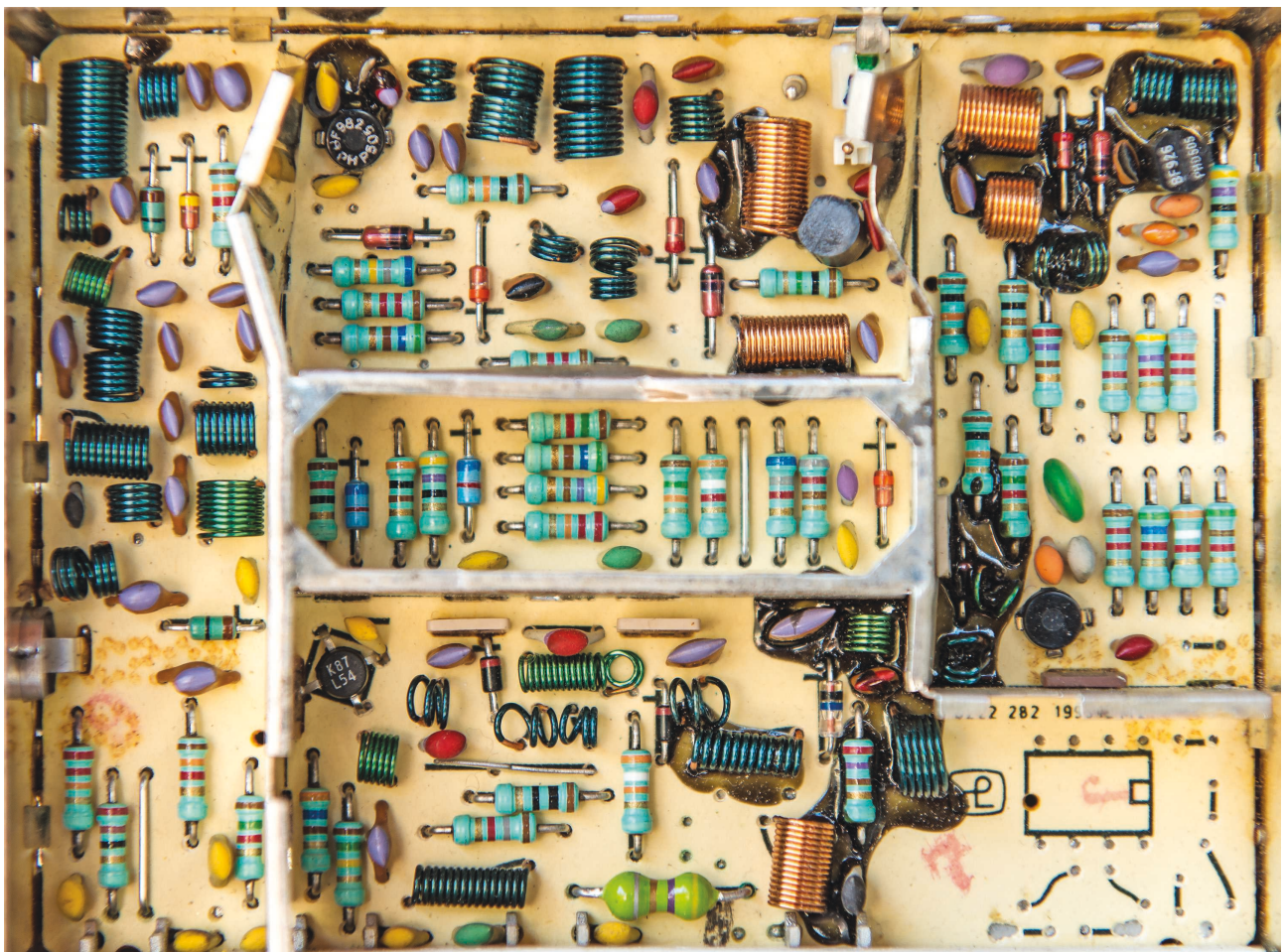


Echoes of the Past: A Journey to Re-Create the Invention of the Transistor and the Earliest Transistor Circuit

Appreciating the Technical Challenges and Genius of Bardeen and Brattain



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The invention of the first transistor—the point-contact transistor—by John Bardeen and Walter Brattain in 1947 marked a pivotal moment in

electronic technology, and arguably an inflection point in human history. To honor the transistor's 75th anniversary, this work presents a historical perspective of the invention of the point-contact transistor and efforts to fabricate replica devices. Rediscovery of contact forming

methods from the days of crystal rectifiers are required to produce point-contact transistors with any gain. The history and accounts of Bardeen and Brattain's work is traversed to help further inform the design parameters and test protocols needed to create a replica

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device. Finally, a working point-contact transistor is made and used to power a replica of a famous demonstrator circuit used to showcase the first transistor: the “Bardeen music box” or “oscillator-amplifier box.”

Introduction

We sometimes forget that there is art in technology, and that making things work is as much knowing the art as it is understanding the physics. Discovery of the transistor effect in point-contact devices by Bardeen and Brattain [1], [2], [3], [4] represents one of the most impactful discoveries in human history. Harnessing the power of electrons and holes in semiconductors has been likened in impact to humanity’s harnessing of fire [3]. If we think of the global transformation that has been brought about by modern electronics, the merit of this analogy is clear. It may even be perceived to understate the impact if we consider the compressed time frame in which modern electronics has transformed the planet: 75 years as opposed to millennia. If today we are like ancient man holding a stick of fire, it is incomprehensible to project what the future may hold.

Bardeen and Brattain’s point-contact transistor, and Shockley’s refinement into the junction transistor, came about because the right people were looking at the right problem at the right time; so it goes with many important discoveries and inventions. Bardeen was arguably one of the greatest condensed-matter physicists of the last century as his two Nobel Prizes in Physics attest. Brattain was a talented experimentalist who knew the art but also the physics behind it. The fact that Brattain and Bardeen shared an office at Bell Labs created a perfect convergence where art and science met, and the unusual and unexpected gain in this three-terminal device could be observed and explained. Yet even getting to this point was an event many decades in the making. First were the crystal rectifiers, curious devices that passed current in one direction but not the other. Braun discovered these in the late 1800s by scratching a metal

wire on a piece of galena (lead sulfide). The usefulness of these devices in wireless telegraphy led to Braun and Marconi sharing the 1908 Nobel Prize [5]. Despite being useful, these devices were not understood. The advent of modern physics and the emerging understanding of the quantum nature of matter and wave-particle duality led to work by physicists such as Sommerfeld, Mott, and Schottky who put forth theories of metals and metal-semiconductor contacts that could explain effects such as rectification. The unique capability of such devices to operate at much higher speeds than electron tubes, coupled with a need for high-speed devices driven by World War II’s parallel battle for technical supremacy, led to advances in materials science that produced higher-quality semiconductors suited for these high-speed rectifiers. “High back voltage germanium” was created to improve rectifier performance, and this material was in Brattain’s hands when the work on trying to find three-terminal semiconductor-based devices for switching and amplification was taking place. Without this material, it is fairly safe to postulate that the discovery of the transistor would not have occurred in 1947. Perhaps it would have eventually occurred, but the world today would be a different place in any case.

When it was proposed during the meeting of the Electron Devices Society committee coordinating efforts to commemorate the 75th anniversary of the invention of the transistor that we re-create the demonstration of the point-contact transistor, it was imagined to be an easy thing. The art has progressed, after all, to a point undreamed of by Bardeen and Brattain in those early days. At the same time, as new pathways are forged, the old pathways are sometimes forgotten and need to be rediscovered. So, it was here, where the art held in a few simple sentences in Bardeen and Brattain’s original paper related to “contact forming,” which would have been obvious to readers at that time, proved to be one of the barriers that needed to be overcome.

The Point-Contact Transistor

Bell Telephone Laboratories in the mid-1940s was fertile ground for work on semiconductor devices. Mervin Kelly, believing in the potential use of semiconductors in the telephone system, had established a group to work on solid-state electronics. Brattain, who had worked on copper oxide rectifiers in the 1930s, was a part of that group when Bardeen joined in 1945. Tasked by Shockley to work on field-effect devices, Brattain began to observe curious effects in the devices with which he was experimenting. Engaging Bardeen as a partner in the effort to work on and explain results as well as chart new experiments, Brattain ultimately wrapped a nonconductive wedge with gold foil, separated the foil at the tip of the wedge with a razor blade, and rigged an apparatus to hold the wedge against the piece of high back voltage germanium. An early reproduction of the device is shown in Figure 1. On 16 December 1947, amplification was observed, and the transistor was born.

Explaining transistor operation was another matter. The same physical effect that enabled the creation of



FIGURE 1. An early reproduction of the first point-contact transistor. This replica is on display at the Holonyak Micro and Nanotechnology Laboratory at the University of Illinois at Urbana-Champaign (on loan from Prof. Jont Allen).

DISCOVERY OF THE TRANSISTOR EFFECT IN POINT-CONTACT DEVICES BY BARDEEN AND BRATTAIN REPRESENTS ONE OF THE MOST IMPACTFUL DISCOVERIES IN HUMAN HISTORY.

earlier rectifiers would be the critical element for the point-contact transistor: the band bending at the surface of a semiconductor either due to the interface with a metal contact or natural surface states. If this effect is strong enough, it is

possible for an inversion layer to form at the surface of the semiconductor crystal, meaning that the dominant carrier type switches. In the case of the n-type germanium used for the first point-contact transistors, in the bulk of the crystal,

negatively charged electrons make up the majority carriers. But at the surface, due to a disruption of the periodic nature of the crystal, states form, which make holes, a positive charge carrier that can be thought of as a lack of an electron, the dominant carrier [6]. This thin, p-type layer at the surface enables the operation of the point-contact transistor and, although the exact mechanism was not verifiably understood, early studies on the device provided some explanation [2], [6]. This band bending and inversion was described in the seminal paper by Bardeen and Brattain that immediately followed their paper describing transistor action [1], [2], and is shown in Figure 2.

Emitter and collector contacts are made on the thin, p-type layer at the surface, with the base contact on the n-type bulk substrate from the bottom of the sample. The emitter is positively biased with respect to the base to inject current in the form of holes into the p-type layer. The collector is negatively biased, which attracts the positively charged holes injected from the emitter, contributing to a portion of the collector current that exits. In addition, a mechanism between the base and collector attracts electrons out of the collector contact to the n-type base region of the device. As this is an inflow of negative charge, this provides an additional positive current out of the collector in addition to the hole current from the emitter. With the two currents combined, the collector current acts to amplify the emitter current, and hence, the device produces a positive gain known as the α of the transistor. An illustration of an active point-contact transistor with the general indication of current flow and carrier direction is presented in Figure 3. It should be noted that this mechanism is slightly different from the transistor effect in the junction transistor, where the minority carrier injection from the emitter into the base is captured by the collector and the base current is largely serving base recombination.

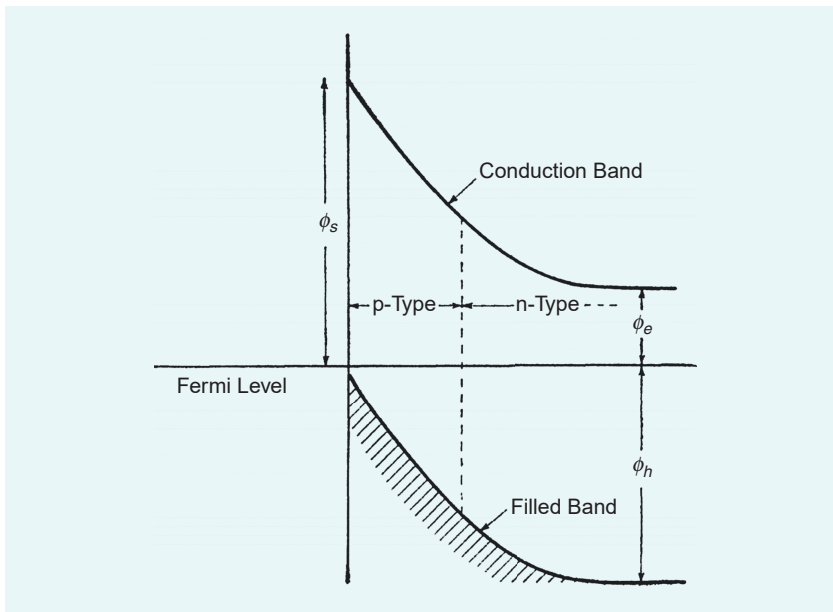


FIGURE 2. A band diagram for n-type germanium with a thin, p-type region formed at the surface due to surface state pinning [2]; this was how Bardeen and Brattain originally described the effect that enabled the p-type hole source in the point-contact transistor. (Source: [2]; Reprinted Figure 2 with permission from W.H. Brattain and J. Bardeen, *Phys. Rev.*, vol. 74, no. 2, pp. 232, 1948. © 2023 American Physical Society; <https://dx.doi.org/10.1103/PhysRev.74.23>.)

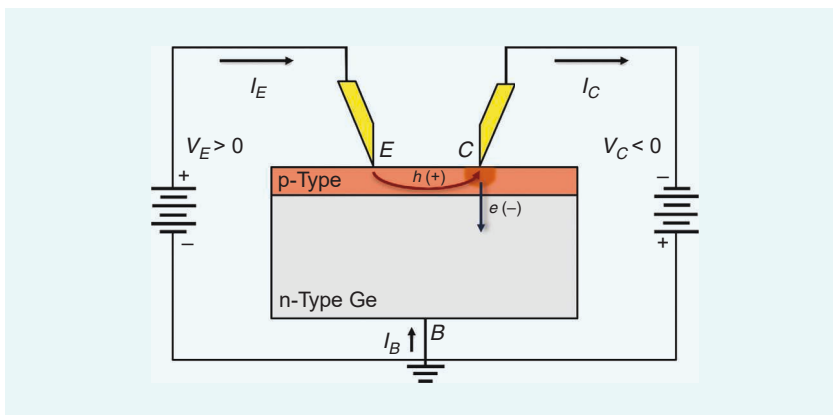


FIGURE 3. An illustration of an active-mode point-contact transistor with a positive emitter bias and negative collector bias. The current directions of each terminal are indicated and the rough propagation of carriers contributing to the collector current are shown.

History Repeats Itself—Following the Path of Discovery

At the time the point-contact transistor was demonstrated, it was not possible

to order high-quality semiconductor wafers from your vendor of choice. The piece of germanium used by Brattain was provided to Bell Labs by Purdue, one of the few groups working on these materials at the time [4]. It had seen several other experiments before its use to make the first transistor. In an interesting parallel, as a consequence of supply-chain issues attributed to the COVID-19 pandemic, germanium, having a conductivity level and type similar to that which was used by Brattain, was likewise difficult to obtain when our efforts began. For the work on recreating a point-contact transistor, an antimony-doped n-type germanium wafer was obtained with a resistivity in the range of 1–10 $\Omega\cdot\text{cm}$, which was on the lower end of the reported ideal resistivity range [1]. At a high level, very little is needed to be done to produce a functional point-contact transistor once the germanium crystal is obtained. One could even learn how to make his or her own at home by modifying certain commercial diodes from a 1950s magazine article [7]. The original device design simply consisted of two tungsten or phosphor bronze wires mounted closely together on the surface of a block of germanium to form the emitter and collector contacts [1]. The base contact is made from a metal connection to the backside of the germanium block. To replicate this, for our own attempt at the point-contact transistor, a germanium wafer was separated into pieces approximately 1 cm $\times$ 1 cm in size. Initially, standard tungsten probe tips typically used for general device electrical characterization were used for the emitter and collector contact (although it was soon discovered that different contact methods had to be explored to make a quality transistor). These tips were mounted on micromanipulators with three linear movement axes to allow micrometer-level control of their position. Referencing the spacing of the original point-contact transistor demonstration, roughly 40 μm between split gold strips on an insulating wedge [1], [4], the tungsten probe tips for our transistor were spaced as close as 10- μm apart, with the hope that the closer spac-

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AT A HIGH LEVEL, VERY LITTLE IS NEEDED TO BE DONE TO PRODUCE A FUNCTIONAL POINT-CONTACT TRANSISTOR ONCE THE GERMANIUM CRYSTAL IS OBTAINED.

ing would improve performance. The base contact on the backside of the thin, 600- μm -thick wafer is made from evaporated nickel and gold, which is contacted by the metal stage the sample rests on during testing.

In theory, our point-contact transistor was complete and all that was left was to characterize it, which was done using a semiconductor parameter analyzer to sweep values and measure the voltages and currents across and through the three device terminals. The result was a transistor effect, but just barely, as demonstrated by the common-base transistor curve measured in Figure 4. No gain was observed in either the emitter or base current; the collector current was smaller than both. Although no base gain is expected for a point-contact transistor, the lack of emitter gain, termed *alpha*, was disappointing. This was indicative of two potential issues: the supposed inverted p-type layer at

the surface was smaller than expected, and the path between the collector contact and the base was too resistive. This would lead us on a journey to rediscover old methods for creating point-contact transistors, from contact preparation methods poorly understood and no longer used in modern transistor devices, to earlier contact solutions that Bardeen and Brattain explored in their quest to fabricate the first transistor.

One key element of the point-contact transistor preparation is the collector-contact formation. Despite not being used for Bardeen and Brattain's very first gold-wedge-based transistor, this process became the standard for production transistors and was used for the results in the first publication of the device [1], [8]. A process common back in their time for the fabrication of germanium high-voltage crystal rectifiers, contact forming is done by passing a large amount of current over a short pulse

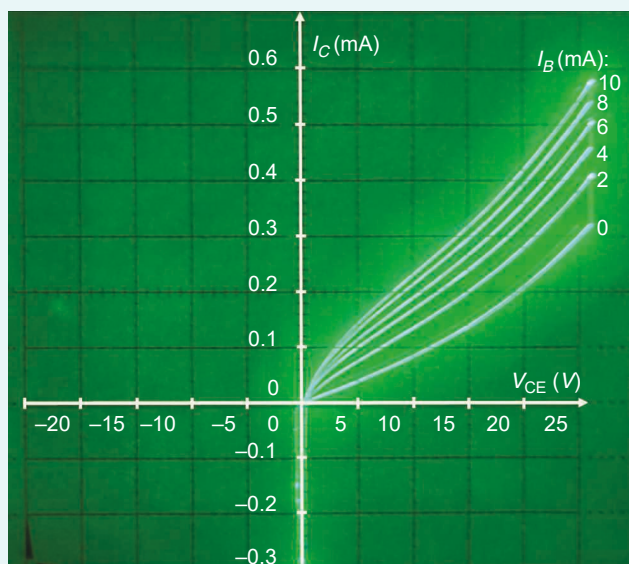


FIGURE 4. A plot of common-base transistor curves measured on an old Tektronix 577 Curve Tracer, demonstrating the transistor behavior of our first attempt at the germanium point-contact transistor; this device consists of two tungsten probe tips acting as the emitter and collector terminals, and a backside Ni/Au layer for the base terminal.

between the point contact and backside contact, lowering the resistance between the two. For the point-contact transistor, this was done between the collector and base contacts. The exact mechanism for the improvement of gain in point-contact transistors is not fully verified. Different hypotheses, including some strong ones from Shockley, postulate a potential conversion of the n-type region near the probe to a larger, permanent p-type region or, alternatively, an introduction of positively charged trap states that would attract electrons from the collector contact [5]. Whatever the cause, this old process was a critical element in enhancing the gain in the point-contact transistor design. The contact forming came with some challenges when determining how to implement it. Various methods for achieving contact forming have been reported with no clear best method, with each sharing in common an issue with low yield [7], [8], [10]. The general method involved sending a high reverse-current pulse through the base and collector terminals, less than 1 A, that required in the range of 30–300 V. One reported method for performing this forming injection includes charging

a capacitor and then switching it to the point contact and quickly discharging it across the base-collector terminals [10]. Another method would involve specialized equipment to control pulsed voltage signals across the contacts, either dc reverse bias or ac forward and reverse injections [8]. This second method is the one performed for our point-contact transistors as it allowed more control of the contact forming process without the need for high-voltage capacitors or switches and is likely also the method used by Bardeen and Brattain as it was reportedly used by Bell Labs, where they did their research [1], [8]. This was attempted with an Hewlett-Packard 214B 100-V pulse-generator and a Tektronix 577 Curve Tracer, which enabled up to 1,000-V, 300- μ s-long pulses, although it was limited to 100 W of maximum power. Various forming attempts were done using the tungsten probe contacts with pulsed voltages up to 200 V, and although some improvements were had, especially in the stability of the curves, the devices still had a gain below one; Figure 5 shows the comparison of a point-contact transistor before and after contact forming.

With just the collector forming not producing close to the results of the original point-contact transistor, the next step was to find the best contact configuration. Coincidentally, this set of experiments would lead back from the first two-wire point-contact transistor to some of Bardeen and Brattain's early experiments preceding it. The next contact design explored was the gold-wedge point-contact transistor, their first demonstration of a solid-state transistor with positive power gain. The main motivation for trying this contact design was to test whether using gold over tungsten would offer any improvements. Using a Teflon wedge, gold foil, and Kapton tape, a similar setup as Bardeen and Brattain's original discovery attempt was made, as depicted in Figure 6(b). The gold was wrapped tightly around the corner of the wedge and affixed by the tape. It was then thinly slit along the edge with a scalpel blade, separating the two contacts. Now it was reported that Brattain had slit the gold and filled the gap with a wax, leaving a very thin, 40- μ m spacing [4]. Unable to replicate his precision, a trial-and-error process of slightly folding back the edge of the separated gold was done until the two contacts were no longer shorted. The final gap measured $\sim$ 200–250 μ m, much larger than Brattain's. Nonetheless, small transistor effects were seen with this gold-wedge contact setup in our own point-contact transistor, although the output stability was poor. Similar to what Bardeen and Brattain were said to have encountered, the exact mount position of the wedge contact was inconsistent and would involve some fidgeting to achieve the proper contact [4]. There was one promising, although incredibly unstable, measurement of the wedge point-contact transistor that occurred, likely due to a lucky positioning of the mount that aligned the two contact strips close together. However, no repeated measurements were able to capture the same performance.

To solve the issues with inconsistent contacts, approaches that involved aligning probes or other connections with the micromanipulators were strictly used after the wedge attempts,

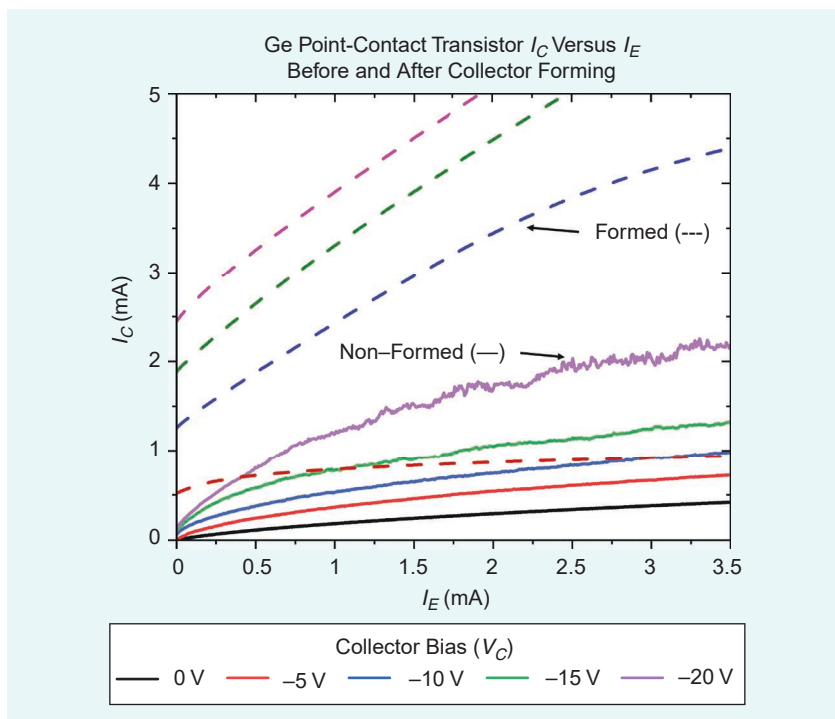


FIGURE 5. A comparison of the emitter gain curves of the gold pad/tungsten probe point-contact transistor before and after collector forming.

as demonstrated in Figure 6. These methods enable precise and close spacing between the emitter and collector contact, which was proving to be a critical dimension for our point-contact transistor given the germanium crystal with which we were working. First, numerous attempts were done to re-create the line contact in replacement of the wedge with both tungsten and gold and mixed contacts. This included gold-wrapped flat scalpels, sideways-mounted tungsten probe tips, and gold-wrapped tungsten probe tips. Collector-forming methods, from 50 to 200-V reverse bias and 300- μ s-long pulses, were attempted with these different contact methods as well. For most of these attempts, performance was on par or worse compared to our first dual-tungsten-probe point-contact transistor tests. The attempts where the collector featured a longer, line-type contact instead of a point had particularly poor results, whereas when the emitter contact was a larger, gold contact and the collector a narrow, tungsten point contact, the highest gain measurement was taken of this set. Yet again, this measurement was not capable of being repeated, a common theme for our point-contact transistor attempts.

One last idea to enable consistent contacts was to not use the probes as the contact material but instead deposit small pads of gold directly onto the surface such that the contact is permanently on the surface and can provide the probing consistency being sought. This approach was yet again going backwards in the history of Bardeen and Brattain's transistor attempts. This deposited gold contact method was indeed the first, and accidental, discovery of the transistor effect on the n-type germanium [4], [11]. Although trying to create something more akin to a field-effect transistor, they deposited small circles of gold over what they thought was an insulating oxide layer and used a tungsten wire as the collector contact [4], [11]. What they initially failed to realize is that the oxide had been washed off, so the gold was directly contacting the surface of the p-type germanium inversion layer, enabling a demonstration of the transistor effect (described as

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increased reverse-bias current through the collector from emitter injection) [4], [11]. Although their attempt at this did not produce any gain, our hope was that by forming the collector contact we could make a point-contact transistor with positive gain and a more consistent contact. To do this, gold squares were evaporated on the germanium piece and patterned by a lithographic liftoff process. Indeed, the results were more consistent, producing much more stable transistor curves, but without forming the collector contact there was no gain, as expected at this point. Many attempts at forming the collector gold pads were done, trying both dc and ac methods. After pulsing 70-V ac (to enable both forward and reverse current injection) across the collector metal pad and base contact, it had initially looked like this device would be destroyed; the collector pad had been visually damaged. Yet, when the transistor curve measurements were taken, the device produced the highest gain thus far. The collector forming had made significant improvement of the gain of the device emitting

a higher collector current at a collector bias of 10 V than a bias of twice that, 20 V, for the nonformed contact. And thus, with a 50 μ m $\times$ 50- μ m gold pad acting as the emitter contact, and a formed tungsten probe spaced approximately 20- μ m away as the collector, a point-contact transistor with positive gain and a stable output was made.

Chasing Alpha—Benchmarking Relative to Bardeen and Brattain

To compare the results of our point-contact transistor, the same measurements reported on Bardeen and Brattain's original transistor paper published in 1948 were taken [1]. The transistor reported in this article is not the first gold-wedge device but is instead a more refined device that likely utilized two phosphor bronze probes placed close together, with the collector lead likely formed by 30-V ac pulses [1], [8]. Bardeen and Brattain characterized this device by grounding the base of the transistor, applying a positive voltage on the emitter (V_e), and applying the negative voltage on the collector (V_c).

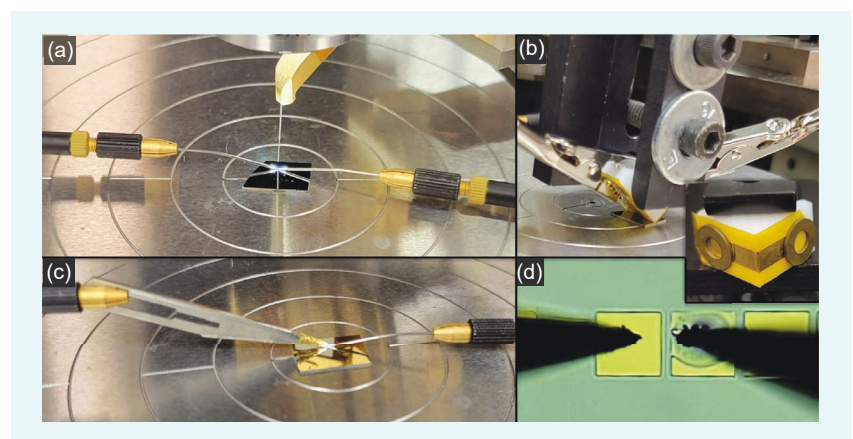


FIGURE 6. A collage of the various point-contact transistor setups we attempted. (a) Two tungsten probes set up as an emitter and collector contact for a point-contact transistor. (b) A gold-wedge point-contact transistor setup. (c) A gold-wrapped scalpel as an emitter and a tungsten probe as a collector setup. (d) Evaporated gold pads set up with a formed collector contact over a degraded pad.

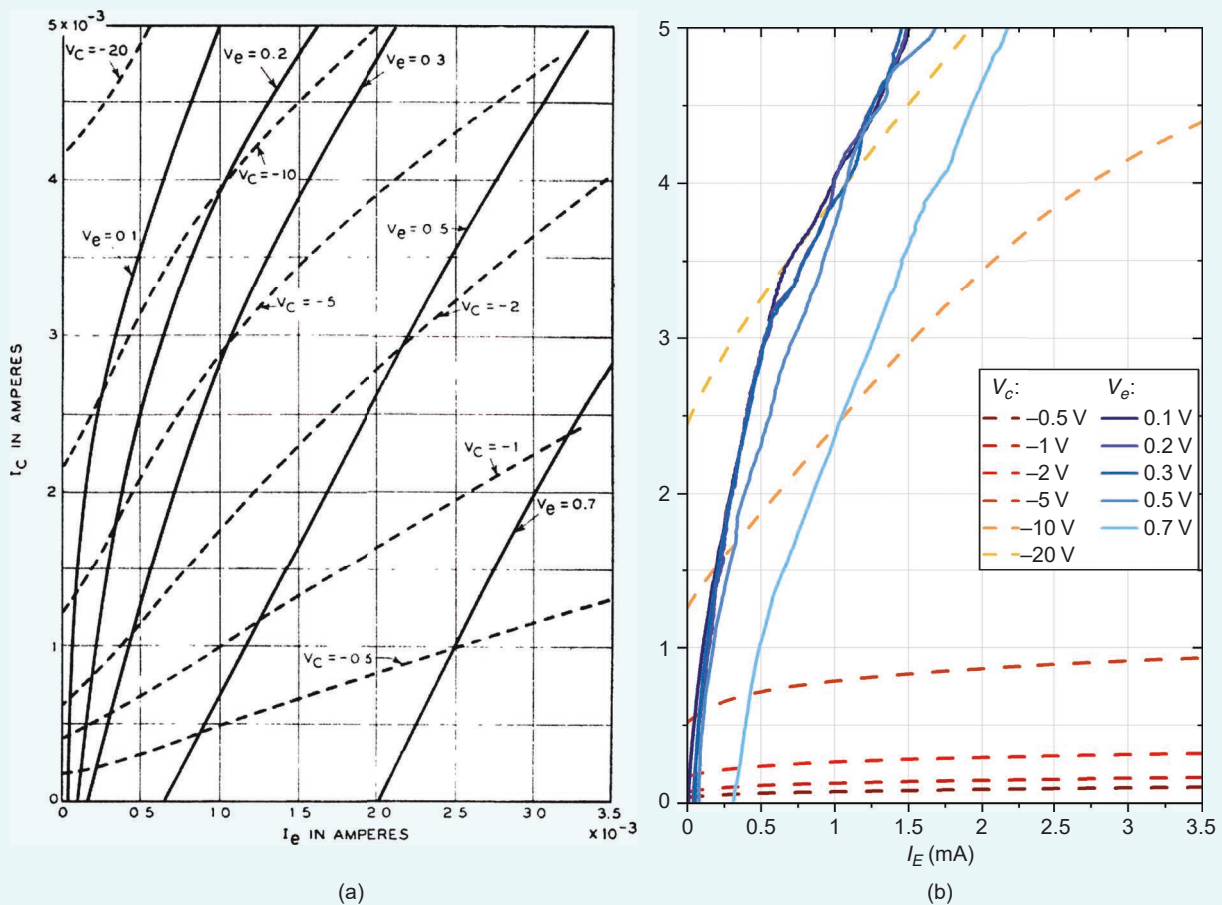


FIGURE 7. (a) An I_C versus I_E plot of Bardeen and Brattain's first published point-contact transistor, demonstrating the alpha gain of the device for either fixed-emitter or fixed-collector voltages [1]. (b) The same plot and parameters measured for our own point-contact transistor attempt, using a $50\text{ }\mu\text{m} \times 50\text{-}\mu\text{m}$ gold pad as the emitter and a formed tungsten probe as the collector. (Source: [1]; Reprinted Figure 7(a) with permission from J. Bardeen and W. H. Brattain, *Phys. Rev.* vol. 74, no. 2, pp. 230, 1948. © 2023 American Physical Society; <https://dx.doi.org/10.1103/PhysRev.74.230>.)

Two different measurements were done in the original paper; one where V_C is fixed and one where V_E is fixed. This



FIGURE 8. Bardeen holding his music box, which was one of the first circuits to use the point-contact transistor; one transistor was used to drive an oscillator circuit and one was used as an amplifier. (Source: University of Illinois Board of Trustees.)

measurement was replicated on our own gold-pad/tungsten-probe point-contact transistor, and the data are presented adjacently to Bardeen and Brattain's for comparison in Figure 7(a) and (b). These tangles of curves can be hard to decipher at a first glance, especially as they are atypical for modern measurements used to characterize transistors (after all, this is the very first transistor demonstrated, so there are no standards to reference). But for the point-contact transistor, characterized by its emitter gain alpha, these plots make the most important feature easy to identify. Bardeen and Brattain defined the alpha of a transistor by the change of the collector current for some change in the emitter current (dI_C/dI_E), which is represented by the slopes of the collec-

tor-current versus emitter-current plots presented here; the more vertical the line is, the higher the alpha. This gain of emitter current is the key ability of the transistor, which makes it useful for circuits such as amplifiers or oscillators. When comparing the data from Bardeen and Brattain's original published transistor, very similar electrical behavior is seen between theirs and our point-contact transistor device. When the emitter voltage is fixed (solid lines), both ours and the original transistor show high alpha gain of more than two. One key difference is that ours demonstrates this large gain for even higher values for V_E , while the original transistor starts to see a reduced gain. This is due to poor current injection in our transistor, leading to smaller amounts of injected

emitter current when compared to similar voltages for the original device. For example, in the original transistor, an emitter voltage of 0.7 V injects 2 mA of current at 0 mA of collector current, while for our transistor, only 0.3 mA is driven. For the measurements when collector voltage is fixed (dashed lines), closer trends at high biases are seen but with much worse gain at low voltages for

our transistor. When biasing the device to -5 V, very little differential emitter gain is seen, with the slope of the curve being almost flat, indicating an alpha of less than one, whereas the original transistor had more noticeably positive slopes. At the 10- and 20-V reverse-bias collector measurements, our transistor starts to match the performance of the original transistor with an alpha of

nearly 1.2, even if the magnitude of total current still trails that of Bardeen and Brattain's transistor. Despite some of the differences, our transistor was still able to demonstrate comparable alpha gain to the first transistor. This gain value was an important milestone to achieve as it was a goal of the project to not just re-create a point-contact transistor but to also use one to drive the oscillations in a music "box" circuit, such as Bardeen had as a demonstration of the first transistor.

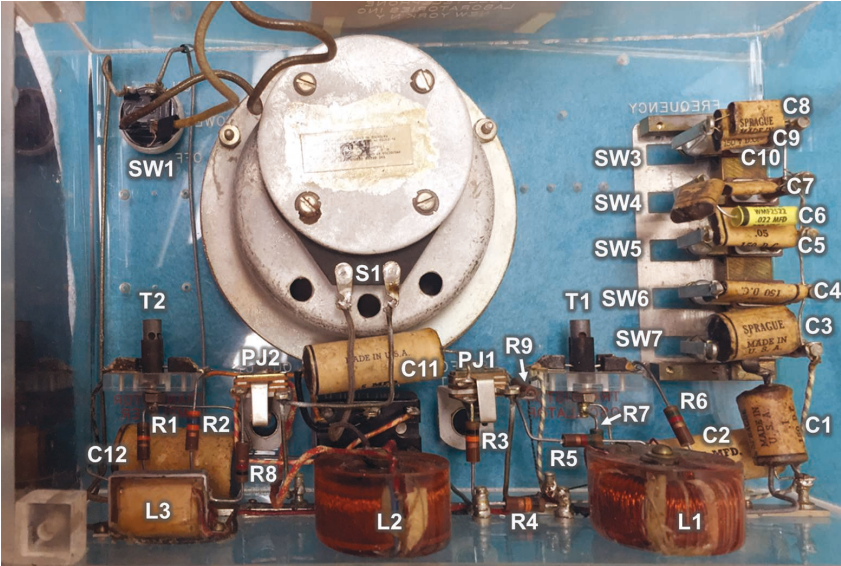


FIGURE 9. An image of the circuit inside Bardeen's original music box, which we annotated as part of the process of tracing and relearning how it functioned.

A More Interesting Demo—Lessons From the Oscillator-Amplifier Box ("Bardeen Music Box")

At some point, it was determined that a simple, portable apparatus was needed to demonstrate the transistor. Three boxes were made by engineers at Bell Labs to demonstrate oscillator and amplifier uses of the transistor, the so-called "oscillator-amplifier boxes." Some of the original "type A" transistors were used to create these boxes, making them likely the oldest transistor-based circuits in existence. Only one of these boxes is known to still exist, it being in the permanent collection at the Spurlock Museum at the University of Illinois at Urbana-Champaign. Bardeen is shown

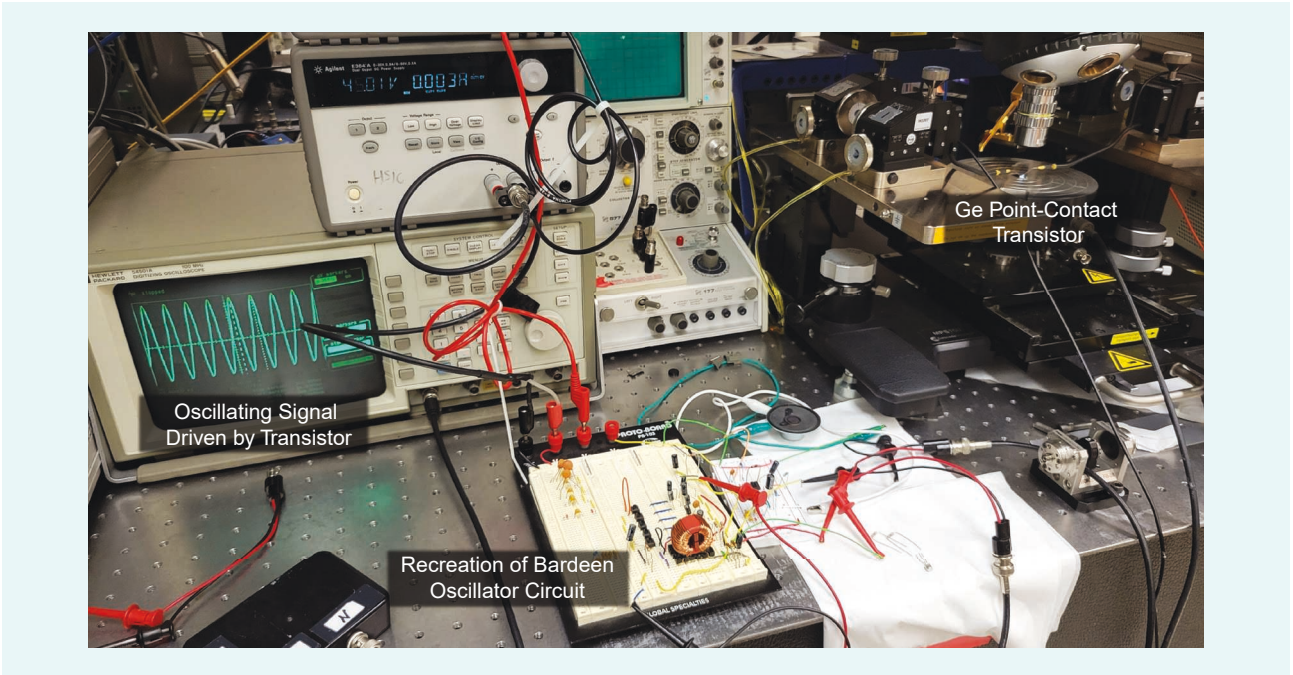


FIGURE 10. An example measurement of the sinusoidal output of the Bardeen oscillator circuit remade with modern components and using our point-contact transistor setup as the gain provider.

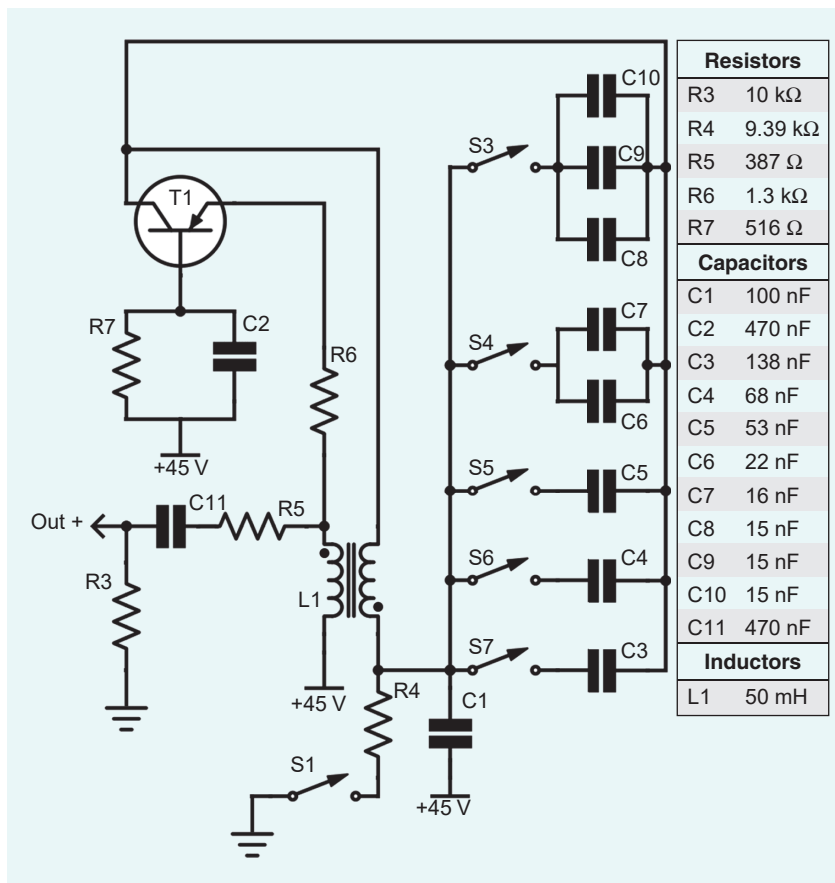


FIGURE 11. The Bardeen oscillator circuit as traced from one of his original music boxes with an inset table of measured component values.

holding one of the original boxes in Figure 8, and a photo of the interior of the box is presented in Figure 9.

The final test of our point-contact transistor was to see whether it could be used to re-create Bardeen's music box. At the time, the key advantage of the point-contact transistor in this portable music box is its small size and "instant" turn on, replacing the role of more bulky vacuum tubes that required time to warm up [11]. With access to Bardeen's original music

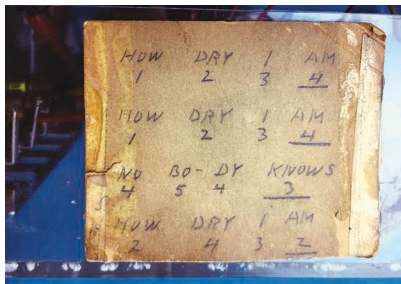


FIGURE 12. The notes and lyrics for playing "How Dry I Am" on Bardeen's music box.

box during a restoration project, the original circuit was mapped out [12]. Having just discovered the transistor, all the components in Bardeen's box were designed for vacuum tube circuits, hence the use of a 45-V battery even though suitable gain could be provided from the transistor at lower voltages [11]. Using measured values for the capacitors and resistors from the original music box, we reconstructed the oscillator part of the circuit from modern components on a breadboard. Our point-contact transistor was contacted and jumpered into the circuit. To provide the 45-V source, an Agilent E3647A dc power supply was used instead of a battery. The result was a sustained oscillation that can then be passed to a buffer amplifier, driving an 8-Ω speaker to produce a constant tone. Although in the Bardeen music box this amplifier portion of the circuit also utilized a point-contact transistor (labeled T2 in the image of the box), we opted to use a modern chip. Different buttons on the breadboard would

reroute the circuit through different capacitors, altering the resonant frequency of the LC bank and, in effect, playing different notes. The apparatus used is shown in Figure 10.

The schematic of the Bardeen oscillator circuit is shown in Figure 11. Although it looks complicated, it operates under a couple of basic principles. The array of capacitors seen on the right is connected to the circuit through a switch, which forms a loop with the inductor. This is referred to as an LC bank and has a natural oscillating frequency of current that usually fades to zero due to resistive elements in the circuit. Some sort of gain is required to overcome this loss and sustain this oscillating current. This is where the point-contact transistor comes in. The inductor in the LC bank is coupled to a second coil (like a differential-mode choke), which induces a copy of the oscillating current into the emitter of a point-contact transistor. As the transistor produces an alpha gain of the emitter current, this oscillating signal is amplified by the base current and exits the collector, feeding back into the LC bank loop, thus providing the extra power to overcome inherent losses and sustain the oscillations. The output is measured across the coupled inductor and resembles a sine wave with a specific frequency. When this output is connected to a speaker drive and speaker, a solid tone is heard. By pressing different buttons, switching said capacitor is a part of the LC bank, different frequencies, and thus tones, are produced and music can be played. The frequencies produced in the original Bardeen box and our recreation range from just under 3 kHz to below 5 kHz.

How Dry I Am

Nick Holonyak Jr., John Bardeen's first graduate student and "father of the LED," would often recount an early seminar given by Bardeen after Bardeen was recruited to the faculty at the University of Illinois at Urbana-Champaign. Bardeen, in his quiet way, described the physics of transistor operation. He then flipped the switch on the "Oscillator-Amplifier Box" and

immediately played the tune “How Dry I Am” using keying notes taped to the top of the box (Figure 12).

“I nearly fell out of my chair,” Holonyak would exclaim when reciting this story. Holonyak immediately saw what had captured the world’s attention: a device that did not need to warm up prior to operating, that would provide near-instantaneous service in whatever application was demanded. Holonyak left the tube group he was working in as a graduate student to join this new professor. His fellow students thought he was crazy; electron tubes were ubiquitous at that time. History has shown that Holonyak was right.

Final Observations

The effort to re-create a point-contact transistor and one of the earliest transistor circuits proved to be an interesting journey through the history of technology. Guided by accounts of Bardeen and Brattain’s efforts and our earlier work to understand the operation of Bardeen’s oscillator-amplifier box, we were able to retrace their steps and create working devices and circuits. Despite our best efforts, we could not match their performance, however, as we were limited by the higher doping density of our germanium. Interestingly, a few questions still remain about the operation of the early point-contact transistors. The creation of a transistor in an n-type sample with no intentional p-doping is enabled by an interesting interplay between surface states, Fermi energies, and the effect on the germanium crystal of “contact forming.” The latter process, especially, left a few unanswered questions, both then and now. The advent of the superior junction transistor ultimately made these questions moot, but the most important discovery, minority carrier injection, had been made.

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