

THE INVENTION OF THE TRANSISTOR

A Thesis Presented

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## Chapter 1

### Introduction

In February of 1964 an article appeared in *Physics Today*<sup>1</sup> that suggested that a solid-state amplifying device may have been invented more than twenty years before the 1948 announcement of the point-contact transistor by Bell Telephone Laboratories (hereafter referred to as Bell Laboratories). In this article Virgil E. Bottom sketched, for what appears to be the first time in scientific or historical literature, three patents filed by Julius E. Lilienfeld in the years 1925 to 1928. Bottom described their structure and his ideas of how they would have worked and concluded "...it must be apparently conceded that he [Lilienfeld] 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."<sup>2</sup>

Three months later in May, 1964, J. B. Johnson of Bell Laboratories took issue with Bottom's interpretation of the work of Lilienfeld.<sup>3</sup> While Johnson agreed that Lilienfeld deserved credit for proposing a solid-state amplifying device, he questioned both Bottom's assessment of the nature of Lilienfeld's devices and whether the devices would have even worked. Bottom described Lilienfeld's amplifiers as being early versions of both the point-contact and junction transistors. Johnson on the other hand believed that Lilienfeld attempted to vary conduction not through the injection of minority carriers but rather by the field-effect, applying an isolated, perpendicular electric field to the current flow.<sup>4</sup>

The story of Lilienfeld gained further significance in 1982 when the American

Physical Society learned it was the beneficiary of a large sum of money in the name of Julius E. Lilienfeld. The money was left in the will of his wife, Beatrice Lilienfeld, who felt that her husband had not received enough credit for his work and chose this way to honor him. William Sweet shed some light on Lilienfeld in an article that announced the establishment of the annual American Physical Society prize that now bears Lilienfeld's name.<sup>5</sup> Little was actually found out about Lilienfeld, and questions remain about his patents for solid-state amplifiers.

At issue is whether Lilienfeld does indeed deserve more credit for his contributions to the development of the transistor. In effort to answer this question both the history surrounding the development of the transistor and Lilienfeld's patents themselves were investigated. Furthermore, experiments were performed to determine if the device described in Lilienfeld's 1933 patent would work as specified or at least if it is plausible that Lilienfeld indeed built the devices he claimed were solid-state amplifiers.

### Prehistory

The beginnings of investigations into the electrical properties of solids may be attributed to Michael Faraday when in 1833 he noticed that the electrical resistance of silver sulfide decreased as its temperature rose.<sup>6</sup> This is opposite of what one would expect for a conductor, and thus Faraday had discovered an important property of what would come to be called semiconductors. The first "solid-state" device, although that term did not come into wide use until much later, came from rectifying effects



discovered by Ferdinand Braun in lead sulfide and various pyrites in 1874.<sup>7</sup> In that same year A. Schuster described the unilateral conductivities in tarnished and untarnished copper wires.<sup>8</sup> Braun's discovery led to the first crystal rectifier, called a cat's whisker rectifier. This consisted of a point contact, the tip of a thin wire, placed against a natural crystal of lead sulfide, otherwise known as galena. With the inception of wireless telegraphy, based on the work of Hertz, Lodge and others, the cat's whisker found wide use in detecting the informational telegraph signal from its carrier wave.

A seemingly unrelated event occurred in the early 1880s when Thomas Edison discovered that electrical particles were emitted from the glowing filament inside of a light bulb. These particles could be detected as electric current on a cold electrode placed in the bulb as a probe. The non-glowing, cold element could not produce these particles, and thus current would flow from the hot filament to the cold filament but not the other way around. Edison got a patent on this arrangement (U.S. Patent 307,031, granted October 21, 1884) but, since he was working with direct current, saw no practical use for it.<sup>9</sup> John A. Fleming realized that this device could be used as a rectifier for alternating current and in 1904 introduced the Fleming valve. The device consisted of a cold plate placed around a hot filament inside of a vacuum bulb.<sup>10</sup> This signaled the beginning of the end for the crystal rectifier, until its revival in the 1940s. The event that finally put a temporary end to the use of crystal devices and spurred the development of radio, occurred in 1906 when Lee de Forest inserted a metal grid into a two electrode valve. Now the flow of electrons between

the electrodes could be controlled by applying an electrostatic potential to the grid.<sup>11</sup> In this way small signals received over the airwaves could be amplified and noise reduction could be achieved. Soon voices could be transmitted with clarity, and thus the vacuum triode advanced the technology of wireless transmission so that radio telephony came to dominate telegraphy as the form of wireless communication.

Radio quickly became a very large industry and the prime mover of electronics development. At the heart of this electronics boom was the vacuum tube. The vacuum tube had its limitations though; it was bulky, ran hot, consumed a large amount of power, was fragile and unreliable. A great deal of effort went into improving the characteristics of the tube, but understandably rivals began to surface. Most notable are the copper-cuprous oxide rectifier of Grondahl<sup>12</sup> and the selenium rectifier first studied by C. E. Fritts in 1883<sup>13</sup> and later developed by Merritt<sup>14</sup> and others in the 1920s.<sup>15</sup> These devices were most suited for power applications and electronic meters; they were not used much in the radio industry. Then the second world war broke out, and the discovery of radar prior to the war brought to the surface another limitation of the vacuum tube, poor high-frequency response. Radar requires frequencies that at that time were too high for vacuum tubes. Also, the war brought with it more complex electronics which made more demands on tube reliability. These problems caused a renewed interest in the crystal rectifier and in understanding the electrical properties of solids.

Industry and academia too were beginning to realize that the physics of solids might lead to important technologies. Some headway was made in the 1930s and

during the war at places like MIT, Purdue and Bell Laboratories.<sup>16</sup> In 1945 Bell Laboratories began a large research effort into the physics of the solid state which eventually led to the invention of the point-contact transistor in 1947. With this discovery of the transistor effect, the effort to make a solid state amplifying device to replace the bulky, unreliable, hot vacuum tube had realized its first major success and the era of solid-state research had begun.

The above discussion represents the history as it is often told, but neglects the attempts prior to Bell Laboratories to make a solid-state amplifying device. The first attempt was made by Julius E. Lilienfeld who received three patents for solid-state amplifying devices in 1930, 1932, and 1933. O. Heil filed for a patent in Germany entitled "Improvements in or Relating to Electrical Amplifiers and Other Control Arrangements and Devices" on March 2, 1934 and was granted a patent in England on December 6, 1935.<sup>17</sup> H. C. Weber entitled his February 27, 1934 patent (U.S. Patent 1,949,383) "Electronic Device".<sup>18</sup> No further information on the Heil or Weber patents has been gathered. The first published results of amplification in a solid-state device, due to the work of R. Hilsch and R. W. Pohl, appeared in 1938.<sup>19</sup> Hilsch and Pohl's was a scientific investigation with no practical aims, and the device produced could not have been used in practical applications due to low frequency response.<sup>20</sup>

#### Julius Edgar Lilienfeld

Julius Lilienfeld was born in Lwow, Poland on April 18, 1882, received his

Ph.D. in 1905 from the University of Berlin and was Professor of Physics at the University of Leipzig from 1910-1927.<sup>21</sup> During his tenure as a professor in Leipzig, Lilienfeld published many articles in the areas of gaseous discharge physics, x-ray production and field emission. He also received numerous patents for various tubes, both gaseous and under vacuum and methods for obtaining vacuums. Some of these include: a Röntgen ray tube with pure electron discharge, a method for welding aluminum to siliceous refractory metals,<sup>22</sup> and a method for producing a vacuum using low temperatures.<sup>23</sup> In his article "More on the Solid-State Amplifier and Lilienfeld" J. B. Johnson gave much credit to Lilienfeld for his contributions to the area of field emission and said that a 1920 article by Lilienfeld on what Lilienfeld called auto-electronic emission "spectacularly put field emission on the map."<sup>24</sup> Johnson also stated that much of the work on field emission up to the time of his article (1964) still reflected the influence of Lilienfeld.<sup>25</sup>

In the second decade of this century Lilienfeld was involved in a controversy regarding the production of x-rays that is worth mentioning. X-rays were discovered through the investigation of a gaseous discharge, and for many years they were produced using a gaseous discharge tube. "It is a characteristic of the low pressure discharge tube that the potential difference between the anode and the cathode remains practically constant for large variations of current through the tube. In order to change the voltage across the tube of this type, it is necessary to alter the pressure of the gas in the tube..."<sup>26</sup> In the period 1908-1912, Lilienfeld developed a high-vacuum x-ray tube which used an oxide-coated emitter for the cathode, i.e., the

electrons originated at the cathode rather than from ionizations in gas in the tube. His work was both published and patented.<sup>27</sup>

In 1913, Irving Langmuir<sup>28</sup> and W. D. Coolidge<sup>29</sup> of General Electric described a high-vacuum x-ray tube which used a pure hot-tungsten cathode as the source of electrons. Their papers also attacked Lilienfeld's work, claiming, for example, that he must have had a poor vacuum. Lilienfeld responded promptly and succinctly, pointing out the errors in what his critics had said about his work.<sup>30</sup> His vacuum, for example, which was assisted by cryogenic pumping using liquid hydrogen, was better than theirs. The criticisms by Langmuir and Coolidge seem to have been based in part on the fact that Lilienfeld's curves of tube current vs. potential deviated somewhat from what later became known as Child's Law,<sup>31</sup> namely that the current should increase as the three-halves power of the potential. However, as was later demonstrated conclusively, there is a saturation effect in a tube such as Lilienfeld's, the current reaching a maximum value at very high potentials due to the nature of the cathode.<sup>32</sup> It appears to have been the onset of this phenomenon that Langmuir and Coolidge misinterpreted as a poor vacuum in Lilienfeld's results.

Lilienfeld appears to have been wrong on some speculations regarding what was happening in the tube, but his laboratory work seems to have been both superb and correct. Coolidge was also claiming to be the first to develop a high-vacuum x-ray tube. Since Lilienfeld's work predated that of Coolidge, its correctness was crucial to Coolidge's claim. X-rays had become big business by the time of this exchange and there may have been more at stake for Lilienfeld, Coolidge, Langmuir,

and General Electric, a leading manufacturer of x-ray equipment, than a lofty interest in scientific correctness. It is reported that Lilienfeld subsequently received a cash settlement of \$100,000 from General Electric involving x-ray patent claims.<sup>33</sup>

Lilienfeld's work changed course when he moved to the United States around 1926. It is not known exactly when he moved, but by 1927 he had the position of Research Director of Amrad, Inc., a manufacturer of radios and radio components located in Malden, Massachusetts.<sup>34</sup> In 1930 the research arm of Amrad was split off as Ergon Research Laboratories, Inc., as Amrad merged with Magnavox.<sup>35</sup> It is not clear why Lilienfeld moved to the United States. However, he was Jewish, and the discrimination against Jews had gathered new force beginning in about 1920. While at Amrad/Ergon, Lilienfeld published and received patents in the area of electrolytic anodization of aluminum, primarily for electrolytic condensers. At approximately the same time as his move to the United States Lilienfeld filed for three patents for devices to be used for controlling electric current. The three patents were filed in the United States in 1926 and in 1928 and granted in 1930, 1932 and 1933.<sup>36</sup> The patent filed in 1926 had been filed earlier in Canada in 1925.<sup>37</sup> It seems likely that Lilienfeld had developed his ideas before moving to the United States and that these patent applications were independent of Amrad/Ergon.

It is important to note the timing of these patents with respect to the electronics developments of the time. Grondahl had announced his copper oxide rectifiers in 1926, and selenium rectifiers came along shortly after that.<sup>38</sup> Also, copper sulfide rectifiers were being developed during this period: Samuel Ruben in 1924,<sup>39</sup>

Lilienfeld and C. H. Thomas in 1927,<sup>40</sup> and Elkon, Inc. was producing battery chargers made with copper sulfide by 1929.<sup>41</sup> However, the primary rectifier being used in the electronics industry was still the vacuum tube. Presumably, Lilienfeld saw how devices made of solid materials were replacing vacuum rectifiers (vacuum diodes) and saw no reason why solid materials should not replace vacuum amplifiers as well. The impetus was certainly there. As Lilienfeld wrote in his December 8, 1928 patent, "Various devices such as relays, thermionic and otherwise, have been utilized for this purpose [controlling electric currents]; and it is the object of the present invention to afford an extremely compact, simple and durable amplifying member which will be particularly efficient for the purpose intended and which, withal, may be constructed at small expense and have extremely long life."<sup>42</sup>

Despite the rather prophetic nature of his patents, regardless of whether or not they worked, they went largely unnoticed by the scientific and engineering community. Only two periodicals have been found that regularly listed recent, relevant patents at the time of Lilienfeld's patents (*Electronics* and *Electronic Industries*), and neither of these periodicals mentioned Lilienfeld. The sole reference other than Bottom's in 1964 and subsequent references after Bottom, is in the 1933 edition of *Chemical Abstracts* which cites a patent for a device for rectifying or detecting electric current.<sup>43</sup> The patent cited is Lilienfeld's 1933 patent entitled "Device for Controlling Electric Current" and claiming a device to be used for amplification. That this device could also be made to rectify was discussed but was not listed as a claim of the patent.

Lilienfeld's work with Ergon research continued until the mid 1930s when he and his wife, formerly Beatrice Ginsburg, moved to the Virgin Islands.<sup>44</sup> Ergon folded in 1935.<sup>45</sup> Lilienfeld continued contributing to the area of electrolytic condensers and patenting related devices into the fifties. Lilienfeld died August 28, 1963.<sup>46</sup>

### Bell Telephone Laboratories

Bell Laboratories was one of several groups in the 1930s to devote effort to understanding solids. Progress was being made in developing the physical theory to account for their properties, but there still existed a disturbing lack of understanding. A. Sommerfeld<sup>47</sup> and F. Bloch<sup>48</sup> made great strides in applying quantum mechanics to solids, and A. H. Wilson<sup>49</sup> made a significant step in using quantum mechanics to describe semiconductors. Wilson also proposed a theory for the rectification noticed at certain metal-semiconductor junctions. This theory was further clarified by Mott<sup>50</sup> and Schottky.<sup>51</sup> Attempts to connect theory and experiment were made most notably at Purdue and Bell Laboratories. Before the second world war much of the research at Bell Laboratories focused on understanding valves, especially the phenomenon of rectification in solids. Both Walter Brattain, an experimentalist who joined Bell Laboratories in 1929, and William Shockley, a theorist who joined Bell Laboratories in 1936, spent their first years with Bell Laboratories working in this branch of research. In 1931 Brattain was assigned to work on the rectification properties of copper oxide, a polycrystalline and complex semiconductor.<sup>52</sup> Later, in 1939, the



two collaborated on an attempt to make a field-effect amplifier out of copper oxide. Shockley pushed the idea despite Brattain's belief that it would not work. The idea was to insert a grid, a tarnished copper wire screen, into the copper oxide layer of an oxidized piece of copper. It was hoped that the grid would influence conduction either through the copper oxide or in the vicinity of the copper-copper oxide junction. This attempt to produce a solid-state analog to the vacuum triode was a failure.<sup>53</sup>

The second world war caused much solid-state research to be put on hold as many scientists found themselves working on new, war related projects. However, some efforts continued both at Purdue and Bell Laboratories. Both places made advances in fabricating purer semiconductors.<sup>54</sup> After the war Purdue went back to fundamentals<sup>55</sup> while Bell Laboratories continued to keep its hand in the practical side of semiconductor research. Two significant events took place in 1945. John Bardeen joined Bell Laboratories and Mervin Kelly, the Executive Vice-President, signed a work authorization that formed a solid-state research program aimed at understanding the basic physics of solids relating to communications.<sup>56</sup> There was a feeling that the telephone system was getting too complex for the mechanical relays used in switching and thus needed the technological improvement of electronic switches. William Shockley, John Bardeen and Walter Brattain were a part of the semiconductor group, and it was hoped that their research would lead to a solid-state amplifying device.<sup>57</sup>

Shockley still had hopes of producing a field-effect device, but despite the theoretical support for such a device, all attempts to produce one failed. John Bardeen suggested a reason. He believed that there may have been energy states at the surface

of the semiconductor that by trapping charge carriers would not only reduce the number of carriers present but also shield the bulk of the semiconductor from the applied field.<sup>58</sup> Thus, the applied field would not be able to significantly alter the conduction in the semiconductor. A series of experiments to test this theory got under way. In 1947 while performing one of these experiments, Walter Brattain and John Bardeen discovered the point-contact effect that led to the point-contact transistor. Brattain and Bardeen found that if two point contacts were placed very close together (between 0.005 and 0.025 cm apart) on the surface of a germanium crystal, one contact could be made to inject minority carriers into the crystal and thereby affect the amount of current flowing into the second contact in such a way as to achieve amplification.<sup>59</sup> The announcement of this discovery was made in July of 1948, and Brattain and Bardeen soon received patents for their device.

Shockley, convinced of a better way to make a transistor, completed the theory for a junction transistor in January of 1948. The device was made in 1951 and became tremendously important to the electronics industry. Shockley was not able, however, to get primary patents on his field-effect device because of prior work by Lilienfeld, Heil and Pohl.<sup>60</sup> In 1952 Shockley published an explanation of a field-effect transistor that avoided the problems of surface states.<sup>61</sup> In 1956 the three men, William Shockley, Walter Brattain and John Bardeen, received the Nobel Prize "for their researches on semiconductors and their discovery of the transistor effect."

It is clear that knowledge of the work of Lilienfeld existed at Bell Laboratories. One would imagine that his ideas would have surfaced when attempts to

make a field-effect device out of copper oxide were performed. Later, after the discovery of the point contact transistor, J.B. Johnson tried to reproduce Lilienfeld's patents without success. Finally, Shockley's attempts to patent his field-effect device were thwarted at least in part by Lilienfeld's prior work. How much his work influenced the group is uncertain. His idea of using a thin oxide to increase the size of the field at the surface of the semiconductor predates the application of this technique by Brattain when investigating Bardeen's surface state theory. This phenomenon led both Bardeen and Brattain to conclude that making a field effect device would be possible. It was in trying to make this device and fortuitously having a hole in the oxide that the point-contact effect was noticed.<sup>62</sup>

Despite the apparent prior discoveries of Lilienfeld, no mention of him was made by Bell Laboratories in any of the publications announcing the discovery of the transistor,<sup>63</sup> in Pearson and Brattain's "History of Semiconductor Research",<sup>64</sup> or in Shockley's "Unipolar Field-Effect Transistor".<sup>65</sup> There are perhaps understandable reasons for this. Lilienfeld's work was not published but rather patented. By the 1950s there was no reason for scientists to cite patents when discussing prior work, although some did. Also, it is likely that for their own patenting reasons Bell Laboratories would have avoided drawing too much attention to work that they would want to distinguish from their own. In fact, the reason Johnson worked on Lilienfeld's patents was to distinguish the point-contact transistor from Lilienfeld's devices.<sup>66</sup> Presumably, since Johnson's attempts to reproduce Lilienfeld's work failed and patents were obtained, the matter was dropped. Also, Pearson and

Brattain's paper was primarily devoted to the development of the theory of semiconductors, and Lilienfeld's contribution was not theoretical. It is understandable then why Bell Laboratories would neglect referencing Lilienfeld's work, but the fact they did says little about whether he made significant contributions that deserve recognition.

After the work of Lilienfeld was reopened by Bottom in 1964, Bardeen commented on the work of Lilienfeld as did J. B. Johnson in his rejoinder to Bottom's article. Johnson distinguished Lilienfeld's work from both the point-contact and junction transistors, saying that Lilienfeld deserved credit for proposing a solid-state amplifier but did not invent or propose the injection or junction transistors.<sup>67</sup> In William Sweet's article Bardeen agreed with Johnson that Lilienfeld's device was not of the point-contact type but told Sweet that even if Lilienfeld's devices did not quite work, there was no reason why devices much like them could not work.

#### Development of the Field Effect

Although the first practical transistors were of the point-contact type, the idea of producing field-effect devices, where the conductivity of a semiconductor is modulated by an applied field, had already existed for two decades. Lilienfeld and Heil were the first to patent devices based on the principle of the field-effect; Lilienfeld in 1925, 1926 and 1928, and Heil in 1934. The earliest record of a scientific discussion of the modulation of conductivity in a thin semiconductor is attributed to G. Liandrat in 1935.<sup>68</sup>

scientific discussion of the modulation of conductivity in a thin semiconductor is attributed to G. Liandrat in 1935.<sup>68</sup>

As mentioned earlier, Bell Laboratories attempted to produce field-effect devices in the 1940s but were unsuccessful. During investigation of the field effect in 1947, Bardeen and Brattain discovered the point-contact transistor. In the next year Shockley and Pearson published the first experimental evidence of modulation of the number of carriers at the surface of a semiconductor by an applied field.<sup>69</sup> In 1952 Shockley published a paper describing a field-effect transistor somewhat different in construction from Lilienfeld's 1933 patent, Heil's device and those in the air around the time of the invention of the point-contact transistor.<sup>70</sup> This device did not deplete carriers in the semiconductor at the interface between the semiconductor and an insulator but rather at the interface between p- and n-type materials, i.e., at a p-n junction. This design was later realized by Dacey and Ross.<sup>71</sup> From this point the development of field-effect transistors took two different paths: devices that modulated the number of majority carriers and devices that modulated the number of minority carriers.

The field-effect amplifiers that had been proposed before the mid 1950s were all based on majority carrier modulation. That is, if one was able to apply a strong enough field across a semiconductor so that it was at least partially depleted of majority carriers, the conductivity of that semiconductor would be reduced. However, the depth into a semiconductor that one could deplete was very small, so this method of obtaining field-effect limited the geometry of the device. To avoid this,

impedance, which with various capacitance effects, limited high-frequency response. These problems prompted the application of thin film technology to field-effect transistors, where thin film semiconductors without prohibitively high resistances were used.

Weimer is usually credited with producing the first thin film transistor (TFT) in 1961,<sup>72</sup> although there was much development of this technology in the decade before this. Weimer chose cadmium sulfide as his semiconductor which had been investigated by R. W. Smith, A. Rose, R. Bockemuehl, and W. Ruppel<sup>73</sup> as well as Weimer and others. TFTs were usable devices that through evaporation techniques could be made very small and linked together into integrated circuits. However, these devices were soon superseded by a more stable design.

The devices that used majority carrier modulation did so in part because ohmic contacts were used to make connections to the semiconductor. Ohmic contacts can supply a great deal of majority carrier current but can not support appreciable minority carrier current. Thus, in forming an inversion layer, minority carriers are supplied by the body of the semiconductor. But since the processes for forming an inversion layer with minority carriers from the body are slow, inversion layers did not play a significant role in the first field-effect designs.

However, workers using junction transistors in the 1950s noticed problems with currents that were not affected by the depletion barrier at the junction as majority currents were. This renewed the investigation of minority carriers, and an explanation of these currents was developed. In a typical n-p-n transistor the p-type region can be

driven into inversion such that its surface contains enough negative ions to bridge the p-type region with an n-type channel. This allows current to flow between the two n-type regions. In 1953 W. L. Brown was able to predict and experimentally verify this behavior and show that this inversion layer could be electrostatically induced.<sup>74</sup> A patent by I. M. Ross in 1957 included the use of an insulating layer to isolate the field used to induce the inversion layer from the semiconductor.<sup>75</sup> In the next few years there followed various designs using different insulators, as finding the right insulator was the key next step.

As opposed to majority carrier transistors, the minority carrier devices did not suffer from geometric limitations because the inversion layer naturally formed a thin layer (30 to 3000 Å) regardless of the semiconductor's thickness. Also, the channel could be completely turned off, yielding 100% carrier modulation. The problem was getting a good enough insulator to withstand the high voltages necessary to invert the surface of the semiconductor. Earlier, in 1956 Atalla, Tannenbaum and Scheibner had suggested thermally growing silicon dioxide on silicon to help reduce surface traps.<sup>76</sup> This proved to be an excellent insulator as well, and in 1960 Kahng and Atalla produced the first modern MOSFET (metal-oxide-semiconductor field-effect transistor).<sup>77</sup>

### The Patents

Between 1926 and 1928 Lilienfeld filed for three patents for solid state amplifying devices. All three devices were to operate like vacuum triodes but were to be smaller, consume less power, not require high voltage and not require a heated filament. Also, in his first patent he explicitly described the amplifier as being applicable to radio. The circuit diagrams given in all of the patents were essentially grounded cathode (or in modern terms grounded emitter or grounded source) amplifier circuits with a biased grid (base or gate). The level of bias depended on the device but was between 0 and 30 V. It is clear from his patents that Lilienfeld was attempting to produce solid-state devices that were "voltage amplifiers" in analogy with the vacuum tube.

#### U.S. Patent 1,745,175

This patent was titled "Method and Apparatus for Controlling Electric Current", filed on October 8, 1926 and granted on January 28, 1930. It specified depositing two conducting strips such as aluminum, platinum, silver, gold or copper close together on an insulating substrate such as glass. Next the glass was to be broken so that a thin conductor such as aluminum foil could be placed in the fracture midway between the two conducting strips. One was then to coat the entire device with a material known to produce a rectifying contact with the foil. To accomplish this a metal could be deposited from a colloidal suspension or "spattered" (evaporated) from a heated piece of wire and subsequently oxidized or sulfurized. The materials



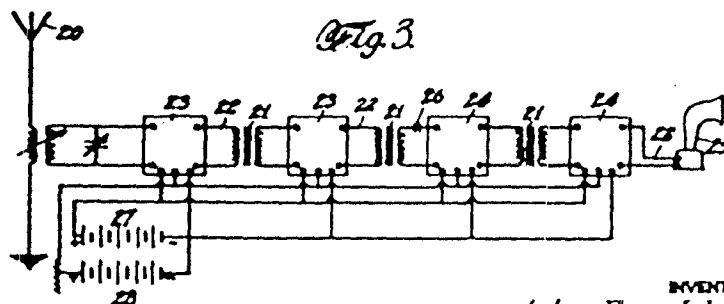
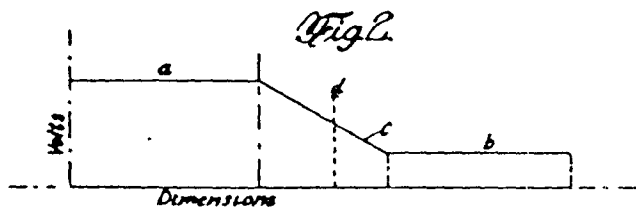
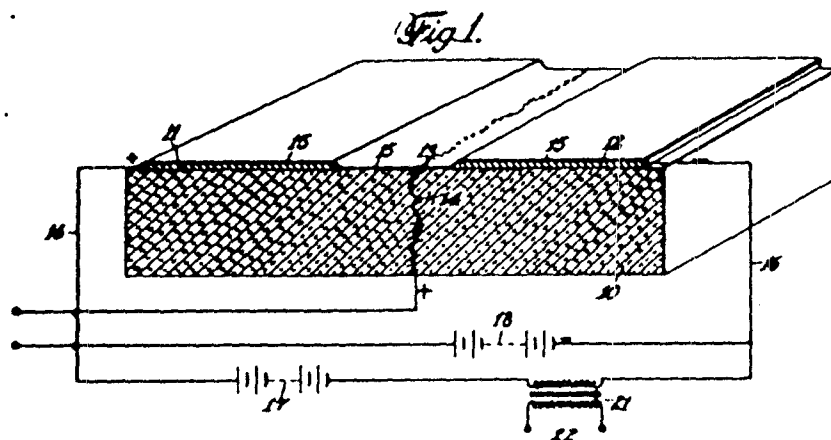
Jan. 28, 1930.

J. E. LILIENFELD

1,745,175

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1928



INVENTOR  
Julius Edgar Lilienfeld  
BY  
Oscar Schmidt  
ATTORNEY

Figure 1  
Diagrams from J. E. Lilienfeld's 1930 Patent

Lilienfeld favored were aluminum for the conducting strips, aluminum foil for the inserted conductor and copper sulfide for the coating. Lilienfeld's diagram of this device is reproduced in Figure 1.

Lilienfeld went on to say that if a potential was placed across the coating, there would be a potential gradient near the foil and between the two conducting strips. If a second, greater potential was placed on the foil, the rectifying junction between the foil and the copper sulfide coating would prevent current from flowing into the foil. However, this second potential could then be varied to act as a valve in the circuit of the copper sulfide coating. Thus, an incoming signal applied to the foil would affect the conductivity of the coating in such a way that the signal would be magnified in the output circuit. Lilienfeld provided diagrams that showed his device as well as the connections needed to make an amplifier. The diagram and the text describe what in modern terms would be called a common emitter or common source amplifier.

Lilienfeld pictured the copper sulfide coating as containing "bipoles" that would line up with an applied field. Further, the conductivity of the coating would be significantly influenced by the degree to which the bipoles were lined up. A second field, applied perpendicularly to the first, that disrupted the alignment of the bipoles would then affect the conductivity of the film. Lilienfeld stressed the need to make the film very thin so that the applied cross field could penetrate the full cross-section of the film. Lilienfeld summarized the nature of his device in the third of the nine claims of the patent where he claimed rights to "the method of controlling the flow of electric current in an electrically conducting medium of minute thickness, which

comprises subjecting the same to an electrostatic influence to impede the flow of said current by maintaining at an intermediate point in proximity thereto a potential in excess of the particular potential prevailing at that point, and varying the degree of excess potential by an impressed oscillating current."<sup>78</sup>

Clearly this was an attempt to make a solid-state device in direct analogy to a vacuum triode. Lilienfeld placed the center electrode, the aluminum foil, at the midpoint of the current flowing through the coating to influence conduction by way of the applied cross field, much like a grid was placed in the center of flow in a vacuum triode. It appears that this device would operate as a junction field-effect transistor (JFET).

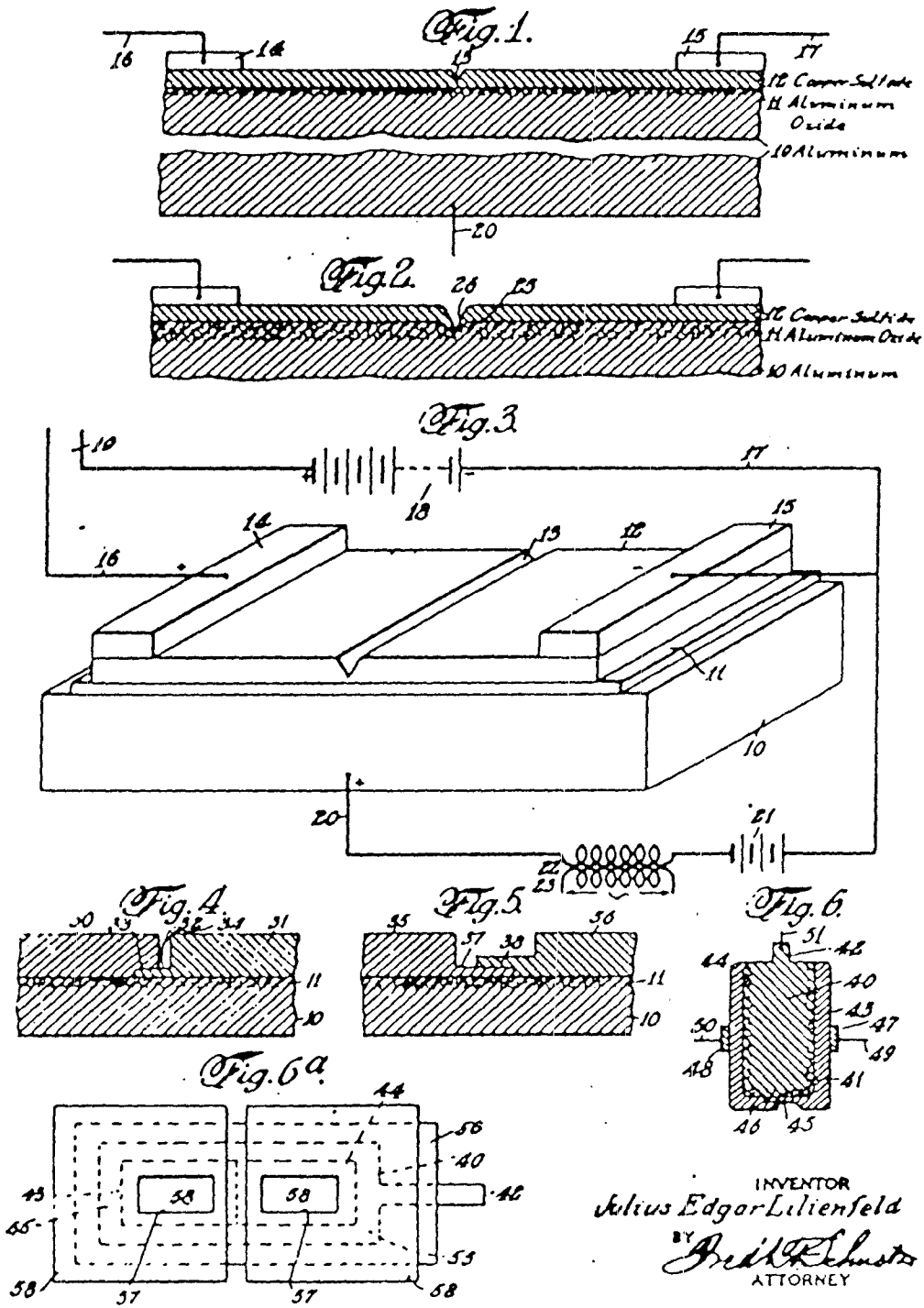
#### U.S. Patent 1,900,018

Titled "Device for Controlling Electric Currents", this patent was filed on March 28, 1928 and granted on March 7, 1933. Again Lilienfeld attempted to make a solid-state analog to the vacuum triode. Here he specified oxidizing a metal such as aluminum, tantalum, tungsten, or magnesium to form an insulating layer on top of the metal. He found that this would provide a strong dielectric; 0.1  $\mu\text{m}$  layers could withstand up to 100 V. Lilienfeld next described depositing a layer such as copper sulfide, copper oxide or lead oxide on top of the insulating oxide layer. Again these layers could be first deposited as metals and later treated to form the desired compound. Also, to provide places for connections, two conductors were to be deposited on top of the conducting layer. Finally, Lilienfeld stressed that a line of

DEVICE FOR CONTROLLING ELECTRIC CURRENT

Filed March 28, 1928

3 Sheets—Sheet 1



INVENTOR  
Julius Edgar Lilienfeld  
BY *Frederick K. Schuster*  
ATTORNEY

Figure 2  
Diagrams from J. E. Lilienfeld's 1933 patent

complete demarcation of approximately molecular thickness be made across the conductive coating. He also stressed the necessity of making the dielectric thin. In this way an extremely high field could be established in the dielectric that could vary the conduction across the line of demarcation in the film. Figure 2 shows Lilienfeld's ideas of the construction of the device and the applicable circuit.

Again Lilienfeld stated that by applying a signal to the base material one could vary the conduction of the coating enough to get an amplified signal in the external circuit. This appears to be the predecessor of the insulated-gate field-effect transistor and the TFT (thin film transistor) of the 1960s. In addition to claims of inventing an amplifier, Lilienfeld claimed rights to a capacitor of high specific capacity, which formed the basis of another patent.

Lilienfeld also discussed a method of making a rectifier. He stated that if the oxide layer was punctured, forming a very small connection between the metallic base and the conductive coating on top of the oxide, then current would flow unidirectionally between the base and the coating. He claimed that this type of rectifier was very reliable, and that the method of connection between the two conductors was a substantial improvement over other dry contact rectifiers. Another interesting note is that Lilienfeld claimed that the oxide coating would often heal itself after breaking down. That is, if the oxide was punctured by a high voltage it would often be able to withstand voltage again if subsequently subjected to a load.

U.S. Patent 1,877,140

Of the three Lilienfeld amplifier patents the device of this patent, titled "Amplifier for Electric Currents", filed on December 8, 1928, and granted on September 13, 1932, perhaps looks the most like a vacuum triode. In fact it is quite similar to the copper oxide device attempted by Shockley and Brattain ten years later. In this patent Lilienfeld sandwiched a layer of metal between two layers of a compound known to produce a high resistance couple to the metal, preferably an asymmetric couple. Lilienfeld stated, "I have found that a very satisfactory amplifier may be constructed with the intermediate layer 12 [see Figure 3] consisting of magnesium, which may be sputtered, condensed or otherwise deposited in a layer upon the surface of one of the outer layers of conducting polarizing compound such as copper sulfide, and the other outer layer of conducting polarizing compound then sputtered or deposited on the opposite uncovered surface of the layer 12."<sup>79</sup> Later in the patent, Lilienfeld suggested sputtering the layers one by one on top of an insulating base material. Foreshadowing the thin film integrated circuits of the sixties he stated, "This [method of forming the devices] will afford a substantial and rugged construction of the amplifier; and it will be appreciated that the completed amplifier will occupy but very small space and a great number thereof may be connected in series in the usual and well-known manner."<sup>80</sup> Lilienfeld pointed out that the inner metal layer should be thin,  $200 \mu\mu$  (it is assumed this means  $2 \text{ \AA}$ ), so that it would be porous. Thus, when the final compound such as copper sulfide was deposited, the deposited layers would fill the pores and make connections through the middle layer.

Sept. 13, 1932

J. E. LILIENFELD

1,877,140

AMPLIFIER FOR ELECTRIC CURRENTS

Filed Dec. 8, 1928 2 Sheets-Sheet 1

Fig. 1.

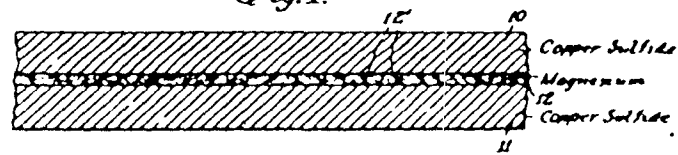


Fig. 2.

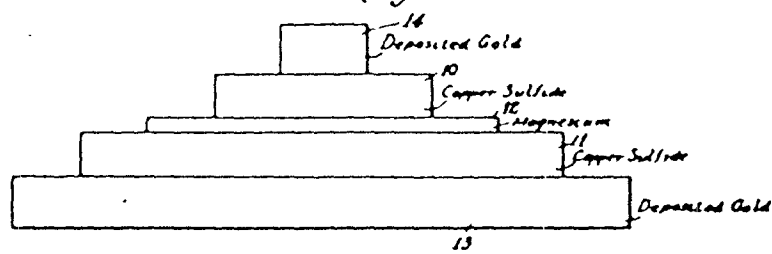


Fig. 3.

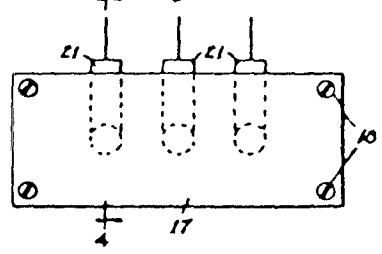


Fig. 4.

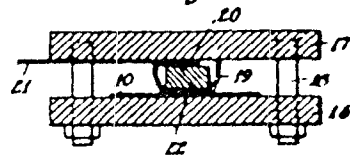
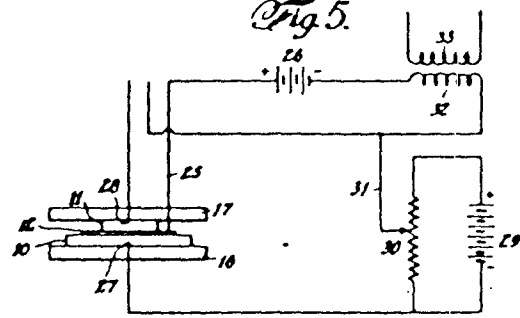


Fig. 5.



INVENTOR  
 Julius Edgar Lilienfeld  
 BY *Frederick Schacht*  
 ATTORNEY

Figure 3  
 Diagrams from J. E. Lilienfeld's 1932 Patent

Thus, the outer layers were connected by small streams of the semiconducting material. The streams, however, passed through a metal that could provide a field to vary conduction between the two outer conductors. Reproductions of some of Lilienfeld's drawings from this patent are shown in Figure 3.

It should be noted that the second patent filed was the third to be granted. For clarity, the patents will henceforth be referred to by their granting dates, 1930, 1932 and 1933.



## Chapter 2

### Experimental

The question of whether Lilienfeld actually made the devices he patented usually surfaces when writers of the history of the development of the transistor mention Lilienfeld's work.<sup>81</sup> In attempting to resolve this question, experimental work was conducted to try to produce a device following Lilienfeld's prescription. Work focused on the 1933 patent for mainly two reasons. The design of this patent is very clearly a type of insulated-gate field-effect transistor. This is conceptually a fairly simple device, and Lilienfeld's design is rather straightforward. The 1933 patent also gives the most detailed description of construction of the three. One difficulty in trying to build one of these devices was deciding what was the most promising process of fabrication given the various processes suggested in the patent. It is probable that if Lilienfeld did make the devices, he did not make them in every way mentioned in the patent but felt that many similar methods would work and wanted his patent to include them.

Below are descriptions of the processes used to make the device specified in the 1933 patent. In all cases an attempt was made to use only techniques and processes that were known to Lilienfeld. Excluded from the following discussion are explanations of the various processes that were attempted but failed to produce testable devices. A brief discussion of these processes is the subject of the final section of this chapter.

### Gate Insulation

Lilienfeld specifies using various metals as a base material on which an insulating layer should be deposited. From his diagrams and from several references throughout the text,<sup>82</sup> aluminum was chosen as the base material on which aluminum oxide was formed as an insulator. Also, around the time that Lilienfeld filed for this patent he was working with oxidized aluminum for electrolytic capacitors.<sup>83</sup>

The simplest way to oxidize just about anything is to heat it in an atmosphere containing oxygen. Unfortunately this forms a very thin, mostly transparent and hardly insulating layer on aluminum. The work on electrolytic capacitors and Lilienfeld's statements in the patent<sup>84</sup> pointed to the process of electrolytic anodization as an appropriate method for oxidizing the aluminum. There is a good deal of literature,<sup>85</sup> including an extensive work by Lilienfeld,<sup>86</sup> on this subject, and the process is fairly simple provided the electrolyte is suitable.

In preparation for anodization, the approximately 30 X 15 X 3 mm pieces of aluminum to be used as anodes were sanded with 180, 400 and 600 grain emery papers. Next, polishing with 5 micron and 1 micron alumina grit followed by a polishing cloth gave the aluminum a mirror like finish. The aluminum was then etched in a bath of hydrochloric, nitric and hydrofluoric acids and deionized water in a concentration of 9:3:2:5 respectively.<sup>87</sup> If all went well the etched aluminum surface would have a smooth but speckled appearance. Sometimes, however, the surface of the aluminum was covered with long, rough striations. These latter samples never produced insulating oxides. The sample was then rinsed in running

water followed by approximately one minute of etching in a dilute solution of hydrochloric acid and deionized water. This was followed by a final rinse in deionized water before placement of the sample in the electrolyte. This rinse was performed in deionized water that was either boiling or at room temperature. There was no noticeable difference in results between these two methods. To facilitate the sample's suspension in the electrolyte, an aluminum strip was spot welded to the sample prior to etching.

The above procedure of polishing and etching the aluminum before anodization was not used universally. The insulating properties of the oxide seemed equally good for samples that were simply well sanded with 600 grain paper and rinsed in running water. Of course the better the polishing the flatter the overall contour of the surface of the oxide.

The aluminum anode and a thin tantalum sheet (3 cm X 6 cm X 100  $\mu\text{m}$ ) for a cathode were then connected to a 500 V direct current power supply and suspended in an electrolyte of Boric acid, 100 g/liter, and Borax, 20 g/liter, in deionized water. This electrolyte is popular in the literature<sup>88</sup> and is listed in varying concentrations. The aluminum was then anodized at constant current,  $\sim 75 \text{ mA/cm}^2$ , to 475 V. The voltage was then held constant and the current let drop until the current remained constant and thus was due to leakage and not formation of the oxide,  $\sim 15 \text{ mA/cm}^2$ . The value of minimum formation current is dependent on the electrolyte used and represents the lowest value of current that will still form an oxide layer. Lilienfeld described this in a 1935 article but used a different electrolyte than under discussion

here. The minimum formation current values for his electrolytes ranged from 0 to 50 mA/cm<sup>2</sup>.<sup>89</sup> The layer formed was grayish, opaque, and fairly rough. The highly polished surfaces possessed an overall smoothness but still suffered from the roughness produced from the anodization process.

With reference to the concentration of the electrolyte, within reasonable limits the exact concentration does not seem to matter very much. In their book on thin films, Robert Berry, Peter Hall, and Murray Harris, state that to avoid corroding the oxide in the electrolyte, aluminum needs to be anodized in an electrolyte with a pH range between about 5.5 and 8.5.<sup>90</sup> This criterion was met by the solution used as well as other solutions of various concentrations. Also, Lilienfeld found that a lower boric acid concentration allowed him to anodize to a higher voltage (up to 800 V) without breaking down the film during formation. However, he shows that for concentrations between 40 and 90 g/liter there is little difference in the resulting capacitance.<sup>91</sup> A more dilute solution was used with moderate success; the breakdown voltage was increased from about 375 V to about 410 V.

This anodization process is relatively easy to perform but is not terribly clean or gentle. There were thus difficulties getting a layer that had good enough insulating properties to remain insulating after subsequent treatments.

#### Semiconducting Coating

Once again Lilienfeld kept his options open when describing the various layers of "substantially more conductive material [than the aluminum oxide]"<sup>92</sup> used to coat

the aluminum oxide. However, his diagrams, references in the text,<sup>93</sup> and known rectifying materials of the time point to copper sulfide. Copper oxide was also known to be used to make rectifiers, but it would probably be difficult to deposit it in that copper would have to be first deposited and then oxidized. Also, in order to get good cuprous oxide, the material used in most copper oxide rectifiers, the copper needs to be oxidized at fairly high temperatures; Grondahl oxidized close to 1040°C. This would cause shorting between the copper sulfide layer and the aluminum gate from either diffusion of the copper through the aluminum oxide or deterioration of the aluminum oxide. Lilienfeld mentions oxidizing copper by treating it with hydrogen peroxide,  $H_2O_2$ ,<sup>94</sup> but this was not attempted.

Between 10 and 250 mg of copper were evaporated onto the oxide in an atmosphere of about  $5 \times 10^{-5}$  Torr. As soon as the sample was taken out of the bell jar of the evaporation system, it was immersed in a bath of carbon disulfide in which sulfur had been dissolved. This sulfurized the copper leaving a thin film of copper sulfide with no doubt varying amounts of oxygen; the sulfurization did not take place under vacuum. If the sulfurization did not take place immediately after the bell jar was raised, the carbon disulfide did a poor job of attacking the copper. This is probably due to a thin, protective layer of oxide that would form on the copper if left too long. After sulfurization, the sample was cleaned in carbon tetrachloride to remove bits of solid sulfur that had not been completely dissolved in the carbon disulfide and had attached themselves to the film.

An alternative method of forming the copper sulfide layer that was used was to simply evaporate powdered copper sulfide onto the aluminum-oxide sample. This was not a method mentioned by Lilienfeld but was felt to be in the spirit of the patent.

Lilienfeld further stressed the need to make a line of "complete demarcation of molecular thickness" in the copper sulfide layer.<sup>95</sup> It is not clear whether he meant a complete but very narrow separation between two layers of copper sulfide or a narrow line that runs across the entire width of the sulfide that makes the sulfide very thin. Both of these designs were attempted in various ways. The first way was to use a razor blade to cut a thin line across the sample. A second method was to first evaporate a very thin layer of copper or copper-sulfide and then mask a portion of this layer before evaporating a thicker layer on top of the first. Widths of 125 and 25  $\mu\text{m}$  were used. In a third method, instead of forming a line that provided a thin layer of copper sulfide, the entire layer was kept thin. Finally, a 25  $\mu\text{m}$  portion of the oxide layer was masked before evaporation to leave a complete separation between two sections of copper sulfide.

To make contact with the copper sulfide, aluminum was evaporated to form two contacts. Three separation widths of these two contacts, which in modern terms form the source and drain, were used: 1.5 mm, 125  $\mu\text{m}$ , and 25  $\mu\text{m}$ .

### Testing

The basic feature claimed by Lilienfeld for this device is that one should be able to vary the conduction through the copper sulfide by applying an electric field

across the oxide. A circuit following the one suggested by Lilienfeld's patent provided a direct current potential applied across the two metal contacts and a load resistor in series. Then another direct current source was connected to one of the metal contacts to the copper sulfide and the other to the aluminum base. This metal contact that is common to both circuits, the source, was grounded. By varying this second (bias) potential both by directly varying the supply voltage and by inserting an alternating current source in series with the bias voltage, modulation of the current through the load resistor could be tested. The test was performed for the four combinations of polarities.

To test for amplification the devices were inserted into a common source amplifier circuit, which is basically the same circuit just described except there are resistors between the second power supply and the drain and between the source and ground. Also, the load was taken off of the drain and thus in parallel with the copper sulfide layer and the source resistor rather than being in series with the drain and the corresponding power supply. See Figure 4. The bias resistor,  $R_b$ , was equal to  $2.2 \text{ k}\Omega$  and the capacitors,  $C_1$  and  $C_2$ , were  $0.1 \text{ }\mu\text{F}$  each. The various other elements of this circuit were varied: supply voltage,  $V_{cc}$ , from 0 to 50 V; bias voltage,  $V_b$ , from 0 to 450 V; source and drain resistors,  $R_s$  and  $R_d$ , from 0 to  $58 \text{ k}\Omega$ ; and load resistors,  $R_l$ , of  $1 \text{ k}\Omega$ ,  $15 \text{ k}\Omega$ ,  $30 \text{ k}\Omega$ , and  $1 \text{ M}\Omega$ . Pressure contacts using lead were made to the aluminum gate, source, and drain.

Finally, the current through and voltage across the copper sulfide layer were varied for different gate biases to obtain current vs. voltage curves for the devices.

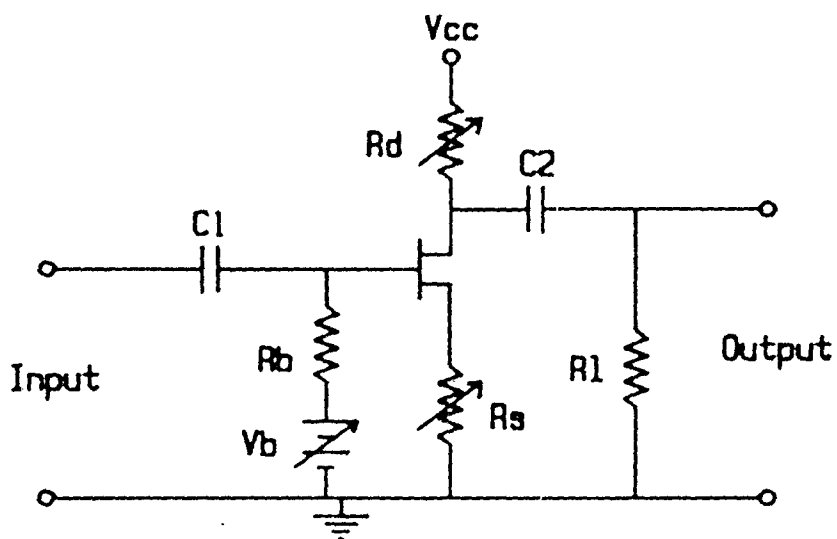


Figure 4  
Common Source Amplifying Circuit

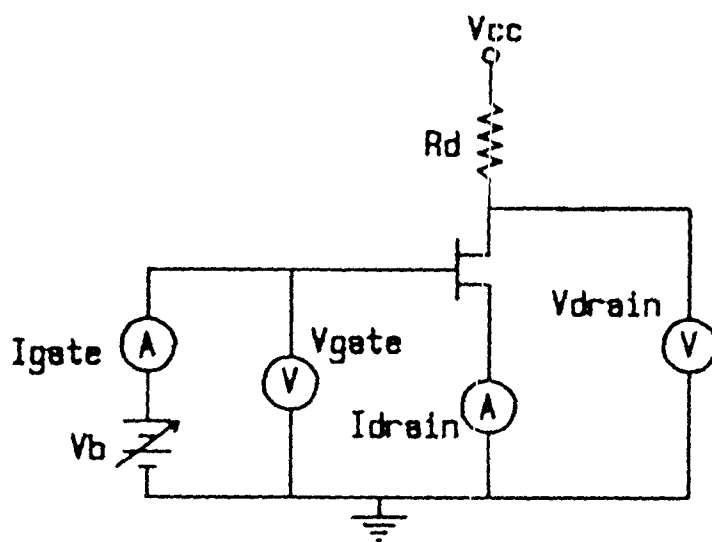


Figure 5  
Circuit Diagram for Obtaining Current vs. Voltage Curves



The circuit diagram is given in Figure 5. The drain resistor,  $R_d$ , was  $2.2 \text{ k}\Omega$ . A curve tracer was not used; the measurements were taken by hand.

In addition to testing the devices to determine if they worked as described in the patent, experiments were performed to gain information about the components of the device. From gate capacitance measurements the thickness of the aluminum oxide was determined. A Dektak, a stylus measuring device, was used to measure the thicknesses of various copper sulfide layers. These layers were deposited both on aluminum oxide layers and on glass. Also, Hall Effect measurements were done to determine the density of carriers and mobilities of the carriers in copper sulfide layers produced by various methods. In order to improve the adhesion of the copper sulfide to the glass substrates used in these experiments, the substrates were "frosted" by wet sanding with 800 grain boron carbide powder (10.5 micron). The sulfide layers were formed by: evaporating copper onto the glass and then sulfurizing the copper by either immersion in a solution of sulfur in carbon disulfide or by heating to  $450^\circ\text{C}$  in a hydrogen sulfide atmosphere; evaporating copper sulfide onto the glass at room temperature; and evaporating copper sulfide onto the glass while the glass was heated to about  $150^\circ\text{C}$ . Hall Effect measurements were attempted at both room temperature and at liquid nitrogen temperatures. The contacts to the copper sulfide layer were pressure contacts with copper, although other metals (tantalum, tungsten, molybdenum, nickel, nichrome) were used with little difference in effect.

Finally, current-voltage characteristics for a diode formed through the oxide layer were obtained.

## Results

### Modulation of Current

During the tests for amplification described above, there was no amplification produced by any of the devices fabricated. Furthermore, it was not possible to vary the conduction in the copper sulfide layer via the applied field, i.e. no field effect was realized. Because of the finite resistance of some of the insulating oxides, some devices allowed sufficient leakage current through the gate to alter current flow through the copper sulfide. This, however, is not a field effect nor could it produce amplification. Also, since the oxide layer forms a capacitor where the aluminum base and the sulfide layer are the two plates, signals were leaked from the gate circuit to the output circuit. At high frequency, 100 kHz, there was low enough reactance such that the output voltage was comparable to the input voltage. Again, this is not amplification or modulation of conductivity in the sulfide layer.

The current-voltage characteristics of the drain for different gate voltages are shown in Figures 6,7 and 8. The figures appear to show some modification of the current-voltage characteristics for different gate voltages. The modification is not large and not predictable. It is believed that at least some of the variation is actually due to heating of the copper sulfide layer during testing. The current flow heats the layer and thus reduces the resistance of the semiconducting layer; this shifts the curve to the left. Therefore, the curves shift to the left as a function of time of operation (amount of heating) not as a function of gate voltage. See Figure 6. This may not be the case in Figure 8. The measurements were made in order of increasing gate

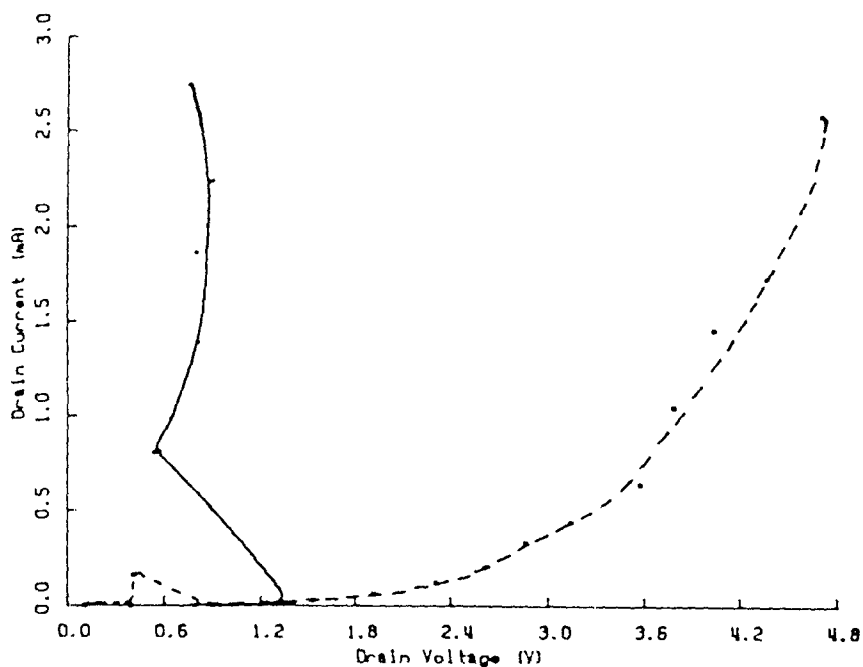


Figure 6

Current vs. Voltage for  $\text{Cu}_2\text{S}$  Evaporated Device

From left to right the gate voltages are 10 V and 6 V respectively.

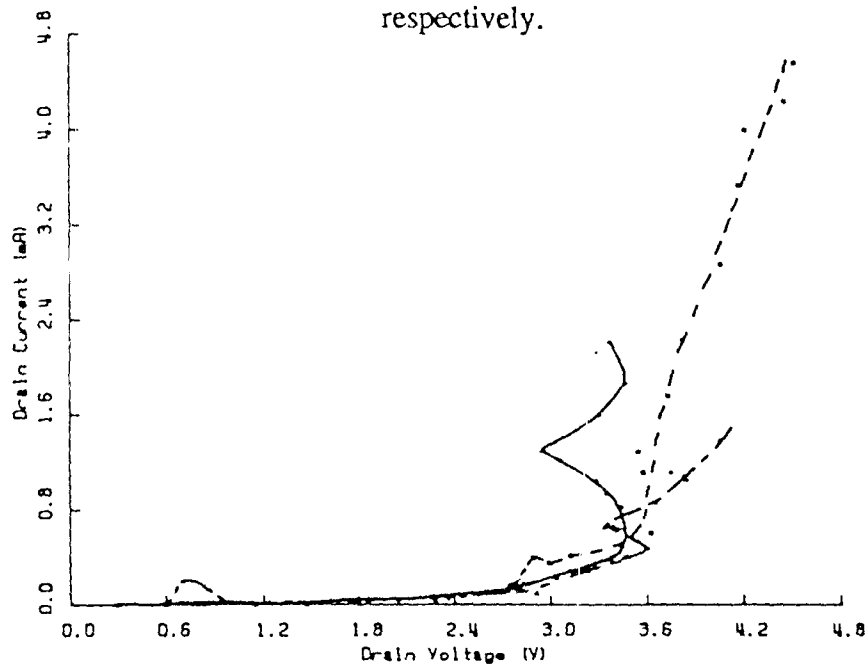
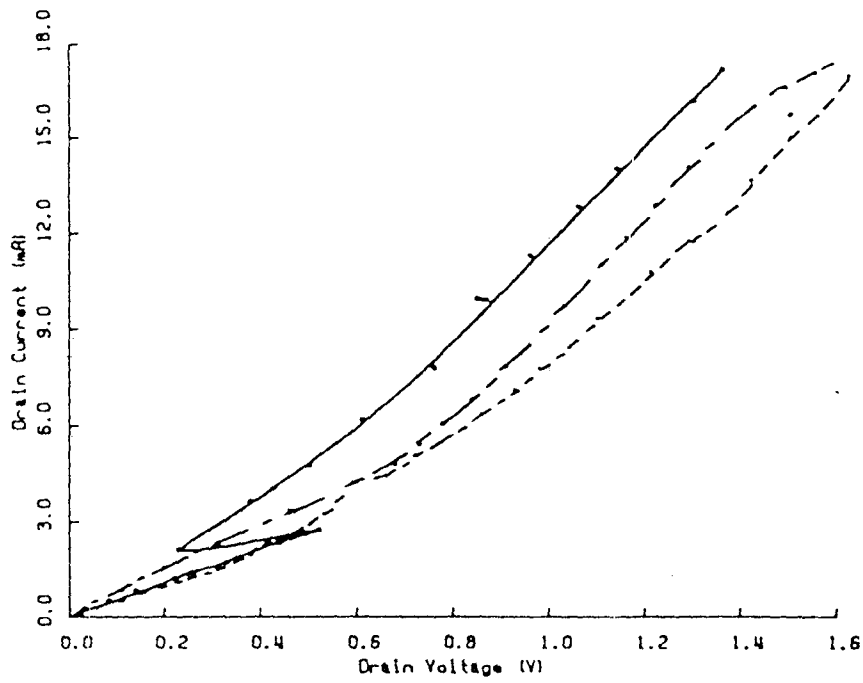


Figure 7

Current vs. Voltage for  $\text{Cu}_2\text{S}$  Evaporated Device

From left to right the gate voltages are 10 V, 6 V, and 8 V respectively. This is the same sample as in Figure 6 at a later time.



**Figure 8**  
**Current vs. Voltage for CS<sub>2</sub> Sulfurized Device**  
From left to right the gate voltages are 2 V, 4 V, and 8 V respectively.

voltage, but it is unclear how good a semiconductor this film was, i.e., whether its resistance would increase or decrease with heating. If there was confidence that heating did not play a significant role (which there is not), it appears the device had a non-negligible transconductance ( $\sim 700 \mu\text{mohs}$ ). The films were very unstable as shown by the fluctuations in the data. The curves extend to the highest voltage possible; above this voltage the current and voltage fluctuated so widely that it was impossible to collect more data.

Often the drain current would suddenly increase, the voltage would sharply decrease, and the gate current would increase. Then, moments later, the values would return to normal. The oxide appeared to be breaking down and then healing. More about the breaking down of the oxide will be discussed later in the paper.

### Component Characteristics

Capacitance measurements were made to determine the thickness of the aluminum oxide layer. An aluminum film was evaporated onto this oxide in a rectangle of area,  $A = 2.16 \text{ cm}^2$ , to form the second plate of the capacitor. These samples had capacitances,  $C$ , in the range 2000-3000 pF. Using a dielectric constant,  $k$ , equal to 10 for aluminum oxide<sup>96</sup> one can calculate the thickness of the oxide layer from the equation

$$C = k\epsilon_0 \frac{A}{d}$$

where  $\epsilon_0$  is the permittivity of free space, and  $d$  is the thickness of the oxide. Since the thickness is much smaller than the dimensions of the area of the capacitor, fringing of the electric field is neglected. This gives a range of thickness between 6 and 10  $\mu\text{m}$ .

The thickness of the copper sulfide layer was much more difficult to obtain. Measurements were made using a Dektak which uses a stylus that runs across the surface of the sample while the machine records a profile of the sample's surface on a strip chart. There were two main difficulties with this process. First, the anodization process for forming the aluminum oxide left the oxide riddled with bumps and pits on the order of a micron deep. Thus, for copper sulfide films thinner than a micron, it was very difficult to see any difference between the profile of just the aluminum oxide and the profile of the copper sulfide coated aluminum oxide. To try and circumvent this problem copper sulfide was deposited on glass. The sulfide did not stick to the glass very well but measurements were made. The second problem was that often the stylus of the Dektak would scratch the film. This caused a great deal of confusion because first the stylus was not raised to the complete height of the top of the film and then was raised erratically because of buildup of the film particles under the stylus. The rough estimate of film thickness from these less than ideal measurements is between 2000 and 3000  $\text{\AA}$ .

To gain some understanding of the nature of the semiconductor being deposited, Hall Effect and resistivity measurements were attempted. The Hall Effect measurements posed many problems. Basically, there was simply too much

uncertainty in the Hall voltage to notice any change in voltage when the sample was introduced to a magnetic field. The uncertainty was usually about 1 mV when Hall voltages on the order of tens or hundreds of microvolts were expected. It was also difficult in the more resistive films to get a high enough current to flow without destroying the film. The circuit diagram of the Hall experiment is shown in Figure 9. Contacts were made with copper strips at either end of the sample and four copper point contacts as Hall probes. Other metals were tried for the end contacts but no significant change in current for a given voltage was noticed. The measurements were also made at liquid nitrogen temperature, but with no success.

To gain a lower limit of the density of carriers,  $n$ , it is assumed that the Hall voltage is less than the uncertainty of measurement,  $\sim 1$  mV. This is applied to the particular measurement where the current was highest, i.e., where one would expect the Hall voltage to be highest. The expression for the Hall Voltage is

$$V_H = \frac{BI}{nqt}$$

The experiment used 0.8 Tesla for the magnetic field,  $B$ ; 300 mA for the current,  $I$ ; and  $1 \mu\text{m}$  for the thickness,  $t$ . With these values the lower limit of  $n$  is  $1.5 \times 10^{19} / \text{cm}^3$ .

During the Hall effect measurements the resistances of the films were measured to provide comparison between the different methods of forming the sulfide layer. These measurements gave approximate resistivities for the films that should not to be compared with known resistivities of bulk material, i.e., the resistivities were not

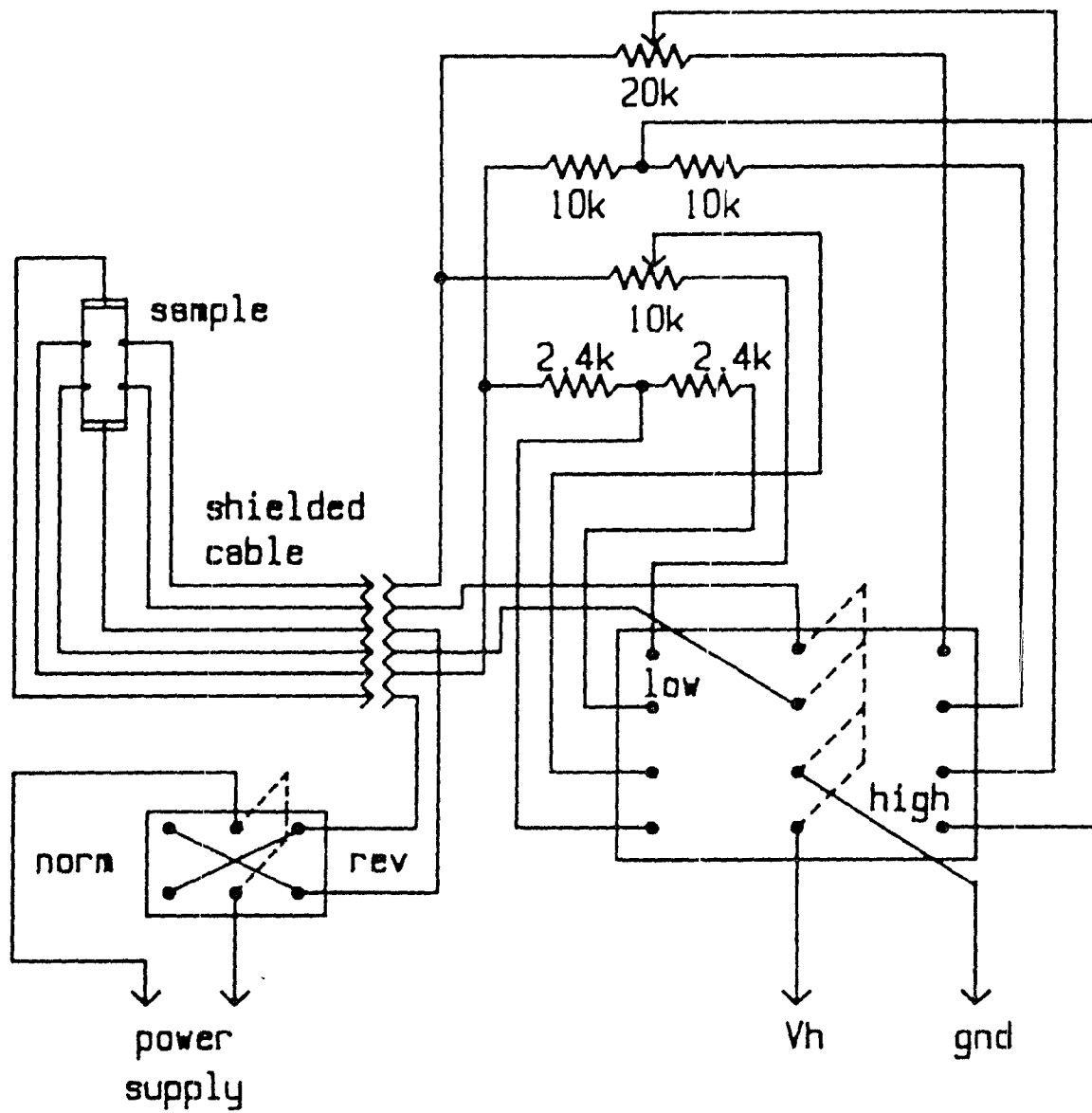


Figure 9  
Circuit Diagram for Hall Effect



corrected to account for the thickness of the films. The films formed by evaporating  $\text{Cu}_2\text{S}$  had the highest resistivities, from 300 to 1000  $\Omega\text{-cm}$  at room temperature, and about 0.2  $\Omega\text{-cm}$  after several minutes of heating from current flow. If during evaporation of  $\text{Cu}_2\text{S}$  the glass was heated to about  $150^\circ\text{C}$ , then the films looked much more homogeneous and metallic but had resistivities approximately the same, 300 to 600  $\Omega\text{-cm}$  at room temperature. When copper was evaporated and then sulfurized in  $\text{CS}_2$ , the formed films had resistivities around  $2 \times 10^{-3} \Omega\text{-cm}$ . The films formed by evaporating copper and then sulfurizing in  $\text{H}_2\text{S}$  had resistivities between  $4 \times 10^{-4}$  and  $9 \times 10^{-4} \Omega\text{-cm}$ . For comparison's sake a thin copper film had a resistivity of  $8 \times 10^{-5} \Omega\text{-cm}$  at room temperature.

When the samples were submerged in liquid nitrogen, only the films formed by evaporating  $\text{Cu}_2\text{S}$ , both when the substrate was heated during formation and when it was not, showed a significantly negative temperature coefficient of resistivity. These films increased in resistivity from that listed above to greater than  $3 \times 10^5 \Omega\text{-cm}$ . The other types of films showed little change in resistivity when cooled to liquid nitrogen temperatures. Although, the resistivity for one film formed by sulfurizing copper in  $\text{H}_2\text{S}$  dropped by a factor of two. This is not the direction one would expect for a semiconductor.

The method of obtaining these resistivities was simply to measure the current though and voltage across the film and the film size. There are of course problems here in that the thicknesses of the films are not known exactly, but it is believed that all of the films spanned approximately the same range of thicknesses, from thin films

of 2000 Å to thick films of 1 μm. There are also uncertainties about the contacts. For the more conductive films this is not a problem. However, the films where Cu<sub>2</sub>S was evaporated have high resistance and negative temperature coefficients, indicative of semiconductors. Furthermore, it is believed the films are p-type, since pure Cu<sub>2</sub>S was evaporated. Thus, the metal contacts could significantly limit the amount of current one was able to put through the film for a given voltage due to one Cu<sub>2</sub>S contact being reverse biased. Little quantitative detail about these films was learned from the Hall effect and resistivity measurements. However, qualitative conclusions can be made. The films formed by sulfurizing an evaporated copper film are not semiconductor like, whereas the films formed by evaporating Cu<sub>2</sub>S have characteristics of a semiconductor.

#### Diode Characteristics and Oxide Healing

As noted above, if a voltage that was a few volts greater than the gate voltage was applied to the drain (or source) of one of the devices, the oxide would begin to break down. This phenomenon was not stable and would sometimes cease. If the breakdown occurred, a diode was formed between the drain (or source) and the gate. Some current-voltage characteristics of these devices are shown in Figures 10, 11, 12, and 13.

This phenomenon was discovered when testing a device for amplification in a common source amplifier circuit. After the drain voltage was increased to a certain point, the output would change from a signal significantly less than the input to a

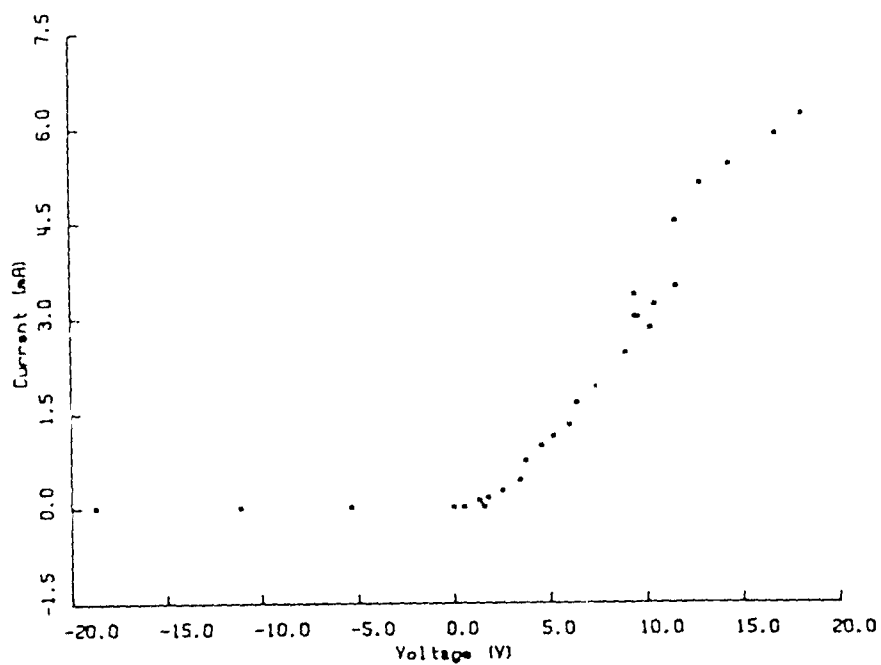


Figure 10  
Current vs. Voltage for  $\text{Cu}_2\text{S}$  Evaporated Diode

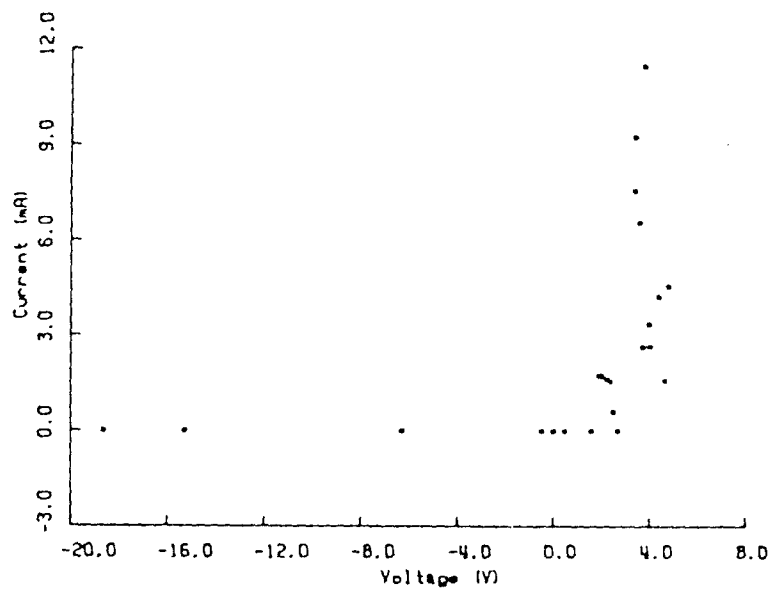


Figure 11  
Current vs. Voltage for  $\text{Cu}_2\text{S}$  Evaporated Diode

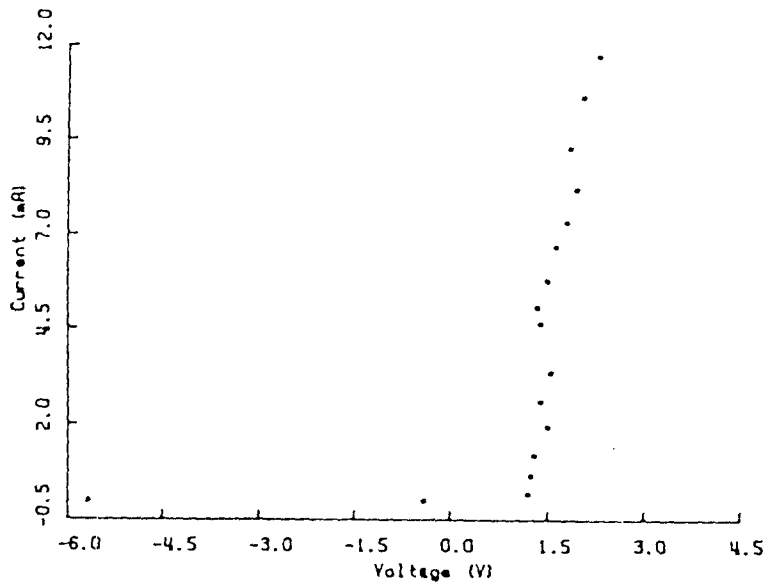


Figure 12  
Current vs. Voltage for CS<sub>2</sub> Sulfurized Diode

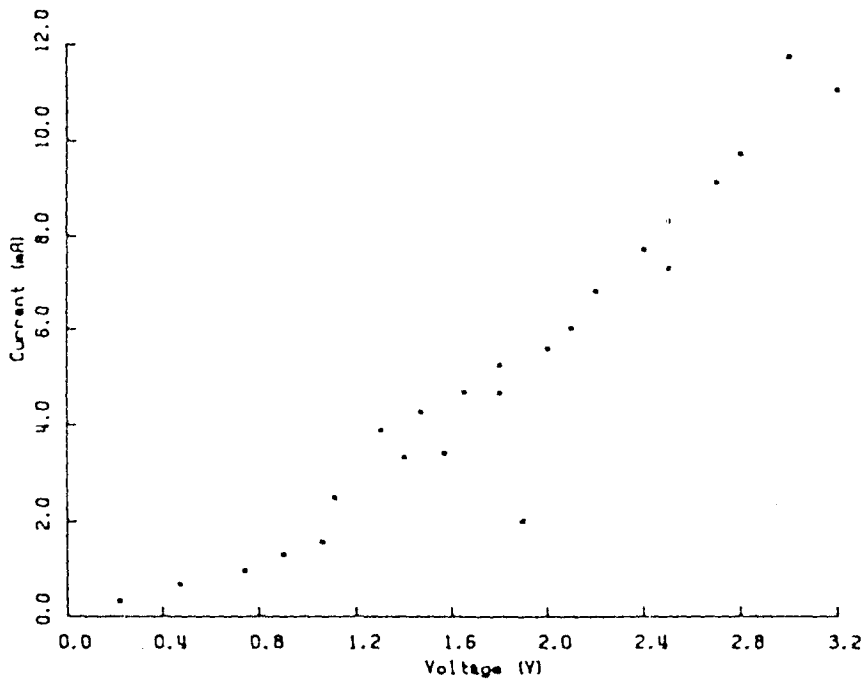


Figure 13  
Current vs. Voltage for CS<sub>2</sub> Sulfurized Diode

signal the size of the input. The amplitude of this signal could then be varied such that the signal could be clipped. The initial small output signal was due simply to leakage of the input signal across the capacitor. When the signal increased to the size of the input, the capacitor must have been breaking down, forming a connection between the input and output circuits. This connection was a rectifying one, however, and thus allowed clipping of the input signal.

The diode was then connected in a circuit shown in Figure 14 to test its rectification abilities. By varying the bias voltage, the signal could be rectified to various degrees. The frequency response of this device was low however. Above 600 Hz the signal became very distorted. Also, there appeared to be a significant forward resistance through the diode. The diodes that clipped well still had a forward resistance on the order of 1 to 10 k $\Omega$ .

This diode has a curious feature in how it turns on and off. The bias voltage essentially operates a switch and controls the level of rectification by the diode. The switch is the oxide layer. If the bias voltage is not high enough, the device does not operate as a diode. The oxide is insulating at this point and thus does not allow connection between the aluminum base and the copper sulfide layer. When the bias is increased to a sufficient level, the oxide breaks down, placing the diode in the circuit. At this point the device acts as a diode and will clip incoming signals. If the bias is then reduced, the oxide resumes its insulating properties, and the device returns to being a capacitor. Thus, it appears that the oxide has the ability to heal itself after being punctured by a high electric field. This effect of oxide healing is shown in

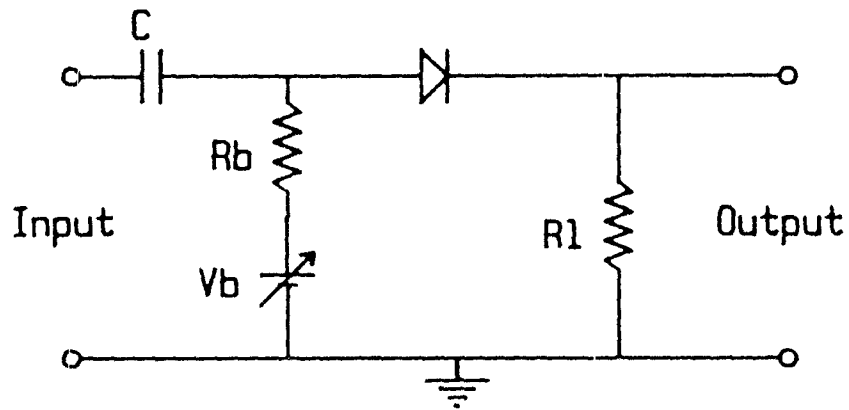


Figure 14  
Circuit Diagram for Signal Rectification

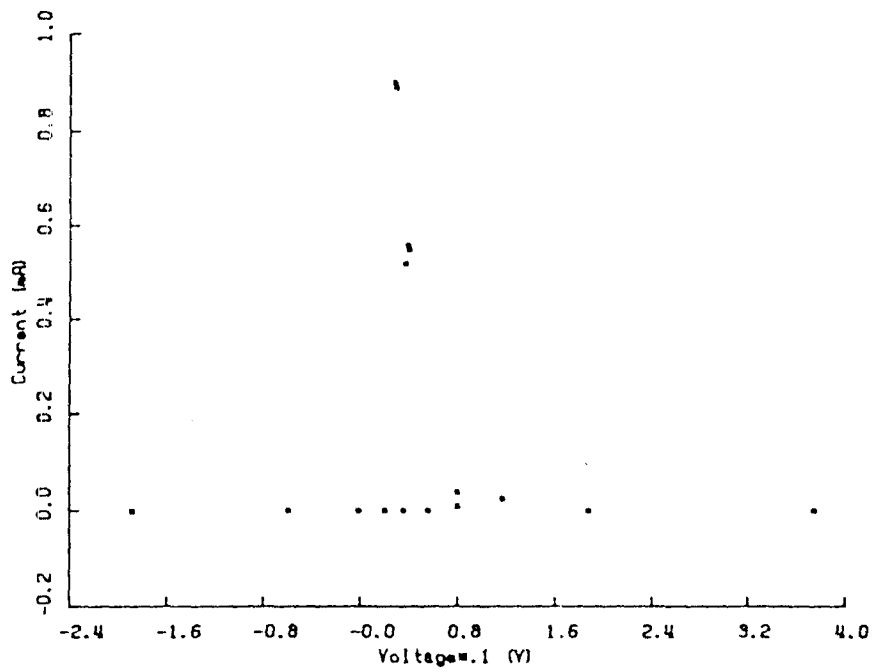


Figure 15  
Oxide Healing

Figure 15. This time the oxide healed itself at a substantial voltage and remained insulating to higher voltages (37.5 V was the highest it was taken, and the diode was still insulating.)

### On Other Fabrication Processes

As mentioned earlier, Lilienfeld's patents, like many patents in general, were decidedly, perhaps purposefully, vague in their descriptions of the specific process used to obtain the devices. Thus, this project explored many different processes until a set of procedures was arrived at that consistently produced testable devices closely resembling those described by Lilienfeld. This section describes the various processes that were attempted but for one reason or another were not useful.

#### Gate Insulation

Initial attempts at forming an aluminum oxide layer simply by heating the aluminum to near melting temperatures, 660°C, did not produce insulating layers. They were thin, transparent, and not insulating. The process found to produce insulating layers was that of anodizing the aluminum in an electrolyte. Certain parts of this process caused problems however.

It was unclear how much surface preparation was needed to produce the best oxide layers. The surface of the aluminum was polished in varying degrees, from sanding with 600 or 400 grain emery paper to polishing with 5 and 1 micron alumina grit and then a polishing cloth. This produced noticeable differences on the surface of

the aluminum as did it affect an overall smoothness of the oxide layer, but it did little to curb the bumpiness produced by the anodization process itself. Layers oxidized to 375 V were smooth and mostly transparent, but were not good insulators. Oxides anodized to voltages between 375 and 450 V showed signs of a roughness from the anodization, were not very transparent and were insulating for pressure contacts. However, once a copper layer was evaporated onto these films, they were usually short circuited. Only the samples anodized to voltages greater than 450 V, 475 V to be safe, were still insulating after evaporation of a metallic film on top of the oxide. However, there was the problem of bumpiness of the oxide layer regardless of the smoothness of the underlying layer. From the Dektak measurements and microscope observations, bumps on the order of microns were present. Therefore, the semiconductor was deposited on a rather rough surface, a surface with bumps deeper than the thickness of the semiconducting coating.

During anodization at voltages above 375 V, sparking at the oxide surface occurred. The roughness of these higher voltage films was no doubt a function of this sparking, and it was most disconcerting to try and produce an insulating film that appeared to be constantly breaking down during formation. However, films that were formed below 375 V, so that no sparking occurred, were just not usable as insulators.

#### Sulfurization of Copper Coating

After the copper layer was deposited on top of the aluminum oxide, the copper was sulfurized. Initial attempts to convert the copper films to copper sulfide consisted



of immersing the sample in sodium disulfide. Sodium disulfide is known to attack copper to form copper sulfide, but it did a poor job here. Most films would show some sulfurization, but often only on the surface, not throughout the film. Sodium sulfide also attacks aluminum and would quickly form bubbles under the copper film which would float the film off the aluminum base before the copper was adequately sulfurized. Having an aluminum oxide layer over the aluminum seemed to slow this deterioration, but again the copper films were not sufficiently sulfurized.

The next attempts to sulfurize copper took place while attempting to produce copper sulfide rectifiers. A solid piece of copper was sprinkled with sulfur and heated to 450°C. Not surprisingly this produced a messy, pitted, partially oxidized, useless sample. A gentler approach was to encapsulate a piece of copper and some ground sulfur in an evacuated tube. This was then heated. Devices cooked to 450°C were highly pitted with silvery black films that cracked and easily brushed off of the copper. Films formed at temperatures between 150 and 200°C also flaked off and slightly pitted the copper. If the copper was left at room temperature or heated to less than 110°C, it was not pitted, the film was bluish, but it still cracked and easily flaked off of the sample. These films were not adequate.

Probably the best way to sulfurize copper is to heat it in an atmosphere of hydrogen sulfide. Cooking below 400°C forms layers of both cupric sulfide,  $\text{CuS}$ , and cuprous sulfide,  $\text{Cu}_2\text{S}$ . Above 400°C one obtains pure cuprous sulfide.<sup>97</sup> This process produced smooth, silvery, bluish gray films. The problem was that to form devices, copper films were deposited on an aluminum oxide layer that needed to

remain insulating. Invariably heating the samples to 450°C would cause the film to short the aluminum oxide. It is not known whether the copper, or copper sulfide, diffused through the oxide, or if weak spots in the oxide upon heating caused holes to form which allowed contact between the copper sulfide and the underlying aluminum.

Lilienfeld mentioned using copper oxide as a film as well. He suggested "spattering" copper onto the aluminum oxide layer with a certain amount of atmosphere present so that the copper was oxidized somewhat during the evaporation.<sup>98</sup> This was attempted with little success. The copper did not evaporate well if there was an atmosphere present. The film formed was black like cupric oxide, not the type desired, and powdery; it easily brushed off.

## Chapter 3

### Physical Analysis

#### Obtaining Field-Effect

As stated earlier, the device described in Lilienfeld's 1933 patent is what would now be called an insulated-gate field-effect transistor. It also resembles a MOSFET (metal-oxide-semiconductor field-effect transistor) in construction but differs in operation. An advantage of both of these types of devices is the very high input impedance. This impedance is seen by input to the gate and is from the insulating oxide coating on the gate metal. The gate electrodes produced for this project saw resistances from the aluminum oxide around  $20\text{ M}\Omega$  and capacitances around  $2000\text{ pF}$ . This oxide coating is designed to be very thin so that an applied voltage produces a very high field at the surface of the semiconductor which lies on top of the aluminum oxide. For oxides on the order of a micron the field is on the order of  $10^6\text{ V/m}$ . The intent of producing this very high field is to use it to vary the conduction in the semiconducting coating adjacent to the oxide. This is analogous to a vacuum tube where the gate acts as the grid and the two contacts to the semiconductor, called the source and drain, provide a direct current much like the cathode and anode, or plate, of a vacuum triode do. In both devices the field from the small input signal varies the conduction of the output circuit and thus the current flowing through it such that the signal can be amplified.

It appears that Lilienfeld imagined conduction in a solid to be determined in part by the alignment of dipoles, the polarized parent atoms of the free electrons

moving about the solid. Thus, a strong field applied to a poor enough conductor could orient these dipoles such to impede or enhance electronic conduction. The analogy between the vacuum tube and the solid-state amplifier cannot be carried this far however. To control the conduction in the semiconducting layer, one must be able to vary the number of carriers in the semiconductor rather than to electrostatically alter the flow of the carriers present as the analogy with the vacuum tube suggests.

In the insulated-gate field-effect transistor the number of carriers is varied near the junction between the semiconductor and the insulator, in the present case the aluminum oxide. Figure 16 shows a typical band diagram for a metal-oxide-semiconductor capacitor. Referring to the figure,  $E_{fm}$  and  $E_{fs}$  are the electrochemical potentials of the metal and semiconductor respectively,  $E_{fi}$  is the intrinsic electrochemical potential of the semiconductor,  $E_v$  and  $E_c$  are the top and bottom of the valence and conduction bands of the semiconductor, and  $w$  is the width of the depletion region. Because of the difference in the work functions and the chemical potentials (together these two quantities form the electrochemical potential) of the metal and the semiconductor, the energy bands are bent when the two are brought together. Since the carriers see different potential energies in the two different solids, there is a force that rearranges the carriers until the potentials are equalized. This rearrangement of carriers forms a space charge region in the semiconductor at the boundary between it and the oxide.

For a p-type semiconductor, as Figure 16 shows, the bands bend downwards from the semiconductor towards the junction. Electrons then have a lower energy or

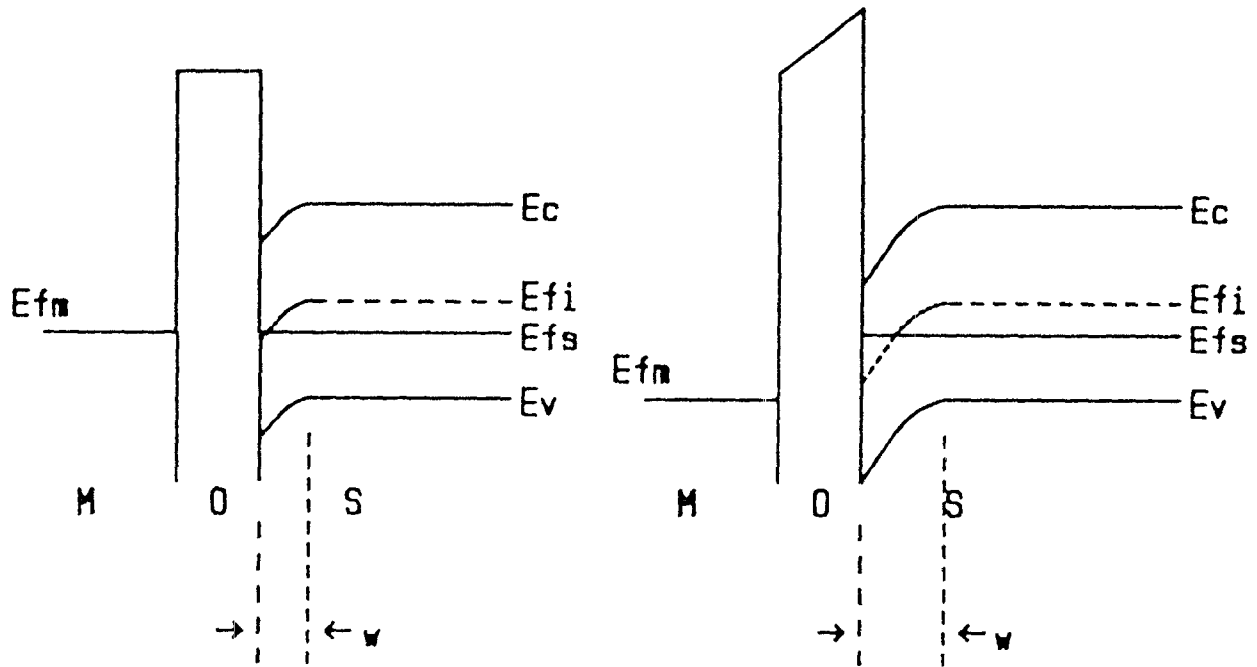


Figure 16: a) b)

**Band Diagram for MOS Capacitor**

In Figure 16 a) there is no bias. In Figure 16 b) there is a bias such that the metal is positive. In both cases the semiconductor is p-type.

are more bound near the oxide. For holes, the carriers in the present discussion, this represents a potential hill. This region is also a place depleted of free carriers, called the depletion region. The holes have been pushed away from the junction by the difference of potential energies of the metal and semiconductor. If a voltage is placed across the junction such that the metal is positive, then the holes will be driven farther away from the junction leaving negatively ionized acceptor atoms to balance the positive charge on the gate. This causes the depletion region to widen. If the bias voltage is very large then eventually electrons make it to the junction such that an inversion layer forms at the surface of the semiconductor.

Now, if the semiconductor is very thin, the depletion region can be made to stretch far enough across it to cut off or at least control the amount of current that can pass through the semiconductor. The ability to control the current then is dependent on two things: the width of the depletion region and the thickness of the semiconductor. The depletion region width is dependent on the number of carriers in the semiconductor and the electric field present at the junction. The relationship between these three quantities can be found by solving Poisson's equation.

To solve this equation a standard simplification called the depletion approximation will be used. This approximation assumes that at the edge of the depletion region the number of free carriers makes an abrupt change from the depletion concentration, where the number of holes and the number of free electrons equals zero, to that of the bulk material. The change is actually more gradual than this and about a Debye length wide. However, the Debye length is inversely

proportional to the square root of the doping concentration, which in the present investigation appears to be high, so the Debye length is small. Also, we are not concerned with the exact shape of the depletion region but only in obtaining a rough idea of how thick the semiconducting layer needs to be to affect the current flow through the semiconductor. For these reasons use of this approximation seems reasonable. So, Poisson's equation becomes

$$\frac{d^2\phi}{dx^2} = -\frac{n_d(x) - n_a(x)}{\epsilon_0},$$

recalling that in the depletion region the donor atoms,  $n_d$ , are ionized so that they are positive, and the reverse is true for the acceptor atoms,  $n_a$ . As a further simplification it is assumed that the material is doped uniformly with acceptor atoms only. This may be stretching it a little but why not; little is known about the sulfide layer, and no attempt was made to provide any sort of gradient in the dopant concentration. The equation can be rewritten as

$$\frac{d\phi}{dx} = \frac{qn_a}{\epsilon_{sc}} \int_w^x dx,$$

where  $w$  is the edge of the depletion region. Thus the electric field is given by

$$E(x) = \frac{qn_a}{\epsilon_{sc}} (x-w),$$

and at the surface of the semiconductor,  $x = 0$ ,

$$E_s = \frac{qn_a w}{\epsilon_{sc}}$$

Now, integrating

$$\int_0^{\varphi(x)} E(x) dx = \frac{qn_a}{\epsilon_{sc}} \int_w^x (x-w) dx$$

to find the potential at the semiconductor surface, we get

$$\varphi(x) = \frac{qn_a}{2\epsilon_{sc}} (w-x)^2.$$

This equation will be used later.

To find the voltage necessary to completely deplete the width of the semiconductor, called the pinch-off voltage, the expression for the electric field at the surface of the semiconductor will be used. If the electric field in the oxide is constant then to achieve a field  $E_s$ , one needs to apply to the metal-oxide contact a voltage of

$$V = E_s d,$$

where  $d$  is the thickness of the oxide. Therefore, for a semiconductor of thickness  $t$ , the expression for the pinch-off voltage,  $V_p$ , is

$$V_p = \frac{qn_a}{2\epsilon_{sc}} t d.$$

For the dielectric constant of copper sulfide the value of 15 will be assumed. This value is somewhat arbitrary but within the limits of most semiconductors ( $\epsilon_{sc}$  is then  $1.3 \times 10^{-10}$  F/m). Thus, for the already determined values of  $n_a = 1.5 \times 10^{19}$  /cm<sup>3</sup>,  $t = 2500$  Å, and  $d = 8$  μm the pinch-off voltage is 18 kV! This is a rather high pinch-



off voltage, much too high to be withstood by the aluminum oxide layer. The above equation can be turned around to see what sort of thickness is needed to obtain a reasonable pinch-off voltage, say 5 V. Using

$$t = \frac{2V_p \epsilon_{sc}}{qn_a d}$$

and the above values, one obtains a thickness of 0.7 Å. This is certainly "of molecular thickness" as Lilienfeld prescribes, but awfully difficult to obtain. These values are of course very dependent on the various values of thickness and the number of carriers. Reducing the number of carriers by an order of magnitude and making the oxide thinner by an order of magnitude increases the needed thickness of the copper sulfide layer to about a hundred atomic layers rather than one.

For completeness, although it does not play a role here, it should be mentioned that there is a maximum depletion width. If the bias voltage across an MOS capacitor, that has a depletion region already formed, is increased, then an inversion layer will form at the surface of the semiconductor. That is, free electrons find their way to the surface. These carriers effectively shield the depletion layer from any additional increase in applied field. To calculate this maximum depletion width, the equation for the potential as a function of  $x$  in the depletion layer will be used. To solve the equation it is assumed that inversion takes place when the band bending is equal to twice the difference between the doped semiconductor electrochemical potential and the semiconductor's intrinsic electrochemical potential,  $\phi_b$ . At the surface  $x = 0$ , and thus the surface potential is given by

$$\phi_b = \frac{qn_a}{2\epsilon_{sc}} w^2.$$

Therefore, the maximum depletion width,  $w_{\max}$ , is given by

$$w_{\max} = \sqrt{\frac{4\epsilon_{sc}\phi_b}{qn_a}}.$$

Now, if  $\phi_b$  is set equal to 0.3 eV/q, which is one fourth of the band gap of  $\text{Cu}_2\text{S}$ ,  $w_{\max}$  equals 81 Å. This does not pose a problem in the above example, but it is easily seen that the high number of carriers,  $1.5 \times 10^{19} / \text{cm}^3$ , causes great difficulty in achieving a field effect both from the standpoint of  $w_{\max}$  and the pinch-off voltage. A more detailed description of the above treatment can be found in Nicollian and Brew's, *MOS (Metal Oxide Semiconductor) Physics and Technology* from which the above development was taken.<sup>99</sup>

The above description does not include the problems pointed out by John Bardeen when Bell Laboratories was trying to make a field-effect transistor. These are the problems of surface states. The surface of a solid changes the nature of the electronic wave functions of the bulk of the solid. This creates energy states present at the surface that are not present in the bulk. Thus, the energy band diagram shown in Figure 16 does not show the whole picture. Actually, there are many states lying within the gap in the semiconductor. The number of states depends on the geometry at the surface, the number of carriers in the semiconductor, the impurities that might be present at the surface, etc. Surface states pose problems because carriers can get

trapped in these states. This can both limit the number of carriers available and shield applied fields.

The situation is further exacerbated by the fact that copper sulfide is polycrystalline. This poses many of the same problems as surface states, but the problems exist throughout the semiconductor, not just at the surface. The traps from the many crystallites could also affect the mobility of the carriers and limit, for example, the frequency response of the device. How these problems affect the properties of the devices made during the work on this paper is not quantitatively addressed. The above remarks are intended only to provide a caveat to the discussion preceding them. The technological problems posed by semiconductors and especially evaporated, polycrystalline semiconductors are complex. But they are not unsurmountable. Practical, evaporated, thin film polycrystalline transistors with designs strikingly similar to Lilienfeld's were developed in the 1960s by Paul Weimer and others.<sup>100</sup>

### The Diode

In his 1933 patent Lilienfeld discussed a rectifier formed by puncturing the oxide layer of an oxidized piece of aluminum and on this depositing copper sulfide or some like compound.<sup>101</sup> Experimentation has shown that producing this type of rectifier is possible.

It appears that this diode works similarly to a cat's whisker rectifier. Assuming that rectification was taking place between the copper sulfide layer and the

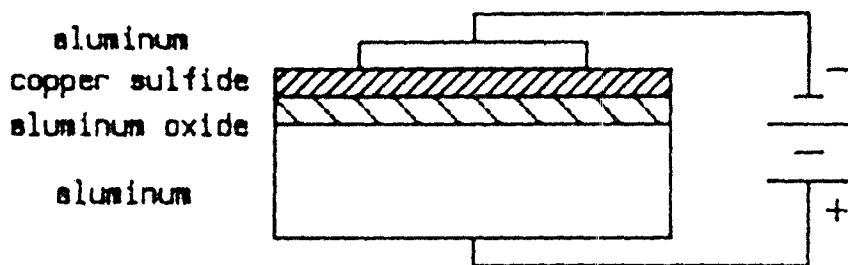
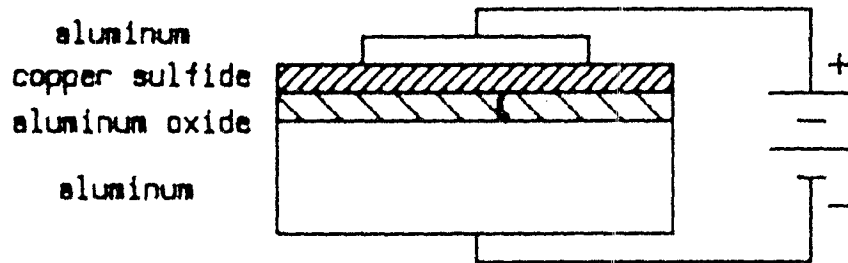


Figure 17  
Schematic of the Diode  
Note the puncture in the oxide of the upper diagram.

aluminum film deposited on top of it, and assuming p-type copper sulfide, forward bias would occur when the copper sulfide was positive and the aluminum negative (See Figure 17). However, observed rectification was in the opposite direction.

If, however, the aluminum base forms a point contact with the copper sulfide - for instance, if the oxide is punctured by a high applied field - then the applied bias would be in the opposite direction. The forward bias would still take place when the copper sulfide was positive and the metal point contact was negative, but in the latter case the metal contact is on the other side; this gives the observed direction of rectification. Since both scenarios have the same materials, it must be the point contact that aids in rectification, so rectification takes place at the aluminum point contact rather than the comparatively large area aluminum contact, and thus, the device is essentially a cat's whisker rectifier.

The fact that there are two copper sulfide-aluminum contacts explains the internal resistance of the diode. When the diode is forward biased the point contact is forward biased but the large area aluminum contact is reversed biased. Having a reversed biased junction is unavoidable for this type of design and significantly adds to the internal resistance of the device, although this resistance would vary with bias.

## Chapter 4

## Conclusions

Since the beginning inquiries into the role of Julius Lilienfeld in the development of the transistor, the importance of his contribution has been unclear. This paper has shown that Lilienfeld's designs were the first attempt at replacing the vacuum triode with a solid state device. Also, with his 1933 patent he was the first to conceive of the insulated-gate field-effect transistor. Although experiments to determine if these devices worked as described failed to show amplification, they lend plausibility to the claim that Lilienfeld indeed performed experiments to test these devices and was not simply patenting an idea. This is evident from the fact that the diode Lilienfeld discussed worked as described. Also, the effect of oxide healing was observed.

As added evidence in support of the claim that Lilienfeld did not simply patent an idea reference is made to Lilienfeld's circuit diagram in the 1933 patent, specifically to the polarity with which he biases the gate electrode. Since it is clear that Lilienfeld was attempting to produce a solid state analog to a vacuum triode, one would expect him to bias the gate, or grid, at a lower potential than that of the source, or cathode, in this voltage amplifier, grounded source, circuit. The polarity he chooses is the opposite of this and is the proper polarity for depleting a p-type semiconductor, such as cuprous sulfide, at the semiconductor surface.

As evidenced by the explanations given in the patents, it does not appear that Lilienfeld completely understood the nature of his devices. To be fair a deep

understanding of conduction in solids did not exist in the mid 1920s. At this time it is likely that P. Drude's theory of 1900 was still the model for conduction in solids. In this theory Drude applied the kinetic theory of gasses to the free conduction electrons in solids. It is not clear how Lilienfeld's ideas of "bipoles" affecting conduction fits with the theories at the time, as no reference to this concept has been found. The first application of quantum mechanics to conduction in metals was by A. Sommerfeld in 1928. F. Bloch tackled the quantum mechanical problem of the motion of an electron in a periodic potential also in 1928, but the first satisfactory quantum mechanical treatment for semiconductors did not appear until A. H. Wilson faced the problem in 1931. Despite the lack of understanding of the time, Lilienfeld recognized the need to make the semiconductor very thin, the need to use a thin insulator to obtain a very large field at the surface of the semiconductor and the importance of obtaining a suitable semiconducting layer, a layer of "substantially greater conductivity than the dielectric"<sup>102</sup> as he called it. Lilienfeld also appears to have been an excellent experimentalist having many successes in various areas.

In addition to being the first to design and patent a field effect transistor, it appears that Lilienfeld was the first to specify the method of "sputtering" or evaporating metallic films in the fabrication of solid state devices. His statements in his 1932 patent clearly foreshadow the thin-film integrated circuits of the 1960s.<sup>103</sup>

Great strides were made towards the understanding of semiconductors in the two decades after Lilienfeld patented his devices. Tremendous improvements in the ability to fabricate semiconductors also occurred during this time. Thus, it is not

surprising that the materials specified in the patents suffer from many limitations. It appears that the methods for sulfurizing copper suggested by Lilienfeld produce tenuous semiconductors at best. However, it must be stated that the wet chemistry and different degrees of vacuum used by Lilienfeld lead to processes that involved a great deal of art. Therefore, it is impossible to determine exactly what Lilienfeld did. Evaporation of  $\text{Cu}_2\text{S}$  produced films that showed high resistivity and negative temperature coefficients characteristic of semiconductors, but these films were still unstable. This method of producing a copper sulfide layer was not mentioned by Lilienfeld despite availability of the necessary technology.

Given the methods of formation, it is probable that the devices envisioned by Lilienfeld would also suffer from surface state problems. It is not clear, however, whether these problems would have made fabrication of workable devices impossible. Finally, the high resistivity of the evaporated  $\text{Cu}_2\text{S}$  films suggest low mobility and low frequency response for the devices. For the above reasons it does not appear that the device patented in Lilienfeld's 1933 patent would have been practical.

Despite Lilienfeld's foresight, he has been given little recognition. In fact before Bottom's article in 1964, Lilienfeld's work on producing a solid state amplifying device was not mentioned. Bell Laboratories knew of Lilienfeld and his patents but failed to mention either in their announcements of their invention of the point-contact transistor. However, by the late 1940s scientists probably would have felt little responsibility to reference patents in scientific literature. Also, in his announcement article of the thin film insulated-gate transistor in 1962, Paul Weimer



claimed that Heil was the first to conceive of this type of device. He did not mention Lilienfeld.

Lilienfeld has been mentioned since Bottom's article in 1964, but there have been misunderstandings. Bottom imagined that the 1930 and 1933 patents worked on the principle of injecting minority carriers to vary the conduction in the semiconducting layer. This is most likely not the case as Johnson stated in his reply to Bottom. Addressing only the 1930 patent, Johnson felt that this device would operate on the field-effect principle, but it is still not completely clear what type of field-effect device it would be or if it is actually a type of bipolar device. W. Gosling concluded in a 1973 article that the 1930 patent described a junction field-effect transistor, the 1932 patent a bipolar transistor and the 1933 patent an insulate-gate field-effect transistor. Thus, in Gosling's eyes all three major types of transistors were designed by Lilienfeld by 1928. In his 1964 article in *IEEE Spectrum*, J. T. Wallmark made the same claim as Weimer, stating that Heil was the first to envision a field effect device. He also gave Weimer credit for using evaporation techniques and other workers of the 1960s such as Hofstein credit for the "insulated gate construction" without mentioning Lilienfeld.<sup>104</sup> *Revolution in Miniature* by Braun and Macdonald contains a claim by the authors that Lilienfeld did not have the means to develop his ideas.<sup>105</sup> Furthermore, a 1968 article in *Electronics* entitled "The Improbable Years", made the statement "There's a general belief that Lilienfeld never implemented his ideas by building the solid state amplifier he described."<sup>106</sup> There is evidence, however, that these claims are incorrect. Perhaps he did not have the facilities or the understanding

to produce the devices of the 1960s, but it appears likely that Lilienfeld indeed performed experiments to develop and test his designs of amplifying devices.

Bardeen was correct when he stated in Sweet's 1987 article, "Lilienfeld deserves great credit for his pioneering effort to make a semiconductor amplifier."<sup>107</sup> Perhaps part of the reason for the lack of recognition of Lilienfeld by the scientific community stems from the fact that Lilienfeld did not publish information on his devices despite publications by him in other areas. One can only speculate as to the reasons for this. The scientific community does not currently spend much of its time considering the scientific contributions contained in patents. This is may not have always been the case, however, at least not in the case of the growing area of electronics in the early part of this century. A few publications, *Electronics*, *Electronic Industries*, and *Proceedings of the Institute of Radio Engineers*, regularly published descriptions of relevant patents. None of these publications announced Lilienfeld's patents, however. By 1928 *Proceedings of the Institute of Radio Engineers* had ceased this practice. *Electronics* stopped in 1943 and *Electronic Industries* sometime between 1946 and 1960. Thus, it is likely that the scientific community would not have noticed Lilienfeld's patents.

However, it is not clear that the science of solid state was ready for a transistor in 1930. Certainly it would have increased interest in the field, but solid state physics has proved to be a field where success is very hard without understanding, and there was not sufficient understanding in 1930 to develop a practical field-effect transistor.

It is this lack of understanding of the time, however, that makes Lilienfeld's patents all the more remarkable.

## Notes

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