Invention of the SOLID-STATE AMPLIFIER

By Virgil E. Bottom

In the light of US patent records, amplifying devices having the basic characteristics of the modern transistor appear to have been designed and used more than a generation ago by an unsung physicist whose death was reported last year. The author of this article, Virgil E. Bottom, is professor of physics and chairman of the Departments of Physics and Mathematics at McMurry College in Abilene, Texas. From 1953 to 1958 he was director of research of the Motorola Semiconductor Division in Phoenix, where he was in charge of the development of the first transistors used in automobile radios.

The obituary column of a recent issue of *Physics Today*[1] carried the announcement of the death of Julius E. Lilienfeld* at his home in the Virgin Islands. Dr. Lilienfeld was a native of Poland, formerly a professor of physics at the University of Leipzig, and became a United States citizen in 1935. The announcement of the passing of Dr. Lilienfeld recalled to mind an experience which the author had in 1953 when he was engaged in a patent search in connection with the development of the germanium transistor. The patent search disclosed three patents[2,3,4] granted in the years 1930, 1932, and 1935, respectively, to Julius Edgar Lilienfeld of Brooklyn and Cedarhurst, New York. The attorney who prepared the patent was Fred'k F. Schuets. A brief inquiry failed to locate either the inventor or his attorney and, inasmuch as the patents had already lapsed, the matter was dropped.

The three patents, however, are of more than passing interest because they appear to disclose the invention of the solid-state amplifier more than two decades before it was rediscovered and made into a practical device.

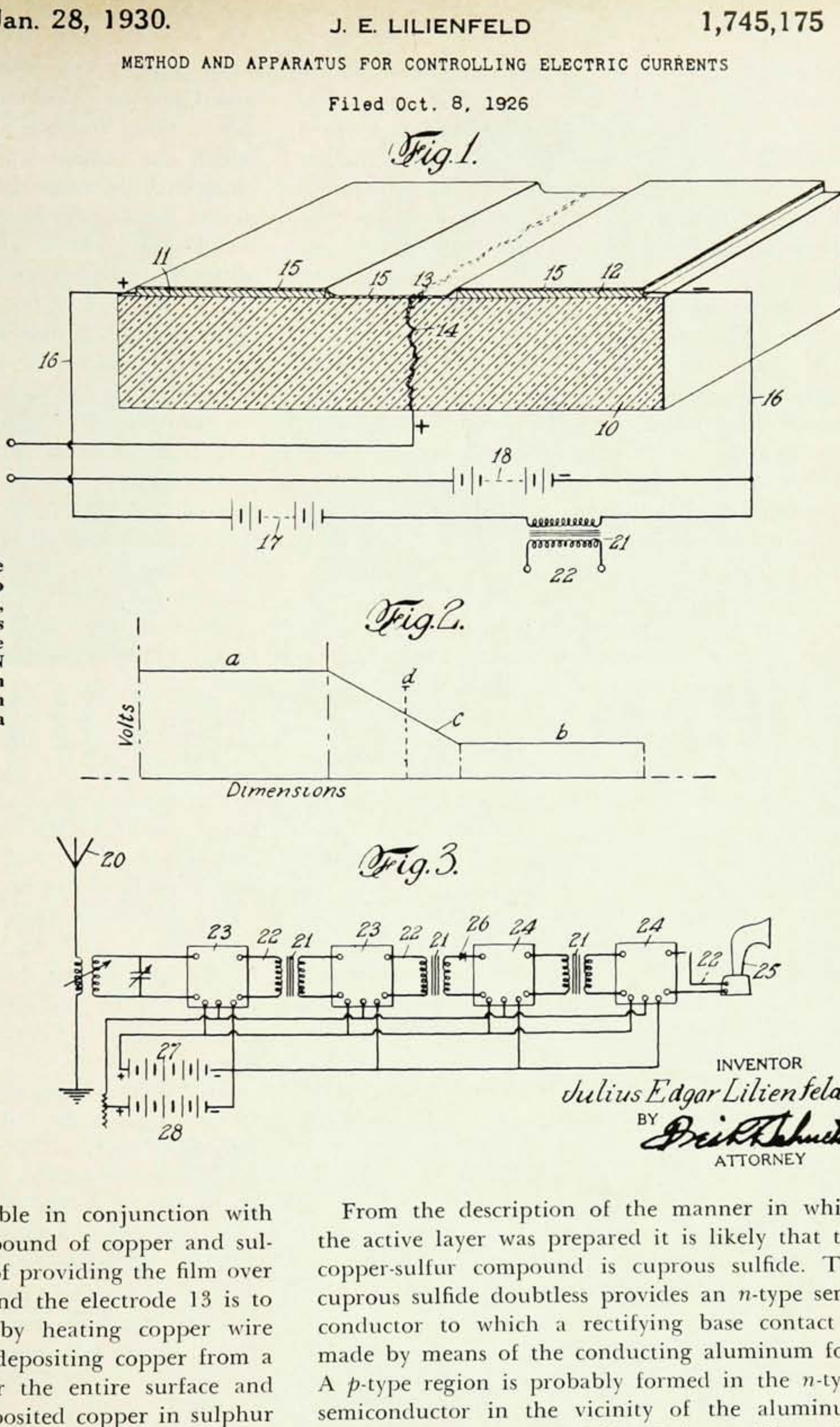
The application for the first of the three patents[2] was filed in the United States Patent Office on October 8, 1926, as Serial No. 140 363 and in Canada on October 22, 1925. The patent is entitled "Method and Apparatus for Controlling Electric Currents". In the preface the inventor says; "Heretofore, thermionic tubes or valves have been generally employed for this purpose; . . . the invention consists in affecting, as by suitable incoming oscillations, a current in an electrically conducting solid of such characteristics that said current will be affected by and respond to electrostatic changes".

The cover page of the first of the three patents is reproduced on page 25. The design and construction of the device, as described in the specifications, is given in the two following paragraphs.

"Referring to the drawings, 10 designates a base member of suitable insulating material, for example, glass; and upon the upper surface of which is secured transversely thereof and along each side a pair of conducting members 11 and 12 as a coating of platinum, gold, silver or copper which may be provided over the glass surface by well-known methods such as chemical reduction, etc. It is desirable that the juxtaposed edges of the two terminal members 11 and 12 be located as closely as possible to each other; and substantially midway of the same there is provided an electrode member 13, which is of minimum dimensions to reduce capacity effect. This member consists of a suitable metal foil, preferably aluminum foil, and may conveniently be secured in position by providing a transverse fracture 14 in the glass and then reassembling the two pieces to retain between the same the said piece of aluminum foil of a thickness approximating one ten-thousandth part of an inch. The upper edge of this foil is arranged to lie flush with the upper surface of the glass 10."

"Over both of the coatings 11 and 12, the intermediate upper surface portion of the glass 10, and the edge of the foil 13 is provided a film or coating 15 of a compound having the property of acting in conjunction with said metal foil electrode as an element of uni-directional conductivity. That is to say, this coating is to be electrically conductive and possess also the property, when associated with other suitable conductors, of establishing at the surface of contact a considerable drop of potential. The thickness of the film, moreover, is minute and of such a degree that the electrical conductivity therethru would be influenced by applying thereto an electrostatic force. A suitable material for this

* The name is spelled "Lillienfeld" in *Physics Today*. The name is usually spelled "Lilienfeld" in the patents, although the spelling "Lillienfeld" appears once in the second patent. [*Note*: The spelling used in the *Physics Today* obituary was probably incorrect. The spelling was "Lillienfeld" in press accounts of his death, and "Lillenfeld" in the most recent Membership List of The American Physical Society—Bull. Am. Phys. Soc., II, 7, 117 (April 1962); but in the previous APS Membership List—Bull. Am. Phys. Soc., II, 3, 102 (September 1958)—the name is given as "Lilienfeld".—ED.]



The drawings on the cover page of US Patent 1 745 175, issued to J. E. Lilienfeld on January 28, 1930, show a device that seems to be a solid-state amplifier of the type now known as the NPN transistor. The patent application was filed in the United States on October 8, 1926, and in Canada on October 22, 1925.

film and especially suitable in conjunction with aluminum foil, is a compound of copper and sulphur. A convenient way of providing the film over the coatings 11 and 12 and the electrode 13 is to spatter metallic copper by heating copper wire within a vacuum, or by depositing copper from a colloidal suspension, over the entire surface and then sulphurizing the deposited copper in sulphur vapor, or by exposure to a suitable gas as hydrogen sulphide or a liquid containing sulphur, as sulphur dissolved in carbon bisulphide."

From the design and the associated circuit, it is clear that the patent discloses the invention of a device which would be known as an *NPN* transistor. The circuit is readily recognized as the conventional common emitter circuit.

From the description of the manner in which the active layer was prepared it is likely that the copper-sulfur compound is cuprous sulfide. The cuprous sulfide doubtless provides an *n*-type semiconductor to which a rectifying base contact is made by means of the conducting aluminum foil. A *p*-type region is probably formed in the *n*-type semiconductor in the vicinity of the aluminum contact. Electrons are injected into this region from the adjacent *n*-type material, thereby changing its conductivity and hence the current through the thin semiconducting layer.

The inventor's explanation of the operation of the device does not take account of the injection of minority carriers across the junction between two regions of opposite conductivity type. Instead, he bases his explanation upon the variation of the resistance of the very thin layer of copper-sulfur compound as a result of the electrostatic field established in it. Although his explanation for the change in the conductivity, based upon alignment of dipoles in the electric field, is probably not correct, the inventor is certainly right in stressing the importance of making the layer extremely thin so that the conductivity can be changed throughout the entire cross section of the layer.

In the second patent[3] Lilienfeld describes a "couple" or, as we would term it today, a rectifying contact between a metal and a chemical compound. He notes that the contact has high resistance when the metal is at a positive potential relative to the compound, thus indicating that the semiconducting compound is n-type.

The inventor proceeds to describe a device constructed in the form of a sandwich by first depositing a layer of copper sulfide and then depositing on it a layer of magnesium having a thickness of about $200\mu\mu$. Finally, a second layer of copper sulfide is deposited over the magnesium. Pressure contacts are made to the three layers and junctions are formed by impressing a high voltage between the magnesium layer and each of the copper-sulfide layers, apparently in much the same way that the collector junction is formed in a point-contact germanium transistor. The resulting structure appears to be an *NPPN* structure with a metallic connection between the two n-type layers. The circuit diagram which is a part of the specification of the patent shows both of the junctions biased in the reverse direction, with one biased to a higher potential than the other. The input signal is impressed across the junction with the higher reverse bias. The current across the other junction flows through the output circuit. It is not clear what part the thin layer of magnesium plays in the operation of the device.

The inventor discloses a number of mechanical configurations and other materials which may be used to construct amplifying devices of the type just described.

In the third patent[4], Lilienfeld discusses the properties of his couples in some detail, explaining that they may be used as rectifiers or detectors and as capacitors having "extremely high specific capacity". In the latter he clearly anticipated the use of a reverse biased *P-N* junction as a variable capacitor.

He also discloses several more designs and methods of construction of his amplifier. Briefly, these involve the deposition of a layer of copper sulfide (cuprous sulfide) onto an oxidized aluminum surface. Two closely spaced contacts are provided on the upper surface of the copper-sulfide layer. These contacts are separated by a region in which the copper-sulfide layer is extremely thin, "approaching molecular thickness". The circuit diagram for the device, used as an amplifier, is the well-known common emitter circuit regularly used with *NPN* transistors.

The mode of operation of the device is readily explained on the basis that a p-type layer is formed in the cuprous sulfate immediately adjacent to the aluminum sheet which forms the base contact of the transistor. Electrons are injected into this very thin layer of p-type semiconductor by the forward bias between the aluminum sheet and one of the metallic contacts which is recognized as the emitter contact. The conductivity in the region is modified by the injected carriers, thereby altering the current through the reverse-biased or collector junction.

Assuming that Dr. Julius E. Lilienfeld and the inventor Julius Edgar Lilienfeld are one and the same person, as seems most probable, it thus appears that Dr. Lilienfeld, at least as early as October 1925 when he filed an application for a Canadian Patent, had constructed and used amplifiers having the basic characteristics of the modern transistor amplifier. His devices must be considered relatively crude in comparison with modern solid-state amplifiers, and his explanation of their operation is not in complete accord with modern solid-state theory. However, little doubt can exist that his devices operate on the basis of conductivity modulation by minority carrier injection in semiconductors, which is the basis of operation of the modern transistor.

Dr. Lilienfeld was apparently ahead of his time in two respects; he did not have a good semiconducting material with which to work, and the theory of semiconductors had not been developed to the extent that he could correctly explain the operation of his devices. Nevertheless, it must apparently be conceded that he invented and used solid-state amplifiers identical in principle with the modern transistor nearly a quarter of a century before it was rediscovered and made into a practical device.

References

1. *Physics Today*, November 1963, p. 104.
2. U.S. Patent, 1 745 175, filed October 8, 1926; granted January 28, 1930.
3. U.S. Patent, 1 877 140, filed December 8, 1928; granted September 13, 1932.
4. U.S. Patent, 1 900 018, filed March 28, 1928; granted March 7, 1933.