# SEMICONDUCTOR MATERIALS AND TECHNOLOGY pdf

*This handbook is a broad review of semiconductor materials and process technology, with emphasis on very large-scale integration (VLSI) and ultra large scale integration (ULSI).*

Some materials, such as copper, aluminium and brass pass electric currents very easily. As they conduct electricity readily, their ability to resist the flow of current is low. They therefore have very low resistivity and so are classed as conductors. Other materials such as plastics or glass have extremely high resistivity so do not conduct electricity. These materials are called insulators. Materials that have a resistivity mid-way between the conductors and insulators do conduct current, but very poorly at normal room temperatures, and so these are called semi-conductors. How well or poorly any material conducts electricity depends on the atomic structure of the material. For an explanation of the atomic structure of materials as applied to electronics, see our page on The Atomic Structure of Matter. Silicon and Germanium, as well as a number of other materials and mixtures of materials in the semiconductor group are widely used in the manufacture of transistors and diodes, as well as integrated circuits such as microprocessors. Semiconductor Doping To make such semiconductor materials suitable for use in transistors and diodes, the resistivity of the material is modified in a controlled way by first making very pure crystals of the semiconductor material. These crystals contain only atoms of one type for example silicon arranged in a regular lattice formation. The idea is that pure semiconductors conduct poorly, because the electrons in their lattice structure are mostly bound very tightly to their atoms, leaving only a few electrons free to move, from atom to atom, through the material, so forming a very weak electric current. By adding impurities with different atomic structures either more or in other cases less, free electrons are added. This controls the ability of the semiconductor to pass current, by effectively changing the resistivity of the material. Some impurities such as Arsenic and Phosphorus add extra free electrons negative charge carriers to the material. This is called N type semiconductor. Other impurities such as Aluminium and Boron can be added in order to remove free electrons, so that the resulting material has fewer free electrons than before. Each missing electron within the crystal structure is called a "hole". As free electrons are negative charge carriers, these holes in the structure are really positive charge carriers. Material doped in this way is called P type semiconductor. Putting P type and N type materials next to each other in a circuit creates a PN junction, and makes a useful device that is called a diode. When a voltage is applied across a diode a current will flow through the diode in one direction but not the other. Making a three-part sandwich PNP or NPN and carefully controlling the levels of doping in the three layers creates a transistor capable of amplification, as well as many other useful functions. Semiconductor Materials in Electronic Devices. Transistors, diodes and integrated circuits can all be classified as semiconductor devices because they are made from semiconductor materials. Early types of transistors and diodes were made from Germanium Ge , but Silicon Si is used today for the vast majority of devices. Germanium is very rarely used in modern transistors however, but does possess some properties that make it useful for devices such as photovoltaic cells to produce electricity in the presence of light. Gallium Ga is also used in electronic devices such as light emitting diodes LEDs , usually as a compound material, i.

## 2: Semiconductors - IHS Technology

*The subject area of electronic devices has undergone a rapid expansion in recent years. New developments are continually accurring all over the world. Progress in the field of electronic devices is, however, dependent upon the production and characterization of device grade material.*

These detectors were somewhat troublesome, however, requiring the operator to move a small tungsten filament the whisker around the surface of a galena lead sulfide or carborundum silicon carbide crystal until it suddenly started working. At the time their operation was completely mysterious. Metal rectifier Another early type of semiconductor device is the metal rectifier in which the semiconductor is copper oxide or selenium. Westinghouse Electric was a major manufacturer of these rectifiers. World War II[ edit ] During World War II, radar research quickly pushed radar receivers to operate at ever higher frequencies and the traditional tube based radio receivers no longer worked well. The introduction of the cavity magnetron from Britain to the United States in during the Tizard Mission resulted in a pressing need for a practical high-frequency amplifier. By this point they had not been in use for a number of years, and no one at the labs had one. After hunting one down at a used radio store in Manhattan , he found that it worked much better than tube-based systems. He spent most of trying to grow more pure versions of the crystals. He soon found that with higher quality crystals their finicky behaviour went away, but so did their ability to operate as a radio detector. One day he found one of his purest crystals nevertheless worked well, and it had a clearly visible crack near the middle. However as he moved about the room trying to test it, the detector would mysteriously work, and then stop again. After some study he found that the behaviour was controlled by the light in the roomâ€"more light caused more conductance in the crystal. He invited several other people to see this crystal, and Walter Brattain immediately realized there was some sort of junction at the crack. Further research cleared up the remaining mystery. The crystal had cracked because either side contained very slightly different amounts of the impurities Ohl could not removeâ€"about 0. One side of the crystal had impurities that added extra electrons the carriers of electric current and made it a "conductor". The other had impurities that wanted to bind to these electrons, making it what he called an "insulator". Because the two parts of the crystal were in contact with each other, the electrons could be pushed out of the conductive side which had extra electrons soon to be known as the emitter and replaced by new ones being provided from a battery, for instance where they would flow into the insulating portion and be collected by the whisker filament named the collector. However, when the voltage was reversed the electrons being pushed into the collector would quickly fill up the "holes" the electron-needy impurities , and conduction would stop almost instantly. This junction of the two crystals or parts of one crystal created a solid-state diode, and the concept soon became known as semiconduction. The mechanism of action when the diode is off has to do with the separation of charge carriers around the junction. This is called a " depletion region ". Development of the diode[ edit ] Armed with the knowledge of how these new diodes worked, a vigorous effort began to learn how to build them on demand. Within a year germanium production had been perfected to the point where military-grade diodes were being used in most radar sets. Development of the transistor[ edit ] Main article: History of the transistor After the war, William Shockley decided to attempt the building of a triode -like semiconductor device. He secured funding and lab space, and went to work on the problem with Brattain and John Bardeen. The key to the development of the transistor was the further understanding of the process of the electron mobility in a semiconductor. It was realized that if there were some way to control the flow of the electrons from the emitter to the collector of this newly discovered diode, an amplifier could be built. For instance, if contacts are placed on both sides of a single type of crystal, current will not flow between them through the crystal. However if a third contact could then "inject" electrons or holes into the material, current would flow. Actually doing this appeared to be very difficult. If the crystal were of any reasonable size, the number of electrons or holes required to be injected would have to be very large, making it less than useful as an amplifier because it would require a large injection current to start with. That said, the whole idea of the crystal diode was that the crystal itself could provide the electrons over a very small distance, the depletion region. The key appeared to be to place the

input and output contacts very close together on the surface of the crystal on either side of this region. Brattain started working on building such a device, and tantalizing hints of amplification continued to appear as the team worked on the problem. Sometimes the system would work but then stop working unexpectedly. In one instance a non-working system started working when placed in water. Ohl and Brattain eventually developed a new branch of quantum mechanics , which became known as surface physics , to account for the behaviour. The electrons in any one piece of the crystal would migrate about due to nearby charges. Electrons in the emitters, or the "holes" in the collectors, would cluster at the surface of the crystal where they could find their opposite charge "floating around" in the air or water. Yet they could be pushed away from the surface with the application of a small amount of charge from any other location on the crystal. Instead of needing a large supply of injected electrons, a very small number in the right place on the crystal would accomplish the same thing. Their understanding solved the problem of needing a very small control area to some degree. Instead of needing two separate semiconductors connected by a common, but tiny, region, a single larger surface would serve. The electron-emitting and collecting leads would both be placed very close together on the top, with the control lead placed on the base of the crystal. When current flowed through this "base" lead, the electrons or holes would be pushed out, across the block of semiconductor, and collect on the far surface. As long as the emitter and collector were very close together, this should allow enough electrons or holes between them to allow conduction to start. The first transistor[ edit ] A stylized replica of the first transistor The Bell team made many attempts to build such a system with various tools, but generally failed. Eventually they had a practical breakthrough. A piece of gold foil was glued to the edge of a plastic wedge, and then the foil was sliced with a razor at the tip of the triangle. The result was two very closely spaced contacts of gold. When the wedge was pushed down onto the surface of a crystal and voltage applied to the other side on the base of the crystal , current started to flow from one contact to the other as the base voltage pushed the electrons away from the base towards the other side near the contacts. The point-contact transistor had been invented. What is now known as the " p–n–p point-contact germanium transistor " operated as a speech amplifier with a power gain of 18 in that trial. Origin of the term "transistor"[ edit ] Bell Telephone Laboratories needed a generic name for their new invention: Pierce , won an internal ballot. This is an abbreviated combination of the words "transconductance" or "transfer", and "varistor". The device logically belongs in the varistor family, and has the transconductance or transfer impedance of a device having gain, so that this combination is descriptive. Improvements in transistor design[ edit ] Shockley was upset about the device being credited to Brattain and Bardeen, who he felt had built it "behind his back" to take the glory. Shockley was incensed, and decided to demonstrate who was the real brains of the operation. This structure went on to be used for the vast majority of all transistors into the s, and evolved into the bipolar junction transistor. With the fragility problems solved, a remaining problem was purity. Making germanium of the required purity was proving to be a serious problem, and limited the yield of transistors that actually worked from a given batch of material. Scientists theorized that silicon would be easier to fabricate, but few investigated this possibility. Teal was the first to develop a working silicon transistor, and his company, the nascent Texas Instruments , profited from its technological edge. From the late s most transistors were silicon-based. Within a few years transistor-based products, most notably easily portable radios, were appearing on the market. The static induction transistor , the first high frequency transistor, was invented by Japanese engineers Jun-ichi Nishizawa and Y.

## 3: Semiconductor device - Wikipedia

*Semiconductor Materials and Process Technology Handbook (VLSI and ULSI) [Gary F. McGuire] on www.enganchecubano.com *FREE* shipping on qualifying offers. This handbook is a broad review of semiconductor materials and process technology, with emphasis on very large-scale integration (VLSI) and ultra large scale integration (ULSI).*

Materials are classified as conductors, insulators, or semiconductors according to their electric conductivity. The classifications can be understood in atomic terms. Electrons in an atom can have only certain well-defined energies, Semiconductor materials Solid-state materials are commonly grouped into three classes: At low temperatures some conductors, semiconductors, and insulators may become superconductors. The conductivities of semiconductors are between these extremes and are generally sensitive to temperature, illumination, magnetic fields, and minute amounts of impurity atoms. For example, the addition of about 10 atoms of boron known as a dopant per million atoms of silicon can increase its electrical conductivity a thousandfold partially accounting for the wide variability shown in the preceding figure. The study of semiconductor materials began in the early 19th century. The elemental semiconductors are those composed of single species of atoms, such as silicon Si , germanium Ge , and tin Sn in column IV and selenium Se and tellurium Te in column VI of the periodic table. There are, however, numerous compound semiconductors, which are composed of two or more elements. Pure silicon is the most important material for integrated circuit applications, and III-V binary and ternary compounds are most significant for light emission. Prior to the invention of the bipolar transistor in , semiconductors were used only as two-terminal devices, such as rectifiers and photodiodes. During the early s germanium was the major semiconductor material. However, it proved unsuitable for many applications, because devices made of the material exhibited high leakage currents at only moderately elevated temperatures. Since the early s silicon has become by far the most widely used semiconductor, virtually supplanting germanium as a material for device fabrication. The main reasons for this are twofold: Thus, silicon technology has become very advanced and pervasive , with silicon devices constituting more than 95 percent of all semiconductor products sold worldwide. Many of the compound semiconductors have some specific electrical and optical properties that are superior to their counterparts in silicon. These semiconductors, especially gallium arsenide, are used mainly for optoelectronic and certain radio frequency RF applications. Electronic properties The semiconductor materials described here are single crystals ; i. Part A of the figure shows a simplified two-dimensional representation of an intrinsic pure silicon crystal that contains negligible impurities. Each silicon atom in the crystal is surrounded by four of its nearest neighbours. Each atom has four electrons in its outer orbit and shares these electrons with its four neighbours. Each shared electron pair constitutes a covalent bond. The force of attraction between the electrons and both nuclei holds the two atoms together. For isolated atoms e. However, when a large number of atoms are brought together to form a crystal, the interaction between the atoms causes the discrete energy levels to spread out into energy bands. When there is no thermal vibration i. The highest filled band is called the valence band. The next band is the conduction band, which is separated from the valence band by an energy gap much larger gaps in crystalline insulators than in semiconductors. This energy gap, also called a bandgap, is a region that designates energies that the electrons in the crystal cannot possess. Most of the important semiconductors have bandgaps in the range 0. The bandgap of silicon, for example, is 1. In contrast, the bandgap of diamond, a good crystalline insulator, is 5. Three bond pictures of a semiconductor. At low temperatures the electrons in a semiconductor are bound in their respective bands in the crystal; consequently, they are not available for electrical conduction. At higher temperatures thermal vibration may break some of the covalent bonds to yield free electrons that can participate in current conduction. Once an electron moves away from a covalent bond, there is an electron vacancy associated with that bond. This vacancy may be filled by a neighbouring electron, which results in a shift of the vacancy location from one crystal site to another. When an electric field is applied to the semiconductor, both the free electrons now residing in the conduction band and the holes left behind in the valence band move through the crystal, producing an electric current. The

electrical conductivity of a material depends on the number of free electrons and holes charge carriers per unit volume and on the rate at which these carriers move under the influence of an electric field. In an intrinsic semiconductor there exists an equal number of free electrons and holes. The electrons and holes, however, have different mobilities; that is, they move with different velocities in an electric field. The electron and hole mobilities in a particular semiconductor generally decrease with increasing temperature. Electrical conduction in intrinsic semiconductors is quite poor at room temperature. To produce higher conduction, one can intentionally introduce impurities typically to a concentration of one part per million host atoms. This is called doping , a process that increases conductivity despite some loss of mobility. For example, if a silicon atom is replaced by an atom with five outer electrons, such as arsenic see part B of the figure , four of the electrons form covalent bonds with the four neighbouring silicon atoms. The fifth electron becomes a conduction electron that is donated to the conduction band. The silicon becomes an n-type semiconductor because of the addition of the electron. The arsenic atom is the donor. Similarly, part C of the figure shows that, if an atom with three outer electrons, such as boron, is substituted for a silicon atom, an additional electron is accepted to form four covalent bonds around the boron atom, and a positively charged hole is created in the valence band. This creates a p-type semiconductor, with the boron constituting an acceptor. The p-n junction If an abrupt change in impurity type from acceptors p-type to donors n-type occurs within a single crystal structure, a p-n junction is formed see parts B and C of the figure. On the p side, the holes constitute the dominant carriers and so are called majority carriers. A few thermally generated electrons will also exist in the p side; these are termed minority carriers. On the n side, the electrons are the majority carriers, while the holes are the minority carriers. Near the junction is a region having no free charge carriers. This region, called the depletion layer, behaves as an insulator. A Current-voltage characteristics of a typical silicon p-n junction. B Forward-bias and C reverse-bias conditions. D The symbol for a p-n junction. The most important characteristic of p-n junctions is that they rectify. Part A of the figure shows the current-voltage characteristics of a typical silicon p-n junction. When a forward bias is applied to the p-n junction i. However, when a reverse bias is applied as in part C of the figure , the charge carriers introduced by the impurities move in opposite directions away from the junction, and only a small leakage current flows. As the reverse bias is increased, the leakage current remains very small until a critical voltage is reached, at which point the current suddenly increases. This sudden increase in current is referred to as the junction breakdown, usually a nondestructive phenomenon if the resulting power dissipation is limited to a safe value. The applied forward voltage is typically less than one volt, but the reverse critical voltage, called the breakdown voltage, can vary from less than one volt to many thousands of volts, depending on the impurity concentration of the junction and other device parameters. Although other junction types have been invented including p-n-p and n-p-n , p-n junctions remain fundamental to semiconductor devices. For further details on applications of these basic semiconductor properties, see transistor and integrated circuit.

## 4: Semiconductor Nanomaterials, Methods and Applications: A Review

*Semiconductor Materials and Technology: Proceedings of the 3rd Intl. Conference and Intensive Tutorial Course on Semiconductor Materials and Technology.*

Silicon crystals are the most common semiconducting materials used in microelectronics and photovoltaics. A large number of elements and compounds have semiconducting properties, including: Silicon and germanium are used here effectively because they have 4 valence electrons in their outermost shell which gives them the ability to gain or lose electrons equally at the same time. Binary compounds, particularly between elements in Groups 13 and 15, such as gallium arsenide , Groups 12 and 16, groups 14 and 16, and between different group 14 elements, e. Certain ternary compounds, oxides and alloys. Organic semiconductors , made of organic compounds. Most common semiconducting materials are crystalline solids, but amorphous and liquid semiconductors are also known. These include hydrogenated amorphous silicon and mixtures of arsenic , selenium and tellurium in a variety of proportions. These compounds share with better known semiconductors the properties of intermediate conductivity and a rapid variation of conductivity with temperature, as well as occasional negative resistance. Such disordered materials lack the rigid crystalline structure of conventional semiconductors such as silicon. They are generally used in thin film structures, which do not require material of higher electronic quality, being relatively insensitive to impurities and radiation damage. Semiconductors for ICs are mass-produced. To create an ideal semiconducting material, chemical purity is paramount. Any small imperfection can have a drastic effect on how the semiconducting material behaves due to the scale at which the materials are used. Crystalline faults are a major cause of defective semiconductor devices. The larger the crystal, the more difficult it is to achieve the necessary perfection. There is a combination of processes that is used to prepare semiconducting materials for ICs. One process is called thermal oxidation , which forms silicon dioxide on the surface of the silicon. This is used as a gate insulator and field oxide. Other processes are called photomasks and photolithography. This process is what creates the patterns on the circuity in the integrated circuit. Ultraviolet light is used along with a photoresist layer to create a chemical change that generates the patterns for the circuit. The part of the silicon that was not covered by the photoresist layer from the previous step can now be etched. The main process typically used today is called plasma etching. Plasma etching usually involves an etch gas pumped in a low-pressure chamber to create plasma. A common etch gas is chlorofluorocarbon , or more commonly known Freon. A high radio-frequency voltage between the cathode and anode is what creates the plasma in the chamber. The silicon wafer is located on the cathode, which causes it to be hit by the positively charged ions that are released from the plasma. The end result is silicon that is etched anisotropically. This is the process that gives the semiconducting material its desired semiconducting properties. It is also known as doping. The process introduces an impure atom to the system, which creates the p-n junction. In order to get the impure atoms embedded in the silicon wafer, the wafer is first put in a 1, degree Celsius chamber. The atoms are injected in and eventually diffuse with the silicon. After the process is completed and the silicon has reached room temperature, the doping process is done and the semiconducting material is ready to be used in an integrated circuit. Electronic band structure and Electrical conduction Filling of the electronic states in various types of materials at equilibrium. Here, height is energy while width is the density of available states for a certain energy in the material listed. In metals and semimetals the Fermi level $E_F$ lies inside at least one band. In insulators and semiconductors the Fermi level is inside a band gap ; however, in semiconductors the bands are near enough to the Fermi level to be thermally populated with electrons or holes. These states are associated with the electronic band structure of the material. Electrical conductivity arises due to the presence of electrons in states that are delocalized extending through the material , however in order to transport electrons a state must be partially filled, containing an electron only part of the time. The energies of these quantum states are critical, since a state is partially filled only if its energy is near the Fermi level see Fermiâ€"Dirac statistics. High conductivity in a material comes from it having many partially filled states and much state delocalization. Metals are good electrical conductors and have many partially filled states with energies near their Fermi level. Insulators , by contrast, have few

partially filled states, their Fermi levels sit within band gaps with few energy states to occupy. Importantly, an insulator can be made to conduct by increasing its temperature: An intrinsic semiconductor has a band gap that is smaller than that of an insulator and at room temperature significant numbers of electrons can be excited to cross the band gap. However, one important feature of semiconductors and some insulators, known as semi-insulators is that their conductivity can be increased and controlled by doping with impurities and gating with electric fields. Doping and gating move either the conduction or valence band much closer to the Fermi level, and greatly increase the number of partially filled states. Some wider-band gap semiconductor materials are sometimes referred to as semi-insulators. When undoped, these have electrical conductivity nearer to that of electrical insulators, however they can be doped making them as useful as semiconductors. Semi-insulators find niche applications in micro-electronics, such as substrates for HEMT. An example of a common semi-insulator is gallium arsenide. Charge carriers electrons and holes [ edit ] Main article: Electron hole The partial filling of the states at the bottom of the conduction band can be understood as adding electrons to that band. The electrons do not stay indefinitely due to the natural thermal recombination but they can move around for some time. The actual concentration of electrons is typically very dilute, and so unlike in metals it is possible to think of the electrons in the conduction band of a semiconductor as a sort of classical ideal gas , where the electrons fly around freely without being subject to the Pauli exclusion principle. In most semiconductors the conduction bands have a parabolic dispersion relation , and so these electrons respond to forces electric field, magnetic field, etc. For partial filling at the top of the valence band, it is helpful to introduce the concept of an electron hole. Although the electrons in the valence band are always moving around, a completely full valence band is inert, not conducting any current. If an electron is taken out of the valence band, then the trajectory that the electron would normally have taken is now missing its charge. For the purposes of electric current, this combination of the full valence band, minus the electron, can be converted into a picture of a completely empty band containing a positively charged particle that moves in the same way as the electron. Combined with the negative effective mass of the electrons at the top of the valence band, we arrive at a picture of a positively charged particle that responds to electric and magnetic fields just as a normal positively charged particle would do in vacuum, again with some positive effective mass. Carrier generation and recombination[ edit ] Main article: Carrier generation and recombination When ionizing radiation strikes a semiconductor, it may excite an electron out of its energy level and consequently leave a hole. This process is known as electron–hole pair generation. Electron-hole pairs are constantly generated from thermal energy as well, in the absence of any external energy source. Electron-hole pairs are also apt to recombine. Conservation of energy demands that these recombination events, in which an electron loses an amount of energy larger than the band gap , be accompanied by the emission of thermal energy in the form of phonons or radiation in the form of photons. In some states, the generation and recombination of electron–hole pairs are in equipoise. The number of electron-hole pairs in the steady state at a given temperature is determined by quantum statistical mechanics. The precise quantum mechanical mechanisms of generation and recombination are governed by conservation of energy and conservation of momentum. As the probability that electrons and holes meet together is proportional to the product of their numbers, the product is in steady state nearly constant at a given temperature, providing that there is no significant electric field which might "flush" carriers of both types, or move them from neighbour regions containing more of them to meet together or externally driven pair generation. The probability of meeting is increased by carrier traps–impurities or dislocations which can trap an electron or hole and hold it until a pair is completed. Such carrier traps are sometimes purposely added to reduce the time needed to reach the steady state.

*Applied Materials Inc., Semiconductor, Flat Panel Display and Solar Photovoltaic Equipment austriamicrosystems, Analog Integrated Circuits Axel Technologies Oy, TV and Video Applications for Mobile, Handheld and Portable Devices.*

Transistor There are many different types of semiconductor material. These different types of semiconductor have slightly different properties and lend themselves to different applications in various forms of semiconductor devices. Some may be applicable for standard signal applications, others for high frequency amplifiers, while other types may be applicable for power applications and harsh environments or others for light emitting applications. All these different applications tend to utilise different types of semiconductor materials. An intrinsic type of semiconductor material made to be very pure chemically. As a result it possesses a very low conductivity level having very few number of charge carriers, namely holes and electrons, which it possesses in equal quantities. Extrinisc types of semiconductor are those where a small amount of impurity has been added to the basic intrinsic material. This creates either an excess or shortage of electrons. In this way two types of semiconductor are available: Electrons are negatively charged carriers. An N-type semiconductor material has an excess of electrons. In this way, free electrons are available within the lattices and their overall movement in one direction under the influence of a potential difference results in an electric current flow. This in an N-type semiconductor, the charge carriers are electrons. In a P-type semiconductor material there is a shortage of electrons, i. Electrons may move from one empty position to another and in this case it can be considered that the holes are moving. This can happen under the influence of a potential difference and the holes can be seen to flow in one direction resulting in an electric current flow. It is actually harder for holes to move than for free electrons to move and therefore the mobility of holes is less than that of free electrons. Holes are positively charged carriers. Semiconductor material groups Most commonly used semiconductor materials are crystalline inorganic solids. These materials are often classified according to their position or group within the periodic table. These groups are determined by the electrons in the outer orbit the particular elements. While most semiconductor materials used are inorganic, a growing number of organic materials are also being investigated and used. Semiconductor materials list There are many different types of semiconductor materials that can be used within electronic devices. Each has its own advantages, disadvantages and areas where it can be used to offer the optimum performance.

## 6: Semiconductor Materials and Technology

*Semiconductor devices are electronic components that exploit the electronic properties of semiconductor materials, principally silicon, germanium, and gallium arsenide, as well as organic semiconductors.*

Pure silicon is the most important material for integrated circuit application, and III-V binary and ternary compounds are most significant for light emission. Prior to the invention of the bipolar transistor in , semiconductors were used only as two-terminal devices, such as rectifiers and photodiodes. During the early s, germanium was the major semiconductor material. However, it proved unsuitable for many applications, because devices made of the material exhibited high leakage currents at only moderately elevated temperatures. Since the early s, silicon has become a practical substitute, virtually supplanting germanium as a material for semiconductor fabrication. The main reasons for this are twofold: Silicon technology is now by far the most advanced among all semiconductor technologies, and silicon-based devices constitute more than 95 percent of all semiconductor hardware sold worldwide. Many of the compound semiconductors have electrical and optical properties that are absent in silicon. These semiconductors, especially gallium arsenide, are used mainly for high-speed and optoelectronic applications. Electronic properties The semiconductor materials treated here are single crystals â€"i. Figure 2A shows a simplified two-dimensional representation of an intrinsic silicon crystal that is very pure and contains a negligibly small amount of impurities. Each silicon atom in the crystal is surrounded by four of its nearest neighbours. Each atom has four electrons in its outer orbit and shares these electrons with its four neighbours. Each shared electron pair constitutes a covalent bond. The force of attraction for the electrons by both nuclei holds the two atoms together. Three bond pictures of a semiconductor. At low temperatures the electrons are bound in their respective positions in the crystal; consequently, they are not available for electrical conduction. At higher temperatures thermal vibration may break some of the covalent bonds. The breaking of a bond yields a free electron that can participate in current conduction. Once an electron moves away from a covalent bond, there is an electron deficiency in that bond. This deficiency may be filled by one of the neighbouring electrons, which results in a shift of the deficiency location from one site to another. This deficiency may thus be regarded as a particle similar to an electron. This fictitious particle, dubbed a hole , carries a positive charge and moves, under the influence of an applied electric field , in a direction opposite to that of an electron. For an isolated atom, the electrons of the atom can have only discrete energy levels. When a large number of atoms are brought together to form a crystal, the interaction between the atoms causes the discrete energy levels to spread out into energy bands. When there is no thermal vibration i. The highest filled band is called the valence band. The next higher band is the conduction band , which is separated from the valence band by an energy gap. This energy gap, also called a bandgap, is a region that designates energies that the electrons in the semiconductor cannot possess. Most of the important semiconductors have bandgaps in the range 0. The bandgap of silicon, for example, is 1. As discussed above, at finite temperatures thermal vibrations will break some bonds. When a bond is broken, a free electron, along with a free hole, results, i. When an electric field is applied to the semiconductor, both the electrons in the conduction band and the holes in the valence band gain kinetic energy and conduct electricity. The electrical conductivity of a material depends on the number of charge carriers i. In an intrinsic semiconductor there exists an equal number of free electrons and free holes. The electrons and holes, however, have different mobilitiesâ€"that is to say, they move with different velocities in an electric field. The mobilities of a given semiconductor generally decrease with increasing temperature or with increased impurity concentration. Electrical conduction in intrinsic semiconductors is quite poor at room temperature. To produce higher conduction, one can intentionally introduce impurities typically to a concentration of one part per million host atoms. This is the so-called doping process. For example, when a silicon atom is replaced by an atom with five outer electrons such as arsenic Figure 2C , four of the electrons form covalent bonds with the four neighbouring silicon atoms. The silicon becomes an n-type semiconductor because of the addition of the electron. The arsenic atom is the donor. This is a p-type semiconductor, with the boron constituting an acceptor. The p-n junction If an abrupt change in impurity type from acceptors p-type to donors n-type occurs

within a single crystal structure, a p-n junction is formed see Figure 3B and 3C. On the p side, the holes constitute the dominant carriers and so are called majority carriers. A few thermally generated electrons will also exist in the p side; these are termed minority carriers. On the n side the electrons are the majority carriers, while the holes are the minority carriers. Near the junction is a region having no free-charge carriers. This region, called the depletion layer , behaves as an insulator. A Current-voltage characteristics of a typical silicon p-n junction. B Forward-bias and C reverse-bias conditions. D The symbol for a p-n junction. The most important characteristic of p-n junctions is that they rectify; that is to say, they allow current to flow easily in only one direction. Figure 3A shows the current-voltage characteristics of a typical silicon p-n junction. When a forward bias is applied to the p-n junction i. However, when a reverse bias is applied in Figure 3C , the charge carriers introduced by the impurities move in opposite directions away from the junction, and only a small leakage current flows initially. As the reverse bias is increased, the current remains very small until a critical voltage is reached, at which point the current suddenly increases. This sudden increase in current is referred to as the junction breakdown, usually a nondestructive phenomenon if the resulting power dissipation is limited to a safe value. The applied forward voltage is usually less than one volt, but the reverse critical voltage, called the breakdown voltage, can vary from less than one volt to many thousands of volts, depending on the impurity concentration of the junction and other device parameters. Two-terminal junction devices A p-n junction diode is a solid-state device that has two terminals. Depending on impurity distribution, device geometry, and biasing condition, a junction diode can perform various functions. There are more than 50, types of diodes with voltage ratings from less than 1 volt to more than 2, volts and current ratings from less than 1 milliampere to more than 5, amperes. A p-n junction also can generate and detect light and convert optical radiation into electrical energy. Rectifier This type of p-n junction diode is specifically designed to rectify an alternating current—i. Such diodes are generally designed for use as power-rectifying devices that operate at frequencies from 50 hertz to 50 kilohertz. The majority of rectifiers have power-dissipation capabilities from 0. A high-voltage rectifier is made from two or more p-n junctions connected in series. Zener diode This voltage regulator is a p-n junction diode that has a precisely tailored impurity distribution to provide a well-defined breakdown voltage. It can be designed to have a breakdown voltage over a wide range from 0. The Zener diode is operated in the reverse direction to serve as a constant voltage source, as a reference voltage for a regulated power supply, and as a protective device against voltage and current transients. Varactor diode The varactor variable reactor is a device whose reactance can be varied in a controlled manner with a bias voltage. It is a p-n junction with a special impurity profile, and its capacitance variation is very sensitive to reverse-biased voltage. Varactors are widely used in parametric amplification, harmonic generation, mixing, detection, and voltage-variable tuning applications. Tunnel diode A tunnel diode consists of a single p-n junction in which both the p and n sides are heavily doped with impurities. The depletion layer is very narrow about angstroms. Under forward biases, the electrons can tunnel or pass directly through the junction, producing a negative resistance effect i. Because of its short tunneling time across the junction and its inherent low noise random fluctuations either of current passing through a device or of voltage developed across it , the tunnel diode is used in special low-power microwave applications, such as a local oscillator and a frequency-locking circuit. Schottky diode Such a diode is one that has a metal-semiconductor contact e. It is named for the German physicist Walter H. Schottky, who in explained the rectifying behaviour of this kind of contact. The Schottky diode is electrically similar to a p-n junction, though the current flow in the diode is due primarily to majority carriers having an inherently fast response. It is used extensively for high-frequency, low-noise mixer and switching circuits. Metal-semiconductor contacts can also be nonrectifying; i. Such a contact is called an ohmic contact. All semiconductor devices as well as integrated circuits need ohmic contacts to make connections to other devices in an electronic system. The p-i-n diode has found wide application in microwave circuits. It can be used as a microwave switch with essentially constant depletion-layer capacitance equal to that of a parallel-plate capacitor having a distance between the plates equal to the i-region thickness and high power-handling capability. Bipolar transistors This type of transistor is one of the most important of the semiconductor devices. It is a bipolar device in that both electrons and holes are involved in the conduction process. The bipolar transistor delivers a change in output current in response

to a change in input voltage at the base. A perspective view of a silicon p-n-p bipolar transistor is shown in Figure 4A. A Perspective of a p-n-p bipolar transistor; B idealized one-dimensional transistor; C symbols for p-n-p and n-p-n bipolar transistors E is an emitter, B is a base, and C is a collector. An idealized, one-dimensional structure of the bipolar transistor, shown in Figure 4B, can be considered as a section of the device along the dashed lines in Figure 4A. The circuit arrangement in Figure 4B is known as a common-base configuration. The arrows indicate the directions of current flow under normal operating conditions—namely, the emitter-base junction is forward-biased and the base-collector junction is reverse-biased. The complementary structure of the p-n-p bipolar transistor is the n-p-n bipolar transistor, which is obtained by interchanging p for n and n for p in Figure 4A. The current flow and voltage polarity are all reversed.

## 7: Semiconductor Materials | Types Groups Classifications | List

*Semiconductor device, electronic circuit component made from a material that is neither a good conductor nor a good insulator (hence semiconductor). Such devices have found wide applications because of their compactness, reliability, and low cost.*

Introduction A semiconductor is a material that has an electrical conductivity between a conductor and an insulator. In semiconductors, the highest occupied energy band, the valence band is completely filled with electrons and the empty next one is the conduction band. The resistivities of the semiconductor can be altered by up to 10 orders of magnitude, by doping or external biases. In the case of conductors, that have very low resistivities, the resistance is difficult to alter, and the highest occupied energy band is partially filled with electrons and the insulator has extremely high resistivities. It is difficult to alter the resistivity through doping or external fields and the bandgap between the valence band and the conduction band is large. In a metallic conductor, the current is carried by the flow of electrons. In semiconductors, current can be carried either by the flow of electrons or by the flow of positively-charged holes in the electron structure of the material. In the past 10 years, nanomaterials with diameters in the range of nm, have become a major interdisciplinary area of research interest and their extremely small feature size has the potential for wide-ranging industrial, biomedical, and electronic applications. Surfaces and interfaces are very important for nanomaterials, but in the case of bulk materials, a relatively small percentage of atoms will be at or near a surface or interface. In nanomaterials, the small feature size ensures that many atoms, perhaps half or more in some cases, will be near the interfaces. Surface properties, such as energy levels, electronic structure, and reactivity can be quite different from interior states, and give rise to quite different material properties. Nanocapsules and nanodevices may present new possibilities for drug delivery, gene therapy, and medical diagnostics. Iijima[1] reported the first observation of carbon nanotubes. Carbon nanotubes have been shown to have unique properties, stiffness and strength, higher than any other material. Carbon nanotubes are used as reinforcing particles in nanocomposites, but also have many other potential applications. They could be the basis for a new era of electronic devices, smaller and more powerful than bulk materials. The nanocomputer was already made based on carbon nanotubes. Materials having sizes in the range of a nanometer scale have unique properties than bulk materials. Recently there has been substantial interest in the preparation, characterization and application of semiconductor nanoparticles that play a major role in several new technologies. When the size of semiconductor materials is reduced to nanoscale, their physical and chemical properties change drastically, resulting in unique properties due to their large surface area or quantum size effect. The conductivity of the semiconductor and its optical properties absorption coefficient and refractive index can be altered. Semiconductor nanomaterials and devices are still in the research stage, but they are promising for applications in many fields, such as solar cells, nanoscale electronic devices, light-emitting diodes, laser technology, waveguide, chemical and biosensors, packaging films, superabsorbents, components of armor, parts of automobiles, and catalysts. Further development of nanotechnology will certainly lead to significant breakthroughs in the semiconductor industry. Semiconductor devices include the various types of transistors, solar cells, many kinds of diodes including the light-emitting diode, the silicon controlled rectifier, and digital and analog integrated circuits. The aim of this review is to overview and highlights the applications of semiconductor nanomaterials and synthetic methods. Herein we describe and discuss the current use of semiconductor nanomaterials and their applications. Introductions to Nanoscience and Nanotechnology In the past few decades, nanoscience and nanotechnology have been making significant progress and their effect on every field has been truly acknowledged in the world. Therefore, in the 21st century, their strategic position has already been established. The study of nanomaterials and nanostructures is a field with the earliest start that has obtained rich achievements. Most countries are involved in the study of nanomaterials and nanostructures in a very remarkable way, such as the development of the front fields of nanoscience and nanotechnology, nanoelectronic technologies and devices, nano or microfabrication techniques, nanobiotechnology, nanomedical diagnosis techniques, nanoenvironmental monitoring and treatment

techniques. The continuation of the indepth study of nanomaterials and nanostructures are placed in an extremely important position. Now, the motivational power for the study of nanomaterials and nanostructures is mainly National Strategy Requirements and enhancements of the national competitive ability in the scientific and technological fields. In addition, the indepth study of nanomaterials and nanostructures is an important source for establishing new principles, new techniques and new methods, thereby potentially leading to breakthroughs in great scientific problems. At the same time, the nanomaterial market is also a native power for the development of nanomaterials. It will stimulate and promote the development of nanomaterials and nanostructures. Recently there has been substantial interest in the preparation and characterization of materials consisting of particles with dimensions in the semiconductor nanocrystalline materials[]. One factor driving the current interest in nanoparticle research is the perceived need for further miniaturization of both optical and electronic devices[5,6]. There are practical constraints associated with current technologies; lithographic methods cannot at present be used with a resolution much less than ca. Semiconductor Nanoparticles Semiconductor nanocrystals NCs are made from a variety of different compounds. Classifications of Semiconductor Nanostructures In nanocrystalline materials, the electrons are confined to regions having one, two or three dimensions Figure 1 when the relative dimension is comparable with the de Broglie wavelength. For a semiconductor like CdSe, the de Broglie wavelength of free electron is around 10 nm. The nanostructures of semiconductor crystals having the z direction below this critical value thin film, layer structure, quantum well are defined as 2D nanostructures. When the dimension both in the x and z direction is below this critical value linear chain structure, quantum wire the nanostructures are defined as 1D and when the y direction is also below this threshold cluster, colloid, nanocrystal, quantum dot it is referred to as 0D. Zero Dimensional 0D Nanostructures In the early stages of research on nano-building block synthesis, zero dimensional shapes were regarded as the most basic and symmetric, including spheres and cubes. Several semiconductor nanocrystals have been grown from the ageing processes of ionic precursors inside organic micelles. However, nanocrystals obtained by this method have relatively poor crystallinity or polydispersity in their size. As an alternative way to solve these problems, a thermal decomposition method of organometallic precursors under hot organic solution was adopted. At first, Chestnoy et al [7] synthesized various IIâ€"VI semiconductor nanospheres with high colloidal stability, using coordinating solvents e. Murray et al [8] successfully developed a more advanced methodology to prepare CdSe nanocrystals of varied sizes via the method of injecting a precursor solution containing dimethylcadmium and trioctylphosphine selenide into a hot trioctylphosphine oxide TOPO solution. The size of nanocrystals varied from 1. Optical spectra clearly exhibited size dependent quantum confinement effects, indicating the high monodispersity and high crystallinity of nanocrystals. Schematic drawing to show the concept of system dimensionality: Quasi One Dimensional 1D Nanostructures The term quasi one dimensional nanostructures is used, because the dimensions are often larger than the indicated threshold, although elongation along one main axis still exists. When the diameter of the nanorod, nanowire or nanotube becomes smaller, there is often a significant change in the properties with respect to crystalline solids or even two dimensional systems. A bismuth nanowire is an excellent example, which transforms into a semiconductor, as the wire diameter becomes smaller. By controlling the growth variables such as temperature, the choice of capping molecules, precursor concentrations, crystalline phases of the nuclei and the choice of the regime between kinetically controlled and thermodynamically controlled growth, various nano-building blocks with multi-dimensionalities have been produced. For example, the use of binary capping molecules such as TOPO and hexylphosphonic acid HPA was effective for the generation of shape anisotropy in CdSe along with the intrinsic hexagonal structure nature. The non-hydrolytic high temperature injection method can be effectively utilized, for high quality nanorods synthesis. Peng et al [9] and Manna et al [10] first reported CdSe nanorods via thermal decomposition of dimethylcadmium and trioctylphosphine selenide, in a hot surfactant mixture of trioctylphosphine oxide and hexylphosphonic acid. The hydrolytic synthesis of IIâ€"VI semiconductors also produces one-dimensional rod-shaped nanocrystals, by shape transformations involving oriented attachment processes. Tang et al [11] reported a shape transformation from a sphere to a rod by the dipole-induced fusion of CdTe individual nanospheres. In the case of group IV semiconductor systems, it is extremely difficult to

obtain nanorods by typical solution based precursor injection methods, due to their highly covalent character. Transition metal oxides consist of an important group of materials used in white pigment, electronic ceramics, cosmetics, support in catalysis, and as photocatalysts. Nanostructured titania are of particular interest, with potential applications as solar cell materials. Chemseddine and Moritz demonstrated elongated $TiO_2$ nanocrystals synthesized by hydrolysis and polycondensation of titanium alkoxide[Ti OR 4], in the presence of tetramethyl ammonium hydroxide, as a stabilizer and reaction catalyst. Penn and Banfield also reported naturally aligned titania nanocrystals under hydrothermal conditions, by adopting an oriented attachment mechanism into the nanocrystal development. The hydrothermal treatment of titanium alkoxide precursors produces diamond shaped anatase titania nanocrystals. Two Dimensional 2D Nanostructures The family of 2D nanosystems encompasses all those systems that exhibit two dimensions exceeding the third one. However, the number and variety of inorganic nano objects belonging to this family is far lower. Indeed, nature tends to organize materials in a three dimensional way. The main synthesis methodologies of 2D nanostructures can be summarized as follows: All 2D flat nanocrystals possess an overall size in the order of 10 nm. Such a size limitation is pursued, in order to prevent the growth along only one specific direction, leading to a 1D system. The synthesis of two dimensional nanocrystals is achieved by the self-assembly of solutions and the constituting elements of these systems are usually metals. Discoidal nanocrystals are typical flat building blocks. They are typically obtained by surfactant assisted synthesis, or anisotropic crystal growth passing through colloidal systems. Silver nanoprisms are synthesized by the irradiation of Ag nanospheres with visible light together with an unexpected colour change from yellow, which is a characteristic surface plasmon band of the spherical particle, to green and finally blue , and a marked change in shape, from nanospheres into nanoprisms[12]. Nanosized prisms from transition metals, such as Pd or Ni or from semiconductors, such as CdS, were also reported. The triangular nanocrystals of CdS turned out to be flat and the crystalline phase was proved to be a hexagonal wurtzite structure. They exhibit different molecular and bulk properties. In particular, 3D nanocrystals superstructures are prepared by assembling basic nanosized building blocks such as; 0D spheres 1D rods and 2D plates, to have bigger sized structures of innovative shapes. For this purpose, 0D nanosystems and mainly nanoparticles are the best choice, since they can easily lead to the highly ordered 3D closely packed patterns, kept together by chemical interparticle interactions. Such superstructures display a face centered cubic packing of CdSe nanocrystals. They exhibit novel optical properties which are different from those of diluted CdSe nanospheres in solution. Core-Shell Nanostructures Surface engineering is an important tool to control the properties of the NCs and in particular optical materials. One important strategy is the over growth of NCs with a shell of a second semiconductor, resulting in a core-shell CS system. This method has been successfully applied to improve the florescence quantum yield and the stability against photo-oxidation by the proper choice of the core and shell materials, to tune the emission wavelength in a large spectral window. After pioneering work in the s, and the development of powerful chemical synthesis routes at the end of s[], a strongly increasing number of articles have been devoted to CSNCs in the last five years. Nowadays, almost any type of core NCs prepared by a robust chemical synthesis method has been over grown with shells of other semiconductor materials. Depending on the bandgap and the relative position of the electronic energy levels of the involved semiconductors, the shell can have different functions in core-shell nanocrystals CSNCs. Types of Core-shell Nanocrystals Two main cases are nominated as type I and type II band alignment, respectively, in which the type-I core shell has a band gap of the shell material larger than the core, and both the electrons and holes confined in the core. In the latter, either the valence band edge or the conduction band edge of the shell material is located in the band gap of the core. The resulting staggered band alignment leads on the excitation of the NC, to a special separation of the hole and the electron in the different regions of the CS structure. Type I heterostructures experience optical transition between the electron and hole states, whose wave functions are localized in the same region in real space, whereas for type II hetrostructures, the electron and hole lie in different regions here, the core and shell of the NCs. The shell separates physically the optically active surface core NC from its surrounding medium. Consequently, the sensitivity of the optical properties changes in the local environment of the NCs surface. With respect to the core NCs, the core-shell CS systems generally enhance the stability against photodegradation. At the same time, the shell growth

reduces the number of surface dangling bonds, which can act as trap states for charge carriers and reduce the fluorescence quantum yield QY. Shell growth is accompanied by a small shift nm of the excitonic peak in the UV-Vis absorption spectrum and the PL wavelength.

## 8: Semiconductor Science and Technology - IOPscience

*The compound semiconductor materials report offers concise and complete information on emerging market segments that will boost the decision-making process and feasibility of investment in global compound semiconductor materials market.*

## 9: Versum Materials - List of Industries Served

*Phonon transport in crystalline semiconductor materials, such as Si, Ge, GaAs, GaN, etc, has been extensively studied over the past two decades. In fact, study of phonon physics in crystalline semiconductor materials in both bulk and nanostructure forms has been the cornerstone of the emerging field of ' nanoscale heat transfer '.*

*Srimad bhagavad gita in kannada The kids guide to making scrapbooks photo albums! Footloose in Cornish folklore Experiment in crime Bridge to Yesterday Synopsis of the origin and progress of architecture Guitar QuickStart Management and supervisory skills The experience of politics: you and American Government. Coping With Diabetes (Coping) Complete book of corporate forms The Window Style Bible Ammunition and Small Arms Machinery State of Montana, Montana Historical Society Counterfeiting and its history Love at First Sight (Fanfare) War And Redemption Building hypermedia applications Introduction to genetic analysis by griffiths et al Laguardias Fire Chief 4. Pathogenesis of Sjogrens Syndrome Learn Spanish the Fast and Fun Way w/4 CDs Organizational learning: A reflective and representative critical issue for HRD Jamie L. Callahan Mysteries marvels of the reptile world The Industrial disputes act, 1947 The Last Mad Lover Dick Whittington And His Cat Catch! A Fishmongers Guide to Greatness A winter round-up. 11. Forging the / Figure 3.2 An Empirical Typology of Teacher Roles with High School Touring gold country The Animal Attraction Complete Lighting Design Notebook 16, summer 1871 spring 1872 A journal from Japan Approaches to programming Fly reels of the House of Hardy I want ice cream (The story box) December the 27th*