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ARTICLE

Brief history of semiconductor science and technology and India's role in the decade after the invention of transistor

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Abstract
This paper presents a brief history of semiconductor science and technology and examines the role of Indian scientists in the decade following the invention of the transistor. The paper first outlines the development towards identifying and understanding the special characteristics of semiconductors. The current understanding of the physics of semiconductors and their properties are briefly mentioned thereafter. A chronological listing of different works, starting from the first report by Volta in 1782 and other scientists, is given, and how their findings gave evidence to this special class of materials is pointed out. In the list, a brief mention is also made about J. C. Bose's invention of the first semiconductor device and his work related to materials, later identified as semiconductors. This listing, with a brief mention, continues by outlining the progress towards developing semiconductor science and technology until the end of World War II. The invention of the transistor, announced on December 23, 1947 created a boom in activities worldwide in semiconductors, improvement in device performance, and announcement of newer semiconductor devices. Indian research in this area over the decade after the invention of the transistor is identified. International research had been in full swing in this period, and some of these developments that paved the way for the invention of integrated circuits in 1958–1960 are listed and discussed. Finally, the reasons are sought for limited work and the general unawareness or lack of interest of Indian workers in this important area, leading to the present Information Age, compared to international activity.

Keywords Semiconductors · Transistors · Information Age · J. C. Bose · Indian research

1 Introduction

Semiconductors and devices, including transistors, circuits made of semiconductor devices, resistors and capacitors grown on the same platform, known as Integrated Circuits (ICs), have revolutionized modern society (Nathan et al., 2023). The ICs, chips as in common parlance, are essential components for computers, mobile handsets, communication equipment, gadgets for entertainment, and many other household appliances. Human civilization has now entered into the Information Age, the foundation of which lies on three pillars: computers, communication, and devices. Chips are essential elements for all the three. They are used in the internet, satellite, long-distance fiber optic communication, aviation, defence, administration, bank services, medical diagnostics, and other essential areas to support modern society. The recent worldwide shortage of chips has stalled production in many areas, including automobiles. The Indian Government is seriously considering developing chips indigenously to combat the chip shortage and become self-independent in chip mass production.

The pertinent question then arises: how have semiconductors attained such importance? The answer will definitely point to the invention of the transistor, first announced in an internal group in Bell Telephone Lab, USA, on December 23, 1947 (Riordan & Hoddeson, 1997). There has been rapid progress within the next decade, leading to the demonstration of IC in 1958 (Kilby, 1959) and then the realization of IC more practically (Noyce, 1959). However, to reach these states, much research has been undertaken to establish the unique properties of semiconductors, to develop a detailed understanding of the physical processes occurring and the methods to grow pure materials exhibiting desired

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properties, methods of doping, and characterization. Such studies led to a rich history of semiconductors and devices (Basu, 2023a, 2023b; Burgess, 2008; Busch, 1989; Esaki, 1981; Lau, 2017; Lukasiak & Zakubowski, 2010; Pearson & Brattain, 1955).

The main aim of the present paper is to give a brief history of semiconductor research, starting from the first report by Volta (1782) and followed by the then stalwarts, including Bose (1901, 1927). The term semiconductor was coined, however a few years later (Weiss, 1910). Though many workers studied and investigated the properties of semiconductors, a real understanding of the physics of semiconductors became available only with the advent of Quantum Mechanics and, more specifically, with the development of the Quantum Theory of Solids. Such studies continued till World War II. However, the real application of semiconductors began after the invention of transistors.

In this paper, the history of semiconductors will be presented from 1782 to 1959 when IC was announced, roughly the next decade after the invention of transistors. A timeline of important developments has already been given by Basu (2023a, 2023b) based on available publications and reports. The present author has gathered some new information since submitting his article (Basu, 2023a, 2023b). Therefore, this paper will revise and rewrite the history by including technological developments and devices reported during the period covered in the present study. It is also interesting to know and assess the contributions of Indian scientists to this critical area. In this respect, the metal-galena (PbS) detector, used by Acharya J. C. Bose in his famous microwave communication experiment, is recognized as the first semiconductor device (Bose, 1901; Lau, 2017; Pearson & Brattain, 1955). Involvement of Indian researchers working in India in this area since Bose is also examined in this paper: a study not yet undertaken so far.

It is necessary to present a brief discussion first on the basic properties of semiconductors and devices in light of the work done by previous workers, which may be examined. This is discussed in the next section, Sect. 2.

The organization of the rest of the paper is described now. A brief account is given in Sect. 3 outlining semiconductor research starting from the initial work by Volta in 1782, followed by other luminaries, including J.C. Bose, and understanding of semiconductor properties afterward, developed fully on the basis of the Quantum Theory of Solids. This section also includes work on materials growth and device fabrication before and after transistors, leading to the invention of ICs. Section 4 identifies Indian researchers working in the area and their work done till the end of 1959. The rapid growth of the subject semiconductor in the post-transistor period, due mainly to international researchers, covering only the next decade ending in 1959, is discussed in Sect. 5. The cut-off year 1959 is chosen because it is difficult to cover all such activities during the next 75 years. The workers in this period are identified, and their work and impact are described in Sect. 5. However, Indian work during this period was insignificant compared to work done by the international community, consisting of even a few Nobel laureates. This comparison is also made in Sect. 6, in which the reasons for insignificant activities by Indian workers are explored. Conclusions are drawn in Sect. 7.

2 Basic properties of semiconductors

Semiconductors belong to a special type of materials, the conductivity of which lies intermediate between that of highly conducting metals and that of poor conductors called insulators. The conductivity of semiconductors is influenced by heat, light, pressure, and the types of impurities present. The materials for the study of physical properties and device applications are crystalline in nature; that is, the atoms within the material maintain a regular interatomic distance. All crystalline solids possess a band structure, the nature of which determines whether the solid is a metal, a semiconductor, or an insulator. The essential features of band structure in semiconductors are now described in the following paragraph. For more details, the reader may consult many excellent textbooks, including the book by Shockley (1953), Streetman and Banerjee (2018), and Sze and Ng (2007).

The atomic system is akin to the solar system. Electrons move in different orbits around their parent nucleus, like planets do around the sun, in an isolated atom, and a quantized energy level characterizes each orbit. When moving in a crystalline solid, the outermost electrons are loosely bound to the respective nuclei but belong to the crystal as a hole. As a result, their discrete energy levels now form an energy band. For semiconductors, the two outermost bands are called the valence band (VB) and the conduction band (CB), which are separated by a forbidden gap, the band gap, having no allowed energy levels. At absolute zero, the lower VB is totally complete, with all electrons occupying all energy states, and the upper CB is empty. Some electrons get enough energy at finite temperatures to be promoted to the higher CB. However, as the number of available energy states in CB is larger than the number of electrons lifted there, electrons may get energy from an external electric field and almost freely move in the band and cause conduction. These electrons also leave some empty states in the VB, and electrons can also move to occupy these empty states, thereby adding to the conduction. It is usual to assume that conduction in VB is due to the movement of the empty states containing positively charged holes. In a pure semiconductor, the number of electrons per unit volume in CB equals the number of holes per unit volume in VB. These numbers may increase with temperature rise but are still small at room temperature. Therefore, the conductivity of pure Si or Ge, called intrinsic semiconductors, at room temperature is quite low and fixed. To increase and control conductivity, a controlled impurity amount is introduced. The process is known as doping. In Si or Ge, doping with Gr. V elements like P or As donates extra electrons to the CB. These dopants are called donors, and the material is called n-type. Gr. III elements like B or Al get electrons from the VB, thereby creating holes in the VB. These impurities are called acceptors, and the material is p-type. Both n and p-type semiconductors are termed extrinsic. By shining light of energy exceeding the band gap energy onto the semiconductor, excess electron–hole pairs can be created and the conductivity can be increased. This phenomenon is known as photoconductivity.

All semiconductors used in experiments and device fabrication need to be single crystals. The material is grown in the form of long cylindrical ingots. Circular discs are sliced from the ingot. These discs, called wafers, are used as substrate, the top part of which is made p or n-type by a process known as epitaxy. These epitaxial layers are then selectively converted into p or n-type, thus forming a p–n junction or a p–n–p or an n–p–n transistor. For this, the epi-layers are oxidized, some parts of the oxidized layers are etched, and impurities are driven into the uncoated regions by diffusion or ion-implantation. Different patterns are imprinted on the oxidized layers for etching and diffusion using masks and a process known as lithography. Different devices like diodes, transistors, light emitting diodes, lasers, detectors etc. are realized by making junctions of p-type and n-type semiconductors. The fabrication of devices and chips requires the growth of ultrapure materials, highly controlled doping, process steps with high precision, sophisticated equipment, as well as well-defined design processes, testing and packaging of finished products, and high-volume production of chips at reduced cost (Sze & Ng, 2007).

It appears, therefore, that a number of equipment, furnaces, soldering metal leads to the different regions for external contacts, testing of devices, packaging, encapsulation of devices, and many more facilities are needed to complete the process and market the devices and chips. All these activities needed many decades to develop and required a large amount of investment.

3 Brief history of semiconductors and devices before transistors

Several reports are now available in the literature describing semiconductor materials' evolution, understanding their basic properties and features distinguishing them from metals and insulators, and their use in devices. These reports treat semiconductors and device applications separately. In the following, we prepare a brief timeline of the development of all these features, including the information provided in all these publications and reports (Basu, 2023a, 2023b; Burgess, 2008; Busch, 1989; Esaki, 1981; Lau, 2017; Lukasiak & Zakubowski, 2010; Pearson & Brattain, 1955). This summary of work will also point out how the subject grew from a mere ad-hoc explanation of the phenomena observed experimentally to a more sound understanding of the material properties and provide guidelines for improvement of the growth of materials and devices. Interested readers are referred to the papers cited above for more technical details. An interesting account of how semiconductors, p–n junctions, transistors, and IC took their present shape is given by Riordan and Hoddeson (1997). Papers in IEEE Trans. Electron Devices (1976) and different chapters in the book edited by Nathan et al. (2023) are also highly recommended.

1782: Alessandro Volta, Italy, observed that an electrometer discharged almost instantaneously by touching its knob with metals, slowly with semiconductors, and did not discharge at all by its contact with an insulator. It is not known which materials he used in the experiments. However, this points out the existence of materials with intermediate conductivity (Busch, 1989; Volta, 1782).

1821: Humphrey Davy, England, studied the temperature dependence of several metals. He noted that the conductivity power of metallic bodies varied with temperature and was lower, in some inverse ratios, as the temperature was higher (Busch, 1989; Davy, 1821).

1833: Michael Faraday, England, extended Davy's experiments to several compounds and found that the change in the conductivity of the compounds was opposite to the nature of metals, as found by Davy. For Ag_2S the room temperature conductivity was very low, while at 175 °C it increased abruptly to reach metallic value. It may be noted that a similar rise in conductivity with temperature is found in crystalline intrinsic semiconductors (Busch, 1989; Faraday, 1839).

1839: Alexandre Edmond Becquerel of France, reported that a voltage developed between a solid and a liquid electrolyte, when struck by light. Though this effect, the photovoltaic effect, was not observed for semiconductors, but later on the study was conducted for semiconductors (Becquerel, 1839; Busch, 1989).

1851: J. W. Hittorf of Germany first reported on the variation of the electric conductivity of Ag_2S and Cu_2S as a function of temperature (Busch, 1989; Hittorf, 1851).

1873: Willborough Smith of the USA observed a decrease in the resistance of the selenium resistor when light fell on it. This is the first observation of photoconductivity in Se, later identified as a semiconductor (Smith, 1873).

1874: Karl Ferdinand Braun of Germany observed conduction and rectification in metallic sulphides. However, this effect had been discovered much earlier by Peter Munck of Rosenschold (see Busch, 1989), who wrote for the *Annalen der Physik und Chemie* in 1835. Arthur Schuster found that a copper oxide layer on wires has rectification properties that cease when the wires are cleaned (Braun, 1874; Busch, 1989).

1876: William Grylls Adams and Richard Evans Day, both of the USA, observed the photovoltaic effect in selenium in 1876 (Adams and Day, 1877).

1878: Edwin Herbert Hall, USA, demonstrated the deflection of flowing charge carriers by an applied magnetic field, now known as the Hall effect. The deflection is the opposite for positive and negative charges, as found later (Hall, 1879).

1894–2001: Jagadish Chandra Bose of India conducted and reported a number of experiments related to wireless communication. For detecting microwave signals, he first used a coherer called a spiral spring detector, which was a steel spring pressing against a metal surface. A cell was used to pass a current through it. Dissatisfied with this detector, around 1897, Bose measured the change in resistivity of dozens of metals and metal compounds exposed to microwaves. He experimented with many substances as contact detectors, focusing on galena. His detectors consisted of a small galena crystal with a metal point contact pressed against it with a thumb screw, mounted inside a closed waveguide ending in a horn antenna to collect the microwaves. Bose passed a current from a battery through the crystal, and a galvanometer was used to measure it. When microwaves struck the crystal, the galvanometer registered a drop in the resistance of the detector. Bose found his detector was also sensitive to visible light and ultraviolet, leading him to call it an *artificial retina* as it was believed that radio signals behave as light. He applied for a US patent for the detector on 30 September 1901, the first patent on a semiconductor device. His galena detector is recognized as the first semiconductor device. It may be mentioned that though Braun discovered rectification in PbS in 1876, he did not continue his work after that (Basu, 2023a, 2023b; Bose, 1901, 1927; Lau, 2017; Pearson & Brattain, 1955).

1897: J J Thomson of England discovered electron. His discovery motivated many workers to study and control the motion of electrons in a vacuum and then in metals and other solids (Thomson, 1897).

1899–1901: V E Riecke of Germany experimented with solids to understand the mechanism of the electric conduction in solids. Riecke postulated the existence of both negatively and positively charged carriers of possibly different concentrations and unequal mobilities. He found a formula for the Hall coefficient, which is practically identical to the one derived later by Peierls (1929). (Busch, 1989; Riecke, 1901).

1900: Paul Drude of Germany gave the theory of electrical conductivity in metals by considering the flow of free electrons (Drude, 1900).

1902–1906: Greenleaf Pickard, USA, examined many semiconductors with metals to examine rectification and was the first to commercialize the use of detectors (Pickard, 1906).

1907: J W Pierce, USA, examined several metal semiconductor diodes and found cat's whisker diode with Si to give good rectification property (Pierce, 1909).

1907: Henry Joseph Round, a British Marconi engineer in England, noticed that by passing a direct current through a silicon carbide (carborundum) point contact junction, a spot of greenish, bluish, or yellowish light was given off at the contact point [Wikipedia rectifier]. Different workers later utilized this light emission phenomenon to produce Light Emitting Diodes (LEDs) (Round, 1907).

1907: Carl Baedecker of Germany made Hall measurements of CuI and showed the presence of positive charges in the material (Baedeker, 1907).

1910: J Weiss, Germany, first coined the term halbleiter (semiconductor) (Weiss, 1910).

1914: Johan Koenigsberger, Germany, classified solid materials like metals, insulators, and "variable conductors" (Koenigsberger and Rechenstein 1906). He preferred variable conductors to semiconductors. Koenigsberger and his coworkers, however, published their research in 1906 (see Busch, 1989; Koeningsberger and Rechenstein 1906)

1918: Jan Czochralski, Poland, developed a way to grow single-crystal silicon. His method was later modified and utilized to grow single crystals of different semiconductors. The method is named after him (Czochralski, 1918).

1922: Union Switch and Signal, a Westinghouse company in the USA, filed its first patent on the copper copper-oxide rectifier. The rectifier was used to convert high-power AC to DC as an alternative to vacuum tube rectifiers and at the same time was used for small current applications (Burgess, 2008; wiki semiconductors).

1922: Oleg Losev, Russia, invented "Negative resistance diode" in biased zincite (zinc oxide) point contact junctions. Olev, a self-taught Russian physicist, worked at the new Nizhny Novgorod Radio Laboratory. He used biased negative resistance crystal junctions to build solid-state amplifiers, oscillators, and amplifying and regenerative radio receivers, 25 years before the invention of the transistor. His amplifier served as an alternative to fragile, expensive vacuum tubes, consuming more energy, but his work was overlooked due to the success of tubes. His technology was dubbed "Crystodyne" by science publisher Hugo Gernsback, who was one of the few people in the West who had paid attention to it. After 10 years, he abandoned research into this technology, and it was forgotten (Losev, 1925). The negative resistance diode was rediscovered with the invention of the tunnel diode in 1957, for which Leo Esaki won the 1973 Nobel Prize in Physics (Esaki, 1958).

1924–1930: Oleg Losev, Russia, independently discovered Light Emitting Diode using biased carborundum and zincite junctions. Apart from this, he was the first to give its working theory and envision practical applications. He published his experiments in 1927 in a Russian journal and the 16 papers he published on LEDs between 1924 and 1930 constitute a comprehensive study of this device (Lau, 2017; Zheludev, 2007).

1925: Julius Edgar Lilienfeld, USA, has been credited with the first patent on the Field Effect Transistor (FET) (filed from Canada in 1925). Lilienfeld was an Austro-Hungarian-American physicist and electrical engineer. He was never able to build a working practical semiconducting device based on this concept since high-purity semiconductor materials were not available to him. In addition, he could not publish articles in learned journals. Therefore, he was not recognized for his FET patent (Lilienfeld, 1925 Wikipedia; Riordan & Hoddeson, 1997).

1927: L. O. Grondahl and P. H. Geiger, USA, developed copper oxide rectifiers and photocells (Grondahl & Geiger, 1927; Pearson & Brattain, 1955).

1928: Maximillian Strutt, Philips Laboratory in Holland and later a Professor of Electrical Engineering at ETH in Zurich, was the first to treat Schrodinger's equation for a periodic potential, which led to Mathieu's differential equation, solved by Floquet in 1873 (Busch, 1989; Strutt, 1928).

1928: Felix Bloch, Germany, first established the band structure of the periodic lattice. He showed the general mathematical character of the eigenfunctions of an electron in a periodic potential: the Bloch functions. Especially. he developed a theory of the temperature dependence of the electrical conductivity of metals, which led to the well-known T^5 law at low temperatures. His theory, however, did not give any clue about the existence of metals, insulators, or semiconductors (Bloch, 1928).

1930: B. Gudden, Germany, published a new review article on the electrical conduction of semiconductors. His opinion was that no *chemically pure* substance would ever be a semiconductor, and the observed properties were due entirely to *impurities.* He concluded that 'semiconductors in the scientific sense of the word—*if they exist at all*—are by far scarcer than originally assumed' (Busch, 1989; Gudden, 1930).

1926–1933: J. Frenkel (1926)**, C. Wagner and W. Schottky (**1930**,** 1931**), and W. Jost** (1933), all from Germany, developed their models of point defects in lattices, which led not only to an understanding of diffusion and ionic conductivity but also to the explanation of the *electronic* conduction of *ionic solids* (Frenkel, 1926; Jost, 1933; Wagner & Schottky, 1930, 1931).

1931: A H Wilson, England, a student of R H Fowler at Cambridge, spent about a year at the Leipzig Institute and drew the conclusions from Strutt's and Bloch's calculations. He was the first to explain the difference between metals and insulators, based on his idea of filled and empty energy bands. In 1931, Wilson published his classic papers on semiconductors and distinguished between 'intrinsic' and 'extrinsic' semiconductors, by taking account of the presence of *donors* and *acceptors*. Wilson's model immediately explains the exponential increase of the concentration of the charge in intrinsic semiconductors (Lau, 2017; Pearson & Brattain, 1955; Wilson, 1931). Busch (1989) rightly pointed out by stating "Alan Wilson, from London, is the real father of the *band theory* of *solids*, which has dominated solid state physics ever since".

1931: W. Heisenberg, Germany, gave the concept of holes. In his opinion, the empty states in the nearly full band, the holes, are equivalent to positively charged carriers. The existence of electrons and holes explains the different signs of the Hall coefficient observed in semiconductors (Heisenberg, 1931).

1933: The selenium rectifier was introduced in 1933 and found a niche in high tension power supplies. Photocells based on selenium were used in light meters.

1938–1939: Walter Schottky, Germany, Neville Mott, England and B. Davydov, Russia independently developed the theory of rectification in a metal–semiconductor junction, the type used in a cat whisker detector. The theory was developed in 1938 independently by Walter Schottky at Siemens & Halske research laboratory in Germany and Nevill Mott at Bristol University (Davydov, 1938, 1939; Mott, 1939; Schottky, 1939).

1938: Chester Carlson, USA, with his assistant Otto Kornei, developed xerography (derived from Greek for "dry writing"). They used a zinc plate coated with sulphur. Carlson eventually used selenium.[1]

1939–1944: The development of radar required the re-invention of the cat's whisker detector in the late 1930s and through World War II in the form of cartridges and glass encapsulated units (Skolnick, 2023).

1940: R. Ohl, USA, identified impurities for creating p–n junction and invented the silicon p–n junction solar cell. He got US Patent 2,402,662 in 1946 for this invention. Unlike the earlier selenium solar cells, the silicon solar cells based on the p–n junction converted sunlight much more efficiently. Ohl also got a US Patent of 2,402,662 in 1946 for his invention of the p–n junction (Ohl, 1941; Riordan & Hoddeson, 1997).

1941: J. H. Schaff of USA introduced the designation of n-type and p-type semiconductors (Scaff, 1941).

1944: **John Robert Woodyard** of USA, developed the methods for adding tiny amounts of solid elements from

[1] https://en.wikipedia.org/wiki/Chester_Carlson.

the nitrogen column of the periodic table to germanium to produce rectifying devices. The invention of doping of semiconductors was quite frequently attributed to Woodyard. He got a patent on the doping of germanium as US Patent 2,530,110, which was filed in 1944 and awarded in 1950 (Lau, 2017; Woodyard, 1944).

1940–1944: K. Lark Horowitz of the USA directed a team of workers at Purdue University to develop pure Ge crystals and the methods to dope them. The Ge crystals were supplied to Bell Telephone Labs and were used by Bardeen and Brattain in their famous experiment (Bray, 2016; Lark Horowitz et al., 1946; Lark Horowitz,1954; Pearson & Brattain, 1955).

The above paragraphs briefly outline the path of research in semiconductor physics, chemistry, devices, and growth technology from 1782 to the end of WWII. A few comments and observations are now in order.

Burgess (2008) identified three different sub-periods in the pre-transitor era: (i) Ad hoc discoveries, mainly experimental, of the now-known properties of semiconductors, like conductivity, photovoltaic effect, rectification, etc., in the nineteenth century; (ii) Early commercialization era beginning from twentieth century exploiting the properties of semiconductors and junctions; (iii) Development of theoretical understanding of semiconductors during 1930–1950. During this sub-period (iii), the involvement of industrial labs and the urge to supply devices for war-time equipment paved the way for rapid advances of the modern era.

Pearson and Brattain (1955) noted that four of the fundamental properties of semiconductors—(i) negative temperature coefficient of resistance, (ii) rectification, (iii) photoconductivity, and (iv) photoelectromotive force had been observed by 1885. However, different materials had been used to observe these properties.

The brief description of the development of semiconductors, outlined above, points out that earlier work depended largely on available materials, mainly impure and non-crystalline in nature. The role of pure crystalline materials and introduction of controlled number of dopants in them became clear after a lot of research. Before that, the pursuit of semiconductor research was considered by many as unfruitful, and the results were not beyond suspicion. Busch (1989) narrated his own experience in the introduction of his paper. He quoted a statement by Wolfgang Pauli expressing his views about semiconductor in a letter to Rudolph Peierls, which reads, "On semiconductors one should not do any work, that's a mess, who knows whether there are semiconductors at all'! (Translated by Busch from German; Pauli, 1985, p. 94).

In the period considered, the lone Indian worker is J. C. Bose, and his first semiconductor device, the galena detector. He also studied Te, another semiconductor, metals, and other materials. At his time and even a decade after that, the term semiconductor did not exist. This notwithstanding, he was given the credit of identifying p and n-type semiconductor by Sir Neville Mott, winner of Physics Nobel in 1977 (for useful sources and further discussion see Basu, 2023a, 2023b). Bose discontinued his research in physical science after 1901. The only Indian publication during the pre-transistor period is due to Dixit (1945).

4 Indian research in a decade after transistor

We now turn our attention to research in the post-transistor era. A careful search of the Indian work done nearly a decade after the invention of the transistor, from 1947 to 1959, identifies 14 publications appearing in journals. Three papers on SiC (Carborundum) were authored by two workers from Raman Research Institute, of which Ramdas wrote two on optical processes (1951, 1953), while the third paper was by Narayanan (1952) on Raman spectroscopy. Though SiC was later identified as a large band gap semiconductor, apparently, the authors intended to study the physical properties of SiC as a material used for other applications without being concerned about its semiconducting behaviour. Krishnan and Jain (1956), in their work on thermionic constants of semiconductors, used the term "semiconductor", presumably for the first time in India. The materials were, however oxide semiconductors, which till then were not much useful semiconductors for applications. Iyenger, a physicist at Bhabha Atomic Research Centre (BARC), collaborated with Brockhouse, at Chalk River, Canada, to report for the first time the lattice vibration spectra of Ge (Brockhouse & Iyenger, 1958), a semiconductor of contemporary interest.

The vibrational spectra of Ge were obtained using the neutron diffraction technique. Brockhouse (1959) alone reported similar spectra for Si next year. However, after his return to India, though Iyenger continued his studies to find vibrational spectra of different materials, semiconductor were not on the list of materials studied by him and his group. Moreover, his work on Ge was done in Canada. It may be mentioned that Brockhouse earned the Nobel Prize in Physics in 1994.

The first Indian paper related to transistor using Ge is due to Daw (1955), in which two transistors were connected in parallel to increase the overall power output and other characteristics of a transistorized circuit. Daw developed an equivalent circuit model for the parallel configuration using the then reported equivalent circuit model of an individual transistor. He then used Ge transistors, available commercially at that time, to verify experimentally his theoretical values. An account of his work has been given in a separate publication by Basu (to be published). Work related to transistors were carried out further and reported by, Achuthan (1957), Bhattacharyya

(1957), Bose (1958), Deb and Daw (1958, 1959a, 1959b), and Deb and Sen (1959). The authors studied the performance parameters of transistors and investigated some physical properties of semiconductor materials useful for transistors.

5 International research in a decade after transistor

In sharp contrast, many workers in different countries, mainly in North America and Europe, as well as in Japan, got deeply involved in the study of physical, chemical, and material properties of semiconductors, identification of new semiconductor materials, like compound semiconductors, the study of device physics and growth and characterization of materials and junctions and development of new circuit applications. It is nearly impossible to mention all such activities, even in the decade after the invention of transistors. Instead, the author has selected, rather arbitrarily, a few notable activities that expanded the knowledge of semiconductor science and technology. Table 1 gives a narrow cross-section of the activities of the international community.

Table 1 clearly indicates the involvement of many researchers in many countries in research in the area of semiconductors in the decade following the invention of transistor. The list of workers includes 10 Nobel laureates already in the group and to be included later, e.g., Feynmann, Esaki, Mott, Kilby, Kroemer, Kohn, and Brockhouse. Other workers represent the elite group of theoretical and experimental physicists.

6 Priority for semiconductors in India and abroad

It is clear from Sects. 4 and 5 that while the international community of researchers was keen on pursuing research in semiconductors, Indian workers either hardly realized the importance of the subject or did not consider entering into the new subject of research. We now attempt to find out in more detail the reasons behind such differences in attitude and approach.

First, all European countries and, later, the USA had a long tradition of semiconductor research over centuries. Many workers were involved in understanding the special characteristics of semiconductors, even before the term semiconductor was coined. They continued their research despite many uncertainties in getting fruitful results. Furthermore, easy access to journals, personal exchange of letters, and international collaboration created a strong knowledge base for the subject. Though vacuum tubes were used more for instrumentation and commercial applications, rectifier diodes found a niche by replacing tubes in a few cases.

The development of RADAR during World War II placed a demand for better cat's whisker diodes for efficient detection of microwave signals. The need for replacing vacuum tube amplifiers and bulky mechanical switches in telephone networks with a solid-state device was felt by American Telephone and Telegraph Co., a telecommunication giant in USA before 1940. The company formed a research group under W. Shockley in its research lab, Bell Telephone Lab, as early as in 1940. The involvement of almost all scientists in WWII halted the project for some time, but work resumed after the end of the war. Shockley and his team first tried on Shockley's concept of conductivity modulation. The experiment did not lead to any amplification of signals. Thereafter, Bardeen and Brattain reported their path-breaking research on point contact transistors (see Riordan & Hoddeson, 1997, for a detailed account).

Transistor's enormous potential and commercial value instantaneously impacted manufacturers and scientific workers in academic institutions and research labs. During the next decade, all workers developed a fine infrastructure for growing good-quality samples and devices, optimizing device performance, and developing a strong knowledge base of theory. In addition, there was ample support from the Governments of all the countries. Many new industries were born to use transistors for hearing aids, and pocket calculators and computer giants like IBM, and other manufacturers like RCA, GE, Motorola, Texas Instruments, Westinghouse, GEC, Philips, Siemens, Sony, to name a few, started using transistors to replace tubes and introduced new appliances for use by common people.

We now discuss the research environment in India. Modern research was definitely initiated by Acharya J.C. Bose without any support from British India. He made many breakthroughs in physical sciences during a limited period covering 1894 to 1901. After that, his focus was shifted to plant science. No worker pursued research in semiconductors after him. The only publication after J. C. Bose was by Dixit (1945) who reported his studies on Cu–CuO_2 rectifiers.

Indian research in physical science quickly attained a high level from almost zero with groundbreaking research by C.V. Raman, D. M. Bose, S.N. Bose, M. N. Saha, H.J. Bhabha, S.K. Mitra, K.S. Krishnan and few other notable scientists. Most of them created their dedicated research teams in many institutions. Their work focused on mathematical physics, quantum theory, particle and nuclear physics, spectroscopy, Xray, astronomy, astrophysics, and ionospheric and space physics. The instruments they developed or used were naturally tube-based. They were either unaware of the term semiconductors and devices or, at best were uninterested in the subject. Research conducted in Applied Science departments, notably the Department

Table 1 Representation of international activities in the next decade after transistor

Year	Authors	Country	Brief description of work (reference)
1947	Bardeen, Brattain	USA, both NL-P 1956	Ge point contact transistor (Bardeen & Brattain 1948, 1949)
1948	Welker and Matare	Germany/France	Transitron/equivalent of transistor (see Riordan 2005)
1951	Shockley et al	USA, NL-P 1956	Junction transistor, p–n junction theory (Shockley et al 1951; Shockley 1953)
1949	Schaff et al.	USA	Formation of barrier in p–n junction of Si (Schaff et al 1949, 1951)
1953	Sparks and Teal	USA	Growth of single crystal Ge by Czochralsky method
1950	Nishizawa and Watanabe	Japan	Static induction transistor, Japan patent
1950	Fröhlich et al.	UK	Electron properties in polar materials
1950	Gubanov	USSR	Theory of contact between two semiconductors (heterojunction)
1950	Bardeen and Shockley	USA; both NL-P	Deformation potential theory to calculate conductivity mobility
1951	Shockley et al.	USA	First Ge n–p–n transistor
1952	Pfann	USA	Zone refining
1951	Goryunova	USSR	Potential for III–V semiconductors (see Lau, 2017)[a]
1952	Welker	Germany	Proposal for III–V semiconductors (Welker 1952)
1953	Schokley	USA	Book "Electrons and holes in semiconductors"
1957	Chapin et al.	USA	Solar cell (US patent)
1955	Kohn and Luttinger	USA; Kohn: NL-C 1998	Theory of donor states
1955	Dresselhaus et al.	USA	Effective mass of electrons by cyclotron resonance experiment
1955	Herman	USA	The electronic energy band structure of silicon and germanium
1957a, 1957b	Kroemer	Germany/USA, NL-P 2000	Work on heterojunction (contact between two dissimilar semiconductors)
1957	Elliott	UK	Theory of excitons (bound electron–hole pairs)
1957	Schrieffer	USA; NL-P 1973	Concept of quantized levels in strongly inverted surface leading to realization of low dimensional electron gas
1958	Brockhouse and Iyenger	Canada: Brockhouse—NL-P 1994	Neutron diffraction to obtain phonon spectra of Ge
1958	Franz	Germany	Change in optical properties under external electric field
1958	Keldysh	USSR	Change in optical properties under external electric field; work of both is known as Franz–Keldysh effect
1959	Kilby	USA, NL-P 2000	Realization of IC with discrete components (work presented in 1958 in conference; US patent application in 1959
1959	Noyce	USA	Fabrication of IC on Si substrate by using planar technology. US patent application in 1959
1958	Esaki	Japan; NL-P 1973	Invention of tunnel diode
1958	Atalla	USA	Si passivation by growth of oxide
1959	Kane	USA	k.p perturbation theory for band structure
1959	Feynmann	USA; NL-P 1965	Concept of nanotechnology using semiconductor devices and other systems[b]

[a] Nina Aleksandrova Goryunova (1916–1971) of USSR also recognized the potential of III-V semiconductors. Goryunova described III–V materials as semiconductors for the first time in 1950 and in her Ph.D. dissertation, completed in 1951 at Leningrad State University

[b] There is plenty of room at the bottom, Address given in Annual Meeting of APS.This transcript of the classic talk that Richard Feynman gave on December 29th, 1959 at the annual meeting of the American Physical Society at the California Institute of Technology (Caltech) was first published in Caltech Engineering and Science, Volume 23:5, February 1960, pp. 22–36. It has been made available on the web at http://www.zyvex.com/nanotech/feynman.html with their kind permission. The scanned original is available

of Applied Physics in CU and the Electrical Engineering Department in IISc, concentrated on power generation, transmission, communication, acoustics, microwaves and space physics. In many institutions, research in the pre-independence period was supported by Indian philanthropists and, to a very limited extent, by the then-British Government.

The question then arises: *Why Indian Scientific community did not rise to the occasion just after transistor?* The main answer may be that researchers in Indian institutions preferred to continue their own lines of research. It may also be possible that they were not properly aware of the latest developments in electronics and electron physics. Furthermore, semiconductor research was not on the priority list of Indian physicists working in reputed institutions. Ramdas and Narayan worked in RRI and Jain in NPL with Krishnan. All of them aimed to investigate the physical processes and phenomena in different materials, not primarily in semiconductor materials and their electronic properties. Both Ramdas and Jain later got involved in semiconductor research. After his return, Iyenger worked with Brockhouse in Canada and pursued his work on lattice dynamics in BARC. However, research in semiconductors was not on the centre's agenda.

It is also of interest to note that no physicists from other established institutions like Universities of Calcutta, Madras, Delhi, Allahabad, BHU, etc., and IISc, and older institutions like IACS and Bose Institute and newer ones like NPL, CEERI, or TIFR, or even a few IITs established in 1950's did not publish in the area of semiconductors. The notable exception is Electronics and Communication (ECE) department of IIT Kharagpur, with two publications on transistors during 1950s.

It is to be noted that the invention of the transistor occurred merely 4 months after the independence of India. The next decade was challenging for Independent India, necessitating policy making in many different areas. Though education and research were encouraged, it was not a suitable period for established institutions to embark on new research areas, particularly in the field of Electronics, in which strong knowledge and awareness were not available. This may seem quite reasonable in explaining the paucity of research publications on semiconductors in the period of concern.

In sharp contrast, the first papers on transistors and semiconductors, only a handful, came from the researchers from the new Institute of Radio Physics and Electronics (InRaPhEl), University of Calcutta (CU), established in 1949 and from ECE department of IIT Kharagpur. It is worthy to note that the first paper from India on the transistor by Daw (1955) appeared only 6 years after the invention of the transistor. Daw got an M.Sc. in RPE in 1952, while Deb, an M.Sc. in Physics from CU, joined RPE as a Lecturer in 1951, and taught Daw and many others. Daw (1955) acknowledged Deb as his supervisor in his paper. After researching on microwaves and vacuum tubes, Deb started work in semiconductor device physics. He may rightly be given the credit of initiating real semiconductor research in India.

Institute of Radio Physics and Electronics was established in 1949 by Prof. S. K. Mitra, the pioneer in radio research in India. It is the first department in any university in India to be engaged in teaching and research in all branches of radio science. Mitra worked in CU under Raman and, after submitting his D.Sc. went to France to work with Mme Curie and then Charles Fabry. However, he soon realized the enormous potential of Electronics that had opened after World War I. He introduced a special paper on Wireless in 1924 and established a wireless lab in the Pure Physics department of CU after resuming his work at CU and published his seminal work on the E layer of the upper atmosphere. He had close contacts with all international leaders in ionospheric and electronics research. After establishing InRaPhEl, he appointed bright young faculty members, encouraged them to initiate research in emerging areas, and sent a few faculty members abroad to learn new subjects and emerging research areas. He read all the journals received by the Institute and distributed new research findings amongst the faculty members interested in the particular area. Thus, Deb and Daw might have received the latest information, including transistors and semiconductors, from him, as well as browsing available journals and periodicals on campus. Prof. Hrishikesh Rakshit, a Ph.D. student of Prof. Mitra in CU, was the first Head of the Department of ECE in IIT Kharagpur. He was likely aware of the enormous potential of electronics and semiconductors, which might have encouraged Achuthan (1957) and Bose (1958) to pursue research on transistors.

This new and exciting field of semiconductors thus became the playground of newer generations of physicists and electronic scientists in two infant departments. Other new institutions like IITs, TIFR, etc., might not be geared up to initiate research or be fully aware of this invention's potential. However, there was a boom in activities during the next two decades with significant contributions from workers in InRaPhEl, Jadavpur University, IISc, TIFR, BARC, IITs, BHU, Delhi University and other universities, CSIR Labs and SSPL. Detailed accounts of the activities in different institutions are planned to be given in future publications.

7 Conclusion

A brief history of semiconductors and devices is outlined for the pre-transistor period, including J C Bose's work. The activities by Indian and international researchers in the next decade presented thereafter point out a lack of interest and awareness in India, and an attempt is made to find out the reasons for the apathy.

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