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Study of Semiconductor Devices

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Abstract—The history of semiconductors is presented beginning with the first documented observation of a semiconductor effect (Faraday), through the development of the first devices (point-contact rectifiers and transistors, early field-effect transistors) and the theory of semiconductors up to the contemporary devices (SOI and multigate devices).

Keywords—band theory, laser, Moore's law, semiconductor, transistor.

Introduction:

There is no doubt that semiconductors changed the world beyond anything that could have been imagined before them. Although people have probably always needed to communicate and process data, it is thanks to the semiconductors that these two important tasks have become easy and take up infinitely less time than, e.g., at the time of vacuum tubes. The history of semiconductors is long and complicated. Obviously, one cannot expect it to fit one short paper. Given this limitation the authors concentrated on the facts they considered the most important and this choice is never fully impartial. Therefore, we apologize in advance to all those Readers who will find that some vital moments of the semiconductor history are missing in this paper. The rest of this paper is organized in four sections devoted to early history of semiconductors, theory of their operation, the actual devices and a short summary.

2. Early History of Semiconductors:

According to G. Busch [1] the term "semiconducting" was used for the first time by Alessandro Volta in 1782. The first documented observation of a semiconductor effect is that of Michael

Faraday (1833), who noticed that the resistance of silver sulfide decreased with temperature, which was different than the dependence observed in metals [2]. An extensive quantitative analysis of the temperature dependence of the electrical conductivity of Ag_2S and Cu_2S was published in 1851 by Johann Hittorf [1]. For some years to come the history of semiconductors focused around two important properties, i.e., rectification of metal-semiconductor junction and sensitivity of semiconductors to light and is briefly described in Subsections 2.1 and 2.2.

2.1. Rectification: In 1874 Karl Ferdinand Braun observed conduction and rectification in metal sulfides probed with a metal point (whisker) [3]. Although Braun's discovery was not immediately appreciated, later it played a significant role in the development of the radio and detection of microwave radiation in WWII radar systems [4] (in 1909 Braun shared a Nobel Prize in physics with Marconi). In 1874 rectification was observed by Arthur Schuster in a circuit made of copper wires bound by screws [4]. Schuster noticed that the effect appeared only after the circuit was not used for some time. As soon as he cleaned the ends of the wires (that is removed copper oxide), the rectification was gone. In this way he discovered copper oxide as a new semiconductor [5]. In 1929 Walter Schottky experimentally con- firmed the presence of a barrier in a metal-semiconductor junction [5].

2.2. Photoconductivity and Photovoltaics: In 1839 Alexander Edmund Becquerel (the father of a great scientist Henri Becquerel) discovered the photovoltaic effect at a junction between a semiconductor and an electrolyte [6]. The photoconductivity in solids was discovered by Willoughby Smith in 1873 during his work on submarine cable testing that required reliable resistors with high resistance [7]. Smith experimented with selenium resistors and observed that light caused a dramatic decrease of their resistance. Adams and Day were the first to discover the photovoltaic effect in a solid material (1876). They noticed that the presence of light could change the direction of the current flowing through the selenium connected to a battery [8]. The first working solar cell was constructed by Charles Fritts in 1883. It consisted of a metal plate and a thin layer of selenium covered with a very thin layer of gold [8]. The efficiency of this cell was below 1% [9].

3. Theory :

In 1878 Edwin Herbert Hall discovered that charge carriers in solids are deflected in magnetic field (Hall effect). This phenomenon was later used to study the properties of semiconductors [10]. Shortly after the discovery of the electron by J. J. Thomson several scientists proposed theories of electron-based conduction in metals. The theory of Eduard Riecke (1899) is particularly interesting, because he assumed the presence of both negative and positive charge carriers with different concentrations and mobilities [1]. Around 1908 Karl Baedeker observed the dependence of the conductivity of copper iodide on the stoichiometry (iodine content). He also measured the Hall effect in this material, which indicated carriers with positive charge [1]. In 1914 Johan Koenigsberger divided solid-state materials into three groups with respected to their conductivity: metals insulators and "variable conductors" [1]. In 1928 Ferdinand Bloch developed the theory of electrons in lattices [10]. In 1930 Bernhard Gudden reported that the observed properties of semiconductors were due exclusively to the presence of impurities and that chemically pure semiconductor did not exist [1].

In 1930 Rudolf Peierls presented the concept of forbidden gaps that was applied to realistic solids by Brillouin the same year. Also in 1930 Kronig and Penney developed a simple, analytical model of periodic potential. In 1931 Alan Wilson developed the band theory of solids based on the idea of empty and filled energy bands (Fig. 1). Wilson also confirmed that the conductivity of semiconductors was due to impurities [10]. In the same year Heisenberg developed the concept of hole (which was implicit in the works of Rudolf Peierls [10]). In 1938 Walter Schottky and Neville F. Mott (Nobel Prize in 1977) independently developed models of the potential barrier and current flow through a metal-semiconductor junction. A year later Schottky improved his model including the presence of space charge. In 1938 Boris Davydov presented a theory of a copper-oxide rectifier including the presence of a p-n junction in the oxide, excess carriers and recombination. He also understood the importance of surface states [11]. In 1942 Hans Bethe developed the theory of thermionic emission (Nobel Prize in 1967).

4. Devices

4.1. Point-Contact Rectifiers : In 1904 J. C. Bose obtained a patent for PbS point-contact rectifiers [12]. G. Pickard was the first to show that silicon point-contact rectifiers were useful in detection of radio waves (patent in 1906) [10]. The selenium and copper oxide rectifiers were developed, respectively, in 1925 by E. Presser and 1926 by L. O. Grondahl [10]. The selenium rectifiers were heavily used in the WWII in military communications and radar equipment [10].

4.2. The p-n Junction : During his work on the detection of radio waves Russel Ohl realized that the problems with cat's whisker detectors were caused by bad quality of the semiconductor. Therefore he melted the silicon in quartz tubes and then let it cool down. The obtained material was still polycrystalline but the electrical tests demonstrated that the properties were much more uniform. Ohl identified the impurities that created the p-n junction that he accidentally obtained during his technological experiments. He held four patents on silicon detectors and p-n junction [13].

4.3. Bipolar Transistor : In 1945 William Shockley put forward a concept of a semiconductor amplifier operating by means of the field-effect principle. The idea was that the application of a transverse electric field would change the conductance of a semiconductor layer. Unfortunately this effect was not observed experimentally. John Bardeen thought that this was due to surface states screening the bulk of the material from the field (Fig. 2). His surface-theory was published in 1947 [14]. While working on the field-effect devices, in December 1947 John Bardeen and Walter Brattain built a germanium point-contact transistor (Fig. 3) and demonstrated that this device exhibited a power gain. There was, however, an uncertainty concerning the mechanism responsible for the transistor action [13]. Bardeen and Brattain were convinced that surface-related phenomena had the dominant role in the operation of the new device while Shockley favoured bulk conduction of minority carriers. About one month later he developed a theory of a p-n junction and a junction transistor [15]. Shockley, Bardeen and Brattain received the Nobel Prize in physics in 1956 (John Bardeen received another one in 1972 for his theory of superconductivity). In February 1948 John Shive demonstrated a correctly operating point-contact transistor with the emitter and collector placed on the opposite sides of a very thin slice of germanium (0.01 cm). This configuration indicated that the conduction was indeed taking place in the bulk, not along the surface (the distance between the emitter and collector along the surface would be much longer) [15]. It was only then that Shockley presented his theory of transistor operation to the coworkers [15], [16]. It is worth remembering that the crucial properties of semiconductors at the time were "structure sensitive" (as Bardeen put it in [14]), that is they were strongly dependent on the purity of the sample. The semiconductor material with which Bardeen and Brattain worked was prepared using a technique developed by Gordon K. Teal and John B. Little based on the Czochralski method. The crystal was then purified using the zone refining method proposed by William G. Pfann [11]. Point-contact transistors were the first to be produced, but they were extremely unstable and the electrical characteristics were hard to control. The first grown junction transistors were manufactured in 1952. They were much better when compared to their point-contact predecessor, but the production was much more difficult. As a result of a complicated doping procedure the grown crystal consisted of three regions forming an n-p-n structure. It had to be cut into individual devices and contacts had to be made. The process was difficult and could not be automated easily. Moreover, a lot of semiconductor material was wasted. In 1952 alloyed junction transistor was reported (two pellets of indium were alloyed on the opposite sides of a slice of silicon). Its production was simpler and less material-consuming and could be automated at least partially. The obtained base width was around 10 μm, which let the device operate up to a few MHz only. The first diffused Ge transistor (diffusion was used to form the base region, while the emitter was alloyed) with a characteristic "mesa" shape was reported in 1954. The base width was 1 μm and the cut-off frequency 500 MHz. It was generally understood that for most applications silicon transistors would be better than germanium ones due to lower reverse currents. The first commercially available silicon devices (grown junction) were manufactured in 1954 by Gordon Teal. The first diffused Si transistor appeared in 1955. To reduce the resistivity of the collector that limited the operation speed without lowering the breakdown voltage too much John Early thought of a collector consisting of two layers, i.e., high-resistivity one on top of a highly doped one. A transistor with epitaxial layer added was reported in 1960. In the same year Jean Hoerni proposed the planar transistor (both base and emitter regions diffused). The oxide that served as a mask was not removed and acted as a passivating layer [15]. Further improvement of speed was proposed by Herbert Kroemer. A built-in electric field could be introduced into the base by means of graded doping. Another way of introducing the electric field in the base he thought of was grading the composition of the semiconductor material itself, which resulted in graded band gap. This heterostructure concept could not be put to practice easily because of fabrication problems [17].

4.4. Integrated Circuit : The transistor was much more reliable, worked faster and generated less heat when compared to the vacuum tubes [18]. Thus it was anticipated that large systems could be built using these devices. The distance between them had, however, to be as short as possible to minimize delays caused by interconnects. In 1958 Jack Kilby demonstrated the first integrated circuit where several devices were fabricated in one silicon substrate and connected by means of wire bonding. Kilby realized that this would be a disadvantage therefore in his patent he proposed formation of interconnects by means of deposition of aluminum on a layer of SiO2 covering the semiconductor material [15]. This has been achieved independently by Robert Noyce in 1959. In 2000 Jack Kilby received a Noble Prize in physics for his achievements.

4.5. Tunnel Diode : Leo Esaki studied heavily doped junctions to find out how high the base of a bipolar transistor could be doped before the injection at the emitter junction became inadequate. He was aware that in very narrow junctions tunneling could take place. He obtained the first Ge tunneling diode in 1957 and a silicon one in 1958. Esaki's presentation at the International Conference of Solid State Physics in Electrons and Telecommunications in 1958 was highly appreciated by Shockley [19]. Unfortunately, Shockley exhibited a complete lack of interest when Robert Noyce came to him to present his idea of a tunnel diode two years earlier. As a result Noyce moved to other projects [20]. The tunnel diode was extremely resistant to the environmental conditions due to the fact that conduction was not based on minority carriers or thermal effects. Moreover, its switching times were much shorter than those of the transistor. Leo Esaki received a Nobel Prize in physics in 1973 for his work on tunneling and superlattices [21], [22].

4.6. Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) : In 1930 and 1933 Julius Lilienfeld obtained patents for devices resembling today's MESFET and MOSFET, respec- tively. In 1934 Oskar Heil applied for a patent for his theoretical work on capacitive control in field-effect transistors [3]. The first bipolar transistors were quite unreliable because semiconductor surface was not properly passivated. A group directed by M. M. Atalla worked on this problem and found out that a layer of silicon dioxide could be the answer [23]. During the course of this work a new concept of a field-effect transistor was developed and the actual device manufactured [24]. Unfortunately, the device could not match the performance of bipolar transistors at the time and was largely forgotten [15]. Several years before Bell Laboratories demonstrated an MOS transistor Paul Weimer and Torkel Wallmark of RCA did work on such devices. Weimer made transistors of cadmium sulfide and cadmium selenide [11]. In 1963 Steven Hofstein and Fredric Heiman published a paper on a silicon MOSFET [25] (Fig. 4). In the same year the first CMOS circuit was proposed by Frank Wanlass [26]. In 1970 Willard Boyle and George Smith presented the concept of charge-coupled devices (CCD) – a semiconductor equivalent of magnetic bubbles [27]. Both scientists received a Nobel Prize in physics in 2009 for their work on CCD.

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