

History of Semiconductor Device and Its Application

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Abstract- This paper presents the origin of semiconductors and device applications. Although the history of semiconductors stretches back to a time as far as 1833, semiconductors made debut in engineering field by dint of Bose's research in the 1890s. Selenium photoelectric cell, Braun's discovery of rectification at metal semiconductor interface and Bose's introductory applications of semiconductors for wireless engineering can be considered the milestones of the 19th century in this regard.

Keywords- Photo voltage, Selenium photoelectric cell, submarine cables, Rectification, photoconductivity.

I. INTRODUCTION

Semiconductor devices-preceded by the adjectives early and primitive usually, refers to the crystal rectifiers used for wireless applications in the early 1900's. In this sense, early 1900's is regarded as the time when the semiconductor devices first came into application. Semiconductor device application is an interest-entirely of the 20th century, in a more rigorous sense, of the second half of the century- but the roots of this discipline extend to the 19th century, too. Semiconductor properties- as fascinating as negative dynamic resistance of junctions were observed. Use of semiconductors for wireless application began in the 1890's. The history of semiconductors in the 19th century lacks proper investigation and integration. How semiconductor properties came to scientists' notice and made debut in the field of application. The beginning of semiconductor research is marked by Faraday's 1833 report on negative temperature coefficient of resistance of silver sulfide. This is the first observation of any semiconductor property. The significant contributor to semiconductor field in chronological order is the French experimental physicist Edmond Becquerel. He observed the photovoltage in the silver chloride coated platinum electrodes [3]. In his experiment, a AgCl coated platinum electrode was immersed in an aqueous nitric acid electrolyte solution. Illumination of the electrode generated photovoltage that altered the EMF produced by the cell, in fact, it produced a reductive (cathodic) photocurrent at the AgCl coated electrode; this was the first reported photovoltaic device. Photovoltage was generated at the Ag/AgCl metal semiconductor contact, Ag at the junction was formed by the absorbed silver clusters in the AgCl electronic states [4].

The another semiconductor research in the decade of 1870. The period selenium was discovered as a semiconductor, rectification at metal semiconductor interface came into scientists' notice.

Willoughby Smith was initially working with submarine cables. He set into experiments with selenium for its high resistance, which appeared suitable for his submarine telegraphy. Smith discovered that the resistance actually depended on the intensity of incident light. When the selenium bars were put inside a box with the sliding cover closed, the resistance was the highest. When glasses of various colors were placed in the way of light, the resistance varied according to the amount of light passing through the glass. But when the cover was removed, the conductivity increased. He also found that the effect was not due to temperature variation.

The first observation of photovoltaic effects in a solid system was made in 1876 [10]. The semiconductor substance was again selenium. They discovered that illuminating a junction between selenium and platinum had a photovoltaic effect. Although the most significant observations of the 19th century came during the period 1870-1885, the semiconductors had not received any device application for any practical purpose yet. It was not until 1890's that any field recruited these materials for any practical use.

Wireless communication is the first field to employ these materials for practical application. After Hertz's demonstration of existence of electromagnetic waves in 1888, a number of scientists got involved with experimenting with these newly discovered waves, and wireless telegraphy became practicable. Among them, Bose was the first person to introduce semiconductors for the reception of wireless waves.

Braun used semiconductors for reception of wireless signals, and in 1901 he realized the advantage of using them for this purpose. Thus ends the history of semiconductor of the 19th century.

II. ORIGIN OF SEMICONDUCTORS, SEMICONDUCTORS OF 19th CENTURY AND THEIR PROPERTIES

Faraday was the first one to discover a peculiar semiconductor property. Hence, the first semiconductor discovered is silver sulfide and the first semiconductor property is negative temperature coefficient.

Becquerel's discovery of photo voltage was a manifestation of a semiconductor property, but hardly could he imagine that he had discovered a semiconductor. In fact, his works with these semiconductor properties led to development of modern photography.

Smith's Selenium, Becquerel's silver compounds, Braun's pyrite and sulfide crystals can be considered the semiconductors of the 19th century. However, selenium happens to be the most important semiconductor of the 19th century, for its photoelectric properties attracted a number of scientists, like Smith, Adams and Day, Fritts, to do research with. As a matter of fact, the photoelectric effects were first observed in the semiconductors (as early as 1873). The first observation of photoelectric properties in a metal came in 1887 by Hertz.

The most significant semiconductor property discovered before 1900 is rectification at metal semiconductor junctions arising from Braun's experiments. This is the first time asymmetric conduction and deviation from Ohm's law was observed. Edison effect- rectification in vacuum tube was discovered in 1884, rectification at electrode electrolyte contact was discovered sometime during the end of the century. This effect is basis of the most basic and the simplest electronic component- the diode. ["If device literature exhibits normal life-cycle characteristics (i.e. from inception to growth, to saturation, and finally to decline), we can state that the inception phase is from 1874 (the first study of metal – semiconductor contacts) to 1947 (the invention of transistor)."] from [16].

The four fundamental properties of semiconductors (i) negative temperature coefficient of resistance, (ii) rectification, (iii) photoconductivity, (iv) photo voltage had been observed. But all the properties did not occur in the same material. This is the reason behind the interesting fact that semiconductors did not appear as a different class of materials featured by a set of properties different from those of both electrical conductors and non-conductors in the 19th century. The scientist could not recognize that selenium, silver sulfide, galena, etc. actually belong to the same class of materials. They regarded them as exceptions of general laws- a more general law to differentiate between metals, semiconductors and insulators came after a long time- precisely in the 1930's. The basis of electronic devices was discovered in 1874 by

Braun, almost three quarters of a century before the semiconductor revolution.

III. PROBLEMS FACED IN RESEARCH OF SEMICONDUCTOR IN THE 19th CENTURY

- Semiconductor research started quite unnoticed in 1833 by Faraday-more than a century before the 1947 breakthrough in semiconductor devices. There was no engineering application for these materials for the most of the time during the 19th century.
- Wireless engineering was the perfect field to employ semiconductors. Transition from wired telegraphy to wireless telegraphy required semiconductors for sensitive reception of waves. It was Bose's merit to introduce semiconductor coherers with auto recovery in place of conventional coherers in the 1890s. The basis of practical application of these materials was formed by Bose's pioneering research, which manifested in the first decade of the 20th century with Marconi's experiment.
- After 1870, semiconductor research divided into two main streams. The photoelectric properties of selenium interested a number of researchers and led the foundation of photovoltaic engineering. On the other hand, researches with semiconductor junctions led to the development of wireless detectors.
- Lack of theoretical foundation was also a reason why these materials did not find the attention of the 19th century scientists. The intriguing properties could not be explained by classical physics of the pre quantum era. For example, until 1906, a hypothesis that rectification occurred at thermal basis, existed among the semiconductor researchers. In the 1930s a complete theoretical foundation of semiconductors was established.
- It is to be noted that the scientists related to this field in that century were more famous for their works in the other field. Faraday's fame is not to be mentioned, Becquerel's discovery laid the foundation of modern photography, Braun is more famous for his oscilloscope.
- Although Bose classified some materials into p types, n types and neutral types, most of scientists could not recognize that semiconductors form a different class of materials. In 1907, it was first systematically shown by 'Hall Effect' that selenium, tellurium and silicon all were semiconductors.

Some of the outcomes of the research of the 19th century may be considered commendable achievements of the semiconductor research in the 19th century which are summarized below:

1. Foundation of photovoltaic research from the research on selenium.
2. Braun's discovery of rectification at metal semiconductor junction making the basis of the electronics in the 20th century.
3. Bose's application of semiconductors to wireless wave detection—first engineering application of semiconductors.

IV. SELENIUM AND FOUNDATION OF PHOTOVOLTAIC ENGINEERING

Researches with photoelectric properties of selenium in the 19th century laid the foundation of photovoltaic engineering. Adams and Day's 1876 discovery of Photo voltage at junctions is the basis of solar cells. They built the first photo element of modern barrier type [1]. The solar cell invented by Fritts' has some features in common with modern silicon solar cells. Selenium devices began to be used widely as photographic exposure meters, rectifiers and battery chargers in the 1920's [1]. Before the advent of silicon and germanium rectifiers, selenium happened to be one of the most important materials for the semiconductor industry. It is noteworthy that, unlike the other semiconductors of the 19th century, selenium did not lose its importance as a semiconductor; selenium and its derivatives are still used for semiconductor device applications. Endeavors in the photovoltaic field intensified after 1950. For photovoltaic application selenium compounds, for example CuInSe_2 are used as principle semiconductors.

V. BRAUN'S EFFORTS AND CONTRIBUTION TO SEMICONDUCTOR RESEARCH

Braun was initially engaged in research with electrical conductivity of metal salts in solution, i.e. electrolytes. His interest ultimately led him to study metal sulfide crystals and other crystalline solids, which, although being solid binary compounds, conduct. In 1874, he disclosed his discovery of rectification effect [8]. He observed that the total resistance depended on the polarity and magnitude of the applied voltage as well as the surface conditions. From his 1874 paper, "With a large quantity of natural and artificial metallic sulfides and greatly varying pieces, the most perfectly formed crystals that I could find, as well as coarse samples, I discovered that their resistance varied with the direction,

intensity and duration of the current. The differences amount up to 30% of the total amount." Among the natural metallic sulfides and pyrites he experimented with were copper pyrite, iron pyrite, galena, and tetrahedrite (copper antimony sulfide). He observed that at small current intensity the material had a higher resistance in a certain direction, as the intensity increased the resistance diminished for both directions. However, as the intensity of current increased, at some stage the resistance in the previously high resistance direction fell below the resistance in the other direction for the same current intensity—this must be the manifestation of breakdown phenomena.

In one of his experiments, he used a shiny tetrahedrite crystal of tetrahedron shape. Two silver wires with their ends flattened were pressed hard to the crystal. One wire was perpendicularly in contact with the surface at the apex, the other was near the base line of the same surface. He found that this type of contact acted as an Ohmic contact, the current intensity was the same in both directions. When second wire was in contact with against the base of tetrahedron, the current intensity varied with the direction.

He continued his experiments until 1883 [17]. His experiments involved dc measurement of current and voltage of the crystals. His experiments and finding were confined to laboratory, as at that time he did not find any practical application of this novel effect. Braun later shifted his interest to other disciplines of physics. However, he had found this early discovery useful for wireless application not until 1901, when he used a telephone to receive the signals by hearing [18]. However, in [19] it has been showed that the wireless applications of semiconductor junction did not originate from his 1874 experiments. The earliest systematic study of semiconductor device is generally attributed to Braun [16]. Braun's work is so remarkable that in most of the historical reviews of semiconductor research, the history of semiconductor research begins with his 1874 discovery. The underlying principle of the most basic semiconductor device—diode is rectification at junction—which was discovered by Braun in the 19th century. The famous cat's whisker diode (point contact rectifier) came into existence from his experiments. Sze termed his 1874 paper as the first systematically approached study of metal semiconductor junction [16].

Development of Semiconductor Device Application:

Introduction of semiconductor materials for the detection of electromagnetic waves is Bose's contribution. To receive the radiation, he used a variety of different metal semiconductor junctions connected to a highly sensitive

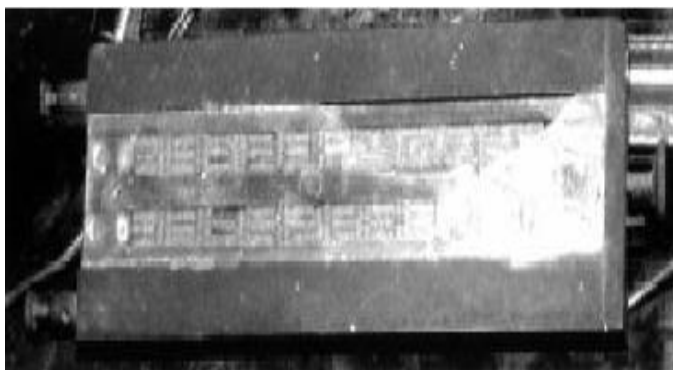
galvanometer in series. He later was awarded the first patent for a semiconductor device in the world. Among his various pioneering solid-state semiconductor receivers are the spiral spring coherer, galena receiver and iron mercury iron coherer (detector) with a telephone.

Bose's Spiral Spring Coherer:

Bose disclosed the invention of this receiver in 1897 at the Royal Society. In this device, thousands of steel springs (2mm in diameter and 1cm in length) were placed side by side in a single layer in the rectangular depression of a square piece of ebonite. The springs were prevented from falling by a glass slide in the front. The contacts between the springs acted as semiconductor junctions. The fine oxide layer on the spring creates the semiconductor. This device was connected in series with a voltaic cell and a dead beat galvanometer. When electric radiation was absorbed by the sensitive contacts, there was a sudden decrease of the resistance and the galvanometer was deflected. This detector has been called Metal Semiconductor Metal (MSM) detector in [20]. This detector was described [21] as a “space irradiated multi contact semiconductor (using the natural oxide of the springs)”.



(a)



(b)

Fig 1: (a) Bose's diagram for spiral spring coherer [26]. (b) Photograph of Bose's spiral spring coherer [26].

Iron-Mercury-Iron Coherer with a Telephone: Receiver for Marconi's 1901

Transatlantic Signaling:

This invention has great historical significance because of the turn-of-the-century scandal regarding Marconi's 1901 transatlantic experiment. On April 27, 1899, Bose disclosed the invention of this device at the Royal Society meeting in London. This device consisted of a U shaped tube filled with mercury. In one limb there was a thin rod plunger, and on the other there was a sensitive material which touched mercury barely. By adjusting the position the plunger by a slide arrangement, the pressure on the contact was adjusted. The circuit was completed through the metal and mercury. The detection of micro waves was possible due to the formation of an oxide film, either on the surface of mercury or on the iron (or both). This formed a junction with rectifying property and by the sliding arrangement suitable oxidized spots were found. Thus this was semiconductor device.

Bondyopadhyay[15] pointed out that after Bose's disclosure of this invention in 1899, it caught the attention of a number of experimenters. Marconi carried his childhood friend and Italian Lieutenant Solari's modification of Bose's “mercury coherer with a telephone” for use in the reception of the first transatlantic wireless signal in December 1901. Scandal spurred regarding reception of the famous signal ‘S’ at Signal Hill in 1901 very soon. The scandal is revisited and critically analyzed in [15] and [23]. Bondyopadhyay concluded that Marconi plagiarized Bose's design, but never in his life acknowledged that. Marconi was well aware of Bose's research and even tried to hire Bose. In 1901, prior to a Royal Institution lecture by Bose, Marconi's Wireless and Telegraphy company's managing director met Bose to with a patent application and asked him not to disclose his inventions there[29]. The price of Marconi's such conduct was that Bose's works in that field remained unknown to the world and he was deprived of the Nobel Prize, 1909. Undoubtedly, Marconi's success in the long distance wireless communication and transatlantic signaling was largely due to Bose's semiconductor Fe-Hg-Fe coherer.

Work on Junctions and Keen observation on Semiconductors:

Bose had some interesting observations working with point contact detectors. One of his curious receivers was the ‘single point iron receiver’. It consisted of a sharp point of iron, pressing against a convex iron surface, pressure being capable of very delicate adjustment by means of a micrometer.

He found that the resistance was not constant, but went through a continuous decrease with increasing applied voltage. Hence, he concluded that the conduction in such cases did not obey Ohm's law. The I-V characteristics of single point iron receiver as measured by Bose. One of these curves is similar to the I-V characteristics of semiconductor junction having the knee approximately at 0.45V. Based on the effect of electromagnetic radiation of the junctions of different materials, he divided materials into three classes, positive, negative and neutral. The positive materials show decrease in resistance under the action of radiation, the negative class shows an increase in resistance, and the neutral class do not show any change in conductivity. On the other hand, he found that junctions formed by positive or negative class materials show non linear I-V characteristics. In case of positive class the I-V curve is concave to the emf axis, and for negative class the I-V curve is convex to the emf axis, thus he correlated the radiation sensitivity and rectification effect of the point contact junctions. Be, Mg, Al, Fe, Co, Ni, Cu etc. belong to the positive class while Li, Na, K, Ca, Br, Ag belong to the negative class. The non-linear characteristic may have originated from the existence of semiconducting or insulating layer at the interface between the substances. The semiconductor junction like characteristics of positive materials may be attributed to the fact that the fine natural oxide layer (Fe₂O₃, Co₂O₃, MgO, Al₂O₃ etc.) on the metals constituted the semiconductor at the junction. On the other hand, in case of negative class materials, he observed the I-V characteristics curve convex, which is, according to [26], manifestation of negative dynamic resistance. This property, analogous to the property of tunnel diode, may be attributed to the fact that the fine natural oxide layer on the metals constituted the extremely thin insulator layer at the junction. To appraise Bose's work, Sir Neville Mott, Nobel Laureate in 1977 for his own contributions to solid-state electronics, remarked [26] that "J.C. Bose was at least 60 years ahead of his time" and "In fact, he had anticipated the existence of P-type and N-type semiconductors."

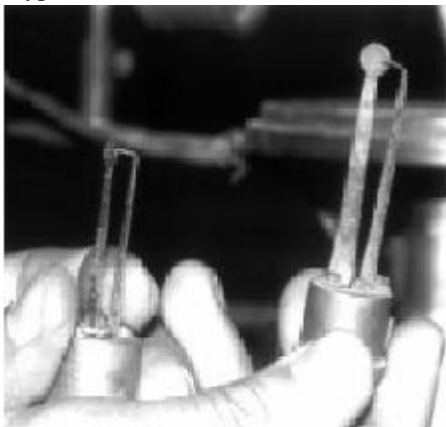


Fig. 2: Bose's point contact detector, removed from the receiving antennas [26]

Bose's Research as IEEE Milestone- A Final Remark:

Undoubtedly semiconductor engineering had its humble beginning in Bose's hands. Bose's inventions might have influenced the great innovators, like Marconi, Braun. Braun, in his Nobel Lecture[30], mentioned that, "The elements(semiconductors) showed the expected detector effect, but at that time offered no advantages over the coherer. As the swing to aural reception of messages took place, I came back to these materials, and recognized their usefulness for this purpose in 1901." It was Bose who introduced the idea of aural reception of signals from semiconductor detectors. Bose's global leadership in semiconductor research referred to the earliest history of semiconductor device applications is undisputed. But, the impact of his contributions to this technology is not publicized and appreciated in the modern context. Bose's research marks the beginning of semiconductor engineering. Hence the author thinks that Bose's seminal research with semiconductors deserve to be identified as an IEEE Milestone.

VI. CONCLUSION

Slow pace and small area of application characterize the pre-1900 history of semiconductor research and semiconductor device applications. But this history surely deserves to be preserved and should be well documented. The roots of photovoltaic engineering, electronic principles and wireless applications of semiconductor devices find ground in the 19th century. No matter how insignificant the contribution of research efforts of this century is to the development of this field in the 20th century, the germ of early 1900 semiconductor device applications was there in the 19th century.

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