

# A Review on Semiconductors Including Applications and Temperature Effects in Semiconductors

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## Abstract

There is no doubt that semiconductors changed the world beyond anything that could have been imagined before them. Although people have probably always needed to communicate and process data, it is thanks to the semiconductors that these two important tasks have become easy and take up infinitely less time than, e.g., at the time of vacuum tubes. Semiconductor materials are the building blocks of the entire electronics and computer industry. Small, lightweight, high speed, and low power consumption devices would not be possible without integrated circuits (chips), which consist of semiconductor materials. This paper provides a general discussion of semiconductor materials, their history, classification and the temperature effects in semiconductors. In this section we provide details about the impact of temperature on the MOSFET energy band gap, carrier density, mobility, carrier diffusion, velocity saturation, current density, threshold voltage, leakage current and interconnect resistance. We also provide the applications of semiconductor materials in different sectors of modern electronics and communications.

**Keywords:** Semiconductor; History of Semiconductor; Temperature effects in semiconductors; Applications of Semiconductors

## 1. Introduction

There are certain substances that are neither good conductors (metals) nor insulators (glass). A substance which has crystalline structure and contains very few free electrons at room temperature is called semiconductors. At room temperature, it behaves like an insulator. Its resistivity lies between that of conductor and insulator. If suitable impurities are added to the semiconductors, controlled conductivity can be provided. Some examples of semiconductors are silicon, germanium, carbon etc. Semiconductors are the basic building block of modern electronics, including transistors, solar cells, light-emitting diodes (LEDs), and digital and analog integrated circuits. The modern understanding of the properties of a semiconductor lies on quantum physics to explain the movement of electrons and holes inside a crystal structure and also in a lattice. An increased knowledge of semiconductor materials and fabrication processes has made possible continuing increases in the complexity and

speed of microprocessors. The electrical conductivity of a semiconductor material increases with increasing temperature, which is behavior opposite to that of a metal. Semiconductor devices can display a range of useful properties such as passing current more easily in one direction than the other, showing variable resistance, and sensitivity to light or heat. Because the electrical properties of a semiconductor material can be modified by controlled addition of impurities or by the application of electrical fields or light, devices made from semiconductors can be used for amplification, switching, and energy conversion. Current conduction in a semiconductor occurs through the movement of free electrons and "holes", collectively known as charge carriers. Adding impurity atoms to a semiconducting material, known as "doping", greatly increases the number of charge carriers within it. When a doped semiconductor contains mostly free holes it is called "p-type", and when it contains mostly free electrons it is known as "n-type". The semiconductor materials used in electronic devices are doped under precise conditions to control the location and concentration of p- and n-type dopants. A single semiconductor crystal can have many p- and n-type regions; the p-n junctions between these regions are responsible for the useful electronic behavior. Some of the properties of semiconductor materials were observed throughout the mid 19th and first decades of the 20th century. Development of quantum physics in turn allowed the development of the transistor in 1948. Although some pure elements and many compounds display semiconductor properties, silicon, germanium, and compounds of gallium are the most widely used in electronic devices. A large number of elements and compounds have semiconducting properties, including [1]; certain pure elements are found in Group XIV of the periodic table; the most commercially important of these elements are silicon and germanium. 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 III and V, such as gallium arsenide, groups II and VI, groups IV and VI, and between different group IV elements, e.g. silicon carbide. 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. Now-a-days semiconductor materials are used in every sector of modern technology. In technical purpose the high temperature materials are used widely. Therefore it is needed to increase the temperature of semiconducting materials. For this reasons the different properties of these materials varied with temperature. In this paper we review the classification of semiconductors, early history of semiconductors and temperature effects in semiconductors. The rest of the paper is organized as follows: in Sec. 2, history of semiconductor is given; Sec. 3 classification of semiconductor is given; Sec.4 temperature effects in semiconductors are given. Finally, the conclusion is given in Sec.5.

## **2. Early history of semiconductors**

The history of the understanding of semiconductors begins with experiments on the electrical properties of materials. The properties of negative temperature coefficient of resistance, rectification, and light-sensitivity

were observed starting in the early 19th century. In 1833, Michael Faraday reported that the resistance of specimens of silver sulfide decreases when they are heated. This is contrary to the behavior of metallic substances such as copper. In 1839, A. E. Becquerel reported observation of a voltage between a solid and a liquid electrolyte when struck by light, the photovoltaic effect. In 1873 Willoughby Smith observed that selenium resistors exhibit decreasing resistance when light falls on them. In 1874 Karl Ferdinand Braun observed conduction and rectification in metallic sulphides, and Arthur Schuster found that a copper oxide layer on wires has rectification properties that ceases when the wires are cleaned. Adams and Day observed the photovoltaic effect in selenium in 1876[2]. A unified explanation of these phenomena required a theory of solid-state physics which developed greatly in the first half of the 20th Century. In 1878 Edwin Herbert Hall demonstrated the deflection of flowing charge carriers by an applied magnetic field, the Hall Effect. The discovery of the electron by J.J. Thomson in 1897 prompted theories of electron-based conduction in solids. Karl Baedeker, by observing a Hall Effect with the reverse sign to that in metals, theorized that copper iodide had positive charge carriers. Johan Koenigsberger classified solid materials as metals, insulators and "variable conductors" in 1914. Felix Bloch published a theory of the movement of electrons through atomic lattices in 1928. In 1930, B. Gudden stated that conductivity in semiconductors was due to minor concentrations of impurities. By 1931, the band theory of conduction had been established by Alan Herries Wilson and the concept of band gaps had been developed. Walter H. Schottky and Nevill Francis Mott developed models of the potential barrier and of the characteristics of a metal-semiconductor junction. By 1938, Boris Davydov had developed a theory of the copper-oxide rectifier, identifying the effect of the p-n junction and the importance of minority carriers and surface states [3]. Agreement between theoretical predictions (based on developing quantum mechanics) and experimental results was sometimes poor. This was later explained by John Bardeen as due to the extreme "structure sensitive" behavior of semiconductors, whose properties change dramatically based on tiny amounts of impurities [3]. Commercially pure materials of the 1920s containing varying proportions of trace contaminants produced differing experimental results. This spurred the development of improved material refining techniques, culminating in modern semiconductor refineries producing materials with parts-per-trillion purity. Devices using semiconductors were at first constructed based on empirical knowledge, before semiconductor theory provided a guide to construction of more capable and reliable devices. Alexander Graham Bell used the light-sensitive property of selenium to transmit sound over a beam of light in 1880. A working solar cell, of low efficiency, was constructed by Charles Fritts in 1883 using a metal plate coated with selenium and a thin layer of gold; the device became commercially useful in photographic light meters in the 1930s [3]. Point-contact microwave detector rectifiers made of lead sulfide were used by Jagadish Chandra Bose in 1904; the cat's-whisker detector using natural galena or other materials became a common device in the development of radio. However, it was somewhat unpredictable in operation and required manual adjustment for best performance. In 1906 H.J. Round observed light emission when electric current passed through silicon carbide crystals, the principle behind the light emitting diode. Oleg Losev observed similar light emission in 1922 but at the time the effect had no practical use. Power rectifiers, using copper oxide and selenium, were developed in the 1920s and became commercially important as an alternative to vacuum tube rectifiers [2, 3]. In the years preceding World War II, infra-red detection and communications devices prompted research into lead-sulfide and lead-selenide materials. These devices were used for detecting ships and aircraft, for infrared rangefinders, and for voice communication systems. The point-contact crystal detector became vital

for microwave radio systems, since available vacuum tube devices could not serve as detectors above about 4000 MHz; advanced radar systems relied on the fast response of crystal detectors. Considerable research and development of silicon materials occurred during the war to develop detectors of consistent quality [3]. Detector and power rectifiers could not amplify a signal. Many efforts were made to develop a solid-state amplifier, but these were unsuccessful because of limited theoretical understanding of semiconductor materials [3]. In 1922 Oleg Losev developed two-terminal, negative resistance amplifiers for radio; however, he perished in the Siege of Leningrad. In 1926 Julius Edgard Lilienfeld patented a device resembling a modern field-effect transistor, but it was not practical. R. Hilsch and R. W. Pohl in 1938 demonstrated a solid-state amplifier using a structure resembling the control grid of a vacuum tube; although the device displayed power gain, it had a cut-off frequency of one cycle per second, too low for any practical applications, but an effective application of the available theory [3]. At Bell Labs, William Shockley and A. Holden started investigating solid-state amplifiers in 1938. The first p-n junction in silicon was observed by Russell Ohl about 1941, when a specimen was found to be light-sensitive, with a sharp boundary between p-type impurity at one end and n-type at the other. A slice cut from the specimen at the p-n boundary developed a voltage when exposed to light. In France, during the war, Herbert Mataré had observed amplification between adjacent point contacts on a germanium base. After the war, Mataré's group announced their "Transistron" amplifier only shortly after Bell Labs announced the "transistor".

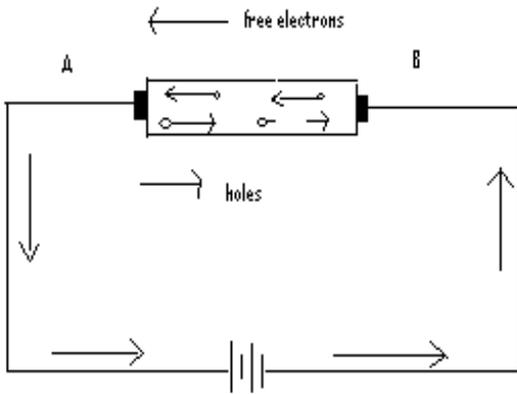
### 3. Classification of Semiconductors

Semiconductors may be classified broadly as

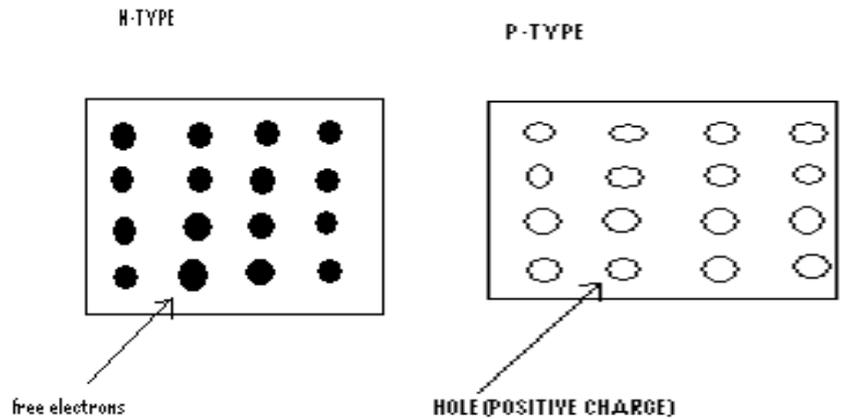
- I. Intrinsic semiconductor
- II. Extrinsic semiconductor

#### **I. Intrinsic semiconductor:**

There are two ways to define an intrinsic semiconductor. In simple words, an intrinsic semiconductor is one which is made up of a very pure semiconductor material. In more technical terminology it can be stated that an intrinsic semiconductor is one where the number of holes is equal to the number of electrons in the conduction band. The forbidden energy gap in case of such semiconductors is very minute and even the energy available at room temperature is sufficient for the valence electrons to jump across to the conduction band. Another characteristic feature of an intrinsic semiconductor is that the Fermi level of such materials lies somewhere in between the valence band and the conduction band. This can be proved mathematically which is beyond the scope of discussion in this article. In case you are not familiar with the term Fermi level, it refers to that level of energy where the probability of finding an electron is 0.5 or half (remember probability is measured on a scale of 0 to 1). If a potential difference is applied across an intrinsic semiconductor, electrons will move towards positive terminal while holes will drift towards negative terminal. The total current inside the semiconductor is the sum of the current due to free electrons and holes. If the temperature of the semiconductor increases, the number of hole-electron pairs increases and current through the semiconductor increases. If temperature falls, the reverse happens.



**Figure 1.** Intrinsic semiconductor



**Figure 2.** Extrinsic semiconductor

## II. Extrinsic semiconductor

These are semiconductors in which the pure state of the semiconductor material is deliberately diluted by adding very minute quantities of impurities. To be more specific, the impurities are known as dopants or doping agents. It must be kept in mind that the addition of such impurities is really very minuscule and a typical dopant could have a concentration of the order of 1 part in a hundred million parts or it is equivalent to 0.01 ppm. The materials chosen for doping are deliberately chosen in such a manner that either they have 5 electrons in their valence band, or they have just 3 electrons in their valence band. Accordingly such dopants are known as pentavalent or trivalent dopants respectively. The type of dopant also gives rise to two types of extrinsic semiconductors namely P-type and N-type semiconductors. A pentavalent dopant such as Antimony are known as donor impurities since they donate an extra electron in the crystal structure which is not required for covalent bonding purposes and is readily available to be shifted to the conduction band. This electron does not give rise to a corresponding hole in the valence band because it is already excess, therefore upon doping with such a material, the base material such as Germanium contains more electrons than holes, hence the nomenclature N-type intrinsic semiconductors. On the other hand when a trivalent dopant such as Boron is added to Germanium additional or extra holes get formed due to the exactly reverse process of what was described in the upper section. Hence this dopant which is also known as acceptor creates a P-type semiconductor. Hence electrons are the majority carriers (of current) in N-type while holes are minority carriers. The reverse is true of P-type semiconductors. Another difference is that whereas the Fermi level of intrinsic semiconductors is somewhere midway between the valence band and the conduction band, it shifts upwards in case of N-type while it drifts downward in case of P-type due to obvious reasons. P-type semiconductor is shown in (figure 2.1) and N-type semiconductor is shown in (figure 2.2).

## 4. Semiconductor Materials

Semiconductors materials can be able to conduct electric current, can be easily regulated, and can act as both

insulators and conductors. These qualities have made semiconductors useful in the electronics field since its inception. The conductivity of the semiconductor is generally sensitive to temperature, illumination, magnetic field, and minute amount of impurity atoms. This sensitivity in conductivity makes the semiconductor one of the most important materials for electronic applications. Table 1 shows a portion of the periodic table related to semiconductors. Table 2 shows a list of some of the element and compound semiconductors.

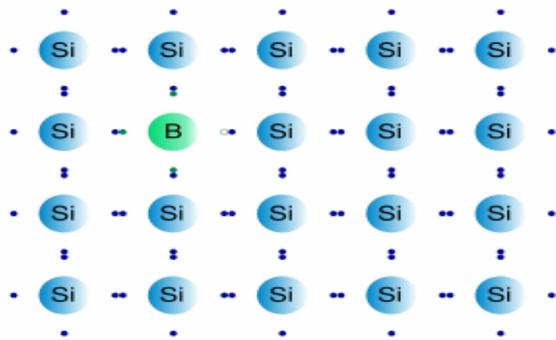


figure 2.1. P- type semiconductor

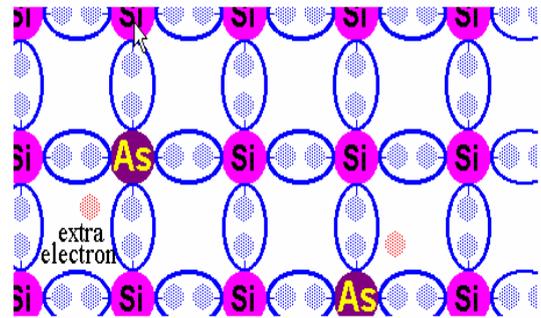


figure 2.2. N- type Semiconductor

Table 1. Portion of the periodic table related to semiconductors

Period	Column II	III	IV	V	VI
2		B Boron	C Carbon	N Nitrogen	
3	Mg Magnesium	Al Aluminum	Si Silicon	P Phosphorus	S Sulfur
4	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium
5	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium
6	Hg Mercury		Pb Lead		

Table 2. Some the element and compound semiconductors

Element	IV-IV Compounds	III-V Compounds	II-VI Compounds	IV-VI Compounds
Si	SiC	AlAs	CdS	PbS
Ge		AlSb	CdSe	PbTe
		BN	CdTe	
		GaAs	ZnS	
		GaP	ZnSe	
		GaSb	ZnTe	
		InAs		
		InP		
		InSb		

**5. Temperature Effects in Semiconductors**

current density, threshold voltage, leakage current, interconnect resistance, and electromigration.

**2.1.1 Energy Band Gap**

Temperature affects the properties of electronic systems in a number of fundamental ways. The most fundamental of properties is the energy band gap,  $E_g$ , which is affected by temperature according to the Varshni equation [1]

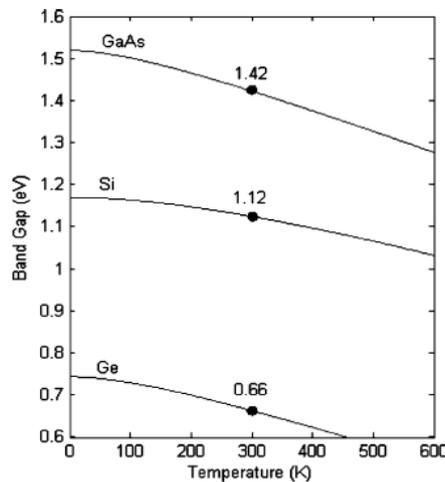
$$E_g(T) = E_g(0) - \frac{\alpha_E T^2}{T + \beta_E} \tag{2.1}$$

where  $E_g(0)$  is the band gap energy at absolute zero on the Kelvin scale in the given material, and  $\alpha_E$  and  $\beta_E$  are material-specific constants. Table 2.1 [2] provides these

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Material	$E_g(0)$ (eV)	$\alpha_E$ (eV/K)	$\beta_E$ (K)
GaAs	1.519	$5.41 * 10^{-4}$	204
Si	1.170	$4.73 * 10^{-4}$	636
Ge	0.7437	$4.77 * 10^{-4}$	235

Table 1 and (1) are used to generate Figure 3, which shows how the band gaps of the three materials decrease as temperature increases (the labeled points are the band gap of each material at room temperature).



**Figure 3.** Energy band gap temperature dependence of GaAs, Si, and Ge.

### 5.2 Semiconductor Conductivity

The conductivity of a semiconductor is given by:

$$\sigma = q (\mu_n n + \mu_p p) \quad (2)$$

where  $\mu_n$  and  $\mu_p$  refer to the mobilities of the electrons and holes, and  $n$  and  $p$  refer to the density of electrons and holes, respectively. Recall that in a doped semiconductor, majority carriers greatly outnumber minority carriers, so the Equation 2 can be reduced to a single term involving the majority carrier. Remember that Equation (2) showed that conductivity depends on both carrier concentration and mobility, so there are a variety of possible temperature dependencies for conductivity. For instance, at fairly low temperature (less than 200 K), the dominant scattering mechanism might be impurity scattering ( $\mu \propto T^{3/2}$ ) while the carrier concentration is determined by extrinsic doping ( $n = N_D^+$ ), therefore, conductivity would be seen to increase with temperature ( $\sigma \propto T^{3/2}$ ). Other possibilities, depending on the material, doping, and temperature will show different temperature dependence of conductivity. One particularly interesting case occurs at high temperatures (above 400k or higher) when carrier concentration is intrinsic and mobility is dominated by lattice scattering ( $\mu_{\text{lattice}} \propto T^{-3/2}$ ). In such cases, the conductivity can easily be shown to vary with temperature as:

$$\sigma \propto \exp\left(\frac{-E_g}{2kT}\right) \quad (3)$$

In this case, conductivity depends only on the semiconductor band gap and the temperature. In this temperature range, measured conductivity data can be used to determine the semiconductor band gap energy,  $E_g$ .

### 5.3 Carrier Density

Carrier densities affect electrical and thermal conductivity, and are a function of the effective density of states in the appropriate band (conduction for n-type, valence for p-type), the Fermi energy level in the material (which is a function of temperature and dopant concentrations), and the temperature as given by the following equations:

$$n = N_C e^{-\frac{E_C - E_F}{kT}} \quad (4)$$

$$p = N_V e^{-\frac{E_F - E_V}{kT}} \quad (5)$$

where  $n$  is the electron density,  $p$  is the hole density,  $N_C$  is the density of states in the conduction band,  $N_V$  is the density of states in the valence band,  $E_C$  is the conduction band energy level,  $E_V$  is the valence band energy level,  $E_F$  is the Fermi energy level,  $k = 1.38 \cdot 10^{-23}$  J/K is the Boltzmann constant, and  $T$  is temperature. The

temperature dependence of carrier density is shown in Figure 4 for a doped material. In the ionization region, there is only enough latent energy in the material to push a few of the dopant carriers into the conduction band. In the extrinsic region, which is the desired region of operation, the carrier concentration is flat over a wide range of temperatures; in this region, all of the dopant carriers have been energized into the conduction band (i.e.  $n = N_D$ ) and there is very little thermal generation of additional carriers. As the temperature increases, the extrinsic region turns into the intrinsic region, and the number of thermally generated carriers exceeds the number of donor carriers. The intrinsic carrier concentration in a material  $n_i$  is generally much smaller than the dopant carrier concentration at room temperature, but  $n_i = (n \cdot p)$  has a very strong temperature dependence [5]

$$n_i \propto T^{1.5} e^{-\frac{E_{g0}}{2kT}} \tag{6}$$

where  $E_{g0}$  is the energy band gap at  $T = 0$  K. Depending upon the dopant concentration, the number of thermally generated carriers can exceed the number of dopant-generated carriers, increasing the potential for thermal variation problems.

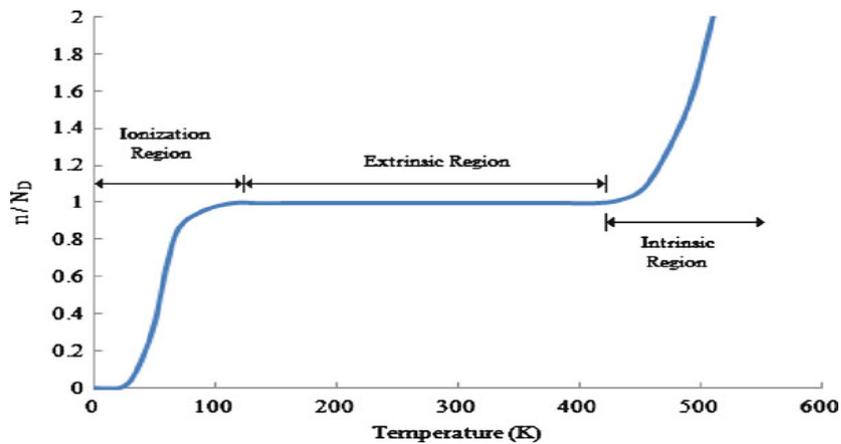


Figure 4. Temperature dependence of n in a doped semiconductor

### 5.4 Mobility

We pay particular attention to the temperature and electric field dependence of mobility, as mobility is one of the two main factors (the other is threshold voltage) resulting in the MOSFET temperature behavior shown later in this chapter. The carrier mobility,  $\mu$  ( $\text{cm}^2/\text{V}\cdot\text{s}$ ), describes the drift velocity of a particle in an applied electric field. Under small to moderate electric fields,  $\mu = v_d/\xi$  where  $v_d$  is the drift velocity, and  $\xi$  is the electric field. MOSFET mobility has very complex temperature dependence, defined by the interplay of the following four scattering parameters: phonon scattering  $\mu_{ph}$ , surface roughness scattering  $\mu_{sr}$ , bulk charge Coulombic scattering  $\mu_{cb}$ , and interface charge Coulombic scattering  $\mu_{int}$  [6]. Each of these scattering parameters is related to the temperature of the material,  $T$ , and the effective transverse electric field in the channel,  $\xi_{eff}$ , which is approximated as [7, 8]

$$\xi_{eff} \approx \frac{(\eta Q_{inv} + Q_b)}{\epsilon_{Si}} \approx \frac{(V_{gs} + V_T)}{6T_{ox}} \quad (7)$$

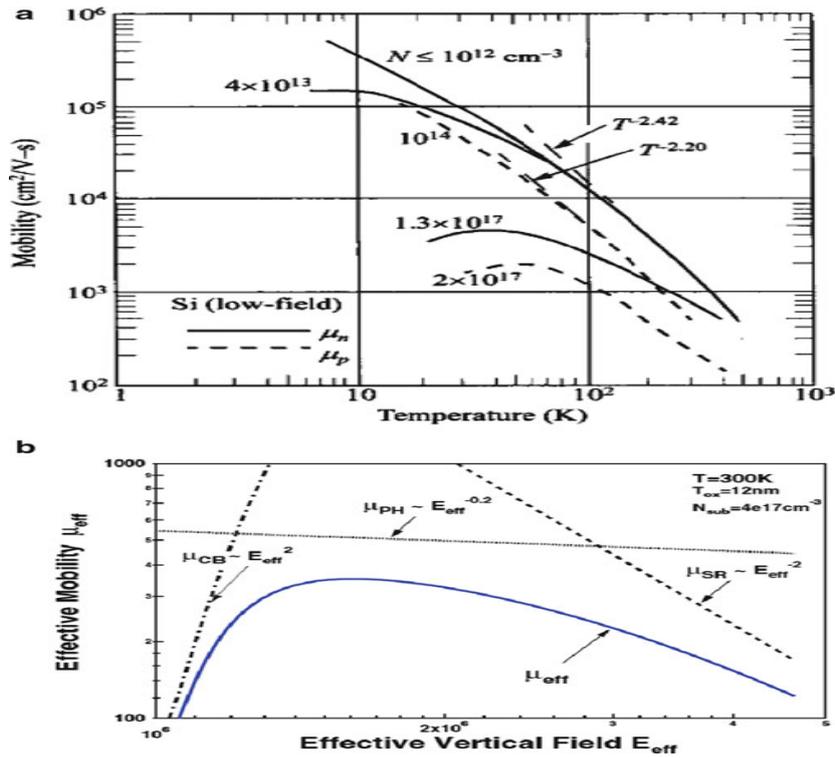
where  $\eta$  is a constant ( $\eta \approx 0.4$  in PMOS devices and  $\eta \approx 0.5$  in NMOS devices),  $Q_{inv}$  is the inversion layer charge density,  $Q_b$  is the substrate depletion charge density, and  $\epsilon_{Si} = 11.7$  is the relative permittivity of Silicon. This approximation is not very convenient for circuit analysis, so  $\xi_{eff}$  is also approximated in terms of the gate-source voltage  $V_{gs}$ , the threshold voltage  $V_T$ , and gate oxide thickness  $T_{ox}$ . The Berkeley Short-Channel IGFET

Model (BSIM), one of the most widely used simulation models, combines these four scattering parameters into an effective mobility,  $\mu_{eff}$  [3] using Matthiessen's rule

$$\frac{1}{\mu_{eff}(T, E_{eff})} \propto \frac{1}{\mu_{ph}(T, E_{eff})} + \frac{1}{\mu_{sr}(T, E_{eff})} + \frac{1}{\mu_{cb}(T, E_{eff})} + \frac{1}{\mu_{int}(T, E_{eff})} \quad (2.6)$$

Phonon scattering refers to the potential for an electron to be scattered by a lattice vibration. As temperature increases, lattice vibrations increase and the probability of an electron being scattered by the lattice increases; thus, high temperature mobilities are limited by phonon scattering ( $\mu_{ph} \propto T^{-3/2}$ ), causing mobility to decrease as temperature increases as shown in Fig. 2.3a. Surface roughness scattering becomes dominant when high electric fields pull electrons closer to the Si/SiO<sub>2</sub> surface ( $\mu_{sr} \propto \xi_{eff}^{-2.1}$ ).

decrease as temperature decreases ( $\mu_{cb} \propto T$ ). This effect is emphasized in the high dopant concentration curves shown in Figure 4a, where mobility decreases with decreasing temperature (e.g. the  $\mu_n = 1.3 \cdot 10^{17}$  dopant concentration line below  $\sim 30$  K). The electric field dependence of mobility is shown in Figure 5b. In bulk Coulombic scattering, increasing  $\xi_{eff}$  increases the charge density in the channel; the associated charge screening reduces the impact of  $\mu_{cb}$  ( $\propto \xi_{eff}^{-2}$ ). At low temperatures, the interface charges have two conflicting dependences. Reduced temperature reduces the carriers' thermal velocity, which increases the impact of interface charges; however, the reduced thermal velocity also reduces the screening effect [9], and this reduction in screening dominates the temperature dependence ( $\mu_{int} \propto T^{-1}$ ). The electric field screening effect is also weakened by the reduced thermal velocity ( $\mu_{int} / \xi_{eff}$ , not  $\xi_{eff}^{-2}$  as in the  $\mu_{cb}$  limit). In this paper, we consider devices operating in the phonon scattering limit, with temperatures  $> 200$  K; thus, mobility will decrease as temperature increases. The temperature dependence of mobility plays a major role in temperature-aware system design. In room temperature Si, the electron mobility,  $\mu_n$ , is nearly three times as large as the hole mobility,  $\mu_p$ , with  $\mu_n = 1,350$  cm<sup>2</sup>/V.s and  $\mu_p = 480$  cm<sup>2</sup>/V.s.



**Figure 5.** (a) Temperature dependence of electron and hole mobilities in Si for different dopant concentrations [5], (b) Field dependence of mobility [10]

### 5.5 Carrier Diffusion

Diffusion is the movement of particles from a region of high concentration to a region of low concentration. Carrier diffusion coefficients  $D_n$  and  $D_p$  (for electrons and holes, respectively) are related to mobility by the Einstein relationship

$$\frac{D}{\mu} = \frac{kT}{q} \tag{9}$$

Here,  $q$  is the charge on an electron ( $1.6 \cdot 10^{-19}$  C), and  $kT/q$  is an important value known as the thermal voltage,  $\phi_T$ . At room temperature (300 K),  $\phi_T = 0.0259$  V.  $D_n$  and  $D_p$  in room temperature silicon are 36 and 12  $\text{cm}^2/\text{s}$ , respectively.

### 5.6 Velocity Saturation

Although saturation velocity has been recently found to be a dominant temperature dependent parameter, notable work had been performed in this area as far back as 1970 [11] using device lengths of 10  $\mu\text{m}$ . In the BSIM4 device model, the impact of temperature on velocity saturation  $v_{sat}$  is modeled by [12]

$$v_{sat} = v_{sat0} \cdot [1 - \alpha_{v_{sat}}(T - T_0)] \tag{10}$$

where  $v_{sat0}$  is the saturation velocity at nominal temperature ( $T_0$ ) and  $\alpha_{vsat}$  is the saturation velocity temperature coefficient. Qualitatively, velocity saturation is the point at which increases in energy no longer cause carrier velocity to increase; instead, the additional energy is lost to phonon generation through lattice interactions. The devices operate in the velocity saturation regime; thus, the impact of temperature on saturation velocity (increasing temperature decreases  $v_{sat}$ ) is one of the most important criteria affecting the overall impact of temperature on device current.

### 4.1.0 Current Density

The temperature dependence of the carrier concentrations, mobilities and diffusion coefficients affect the temperature behavior of the carrier current densities, with the carrier densities defined by the following formulas [10]:

$$J_N = q\mu_n n \xi + qD_n \nabla n \tag{2.9}$$

$$J_P = q\mu_p p \xi - qD_p \nabla p \tag{2.10}$$

where  $J_N$  and  $J_P$  are the electron and hole current densities, respectively. The first term in each equation is the *drift* component of the total current, with  $\mu_n$  and  $\mu_p$  corresponding to the electron and hole mobilities, respectively;  $\xi$  is the electric field. The second term in each equation is the *diffusion* component of the total current, with  $\nabla n$  and  $\nabla p$  corresponding to the electron and hole concentration gradients (if there is no concentration gradient, there is no diffusion). The temperature dependent parameter in the second term is the diffusion coefficient. Increased temperature increases particle kinetic energy, increasing the diffusion component of the mobility and the carrier density. The mobility term was shown in figure 4 to decrease as temperature increases (in the lattice vibration-limited case) while the carrier density remains nearly fixed with temperature over the extrinsic range (our intended range of operation), as indicated by Figure 3. Thus, we determine that the drift component of the total current decreases as temperature increases. The drift and diffusion currents have opposing temperature dependencies, which causes the net current change to depend on the applied electric field. In the high-field (drift-dominated) case, current decreases as temperature increases; in the low-field (diffusion-dominated) case, current increases as temperature increases. However, if the system in question is a multi-voltage system, and the system has both drift- and diffusion-dominated components, the impact of temperature variation may become less well-defined. The difference between a drift-dominated system and a diffusion-dominated system is defined by the threshold voltage,  $V_T$ .

### 5.8 Threshold Voltage

The MOSFET threshold voltage is given by [5]

$$V_T = V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F} \tag{12}$$

where  $V_{FB} = \phi_{gs} - (Q_{ss}/C_{ox})$  is the flat band voltage, with the gate-substrate contact potential  $\phi_{gs} = \phi_T \cdot \ln(N_A N_G / n_i^2)$ ,  $N_A$  and  $N_G$  are the substrate and gate doping concentrations, respectively,  $Q_{ss}$  the surface charge density, and  $C_{ox}$  the oxide capacitance;  $\gamma = C_{ox}(2q\epsilon_{Si}N_A)^{0.5}$  is a body effect parameter, with  $\epsilon_{Si}$  the relative permittivity of Si;  $\phi_F = \phi_T \cdot \ln(N_A/n_i)$  is the Fermi energy with the thermal voltage  $\phi_T = kT/q$ , and  $n_i$  the intrinsic carrier concentration of Si. Of the parameters in (12),  $\phi_{gs}$  and  $\phi_F$  vary with temperature (each contains  $\phi_T$  and  $n_i$  terms). The threshold voltage temperature dependence  $\partial V_T/\partial T$  may thus be written as [14]

$$\frac{\partial V_T}{\partial T} = \frac{\partial \phi_{gs}}{\partial T} + 2 \frac{\partial \phi_F}{\partial T} + \frac{\gamma}{\sqrt{2\phi_F}} \frac{\partial \phi_F}{\partial T} \tag{13}$$

where the temperature dependencies of  $\phi_{gs}$  and  $\phi_F$  are [14]

$$\begin{aligned} \frac{\partial \phi_{gs}}{\partial T} &= \frac{1}{T} \left( \phi_{gs} + \frac{E_{G0}}{q} + \frac{3kT}{q} \right) \\ \frac{\partial \phi_F}{\partial T} &= \frac{1}{T} \left[ \phi_F - \left( \frac{E_{G0}}{2q} + \frac{3kT}{2q} \right) \right] \end{aligned} \tag{14}$$

Filanovsky [14] used empirical parameters from a 0.35  $\mu\text{m}$  CMOS technology to determine that the three terms in (13) are -3.1, 2.7, and -0.43 mV/K, resulting in a net threshold temperature coefficient of -0.83 mV/K. The threshold voltage in a MOSFET is commonly modeled to decrease linearly with increasing temperature; the parameter is plotted in Figure 6 over a range of oxide thicknesses  $d$  and dopant concentrations  $N_A$ .

### 5.9 Leakage Current

Subthreshold leakage current  $I_{sub}$  is exponentially dependent on temperature, as shown in Figure 7; a common rule of thumb is that leakage current doubles for every 10°C increase in temperature [15]. When  $V_{GS} = 0$ ,  $I_{sub}$  may be represented by the Shockley diode model

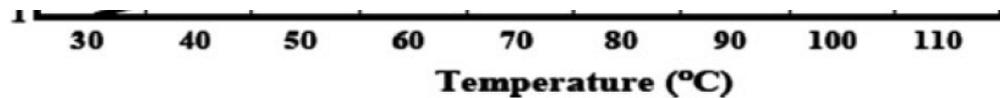
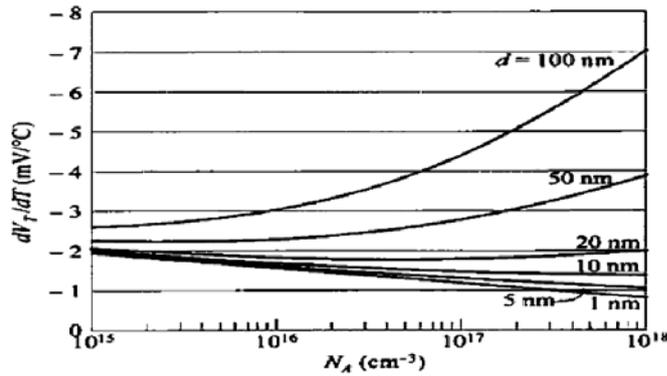


Fig. 2.5 Temperature dependence of subthreshold leakage current ( $V_{GS} = 0$  V) [14]

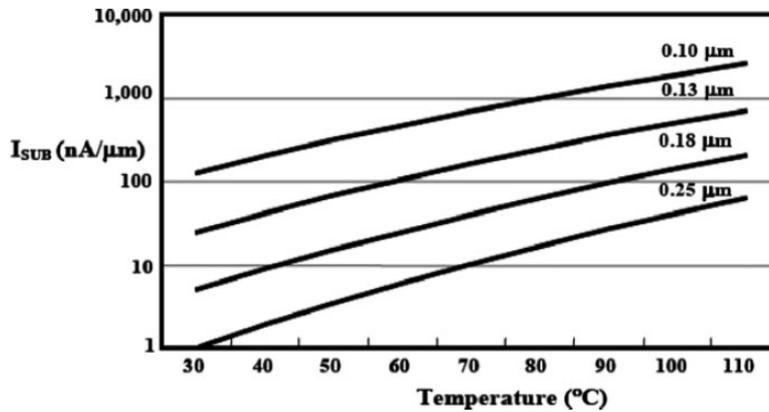
$$I_0 = A T e^{-\frac{1.12}{2\phi_T}} \tag{2.16}$$

where  $I_0$  is the reverse saturation current [12],  $A$  is a constant, and  $V_{DS}$  is the drain-source voltage. Recalling that  $\phi_T = kT/q$ , we see that  $I_0$  is responsible for the exponential temperature dependence shown in Fig. 2.5.

threshold leakage current [16].



**Figure 6.** Change in threshold voltage temperature dependence at room temperature vs. dopant concentration, with oxide thickness  $d$  [5].



**Figure 7.** Temperature dependence of sub- threshold leakage current ( $V_{GS} = 0$  V) [17].

### 5.10 Interconnect Resistance

The interconnect resistance  $R$  is related to temperature by

$$R(T) = R_0[1 + \alpha_R(T - T_0)] \tag{17}$$

where  $T$  is the temperature,  $R_0$  is the resistance at nominal temperature  $T_0$ , and  $\alpha_R$  is an empirical term named the temperature coefficient of resistance. Al and Cu interconnects have similar values of  $\alpha_R$  —0.004308 and 0.00401, respectively. Over the military-specified temperature range, Al wire resistances can change by up to 77.5% while Cu wire resistances can change by up to 72.2%. Interconnect resistance increases with increasing temperature, complicating evaluation of the impact of temperature on interconnect links—in these applications, the MOSFET currents may either increase or decrease in temperature (as explored in the next subsection), which means that the impact of temperature on interconnect resistance can either add to the system temperature

dependence or reduce the temperature dependence, depending on the operating conditions.

## **6. Applications of Semiconductors**

### ***6.1 Applications of Semiconductors in Electronic Devices***

Semiconductors are the materials that conduct electric current, can be easily regulated, and can act as both insulators and conductors. These qualities have made semiconductors useful in the field of electronics. Semiconductor devices are all around us. They can be found in just about every commercial product we contact, from the family car to the pocket calculator. Today semiconductor devices are omnipresent in a wide range of industries, including computers, communications, aerospace, manufacturing, agriculture, and healthcare. Semiconductors have made electronic devices – such as MP3 players, HDTVs / TVs, CD players, computers, and cell phones – smaller, cheaper, faster, and more reliable.

Science and industry also depend heavily on semiconductor devices. Research laboratories use these devices in all sorts of electronic instruments to perform tests, measurements, and numerous other experimental tasks. Industrial control systems (such as those used to manufacture automobiles) and automatic telephone exchanges also use semiconductors. Even today heavy-duty versions of the solid-state rectifier diode are being used to convert large amounts of power for electric railroads. Of the many different applications for solid-state devices, space systems, computers, and data processing equipment are some of the largest consumers.

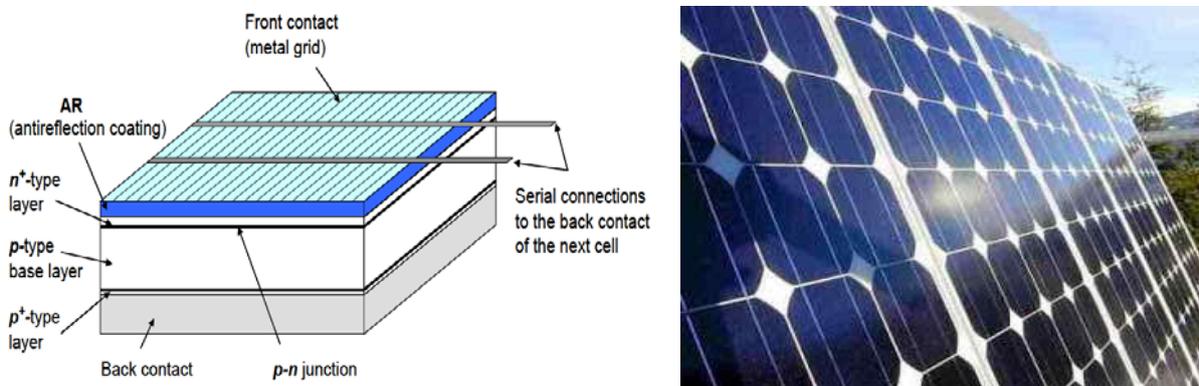
**In the following section we will explore the most important applications:**

- 1- Flat panel displays: Computers, television, mobile handheld devices
- 2- High brightness LEDs: solid state lighting, large display panels, automotive applications, LCD backlighting.
- 3- Imaging array sensors: Digital cameras.
- 4- Diode lasers.
- 5- Optical storage, mice.
- 6- Robotics.**
- 7- Medical Electronics.
- 8- Industrial Electronics.
- 9- Telecommunications.
- 10- Wireless Communication.
- 11- Global Positioning By Satellite (GPS).
- 12- Smart Cards.
- 13- Memories.

### ***6.2 Applications of Semiconductors in Solar Cells***

Now-a-days most of the solar cells the absorption of photons, as a result of the generation of the charge carriers, and the subsequent separation of the photo-generated charge carriers take place in semiconductor

materials. Therefore, the semiconductor layers are the most important parts of a solar cell and they form the central part of the solar cell. There are a number of different semiconductor materials that are suitable for the conversion of photons energy into electrical energy. The crystalline silicon (c-Si) solar cell, which dominates the PV market at present, has a simple structure, and provides a superior example of a typical solar cell structure. Figure 8 shows the essential features of c-Si solar cells. An absorber material is typically a moderately doped p-type square wafer having thickness around 300  $\mu\text{m}$  and an area of  $10 \times 10 \text{ cm}^2$  or  $12.5 \times 12.5 \text{ cm}^2$ . On both sides of the c-Si wafer a highly doped layer is formed,  $n^+$ -type on the top side and  $p^+$ -type on the back side, respectively. These highly doped layers help to separate the photo-generated charge carriers from the bulk of the c-Si wafer. The trend in the photovoltaic industry is to reduce the thickness of wafers up to 250  $\mu\text{m}$  and to increase the area to  $20 \times 20 \text{ cm}^2$ .



**Figure 8.** A typical structure of a c-Si solar cell.

In addition to semiconductor layers, solar cells consist of a top and bottom metallic grid or another electrical contact that collects the separated charge carriers and connects the cell to a load. Usually, a thin layer that serves as an antireflective coating covers the topside of the cell in order to decrease the reflection of light from the cell. In order to protect the cell against the effects of outer environment during its operation, a glass sheet or other type of transparent encapsulant is attached to both sides of the cell. In case of thin-film solar cells, layers that constitute the cell are deposited on a substrate carrier. When the processing temperature during the deposition of the layers is low, a wide range of low-cost substrates such as glass sheet, metal or polymer foil can be used. The first successful solar cell was made from c-Si and c-Si is still the most widely used PV material. Therefore we can use c-Si as an example to explain semiconductor properties that are relevant to solar cell operation. This gives us a basic understanding of how solar cells based on other semiconductor materials work. The central semiconductor parameters that determine the design and performance of a solar cell are:

- i) Concentrations of doping atoms, which can be of two different types; donor atoms which donate free electrons,  $N_D$ , or acceptor atoms, which accept electrons,  $N_A$ . The concentrations determine the width of a space-charge region of a junction.

ii) Mobility,  $\mu$ , and diffusion coefficient,  $D$ , of charge carriers that characterize carriers transport due to drift and diffusion, respectively.

iii) Lifetime,  $\tau$ , and diffusion length,  $L$ , of the excess carriers that characterize the recombination-generation processes.

iv) Band gap energy,  $E_g$ , absorption coefficient,  $\alpha$ , and refractive index,  $n$ , that characterize the ability of a semiconductor to absorb visible and other radiation.

### **6.3 Applications of Semiconductors in Telecommunications**

The telecommunications industry is growing larger than ever mainly due to the demand for faster information transfer. Fiber optic communication is rapidly becoming the backbone for voice, video, and internet data transfer. As this industry matures, the components for broadband fiber networking undergo continuous research and development. These components include VCSEL and edge-emitting lasers, thin-film DWDM filters and waveguides for multiplexing/demultiplexing, EDFA and Raman amplifiers, photodiode detectors, and more. Thin films are critical to the performance of these devices. Spectroscopic ellipsometry (SE) is uniquely suited to measure both film thickness and refractive index at telecom wavelengths in the infrared.

#### **Transmitters and Receivers**

Optical communication literally begins and ends with a transmitter and receiver. In the transmitter, lasers produce light to travel down the fiber encoded with information. In the end, the receiver converts this light to an electronic signal via a photodiode detector. Thin alloy semiconductor films play an important role in both components.

##### **A. Laser Sources**

Semiconductor lasers are designed to operate in the near infrared at 1310 nm or 1550 nm for fiber-optic communication. Another important wavelength is 980nm used for pump lasers. Semiconductor lasers create light via optical transitions between energy levels in a direct band gap semiconducting film. Ternary and quaternary alloy semiconductors offer the flexibility to tune the desired emission wavelength by changing the composition of the materials, as the band gap is dependent on the ratio of materials in the alloy. For instance, the quaternary material  $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$  can provide laser emission in the  $1.1\mu\text{m} < \lambda < 1.6\mu\text{m}$  range depending on alloy ratio ( $x$  and  $y$ ). Similarly, the ternary material  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  can be varied for use in pump lasers.

##### **B. Photodiode Detectors**

The same energy levels that produce laser light will absorb light to excite electrons to an elevated state. Absorption frees electrons from their atoms to create a measurable electric current which is directly related to the intensity of light shining on the detector. The energy levels adjust with alloy concentration, resulting in varying amount of absorption at different wavelengths. This variation in optical properties is described by the

material optical constants, commonly known as  $n$  and  $k$  or  $\epsilon_1$  and  $\epsilon_2$ . The optical constant shape corresponds to the material's electronic transitions. Thus, the optical constants become a "fingerprint" for the semiconductor. For example, in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , the direct bandgap shifts toward shorter wavelengths with increasing aluminum concentration,  $x$ . This is seen in Figure 8 as an absorption edge shift toward shorter wavelengths, along with similar shifts in each high-energy transition [19-22].

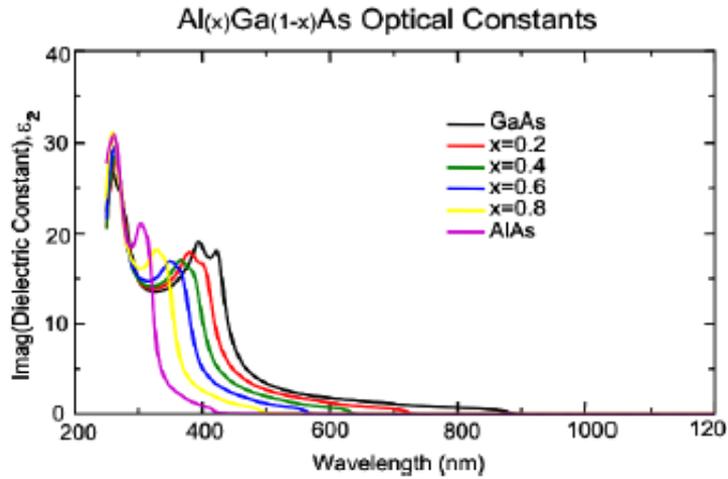


Figure 8. Changes in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  with alloy ratio,  $x$ .

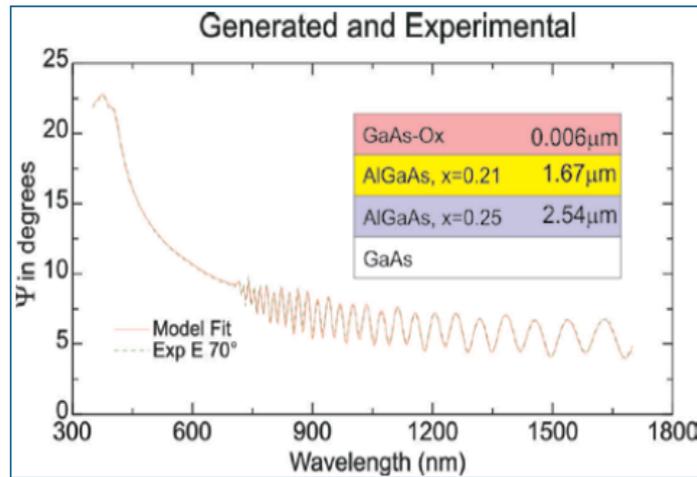


Figure 9. Data and fits for bi-layer compound semiconductor

### Spectroscopic Ellipsometry

Spectroscopic ellipsometry takes advantage of the changing optical constants in a semiconductor to determine alloy ratio. Accurate alloy ratio measurements require a database of the optical constants for different

compositions. Fortunately, the energy bands shift systematically with changing composition. Thus, a series of five to ten samples that cover the full range of compositions will provide enough information to setup an alloy model. The alloy model creates the correct optical constants for any specified alloy ratio,  $x$ . If an alloy ratio is specified between two of the original database values, an appropriate interpolation is performed. This is enhanced by using the alloyshifting model developed by Snyder. In practice, the optical constants can be properly described by simply selecting the correct alloy ratio. In Figure 9, we show the ellipsometric measurement from a bi-layer semiconductor stack. Five fit parameters were used to match this data: three layer thicknesses (including the surface oxide) and two alloy compositions. The AlGaAs material has a larger bandgap than used for source lasers. However, it is acceptable for pump laser wavelengths. The pump laser is used to supply energy to EDFA and Raman amplifiers. For example, a pump laser at 980nm can excite Erbium to a higher energy state that emits light near 1550nm.

#### ***6.4 Applications of Semiconductors in wireless communications***

The market for the semiconductors that power wireless communications is undergoing dramatic changes. Based on the data from strategy Analytics, the estimated overall industry growth rate will average 6 percent from 2011 to 2015. A large share of that growth will be attributable to two categories: smartphones and connected devices such as iPads. Today, mobile application processors operate at 5 to 10 percent of a typical laptop's computing power, yet that gap is rapidly narrowing as smartphones run applications from mobile video to mobile games and their energy consumption is lower than laptop's by a factor of 10 to 30 times.

Now-a-days semiconductor materials are used at large amount in smartphones and tablet devices and these devices are continue to progress toward higher functionality and performance. Toshiba contributes to the evolution of the mobile system-involving very high speed files and data transfer with TransferJet™, High Efficient and quick Charger with WPC wireless charger and USB charger solution, High quality voice and sound with Audio CODECs and Amplifiers for Smart Phone, Tablet PCs and Smart accessories.

#### ***6.5 Applications of Semiconductors in Computers***

Semiconductors are one of the most important enabling technologies for digital computers. They are the foundation of all modern electronic devices which use circuitry. These materials were first introduced to computing to solve issues related to vacuum tubes used in analog computers. The tubes would often leak, and the metals used to transmit electrons within them would frequently burn out. Semiconductors did not suffer these issues. Semiconductor materials conduct electrons in an entirely different manner than metals, causing them to avoid burn out. Unlike vacuum tubes, semiconductors did not need to warm up over long periods of time prior to use. Additionally, they required far less space than a series of vacuum tubes. The first semiconductor based transistor was made in 1947. The first integrated circuit based on semiconductor technology followed shortly after, in 1959. All the semiconductor materials are not used in computers. The material which has become the standard semiconductor for circuitry is silicon. Silicon is the most abundant element in the earth's crust, and is accessible from almost anywhere on earth. This makes silicon inexpensive, driving down the cost of computers and other technological devices. Some computers use other

semiconductor materials to achieve faster electron conduction speeds. An example is germanium with a small concentration of arsenic impurities. While this material achieves faster conduction rates, its cost is significantly higher than silicon.

## **7. Conclusion**

Silicon may be considered as the information carrier of our times. In the history of information there were two revolutions (approximately 500 years apart). The first was that of Johan Gutenberg who made information available to many, the other is the invention of the transistor. Currently the global amount of information doubles every year. Many things we are taking for granted (such as, e.g., computers, Internet and mobile phones) would not be possible without silicon microelectronics. Electronic circuits are also present in cars, home appliances, machinery, etc. Optoelectronic devices are equally important in everyday life, e.g., fiber optic communications for data transfer, data storage (CD and DVD recorders), digital cameras, etc. Since the beginning of semiconductor electronics the number of transistors in an integrated circuit has been increasing exponentially with time. In summary we have presented the outline of semiconductors, their early history and classification. We have also studied the temperature effects in semiconductors. The energy band gap, mobility, threshold voltage and saturation velocity are decrease with increasing temperature. On the other hand the conductivity, carrier density, leakage current and interconnect resistant increase with increasing temperature. We have also studied the applications of semiconductors in basic electronic devices, telecommunication and wireless systems and finally in solar system.

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