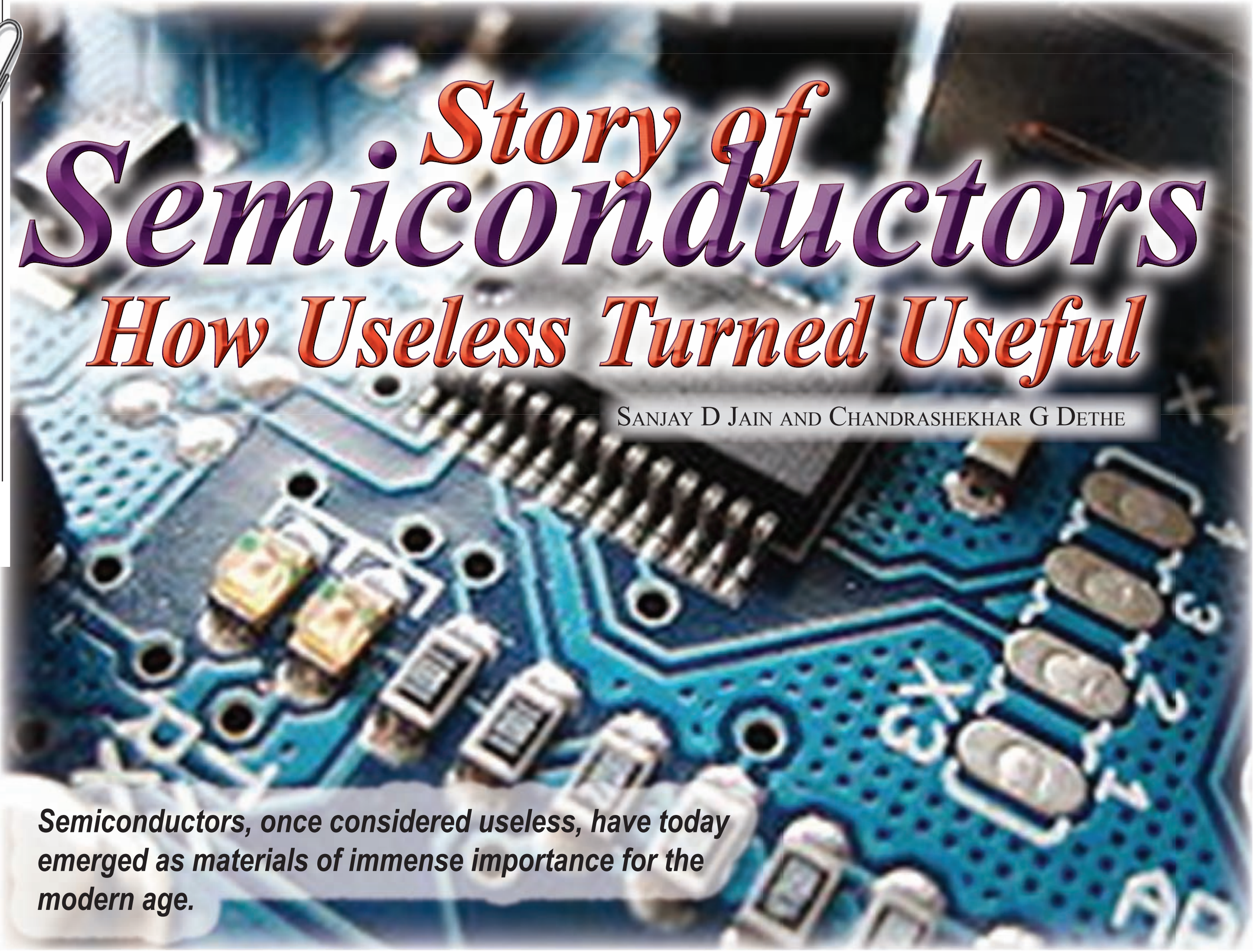

Story of Semiconductors
How Useless Turned Useful

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Semiconductors, once considered useless, have today emerged as materials of immense importance for the modern age.

We cannot think of the modern world without mobile phones, laptops, television sets, digital cloaks, video games and many other such products. However, none of these would have been possible today had semiconductors not been discovered. Semiconductor devices are at the heart of the microelectronic revolution that ushered in the information age of today.

However, till about a hundred years back these most useful materials of today were considered almost useless. Ever since engineering began to work with electricity, materials of two categories—conductors and insulators—have been in use. The use of a current-carrying metallic wire clad with an insulating material shows that these materials enjoyed almost equal importance in electricity. Semiconductors had been known for quite some time – but as materials good for nothing – neither good conductors, nor good insulators. Both electrical engineering and electronics paid no attention to them for a long time.

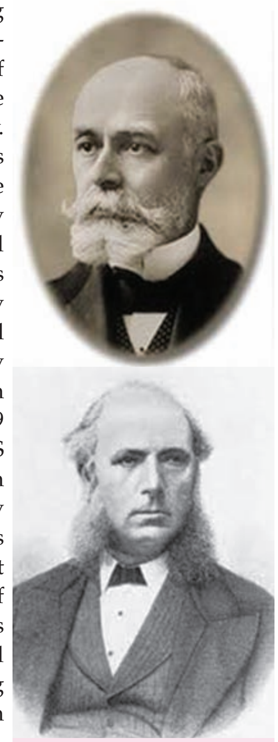
Early History

Conductors and insulators were clearly differentiated on the basis of whether they assist or oppose the flow of free electrons under the application of a voltage. It was also well understood that a conductor, when heated, should decrease its resistivity because heat randomizes the electron flow thus reducing the current flow.

Michael Faraday

Semiconductors behave oppositely, that is, their resistivity decreases upon heating. This was noticed by Michael Faraday the first time in 1833 when he found that the resistance of silver sulphide decreased with temperature. This is considered the first documented observation of a semiconductor effect.

In the following years some interesting properties of semiconductors were noticed sporadically. Semiconductors also show a change in their resistivity when illuminated with light. This was observed by Alexandre Becquerel in 1839 and by Willoughby Smith in 1873. In 1879 Edwin Hall, a US physicist, made an important discovery that charge carriers in solids deflect in the presence of magnetic field. This discovery proved useful in studying semiconductors in later years.



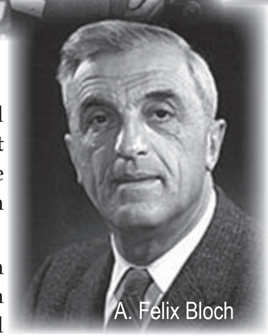
Alexandre Becquerel (Top)
Willoughby Smith (above)


Karl Braun (left)

Semiconductors, once considered useless, have today turned most useful and have emerged as materials of immense importance for the modern age.


Enrico Fermi


P. A. M. Dirac


A. Felix Bloch


Rudolf Peierls

Some semiconductors emit light when electric current is passed through them (the principle behind the light emitting diode). This was observed by H.J. Round in silicon carbide crystals in 1906. Semiconductors can also convert ac into dc, a phenomenon called rectification. This was observed by Karl Braun and Arthur Schuster in 1874.

These unique properties were also converted into useful applications by scientists of that era. In 1880, Alexander Graham Bell used the light-sensitive property of a semiconductor to transmit sound over a beam of light. In 1904, Jagadish Chandra Bose made use of point-contact microwave detector rectifiers made of lead sulfide. He was the first to use semiconductor junctions to detect radio signals. The significant contributions of J.C. Bose were highlighted by Sir Nevill Mott, Nobel Laureate in 1977 for solid-state electronics, in the words: "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".

Band Theory Opens New Treasures

The first quarter of the last century saw emergence of quantum mechanics which unraveled many mysteries of the microworld. This knowledge was applied by both physicists and engineers with lot of enthusiasm to probe deeper into the mechanisms of electrical conduction in solids.

In 1926, Enrico Fermi, an Italian physicist, along with P.A.M. Dirac, an English theoretical physicist who studied electrical engineering before switching first to mathematics and then to physics, put forward a theory that collective behavior of electrons in a solid can be studied using what came to be known as Fermi-Dirac statistics. Electrons came to be known as fermions in this theory.

In 1928, A. Felix Bloch, a Swiss physicist, who did his undergraduate work in engineering, systematically studied the effect of periodic potential (produced by atoms in solids) on electron motion and explained the formation of energy bands in solids. In 1930, Rudolf Peierls presented the concept of forbidden gaps and in 1931 Alan Wilson developed the band theory of solids based on the idea of empty and filled energy bands. In the same year Heisenberg developed the concept of "hole" that was pioneered by Rudolf Peierls.

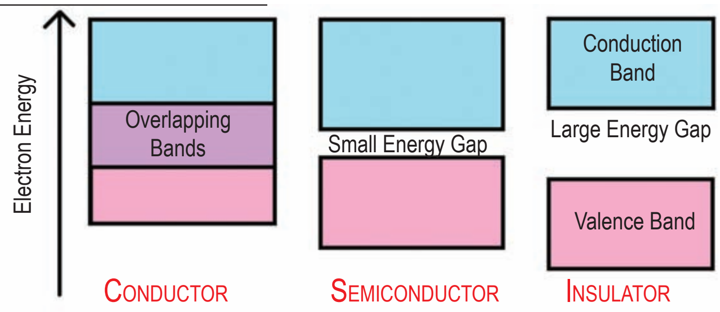
Band theory is based on the concept of energy bands in solids that get formed due to splitting of energy levels that are present in individual isolated atoms. When such atoms at large distances (as they are in a gas) are brought together to form closely packed aggregates (as they are in a solid) each level splits into the same number of levels as the number of atoms brought together. As 6.0221×10^{23} atoms form one mole of a solid, splitting of individual levels into such an enormous number converts energy levels into energy bands. The diagram showing the splitting of levels as the interatomic distance is reduced is called the band diagram and each solid has a unique band diagram that decides its electrical behavior.

The lower energy band so formed is called the valence band and the higher energy band is called the conduction band. The energy difference between them, called the forbidden energy band gap, emerged as a concept of crucial importance in band theory. In this picture the process of making a bound electron free is modeled as an electron jumping from the valence band to the conduction band and energy gap is basically the energy required to achieve this.

Thus, it was understood that materials in which the energy gap is zero (i.e., the two bands overlap) contain ample free electrons and hence conduct electricity (conductors). Materials having a large energy gap have majority of their electrons bound and hence do not conduct electricity (insulators).

Semiconductors were now understood as materials with small and surmountable energy gap, i.e., materials in which electrons are not free but they are also not bound as strongly as they are in insulators and can be promoted from valence band to conduction band by supplying a small amount of energy – equal to the energy gap.

During the same period Robert Pohl who was pioneering experimental research in semiconductors observed that the properties of semiconductors change drastically with the addition of small amounts of impurities.



A simplified diagram illustrating the energy bands of an insulator, a semiconductor, and a conductor

Band theory provided deeper insight into the novelties of semiconductors and opened new treasures of knowledge. As capabilities of semiconductors started getting noticed, a large number of them were probed with silicon and germanium attracting most of the attention due to a very high degree of purity obtainable with them.

Germanium was isolated as a new element in 1886 by the German chemist Clemens Winkler who gave this name in honour of his homeland. However, Mendeleev had already predicted the existence of germanium in 1869 and called it ekasilicon to bring home its closeness with silicon, which was already known at that time. When the UK and the US were working on a radar project during World War-II they heavily funded semiconductor research and the material that came to their assistance was germanium. It was an irony that the material that was discovered in Germany was also responsible for the defeat of Germany.

Development of Semiconductor Devices

Earlier, the devices based on semiconductors were constructed using empirical knowledge, but band theory provided a guide to construction of more capable and reliable devices. The knowledge of band theory also found applications in the development of tailor-made materials of desired band gap for specific applications. This came to be known as band gap engineering.

That the number of free electrons (and hence the electrical properties) of a semiconductor could be controlled externally either with the supply of Eg or by doping (adding in small quantities) it with impurities became the basis for the development of many semiconductor devices. Photoconductor and thermistor are two examples of such devices, which employ optical energy and thermal energy, respectively, for making electrons free. However, the most remarkable improvement in the electrical conductivity of semiconductors was found with doping. For example, the addition of 1 phosphorous atom per 108 silicon atoms is found to increase the electrical conductivity of silicon about 27,000 times.

These results could be explained using the concept of hole. An electron jumping from valence band to conduction band is said to leave behind a hole. Though hole is just a vacancy created by an electron leaving its usual place, the concept became very useful in understanding the mechanism of conduction in semiconductors. Like air bubbles in a tube filled with water and closed at each end, holes – considered as carriers with positive charge moving opposite to the flow of electrons – came to be understood as additional contributors to conduction in semiconductors. Semiconductors now came to be known of two types – p-type semiconductors in which holes are majority carriers and n-type semiconductors in which electrons are majority carriers.

Development of n-type and p-type semiconductors further led to the development of many new and novel devices the foremost among them being the p-n junction diode. The first p-n junction in silicon was observed by Russell Ohl, an American engineer who was a notable semiconductor researcher, in 1941.

Russell Ohl

P-N junction diodes replaced the existing vacuum tube diodes due to advantages in cost, size, reliability and efficiency. Several other diodes have been developed so far to serve a wide range of applications including the well-known applications for rectification and voltage regulation (see Table 1 for a few examples). These discoveries triggered renewed interest among physicists and engineers to develop devices based on p-n junction, called the junction devices.

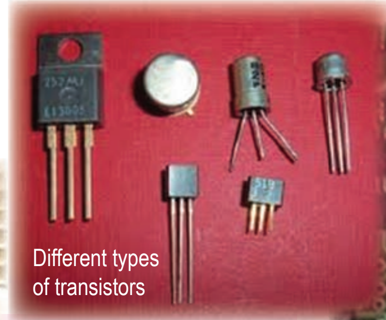
The crowning achievement came in 1948 when Schockley, Bardeen and Brattain made one of the most remarkable discoveries of the twentieth century, the discovery of a transistor. Coming from three different countries (Schockley from England, Bardeen from USA and Brattain from China) and with different interests (Brattain was more interested in experiments whereas theory interested Bardeen and Schockley more) they worked together in a semiconductor research group of Bell Telephone Laboratory, USA to develop this fundamental building block of the modern electronic industry.

Transistor is an ingenious discovery. By appropriate doping of its three regions (emitter, base and collector) and biasing of its two diodes (emitter-base diode and base-collector diode) it makes almost the same current flow from a region of low resistance to a region of high resistance. It is not possible to construct an electrical

TABLE 1: EXAMPLES OF DIODES AND THEIR APPLICATIONS

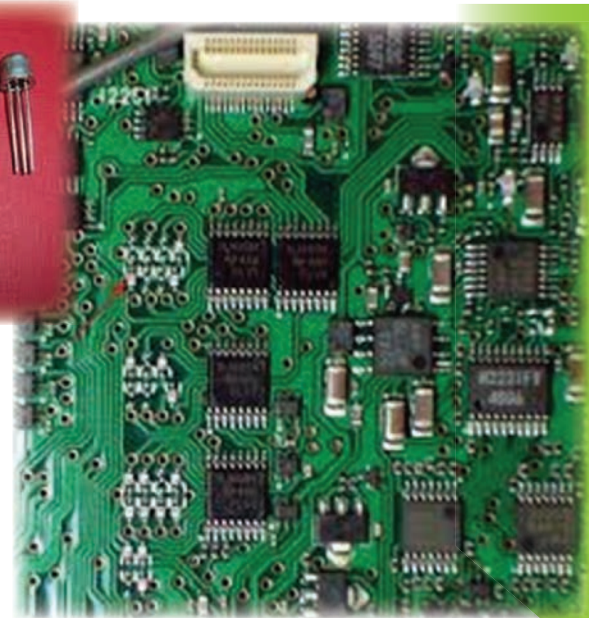
Diode	Applications
Zener diode	As voltage regulation devices
Tunnel diode	As microwave negative - resistance amplifiers and oscillators and as fast switches in computers
Varactor diode	As low noise parametric amplifiers, harmonic frequency generators and frequency converters or mixers
Photodiode	In sound films, computer cards and light driven switches
Solar cell	In space applications for converting solar energy into electrical power
Light Emitting Diode	As light emitters in visual display units and in production of optically coupled circuits.

Schockley, Bardeen and Brattain



Different types of transistors

Jack Kilby



Integrated Circuit

circuit that can achieve this because current always diminishes when flowing through a high resistance. Aptly named as transistor (contraction of transfer + resistor) for this reason, it makes electronically possible what is electrically impossible.

Transistor, like diode, also evolved in different forms and types to serve different applications. From the earliest npn and pnp types many new types were invented, a few of which are field effect transistor (FET), junction field effect transistor (JFET) and metal-oxide-semiconductor field effect transistor (MOSFET).

As the tree of knowledge expanded, it paved way for the progressive miniaturisation of electronic components and circuits. The problem which the electronic industry now faced was how to assemble a large of number of transistors on a board to achieve circuits that could perform complex tasks. A breakthrough came in 1958 from a brilliant engineer at Texas instruments, Jack Kilby, who proposed a revolutionary concept of creating all components of an electronic circuit in a single semiconductor chip, called an integrated circuit (IC).

The Chip Revolution

Since the invention of the first IC, the size and cost of IC has been steadily decreasing. This progress received a major boost in the early 1970s when Hoff and his team developed the first microprocessor, an IC chip capable of performing all functions of the computer's central processing unit (CPU). In 1976, Intel announced the production of an eight-bit computer on a single silicon chip.

The miniaturization of technology made the chip a ubiquitous component of almost all modern gadgets and machines such as CPU and RAM chips in computers, chips in automobile engineering to improve fuel economy and reduce pollution, chips for games and entertainment, and chips for implants used in medical technology. The chip revolution made the most profound impact on our society. It ushered in the era of the smart technology.

Smart technology uses computer systems and microprocessors to enable everyday tasks, e.g., automatic teller machine (ATM), bar code scanners and biometric security machines. A smart card has embedded integrated circuits that can store a vast amount of data and programs that can be used for purposes such as identification and authentication. Biometric security machines scan a part of a person's body and compare the scanned image to identify that person.

Gordon Moore, the co-founder of Intel, predicted in 1965 that the number of transistors on a chip would double every year in the same cost of production. This is known as Moore's law. At that time chips had only 50 transistors; today a chip can have more than 1 billion transistors. The trend has continued so far and is not expected to stop until 2015 or later. Lawrence Krauss and Glenn Starkman even announced an ultimate limit of around 600 years for Moore's law.

As the story unfolded, the range of applications for semiconductors widened. Semiconductors, once considered useless, have today turned most useful and have emerged as materials of immense importance for the modern age.

Smart technology has enabled everyday tasks such as ATM, biometric security machines and bar code scanners

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