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The Transistor was Invented 75 Years Ago: A Big Milestone in Human History

by Hiroshi Iwai and Durga Misra

Seventy-five years ago, on December 16, 1947, the transistor was invented by William Shockley, John Bardeen, and Walter Brattain at Bell Telephone Laboratories. **This was a big milestone in human history as it was the origin of the field of micro/nano electronics, which is now resulting in a super-intelligent society.** The technological revolution that followed the invention of the transistor is astounding and has moved mankind forward in countless ways. This paper describes the process of the technological development behind the invention of the transistor, and discusses the meaning and impact of its invention on human history.

Progress of Communication and Information Processing in Human History

Innovations in communication and information processing have been a driving force in the evolution of human culture and society, and this advancement can be divided into three waves of seminal achievements. **The first wave of innovation was the invention of language** long ago in human prehistory. Through language, we could communicate and think deeply and widely. **The second wave was the invention of characters/letters** 5000 to 10,000 years ago. Through characters/letters, we could communicate accurately with people who lived in faraway places and over many generations in time scale. **The third wave was the invention of electric information**, which started about 175 years ago. **With electric information, we could communicate over long distances instantaneously, and make machines that can process huge amounts of information in a short time.**

Technological Leaps in Electric Information Technology

There have also been three stages of technological leaps during the electric information technology wave. **The first leap was the instantaneous and long-distance transportation of information (and energy) through electric wires.** This was the beginning of electrical engineering. Information transportation was accomplished

by the “practical electric telegraph” technology invented by Samuel Morse and others in the late 1830s to the middle of the 1840s.¹ Through the electric telegraph, we could communicate long-distance instantaneously in long sentences with accuracy. By the 1870s, the world became connected by the electric telegraph through submarine cables. Because of the decay of the electric signal on the long electric wire, amplification of the signal in the middle of the wire was necessary. This amplification was accomplished by a relay which was invented in the middle of the 1840s (shown in Fig. 1). The relay is a kind of three-terminal mechanical-switching device, operating by the electromagnetic force controlled by the input current flowing in the magnetic coil. **The relay was the first amplifier** for an electric signal, but it was only a **digital amplifier operating at a very low frequency** because of the mechanical switching operation.

The second leap was the invention of triode vacuum tubes in 1906 by Lee de Forest.² This was the **first three-terminal electron device**. The thermo-electron beam in vacuum emitted from the heated cathode to the anode was modulated by the grid potential that was inserted in the beam, as shown in Fig. 2. The triode vacuum tube was the first analog and digital amplifier which could operate at a very high frequency, almost near the GHz range. The triode can be used to manipulate the movement of electrons by the grid bias as we wish, and this was **the beginning of electronics or electronic engineering**. Through electronics, we were able to treat information electrically, and not only perform telecommunication by wireless radio/TV broadcast, but also information/data processing, automatic machine-control, and computer operations. Later artificial intelligence (AI) was also realized.

The third leap was the invention of the transistor (or the solid-state amplifier) in 1947 and the resulting micro/nano electronics with the invention of photolithography.^{3,4} Micro/nano electronics or continuous miniaturization of electronic devices was a totally new concept in electronics. As shown in Fig. 3, the **reduction of the dimension of electronic devices by 10^5 times over the past 115 years** (since the invention of triode vacuum tubes), has brought us **tremendous performance increases of billions to trillion times in operation speed, power consumption, volume, weight, and cost.** **The invention of the transistor in 1947 was the origin of the device miniaturization that has made possible the revolution we are now experiencing: a super-intelligent society with nanoelectronics.**

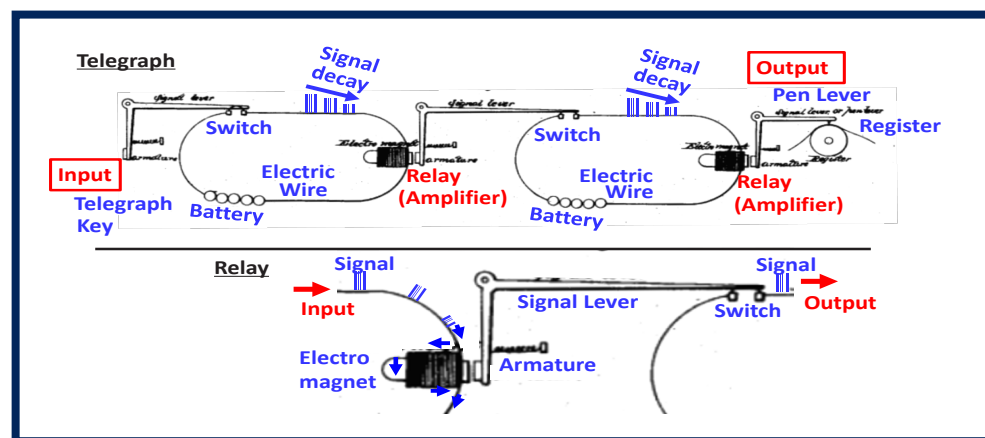


FIG. 1. Long-distance electric telegraph using relays as the signal amplifiers, proposed by S. Morse in his patent,¹ reissued on June 13, 1848. The relay was used as a digital signal amplifier. This is one of the beginnings of electrical engineering.

The Road to the Invention of the Transistor

By the mid-1940s, electronics—which started with the invention of the triode vacuum tube in 1906—had brought great benefits to human society. However, the relatively long electron transit time—due to the difficulty in decreasing the vacuum-tube size—made it impossible to operate at the microwave frequency range. Also, the need to heat the cathode electrode above 1000°C for

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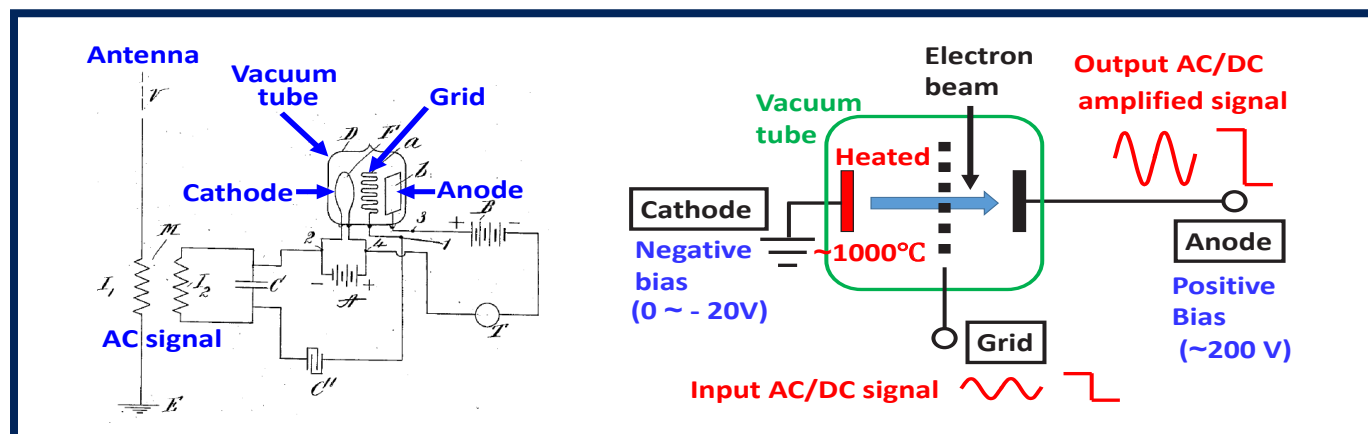


FIG. 2. Triode vacuum tube invented by Lee de Forest in 1906.² This is the first analog solid-state amplifier and the first three-terminal electron device. In his patent, "anode" was described as "plate." This is the beginning of electronics.

emitting the electrons hampered power saving and heat insulation of the systems. **Many people dreamed of replacing the triode vacuum tube with some kind of a three-terminal solid-state amplifier to solve these problems.**

Control of an electron current in a vacuum using the grid potential was easy. However, control of the electron current in a solid-state conductor (or metal) was almost impossible because of the huge density of the free carriers, as shown in Fig. 4. On the other hand, in the case of insulators, there is no current flow at all. Thus, semiconductors that have lower electron density were thought to be candidates.

The use of semiconductors had already started for commercial point-contact rectifiers (or crystal detectors) from the beginning of the 20th century for demodulating wireless radio waves to the audio signal using their nonlinear characteristics.⁵⁻⁷ Semiconductor rectifiers were used popularly for low-priced radio receivers and very high-frequency microwave receivers for which triode vacuum tubes were not suitable. However, the rectifiers had very limited ability to treat the signals (e.g., they had no signal amplification ability), which was a result of the nature of two-terminal devices. Thus, **a demand for three-terminal semiconductor rectifiers was created.**

A seemingly easy idea for creation of three-terminal solid-state amplifiers could be to control the electron (or hole) current by

the potential of the grid electrode inserted in the depletion region where there are much fewer free carriers, as shown in Fig. 5 (a) and (b). The concept of the depletion region became recognized through the rectifying theories developed by Walter Schottky,^{8,9} Nevil F. Mott,¹⁰ and Boris Davydov in 1938.¹¹ These types of devices were proposed by a German company, AGE, in 1929¹² and W. Shockley in 1939,¹³ but no successful results were reported, except for a case by Rudolf Hilsch and Robert Wichard Pohl of Göttingen Universität in 1938,¹⁴ as shown in Fig. 6.

Hilsch and Pohl used a KBr crystal. KBr is an ionic crystal with a wide bandgap (7 ~ 8 eV) and is an insulator rather than a semiconductor. Electrons were injected from the point-contact cathode electrode into the KBr crystal (2 x 5 mm cross-section and 10 mm length) at a high temperature of 490°C. There were almost no carriers other than the injected electrons and the ions of KBr, the latter of which amount to about 3% of the injected electrons at 490°C. The injected current was modulated by the potential of a Pt grid electrode inserted into KBr at 2 mm distance from the cathode. The Pt-to-KBr contact was a Schottky contact and there was a very small leakage of current at the grid voltage (V_g) of 0 ~ 13 V. The maximum current amplitude (I_A/I_G) of 20 was observed by the experiment, where I_A is the anode current. The mobility of electrons in KBr was very low and the transit time of electrons in the KBr crystal of 10 mm was 10 seconds. Thus, the operating frequency was estimated to be only sub-Hz.

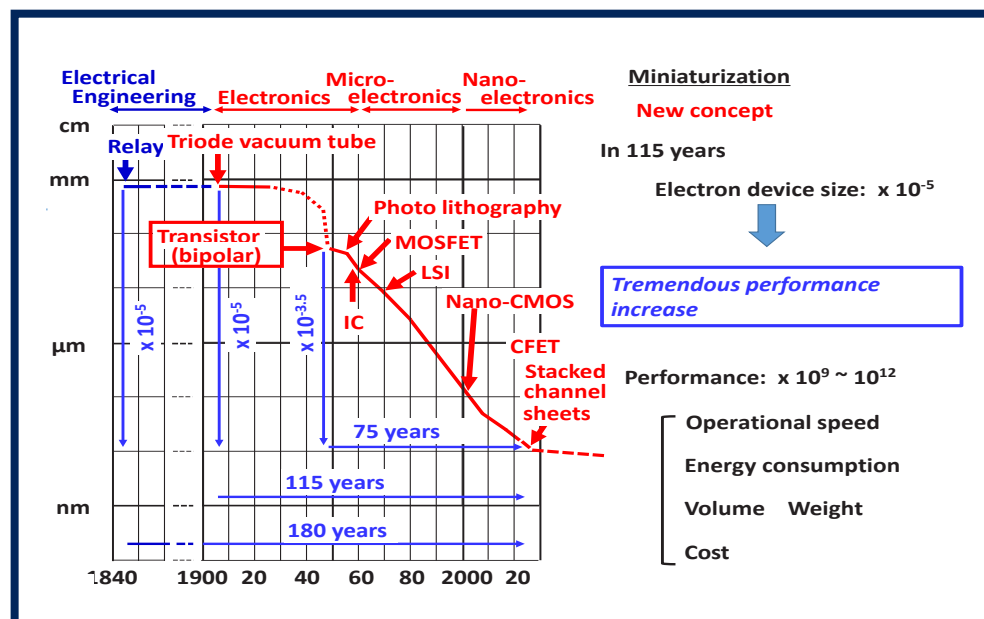


FIG. 3. Trend of the miniaturization of electric and electron devices, and its impact.

This result was the first experimental record of a solid-state amplifier and a type of MESFET (Metal-Semiconductor Field Effect Transistor), although the performance was not satisfactory at all, basically because KBr is an insulator. They also investigated the possibility of a Cu-Cu₂O (semiconductor) rectifier in order to operate at a higher frequency at room temperature, but the depletion layer width was found to be 0.1 μm, and they reached the conclusion that it was not possible to make the solid-state amplifier by inserting the grid into the semiconductor.

Another approach for the semiconductor amplifier was to use the ultra-thin semiconductor film and control the lateral current in the film by a vertical electric field. The vertical field was applied

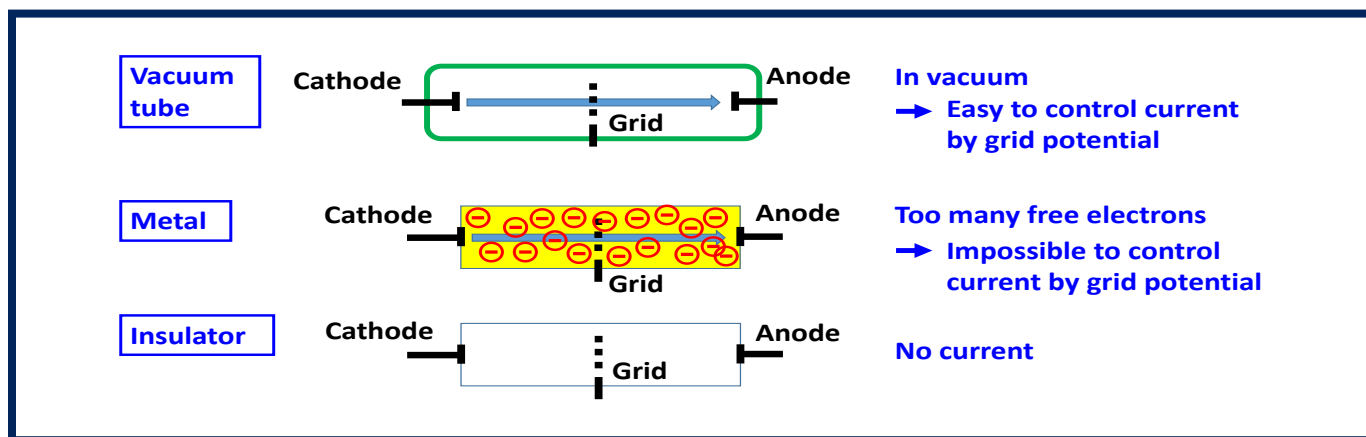


FIG. 4. Difficulty of realizing the solid-state amplifier using conductors and insulators.

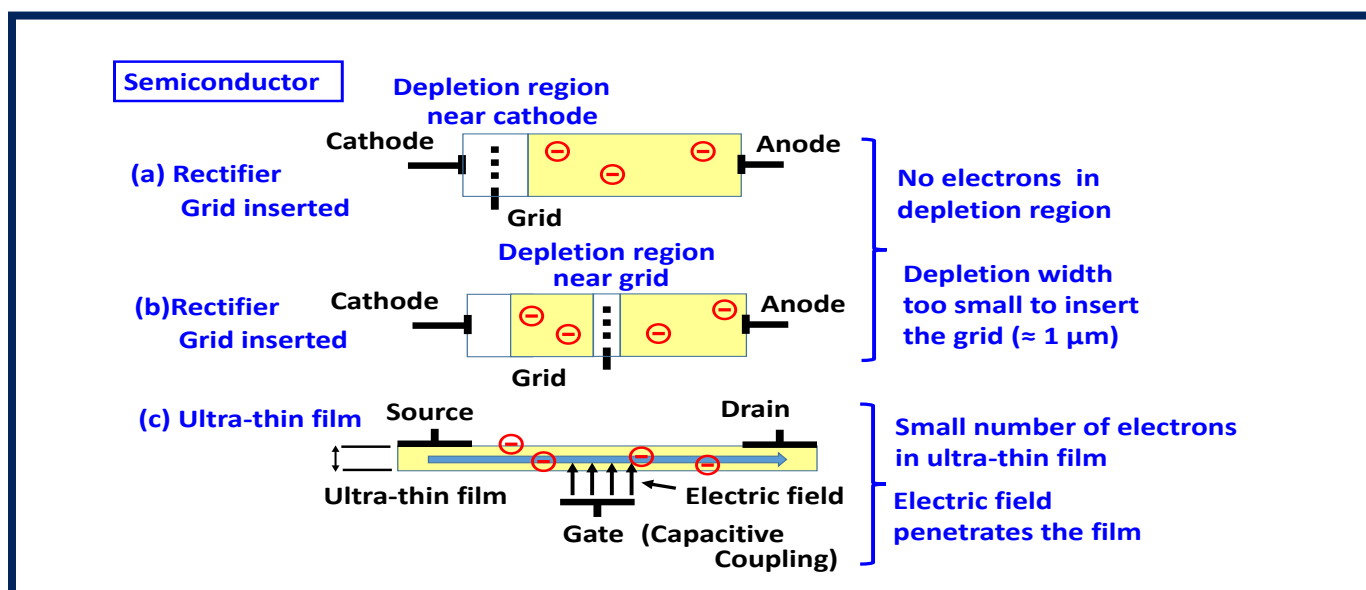


FIG. 5. The ideas behind semiconductor solid-state amplifiers: (a) Grid insertion at the depletion region near the point-contact cathode. (b) The case that the grid mesh creates the depletion layer: (c) Thin-film semiconductor with outside gate electrode. (c) is an FET (MISFET or MESFET) structure. (a) and (b) are also FETs but MESFETs.

remotely by the gate electrode voltage with capacitive coupling, as shown in Fig. 5 (c). This is also a kind of FET, although the name of the transistor did not exist until 1948.

Even before the ideas of the grid-inserted structures, the idea of ultra-thin semiconductor film MESFET in 1925¹⁵ and MISFET (Metal Insulator Semiconductor FET)/MOSFET (Metal Oxide Semiconductor FET)¹⁶ in 1928 were filed as patents by Julius E. Lilienfeld. Figure 7 shows the case of his MOSFET. There are no records of experimental results of Lilienfeld's MESFET and MOSFET. In the early 1960s, J. B. Johnson fabricated Lilienfeld's MOSFET, but observed no amplification or even modulation.¹⁷ The reason was probably the very low mobility of holes in Cu_2S ($\sim 1 \text{ cm}^2\text{V}^{-1}\text{sec}^{-1}$), and the effect of surface states on the surface of the film. Later, the ideas of MISFETs/MOSFETs were proposed by several people—Oskar Heil in 1934,¹⁸ Heinrich Welker in 1945,¹⁹ and even by W. Shockley in 1945¹³ and others. But none of them showed successful amplification results until 1960, because of immature semiconductor quality and poor understanding of and technology to control the semiconductor surface.

The Invention of the Transistor in 1947

Shockley's group at Bell Laboratories started the development of the solid-state amplifier after World War II and continued to research surface states for the purpose of developing FETs. Shockley's first attempted MISFET with an air gap as a gate insulator in 1945¹³ did

not work because the surface state charges shielded the electric field from the gate.²⁰ Based on Walter Brattain's and others' research on surface state charge compensation,^{21,22} John Bardeen proposed to modulate the injected surface current—from the point-contact source electrode—by the gate electrode immersed in a drop of distilled water on November 21, 1947^{23–25} as shown in Fig. 8.^{26,27} The high-resistivity distilled water was used as a gate insulator and the water molecule dipoles at the semiconductor interface enhanced the local electric field to control the channel current.^{21,22,28,29} This is a kind of a vertical MISFET using distilled water as the gate insulator. The dielectric constant of the water is about 80, and the electric flux density in the water is about 80 times larger than that of air. Current and power gains were observed for the first time at Bell Laboratories, but there was no voltage gain.²⁷

Eventually the distilled water was replaced by glycol borate in order to solve the problem of water evaporation and disappearance during the measurements.^{21,22,24,25} On December 8, 1947, Bardeen proposed using a Ge semiconductor used for “high back voltage” rectifiers with high breakdown voltage, which was supposed to have low defect and impurity densities.^{24,25} They obtained a power gain of 330 and a voltage gain of 2,^{24,25} but the maximum operation frequency was only 8 Hz^{21,22} because of low reaction time of the dipoles for electrolyte. On December 10, 1947,²⁵ Brattain accidentally grew an anodic oxidized Ge film by applying -45V to the glycol borate.^{21,22,25,30} The team decided to use the Ge oxide film as the

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gate insulator—instead of the glycol borate—in order to improve the frequency dependence. Ge oxides are dielectrics and the dipole effects were expected.

Figure 9 shows the planned/executed sample structures (prepared by Robert B. Gibney) and circuit configurations. **It happened that the Ge oxides disappeared through the water treatment to wash off the glycol borate before the gate electrode metal deposition.**^{21, 22} At the initial measurement, Brattain ruined one of the gate electrodes by accidentally shorting it with the point-contact source electrode when he placed the point-contact electrode inside of the ring-shaped gate electrode.²⁵ Then, he put the point-contact electrode near the peripheral of the gate electrode and **obtained a voltage amplification effect when he changed the polarity of the DC bias of the “gate” electrode (or actually, it was named “emitter” immediately after) at 1 kHz on December 12, 1947, but still no power amplification was observed.**^{25, 27}

Bardeen proposed to put the source and gate electrode within a distance of 50 μm in order to increase the amplification²⁷ and Brattain made the structure using gold foils as the electrodes separated by 20 μm .^{21, 22, 31, 32} as shown in Fig. 10. With this structure, on December 16, 1947, both the voltage and the power gains were confirmed at 1 kHz.^{31, 32} Under the condition of grid bias = +1 V, plate bias = -15 V, and output load resistance = 10 k Ω , a voltage gain of 15 and a power gain of 1.3 were measured.³¹ AC input and output voltages were 0.6 and 10 V, respectively, and input

and output AC powers were 7.5 and 10 mW, respectively.³¹ **This represents the discovery of the point-contact transistor effect and the invention of the point-contact transistor.**

Although gold foils were used as the electrodes in the experiment, two metal tungsten needles were used as the emitter and collector electrodes later in commercial devices. The patent³² describes a thin p-type Ge layer at the surface of the n-type Ge substrate. Bardeen initially thought that the surface p-type layer was necessary for the injected hole current to reach the collector effectively. However, it was soon found, on February 13, 1948,³¹ by John N. Shive, that **the thin p-type surface layer is not necessary for the transistor action because the minority carriers (holes in this case) can migrate in the n-Ge base for a sufficiently long distance.**³³ The name “transistor” was proposed by John R. Pierce as an “abbreviated combination of the words ‘transconductance’ or ‘transfer’ and ‘varistor,’” and determined by a ballot among several candidates on May 28, 1948.³⁴

Operation Mechanism of the Point-Contact Transistor

In December 1947, Brattain and Bardeen happened to discover the point-contact transistor operation during experimental work aimed at realizing FET operation. This device is not the FET that modulates the surface lateral current by the gate vertical field. It took some time to understand the mechanism of the amplification (or transistor action)

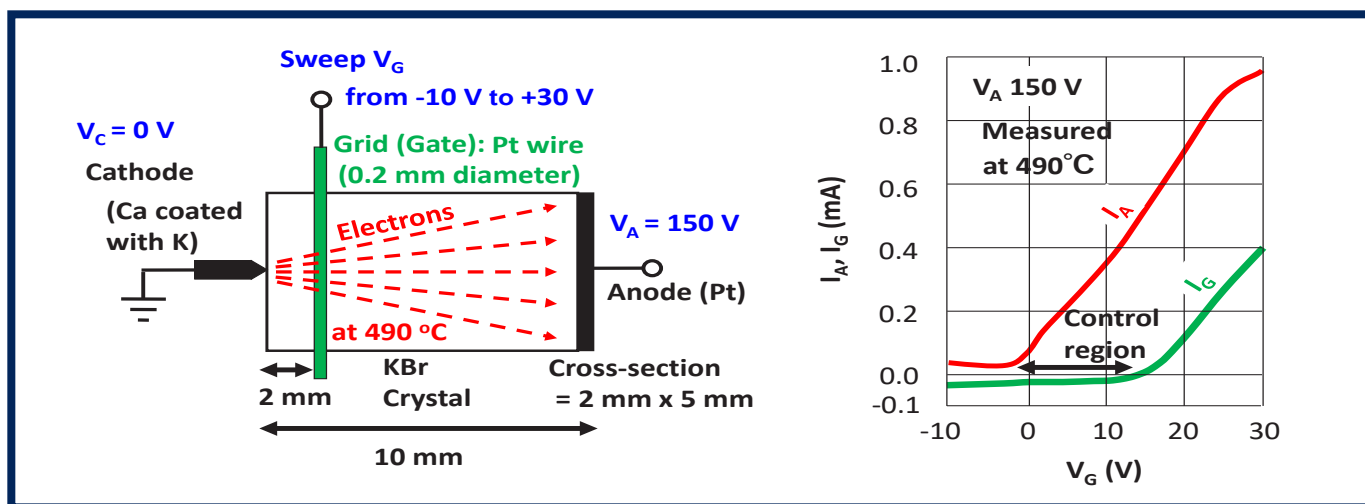


FIG. 6. The first experimental results of a solid-state amplifier using KBr crystal in 1938.¹⁴ It operated at 490 °C. Operating frequency was supposed to be less than 1 Hz. A Pt grid was inserted in the KBr crystal. There were almost no carriers other than injected from the point-contact cathodes.

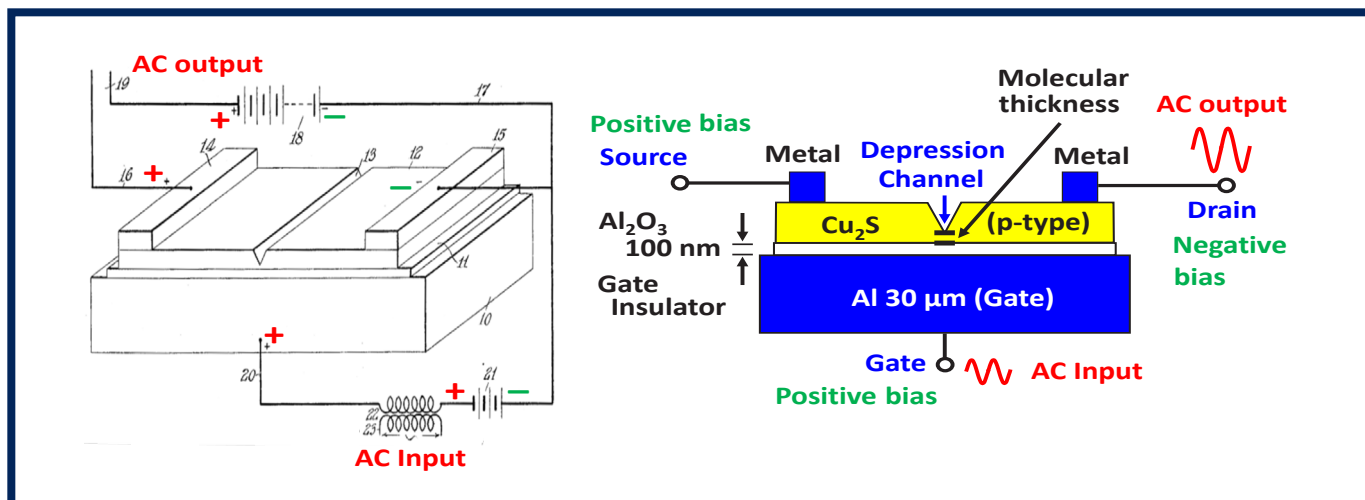


FIG. 7. First MOSFET idea proposed by J. Lilienfeld in 1928.¹⁵ No experimental records were published. Cu_2S is a p-type semiconductor (almost insulator) with low hole mobility. The FET is a normally-on type. Electrode names “source,” “gate,” and “drain” were labeled by the authors to aid in understanding.

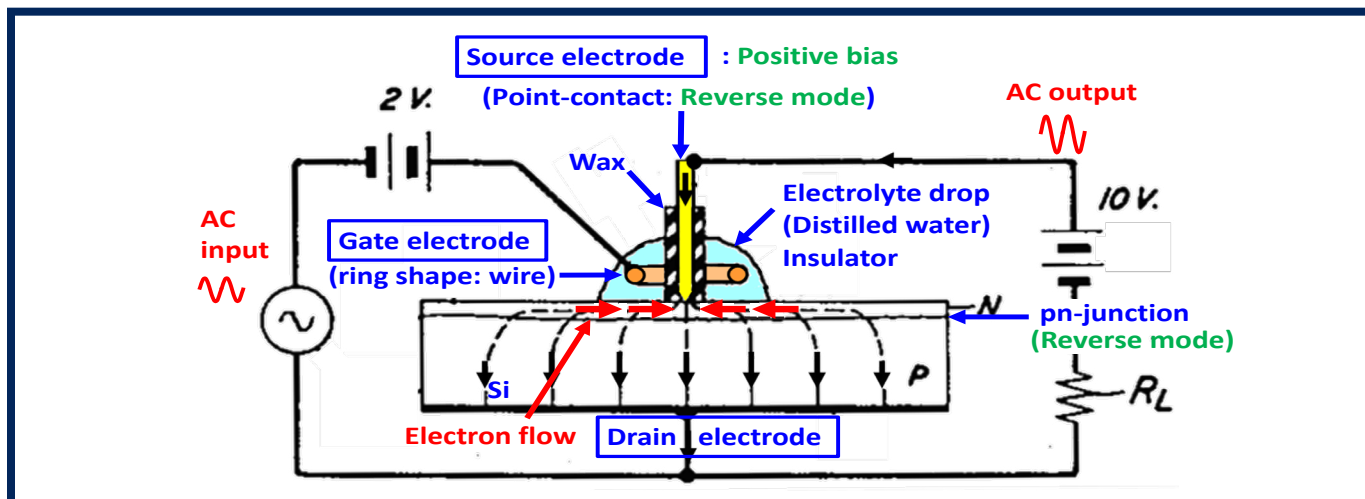


FIG. 8. First solid-state device by Bell Laboratories for which the amplifications were confirmed on November 21, 1947.^{23, 26} Shockley's first idea of MISFET in 1945 used an air gap as the gate insulator¹³; that did not work because of the shielding effect of the gate field by the surface states.^{13, 20} The water dipoles compensated the electric field from the trapped electrons at the surface states. Because of the slow reaction time of the water dipole, the maximum operating frequency was several Hz. Electrode names "source," "gate," and "drain" were labeled by authors to aid in understanding.

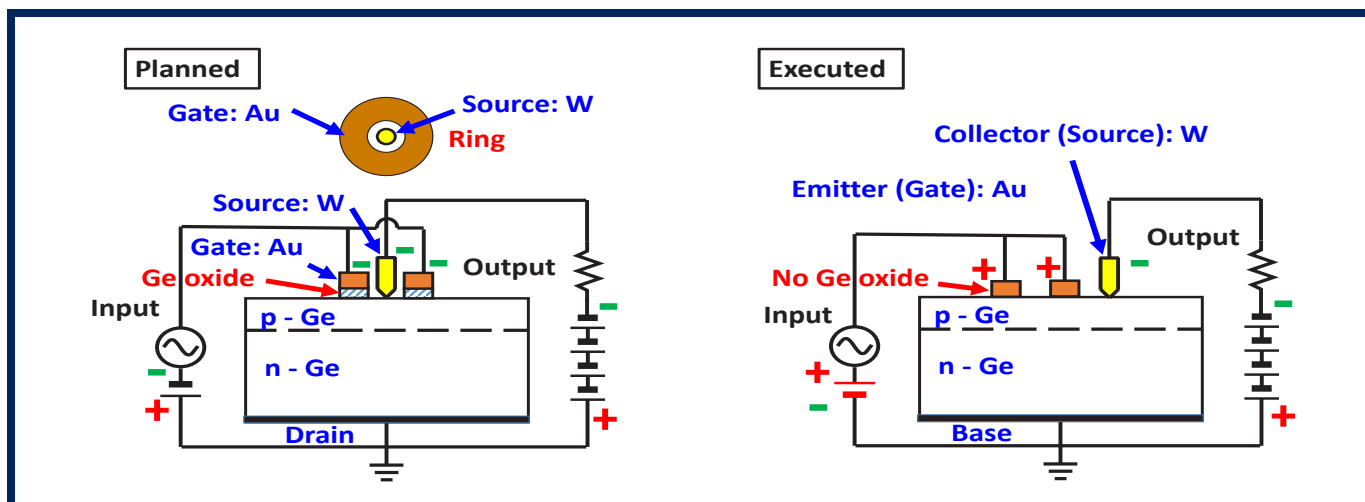


FIG. 9. The first point-contact transistor operated at 1 kHz with power gain on December 12, 1947.^{25, 27} They planned to fabricate a MOSFET with anodic Ge oxide as the gate insulator; but the Ge oxide happened to be washed away by the water treatment. Electrode names "source," "gate," "drain," "emitter," "base," and "collector" were labeled by the authors to aid in understanding.

of the point-contact transistor.^{32, 35} The point-contact transistor is a device that modulates the vertical electron current injected from the collector metal by the hole current injected from the emitter metal, as shown in Fig. 11.^{35, 36} The injected hole current finally flows into the collector metal (the most negative electrode), resulting in the elevation of the local potential and carrier concentrations in the Ge near the collector contact. The collector contact is the Schottky reverse-mode-junction that is sensitive to the Ge potential and carrier concentration,^{9, 36} resulting in the enhancement of the electron injection from the collector metal in this case. This scheme is the mechanism of the collector electron current amplification by the emitter hole current injection.

The Invention of the Bipolar Junction Transistor

Shockley felt frustrated by the fact that he was not an inventor of the transistor.¹³ He worked to "invent new semiconductor amplifier principles" from December 31, 1947, and "completed conception of junction transistor" on January 23, 1948,^{13, 37} as shown in Fig. 12. The junction transistor is a device that modulates the n-Ge emitter electron-current to the n-Ge collector via the p-Ge base due to p-Ge base potential applied through the base electrode.

Elevation of the p-Ge potential increases the emitter electron current at the forward-biased emitter-base pn junction. Because collector potential is set to the most positive potential, the injected emitter electron current into the p-Ge base flows finally into the n-collector. This process is the mechanism of the bipolar junction transistor operation. The ratio of the base hole current to the emitter electron current at the pn junction is related to the ratio of emitter donor concentration to the base acceptor concentration that is typically set to 100. Thus, there is emitter current amplification by the base current.

After the Invention of the Bipolar Junction Transistor

Because of the mechanical instability of the point-contact transistor, it disappeared from the market by the middle of the 1950s, and junction transistors started to be widely used for many intelligent applications, including the NASA Apollo Project, and eventually replaced vacuum tubes by the middle of the 1960s. During this period, various key semiconductor process technologies were developed, resulting in the invention and successful operation of the MOSFET in 1960,^{39, 40} as shown in Fig. 13. One of the key technologies for the realization

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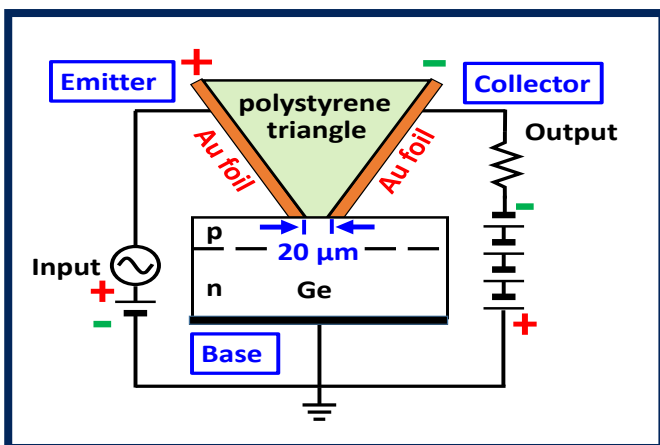


FIG. 10. The first successful point-contact transistor with both power and voltage gains at 1 kHz fabricated and measured by Brattain on December 16, 1947.^{21, 22, 23, 31} The distance between the emitter and collector electrodes was set to 20 μm in order to enhance the amplification.

of the MOSFET was high-temperature thermally grown gate SiO_2 in order to stabilize the semiconductor surface with small surface state concentration.^{40, 41} MOSFETs are now the mainstream devices for the recent nano-CMOS integrated circuits. In the near future, a super-intelligent society will realize new technologies such as AI constructed on nanoelectronics, which originated with the transistor's invention 75 years ago.

Summary and Conclusions

The process through which the transistor was developed was described. The first transistor, the point-contact transistor, happened to be developed unintentionally in the course of FET development in December 1947. The operation mechanism (i.e., the bipolar transistor action) of the point-contact transistor was beyond the inventors' original contemplation. In January 1948, immediately after the invention of the point-contact transistor, the idea of the bipolar junction transistor was inspired by the invention of the point-contact transistor. Because of the mechanical instability of the point contact, the bipolar junction transistor replaced the point-contact transistor in the market in the early 1950s. Bipolar junction transistors were the main solid-state devices in the 1950s and 1960s and contributed

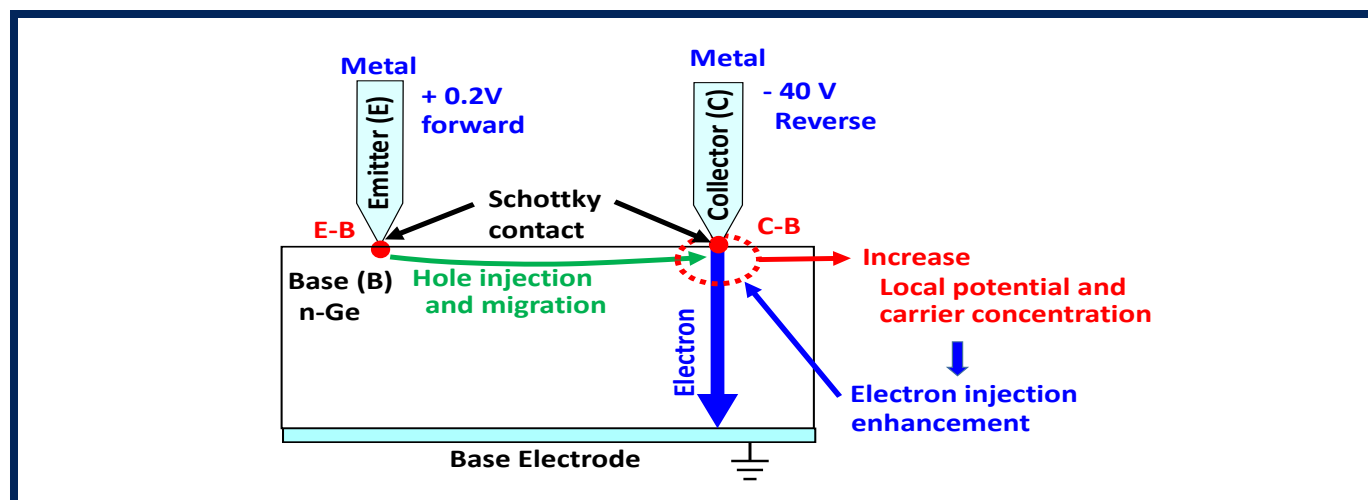


FIG. 11. Operation mechanism of the point-contact transistor.^{35, 36}

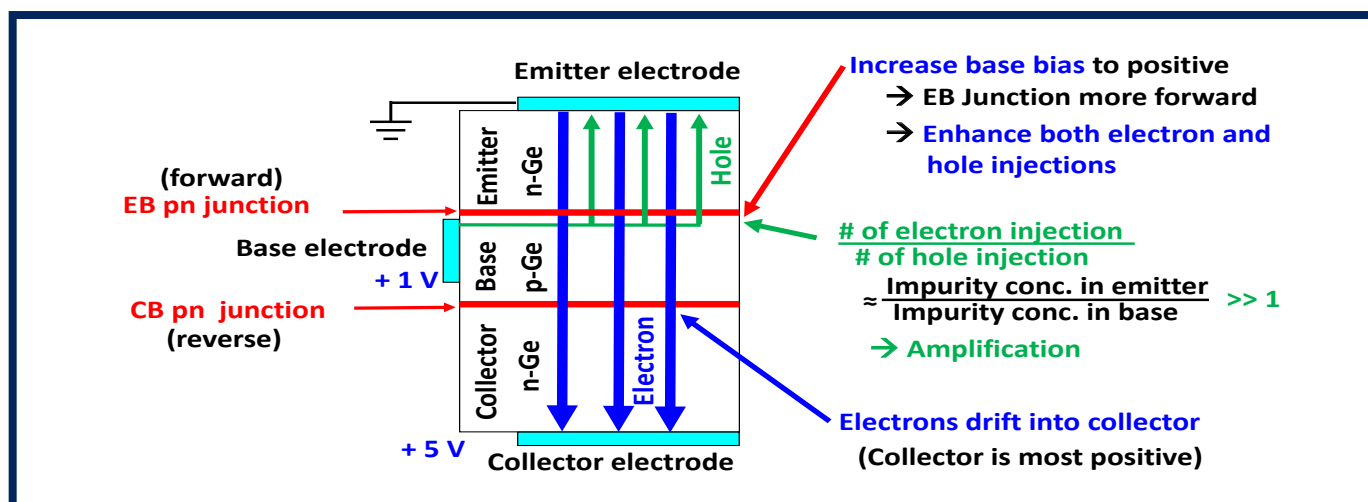


FIG. 12. Operation mechanism of the bipolar junction transistor by Shockley on January 23, 1948.^{13, 37}

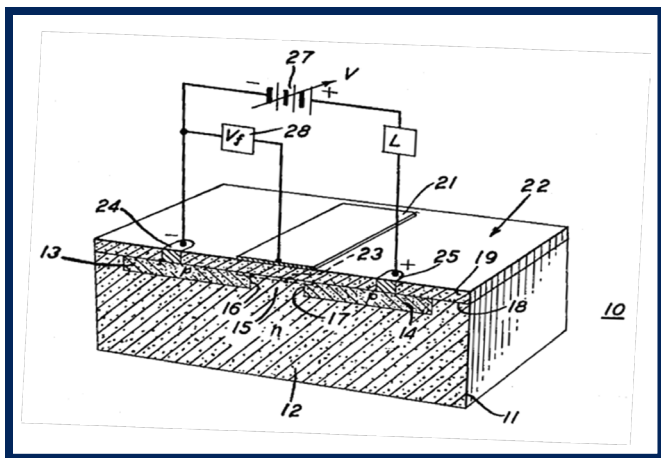


FIG. 13. The first successful operation of MOSFETs by Kahng and Atalla in 1960.^{38, 39} One of the key technologies for the realization of the MOSFET was high-temperature thermally grown gate SiO_2 to stabilize the semiconductor surface with small surface state concentration.⁴⁰ Kahng and Atalla used steam oxidation at 650°C under high pressure of $40 \sim 50 \text{ atm}$.⁴¹

greatly to the electronic society in that period. During that period, various semiconductor process technologies were developed, resulting in the invention and successful operation of the MOSFET in 1960, which is now the mainstream device for the recent nano-CMOS integrated circuits.

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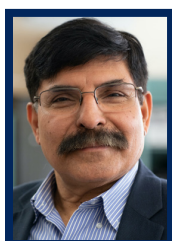
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Honors & Awards: Include Fellow of ECS and Awarded Life Member. Recipient of the ECS Thomas Callinan Award and the Electronic and Photonic Division Award.

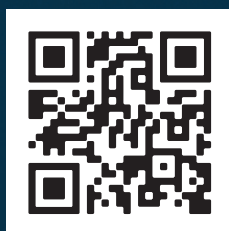
Work with ECS: He has been the Chair of Dielectric Science and Technology Division of ECS and has been organizing technical symposia at ECS for the last 30 years.

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