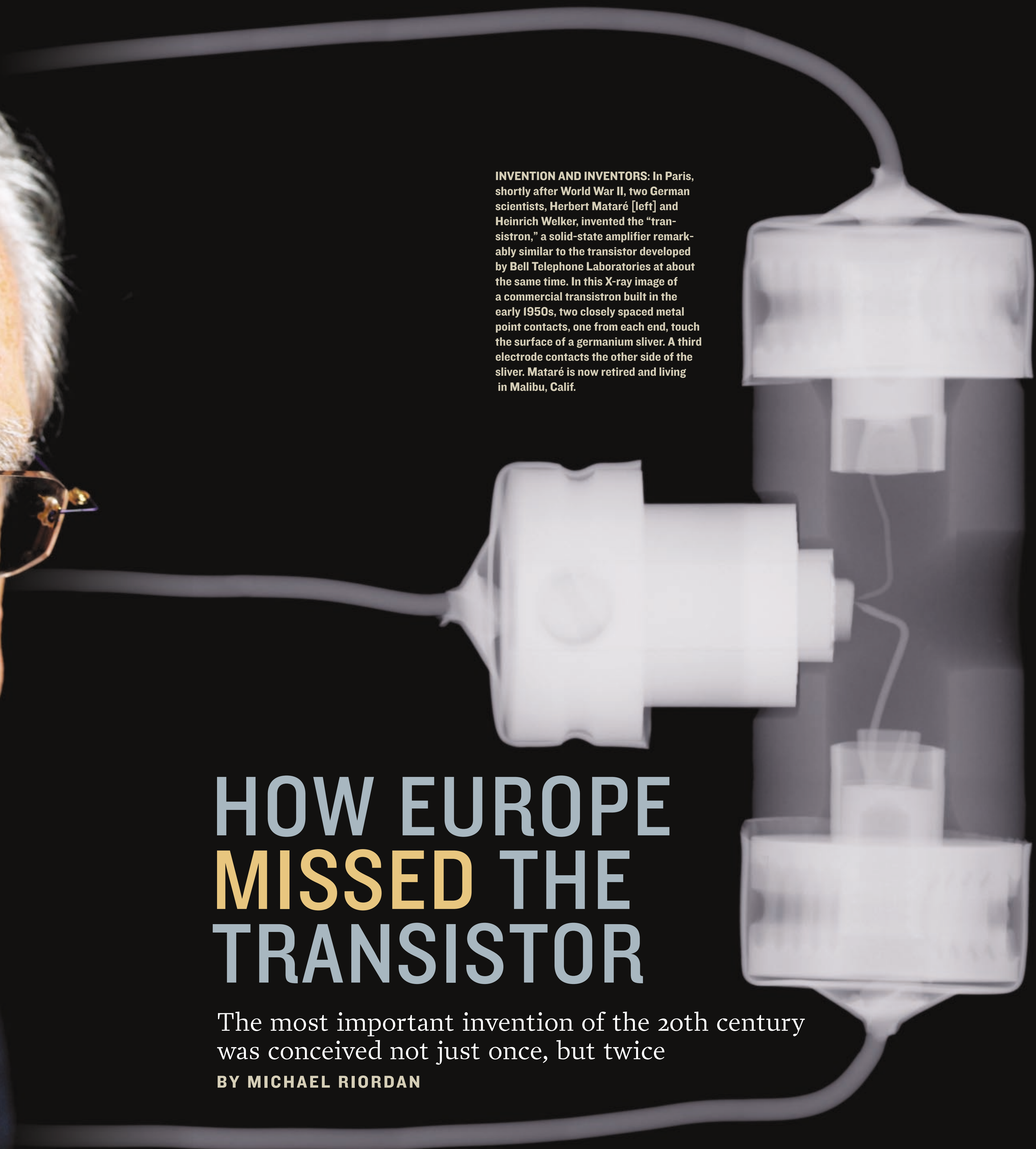
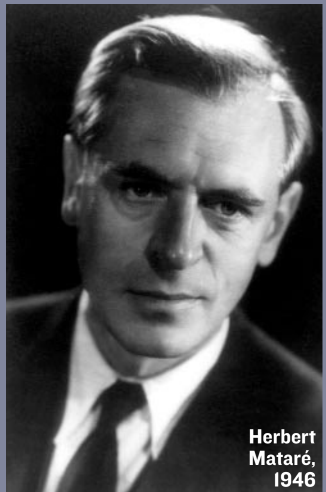


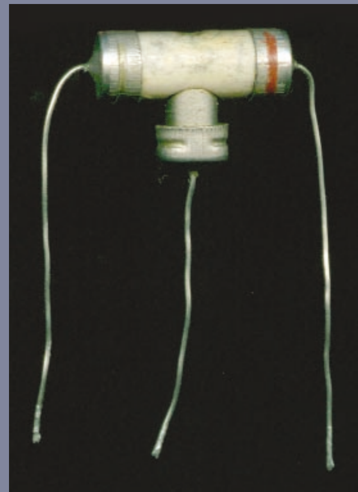
INVENTION AND INVENTORS: In Paris, shortly after World War II, two German scientists, Herbert Mataré [left] and Heinrich Welker, invented the "transistron," a solid-state amplifier remarkably similar to the transistor developed by Bell Telephone Laboratories at about the same time. In this X-ray image of a commercial transistron built in the early 1950s, two closely spaced metal point contacts, one from each end, touch the surface of a germanium sliver. A third electrode contacts the other side of the sliver. Mataré is now retired and living in Malibu, Calif.

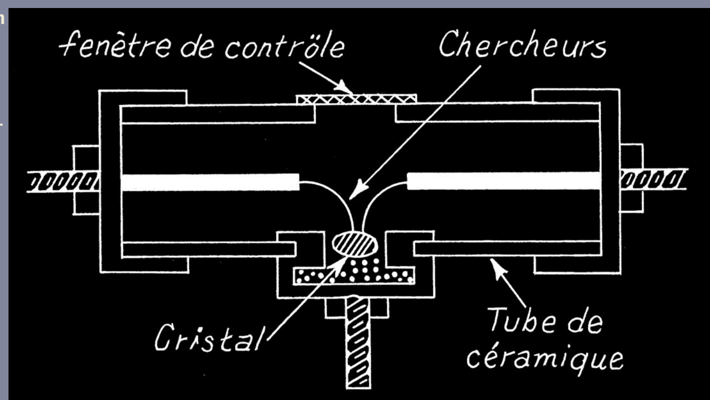
HOW EUROPE MISSED THE TRANSISTOR

The most important invention of the 20th century was conceived not just once, but twice

BY MICHAEL RIORDAN







TRANSISTOR TWIN: The cross-section drawing [right] from the French magazine *Toute la Radio* depicts the inside of a commercial Westinghouse transistron [above center]. In the drawing, the two metal points (*chercheurs*) contact the surface of a germanium sliver (*cristal*). A technician adjusted the positions of the two contacts to give the proper electrical characteristics while viewing them through a window (*fenêtre*). The internal structure is similar to Bell Labs' first prototype point-contact transistor [far right], produced in 1948.

GETTING TO THE POINT: After John Bardeen and Walter Brattain invented the point-contact transistor in December 1947, Bell Telephone Laboratories quickly began producing its Type A transistor. In the picture above, two metal points, called the emitter and the collector, contact the surface of a germanium sliver, which has a third contact known as the base attached to its back side.

IN LATE 1948, shortly after Bell Telephone Laboratories had announced the invention of the transistor, surprising reports began coming in from Europe. Two physicists from the German radar program, Herbert Mataré and Heinrich Welker, claimed to have invented a strikingly similar semiconductor device, which they called the transistron, while working at a Westinghouse subsidiary in Paris.

The resemblance between the two awkward contraptions was uncanny. In fact, they were almost identical! Just like the revolutionary Bell Labs device, dubbed the point-contact transistor, the transistron featured two closely spaced metal points poking into the surface of a narrow germanium sliver. The news from Paris was particularly troubling at Bell Labs, for its initial attempts to manufacture such a delicate gizmo were then running into severe difficulties with noise, stability, and uniformity.

So in May 1949, Bell Labs researcher Alan Holden made a sortie to Paris while visiting England, to snoop around the city and see the purported invention for himself. "This business of the French transistors would be hard to unravel, i.e., whether they developed them independently," he confided in a 14 May letter to William B. Shockley, leader of the Bell Labs solid-state physics group. "As we arrived, they were transmitting to a little portable radio receiver outdoors from a transmitter indoors, which they said was modulated by a transistor."

Four days later, France's Secretary of Postes, Télégraphes et Téléphones (PTT), the ministry funding Mataré and Welker's research, announced the invention of the transistron to the French press, lauding the pair's achievement as a "*brilliante réalisation de la recherche française*." Only four years after World War II had ended in Europe, a shining technological phoenix had miraculously risen from the still-smoldering ashes of the devastation.

"This PTT bunch in Paris seems very good to me," Holden candidly admitted in his letter. "They have little groups in all sorts of rat holes, farm houses, cheese factories, and jails in the Paris suburbs. They are all young and eager." And one of these small, aggressive research groups, holed up in a converted house in the nearby village of Aulnay-sous-Bois, had apparently come through spectacularly with what might well be the invention of the century—a semiconducting device that would spawn a massive new global industry of incalculable value. Or had it?

As was true for the Bell Labs transistor, invented by John Bardeen and Walter H. Brattain in December 1947, the technology that led to the transistron emerged from wartime research on semiconductor materials, which were sorely needed in radar receivers. In the European case, it was the German radar program that spawned the invention. Both Mataré and Welker played crucial roles in this crash R&D program, working at different ends of the war-torn country.

Mataré [see photo in "Transistor Twin"], who shared his remembrances from his home in Malibu, Calif., joined the German research effort in September 1939, just as Hitler's mighty army rumbled across Poland. Having received the equivalent of a master's degree in applied physics from Aachen Technical University, he began doing radar research at Telefunken AG's labs in Berlin. There he developed techniques to suppress noise in superheterodyne mixers, which convert the high-frequency radar signals rebounding from radar targets into lower-frequency signals that can be manipulated more easily in electronic circuits. Based on this research, published in 1942, Mataré earned his doctorate from the Technical University of Berlin.

PRECEDING PAGES: LEFT: DEVICE COURTESY DR. ANDREW WYLIE; PHOTO: GUSTO IMAGES; RIGHT: ANDREAS TEICHMANN
THIS PAGE, CLOCKWISE FROM LEFT: HERBERT MATARÉ; DR. ANDREW WYLIE; SIEMENS AG; MICHAEL RIORDAN/BELL LABS; ARMAND VAN DORMAEL

At the time, German radar systems operated at wavelengths as short as half a meter. But the systems could not work at shorter wavelengths, which would have been better able to discern smaller targets, like enemy aircraft. The problem was that the vacuum-tube diodes that rectified current in the early radar receivers could not function at the high frequencies involved. Their dimensions—especially the gap between the diode's anode and cathode—were too large to cope with ultrashort, high-frequency waves. As a possible substitute, Mataré began experimenting on his own with solid-state crystal rectifiers similar to the "cat's-whisker" detectors he had tinkered with as a teenager.

During the 1920s, he built crystal radio sets to listen to classical music on the radio waves then beginning to fill the ether. Of Belgian extraction, he was raised in Aachen, Germany, in a family immersed in music. At the heart of each of his radios was a tiny chip of semiconductor material, such as galena (lead sulfide) or silicon, with a fragile wire jabbed gingerly into its surface. For reasons nobody fully understood until the late 1930s, this detector rectified the alternating-current signal from the antenna into the direct-current signal needed to drive headphones.

Similar point-contact devices, especially those made with silicon, could be used as the rectifier required in the superheterodyne mixer circuit of a radar receiver, which shifts the received frequencies down by mixing the input signal with the output of an internal oscillator. Because the electrical action of such a crystal rectifier is confined to a very small, almost microscopic region on the semiconductor surface, the device can rectify currents at relatively high frequencies.

Theoretical work by Walther Schottky at Siemens AG, in Munich, Germany, and by Nevill F. Mott at the University of Bristol, in England, had given Mataré and other radar researchers a much better understanding of what was happening beneath the sharp metal point. When the point touched the semiconductor surface, excess electrons quickly flowed into it, leaving behind a neutral "barrier layer" less than a micrometer deep in the material just underneath it. This narrow zone then acted like an asymmetric barrier to the further flow of electrons. They could jump the barrier much more readily from the semiconductor surface to the metal point than vice versa, in effect restricting current flow to one direction.

As the war ground on, the leaders of the Berlin-based German radar establishment urged the Luftwaffe to pursue research on systems operating at wavelengths well below 50 centimeters—in what we now call the microwave range. They argued that such systems would be small enough to mount in warplanes and detect approaching enemy aircraft through dense clouds and fog.

But German military leaders, basking smugly in their early victories, ignored those pleas. Luftwaffe chief Hermann Göring, who had served as an open-cockpit fighter pilot in World War I, adamantly believed that the intrinsic fighting abilities of his Aryan warriors made electronic systems superfluous. "My pilots," he bragged, "do not need a cinema on board!"

Everything changed after February 1943, however, when a British Sterling bomber downed over Rotterdam in the Netherlands revealed how far behind the Allies Germany had fallen in radar technology. Göring ordered a thorough analysis of the bomber's 9-cm radar system and recalled more than a thousand scientists, engineers, and technicians from the front in a desperate attempt to catch up. By summer they had built a working prototype, but it was much too late. Allied bombers, aided by onboard radar systems that allowed pilots to operate even in foul weather, were pulverizing German cities with increasing impunity.

Mataré recalled the sudden urgency in an interview. He intensified his previous R&D efforts on crystal rectifiers, particularly those made of silicon, which seemed best suited for microwave reception. But the Allied bombing of Berlin was making life exceedingly difficult for Telefunken researchers. "I spent many hours in subway stations during bomb attacks," he wrote in an unpublished memoir. So in January 1944, the company shifted much of its radar research to Breslau in Silesia (now Wroclaw, Poland). Mataré worked in an old convent in nearby Leubus.

Laboring full-time to get silicon rectifiers into production, Mataré had scant opportunity to work on reducing the oscillator noise in radar receivers—an outgrowth of his doctoral dissertation. But he did manage to build and study an intriguing new device, the crystal "duodiode," in which two closely spaced metal points contact the semiconductor surface, forming two adjacent crystal rectifiers. If they possess the same resistance and capacitance, these two rectifiers can be used in a special circuit to cancel out noise from the oscillator of a superheterodyne mixer. The noise through one rectifier adds to the overall signal transmitted by the mixer, and the noise through the other rectifier subtracts from that signal. But to ensure identical electrical characteristics, the points must be extremely close—far less than a millimeter apart—so that both contact the same tiny crystal grain on the surface of the semiconductor.

Mataré worked with silicon samples provided by physicist Karl Seiler in Breslau and germanium samples from a Luftwaffe research team near Munich that included Welker, his future co-worker. Although silicon worked better for radar receivers because it rectified at higher frequencies, germanium duodiodes exhibited intriguing behavior. When the two points touched the surface less than 100 micrometers apart, Mataré claims, he occasionally noticed that by varying the voltage on one he could influence the current through the other—a phenomenon he dubbed "interference." It seemed as if one of his points could affect a region extending far beyond the narrow barrier layer predicted by Schottky's theory.

Mataré had stumbled upon a method to influence this layer, which had stubbornly blocked earlier attempts to make a solid-state amplifier. But wartime urgencies kept him from pursuing this intriguing possibility much further.

Germany's eastern front collapsed in January 1945, and the Russian Army was swiftly approaching Breslau. The Telefunken lab in Leubus was hastily abandoned, and all of Mataré's lab books and records were burned to keep them out of enemy hands. The group attempted to reconstitute its R&D program in central Germany, but the U.S. Army terminated this effort when it swept through in April 1945, mercifully sending Mataré home to rejoin his family in nearby Kassel.

Mataré's future colleague Welker wasn't spared the indignities of war, either. Allied bombs destroyed his laboratory near Munich in October 1944. Early the following year, this theoretical physicist, who during the 1930s had worked on the quantum mechanics of electrons in metals, began speculating about how to use silicon and germanium to fabricate a solid-state amplifier.

These two elements were widely regarded as metals during the 1930s, but their apparent metallic behavior was due largely to the high level of impurities in the available samples. When foreign atoms of elements in the fifth column of the periodic table—arsenic and phosphorus, for example—become lodged in the tetrahedral crystal structure of silicon or germanium, four of their five outermost electrons form strong bonds with nearby atoms, but the fifth is easily knocked away and can thus transfer current through the crystal. The much-higher-purity silicon and germanium that researchers used to build radar systems during World War II had far fewer of such current carriers and behaved more like semiconductors than like metals.

In early 1945, Welker, who was mastering the art of purifying germanium, recognized that the two semiconductors could be used to make what we now call a field-effect transistor. In fact, the device he had in mind was strikingly similar to one that Shockley was to suggest at Bell Labs a few months later.

In this scheme, an electric field from a metal plate should penetrate into a thin surface layer of a semiconductor strip beneath it, ripping electrons loose from their parent atoms to serve as current carriers. A voltage applied across the semiconductor strip would induce a current through it. Crucially, a varying voltage on the metal plate would modulate the current through the strip. Thus, small input signals would result in large output currents flowing through the strip. Or so Welker figured.

But tests he performed in March 1945 revealed no such amplification. In his logbook he recorded "only small effects," orders of magnitude less than what was predicted by Schottky's theory. Shockley, Brattain, and their Bell Labs colleagues attempted similar tests that very same spring, with similarly disappointing results.

The failures soon led Bardeen to postulate a novel idea of "surface states"—that free electrons were somehow huddling on the semiconductor surface, shielding out the field. This conjecture, and Brattain's follow-up experiments to determine the physical nature of the surface states, led to their invention of the point-contact transistor in December 1947—a month after they discovered how to overcome the shielding.

After his failures, Welker returned to research on germanium and resumed the theoretical studies of superconductivity he had reluctantly abandoned during the war. In 1946, British and French intelligence agents interrogated him about his involvement in German radar. They subsequently offered him an opportunity to work in Paris in an R&D operation set up under the auspices of a Westinghouse subsidiary, Compagnie des Freins et Signaux Westinghouse. The immediate goal was to manufacture germanium rectifiers for telecommunications and military electronics.

While teaching in Aachen at his alma mater in 1946, Mataré was also interviewed by agents. Fluent in French, he received a similar offer. He eagerly agreed to join the Paris effort, because doing research in devastated, occupied Germany was almost impossible.

Then in their mid-thirties, the two German physicists met in Paris and began organizing their operation. They found a vacant two-story stone house in the middle-class suburb of Aulnay-sous-Bois, just northwest of the city. In its basement, Welker set up his equipment to purify and crystallize germanium. Mataré's testing and measurements laboratory went on the ground floor, where later that year a production line began fabricating what soon amounted to thousands of rectifiers per month.

On the top floor the men kept offices and rooms where they often stayed overnight—especially during that frantic first year. Mataré wistfully remembers awakening now and then to the soft trills of Welker playing his violin in the adjoining room.

With the rectifiers finally in production by late 1947, Welker resumed his research on superconductivity, while Mataré began to address the curious interference effects he had seen in germanium duodiodes during the war. When he put the two point contacts less than 100 μm apart, he again occasionally could get one of them to influence the other. With a positive voltage on one point, in fact, he could modulate and even amplify the electrical signal at the other! Mataré reckons he first recognized this effect in early 1948 (perhaps a month or two after Bardeen and Brattain's breakthrough at Bell Labs). But it still happened only sporadically.

On a hunch, he asked Welker to fashion larger germanium samples, from which they could cut slivers of higher purity. Using this higher-grade material, Mataré finally got consistent amplification in June 1948, six months after Bardeen and Brattain. Encouraged by this success, they phoned PTT Secretary Eugène Thomas and invited him over for a demonstration. But Thomas was apparently too busy—or perhaps not interested enough—to come by.

About that time, Welker put aside his theoretical work and tried to analyze what was going on just beneath the shiny germanium surface of Mataré's odd contraption. In an undated, handwritten document, now in the archives of Munich's Deutsches Museum, Welker speculated that one point—which he called the *"électrode de commande,"* or "control electrode"—was inducing strong electric fields in the germanium just beneath the other electrode, altering the material's conductivity there.

But Mataré was not buying that explanation, which followed the logic of Welker's unsuccessful 1945 attempt at a semiconductor amplifier. If the phenomenon were caused by an electric field, Mataré remembers thinking, he should have witnessed a decrease in the current at the second electrode, not the increase he observed on his oscilloscope. According to this field-effect idea, a positive potential on the control electrode would induce negative charges in the germanium under the other electrode, which should reinforce the current-blocking effects of the barrier layer there.

TUNING IN: At the Düsseldorf Radio Fair in 1953, the German firm Intermetall unveiled what was probably the world's first transistor radio, more than a year before Texas Instruments claimed that milestone. The radio's amplifier circuit was built around four point-contact transistors made by Intermetall, which Herbert Mataré and businessman Jakob Michael had founded in 1952.

HERBERT MATARÉ/INTERMETALL

Mataré argued instead that the control electrode must be injecting positive charges, called holes, into the germanium. And perhaps by trickling along the boundary between two crystal grains, he guessed, they reached the other electrode—many micrometers distant. There they would bolster the conductivity under this electrode and enhance the current through it. "Welker didn't really understand my measurements," Mataré says. "At the time he was too busy studying superconductivity."

But as the two men were debating the merits of their competing interpretations, surprising news arrived from across the Atlantic. In a 30 June press conference, Bell Labs suddenly lifted its six-month veil of secrecy and announced the invention of the transistor by Bardeen, Brattain, and Shockley. The breakthrough was reported in *The New York Times* on 1 July and published in the 15 July issue of *Physical Review*. Incredibly, the Bell Labs solid-state amplifier also had a pair of closely spaced metal points prodding into a germanium surface. [See photo, "Getting to the Point."]

Mataré soon learned Bardeen and Brattain's explanation of the curious effects he had been observing. Electrons trapped on the germanium surface induce a shallow, positively charged layer just beneath it. Holes emitted by the control electrode (which they had dubbed the "emitter") travel easily within this layer over to the output electrode (or "collector"), markedly boosting the conductivity beneath it and therefore the current flowing through it.

After the Bell Labs revelations, Mataré and Welker had little difficulty getting the PTT minister to visit their lab. Thomas urged them to apply for a French patent on their semiconductor triode; he also suggested they call it by a slightly different name: transistron. So the two physicists hastily wrote up a patent disclosure and passed it on to the Westinghouse lawyers.

On 13 August, the company submitted a patent application for a *"Nouveau système cristallin à plusieurs électrodes réalisant des effets de* [sic] *relais électroniques"* to the Ministry of Industry and Commerce. Its brief description of what might be happening inside the germanium mostly followed Welker's field-effect interpretation but was probably influenced by Bardeen and Brattain's explanations.

By the May 1949 press conference, the two Germans had the device [see X-ray image in "Invention and Inventors"] in limited production and were beginning to ship units for use by the PTT as amplifiers in the telephone system—initially in the line between Paris and Limoges. Speaking to the Paris press, Thomas compared these devices with vacuum tubes and demonstrated their use in radio receivers. Reporters hailed the two physicists as *"les pères du transistron"* (the fathers of the transistron). The French device "turns out...to be superior to its American counterpart," read a more measured but still favorable account in *Toute la Radio*, a technical journal [see drawing and photo in "Transistor Twin"]. "The latter has a limited lifetime and appears to be fairly unstable, whereas the existing transistrons do not show any sign of fatigue."

According to Mataré, this superiority could be attributed to the care they employed in fabricating their devices. While observing the process with microscopes, the women working on the small assembly line would measure current-voltage curves for both metal points with oscilloscopes and fix the points rigidly on the germanium with drops of epoxy after the curves matched the desired characteristics. When Brattain and Shockley visited the Paris group in 1950, Mataré showed them telephone amplifiers made with his transistrons—which allowed him to place a call all the way to Algiers. "That's quite something," admitted Shockley a bit guardedly, Mataré recalls half a century later.

But the French government and Westinghouse failed to capitalize on the technical advantages in semiconductors that they then appeared to have. After Hiroshima, nuclear physics had emerged as the dominant scientific discipline in the public mind, and nuclear power was widely heralded as the wave of the future. France became enchanted with pursuing the nuclear genie unbottled in the 1940s, while ignorant of its promising transistron.

Mataré and Welker struggled on in Paris for two more years, but as support for their operation waned during the early 1950s, they started looking for jobs in their native land. In 1951 Welker accepted a post at Siemens in Erlangen, Germany, where he pioneered early research on III-V compound semiconductors, such as gallium arsenide. In the late 1950s and early 1960s, those materials fostered a small optoelectronics revolution in semiconductor lasers and light-emitting diodes. Welker became head of all R&D projects at Siemens in 1969 and retired in 1977. He died in 1981.

In 1952, with solid funding from a wealthy German businessman, Jakob Michael, Mataré moved to Düsseldorf, Germany, and founded a company called Intermetall. It began manufacturing germanium rectifiers and transistors similar to the point-contact devices he had made in Paris. The company bought or built equipment that helped it produce semiconductor devices of even higher quality.

The summit of Intermetall's achievements came at the 1953 Düsseldorf Radio Fair. There a young, dark-haired woman demonstrated what was probably the world's first transistor radio, built around four Intermetall point-contact transistors [see photo, "Tuning In"] more than a year before Texas Instruments Inc., in Dallas, publicly claimed that milestone for itself.

But after Michael sold the firm to Clevite Corp., then in Cleveland, later that year, its focus shifted almost exclusively to production and away from research. Discouraged by that about-face, Mataré left Germany and immigrated to the United States, where he found work in the U.S. semiconductor industry. Even today, at 93, the IEEE Life Fellow remains active, consulting from his Malibu home on such projects as a large, innovative photovoltaic array built in Southern California [see The Back Story, in this issue].

What is arguably the most important invention of the 20th century remarkably occurred twice—and independently. Given the secrecy shrouding the Bell Labs device, there is no possibility Mataré and Welker could have been influenced by knowledge of it before July 1948, when news of the revolutionary invention became widespread. And it seems clear from the still-sketchy historical record that they indeed had a working, reliable amplifier by that time.

This dual, nearly simultaneous breakthrough can be attributed in part to the tremendous wartime advances in purifying silicon and, in particular, germanium. In both cases, germanium played the crucial gateway role, for in the immediate postwar years it could be refined much more easily and with substantially higher purities than silicon. Such high-purity semiconductor material was absolutely essential for fabricating the first transistors.

But the Bell Labs team had clear priority—and a superior physical understanding of how the electrons and holes were flowing inside germanium. That advantage proved critical to subsequent achievements, such as Shockley's junction transistor [see "The Lost History of the Transistor," *IEEE Spectrum*, May 2004], which was much easier to mass-produce with high reliability and uniformity. By the mid-1950s, nobody was trying to make point-contact transistors any longer, and the industry was moving on to silicon.

A factor crucial to success in the nascent semiconductor industry was the *sustained* innovation that flourished at Bell Labs—as well as at Texas Instruments and Fairchild Semiconductor—leading to silicon transistors and integrated circuits. And that required extensive infrastructure, both material and intellectual, to keep these companies at the frontiers of this fast-moving field. Such an infrastructure already existed in the United States after World War II because of its wartime radar efforts. But France had no comparable infrastructure and had to import talent from occupied Germany, which could not exploit its own radar expertise until the 1950s.

In the absence of any such advantages, it was inevitable that Europe's fledgling transistor would soon be eclipsed by other, better semiconductor devices and eventually fade from memory. ■

ABOUT THE AUTHOR

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TO PROBE FURTHER

For more details on the invention of the transistron, see "The 'French' Transistor," by Armand Van Dormael, in *Proceedings of the 2004 IEEE Conference on the History of Electronics*, Bletchley Park, England, June 2004. It is available on the Web at http://www.ieee.org/organizations/history_center/Che2004/VanDormael.pdf.