate II.

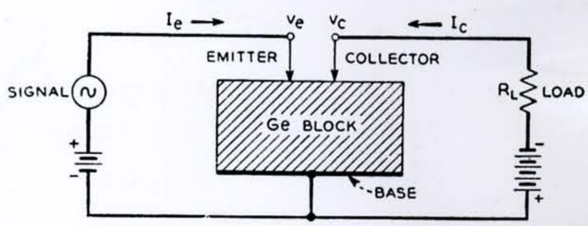
PLATE II.

COMMITTEE ON SCIENCE AND THE ARTS, THE FRANKLIN INSTITUTE



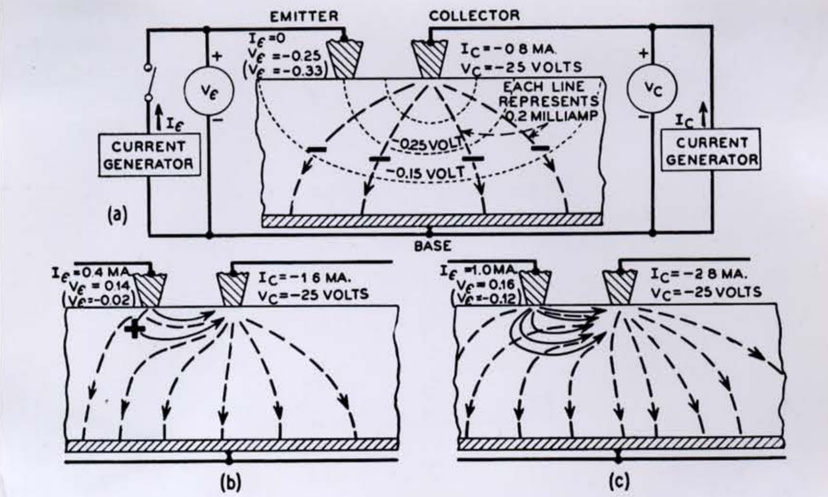
S. & A. Case No. 3247,
The Stuart Ballantine Medal.
Plate III.

PLATE III.



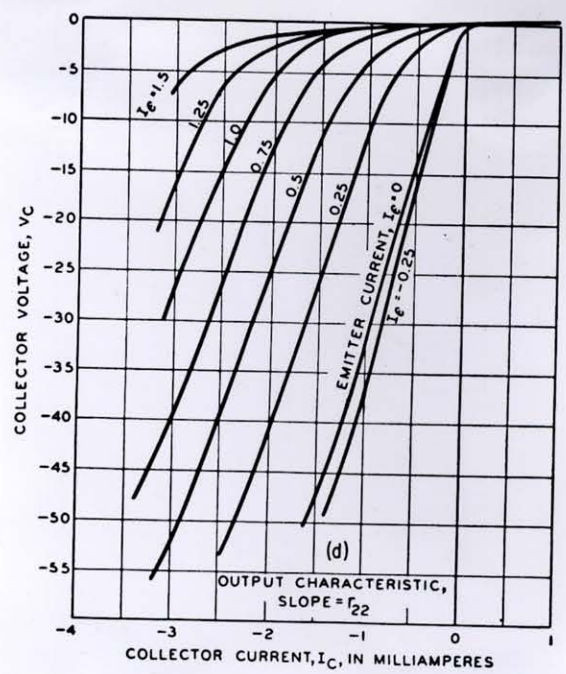
S. & A. Case No. 3247,
The Stuart Ballantine Medal.
Plate IV.

PLATE IV.



S. & A. Case No. 3247,
The Stuart Ballantine Medal.
Plate V.

PLATE V.



S. & A. Case No. 3247,
The Stuart Ballantine Medal.
Plate VI.

PLATE VI.