

JOHN BARDEEN and TRANSISTOR PHYSICS*

Howard R. Huff

International SEMATECH, Inc.

Austin, TX 78741

Abstract. John Bardeen and Walter Brattain invented the point-contact semiconductor amplifier (transistor action) in polycrystalline germanium (also observed in polycrystalline silicon) on Dec. 15, 1947, for which they received a patent on Oct. 3, 1950. Bill Shockley was not a co-patent holder on Bardeen and Brattain's point-contact semiconductor amplifier patent since Julius Lilienfeld had already received a patent in 1930 for what would have been Shockley's contribution; namely, the field-effect methodology. Shockley received patents for both his minority-carrier injection concept and junction transistor theory, however, and deservedly shared the Nobel prize with Bardeen and Brattain for his seminal contributions of injection, p-n junction theory and junction transistor theory. We will review the events leading up to the invention of Bardeen and Brattain's point-contact semiconductor amplifier during the magic month of November 17 - December 16, 1947 and the invention of Shockley's junction semiconductor amplifier during his magic month of December 24, 1947 - January 23, 1948. It was during the course of Bardeen and Brattain's research in November, 1947 that Bardeen also patented the essence of the MOS transistor, wherein the induced minority carriers were confined to the inversion layer enroute to the collector. C.T. Sah has described this device as a sourceless MOS transistor. Indeed, John Bardeen, co-inventor of the point-contact semiconductor amplifier and inventor of the MOS transistor, may rightly be called the *father* of modern electronics.

INTRODUCTION

Mervin Kelly, Bell Telephone Laboratory's (BTL) research director, established an interdisciplinary team in 1945 with the goal of replacing the vacuum tube amplifier and the electro-mechanical relay type devices, utilized in the Bell System, by a solid-state amplifier and switch, respectively. Contrary to popular opinion, the BTL team was mission oriented, albeit with a scientific scaffolding. The resulting point-contact semiconductor amplifier (transistor action) was invented by John Bardeen and Walter Brattain on Dec. 15, 1947, which ushered in the solid-state electronics age. The scientific background, personnel involved and the intertwining of these historic events in the mid -1940's are described.

The scope of the article is to initially present a brief resume of majority and minority carriers followed by the introduction of the field-effect experiment, Bill Shockley's original approach to develop a solid-state amplifier. Bardeen and Brattain's magic month of November 17 - December 16, 1947 is then presented during which they invented their point-contact semiconductor amplifier and identified transistor action. This is followed by an examination as to whether the minority carriers are transported along the surface or exhibit some non-trivial component through the bulk.

The discussion on the point-contact semiconductor amplifier is then completed with a discussion on contemporaneous events, in particular the research conducted by Karl Lark-Horovitz and Ralph Bray of Purdue, followed by the naming of the transistor and the patent priorities. Shockley's magic month of December 24, 1947 - January 23, 1948 is then discussed, culminating in Shockley's seminal contributions of injection, pn junction theory and junction transistor theory. Finally, the evolving direction of transistor research is briefly discussed followed by a summary.

MAJORITY AND MINORITY CARRIERS - A RESUME

At 0K, silicon and germanium are perfect insulators inasmuch as the isotopes of each element exhibit only zero-point (weakly coupled) atomic vibrations. At any non-zero temperature, however, thermodynamic requirements introduce a degree of disorder (entropy) into the crystal structure so as to minimize the Gibbs free energy at thermal equilibrium (1). Atoms transfer off the substitutional sites onto interstitial sites — also referred to as self-interstitials — creating several classes of point defects. The absence of atoms on substitutional sites are referred to as vacancies; near-surface atoms transferring to the surface also create vacancies. Various paired interactions between vacancies and self-interstitials also occur; one such complex is called the Frenkel defect (2). Distributed within the vibrating system of atoms and vacancy-interstitial point defects at finite temperatures are free carriers

* An initial version was published in *ULSI Process Integration* (edited by C.L. Claeys, H. Iwai, G. Bronner and R. Fair, eds.), PV **99-18**, 19-55 (1999), The Electrochemical Society, Inc.

generated by collisions between the atoms and phonons (quantized crystal vibrations). Electrons excited out of the valence band with energies greater than the energy gap populate the multiple conduction-band minima at non-zero values of the wave vector \mathbf{k} (i.e., different directions in the crystal are generally expressed as the reciprocals of these directions and the ensemble is referred to as reciprocal (\mathbf{k}) space) and are referred to as “intrinsic” (n_i) electrons. Concurrently, an equal number of (light and heavy mass) holes (the absence of electrons) are left resident at the valence-band maximum at the wave vector $\mathbf{k} = 0$ along with holes resident at the split-off valence band, also at $\mathbf{k} = 0$ (2). The total sum of these holes is referred to as “intrinsic” (p_i) holes, although the split-off holes are often ignored. The intrinsic electron-hole excitation phenomenon is described by the mass-action relationship (2):

$$n_i p_i = n_i^2 \quad (1)$$

The offset in \mathbf{k} space of the valence-band maximum and conduction-band minima accounts for the designation of the group-IVa semiconductors (except gray tin) as indirect energy-gap semiconductors.

Group-Va donor impurities such as phosphorous, arsenic or antimony result in free electrons (n) in the conduction band (n-type semiconductor) while the group-IIIA acceptor impurities such as boron result in free holes (p) in the valence band (p-type semiconductor). These dopants occupy substitutional sites in the group-IVa semiconductors and donate one more or one less electron than the host group-IVa semiconductor for n- and p-type semiconductors, respectively (2-4). The donor (acceptor) impurity becomes positively (negatively) charged when the free electron (hole) resides in the conduction (valence) band. Charge neutrality requires:

$$n + N_A^- = p + N_D^+ \quad (2)$$

One may utilize the charge neutrality condition from eq. (2) with the generalized mass-action relationship (applicable in the case of non-degenerate statistics at thermal equilibrium) in eq. 3 (2,3) to relate the electron and hole concentrations:

$$n p = n_i^2 \quad (3)$$

where n is the total number of free electrons per cm^3 , p is the total number of free holes per cm^3 and n_i is the intrinsic thermal equilibrium concentration of electrons (equal to holes). For example, an (essentially) uncompensated p-type silicon wafer at 300K with an acceptor concentration N_A of 1.3×10^{15}

boron atoms per cm^3 (10 ohm-cm) and an intrinsic concentration of 1.07×10^{10} per cm^3 (5), has hole and electron concentrations:

$$p \approx N_A^- = 1.3 \times 10^{15} \text{ cm}^{-3} \quad (4)$$

$$n = n_i^2 / p = 8.81 \times 10^4 \text{ cm}^{-3} \quad (5)$$

In this case, the holes are referred to as majority carriers and the electrons are referred to as minority carriers. Under thermal equilibrium conditions, the electron (minority carrier) contribution to the extrinsic conductivity is negligible in comparison to the hole (majority carrier) contribution. Analogously, in a host n-type semiconductor, electrons and holes are referred to as majority carriers and minority carriers, respectively.

The energy bands near the surface of semiconductors such as silicon and germanium have been observed to bend as the result of boundary layers such as metals or, in the case of a free surface, the depletion of free carriers due to their capture in surface states (see section 3) (3,6). The energy band bending near the surface is due to the fixed, ionized (negatively-charged) acceptors (p-type) or (positively-charged) donors (n-type) as described by Poisson's equation (2). If the energy bandbending proceeds sufficiently beyond depletion (there are essentially no free carriers in the depletion layer), an inversion layer is formed extremely near the surface (see Figure 1) (7). The depletion layer is typically about one μm and the inversion layer is several tens of nm (6). The spatial region of the energy bandbending is referred to as the Surface Space Charge Region (SSCR). The free carriers formed within the inversion layer (opposite in charge type from the bulk free carriers) are designated as minority carriers relative to the (bulk) majority carriers generated from the spatially fixed dopant impurity uniformly distributed throughout the sample volume, including the spatial region of the surface inversion layer. The minority carriers in the inversion layer, however, are the dominant source of free carriers and control the surface conductivity. The inversion layer can be induced by electrical methods, such as a capacitively applied electric field, chemical species adsorbed on the surface or intrinsic surface states (see section on The Field Effect).

BACKGROUND – THE FIELD EFFECT

The development of a solid-state semiconductor amplifier was initiated by Bill Shockley utilizing the concept of the field effect to modulate the surface

conductance (8). A parallel plate capacitor comprised of a semiconductor and a metal, separated by a dielectric medium, are placed in the circuit schematically illustrated in Figure 2a. An electric field is capacitively applied normal to the semiconductor surface. By the proper choice of bias

polarity (consider an n-type semiconductor for concreteness and, therefore, a positive polarity on the metal electrode), the majority-carrier concentration in the n-type semiconductor can be increased by electrostatic induction (see Figure 2b) (9).

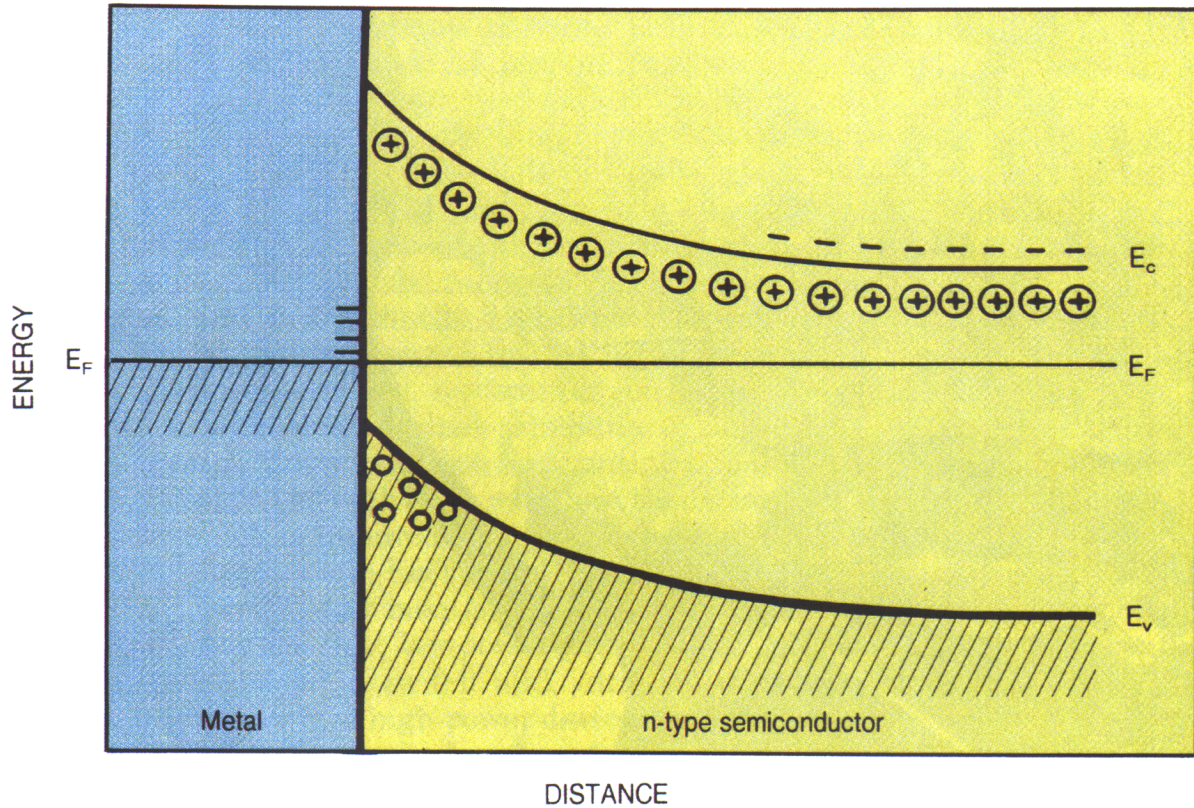


FIGURE 1. Barrier layer at the metal-semiconductor contact at equilibrium. The curves E_c , E_F and E_v in this energy diagram are the conduction band edge, the Fermi level and the valence band edge, respectively. Minus signs represent electrons in the conduction band; plus signs in circles, fixed positive charges; circles, holes. Horizontal lines at the metal-semiconductor interface represent surface states [after (7) with permission of the American Institute of Physics].

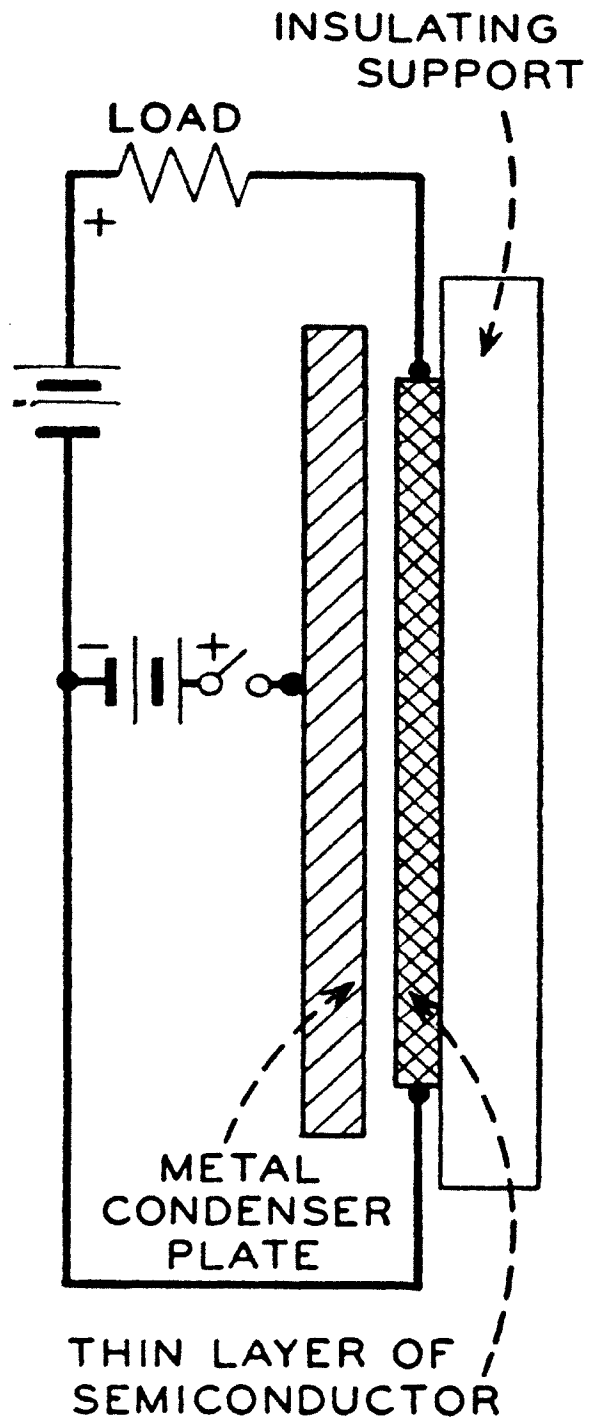


FIGURE 2a. Circuit schematic for the modulation of conductance by the "field effect" (8) [after W. Shockley, *Electrons and Holes in Semiconductors*, New York, D. Van Nostrand, 1950].

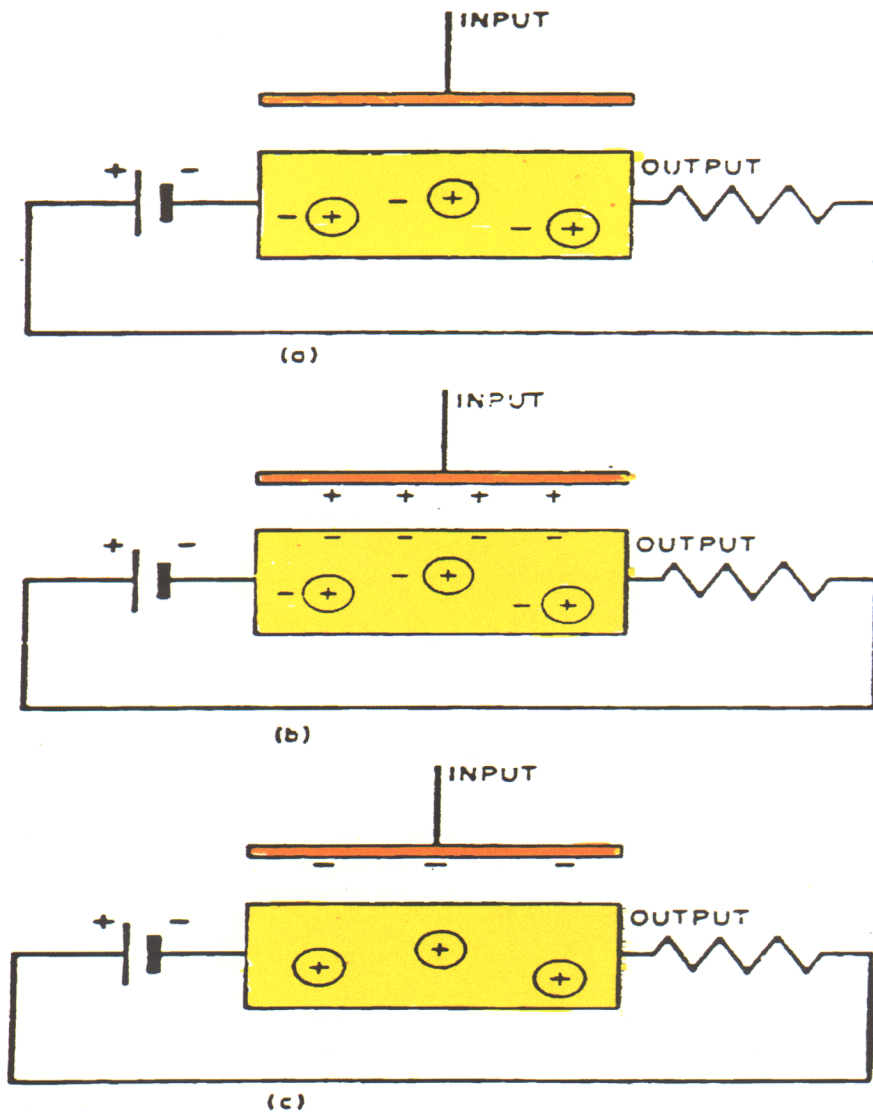


FIGURE 2b. The theory of a field-effect transistor using a thin layer of semiconductor (with no surface states): (a) The structure of the transistor with no control voltage applied. (b) The situation prevailing when a positive charge is placed on a control plate to increase the conductance of the semiconductor (by electrostatically inducing electrons in the semiconductor) (c) The situation when a negative charge is put on the capacitor plate to reduce the conductance of the semiconductor [after (9), © 1984 IEEE].

This is especially important inasmuch as Shockley's field-effect device was anticipated to be a majority-carrier device whereas the point-contact semiconductor amplifier (transistor action) invented by Bardeen and Brattain was a (the first) minority-carrier device (10,11). Bardeen and Brattain were the first to increase the minority-carrier concentration in a semiconductor by a current, whereas previous methods involved optical or thermal processes

(12,13). The change in conductance ($\approx 10\%$), however, was much less than expected on the basis of classical electrostatics, assuming the induced carriers possessed a mobility (velocity per unit electric field) equal to that of the bulk majority carriers (14). Nevertheless, this proof of principle was important in establishing that the effect, believed to be the most direct approach to achieving a solid-state amplifier,

was not in violation of the laws of semiconductors and statistical mechanics (8).

The observed discrepancy was interpreted by Bardeen (15) as a consequence of surface trapping levels which immobilized a significant fraction of the induced charge carriers. That is, the electric field lines of force, for positive-bias polarity, were mainly terminated on the electrons trapped in surface states rather than terminating on free-electrons electrostatically induced in the semiconductor conduction band (8,9). The surface states apparently blocked the external electric field, shielding the semiconductor interior from being probed. Although the anticipated modulation of the sample conductivity was not achieved, the existence of surface states on the free surface of a semiconductor was thus demonstrated (14).

Bardeen's surface state theory (15) clarified the lack of a significant modulation of the surface conductance in the field effect experiment (8,14), a host of additional experimental conundrums dating to the late 1920's (16) and substantiated theoretical expectations which indicated that surface states were indeed expected, based on quantum-mechanical considerations (17-19). Bardeen's surface states additionally set the stage for further scientific research (9,20,21) which led to the invention of the point-contact semiconductor amplifier (transistor action) (10,11), junction transistor (22) and, as discussed in the section on patents, the essence of the metal-oxide-semiconductor field-effect transistor (MOSFET). Shockley has described Bardeen's surface-state hypothesis "as one of the most significant research ideas of the semiconductor program" (9).

POINT-CONTACT SEMICONDUCTOR AMPLIFIER

Surface-States Control

It was during the course of their research, to obviate the influence of the surface states in the development of a solid-state amplifier, that Bardeen and Brattain invented the point-contact semiconductor amplifier (transistor action) and demonstrated the concept of minority-carrier transport (10,11). As noted earlier, the point-contact semiconductor amplifier was the first device to operate based on minority carriers introduced by a current. The introduction of minority carriers by a current is possible because its space charge can be

neutralized by the concurrent introduction of an equal number of majority carriers. Nevertheless, the change in minority-carrier concentration can be enormous while the (equal) change in majority-carrier concentration is trivial compared to the already existing majority-carrier concentration, as seen utilizing the generalized mass-action relationship in eq. 3.

Bardeen and Brattain successfully negated the influence of the surface states on Nov. 21, 1947 following a suggestion on Nov. 17th by Robert Gibney. Gibney noted that Brattain's electrolytic photovoltaic experiments might be enhanced by appropriately biasing the electrolyte (i.e., by varying the d.c. potential on the vibrating electrode) to enhance neutralization of the surface states via the electrolyte's ions (23-25). Thus began the magic month between Nov. 17th and Dec. 16th, which witnessed the development and birth of the point-contact semiconductor amplifier (transistor action) (10,11). The change in the polarity of the voltage increased (+) or decreased (-) the change in the contact potential (difference in surface potential between two materials, taking into account the presence of surface dipole moments) induced by the photovoltaic effect. That is, positive ions (or in the case of a H₂O electrolyte, the positive dipole of the H₂O molecule) migrated (or aligned) to the p-type silicon surface in the case of a positively applied bias where they neutralized the (negatively charged) surface states and, therefore, enhanced the internal electric field at the semiconductor surface due to the repulsion of holes near the semiconductor surface. The electric field lines of force from the positive ions that are not terminated on the negatively charged surface states are terminated on the negatively charged acceptor ions in the SSCR, leading to an increased energy bandbending. Upon illumination of the semiconductor, the photogenerated free electrons and holes are swept by the internal (surface) electric field to the surface and bulk, respectively, thereby increasing the contact potential. Analogously, a negative bias on the electrode in the electrolyte aligns the negative ions (or the negative dipole of the H₂O molecule) to the surface, reducing the internal electric field at the semiconductor surface, thereby decreasing the contact potential (9). This research culminated in the concept of an amplifier, described by Brattain and Gibney in their "034" patent (26) on Nov. 24th (see entry No. 1 in Table one) (20), utilizing the electrolyte to obtain a high electric field at the surface via the field effect.

No.	Invention	Conception	Reduction to Practice	Patent Dates		Inventors
				Filed	Issued (b)	
1...	Electrolyte F.E.T.....	20 Nov '47	21 Nov '47	26 Feb '48	3 Oct '50	WHB / RBG
2...	Inver. Layer IGFET.....	23 Nov '47	?	26 Feb '48	3 Oct '50	JB
3...	Elect-Form Inver. Layer...	Dec '47 ?	Dec '47 ?	26 Feb '48	17 Jul '51	RBG
4...	Point-Contact Transistor...	15 Dec '47	23 Dec '47	17 Jun '48 (a)	3 Oct '50	JB / WHB
5...	Junction Transistor.....	23 Jan '48	Apr '50	26 Jun '48	25 Sep '51	WS

a. Originally filed 26 Feb '48; abandoned and refiled to include current gain at collector.

b. Patent numbers: 2,524,034; 2,524,033; 2,560,792; 2,524,035; 2,569,347.

Table 1. Five Transistor Device Patents Filed Before Public Announcement on June 30, 1948 (after 20)

Concurrently, (Nov. 23rd), Bardeen comprehended that it was not efficient to modulate the conductivity of a slab of semiconductor via the field effect. Bardeen has noted (9): "... *It occurred to the writer [Bardeen] that the effect [semiconductor amplification] might be observed in the thin n-type layer on the surface of a block of p-type Si...*".

Figure 3, often used by Bardeen in lectures describing his early research (27), illustrates his circuit configuration for the electrolytic control (neutralization) of surface states (via an appropriately biased drop of electrolyte [distilled water] contacting the surface) to manipulate the current flowing into a point contact using a chemical vapor deposition (CVD) p-type polycrystalline silicon sample with an n-type inversion layer (formed by a chemical pre-treatment). As noted above, with the electrode in the electrolyte made positive, the positive dipoles of the electrolyte species aligned itself to the semiconductor surface, neutralizing the negatively charged surface states. This "removal" of the surface states influence permitted holes emitted from an insulated point-contact electrode making electrical contact with the p-type polycrystalline silicon to be modulated, in

their passage to the base electrode on the other side of the p-type silicon, by varying the potential of the control electrode in the electrolyte relative to the base electrode. That is, the holes easily transferred from the n-type inversion layer into the p-type bulk. Significant modulation of the free carriers (electrons) was achieved by the control electrode. Alternatively, one may interpret the positive potential on the electrode in the electrolyte inducing electrons in the n-type inversion layer, a significant number of which flowed to the positively-biased point contact, in conjunction with the electrons already present in the inversion layer also being attracted to the point contact. However slightly, current amplification (and power) was observed with this circuit configuration (see 21-November entry in Table two). This was the first recorded power gain in a solid-state amplifier. The validity of the field-effect principle (8,14) was explicitly demonstrated as was the benefit of the neutralization of surface states. When the control electrode in the electrolyte was negative, a decrease in the amplitude of the modulated current was obtained, although a residual leakage current was measured (28).

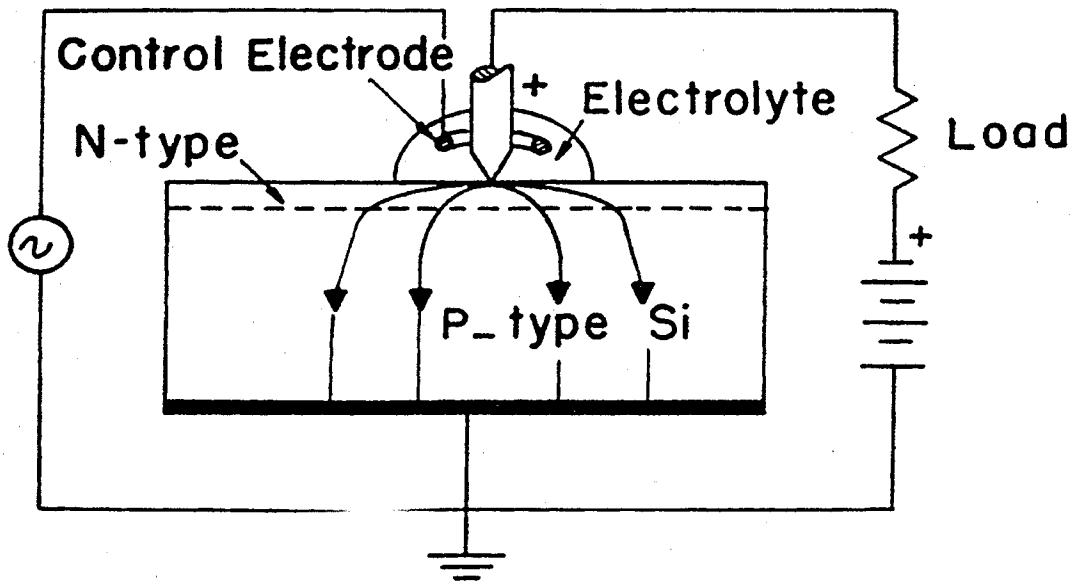


FIGURE 3. Schematic illustration of one of the experimental arrangements employed by Bardeen and Brattain in a room-temperature test of Bardeen's proposal that the surface trapping states for electrons (or holes) were responsible for the difficulties encountered in developing a field-effect transistor. In this example, an insulated, point-contact electrode makes electrical contact with a specimen of p-type silicon, introducing a current of holes, which spreads into the semiconductor and flows to the base electrode at the bottom of the specimen. A second, control, electrode which is immersed in an electrolytic fluid making electrical contact with the silicon is shown. The fluid covers a comparatively large area. Bardeen and Brattain found that the ions in the fluid interacted with the surface trapping states in such a way as to neutralize them, at least in part. The current from the point contact electrode to the base could be modulated by varying the potential of the electrolytic fluid relative to that on the base. This diagram, incidentally, also displays the type of inversion (or depletion) layer at the upper surface of the semiconductor which the investigators used in the experiment with polycrystalline silicon. This figure was used by Bardeen in lectures describing his early work. [Courtesy of the Bardeen Archives of the University of Illinois and N. Holonyak, after (27)].

Bardeen developed the concept of utilizing the inversion layer (which exhibited a better carrier mobility than a deposited thin film) to confine the minority-carrier transport, in series with a reverse-biased n-p junction. Bardeen patented this phenomenon ("033" patent) (29) as the gated surface inversion layer (see entry No. 2 in Table one) and described its importance during his Nobel lecture (30) and elsewhere (31). Bardeen's "033" patent (29) was the progenitor of the MOSFET and has been described by Sah as a sourceless MOS transistor (32). Further details are presented in the section on patents. Concurrently, Gibney was developing his "792" patent (33) on the methodology for preparing an inversion layer on a semiconductor by a chemical pre-treatment procedure (33) (see entry No. 3 in Table one).

During the week of Nov. 24th, a number of experimental modifications were made to Bardeen's circuit structure. These included replacing Si by Ge (see section 4b), the tungsten probes by gold and fabricating the insulation on the probe structure with Duco lacquer instead of paraffin glue. It was also recognized that the electrolytic drop covered a larger area than necessary, therefore requiring larger control currents than a proper design would need. During this time, Brattain and Gerald Pearson also applied an appropriately biased drop of a glycol borate electrolyte—commonly known as "gu"—(suggested on Dec. 4th by Bert Moore to Bardeen and Brattain for their continuing experiments, since water tended to evaporate quickly) (34) across a p-n junction following Shockley's suggestion (9). Indeed, the current flowing through the p-n junction could be manipulated by this arrangement (23,35).

DATE (1947)	DIELECTRIC MATERIAL	SEMI- CONDUCTOR MATERIAL	INVERSION LAYER FORMATION	AMPLIFICATION			FREQ. RANGE (cycles)	BIAS	
				VOLTAGE	CURRENT	POWER		ELECTRODE CONTACT	POINT CONTACT
21-Nov	DISTILLED H ₂ O	P-TYPE SILICON	CHEMICAL	NO	YES	YES	< 10	(+)	(+)
08-Dec	GU	N-TYPE GERMANIUM (HIGH BACK- VOLTAGE)	ELECTRICAL	YES	NO	YES	< 10	(-)	(-)
10-Dec	GU	N-TYPE GERMANIUM (HIGH BACK- VOLTAGE)	CHEMICAL	YES	YES	YES	< 10	(-)	(-)
15-Dec	"GeO ₂ "	N-TYPE GERMANIUM (HIGH BACK- VOLTAGE)	CHEMICAL	YES	NO	NO	10 - 10 ⁴	(+)	(-)
16-Dec	NONE	N-TYPE GERMANIUM (HIGH BACK- VOLTAGE)	CHEMICAL	YES	YES	YES	10 - 10 ⁴	(+)	(-)

Table 2. Bardeen / Brattain's Magic Month: November 17 - December 16, 1947

The two critical concepts of the inversion layer and the field-effect principle could now be exploited. There still remained, however, two obstacles: (a) voltage amplification was not observed and (b) the frequency modulation was less than 10 cycles. As regards the latter issue, Brattain and Gibney had already anticipated this concern in their "034" patent (26) noting that "it is of course evident that the liquid dielectric could be replaced by a solid dielectric if one can be found having the proper ionic mobility to form such a dipole layer at the surface of the semiconductor" (26). Finally, Brattain summarized three device configurations in his notebook on Dec. 4th (37). The first one was consonant with the "034" and "033" patents for modulating the resistance of a thin surface layer with a voltage applied to the electrolyte and the second supported Shockley's proposal to modulate the p-n junction resistance by a voltage applied to a drop of electrolyte over the junction (9). The third device configuration described by Brattain was truly prescient in that it anticipated the "035" point-contact semiconductor amplifier patent (36) (see entry No. 4 in Table one) in that it had the two points *directly* contacting the silicon.

Brattain noted the "two points close together [facilitated] the potential on one point to modulate the current flowing from the other point to the silicon" (37).

Minority-Carrier Modulation

Shockley described his junction field effect transistor and resulting voltage gain, using a sufficiently reverse-biased p-n junction (with the aforementioned electrolyte over the junction) at lunch with Bardeen and Brattain on Dec. 8th. Bardeen subsequently suggested to Brattain that they accordingly utilize high back-voltage Ge (i.e., Ge with good rectification – asymmetric current-voltage characteristic) (3) to obtain a large reverse-biased voltage at the p-n junction, perhaps also stimulated by Pearson's use of similar material on field-effect experiments. Bardeen and Brattain accordingly utilized an n-type sample of Ge with good rectification characteristics (without a chemically induced inversion layer) and the "gu" electrolyte in the experimental arrangement as in Figure 3 (with the opposite voltage polarities). They found that when

the electrode in the electrolyte was made negative, the current at the negatively biased point-contact increased. Bardeen surmised that they were inducing an increase in the hole population by the electrostatic induction of a p-type inversion layer in the n-type Ge sample and achieved significant voltage (2x) and power (330x) gain by the holes flowing to the negative polarity point contact (see 8-December entry in Table two). Bardeen and Brattain then repeated the experiment on Dec. 10th with a different n-type germanium sample and, in this case, a chemically prepared p-type inversion layer, as in the original Si experiments (see 10-December entry in Table two) (35) and obtained an immense power gain of 6000x and a slight current (10%) as well as voltage gain (23). The continued use of an electrolyte

as the passivating medium, however, greatly limited the frequency modulation that could be achieved due to the ionic mobility in the electrolyte.

Brattain had also observed during the experiments on Dec. 10th that the application of a large negative voltage on the electrode resulted in a thin film growing on the germanium surface, which Gibney suggested was probably the electrochemical anodic growth of germanium dioxide. Since the oxide was surmised to be insulating, Bardeen and Brattain decided to put a metal electrode on top of the oxide (thereby expecting a higher electric field at the semiconductor surface due to the replacement of the electrolyte by a solid dielectric) and anticipated both a power gain and a higher frequency response.

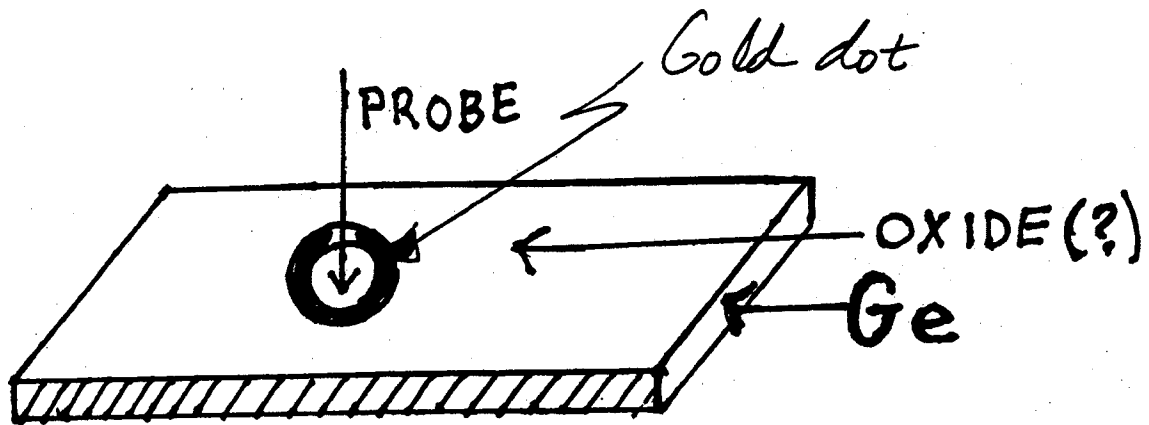


FIGURE 4. Ring (gold) - dot structure with germanium covered (presumably) by a germanium oxide film [after (38)].

Accordingly, the electrolyte was replaced by a thin germanium oxide film on Dec. 12th, fabricated by electrolytic anodization on a different high back-voltage sample of n-type germanium (prepared with a chemically induced p-type inversion layer). Figure 4 schematically illustrates a circular gold metal film in the form of an annular ring deposited on the germanium dioxide, with an insulated point-contact electrode in the center of the ring making electrical contact directly with the germanium (38). Bardeen and Brattain anticipated that a negative polarity on the gold ring would electrostatically induce positive charges in the p-type inversion layer of the germanium sample, similar to the case of an appropriated biased control electrode in the electrolyte. It was expected that a portion of the induced holes would flow to the negatively biased point-contact probe (9); equivalently, electrons

emitted from the negatively-biased point contact would flow mainly to the n-type bulk, modulated by the bias on the gold contact, analogous to Figure 3. The application of a negative voltage to both the metal ring and point-contact probe, however, did not result in any observed effect (23). During the test, Brattain inadvertently shorted out the probe to the ring at a very high negative voltage. Testing other spots on the germanium surface, however, seemed to indicate that the probe was making direct contact with the germanium surface, as if the germanium oxide were not present, as indeed had also appeared to be the case during preliminary tests on the sample. It was at this point that Brattain realized he had probably washed off the germanium oxide due to its water solubility during a pre-clean (39). Brattain has subsequently summarized his view as to what happened (40):

"We were using gl[y]caborate as the electrolyte and noticed an anodic oxide film growing on the surface of the germanium so we anodized the surface of a piece of germanium, washed off the glycoborate and evaporated the gold spots on it. As it turned out the germanium oxide was soluble in water and we had also washed it off! So these experiments were done on a freshly anodized surface of germanium, and the first transistor was made on one of these samples anodized in this way!"

Nevertheless, Brattain continued experimenting on Dec. 15th with various combinations of voltage polarities on both the gold electrode and the point-contact electrode, the latter having been moved adjacent (just outside) the former electrode. One such combination had the gold electrode positively biased and the point-contact negatively biased, resulting in a voltage amplification of holes emitted from the gold electrode and collected at the point-contact (see 15-December entry in Table two); modulation was achieved by varying the potential of the emitting gold electrode. Bray has suggested Bardeen and Brattain might have utilized ac signals on both electrodes, with appropriate phases, (over and above the modulation effect at the emitter), thereby "explaining" their "selection" of the above choice of voltages and polarities that gave semiconductor amplification (transistor action) (41). In any case, the observed effect (with the gold electrode positively biased and the point contact negatively biased) was the opposite to what would have been expected if the oxide were present. In that case, a positive voltage applied to the gold electrode would have been expected to electrostatically induce electrons in the p-type inversion layer with a resultant decrease in the hole flow to the negatively biased point contact. Bardeen and Brattain had discovered "that it is possible to increase the conductivity by current flow from an appropriate contact on the germanium (31)." This was the first observation of semiconductor amplification (i.e., the transistor effect.) Although there was no power gain, there was a 2x voltage gain, independent of frequency up to 10⁴ Hz (23). Bardeen and Brattain concluded that the observed voltage gain was due to holes emitted from the positively-biased gold electrode into the germanium's p-type inversion layer and collected at the negatively-biased collector. A signal applied between the emitter and the base electrode appeared in amplified form across a high-resistance load between the collector and the base (10). This observation resulted in the conception of the point-contact semiconductor amplifier and Bardeen and Brattain's "035" patent disclosure (36)

(see entry No. 4 in Table one). Michael Riordan and Lillian Hoddeson have noted that although Bardeen and Brattain failed to observe any power amplification with this configuration, Bardeen suggested a power gain should occur if two narrow contacts could be spaced only a few mils apart (23).

Historic Day – December 16, 1947

The Dec. 15th experiment quickly led to the experimental configuration utilized by Bardeen and Brattain on Dec. 16th, as shown in Figure 5. Specifically, Bardeen and Brattain utilized the same piece of germanium as used for the gold ring studies (i.e., n-type polycrystalline germanium with a chemically induced p-type inversion layer) (10,11). The germanium sample into which the plastic wedge pressed two stripes of gold foil is about half a centimeter long (42). The emitter was biased positively and emitted holes; the collector was biased negatively and collected the emitted holes. Both voltage and current amplification of an input signal, up to 10³ Hz with a power gain of about 2 dB, was achieved (see 16-December entry in Table two). One can clearly see the evaporated gold electrode in Figure 5 (from the Dec. 15th experiment) adjacent to the plastic wedge utilized for the definitive transistor experiment.

Brattain has described how he achieved the point-contact separation — two parallel lines spaced about 50 μm apart — by cutting an evaporated strip of gold foil with a razor blade (43): *"I accomplished it by getting my technical aide to cut me a polystyrene triangle which had a smart, narrow, flat edge and I cemented a piece of gold foil on it. After I got the gold on the triangle, very firmly, and dried, and we made contact to both ends of the gold, I took a razor and very carefully cut the gold in two at the apex of the triangle. I could tell when I had separated the gold. That's all I did. I cut carefully with the razor until the circuit opened and put it on a spring and put it down on the same piece of germanium that had been anodized but standing around the room now for pretty near a week probably. I found that if I wiggled it just right so that I had contact with both ends of the gold that I could make one contact an emitter and the other a collector, and that I had an amplifier with the order of magnitude of 100 amplification, clear up to the audio range."*