Silicon – A Versatile Material

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SILICON A Versatile Material!

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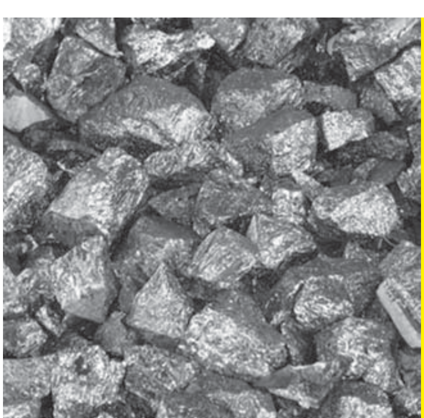
Silicon is one of man's most useful elements. Its applications extend from the IC industry to biology and solar cells.

THE ability to fabricate tens of millions of individual components (diodes, transistors etc.) on a minute silicon chip has enabled the modern information age. Now a days the essence of this silicon IC technology is almost a household word.

The word 'Silicon' originated from silicium (Latin), meaning what was more generally termed as "the flints" or "Hard Rocks". It is an abundant non-metallic element found throughout the Universe. On earth, silicon is one of the most common elements after oxygen and carbon. It was first discovered as an element by a Swedish chemist named Jacob Berzelius in 1824. He prepared amorphous (non-crystalline) silicon through the heating of sodium (Na) and silicon-tetrafluoride (SiF_4). The first crystalline silicon was prepared by Henry Sainte-Claire Deville in 1854. But the popularity of silicon blossomed with the invention of the silicon Integrated Circuit (IC) – a revolutionary concept in the field of electronics.

Only a small portion of the total silicon consumption is used up in IC technology. Silicon finds application in many areas starting from steel, alloys, bronzes, solar cell, MEMS to the biomedical sector. Additionally, silicon-based fertilizers have been proved to have plant susceptibility to fight diseases.



In the form of sand and clay it is used to make concrete and brick; it is a useful refractory material for high-temperature work, and in the form of silicates it is used in making enamels, pottery, etc.

Raw Material and Purification

Naturally occurring silicon is in impure form mixed with a host of other minerals. Therefore, it must be refined to different grades and finally converted in to crystalline form. This is usually a multistage process.

First of all quartzite (a type of sand that is the source of silicon) with carbon source (like coal or coke) is heated in an arc furnace at an elevated temperature (~2000^{0}C) resulting in 98% pure metallurgical grade silicon (MGS). Most of the silicon that is used in the industry is of the MGS form. A small portion of this MGS is purified further to electronic grade silicon (EGS) for Solar cell and IC industry.

For this, the MGS is first converted to Tri-chloro-silane ($SiHCl_3$) by reacting with gaseous HCl. $SiHCl_3$ is liquid at room temperature, therefore, by fractional distillation process it can be purified to electronic grade. Pure $SiHCl_3$ is decomposed at an elevated temperature in to electronic grade polycrystalline silicon.

The single crystal of silicon is grown by Czochralski (CZ) technique. Here the pieces of EGS are placed and melted (1400^{0}C). A seed crystal is immersed into the surface of the melt and then slowly withdrawn while rotating resulting in a single crystal silicon ingot. Later the ingot is sliced into thin wafers and polished. Such silicon wafers are used


Silicon ingot and wafers


Conductors

Jack Kilby of Texas Instruments was the first to demonstrate the monolithic arrangement of electronic components on germanium in 1959 and thus the IC was born.

for fabrication of IC, Solar cell and MEMS based devices.

Applications of Silicon

IC Industry

Silicon gained popularity and mass recognition with the advent of the Integrated Circuit (IC) industry. IC is a miniaturized electronic circuit consisting of numerous transistors, diodes, resistors and capacitors built on a common substrate and interconnected to perform desired functions. In most of the cases silicon is chosen as the basic semiconductor substrate because of many technological advantages. Currently, about 88% of the IC market is MOS (Metal-Oxide-Semiconductor) based and about 8% is BJT (Bipolar Junction Transistor) based. Remaining 4% is based on compound semiconductor for high frequency applications [Source: *Solid State Electronic Devices, 5th Ed., by B.G. Streetman & S. Banerjee*].

Jack Kilby of Texas Instruments was the first to demonstrate the monolithic arrangement of electronic components on germanium in 1959 and thus the IC was born. Almost simultaneously, Robert Noyce of Fairchild Semiconductor demonstrated IC on silicon ushing in the technological revolution. The transistor count in an IC chip since then has roughly doubled every 18 months *(Moore's Law)*. Modern computing, communications, manufacturing and transport systems, all depend on the existence of integrated circuits. Today the most advanced circuits on a chip contain several hundred millions of components. The ICs can be classified depending on the component count.

Types of ICs

Integration	Transistor count per chip
Small Scale Integration (SSI)	$1\text{-}10^2$
Medium Scale Integration (MSI)	$10^2 – 10^3$
Large Scale Integration (LSI)	$10^3 – 10^5$
Very Large Scale Integration (VLSI)	$10^5 – 10^6$
Ultra Large Scale Integration (ULSI)	$10^6 – 10^9$

The main factor that has enabled this increase in transistor count is the ability to shrink or scale-down the device feature size largely facilitated by a very stable Si-SiO_2 system. While scaling represents an opportunity, it also presents tremendous technological challenges like photolithography, etching, doping, thin film deposition, and packaging. Moreover, small feature size also requires device fabrication in extremely clean environments (Clean Room).

Silicon steel & Silicon bronzes

Silicon like manganese is present in all steels as a cheap deoxidizer. When steel contains more than 0.60% silicon, it is classified as silicon steel. It is the most important soft magnetic material in use today and has important physical properties like increased resistivity, decreased hysteresis loss, increased permeability and negligible aging compared to the earlier soft magnetic material – iron. Use of silicon steel varies in quantities from the few ounces used in small relays or pulse transformers to tons used in generators, motors and transformers.

The term bronze was originally applied to the copper-tin alloys; however, this is now used for alloys of copper and tin/aluminum/silicon etc. Commercial silicon bronzes, which generally contain less than 5% silicon, are single-phase alloys. These are the strongest of the work hardenable copper alloys having mechanical properties comparable to mild steel and corrosion resistance comparable to copper. Silicon bronzes are used for tanks, pressure vessels, marine construction and hydraulic pressure lines.

Solar cell

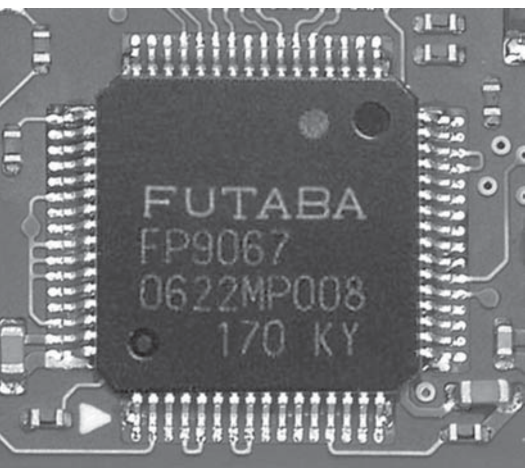
Solar energy is often expressed as the most promising secure and environment friendly alternative energy source. In a solar cell, electron-hole pairs are produced by absorption of light (solar radiation). These pairs are then separated by the electric field present in the cell (p-n junction). Although space quality solar cell is fabricated on GaAs substrates, nearly 90% of solar cell in the world (for commercial application) is made from refined, high purity crystalline silicon. But the growth of both IC and solar cell industries has put increasing pressure on relatively limited supplies of high quality silicon, consequently driving up the price.

But researchers have now found a cheaper form of silicon, dirty silicon (silicon with metal impurity and defects), which could pave the way for cheaper solar energy.

Silicone

The second largest application of pure silicon is as a raw material in the production of silicone (about 40% of the world consumption of silicon). It is a durable synthetic resin with a structure based on chains of silicon and oxygen atoms with organic side chains. By varying the -Si-O- chain lengths, side groups and cross-linking, silicones can be synthesized with a wide variety of properties and compositions. Various organic groups such as methyl or the benzene ring may be bonded to the silicon.

Solar Cell (above) Chip (below)



They can vary in consistency from liquid to gel to rubber to hard plastic. Properties like thermal stability, flexibility, good electrical insulation, low chemical reactivity and toxicity make silicone a versatile material. It also has excellent resistance to oxygen, ozone and sunlight. They find many uses in oils, greases, and rubber-like materials. Silicone oils are very desirable since they do not decompose at high temperature and do not become viscous. Other silicones are used in hydraulic fluids, electrical insulators and as moisture proofing agent in fabrics.

Silicone is also used in mold-making material to create rubber molds that can be used for production casting of resins, foams, rubber and low-temp alloys. Multiple layers of silicone often insulate automotive spark plug wires. Electronic components are sometimes protected from environmental influence by enclosing them in silicone. This increases the stability against mechanical shock, radiation, vibration and especially the electrical insulation. Silicone has many more biomedical applications such as artificial breast implants and contact lenses etc.

Silica, as sand, is a principal ingredient of glass, one of the most inexpensive of materials with excellent mechanical, optical, thermal and electrical properties.

MEMS

The field of MEMS (Micro Electro-Mechanical System) was originated by Prof. R.P. Feynman in 1959, when he delivered the famous lecture "There's Plenty of Room at the Bottom". In this lecture, he talked about manipulating and controlling things at the micro-level. It promises to revolutionize almost all the areas starting from microelectronics to micromachining technologies. The monolithic merger of micromechanics (Sensors and Actuators) and microelectronics (IC) leads to the evolution of integrated MEMS (I-MEMS) system on a chip.

The economies of scale, ready availability of cheap high quality material and ability to incorporate electronic functionality make silicon attractive for a wide variety of MEMS applications. Mechanical advantage emerges from the fact that the single crystal silicon is almost perfectly obeying Hook's law having no hysteresis and hence no energy dissipation. Also, the elastic constants of silicon are almost comparable with steel. Near absence of fatigue makes silicon-based mechanical structures highly reliable with service life times in the range of billions to trillions of cycles without breaking.

Today, a wide variety of commercial MEMS devices like pressure sensor, accelerometer, gyroscope, RF MEMS and Bio-MEMS devices are available in the market. In defense and space applications MEMS based devices are widely used due to their small size, low power consumption, low cost and weight and high degree of reliability. The Solid State Physics Laboratory in Lucknow is working on development of a number of MEMS devices like Microbolometer, Vibration Sensor, Microaccelerometer, RF Antenna etc.

Silicon in Biology

Silicon also promotes firmness and strength in human tissues. It is part of the arteries, tendons, skin, connective tissue, and eyes. This mineral is also present with the chondroitin sulfates of cartilage, and works with calcium to help restore bones. Research shows silicon is important to plant and animal life. Results of studies on animals suggest that silicon may be essential to humans. This mineral is able to form long molecules, much the same, as in carbon, and gives these complex configurations some durability and strength. It represents about 0.05 per cent of our body weight. Human tissues often contain from 6 to 90 mg of silica per 100 grams of dry tissues. Lung tissue may vary from 10 mg in infancy to as much as 2000 mg per 100 grams in old age.

Silicon is an essential element in biology, although only tiny traces of it appear to be required by animals. It is much more important to the metabolism of plants, particularly many grasses. The beneficial effects of adequate silicon include decreased susceptibility to fungal pathogens (and insects) and amelioration of abiotic stresses. Furthermore, rice is considered to be a silicon accumulator. Numerous studies have shown that the disease resistance of rice increases in reponse to silicon fertilization.

In the form of sand and clay it is used to make concrete and brick; it is a useful refractory material for high-temperature work, and in the form of silicates it is used in making enamels, pottery, etc. Silica, as sand, is a principal ingredient of glass, one of the most inexpensive of materials with excellent mechanical, optical, thermal and electrical properties. There are also several forms of amorphous silica with water, such as the opal or the *geyserite*. From these, the black opal of Australia stands out, being one of the most valuable precious stones.

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