International Journal of Advanced Multidisciplinary Research
ISSN: 2393-8870
www.ijarm.com
(A Peer Reviewed, Referred, Indexed and Open Access Journal)
DOI: 10.22192/ijamr Volume 9, Issue 1 -2022

Review Article

DOI: http://dx.doi.org/10.22192/ijamr.2022.09.01.004

The journey of Semiconductor Research: Study

Shivpal Yadav
University of Allahabad, India, Prayagraj, 211002.
E-mail: *yadavshivpal05@gmail.com*
https://orcid.org/0000-0002-5975-9674

Keywords

Semiconductor, Vacuum tubes, Diodes, Transistors, LED, Laser, IC and Fairchild, Intel, MOSFETs, FETs, CMOS.

Abstract

Nowadays Human life is completely fulfilled by electronic gadgets. The Heart of electronic gadgets is a semiconductor. Semiconductor research started from VOLTA (inventor of the battery) and or FARADAY. Semiconductor research started in practical view or manufacturing, with Bose's research (cat's whisker) in the 1890s. Here, You can get information about the contribution of scientists in semiconductor research and also you can see how much development in semiconductor research in 19th, 20th and 21st century. Remembered, the contribution of industries founded from the preliminary stages of semiconductor products to modern and their great impact on the semiconductor industry/market and its growth. A brief historical journey of the creation of vacuum tube, diode, transistor, IC, laser and LED is also mentioned here.

[In memories of first crush/love]

1. Introduction

Many people believe that metals are classified into conductor, semiconductor and insulator. Metals are classified into only two categories as conductor and insulator. Silicon is an insulator, but when it is mixed with impurities like oxide, sulphide, it behaves like a half/nearly-conductor, which means its conductivity lies between a conductor and insulator. Semiconductor research has evolved around three products: vacuum tubes, transistors and integrated circuits. Many geniuses have contributed to semiconductor research. I will try to collect all the experiments on them.

In 1883, Thomas Alva Edison discovered the Edison effect and then Fleming applied it to create a vacuum tube diode. In the amplification and distribution of electrical energy, diodes and triodes were instrumental. While vacuum tubes were expensive, fragile and had high energy consumption. Metal-semiconductor contacts date back to Braun's early work in 1874, who discovered the asymmetric nature of electrical conduction, such as copper iron and lead sulphides, between metal contacts and semiconductors. This is the first report of asymmetric conduction and divergence from the law of Ohm.

Selenium was the most important semiconductor of the 19th century, Because of its photoelectric properties, a large number of scientists, like Smiths Adams and Day Fritts, were attracted to research. As a matter of the fact, the photoelectric effects were first observed in the semiconductors (as early as 1873). The first observation of photoelectric properties in metal came in 1887 by Hertz.

Edison effect rectification in a vacuum tube was discovered in 1884, rectification at Electrode - electrolyte contact was discovered sometime during the end of the century. This effect is the basis of the basic and simplest electronic component the diode. By 1935, selenium rectifiers and silicon point-contact diodes were available for use as radio detectors. In 1942, Bethe developed the thermionic-emission theory, according to which the current is determined by the process of the emission of electrons into the metal rather than by drift or diffusion. With the development of radar, the need for better and well-grounded detector diodes and mixers increased. Methods of performing high purity silicon and germanium were developed during this time, and germanium diodes became a key component in radar systems during World War II. In 1947, John Bardeen, Walter Brattain and William Shockley at Bell Telephone Laboratories (BTL) developed the transistor, and they received the Nobel Prize for their creation.

The circuits at that time were discrete/ discontinuous in that each element had to be individually connected by wires to form the circuit. In 1952, An idea of an integrated circuit was proposed by Geoffrey W. A. Dummer, a British electronics expert in the Royal Radar Establishment. Circuits consist of many active devices (transistors, diodes, etc.) and passive devices (capacitors, resistors, etc.) both can be fabricated on a single unit of semiconductor material. The first IC was fabricated in February 1959 by Jack Kilby of Texas Instruments. In July 1959, a planar version of the IC was independently developed by Robert Noyce of Fairchild. The time delay of signals between devices is short, so that high frequency and high-speed circuits are now possible with IC that were not practical with discrete circuits. In high-speed computers, for example, the logic and memory circuits can be placed very close to each other to minimize time delays. From 1961, mostly all semiconductor affiliated firms are produced integrated circuits with designs of equipment changed rapidly and ready to adopt new technology. Bipolar junction transistors and digital integrated circuits were made first, but analogue integrated circuits, like large-scale integration (LSI) and very-large-scale integration (VLSI) followed by the mid-1970s. VLSI consists of thousands of circuits with on and off switches or gates between them on a single chip. Microcomputers, medical equipment, video cameras and communication satellites are the only example of devices made possible by IC.

Practical MOS (metal-oxide-semiconductor) transistors were then developed in the mid-1960s and 1970s. The MOS technologies, especially CMOS (complementary metal-oxide-semiconductor), have become a major focus for IC design and development. Silicon is the main semiconductor material, while gallium, arsenic and other compound semiconductor materials are used for optical devices and special applications requiring very high-frequency devices.

Semiconductor devices can be classified into:

(I) TWO TERMINAL: Gun diode and Tunnel diode, Laser diode, LED, Photocell, Solar cell, etc.

(II) THREE TERMINAL: Bipolar Transistor, Darling ton Transistor, Field Effect Transistor, Thyristor and Unijunction Transistor.

(III) FOUR TERMINAL and MULTITERMINAL: RAM, ROM, Microprocessor and IC.

2. Semiconductor research in 18th -19th century [rectification, photovoltaic and diodes]:

Alessandro Giuseppe Antonio Anastasio VOLTA (1745-1827) is famous as the inventor of the battery, In1782, VOLTA published a paper in Philosophical Transactions of the Royal Society of London. It was unclear, but in the English translation, a small passage can be found as follows:

"The surface of those bodies does not contract any electricity or if the electricity adheres to them, it vanishes soon, on account of their semi-conducting nature; for which reason, they can't answer the office of an electrophorus and therefore are more fit to be used as condensers for electricity.''[ULSI front-end technology]_[2]

Thus, we can say that the term semiconductor was first used by VOLTA in 1782.

HUMPHRY DAVY (1778-1829), discovered Chlorine and Iodine. In 1821, Davy observed the effect of increasing temperature on the electrical conductivity of metals as follows.

"The most remarkable general result that I obtained by these researches, and which I shall mention first, as it influences all others, was that the conducting power of metallic bodies varied with the temperature and was lower in some inverse ratio as the temperature was higher.'' [ULSI front-end technology]_ [2]

MICHAEL FARADAY (1791-1867) was a British chemist and physicist, In 1833 he observed that the electrical conductivity of silver sulphide increased (or resistance of silver sulphide decreased) with increasing temperature as follows,

"The effect of heat in increasing the conducting power of many substances, especially for electricity of high tension is well known. I have lately met with an extraordinary case of this kind, which is well known. I have lately met with an extraordinary case of this kind, for electricity of low tension or that of the voltaic pile and which is in direct contrast with the influence of heat upon metallic bodies and described by Sir Humphry Davy."_ [2]

Michael Faraday once a time served as Davy's assistance.

The first observed off the semiconductor property Faraday's 1833 report on the negative temperature resistance coefficient of silver sulphide. For a metal, with increasing temperature, the electrical conductivity decreases. Thus Faraday's effect or the semiconductor effect usually found that semiconductor is opposite to metals in this situation.

2.1. Photovoltaic effect: In 1839, A French scientist ALEXANDRE- EDMOND BECQUEREL (1820-1891) discovered the photovoltaic effect. He was the father of HENRI BECQUEREL, who was a winner of the 1903 NOBEL PRIZE for discovering radioactivity. He (A.E. Becquerel) discovered the photovoltaic effect at a junction between a semiconductor and an electrolyte. Two metal electrodes are connected to the electrolyte and semiconductor respectively. In his experiment, AgCl coated a platinum electrode was immersed in an aqueous nitric acid electrolyte solution. Illumination of the electrode generated photovoltaic. It produced a reductive photo-current at an electrode. Today's this type of device, known as photo-electrochemical solar cell, for example, semiconductor liquid junction solar cell.

WILLOUGHBY SMITH (1828-1891), an electrical engineer, working on underwater telephone cable projects. In 1849, he supervised the manufacturing laying of 30 miles of underwater telephone cable from Dover. In 1873, Smith reached the discovery of the photo-conductivity of selenium by a beautiful experimental story. Smith developed a system for continuous underwater cable checking while it was being laid down. Smith wanted a material with very high resistance, but not a complete insulator for his testing circuit. He preferred selenium rods that were appropriate for submarine telegraphy. Selenium showed some form of unpredictable resistance, it turned out. Smith noticed that the resistance of the selenium depended on light shining on it. The selenium was loaded into a sliding cover container. With the cover closed, the resistance was top, but it dropped when the cover was open such as the light shining on the selenium. In 1873 in "*issue of scientific journal nature*," Smith published a paper on its title "*Effect of light on selenium during the passing of an electrical current."*

W.G. ADAMS (WILLIAM GRYLLS ADAMS 1836-1915) and R.E.DAY(Richard Evans Day, student of Adams) observed the photovoltaic effect in selenium without any liquid and reported, their his observation in 1877. This selenium may be considered as the first semiconductor solid-state electronics discovered by mankind. In 1883, CHARLES EDGER FRITTS built a selenium solar cell. Thin selenium wafers are known to be shielded by a very thin semi-transparent gold wires and a protective layer of glass. BUILTKURT LEHOVEC (1918-2012) may be the first scientist who came up with an explanation of the solar cell effect. In 1948, he published his theory in the US Journal of Physical Review. He is also known as the inventor of p-n junction isolation, which is most useful in integrated circuit technology. *[2]*

2.2. Rectification:[one of the biggest discovery of 19th century in semiconductor research]: KARL FERDINAND BRAUN (1850-1918), German scientist, who shared 1909 NOBEL PRIZE with Guglielmo Marconi in recognition of their contributions to the development of wireless telegraphy. In 1874, Braun disclosed his discovery of the rectification effect at the contact between certain materials, especially natural crystals. He noticed that the resistance of the semiconductor, natural crystal (sulphide component) depends on the polarity and magnitude of the applied voltage as well as surface conditions. From his 1874 papers,

"With a large quantity of natural and artificial metallic sulphides 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."[ULSI front-end Technology]_ [2]

Braun's work, the asymmetric current-voltage characteristic first reported by Braun in 1874 papers, is so remarkable. Those materials that obey Ohm's law (conductor), has a current-voltage characteristic curve that is linear as well as symmetric. For certain metallic sulphides (today's semiconductor), Braun thus stated that the presence of non-linear and asymmetric current-voltage characteristics. For example, lead sulphide (PdS) is a semiconductor with a band-gap of about 0.4electron-volt. Galena is a naturally occurring mineral form of lead sulphide. The theory of asymmetric current-voltage characteristics was explained by German scientist WALTER SCHOTTKY.

In 1874, rectification was observed in a circuit made of copper wires linked by screws by Arthur Schuster. Schuster's discovery of rectification to contacts between the tarnished and untarnished copper wire. Schuster observed that only after the circuit was not used for some even does the effect appear. The rectification was gone as soon as he cleaned the ends of the wires (that is, removed copper oxide). This is how copper oxide was discovered as a new semiconductor. That is Braun experimented on nearly all natural metallic sulphides and pyrites, like copper pyrite, iron pyrite, galena and tetra-hedrite (copper antimony sulphide). He continued his experiments until 1883. The copper oxide coating on the untarnished wire probably acted as the semiconductor in Schuster's experiment, giving a rectification property to the touch. In 1929, the existence of a barrier in a metal-semiconductor junction was confirmed experimentally by Walter Schottky.

2.3 Vacuum tube era: The discovery of germanium element (Ge) is attributed to German chemist CLEMENS ALEXANDER WINKLER (1838-1904). Silicon was discovered before germanium. In 1824, Swedish chemist Jones, Jacob Berzelius (1779-1848) prepared amorphous silicon by heating the mixture of potassium and silicon tetrafluoride (SiF4). A German chemist Friedrich Wohler (1800-1882) prepared the silicon in crystalline form. Whittier Pickard (1847-1956) filed a patent for a silicon-based radio detector. Primitive Si point contact detectors are no longer used for AM radio detectors, but modern Si point contact detectors are still used at UHF (ultra-high frequencies) range (1-2 GHz) microwave frequencies. Primitive radio detectors were almost totally replaced by vacuum tube diode detectors. Thomas Alva Edison (1847-1931) independently research the basic principle of operation of the vacuum tube diode in 1880 and 1883, Thomas Alva Edison discovered that electrons will flow from one metal conductor to another through the vacuum. This discovery of the conductor is known as the Edison effect. In 1897, Sir JOHN AMBROSE FLEMING (1849-1945) was a scientist, applied the Edison effect in inverting a two-element electron tube called a diode, inventor of vacuum tube diodes and he got the US patent 803,684 in 1905 for this invention._ *[8]*

Vacuum tube diode detectors can't amplify electrical signals. The situation was completely changed by the invention of vacuum tube triodes, tetrode and pentodes. In 1906, Lee de Forest (1873-1967), invented vacuum tube triodes (He utilized the Edison effect to invert a three-element tube called the triode.) and he got patent 879,532 in 1908 for this invention. Walter Schottky invented vacuum tube tetrode and he received a German patent of 300,617 in 1916. Benard D.H. Tellegen invented the vacuum tube pentodes and he got the US patent 1,945,640 in 1934.

The vacuum tube diode detector has difficulty operating at microwave frequencies. The need for microwave radar for aircraft detection before and during the second world war (WWII 1939-1945) gave new life for semiconductor diode detectors. The size of an antenna required for radar can be decreased by using higher frequencies. At GHz frequencies, the old cat's whisker detector, which is a semiconductor diode detector, was found to be better than a vacuum tube. In an old cat's whisker detector, the depletion region is very small and the transit time is therefore small. [8]

Thus, the semiconductor had not received any device application for practical use until 1890. After Hertz demonstrated the existence of electromagnetic waves in 1888, scientists got interested in the discovery of electromagnetic waves and then wireless telegraphy became practicable. Sir Jagadish Chandra Bose – the pioneer of semiconductor device application was the first person who introduces semiconductors for the reception, received to detect the wireless waves. He applied various metal-semiconductor junctions linked to a strongly galvanic meter in series to collect radiation.

Bose disclosed the invention of this receiver (Bose's spiral spring coherer) in 1897 at the Royal Society. This device was contained thousands of steel springs (2 mm in diameter and 1 cm in length) that were placed side by side in a single layer in the rectangular depression on a square piece of ebonite, ebonite. A glass slide in the front stopped the springs from falling. The interactions between the springs acted as junctions of the semiconductor. The semiconductor is formed by the fine oxide layer in the spring. A voltaic cell and a deadbeat galvanometer were connected in series to this unit. As electric radiation was absorbed by the sensitive contacts, and the galvanometer was deflected, there was a sudden decrease in resistance. This detector is called a detector of metal-semiconductor-metal (MSM). This detector was described as a space irradiated multi-contact semiconductor (using the natural oxide of springs). Some pioneering solid-state semiconductor receivers are the spiral spring coherer, galena receiver and iron, mercury coherer (detector) with a telephone. [7]

Thus, this wonderful story is started from Faraday's silver sulphide in 1833 to Bose's spiral spring detector in 1897.

3. Semiconductor research in 19th -20th century:

In 1901, the very first semiconductor device, called CAT WHISKERS, was patented by J.C. Bose. Cat Whiskers was a point-contact semiconductor rectifier used for detecting radio waves. Sir J.C. Bose gets the first patent for the semiconductor diode detector, is the galena detector which invented nearly 1894-98 and demonstrated in Royal Institution Discourse in 1900. This device could detect nearly all kinds of radiation like light waves. He called his galena point contact detector an artificial retina (because only light waves could be detected by proper arrangement), a universal radiometer or tejometer (Sanskrit tej means radiation). He invented this device for the reception of signals in wireless or another telegraphy. From his patent application,

"A coherer or detector of electrical disturbances Hertzian waves, light waves or other radiations, comprising contacting pieces of sensitive substances has a characteristic curve (giving the relation between an increasing electromotive force and the resultant current passing through the sensitive substance), which is not straight but is either convex or concave to the axis of electromotive force and in which the return curve with a decreasing electromotive force when taken slowly approximately coincides with the former curve, in combination with means for adjusting the force of contact between said contacting pieces."[Asif][8]

The main difference between Bose's detector and early 1900 detectors is that Bose's detector worked on millimetre waves range and his detector junctions were directly illuminated by the waves. In one limb there was a thin rod plunger and on the other, there was a sensitive material with touches mercury barely. By adjusting the position, the plunger by a side arrangement, the pressure applied on the contact was adjusted. The circuit was completed through the metal and mercury. The detection of microwaves 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 shielding arrangement suitable oxidized spots were found. *[8]*

Germanium is less expensive. In addition, Si retains its semiconducting properties at a higher temperature than germanium. At temperatures up to degrees Celsius, silicon diodes can be operated while Ge diodes can't be operated above 85 degrees Celsius. Another significant Si property was not realized at the time, but was necessary for the production of the low-cost transistor and integrated circuits; Si, unlike Ge, forms a tenaciously adhering oxide film with excellent electrical insulating properties when it is heated to high temperature in the presence of oxygen. The film is used as a mask to allow the desired impurities to be introduced into it during the manufacture of semiconductor devices that alter the electrical properties of silicon. The mask pattern, shaped by a photolithographic process, allows tiny transistors to be produced.

3.1. Point-contact rectifiers: In 1904, J.C. Bose obtained a patent for PbS point-contact rectifiers. G.Pickard was the first to show that silicon point-contact rectifiers were useful in the detection of radio waves (patented in 1906). The selenium and copper oxide rectifiers were developed, respectively, in 1925 by E. Presser and 1926 by L.O.Grondahl. Selenium rectifiers were used widely in military communications and radar equipment during WWII. *[7]*

3.2. Invention of p-n junction: Russell Shoemaker Ohl (1898-1987) and his colleagues at the Bell Laboratories succeeded in a reproducible way in generating p-type silicon, n-type silicon. He made the first p-n junction silicon as follows. Scaff and Ohl released a study on their attempt to create silicon microwave detectors in 1947. Morrison showed, through actual calculation, the superiority of silicon detectors relative to vacuum tube detectors at microwave frequencies. Ohl worked with a silicon crystal sample in 1940 that had a crack in its centre. When he noticed that when the sample was exposed to light, the current flowing between the two sides of the crack created a substantial jump, he used an ohmmeter to verify the electrical resistance of the sample. The broken silicon specimen, however, was quite a curiosity. In the Bell laboratories, Ohl showed the sample to his colleagues and they together deduced that the crack was a lucky mistake. When the molten silicon froze in the crucible, it marked the dividing line that had happened. Different impurities or contaminants in the silicon had been separated into various regions at that point, with the crack separating them. As a result, there were extra electrons around them in the silicon atoms in the area on one side of the fracture. The other area was the opposite; there was a small shortage of electrons in its crystallised silicon. They named the two regions p and n, p stand for positive type and n for negative type. The p-n junction was considered the barrier between the impurities. The junction represents a barrier, preventing the excess electrons in the n-region from travelling over a top region that is short of electrons, resulting in zero current. However, there is a flow of current when the sample is irradiated with light, resulting in a basic tool that can turn light into electrical energy. The silicon p-n junction solar cell was thus invented by Ohl; for this invention, he obtained the US patent 2,402,662 in 1946. Unlike the earlier selenium solar cells, the silicon solar cells based on the p-n junction converted sunlight much more effectively.

The invention of semiconductor doping has been credited quite often to JOHN ROBERT WOODYARD (1904-1981). He got a patent on the doping of Ge as US patent 2,530,110, which was filed in 1944 and awarded in 1950.

3.3. Journey of transistor: The point-contact transistor was invented at the bell phone laboratories in Murray Hill, New Jersey after WWII, by John Bardeen (1908-1991) and Walter Houser Brattain(1902-1987). To replace vacuum tubes as mechanical relays in telecommunications, they examined the action of germanium crystals as semiconductors. The vacuum tubes used to amplify music and voice made long-distance calling possible, but the tubes absorbed heat generated by electricity and burned out quickly, requiring high maintenance. Walter Brattain and John Bardeen, who constructed the point-contact transistor, were two gold foil contacts sitting on a germanium crystal as electrical current is applied to one contact, the frequency of the current flowing through the other contact is increased by the germanium used by the physicists, a semiconductor with a spring-mounted against it with two closely spaced gold contacts. The germanium chunk had an external layer with an overabundance of electrons and it inserted points without electrons as an electrical signal passed through the gold foil, creating a thin layer with an electron deficiency. A modest positive current placed on one of the two contacts affected the current which passed between the other contact and the base where the Ge was attached. The physicists saw a modest change in the first contact current triggered a greater shift the second contact current acting as an amplifier. William Shockley enhanced their work by creating a junction transistor with n and p-type germanium sandwiches. In 1952, the junction transistors were first used as a hearing aid in a commercial product. The first transistor radio, Frequency Regency TR1, was produced in 1954. John Bardeen and Walter Brattain issued a patent for their transistor, while WILLIAM SHOCKLEY applied for a transistor affect patent and a transistor amplifier. For their discovery of the transistor effect, W.B.Shockley, John Bardeen and Walter Houser Brattain were awarded the 1956 Nobel Prize in physics. *[2][8]*

WILLIAM BRADFORD SHOCKLEY (1910-1989) invented the junction transistor that led to power efficiency, readiability and compactness of electronic circuits far beyond the limitations of vacuum tubes. It was JOHN ROBINSON PIERCE who at the request of Brattain, came to the name “transistor’’. At that time, Pierce was the supervisor of the Bell Laboratories team. Actually, In 1945, William Shockley put forward a concept of a semiconductor amplifier operating through the field-effect principle. The idea was the application of a transverse electric field would change the conductance of a semiconductor layer. Unfortunately, this effect was not observed experimentally.

Moore and Robert Norton Noyce quitted joining Fairchild semiconductor. Jean Hoerni was known about the evolution of the planar structure. Gordon Moore and Robert Noyce have been famous as two of the three founders of Intel (integrated electronics) company.

Using a technique developed by Gordon K.Teal and John B, the semiconductor material Bardeen and Brattain worked with was prepared. Little based on the Czochralski method. The crystal was then purified using the zone refining method proposed by William G. Pfann. Point-contact transistors were the first to be produced, but they were extremely unstable and the electrical characteristics were hard to control. In 1952, the first expanded junction transistors were manufactured. When compared to their point-contact predecessor, they were much better, but the production was much more difficult. As a result of a complicated doping procedure, three regions forming an np-n structure consisted of the cultivated crystal. It had to be split into individual devices, and it was important to make contacts. The procedure was complex and could not be easily automated. In addition, a significant amount of semiconductor material was lost. It was announced in 1952 that the alloyed transistor junction (Two pellets of Indium were alloyed on the opposite sides of a slice of silicon).

It is also known, in addition to US scientists, that two German physicists, Herbert Franz Matare and Heinrich Welker, who worked in France after the Second World War, invented something similar to a transistor independently around 1948, approximately at the same time. Matare, in 1952, co-founded the INTERMETAll Company to manufacture diodes and transistors. Welker joined Siemens and eventually became its director of research. For conducting fundamental research on III-V semiconductors, he is also remembered. In 1952, based on the elements contained in columns III and V of the periodic table, he introduced semiconductors as potentially useful for electronic devices. In the search for an effective communication laser, one of the gallium arsenide (GaAs) was to feature prominently. He is thus remembered as the scientist who recognized the potential of semiconductors in III-V.

The first transistor made in the Bell laboratories was based on germanium. Ge has a small bandgap of about 0.7eV. When the temperature increases, leakage current increases exponentially. Silicon has a longer band-gap of about 1.1eV. It can be easily seen that silicon transistors will have much better thermal stability compared to Ge transistors. Texas Instruments created the first efficient Si transistors. Gordon Kidd Teal was the team leader responsible for this achievement. Before joining TI, he worked for Bell Laboratories. Scientists working at the Bell Laboratories have also managed to make silicon transistors after TI's success in producing silicon transistors. For example, Tanenbaum and Thomas published a paper *"Diffused emitter and base silicon transistors"* in 1959. Aschner published a paper, *"A double diffused silicon high-frequency switching transistor produced by oxide masking techniques" in 1959.* Theuer et al., In1960, a renowned paper on *"Bpitaxial diffused transistors"* was published. For discrete silicon transistors, the double diffused epitaxial transistor eventually becomes the standard structure. As compared to the vacuum tubes, the transistor was much more efficient, operated quicker and produced less heat. Thus, it was expected that these devices could be used to build large systems.

3.4. Journey of integrated circuit:

Before the invention of the IC, different components (vacuum tubes or transistors, diodes, capacitors, resistors and inductors) were individuals bound together by electronic devices. The common feature of these efforts was the cabling discrete and separately packaged system components together.

In 1958, During the works at TEXAS INSTRUMENTS(TI), Jack Kilby (Jack st. Clair Kilby, 1923-2005) 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 theformation of interconnecting means of deposition of aluminium on a layer of SiO2 covering the semiconductor material. This(its planar version) has been achieved independently by Robert Noyce in 1959. Robert Norton Noyce (1927-90) also claimed to have invented the integrated circuit. Actually, many years later, Kilby published about the history of his invention. Therefore, In 2000, J.S.Kilby wins Nobel prize for his invention of integrated circuits (IC)**.**

Typically, Kilby is credited with introducing the idea of combining system and circuit components on a single silicon chip, while Noyce is credited with creating the process for integrating the separate components. There is more than one transistor in an integrated circuit and thus device isolation is necessary. 'Junction isolation' was pioneered by Kurt Lehovec (1918-2012). For this, he received US Patent 3,029,366. Jean Amedee Hoerni (1924-97) pioneered ‘planar technology’. He obtained US patent 3,025,589 and US patent 3,064,167.

Early IC contained about 10 individual components on a silicon chip of 3mm(0.12inch) square. By 1970, at no increases in prices, the number was up to 1000 on a chip of the same scale. Late in the following year, the first microprocessor was introduced. The device contained all the arithmetic, logic and control circuity required to perform the functions of a computer’s central processing unit(CPU). A team at INTEL Corporation, the same company that also introduced the memory IC in 1971, created this type of large-scale IC. The stage has now been created for small electronic devices to be computerized. Computers were simply isolated pieces of equipment used mostly for data processing and scientific calculations before the microprocessor arrived on site. The high demand produced by these initial applications for microprocessors led to high volume production and a significant cost reduction. This in turn promoted and uses of the devices in many other applications, for example, in household applications and automobiles. Continuous advances in IC technology have given rise to very large-scale integration (VLSI), which has greatly increased microprocessor circuit density. [11]

Cheap microprocessors had stimulated computerization of a huge variety of consumer products by the mid-1980s. By mid1986-memory IC with a capacity of 262,144 bits(binary digits) were available. In fact, Gordon Moore, observed as early as 1965 that the complexity of IC was approximately doubled every 18-24 months, which was still the case in 2000. This is known as ‘Moore’s law’ and is widely used in forecasting the technological requirements for manufacturing future of IC.

An important advantage of IC is the result of devices being fabricated very close to each other. The time delay of signals between devices is short, so that high frequency and high speed circuits are now possible with IC that we’re a not practical with discrete circuits. In addition, parasitic capacitance and inductance devices are reduced, which also provides improvement in the speed of the system.

Integration scale’ is basically the number of component devices typically the transistors within an integrated circuit. Historically, it has been classified into ranges of integration (Di Giacomo 1989) and (Chang 2000) as a table;

Integration scale	Acronym	Transistors per ic
Small scale integration	SSI	10-1000
Medium scale integration	MSI	1000-10000
Large scale integration	LSI	10000-100000
Very large scale integration	VLSI	100000-1000000
Ultra large scale integration	ULSI	1000000-1000000000
Giga scale integration	GSI	>1000000000

[Robert Doering]*[11]*

Lithography is also necessary that the component devices have excellent and improved electronic performance as they are downscaled. A strategy called, 'constant electric-field scaling' was proposed by Dennard as an approach to achieving this for metal oxide, silicon field effect transistors(MOSFETs), which largely replaced bipolar devices in most IC types during the 1970s and 1980s.

3.5. Tunnel diode: Leo Esaki obtained the first Ge tunnelling diode in 1957 and a silicon one in 1958. Esaki's presentation at the International Conference of Solid state physics in electronics and Telecommunications in 1958 was highly appreciated by Shockley. Because conduction was not based on minority carriers or thermal effects, the tunnel diode was exceptionally resistant to environmental conditions. In addition, its switching times were much shorter than the transistor. Leo Esaki received a Nobel Prize in physics in 1957 for his work on tunnelling and super-lattices._ *[7]*

3.6. Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET): Julius Lilienfield obtained patents for devices similar to today's MESFET and MOSFET, respectively, in 1930 and 1933. In 1934, Oskar Heil applied for a patent for his theoretical work on capacitive control FET transistors.

A group directed by M.M.Atalla worked on the quite unreliable problem of bi-polar transistors and found that a layer of silicon dioxide could be the answer. During this work, a new concept of a field-effect transistor(FET) was developed, and the actual device was manufactured. POUL WEIMER and TORKEL WALLMARK of RCA worked on such devices several years before Bell Laboratories proved on MOS Transistor. Weimer developed Cadmium Sulphide and Cadmium Selenide transistors. Steven Hofstein and Fredric Heiman published a year on a silicon MOSFET in 1963. In the same year, the first CMOS circuit was proposed by FRANK WANLASS. The concept of charge-coupled devices (CCD), a semiconductor equivalent to magnetic bubbles was introduced in 1970 by WILLARD BOYLE and GEORGE SMITH. For their work on CCD, both scientists were awarded the Nobel Prize in Physics in 2009.

Early MOSFETs had an aluminium gate, development of a poly-Silicon gate led to a self-aligned device, where the gate itself constitutes the mask for source and drain diffusion. Parasitic gate-to-source and gate-to-drain capabilities associated with gate overlap could be controlled in this way. Gates made of refractory metal silicide were suggested because polysilicon had relatively high resistance.

The reduction in the size of the device resulted in the so-called short-channel effects (SCE) including the roll-off of the threshold voltage and the reduction of the drain-induced barrier. A reduction in the depth of a source and drain combined with efforts to prevent increased resistance (e.g., lightly doped drain, elevated source, drain) or possibly Schottky barriers Source/Drain. Short-channel effects when gate oxide is thin are considerably reduced. As a result of decreased thickness, gate leakage current grows, increasing power consumption of the entire chip, which is an undesirable effect for battery-powered mobile systems. Apart from leakage current, the reduction of gate-oxide thickness increases the susceptibility of the device to boron penetration from the poly-Silicon gate into the channel.

3.7. Journey of Light Emitted Diodes (LED): Semiconductors are widely used for radiated emissions and detection. In 1907, the first report on light emitted from a semiconductor appeared by J. Round. Fundamental work in this area was conducted, among others, by Losev. But do we know, who invented the LED and when? The story is a tragic one about a young and highly talented scientist who spent his working life in several Soviet Radio Laboratories as a technician, eventually dying of hunger in 1942 at the age of 39 during the Leningrad blockade. His name was OLEG Vladimirovich LOSEV. Losev received no formal education, but he published 43 papers in leading Russian, British and German research journals during the period of his short research career and was 16 patents were granted, of which he was the sole author. He made several major solid-state electronics discoveries, including crystalline, the first solid-state semiconductor amplifier and generator. In the mid-1920s, when a current passed through them, Losev observed light emissions from zinc oxide and silicon carbide crystal rectifier diodes used in radio receivers. Losev's first paper on the emission of silicon carbide diodes, *'Luminous carborundum [silicon carbide] detector and crystal detection,'* was published in 1927 in Nizhniy Novgorod, Russia, in the journal *Telegrafiya I Telefoniya bez Provodov (wireless telegraphy and telephony). [5]*

Losev set the current threshold for the onset of light emission from the point of contact between a metal wire and a silicon carbide crystal in his first paper on the LED and recorded the spectrum of this light. He also studied the temperature dependence of the emission down to the temperature of liquefied air (a predominantly nitrogen-based mixture of gases used at the time) and by applying an alternating current to the contact, the LED emission was modulated up to the frequency of 78.5 kHz. *[5]*

3.8. Solid state optoelectronics centenary*:* The story would not be complete without mentioning one other remarkable person who has enjoyed better professional recognition Henry J.Round, one of Marconi's assistants in England and later chief of Marconi Research. In February 1907, Round published a 24-line note reporting a "bright glow" from a carborundum diode in the electrical world. No follow-up publication was published and Losev was not aware of this small note. As suggested by Egon Lner, it is not appropriate to credit Round with the invention of the LED, but he should be recognized as the discoverer of the phenomenon of electroluminescence. *[4]*

3.9. Journey Of Laser (Light Amplification Stimulated Emission Radiation): The early microwave quantum electronics studies set the stage for extending the principles of quantum electronics from the MASER to the LASER to the optical range. In 1964, Townes, Basov and Prokhorov are awarded the Nobel Prize in Physics for their fundamental work in the field of quantum electronics, Which led to the construction based on the maser-laser principle of oscillators and amplifiers. First of all, this applies to three key components of the quantum generators; the medium of matter gain with the energy level structure in which radiation can be generated in the desired frequency range, population inversion methods, and the electrodynamic system in which radiation interacts with the medium of gain. Since 1939, V.A.Fabrikant points out in his thesis Doctor of Science (Habilitation) that population inversion should lend to Light wave amplification and suggests the use of second-kind collisions to achieve such an inversion. In 1940, conditions for observing the adverse absorption in the discharge of gas were analyzed. *[*5*]*

Theodore H.Maiman, a physicist at Hughes Research Laboraton's in Malibu, Calif, built the first laser on May 16, 1960, using a synthetic ruby cylinder measuring one centimetre in diameter and two centimetres long, with silver-coated ends to make them reflective and capable of serving as a Febry-Perot Resonator. Maiman uses photographic flashlamps as the laser pump source. As the laser pump source, Maiman utilizes photographic flashlamps. To obtain negative temperatures, it is proposed to use the impurity ionization mechanism, which operates at a low temperature in a semiconductor sample when an electric field pulse is applied (the stimulated emission phenomena).*[5]*

Mention that the first indication of the stimulated emission in the gates. P-N junction has been discovered earlier at the Ioffe Physical-Technical Institute(Fiztekh). Robert N.Hall, a device now used in all compact disk players and laser printers and most optical fibre communication systems, invented the semiconductor injection laser in 1962. The first report on laser action in a semiconductor (GaAs) was published by Robert Hall and his group at General Electric (Schenectady, NY) in September 1962 and by IBM and MIT (Massachusetts Institute of Technology) groups reported success within weeks of his results. Soon after, researchers reported Lansing in a variety of materials, all wavelengths in the Near-Infrared.

Further research in this area went in two directions, i.e. a wider range of materials to obtain a wider range of wavelengths and new device structure concepts. In 1962, Herbert Kroemer and Zhores Alferov came up with the idea of semiconductor lasers independently. When the first report on semiconductor lasers appeared, he realized that double-heterostructure of the p-i-n-type should be used in these devices. He obtained the first practical heterostructure devices and the first hetero-structure laser.

In 2000, Alferov and Kroemer received a Nobel Prize in physics for their achievements in the area of semiconductor heterostructure used in high-speed-and optoelectronic. Now, significant progress in semiconductor lasers is associated among others, with the use of quantum wells and new materials, especially gallium nitride.

In 1963, from LEBEDEV Physics Institute (PhIAN), MOSOV, the visible, coherent light emission was obtained from GaAsP, by Holonyak N. And Bevacqe S.F; This category includes lasers for optical data storage used in devices such as CD players, disk mastering, magneto-optical, optical ROM, and holographic storage.*[5]*

Table; Timeline of development of laser---
1. Idea of semiconductor lasers (electrical field) Basov, Vul, Popov (1958)
2.Idea of junction lasers (injection, p-n junction): Basov, Krokhin, Popov (1961)
3. First observation of the gain (GaAs): Fiztekh, Leningrad (1961)
4.Development of injection lasers (GaAs): USA(Hall, sept,1962), USSR(Jan,1963)
5. Pumping by electron beam (CdS): PhIAN, Moscow (1964)
6. Optical pumping (GaAs): PhIAN (1965)
7. Injection under electric field: USA (1965)
8.Heterojection lasers (GaAs-AlGaAS): Alferov (1968)
9.Using of quaternary compounds (GaInAsP): GIRETMET, phIAn (1971)
10. Streamer Discharge laser (CdS): Nicoll, USA (1973)
11.Lasers with distributed feedback (DFB) and Bragg reflectors (DBR): Fiztekh(1974)
12.Quantum-well laser (QW): Holonyak, USA (1978)
13.Lasers with vertical-cavity surface-emitting structures (VCSEL): Iga, Japan (1979)
14. Lasers (Masers) in crossed ‘curl of Eand H’ fields (p-Ge): Vorob’ev, USSR (1982)
15. Lasers with n-i-p-i structure (GaAs): FRG (1985)
16. Quantum-wire lasers: USA, JAPAN (1989)
17. Asymmetric multiple-quantum-well heterostructure (AMQWH) lasers: Shimizu, JAPAN (1989)
18. II-VI compound quantum-well heterostructure lasers (ZnSe): Haase, USA (1991)
19.Quantum-dot lasers: JAPAN, USA, Germany, Fiztekh (1994)
20.Quantum Cascrde lasers (QC, Unipolar): Capasso, USA (1994)
21.GaN-based heterostructure lasers (blu): Nakamura, JAPAN (1995)
22.Organic semiconductor lasers (tetracene): Batlogg, USA (2000)
23. Terrahertz radiation emitting laser diodes: RUSSIA, USA, ITALY, UK, SWITZERLAND (2002)

[V.K.Kononenko et al.][5]

4. Semiconductor research in two decade of 21st century:

The integrated circuit industry, is fast approaching challenges to continued device miniaturization. As a result, both evolutionary and revolutionary approaches are being considered for replacing conventional CMOS technology. The alternative of this technology is varied on Si- based MOSFETs (Silicon-on-insulator: SOI) and FETs. The source and drain regions of SOI devices are grown onto an insulating layer, resulting in a significantly lower parasitic capacitance, better device isolation, and excellent radiation immunity compared to conventional CMOS devices. *[25]*

In FETs, when the channel width becomes on the order of sub-10nm (small nanoscale), performance affected due to quantum confinement effects. To solve this problem, use the vertical dimension to your advantage and fabricate a fin-like conduction channel wrapped in oxides and gate electronics, resulting in a FinFET configuration with a smaller device, footprint, higher gate efficiency, and lower power consumption. For instance, a 2D MoS2 planar FET with a single carbon nanotube (CNT) gate was demonstrated, allowing FET gate lengths to be reduced to sub-1nm. CNT can also be used as an ultra-narrow conducting channel in conjunction with graphene sources and drains. For developing novel FinFETs, a few-layered semiconductor MoS2 as well as CNT films were used to replace the traditional Si channel. *[24]*

The increase of the subthreshold leakage in advanced nano scale devices lead to a dramatic enhancement of the power consumption. To solve this, we need such MOSFET devices which have a minimum value of subthreshold swing “S”, which we get by using fully depleted channels. In 1985, simulation demonstrated the first fully depleted SOI MOSFET with an ideal swing of about 60mV/decade. In 1987, the first volume inverted multi-gate MOSFET was demonstrated.*[23]*

Quantum –Dots Devices & Cellular Automata:

The information is contained in the arrangement of the charges, according to the quantum-dot array principle. This means that instead currents flowing through wires, the devices interact via direct coulomb coupling. The quantum dot cellular automata scheme involves placing each dot at the corner of a square in a four-site cell. Each cell has two more mobile electrons that can tunnel between the cell's four different sites. Tunneling mobile electrons must be localised within each cell, according to the assumption that the spatial separation between each cell is sufficiently large. *[25]*

The quantum-dot logic functions can be used to create conventional AND and OR gates. As a result, quantum-dot cellular automata can perform all important logical operations (QCA).

4.1. Two decade of 21st Century of Semiconductor: “Equivalent Scaling Era”

With the introduction of strained Silicon into the CMOS manufacturing process in 2003, the first success was achieved. In 2007, a revolutionary new dielectric, based on hafnium, was introduced to the market. It has a dielectric constant that is 3-5 times that of its predecessor (depending on details of process implementation and film composition). The introduction of "Tri-gate" transistors into manufacturing in 2011 was the equivalent scaling era's third major success. The industry's determination to achieve these levels of miniaturisation in the manufacturing environment has been demonstrated by advancements in lithographic techniques.*[21]*

4.2. Future in 21st century:

1. Flexible Electronics/Organic Electronics: Flexible electronics is a semiconductor industry revolution fueled by the mechanical characteristics of the material rather than its electronic properties. With a wide range of applications, such as flexible displays, medical image sensors, and smart wearables, mounting semiconductors (functional component) onto a flexible substrate has many advantages, such as being bendable, scalable, portable, and lightweight. In the next generation of deformable electronics, plastic inorganic materials hold a lot of promise. *[26]*

2. Molecular Computing: Molecules have been proposed as candidates for nanometer-scale hardware. Molecular electronics have the potential to enable ultra-compact computing (i.e., a microprocessor in a pinhead). Molecular devices offer a revolutionary trend in electronics: highly miniaturised, low-power devices that are relatively inexpensive to fabricate and mass produce, when combined with their expected lower power consumption.*[25]*

Novel materials and innovative device architectures, such as 2D layers, 1D structures, hetero-structures, and quantum wells, are promising solutions for future high-performance devices.

5. Fabrication of semiconductor devices*:*

Experimentally observed transistor action in n-type polycrystalline germanium on December 16, 1947, by John Bardeen and Walter Brattain. Starting in 1951, the Western Electric Division of AT &T manufactured the point-contact transistor for ten years. With the implementation of single crystalline semiconductor materials in the early 1950s, however, p- n junction(bulk) transistors began replacing the point-contact transistor, silicon began to replace Ge and the transfer of transistor technology from the laboratories to the fabrication accelerated.

The Si-SiO2 diffusion technology transferred to Schockley Semiconductor from AT&T's Bell Telephone Laboratories (BTL) and thus to the Fairchild Semiconductor Corporation, led to the Silicon Valley phenomenon and the creation of the IC industry. Indeed, Gordon Moore pointed out that the critical role of John Moll's BTL laboratory in 1954 and the development of oxidation, diffusion, lithography, aluminium metallization and thermo-compression bonding techniques for the production of junction transistors and silicon bonding techniques are no longer just an industry but an economic and cultural phenomenon. *[1]*

The early years of the IC, from the 256 bits to the 4M DRAM are then reviewed, building on Bob Dennard’s one transistor cell structure and associated scaling methodology. The remarkably prescient assessment by Gordon Moore of the number of memory bits would double per year (now taken as about 18 months), enshrined as Moore's law became the productivity criterion by which the IC industry grew at a compound annual growth rate of about 25 per cent, as shown in the International Semiconductor Technology Roadmap (ITRS). However, more than just monitoring productivity is required, whether by staying on the productivity curve or increasing production efficiency.

5.1. *Silicon crystal growth / Crystal growth technology*:

In 1916, when he accidentally dipped his pen into a crucible of molten tin rather than his inkwell, JAN CZOCHRALSKI (1885-1953) discovered the Czochralski method. He pulled his pen out immediately to find that a thin thread of solidified metal was hanging from his pen's nib. The nib was replaced with a capillary and Czochralski verified that a single crystal was the crystallized metal. The experiments of Czochralski produced single crystals that were a millimetre in diameter and up to 150 cm long. Czochralski technique is currently the principal technology to grow large Si and Ge single crystal. Czochralski Si wafers are usually contaminated by oxygen. However, oxygen contamination is not so bad. It affects the mechanical strength of the Si. It can also help to better impurities. During crystal growth or subsequent process, silicon may be contaminated by various impurities. “Gathering” of impurities can be important._ *[15]*

In 1950, Gordon K. Teal and John B. Little, scientists working in the Bell Telephone Laboratory, grew Si single crystals. Subsequently, Teal left Bell Laboratories to join Texas

Instruments. In TI, Teal developed the first workable Si transistors. Teal believed that the fundamental property of a crystalline semiconductor, which would result in its technological significance, was the concentration, type and mobility of free carriers that were easily controllable and spatially variable, which was indeed found to be the case. Teal's fundamental focus on the planning and portrayal of single-crystal material, nonetheless, encouraged test check of various quantum hypothetical concepts produced for electrons and holes in crystalline semiconductors, such as powerful mass float and portability of conductivity, transporter lifetime and burrowing and explanation of various marvels in p-n junctions and fact, displayed significantly improved characteristics contrasted with polycrystalline samples. Teal also reported injecting carrier lifetimes greater than 200 microseconds in single-crystal germanium as compared to significantly lower carrier lifetimes of 1-5 microseconds in polycrystalline Ge. By early 1950, all investigators of the semiconducting properties and p-n junction studies of germanium and silicon preferred to use pulled single crystals. Teal filed for a p-n junction patent in single-crystal Ge in 1950 and the first bipolar junction transistor (np-n) was achieved in single-crystal Ge (grown-junction technique) by Shockley, Morgan sparks and Teal in 1951.

The description of dopant distribution during single crystal growth by normal freezing was described by William Pfann, via the related zone-refining techniques.

***5.2.* Bipolar transistor fabrication/ grown junction bipolar transistors:** The role of impurities of groups III and V was deduced in silicon as p and n-type dopants, respectively. Greiner's X-ray studies of the variation of the lattice constant proved the n and p-type impurity dopants like phosphorus and boron. This led, based on the *"double-doping technique"* in 1951, to the first developed junction n-p-n transistors. Only one slice of np-n Ge junction transistors could be fabricated by this technique, which was subsequently superseded by ROBERT HALL's "*RATE-GROWTH"* technique in 1952. This technique is based on the variation of the incorporation of the acceptor or donor impurities into the solidifying Ge semiconductor with the crystal growth rate. In conjunction with SAWYER and PHILIP FOY, the silicon devices first reported by GERALD PEARSON in 1952 used the technique to produce Si diode rectifiers via an aluminium-doped (p-type) wire alloyed with an n-type Si material. *[1] [2]*

***5.2.1.* Alloy bipolar transistors and grown-junction transistors:** John Saby and J. Trevor Law developed the alloy transistor in 1952. Crystal dissolution and regrowth or local liquid phase epitaxy (LPE) on Si or Ge surfaces has been described as the alloying process.

There is a fundamental difference between the alloy and grown-junction transistors in the emitter-base and base-collector junctions. While the grown junctions are graded, the alloy junctions are abrupt (of the 'step' type). Consequently, due to the emitter-base step junction, the alloy transistor showed a higher alpha cut-off frequency range (5-10 MHz) than the grown-junction transistor (1-10MHz), although the abrupt base-collector junction of the alloy transistor resulted in a higher capacitance per unit area, tending to restrict the high-frequency response. An alternative method of transistor production, identified as a surface barrier alloy transistor, was able to achieve cut off frequencies of up to 50 MHz using an electrochemical manufacturing technique. Using a jet etching technique, Philco pioneered the approach, where the Ge is etched by the electronically controlled jet of the electrolyte. Subsequent alloy contacts on each side of the thinned base material resulted in a higher cut off frequency, due to the factor ten smaller base width, compared to the grown-junction transistor. *[1]*

5.2.2. Diffused bipolar transistors: In practice, the double doping and rate-growth methods were crucial to proving the theory of the junction transistor. This situation was corrected by the introduction of solid-state diffusion procedures, with a key patent granted to Scaff and Henry Theurer in 1951 (filed in 1947) and implemented by PEARSON and CALVIN FULLER, through the in-diffusion of impurities over the entire slice of the semiconductor in a controlled environment. To ensure a controlled dopant concentration at the semiconductor surface, the technique involved exposure of the semiconductor slice to a vapour containing sufficient dopant concentration to the carrier gas, and to a sufficiently high temperature for diffusion rates to be generated to ensure accurate control of the dopant penetration depth in the semiconductor. Diffuse layers of 10-20 micrometres have been obtained. *[1]*

Fuller published the initial study of diffusion donors and acceptors in Ge, followed by the study of silicon diffusion by Fuller and Ditzenberger. With peak reverse voltages of 400V and current ratings of 400 mA, Prince described the silicon diffused junction rectifier in 1956. By the mid-1950, the manufacture of both n-p-n and p-n-p transistor structures solid-state diffusion processes in a mesa structure was facilitated by improvements in semiconductor processes. *[1]*

LEE fabricated a p-n-p Ge mesa transistor in 1954 with a base width of 1 micrometre by a diffused arsenic base and alloyed Al emitter. The current amplification factor and cut-off frequencies are 0.98 and 500 MHz, respectively. Ge mesa transistors were manufactured with base widths of 0.2 micrometres in 1959 and Si with cut-off frequencies approaching 1000 MHz were manufactured with double-diffused planar epitaxial structures in the early sixties. TANNENBAUM and THOMAS fabricated a diffused base and emitter n-p-n mesa Si transistor with a base width of 2 micrometres in 1956 with a current amplification factor and cut-off frequency of 0.97 and 120 MHz respectively.

Table: Technology evolution for controlled base width transistors;

TECHNOLOGY:	APPROXIMATE YEAR:	AUTHOR/ INVENTOR:
1. Alloy	Hall	1950
2. Double- doping	Teal	1951
3.Rate-grown	Hall	1952
4.Electrochemical thinned base	Tiley and Williams	1953
5. P-N-Ep(N-P-I-N)	Tarly	1954
6. Diffused base	Pearson and Fuller	1954
7.Planar process	Hoerni	1960
8.Epitaxy	Teal,Sangster,Mark, Thewreer	1954,1957-1960

[Howard R. Huff et al.]*[1]*

5.2.3. Mosfet transistor fabrication:

For the successful commercialization of the MOSFET and implementation of the DRAM memory era in 1970, the description of the oxidation process and methodologies for controlling the electrical properties of the Si and SiO2 interface in late 1950 were essential. Device reliability studies by Ed Snow. At Fairchild Semiconductor, Grove, Deal and Sah identified that sodium contamination in SiO2, introduced by the heated tungsten aluminium evaporation filament, was mobile under voltage stress, caused device risk of experiencing to drift under operating bias, and increased operating temperature was amplified. The Fairchild team also observed that electron-beam evaporation did not introduce sodium by developing sodium control techniques and, in addition, developed a comprehensive understanding of the phenomena that are fundamental to all modern MOSFET systems in the metal oxide silicon system.

In terms of 17 types of charge mechanisms, Deal described the stability of the silicon, silicon dioxide electrical interface and the associated effects of silicon dioxide. [1]

Techniques were developed for the passivation of surface states introduced during thermal processing at the Si, SiO2 interface. In 1965, the significance of a post-SiO2 anneal in an ambient hydrogen bearing and nitrogen anneal to stabilize the Si-SiO2 interface and lower the fixed charge was described by Pieter Balk in the case of the Al-SiO2-Si system, Qf. Kooi from Philips Research Labs of Eindhoven confirmed Balk's research. *[1]*

5.3. Integrated circuit fabrication:

Nevertheless, Kilby, who worked at Texas Instruments Incorporated and filed a patent application on February 6, 1959, explicitly "described a concept that allowed the manufacture of all the necessary components of the desired active and passive circuits in a simple piece of semiconductor and their in situ interconnection, using relatively simple steps." Kilby's initial proof of concept was a phase shift oscillator, built with about ten components, in Ge for expediency on September 12, 1958. Wire binding was utilised to interconnect the components within the chip. A few weeks later, a flip-flop circuit was made and a patent application covering both Ge and Si was prepared and filed (February 6, 1959). The first commercially available ICs to be produced in silicon for binary counter, flip-flop, or shift register applications were announced by Texas Instruments in March 1960. With the subsequent planar process patent submission by Hoerni of Fairchild Semiconductor Corporation on May 1, 1959, and due to how the interconnection was described in Kilby’s patent compared to Noyce’s IC patent application, filed on July 30, 1959. Noyce was awarded a patent before Kilby’s (April 25, 1961, compared to June 23, 1961).

Even though the bipolar transistor showed better execution features such as switching speed, the MOSFET transistor, the simplicity of the process and smaller IC chip size of the last settled on it as the favoured decision for driving edge design rule applications to be actualized. INTEL's 3-transistor silicon-entryway PMOS, 1K measure reported in 1970, was the first mass-created business MOS measure design. Preceding 1972, Terman and Hodges surveyed some of these memory developments, regularly alluded to as the period of small-scale integration (SSI).

Table: Dram process and ic evoluation (circa 1992)

Parameter	Units	ULSI	VLSI	LSI	MSI
Bits/chip	number	10^7-10^9	10^5-10^7	10^3-10^5	10^2-10^3
Design rule	micrometre	<1	1-3	3-5	5-10
Power-delay Product	PJ	$<10^{-2}$	10^{-2}- 1	1- 10	10-100
Mask-levels	number	15-20	8-15	6-10	5-6
Chip area	mm^2	50-280	25-50	10-25	10
Junction depth	micrometre	0.04 – 0.2	0.2 – 0.5	0.5 – 1.2	1.2 -2
Storage cell capacitor equivalent oxide thickness	Nano meter	3.5 – 12.5	12.5 -40	40 -90	90 -120

[Howard R. Huff et al.]*[1]*

Fairchild announced a 64 bit SRAM (six-transistor cell design), enhancement Mode-p channel MOSFET in 1964, followed by RCA's announcement and production of an enhanced mode n-channel MOSFET in 1964, also based on Hofstein and Heiman's research. In comparison to milliwatts of standby power for the equivalent bipolar and PMOS gates, Frank Wanlass initial demonstration circuit, a two-transistor inventor, consumed a few nanowatts of standby power. Interestingly, to achieve a n-channel enhancement mode device to work in conjunction with the conventional PMOS enhancement-mode transistor, Wanlass used Heiman's back bias methodology.*[1]*

MOSTEK Incorporated, set up in 1968, was the first semiconductor organisation solely devoted to MOSFET IC assembling. Shortly thereafter, Texas Instruments introduced the 256 and 1K DRAM MOSFET IC in 1970 and 1972, respectively. INTEL introduced the 1K PMOSFET DRAM in 1970. Indeed, Intel's 1K p-channel (PMOS) DRAM (polysilicon gate), based on a 3-transistor cell design, initiated the beginning of the MOS memory take-over of the ferrite core memory market through its implementation at computer maker Honeywell Incorporation. *[1]*

The MOSFET IC revolution exploded when IBM closed the n-channel silicon MOSFET (NMOS), instead of the slower p-channel Si MOSFET, for its mainframe memory computer (IBM-370,158) that was delivered in 1973. Intel and MOSTEK were early suppliers, followed by Texas Instruments in 1974. TI and MOSKET utilised a single-metal-word-line, single-diffused-bit line, where the metal was Al and the source and drain were formed by diffusion. TI utilised POCl3 to form the diffused source and drain. A single-poly-word-line, single-metal (Al)-bit line was the 4K NMOS DRAM cell built by Intel. In 1976, the 16K DRAM was announced, with three major modifications made compared to the 4K DRAM, noted by Sah. These were a reduction of the design rules from the 7-8 micrometre regime for the 4K DRAM to about the 5-micrometre range for the 16K DRAM; the removal of the source diffusion, which became known as the merged one-transistor DRAM cell; and an overlapping double polysilicon gate, one for the source-less transistor (the pass gate) and the second for the storage capacitor, thereby forming the merged one-transistor DRAM cell. *[1]*

7. Journey of semiconductor physics:

Edwin Herbert Hall, who discovered the Hall effect, was an American physicist (1855-1938). Above all, the findings before the electron's discovery. Eventually, a British physicist, Sir Joseph John Thomson, discovered the electron in 1897. However, it was an Irish physicist, George Johnstone Stoney, who coined the term electron. In addition, the first theory of electronic conduction was proposed by PAUL DRUDE, a prominent German scientist, resulting in Drude's model. Drude's model was later refined by Arnold Sommerfield and Hans Bethe. Erwin Schrodinger is famous for his Schrodinger equations, which are important for solving problems in quantum electronics. The theory of electrons in crystal lattices, which is the basis for the quantum theory of electrical conduction, was provided by Felix Bloch, a PhD student of Werner Heisenberg, in his PhD dissertation. According to Bloch, the electrons can move without scattering if the crystal lattice is perfect and there is no lattice vibration. The significance of Bloch's work is that electrons in silicon can be modelled as Bloch waves. He recognised the distinction between conductors and insulators in 1930; conductors have only partially filled upper energy bands for electrons to acquire kinetic theory in this band; the upper energy band is filled with an insulator. [*2]*

Sir Alan Herries Wilson was a British physicist in charge of the modern theory of bands. The existence of impurities in a semiconductor leads electrons to the vacant upper energy band. While Bloch modelled electrons as waves, Wilson explained the distinction between metals, semiconductors and insulators using band theory. The valence band and the conduction band of Si are quite frequently represented by an E-K diagram where the energy E, is plotted against the wave vector k. In 2005, to praise Wilson, CAHN published a short article. For semiconductors, Tamm is famous for Tamm surface states. FRENKEL is well-known for the POOLE-FRENKEL effect, which is used to model insulator leakage current. BERTRAM NEVILLE BROCKHOUSE developed the neutron scattering technique used to measure the E-K diagram for phonons in Si. CLIFFORD GHENWOOD SHULL, who also worked on neutron scattering, shared the 1994 Nobel Prize in physics. [2]

Maxwell-Boltzmann statistics were named after James Clerk Maxwell (1831-1879) and also after Lading Boltzmann (1844-1906). Maxwell is famous for Maxwell's Equations in electromagnetism. The constant of Boltzmann is frequently used in semiconductor textbooks. It is a great tragedy that he hanged himself in 1906. Although Boltzmann first associated entropy and probability in 1877, until Max Planck (1858-1947) first introduced k and gave it an accurate value, the relationship was never expressed with a particular constant in his derivation of the law of black body radiation in 1900. Thus, Boltzmann did not create the Boltzmann constant, but Max Planck named it after him. [2]

Edwin Herbert Hall discovered in 1878 that charge carriers are deflected in the magnetic field in solids (Hall effect). To study the properties of semiconductors, this phenomenon was later used. Shortly after the electron was discovered by J.J. Thomson, Several researchers suggested theories of electron-based conduction in metals by Thomson. The theory of Eduard Riecke (1899) is particularly interesting because it assumes that negative and positive charge carriers with different concentrations and motions are both negative and positive. The dependence of the conductivity of copper iodide on stoichiometry was observed by Karl Baedeker around 1908. He also measured the Hall effect in this material, which indicted carriers with a positive charge. In 1914, JOHN KOENIGSBERGER divided solid-state materials into three groups concerning their conductivity: metals, insulators, and variable conductors. The theory of electrons in lattices was developed in 1928 by Ferdinand Bloch. Bernhard Gudden reported in 1930 that the observed properties of semiconductors were solely due to the presence of impurities and that there were no chemically pure semiconductors. *[6]*

Rudolf Peierls introduced the concept of forbidden gaps in 1930, which BRILLOUIN applied to realistic solids the same year. Kronig and Penney also developed, in 1930, a simple, analytical model of the periodic potential. ALAN WILSON developed the band theory of solids in 1931, based on the concept of vacant and packed energy bands. Wilson has also confirmed the conductivity of semiconductors as being due to impurities. Models of the potential barrier and current flow through a metal-semiconductor junction were independently developed in 1938 by WALTER SCHOTTKY and NEVILLE F. MOTT (Nobel Prize in 1977). Schottky enhanced his model a year later, including the presence of space charges. A copper-oxide rectifier theory, including the presence of a p-n junction in the oxide, excess carriers and recombination, was presented by Boris Davydov in 1938. He understood the significance of surface states as well. Hans Bethe developed the thermionic emission theory in 1942 (Nobel Prize in 1967). *[6]*

8. Conclusion

Silicon may be viewed as the information carrier of our time. The global amount of information is currently doubling every year. Without silicone microelectronics, many of the things we take for granted (such as computers, the Internet and mobile phones) would not be possible. In vehicles, home appliances, machinery, etc., electronic circuits are also present. Optoelectronic devices are equally important in everyday life, e.g., fibre optics communications for data transfer, data storage (CD and DVD recorders), digital cameras, etc.

If we had lost geniuses like Losev, Boltzmann, and many more, who lost their lives via suicide and other ways before time, we could have solved the problems and invented new things. The future still holds a few surprises, we are pretty sure. Extensive studies on graphene, multi-gates, organic electronics, quantum devices, microsystems, silicon integration with other materials and many other issues are being conductor.

Acknowledgments

This is my first research paper, inspired by the many professors who met me during my summer research training, many conferences, and also during my internship program. So this manuscript is dedicated to all my inspirational people.

Appendix:

A. Intel: Integrated Electronics, company.
B. AgCl: Silver Chloride.
C.FET: Field Effect Transistor.
D. GaAs: Gallium Arsenides
E. BTL: Bell Telephone Laboratories.
F. eV: Electron-volt(unit).
G. Khz: Kilo-Hertz.
H. PbS: Lead Sulphide.
I. FET: Field Effect Transistor
J. CNT: Carbon Nano Tube
K. 2D & 1D: two Dimensional & one dimensional
L. nm & mm : nanometre & millimetre

References

[1] *Howard R.Huff, "From the Lab to the Fab: Transistors to Integrated Circuits",AIP conference proceedings 683,3(2003),https://doi.org/10.1063/1.1622451/.*

[2] *ULSI Front-End Technology, "Introduction to the History of Semiconductors",* https://www.worldscientific.com/doi/pdf/10.1142/9789813222168_0001/, ***pp. 1-43 (2017)***

[3] *Daniel Holbrook, W.M.Cohen, D.A.Hounshell and Steven Klepper, "The Nature, sources, and consequences of Firm differences in the early History of the Semiconductor Industry", strat. Mgmt. J.; 21:1017-1041 (2000).*

[4] *Nikolay Zheludev, "The life and times of the LED-a-100-year history", naturephotonics|VOL 1|April 2007| www.nature.com/naturephotonics/.*

[5] *V.K.Kononenko, "History and developments of Semiconductor Lasers", stepanov institute of physics, Belarus.*

[6] *Lidia Lukasiak and Andrzej Jakubowski, "History of Semiconductors", Journal of Telecommunications and information Technology 1/2010.*

[7] *Donald A. Neamen 4th edition books, "Semiconductor Physics and Devices", The McGraw Hill companies.*

[8] *Asif I. Khan, "Pre-1900 Semiconductor Research and Semiconductor Device Applications" https://www.researchgate.net/publication/266863177/.*

[9] *www.computerhistory.org/siliconengine/*

[10] *www.Azonano.com/article.aspx? ArticleID =4222*

[11] *Robert Doering, "Physics-to-Technology partnerships in the semiconductor industry",2020.* https://doi.org/10.1093/acrefore/9780190871994.013.27

[12] www.Semiconductormuseum.com/

[13] *www.Britannica.com/technology/electronics/*the-semiconductor-revolution

[14] *Tudor Jenkins, "A brief history of.... semiconductors", IOP publishing-physics education,40(50) 430-439.*

[15] *https://en.wikipedia.org/wiki/dan-czochralski/*

[16] *https://www.thoughtco.com/the-history-of-the-transistor-1992547*

[17] *https://www.photonics.com/Articles/A_History_of_the_Laser_1960_-_2019/a42279*

[18] *Heyang Chen|Tian-Ran Wei|Kunpeng Zhao | Pengfei Qiu | Lidong Chen | Jian He \ Zun Shi, "Room-temperature plastic inorganic semiconductors for flexible and deformable electrons, InfoMat. 2021;3: 22-35, DOI:10.1002/inf2.12149 www.wileyonlinelibrary.com/journal/inf2/*

[19] *Hiroyuki Kabasawa, "MR Imaging in the 21st century: Technical innovation over the first two Decades", Mega Reson Med Sci, doi:10.2463/mrms.rev.2021-0011*

[20] *Eleanor Mullen and Michael A. morris, "Green Nanofabrication opportunities in the Semiconductor industry: A life cycle perspective, Nanomaterials2021,11, 1085. https://doi.org/10.3390/nano11051085,*

[21] Paolo A. Gargini, "Challenges for the semiconductor industry in the 21st century", ECS Transactions, 50(5) 3-11(2012) 10.1149/05005.0003ecst©The Electrochemical Society.

[22] John Orton, "The story of semiconductors", Oxford University Press, ISBN 0 19 853083 8(hbk)

[23] Francis Balestra, "Ultra low power and high performance nanoelectronic devices", 978-1-5090-6625-4/17/$31.00©2017 IEEE p1049-1052.

[24] Mao-Lin Chen, "A FinFET with one atomic layer channel", nature communications, (2020) 11;1205 | https://doi:org/10.1038/41467-020-15096-01

[25] Kevin F. Brennan, April S. Brown , "Theory of modern Electronic Semiconductor Devices", wiley interscience publication ISBN 0-471-41541-3

[26] Bo Yang, Sila Jin, Shuang Guo, Yeonju Park, Lei Chen, Bing Zhao and Young Mee Jung, " Recent Development of SERS Technology: Semiconductor- Based Study",ACS omega, 2019, 4, 20101-20108. https://pubs.acs.org/journal/acsodf

Introduction of Author: I am Shivpal Yadav. I completed my M.Sc in physics (electronics specialized)(2019-2021) from the University of Allahabad, India. I have completed my Bachelor/B.Sc. (2016-19) from the University of Allabad. I completed the SUMMER RESEARCH TRAINING PROGRAM 2020 ONLINE at CSIR-NEIST, INDIA. I have also completed my internship. My first work paper, titled "Application of the Internet of Things [IoT] in Education", is published in the book titled "Contemporary Research in Multidisciplinary Studies: Volume 3" with ISBN 979-8491606825.
https://sites.google.com/view/shivpalyadav/home

Access this Article in Online	
	Website: www.ijarm.com
Quick Response Code	Subject: Physics
DOI:10.22192/ijamr.2022.09.01.004	

How to cite this article:
Shivpal Yadav. (2022). The journey of Semiconductor Research: Study. Int. J. Adv. Multidiscip. Res. 9(1): 46-67.
DOI: http://dx.doi.org/10.22192/ijamr.2022.09.01.004