

Chapter one

Introduction

1.1. Introduction

The work is a presents theoretical review of the semiconductors and metal-semiconductor contacts (MSC) historical background and the effective of the work functions of some metals to improve the efficiency of the semiconductor by used MSC. This research gives a brief historical review of semiconductor and MSC.

Semiconductors are called semiconductor because their ability to conduct electricity is neither very great nor very small. Indeed, the conductivity of typical semiconductor can be controlled by temperature[1].

Metal-semiconductor contacts consider one of the semiconductor devices, and divided into two categories: 1. Schottky barriers. 2. Ohmic contacts. Schottky barriers are called rectifying contact [2]. In an ideal metal-semiconductor contact the height of the Schottky barrier in the semiconductor is equal to the difference of the metal and semiconductor work functions[3]. An ohmic contact is defined as a metal-semiconductor contact that has a negligible contact resistance relative to the bulk or series resistance of the semiconductor and called nonrectifying contact. Semiconductor devices (SD) or integrated circuits have been studied for over 140 years. Today we have largest number of electronic devices. The metal-semiconductor interface, this building block was the first SD ever studied in the year 1874. This interface can be used as a rectifying contact, that is the device allow electrical current to flow easily only in one direction or as an ohmic contact, which can pass current in either direction with a low resistance. The earliest systematic study of SD (MSC) is generally attributed to Braun, who in 1874 discovered the resistance of contact between metal and metal sulfides and also, light emitted diode was invented 1907 by Round, bipolar transistor 1947 by Bardeen, Brattain and Shockley, p-n junction 1949 by Shockley, solar cell 1954

by Chpin and Fuller, Heterojunction bipolar transistor 1957 by Kroemer, MOSFET 1960 by Kahng and Atalla, MESFET 1966 by Mead, MODFET 1980 by Mimura et al., 20nm MOSFET 2001 by Chau[4].

1.2. The statement problem of the thesis

In this research area according to my knowledge there is no studies have investigated the effect of the high or low work functions of metal to arrange the electron flow in the correct direction and enhancement the efficiency of the semiconductors, clearly. Most of researches were focused on others sides to increasing the concentrations carriers of the semiconductors.

This reasons motivated me to choose this work to obtain knowledge will also enable me to contribute to the information which based on the electronic technology.

1.3. Hypothesis of the thesis

In this work the hypothesis is made that a metal semiconductor contacts between gold or nickel and silicon enhance the efficiency of the semiconductors.

1.4. Aims of the thesis

The aims of this study was overview theoretical of the metal semiconductor contacts and determine the effective of the high work functions for some metals on semiconductors to improve the efficiency of semiconductors by used metal semiconductor contacts.

1.5. Importance of the thesis

This study concern with semiconductors due to of it potential importance in different sectors of human life. A Semiconductors they have multi-functions and used in bulkily in the electronic devices such as microelectronic and optoelectronic. The most elements which are used in semiconductors they are low cost material and available.

The modern information technology is based on integrated semiconductor circuits (IC) that are used for data processing (logic), data storage (memory) and data transfer in networks for example glass fiber networks, where optoelectronic devices such as detectors. While more than 90% of the semiconductor ICs are fabricated on silicon wafers, the major material base for optoelectronic devices are the III-V semiconductors, and particularly gallium arsenide[5]. Many important semiconductor technologies have been derived from processes invented centuries ago. For example the lithography process was invented in 1798, in this first process the pattern or image was transferred from a stone plate (litho)[4].

The reason is that the elemental semiconductor silicon permits the highest density of integration, i.e. the smallest size of devices, while the much stronger coupling of electric transitions to the electromagnetic field in the case of direct band gap III-V semiconductors is essential for optoelectronic devices. All importance which mentioned above they are lead me to investigate this work.

1.6. Literature review

In recent years, researcher efforts have focus on the use of semiconductors as alternative material for electronic devices. Many studies carry out to investigate the efficiency of electrical conductivity for semiconductors materials used metal semiconductor contact. The previous studies on **rectifying properties of a metal-semiconductor contact** reported by **V. I. STRIKHA**, he tested gold-silicon contact and calculated the current-voltage characteristics of a metal-semiconductor contact and comparing between the theoretical expressions and experimental data. He was found that agreement for low resistivity silicon diodes [6]. **Low resistance contact to n-type germanium** investigated by **Jui Yen Joson Lin** he used first metal-insulator semiconductor contact to reduce the contact resistance barrier height. The second germanide contact in conjunction with high doping techniques, and found that the low resistance due to activation level and sergregation effect [7]. **Rectification Properties of Metal**

Semiconductor Contacts presented by **E. H. Borneman and et.al** they are used metal semiconductor contacts of a number of different metals were made on *n*- and *p*-type germanium using jet etching and plating techniques. And they found that there was no correlation between the reverse saturation current densities of these diodes and such properties of the metals as work function on *n*-type germanium, but in *p*-type all metals plated produced ohmic contacts of resistivity[8]. **Role of Virtual Gap States and Defects in Metal-Semiconductor Contacts** tested by **W. Monch** he has reported for metal and silicide-silicon contacts are analyzed. And he investigated the virtual gap states determine the barrier heights when either the defect density is low [9]. **Mechanisms of Schottky-barrier formation in metal–semiconductor contacts** discussed by Winfried Monch used two principally different types of electronic states first, adatom-related surface states of donor character and second, the continuum of adsorbate-induced interface states, and determined the surface position of the Fermi level within the semiconductor band gap [10]. **Metal contacts to gallium nitride** presented by **J. S. Foresi and T. D. Moustakas** they report measurements on the nature of aluminum and gold contacts to GaN, and they were found that Current-voltage characterization shows that the as-deposited aluminum contacts are ohmic while the as-deposited gold contacts are rectifying. The gold contacts become ohmic after annealing at 575°C [11]. **Nickel-plated front contacts for front and rear emitter silicon solar cells** introduced by **Michael Rauer and et.al** they were investigated the application of nickel-plated front contacts to front and rear emitter silicon solar cells and compared identically processed *p*- and *n*-type Si solar cells featuring and carried out contact annealing temperature for the thermal formation of the nickel silicide (NiSi_x) after the electroless Ni plating has a significant influence on the NiSi_x layer thickness[12]. **Contact Resistance of Nickel/Germanium/ Gold, Palladium/Germanium/ Titanium/Platinum, and Titanium/ Palladium Ohmic Contacts to Gallium Arsenide and Its Temperature dependence from 4.2 to 350K** presented by **Kenneth A. Jones**

and et.al they were found the specific resistance and contact resistance of NiGeAu and PdGeTiPt ohmic contacts to n-type GeAs and TiPd and PdGeTiPt ohmic contacts to p-type GeAs were determined as function of temperature between 4.2 and 350K [13]. **Formation of a low ohmic contact nickel silicide layer on textured silicon wafers using electroless nickel plating** reported by A. Nguyen and et.al they were found The nickel silicide contact is formed by annealing a thin nickel seed layer that is deposited on the silicon surface using two different alternative seed layer (ASL) [14]. **Low nickel germanide contact resistances by carrier activation enhancement techniques for germanium CMOS application** investigated by Hidenori Miyoshi and et.al they used the CAE technique, and obtained low specific contact resistivity ρ_c values of $6.4 \times 10^{-7} \Omega \text{ cm}^2$ for the NiGe/n⁺-Ge contact and $4.0 \times 10^{-8} \Omega \text{ cm}^2$ for the NiGe/p⁺-Ge contact[15]. **Reaction of nickel-based ohmic contacts with n-type 4H silicon carbide** discussed by B. Barda and P. Macháček compared three nickel-based metallization on Si-face of n-type 4H-SiC and found that the degree of interaction between the metallization and silicon carbide was determined by the AFM (Atomic Force Microscopy) scanning of the SiC substrate after the selective etching of the metallization[16]. **Silicon-nanowire transistor with intruded nickel-silicide contacts** reported by Walter M. Weber and et.al they investigated Schottky barrier field effect transistors based on individual catalytically-grown and undoped Si-nanowires (NW) with respect to their gate length [17].

1.7. Thesis overview

This thesis contents four chapters briefly describe in the paragraph that flow. The novel aspect of the thesis include: The comparison between the gold, rhodium, nickel, platinum and palladium as the good conductor, contacts with silicon, germanium, gallium arsenide, copper oxide and aluminum arsenide.

Chapter 1 is the general introduction of the study and describes semiconductors and metal – semiconductor contacts, it covers the background information on semiconductor, the problem statement, hypothesis, objective, importance, literature review and thesis overview are given in this chapter.

Chapter 2 presents the introduction about semiconductors, types of semiconductors, electronic band structures of semiconductors and properties of semiconductors.

Chapter 3 discusses the introduction about metal – semiconductor contacts, Schottky barriers diode and metal – semiconductor ohmic contacts are presented in this chapter.

Chapter 4 reports calculations of Schottky barrier height and built in potential for some metals, introduction, discussions, general conclusions, recommendations and references all that investigated in this chapter.

Chapter two

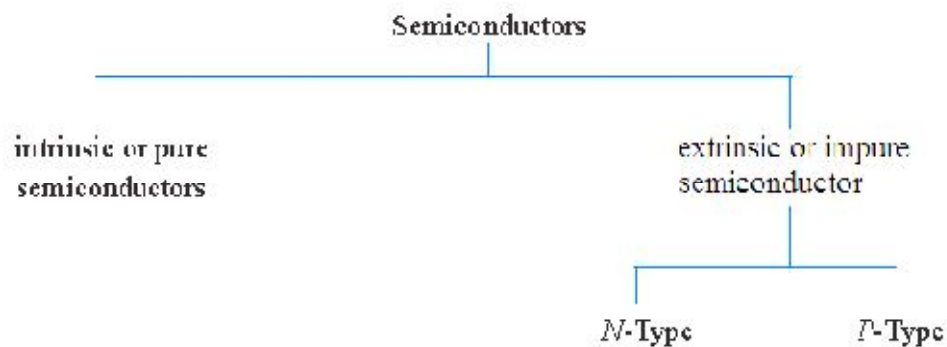
Introduction of semiconductors

2.1. Introduction

A semiconductor is defined as a solid crystalline whose electrical conductivity is intermediate between that of a metal and an insulator [18]. Semiconductors have been studied for a long time, since 1920, but were recognized as wonder materials only after the transistor was invented by Schokkley, Bardeen and Barttain in 1940[19].

2.2. Types of semiconductors

Semiconductors are mainly classified into two categories: Intrinsic or pure and extrinsic or impure semiconductors as shown below:



2.2.1. Intrinsic semiconductors

An intrinsic semiconductor has no impurities and the number of electrons n , in the conduction band exactly matches the number of holes p , in the valence band, $n = p$. The number of electrons or holes is named the intrinsic carrier concentration n_i . This carrier concentration is given by the probability that a state at energy E is filled as given by the Fermi function [1, 20]:

$$n_i = \int_{E_c}^{\infty} f(E) g(E) dE \quad (2.1)$$

Also semiconductors that are chemically pure are called intrinsic semiconductors. These include a number of chemically pure elements such as Si,

Ge, Se, Te and also many chemical compounds GaAs, InSb, InAs, etc [21]. When a semiconductor is taken at 0 K then it behaves as an insulator and conduction occurs at higher temperature due to thermal excitation of electrons from the valence band to the conduction band as shown in figure 2.1. below shows the intrinsic semiconductors at $T = 0\text{ K}$ and $T > 0\text{ K}$ [22].

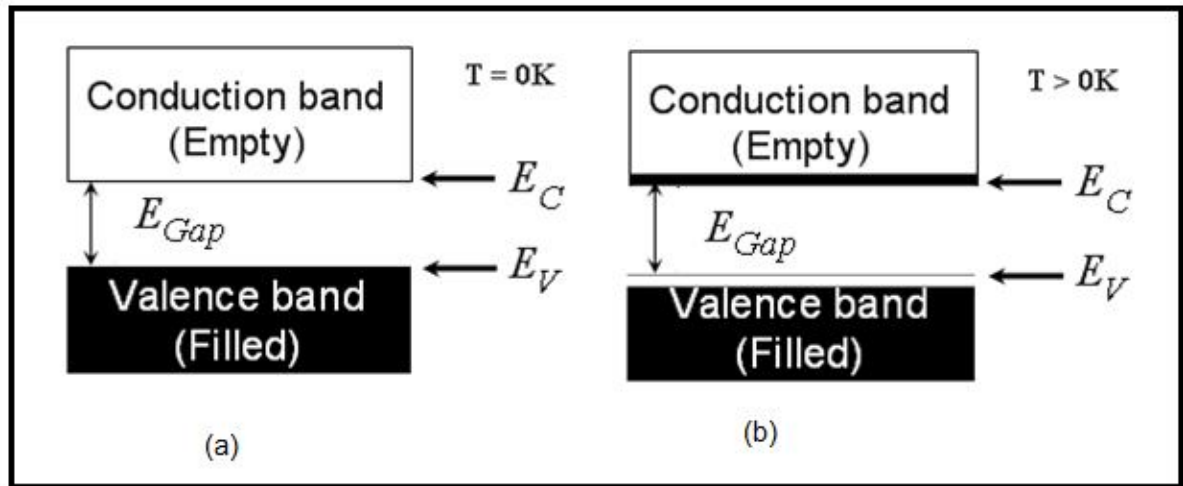


Fig. 2.1. Shows the valence band and conduction band, (a) at temperature $T=0\text{K}$ and (b) at $T > 0\text{K}$ [22].

At $T = 0\text{K}$, there are no electrons in the conduction band and the semiconductor does not conduct, but at $T > 0\text{K}$, some fraction of electrons have sufficient thermal kinetic energy to overcome the gap and jump to the conduction band.

2.2.1.1. Intrinsic carrier concentrations

At any finite, nonzero temperature thermal excitation within the solid will result in promotion of carriers from one band to other. This promotion of carriers produces a nonzero conductivity within the semiconductor [23]. We want the concentration of intrinsic carrier as a function of temperature, in terms of the band gap. Let E_f be the Fermi level of the intrinsic semiconductor at equilibrium then the number of electrons per unit volume in the conduction band is given by [1, 20-22, 24]:

$$n = 2 \left(\frac{2m_e\pi K_B T}{h^2} \right)^{3/2} \exp\left(\frac{E_f - E_c}{K_B T}\right) \quad (2.2)$$

And the number of hole per unit volume in the valence band is obtained:

$$p = 2 \left(\frac{2m_h\pi K_B T}{h^2} \right)^{3/2} \exp\left(\frac{E_v - E_f}{K_B T}\right) \quad (2.3)$$

The concentrations of electrons and holes in an intrinsic semiconductor, n and p are equal and may be calculated from the expression:

$n_i^2 = np$ by using equations (2.2) and (2.3) we get:

$$n_i^2 = N_C N_V \exp\left(\frac{-(E_C - E_V)}{K_B T}\right) \quad (2.4)$$

Taking the square-root gives a value for n_i which does not depend upon E_f

$$n_i = (N_C N_V)^{1/2} \exp\left(\frac{-E_g}{2K_B T}\right) \quad (2.5)$$

Where E_g is the energy band between the conduction and valence bands, K_B is Boltzmann's constant, N_C and N_V are the effective densities of states in conduction and valence bands respectively and T is the temperature. The effective densities of states are given by:

$$N_C = 2 \left(\frac{2m_n\pi K_B T}{h^2} \right)^{3/2} \text{ and } N_V = 2 \left(\frac{2m_p\pi K_B T}{h^2} \right)^{3/2} \quad (2.6)$$

Where m_n and m_p are the effective masses of the electrons and holes respectively and h is Planck's constant.

The most important point to note about Equation (2.5) is that n_i depends exponentially with temperature on half of the semiconductor energy gap. Narrow gap semiconductors will have large intrinsic carrier concentrations while wide-gap materials will have fewer mobile carriers at a given temperature. Then the intrinsic carrier concentration[1]

2.2.1.2. The law of mass action

The law of mass action may take the product of the general expression for n and p as given by [21]:

$$n_i^2 = np \quad (2.7)$$

Eq. (2.7): state that the product of n and p is always constant for a given semiconductor material at a given temperature.

Table 2.1. Effective density of state function and effective mass values for some semiconductors [25].

Element	$N_c (cm^{-3})$	$N_v (cm^{-3})$	m_n/m_o	m_p/m_o
Silicon	2.80×10^{19}	1.04×10^{19}	1.080	0.56
Gallium arsenide	4.70×10^{17}	7.00×10^{18}	0.067	0.48
Germanium	1.04×10^{19}	6.00×10^{18}	0.550	0.37

2.2.1.3. The intrinsic Fermi level position

The Fermi energy level is located near the centre of the forbidden band gap for the intrinsic semiconductor. We can get from equations (2.2) and (2.3) the intrinsic semiconductor $n = p$ hence,

$$2 \left(\frac{2m_e \pi K_B T}{h^2} \right)^{3/2} \exp \left(\frac{E_f - E_c}{K_B T} \right) = 2 \left(\frac{2m_h \pi K_B T}{h^2} \right)^{3/2} \exp \left(\frac{E_v - E_f}{K_B T} \right)$$

$$m_e^{3/2} \exp \left(\frac{E_f - E_c}{K_B T} \right) = m_h^{3/2} \exp \left(\frac{E_v - E_f}{K_B T} \right)$$

$$2E_f - E_c - E_v = K_B T \ln \left(\frac{m_h}{m_e} \right)^{3/2}$$

$$E_f = \frac{1}{2}(E_c + E_v) + K_B T \frac{3}{4} \ln\left[\frac{m_h}{m_e}\right]$$

If the effective masses $m_e = m_h$ then

$$E_f = \frac{E_c + E_v}{2} \text{ hence } \ln(1) = 0 \quad (2.8)$$

2.2.2. Extrinsic semiconductors

An extrinsic semiconductor is defined as a semiconductor in which controlled amounts of specific dopant or impurity atoms have been added so that the thermal-equilibrium electron and hole concentrations are different from the intrinsic carrier concentration and classifies into two categories [25]:

2.2.2.1. n-type extrinsic semiconductors

Is a type of extrinsic semiconductor where the dopant atoms are capable of providing extra conduction electrons to the host material (e.g. phosphorus in silicon). This creates an excess of negative (n-type) electron charge carriers.

This type of semiconductor is obtained when we added antimony (Sb) to pure germanium or arsenic (As) to pure silicon.

2.2.2.1.1. Donor n-type impurities

When a semiconductor is doped with donor impurities, impurity energy levels are introduced that usually lie within the energy gap. A donor impurity has a donor level which is defined as being neutral if filled by an electron, and positive if empty.

Dopant with 5 valence electrons (e.g. P, As, Sb) 4 electrons used for covalent bonds with surrounding Si atoms, one electron left over electron is loosely bound only small amount of energy needed to lift it into conduction band (0.05 eV in Si) n-type semiconductor has conduction electrons no holes (apart from the few intrinsic holes) doping fraction of 10^{-8} Sb in Si yields about 5×10^{16} conduction

electrons centimeter per cubic at room temperature, i.e. gain of 5×10^6 over intrinsic Si [20].

2.2.2.1.2. Carriers concentrations

The concept of free electrons and corresponding holes in a solid semiconductor is a useful tool for understanding conduction through the solid. At temperatures above absolute zero, some electrons in an n-type semiconductor are expected to be excited from the energy level of the dopant into the conduction band. The probability of finding a carrier is calculated based on the Fermi function and the separation of the dopant state from the band edge is given by [1]:

$$n = \frac{N_D}{\exp((E_C - E_D)/K_B T) + 1} \approx N_D \exp - (E_C - E_D)/K_B T \quad (2.9)$$

Where E_D is the donor energy, E_C is the conduction band edge energy and N_D is concentration of donor.

2.2.2.2. P-type extrinsic semiconductors

This type of semiconductor is obtained when traces of a trivalent like boron (B) are added to a pure germanium crystal. In this case, the three valence electrons of boron atom form covalent bonds with four surrounding germanium atoms but one bond is left incomplete and gives rise to a hole.

Thus boron which is called an acceptor impurity causes as many positive holes in a germanium crystal as there are boron atoms thereby producing a P-type extrinsic semiconductor.

2.2.2.2.1. Acceptor p-type impurities

When a semiconductor is doped with donor impurities an acceptor level is neutral if empty and negative if filled by an electron. These energy levels are important in calculating the fraction of dopants being ionized. dopant with 3 valence electrons (e.g. B, Al, Ga, In) only 3 of the 4 covalent bonds filled vacancy in the fourth covalent bond hole “p-type semiconductor” has mobile holes very few mobile electrons (only the intrinsic ones) [20].

2.2.2.2. Carrier concentrations

Holes in these dopant states can be easily released into the bands if the energy of the state is within a small number of thermal energy units (i.e. $K_B T$) of the appropriate band edge (valence band for acceptors). The probability of finding a carrier is calculated based on the Fermi function and the separation of the dopant state from the band edge is given by [1]:

$$P = \frac{N_A}{\exp((E_A - E_V)/K_B T) + 1} \approx N_A \exp(-(E_A - E_V)/K_B T) \quad (2.10)$$

Where E_A is the acceptor energy, E_V is the valence band edge energy and N_A is concentration of acceptor.

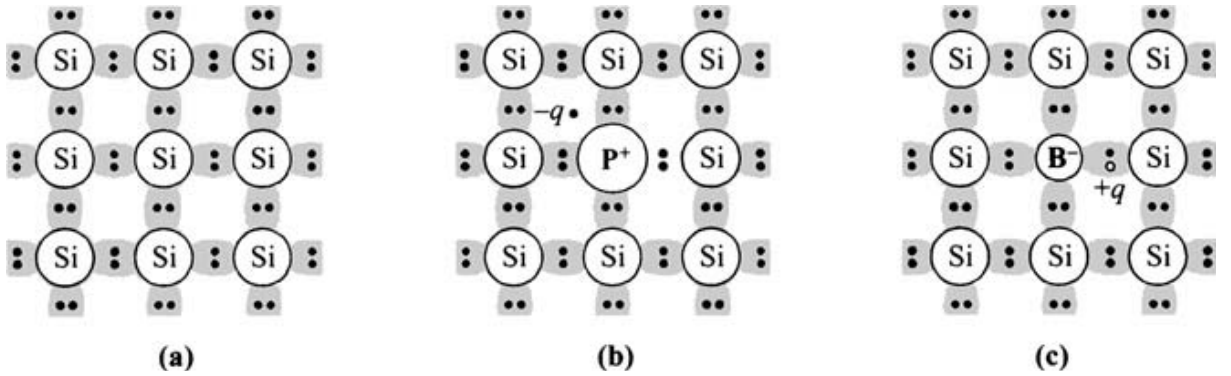


Fig. 2.2. Three basic bond pictures of a semiconductor. (a) Intrinsic Si with no impurity. (b) n-type Si with donor (phosphorus). (c) p-type Si with acceptor (boron) [20].

2.2.2.3. The extrinsic Fermi level

When impurities are introduced to the semiconductor crystals, depending on the impurity energy level and the lattice temperature, not all dopants are necessarily ionized. The ionized concentration for donors is given by[20]:

$$N_D^+ = \frac{N_D}{1 + g_D \exp[(E_F - E_D)/K_B T]} \quad (2.11)$$

Where g_D is the ground-state degeneracy of the donor impurity level and equal to 2 because a donor level can accept one electron with either spin (or can have no electron).

When acceptor impurities of concentration N_A are added to a semiconductor crystal, a similar expression can be written for the ionized acceptors

$$N_A^- = \frac{N_A}{1 + g_A \exp[(E_A - E_F)/K_B T]} \quad (2.12)$$

Where g_A is the ground state degeneracy of the acceptor impurity level.

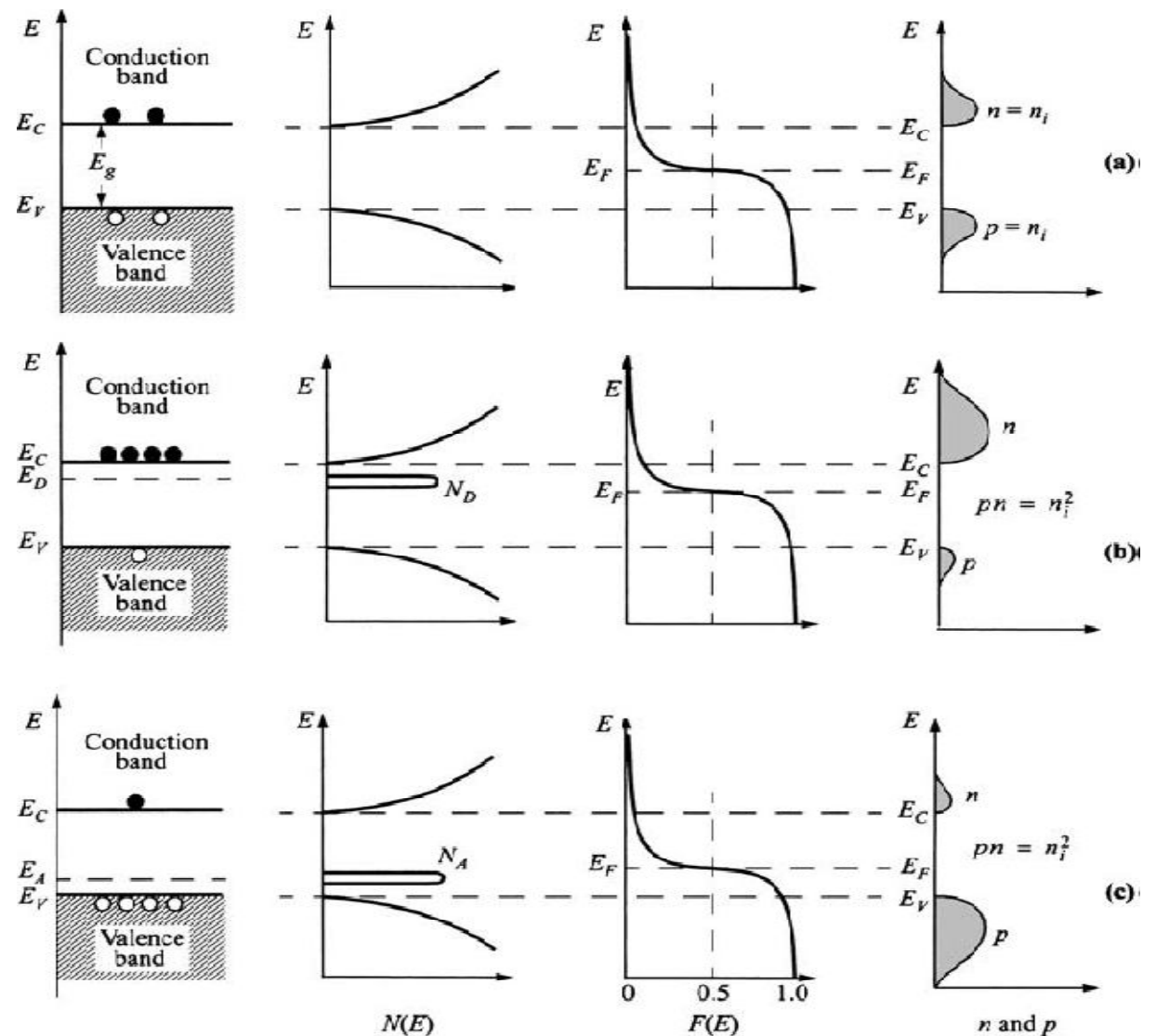


Fig. 2.3. Schematic band diagram, density of states, Fermi-Dirac distribution, and carrier concentrations for (a)intrinsic, (b) n-type, and (c) p-type semiconductors at thermal equilibrium[20].

2.3. Electronic band structures of semiconductors

2.3.1. The band gap

The band gap is the difference in energy between the lowest point of conduction band and highest point of the valence band. The lowest point in the conduction band is called the conduction band edge and the highest point in the valence band is called the valence band edge [22].

2.3.1.1. Direct gap

In a direct band gap semiconductor, the top of the valence band and the bottom of the conduction band occur at the same value of momentum.

2.3.1.2. Indirect gap

In an indirect band gap semiconductor, the maximum energy of the valence band occurs at a different value of momentum to the minimum in the conduction band energy as in schematic 2.4 below.

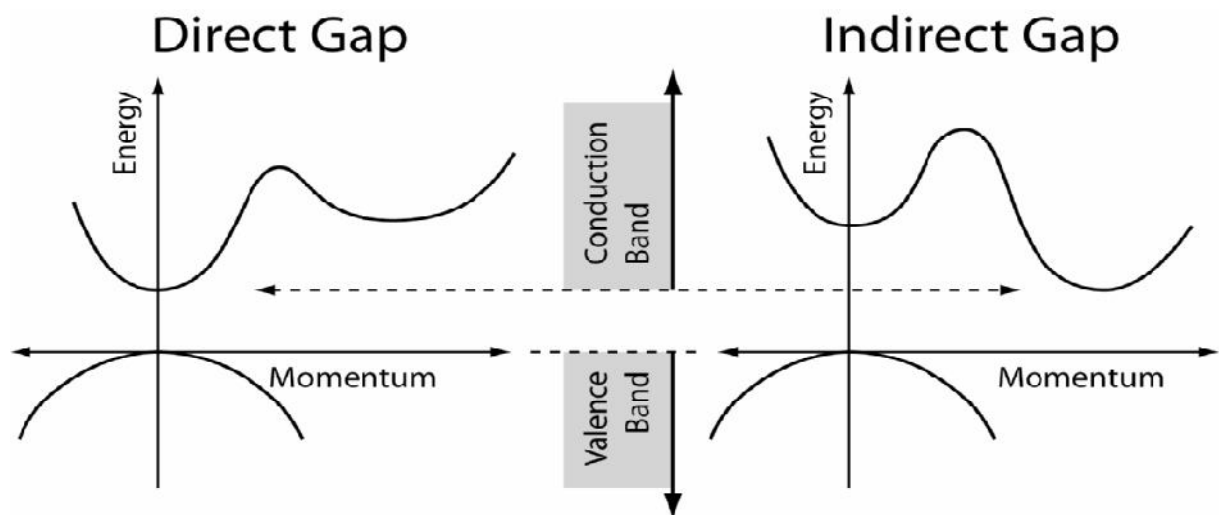


Fig. 2.4. A schematic of the difference between a direct gap and an indirect gap semiconductor[1].

Table2.2. Energy gap between the valence and conduction bands [22].

Crystal	Gap	E_g <i>ev</i>		Crystal	Gap	E_g <i>ev</i>	
		0K	300K			0K	300K
Diamond	i	5.400		SiC(hex)	i	3.000	
Si	i	1.170	1.11	Te	d	0.330	
Ge	i	0.744	0.66	Cu ₂ O	d	2.172	
InSb	d	0.230	0.17	SuTe	d	0.300	0.18
InAs	d	0.430	0.36	CdTe	d	1.604	1.44
GaAs	d	1.520	1.43	CdSe	d	1.840	1.74
AlSb	i	1.650	1.60	CdS	d	2.582	2.42

(i = indirect gap and d = direct gap)

The direct and indirect behaviours the critical aspects of the energy band structures of these two types of semiconductor are shown schematically in figure 2.4. above.

2.3.2. The effective masses

In many semiconductors it has been possible to determine by cyclotron resonance the effective masses of carriers in the conduction and valence bands near the band edges.

Table 2.3. Effective masses of electrons and holes in direct gap semiconductors [22].

Crystal	Electron m_e/m	Heavy hole m_{hh}/m	Light hole m_{lh}/m	Split off hole m_{soh}/m	Spin-orbit Δ, ev
InSb	0.015	0.39	0.021	0.11	0.820
InAs	0.026	0.41	0.025	0.08	0.430
InP	0.073	0.40	0.078	0.15	0.011
GaSb	0.047	0.30	0.006	0.14	0.800
GaAs	0.066	0.50	0.082	0.17	0.340
Cu ₂ O	0.990		0.580	0.69	0.130

2.3.3. Majority and minority carriers

In an n-type material the electron is called the majority carrier and hole is the minority carrier. And in a p-type material the hole is called the majority carrier and the electron is the minority carrier as shown in Fig.2.5 below.

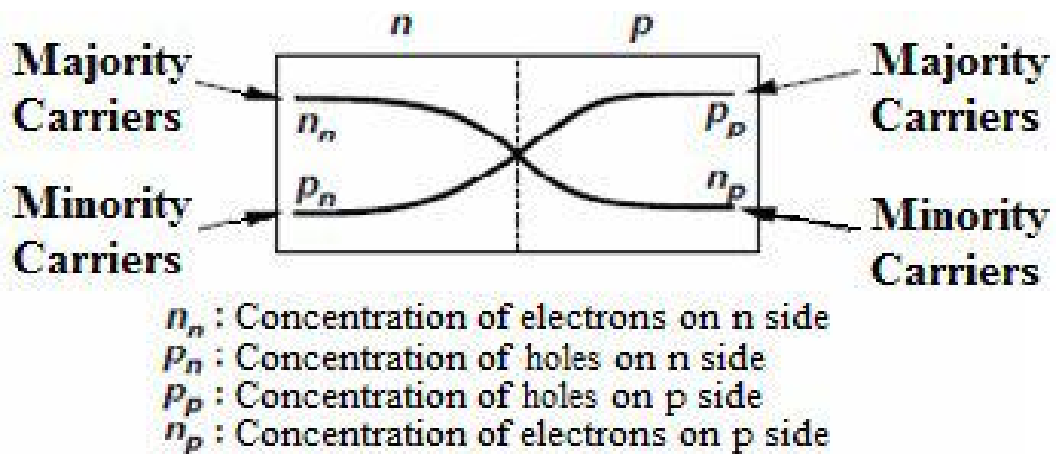


Fig. 2.5. The majority and minority carriers[26].

2.3.4. Elements used to make semiconductors

The study of semiconductor materials began in the early nineteenth century. Over the years many semiconductors have been investigated. Table 2.4 shows a portion of the periodic table related to semiconductors.

Table 2.4 Portion of the Periodic Table Related to Semiconductors [4].

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

The element semiconductors, those composed of single species of atoms, such as silicon (Si) and germanium (Ge) can be found in Column IV. In the early 1950s, germanium was the major semiconductor material. Since the early 1960s silicon has become a practical substitute and has now virtually supplanted germanium as a material for semiconductor fabrication.

All of these chemical bonds yield an average of four valence electrons per atom. These valence electrons are shared between all the atoms in the silicon crystal.

When being manufactured, purity must be very carefully controlled. Intentionally added impurities are called dopants. Dopants are added in a controlled environment and it is known beforehand how many impurity atoms will be added and what the effect will be shown in figure 2.6 below.

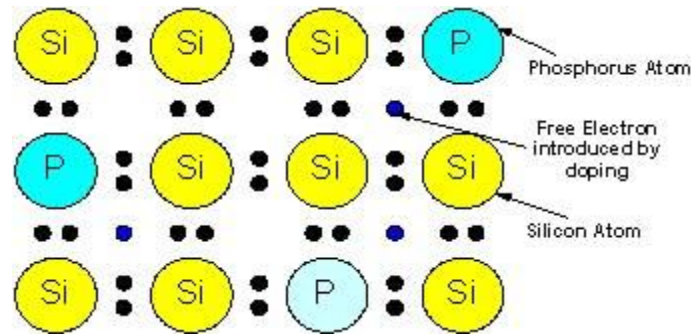


Fig. 2.6 Silicon atoms doping with phosphorus atoms [24, 27].

2.4. Properties of Semiconductors:

Semiconductors have many useful properties that insulators and conductors do not possess. These properties are based on the fact that an electron can jump from the valence band to the conduction band and vice versa. Temperature can give this little extra energy to an electron and make it jump to the conduction band thus creating a hole in the valence band. Light can also give this energy boost and create what we call an electron-hole pair, a free electron and a free hole this phenomenon is called absorption. Photoconductivity is the increase of current in a semiconductor due to the absorption of photons.

2.4.1. Resistance, capacitance, and inductance

Resistance R , capacitance C , and inductance L , are all observable phenomena used in circuit elements. These underlying properties are the resistivity ρ , of a conducting material in a resistor, the dielectric constant ϵ , of the insulating material in a capacitor, and the permeability μ_B , in an inductance. The relationships are as follows [1]:

$$R = \rho l / A \quad (2.13)$$

Where l is the length of the conductor and A is its cross-sectional area. The resistivity ρ , of a conductor is inversely related to its conductivity σ as $\rho=1/\sigma$. Likewise, C and ϵ are related through

$$C = \epsilon A/d \quad (2.14)$$

Here A is the area of the capacitor plates and d is their separation or the thickness of the insulating (dielectric) material between them.

$$L = \mu_B N^2 A/l \quad (2.15)$$

Where N is the number of turns of wire in the coil, A is the coil area, and l is the coil length.

2.4.1.1 Mobility and electrical conductivity

Much more common and more relevant to most electronic applications is electronic conductivity. When a material is placed in an electric field, E , a current density J , given by $J = \sigma E$, is induced. Here σ is the electrical conductivity is given by [1]:

$$\sigma = q(\mu_p p - \mu_n n) \quad (2.16)$$

Where q is the moving carrier charge, μ_n and μ_p are the electron and hole mobilities, and n and p are the electron and hole mobile carrier concentrations, respectively.

The mobilities μ_n and μ_p are given by:

$$\mu_n = q\tau/m_n \text{ and } \mu_p = q\tau/m_p \quad (2.17)$$

2.4.1.2 Dielectric constant, piezoelectric response and permeability

The dielectric constant and permeability of materials are directly related to their ability to be polarized or magnetized, respectively. In general terms, polarizability is related to the magnitude of the motion of charge in a material resulting from the application of an external electric field. In such a field, electrons would naturally tend to move. Likewise, positive and negative ions

would move and in opposite directions.. Their motion results in the accumulation of negative charge in the material at the positive end of the external electric field see figure 2.7[1].

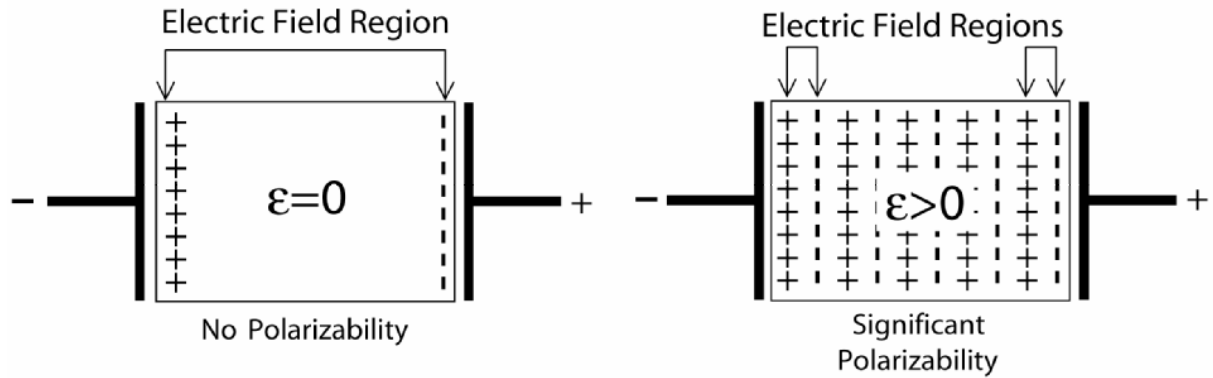


Fig. 2.7. A schematic diagram showing the response of a dielectric material to an applied electric field[1].

Most compound semiconductors exhibit a piezoelectric response. Typical magnitudes of this response for some common semiconductors are presented in table 2.4. The permeability of a material is tied to its ability to be magnetized as dielectric response is tied to the ability to be polarized.

Table 2.5. Typical piezoelectric stress coefficients for selected materials [1].

Material	$e_{31}(c/m^2)$	$e_{33}(c/m^2)$	Material	$e_{31}(c/m^2)$	$e_{33}(c/m^2)$
ZnO	-0.51	0.89	AlN	-0.60	-0.47
CdTe	-0.01	0.03	GaN	-0.49	-0.84
ZnS	-0.05	0.10	AlAs	0.01	-0.01
GaP	0.03	-0.07	GaAs	0.06	-0.12
InP	-0.02	0.04	AlSb	0.02	-0.04
AlP	0.02	0.04	GaSb	0.06	-0.12

Note: The change in polarization δP_i along direction i is given by:

$$\delta p_i = \sum_j e_{ij} \epsilon_j \text{ Where } \epsilon_j \text{ is the strain along direction } j.$$

2.4.2. Optical properties

Optical measurement constitutes the most-important means of determining the band structures of semiconductors. Photon-induced electronic transitions can

occur between different bands, which lead to the determination of the energy band gap, or within a single band such as the free-carrier absorption. The optical properties of semiconductor are characterized by the complex refractive index [20, 28].

$$\bar{n} = n_r - ik_e \quad (2.18)$$

The real part of the refractive index n_r , determines the propagation velocity (v) and wavelength (λ)

$$n_r = c/v = \lambda_o/\lambda \quad (2.19)$$

The imaginary part k_e called the extinction coefficient, determines the absorption coefficient

$$\alpha = 4\pi k_e/\lambda \quad (2.20)$$

Also in semiconductors, the absorption coefficient is a strong function of the wavelength or photon energy. Near the absorption edge, the absorption coefficient can be expressed as

$$\alpha \propto (hv - E_g)^\gamma \quad (2.21)$$

Where hv is the photon energy and γ is constant.

2.4.3. Thermal properties

When a temperature gradient exists in a semiconductor in addition to an applied electric field, the total current density (in one dimension) is [1, 20].

$$J = \sigma \left(\frac{1}{q} \frac{dE_f}{dx} - \xi \frac{dT}{dx} \right) \quad (2.22)$$

Where ξ is the thermoelectric power. the thermoelectric power is given by

$$\xi = -\frac{K_B}{q} \left[\frac{[5/2 - s + \ln(N_C/n)]n\mu_n - [5/2 - s - \ln(N_v/p)]p\mu_p}{n\mu_n + p\mu_p} \right] \quad (2.23)$$

This equation indicates that the thermoelectric power is negative for n-type semiconductors and positive for p-type semiconductors, a fact often used to determine the conduction type of a semiconductor.

Another important thermal effect is thermal conduction. It is a diffusion type of

process where the heat flow Q is driven by the temperature gradient

$$Q = -K \frac{dT}{dx} \quad (2.24)$$

The thermal conductivity K has the major components of phonon (lattice) conduction K_L and mixed free-carrier conduction K_M of electrons and holes,

$$K = K_L + K_M \quad (2.25)$$

The lattice contribution is carried out by diffusion and scattering of phonons. These scattering events include many types, such as phonons to phonons. The overall effect can be interpreted as

$$K_L = \frac{1}{3} C_V V_{ph} \lambda_{ph} \quad (2.26)$$

Where C_V is the specific heat, V_{ph} is the phonon velocity and λ_{ph} is the phonon mean free path.

The contribution due to mixed carrier is given by:

$$K_M = \frac{(\frac{5}{2} - s) K^2 \sigma T}{q^2} + \frac{K^2 \sigma T [5 - 2s + (E_g/KT)]^2 np \mu_n \mu_p}{q^2 (n \mu_n + p \mu_p)^2} \quad (2.27)$$

Where s is constant and σ is electrical conductivity.

Chapter three

Metal-semiconductor contacts

3.1. Introduction

In this chapter, we will consider the metal-semiconductor junction in which the material on each side of the junction is not the same. These junctions can also produce diodes.

Semiconductor devices, or integrated circuits, must make contact with the outside world. This contact is made through non-rectifying metal-semiconductor junctions, or ohmic contacts. An ohmic contact is a low-resistance junction providing current conduction in both directions. We will examine the conditions that yield metal-semiconductor ohmic contacts[25].

3.2. The Schottky barriers diode

One of the first practical semiconductor devices used in the early 1900s was the metal-semiconductor diode. This diode, also called a point contact diode, was made by touching a metallic whisker to an exposed semiconductor surface. These metal semiconductor diodes were not easily reproduced or mechanically reliable and were replaced by the pn junction in the 1950s.

In this section, we will consider the metal-semiconductor rectifying contact, or Schottky barrier diode. In most cases, the rectifying contacts are made on n-type semiconductors; for this reason we will concentrate on this type of diode[1, 25].

3.2.1 Qualitative characteristics

The ideal energy-band diagram for a particular metal and n-type semiconductor before and after making contact is shown in figure 3.1. The vacuum level is used as a reference level. The parameter Φ_m is the metal work function, Φ_s is the semiconductor work function, and x_s is known as the electron affinity. The work functions of various metals are given in table 3.1. and the electron affinities of

several semiconductors are given in table 3.2. In figure 3.1. we have assumed that $\Phi_m > \Phi_s$ before contact in an n-type semiconductor, the Fermi level in the semiconductor was above that in the metal. In order for the Fermi level to become a constant through the system in thermal equilibrium, electrons from the semiconductor flow into the lower energy states in the metal. The parameter Φ_B the ideal barrier height of the semiconductor contact, the potential barrier seen by electrons in the metal trying to move into the semiconductor[1, 25].

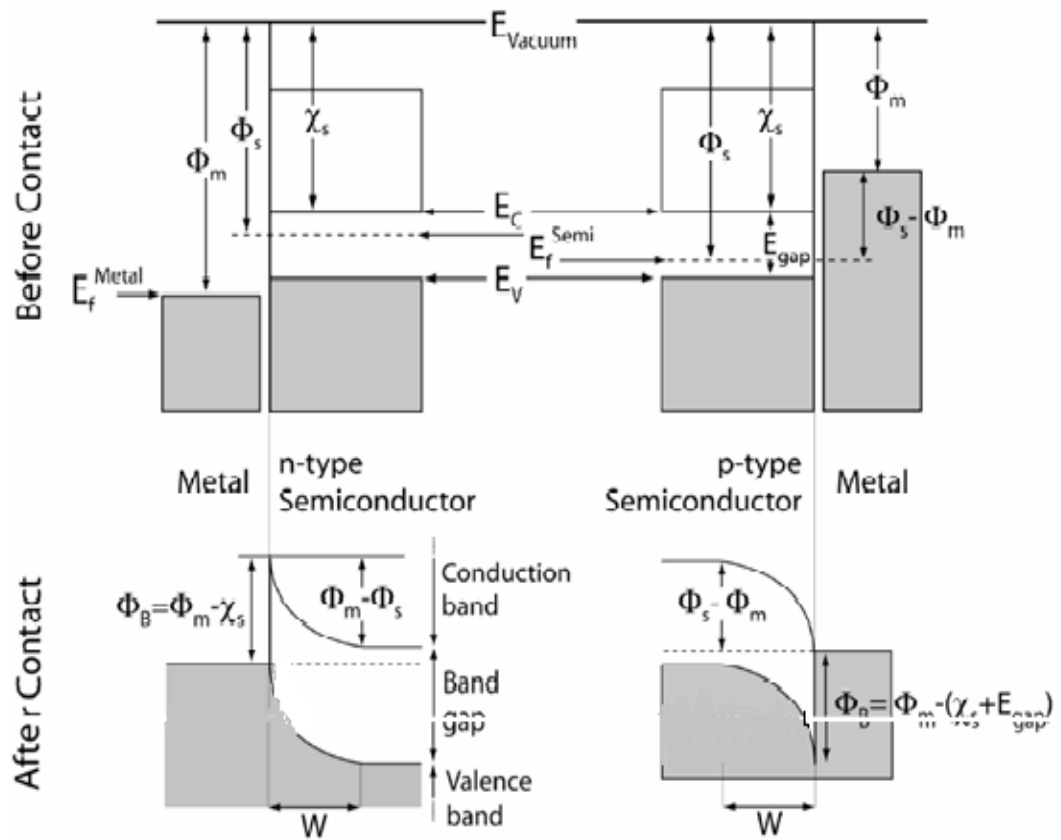


Fig. 3.1. Shows the definitions of the electron affinity χ_s of the semiconductor and the work functions of the semiconductor Φ_s and metal Φ_m . Also indicated are the depletion width W , the Fermi levels, band edges, and the Schottky barrier heights Φ_B [1].

Table 3.1. Work functions of some elements [25].

Elements		Work function Φ_m (ev)
Au	gold	5.10
Ni	nickel	5.15
Ti	titanium	4.33
Ag	silver	4.26
Mo	molybdenum	4.60
Al	aluminum	4.28
W	tungsten	4.55
Pd	palladium	5.65
Cr	chromium	4.50
Er	erbium	3.00
Sc	scandium	3.50
Mn	manganese	4.10
Cu	copper	4.65
Fe	iron	4.50
Rh	rhodium	4.98
Pt	platinum	5.12

Table 3.2. Electron affinity of some semiconductors [25].

Element		Electron affinity χ (ev)
Ge	germanium	4.13
Si	silicon	4.01
GaAs	gallium arsenide	4.07
AlAs	aluminum arsenide	3.50
cu_2o	copper oxide [29]	3.46

Fortunately, a Schottky diode can be made to operate as an ohmic contact in many cases by increasing the doping level of the semiconductor near the junction. In this case the depletion width in the semiconductor becomes very small depletion regions lead to very low tunneling breakdown voltages. Once breakdown occurs the diode operates as an ohmic contact.

This barrier is known as the Schottky barrier and is given by[25]:

$$\Phi_B = \Phi_m - \chi_s \quad (3.1)$$

On the semiconductor side, V_{bi} is the built-in potential barrier is given by:

$$V_{bi} = \Phi_B - \Phi_n \quad (3.2)$$

If we apply a positive voltage to the semiconductor with respect to the metal, the V_{bi} increases while Φ_B remains constant. This bias condition is the reverse bias. If a positive voltage is applied to the metal with respect to the semiconductor, the V_{bi} is reduced while Φ_B again remains constant. The energy-band diagrams for the reverse and forward bias are shown in figures 3.2a. and 3.2b., where V_R is the magnitude of the reverse-bias voltage and V_a is the magnitude of the forward-bias voltage [4, 25].

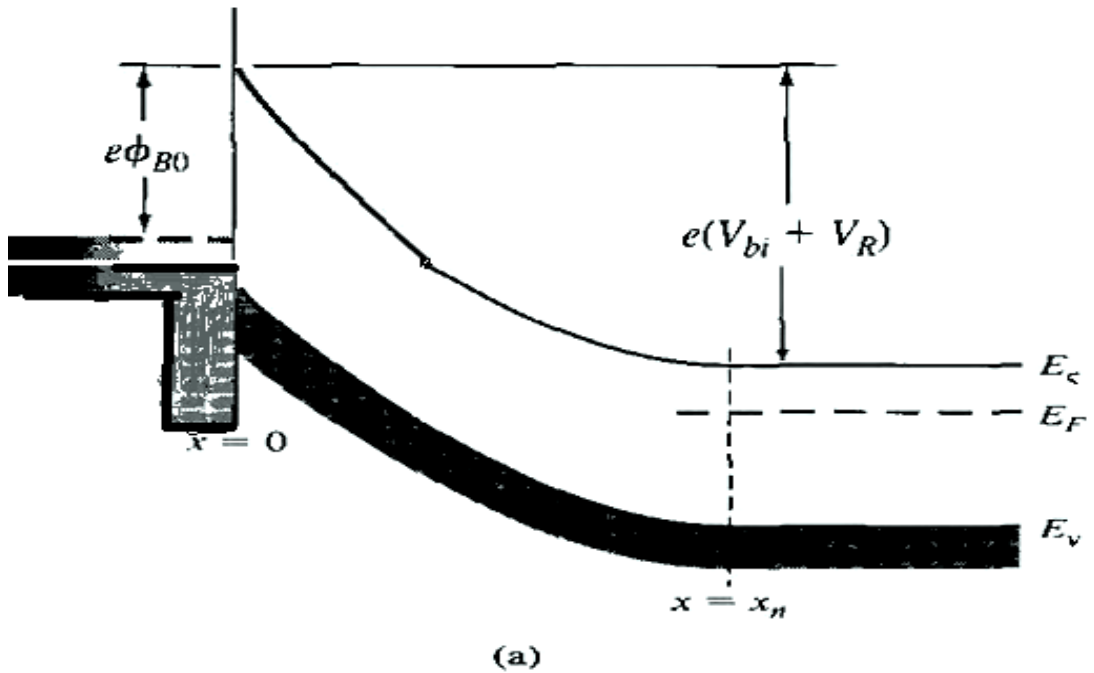


Fig. 3.2a. Ideal energy band diagram of a metal-semiconductor junction under reverse bias [25].

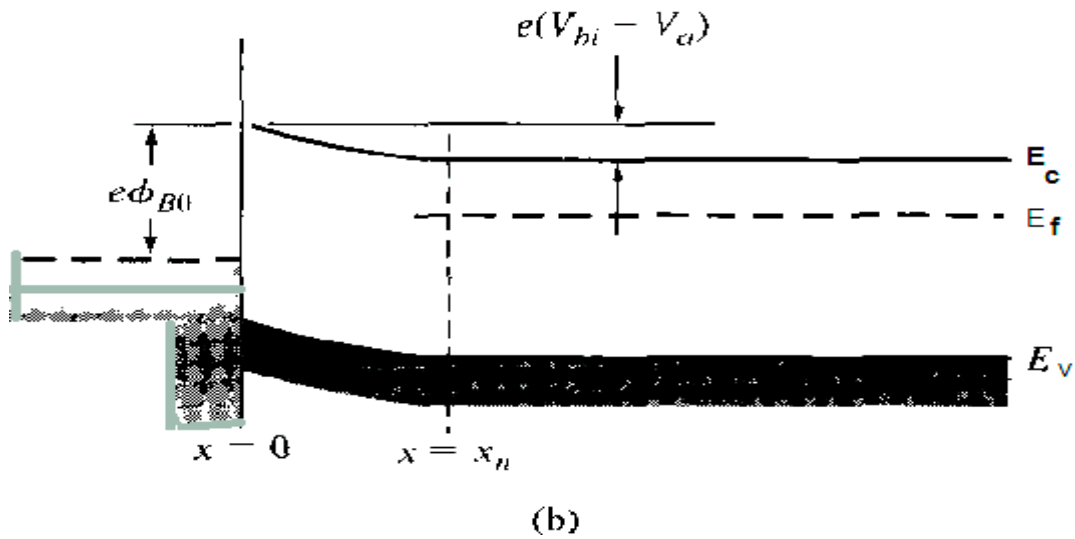


Fig. 3.2b. Ideal energy-band diagram of a metal-semiconductor junction under forward bias [25].

Table 3.3. work function of some semiconductors [30].

Elements		Work function $\Phi_m (ev)$
Ge	germanium	4.78
Si	silicon	4.73
GaAs	gallium arsenide	4.69
Cu_2O	copper oxide	5.30
AlAs	aluminum [31]	4.80

When contact is made between a metal and a semiconductor, electrons flow from one material to the other as determined by their relative Fermi levels. This flow can lead to depletion or enhancement of the majority carriers. There are four possible situations to consider: a low work function metal in contact with (1) a p-type or (2) an n-type semiconductor, and the same cases for a high work function metal. High and low work function here simply indicate whether the Fermi level for the metal lies above or below the Fermi level of the semiconductor before contact is made. These four possibilities are shown schematically in figure 3.3.[1, 25].

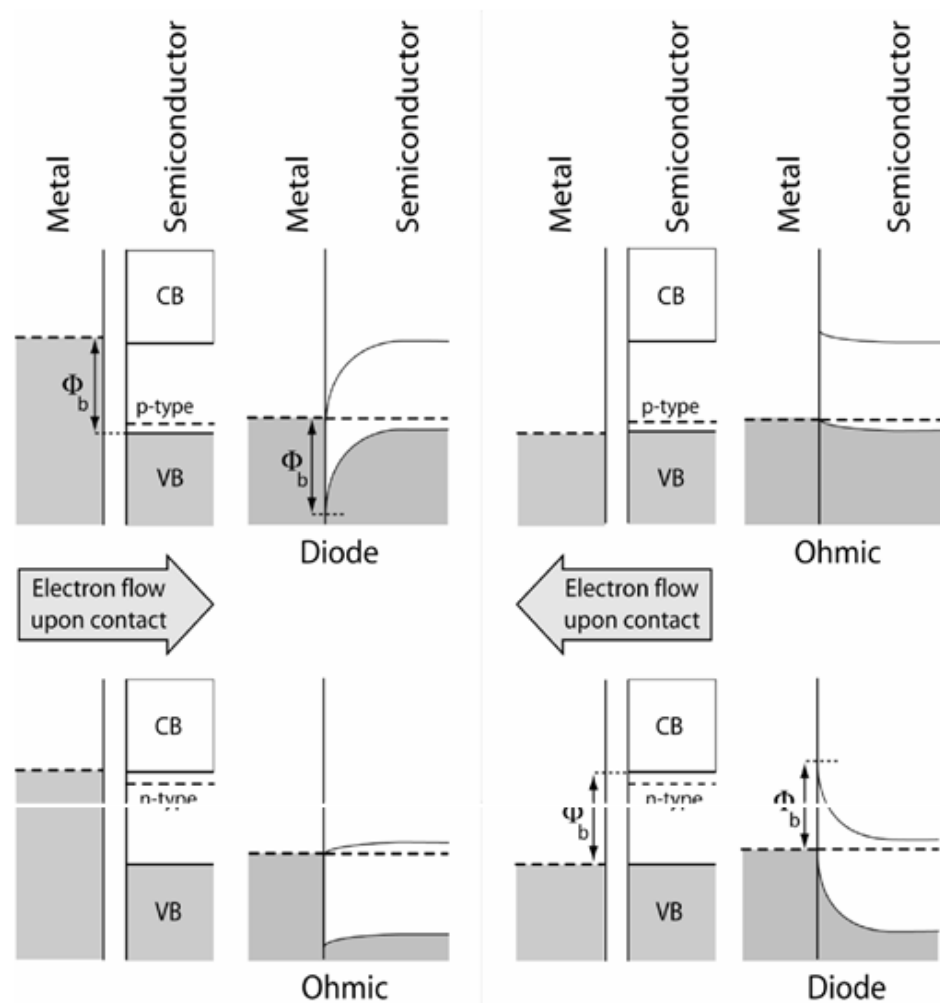


Fig. 3.3. The four possible metal-semiconductor cases before and after contact. Two of the four produce ohmic contacts (resistors) while the others produce Schottky diodes [1].

An applied bias voltage appears across this relatively insulating depletion region, as in a homojunction. This means that the applied voltage modifies the chemical potential of electrons across the junction and induces current flow as shown in figure 3.4. For positive applied voltages (forward bias under the definition of positive here), the barrier for majority electrons in the semiconductor to move into the metal is decreased, causing them to diffuse into the metal over the barrier. The diffusion current changes exponentially with bias voltage, as it does in a p-n junction [25].

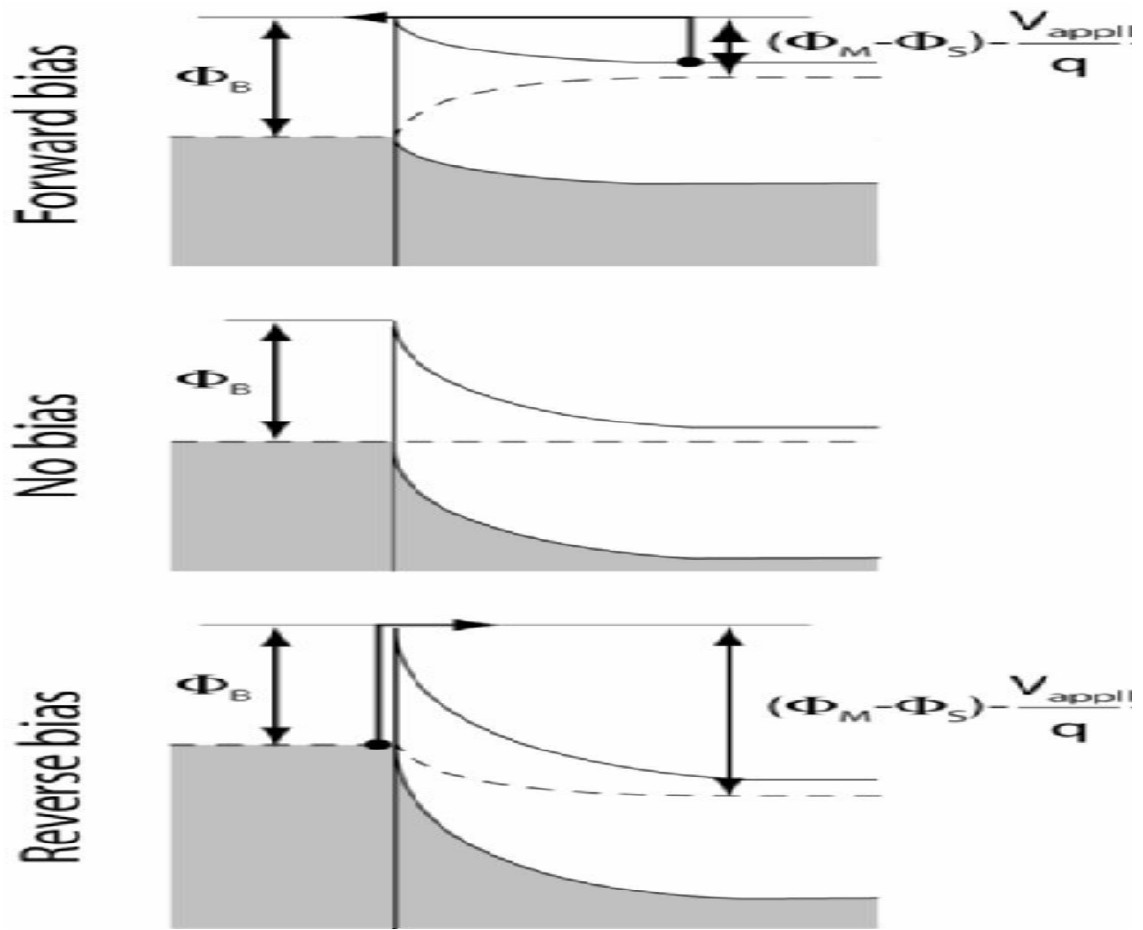


Fig. 3.4. The effects of bias voltage on Schottky diode band edges and band bending [1].

3.2.2 Real Schottky diodes

Unfortunately, the real situation with Schottky diodes is not so good as such problems was provided in equation $J = J_0(e^{qv/aK_BT} - 1)$ where a diode ideality factor appears. Theoretically, one can measure the work function of both the metal and the semiconductor using photoelectron spectroscopy and other techniques. From this and the work function of the metal, one should be able to estimate the Schottky barrier height.

Unfortunately, it is often very difficult to determine the Fermi level of semiconductors because of the dangling bonds at their surfaces. The typical barrier potential in a real Schottky diode is shown schematically in figure 3.5. Clearly it does not match the shape given in figures 3.1, 3.3. and 3.4. [1].

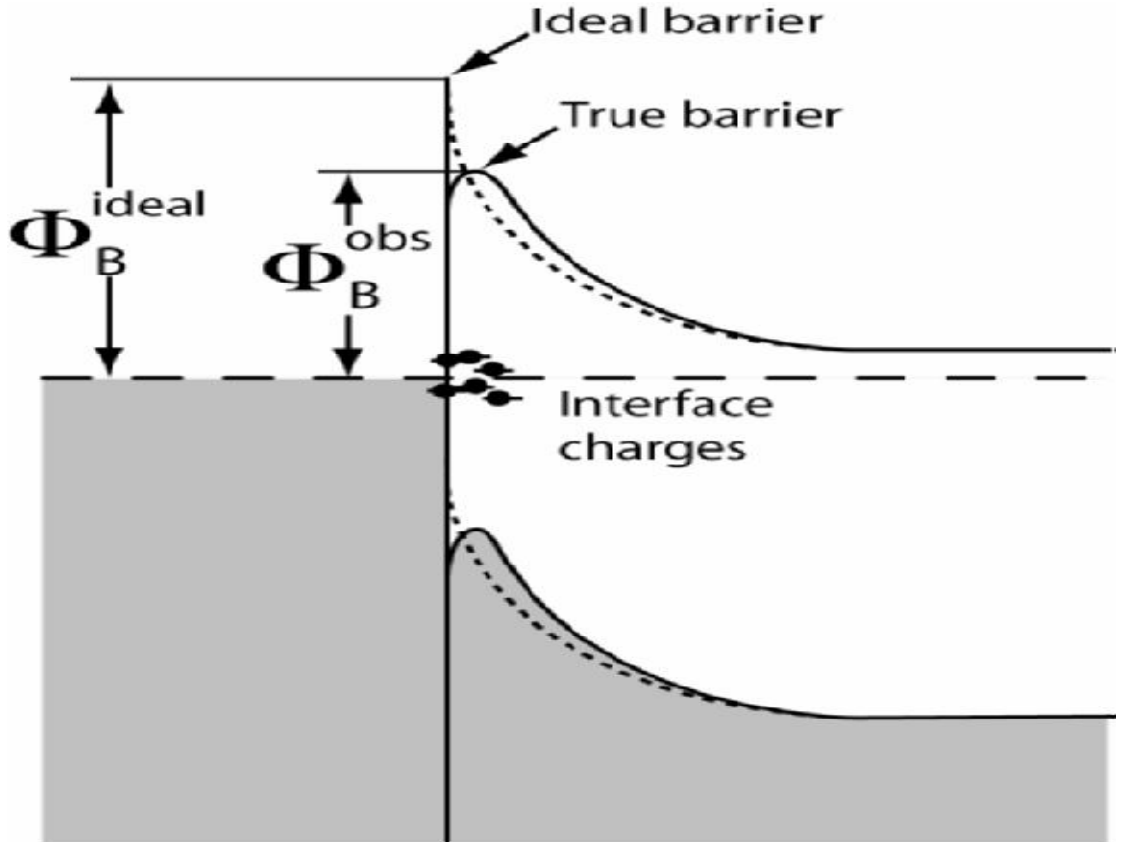


Fig. 3.5. A defective Schottky contact, typical of real barriers. The small lines indicate defect states in the semiconductor [1].

3.2.3 Ideal junction properties

We can determine the electrostatic properties of the junction in the same way as we did for the pn junction. The electric field in the space charge region is determined from Poisson's equation. We have that [25]

$$\frac{dE}{dx} = \frac{\rho(x)}{\epsilon_s} \quad (3.3)$$

Where $\rho(x)$ is the space charge volume density and ϵ_s is the permittivity of the semiconductor. If we assume that the semiconductor doping is uniform, then by integrating Equation (3.3) we obtain:

$$E = \int \frac{eN_d}{\epsilon_s} dx = \frac{eN_d x}{\epsilon_s} + c \quad (3.4)$$

Where C is a constant of integration. The electric field is zero at the space charge edge in the semiconductor, so the constant of integration can be found as

$$C = - \frac{eN_d x_n}{\epsilon_s} \quad (3.5)$$

If we substitute Eq. (3.5) in (3.4) the electric field can then be written as:

$$E = - \frac{eN_d}{\epsilon_s} (x_n - x) \quad (3.6)$$

The space charge region width W , may be calculated as we did for the pn junction. The result is identical to that of a one-sided p^+n junction. For the uniformly doped semiconductor we have:

$$W = x_n = \left[\frac{2\epsilon_s(V_{bi} + V_R)}{eN_d} \right]^{1/2} \quad (3.7)$$

Where V_R is the magnitude of the applied reverse-bias voltage. We are again assuming an abrupt junction approximation.

3.2.4. Nonideal effects on the barrier height

Several effects will alter the actual Schottky barrier height from the theoretical value given by equation (3.1). The first effect we will consider is the Schottky effect or image-force-induced lowering of the potential barrier. An electron in a dielectric at a distance x from the metal will create an electric field. The field lines must be perpendicular to the metal surface and will be the same as if an image charge $+e$ is located at the same distance from the metal surface, but inside the metal. This image effect is shown in figure 3.6. [25].

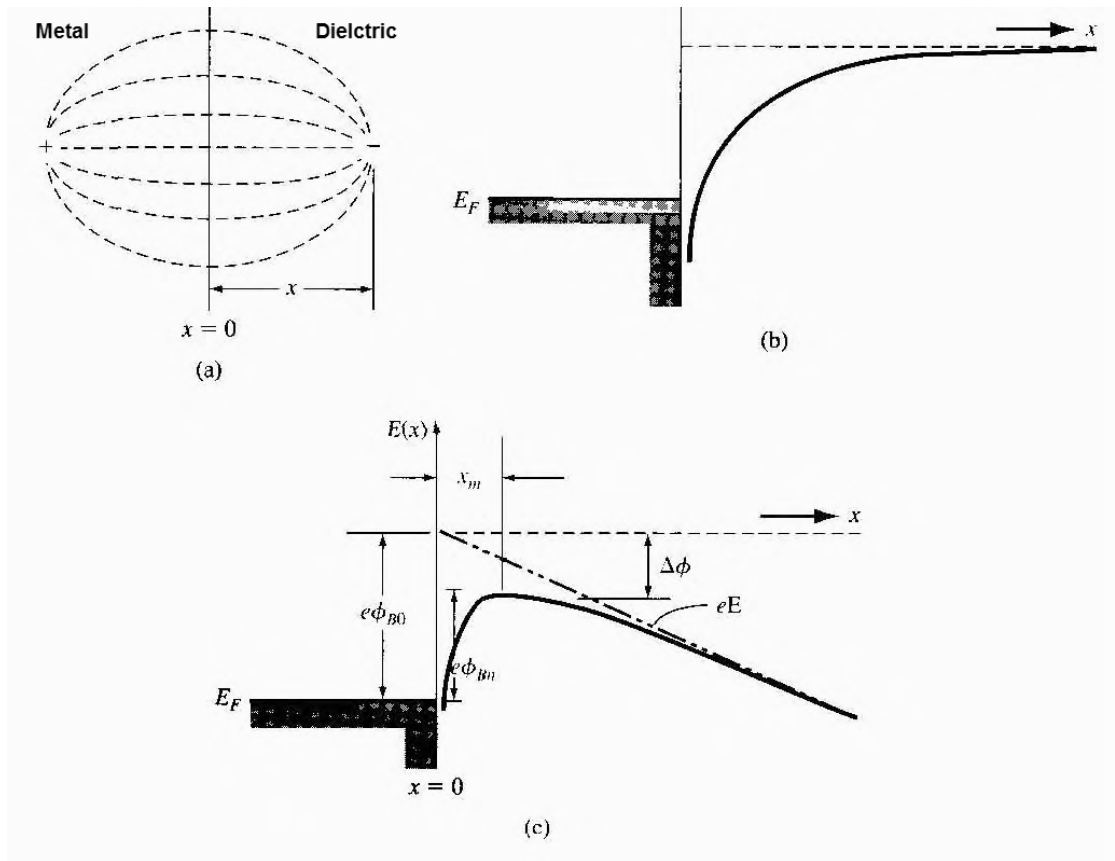


Fig. 3.6. (a) Image charge and electric field lines at a metal-dielectric interface. (b) Distortion of the potential barrier due to image forces with zero electric field and (c) With a constant electric field [25].

3.2.5 Current-voltage relationship

The current transport in a metal-semiconductor junction is due mainly to majority carriers as opposed to minority carriers in a pn junction. The basic process in the rectifying contact with an n-type semiconductor is by transport of electrons over the potential barrier. Which can be described by the thermionic emission theory. The thermionic emission characteristics are derived by using the assumptions that the barrier height is much larger than KT , so that the Maxwell-Boltzmann approximation applies and that thermal equilibrium is not affected by this process.

Figure 3.7 shows the one-dimensional barrier with an applied forward-bias voltage V_a and shows two electron current density components. The current

$J_{S \rightarrow M}$ is the electron current density due to the flow of electrons from the semiconductor into the metal, and the current $J_{M \rightarrow S}$ is the electron current density due to the flow of electrons from the metal into the semiconductor. The subscripts of the currents indicate the direction of electron flow. The conventional current direction is opposite to electron flow. The current density $J_{S \rightarrow M}$ is a function of the concentration of electrons which have x-directed velocities sufficient to overcome the barrier. We may write [4, 25]:

$$J_{S \rightarrow M} = e \int_E^{\infty} v_x dn \quad (3.8)$$

Where E is the minimum energy required for thermionic emission into the metal, v_x is the carrier velocity in the direction of transport and e is the magnitude of the electronic charge. The incremental electron concentration is given by:

$$dn = g_c(E) f_F(E) dE \quad (3.9)$$

Where $g_c(E)$ is the density of states in the conduction band and $f_F(E)$ is the Fermi-Dirac probability function. Assuming that the Maxwell-Boltzmann approximation applies, we may write:

$$dn = \frac{4\pi(2m_n)^{3/2}}{h^3} \sqrt{E - E_c} \exp\left[-\frac{(E - E_f)}{KT}\right] dE \quad (3.10)$$

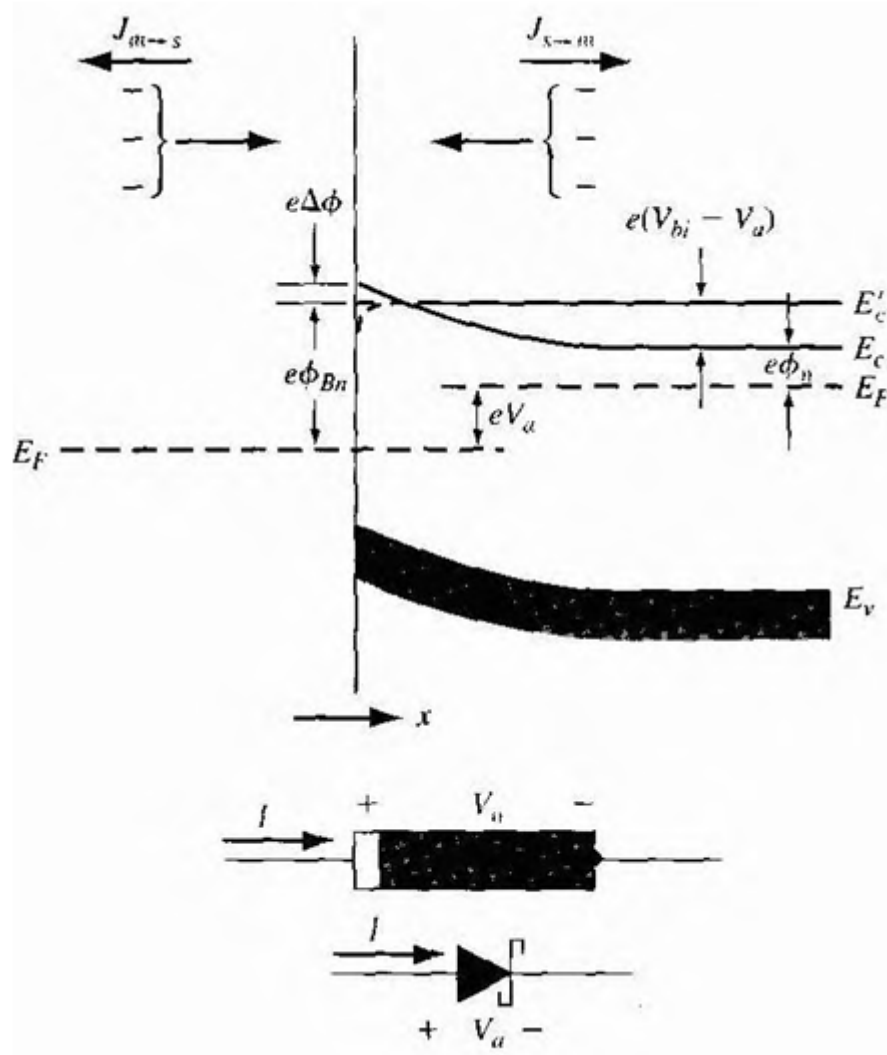


Fig. 3.7. Energy-band diagram of a forward-biased metal semiconductor junction including the image lowering effect [25].

The net current density in the metal-to-semiconductor junction can be written as

$$J = J_{S \rightarrow M} - J_{M \rightarrow S} \quad (3.11)$$

Which is defined to be positive in the direction from the metal to the semiconductor. We find that:

$$J = \left[A^* T^2 \exp\left(\frac{-e\Phi_{Bn}}{KT}\right) \right] \left[\exp\left(\frac{eV_a}{KT}\right) - 1 \right] \quad (3.12)$$

$$\text{Where } A^* = \frac{4\pi m_n k^2}{h^3} \quad (3.13)$$

The parameter A^* is called the effective Richardson constant for thermionic emission. Equation 3.12) can be written in the usual diode form as:

$$J = J_{ST} \left[\exp\left(\frac{ev_a}{KT}\right) - 1 \right] \quad (3.14)$$

Where J_{ST} is the reverse-saturation current density and is given by

$$J_{ST} = \left[A^* T^2 \exp\left(\frac{-e\Phi B_n}{KT}\right) \right] \quad (3.15)$$

We may recall that the Schottky barrier height ΦB_n changes because of the image force lowering. We have that $\Phi B_n = \Phi B_o - \Delta\Phi$. Then we can write Equation (3.15) as:

$$J_{ST} = A^* T^2 \exp\left(\frac{-e\Phi B_n}{KT}\right) \exp\left(\frac{e\Delta\Phi}{KT}\right) \quad (3.16)$$

The change in barrier height, will increase with an increase in the electric field, or with an increase in the applied reverse-bias voltage. Figure 3.8 shows a typical reverse-bias current-voltage characteristic of a Schottky barrier diode.

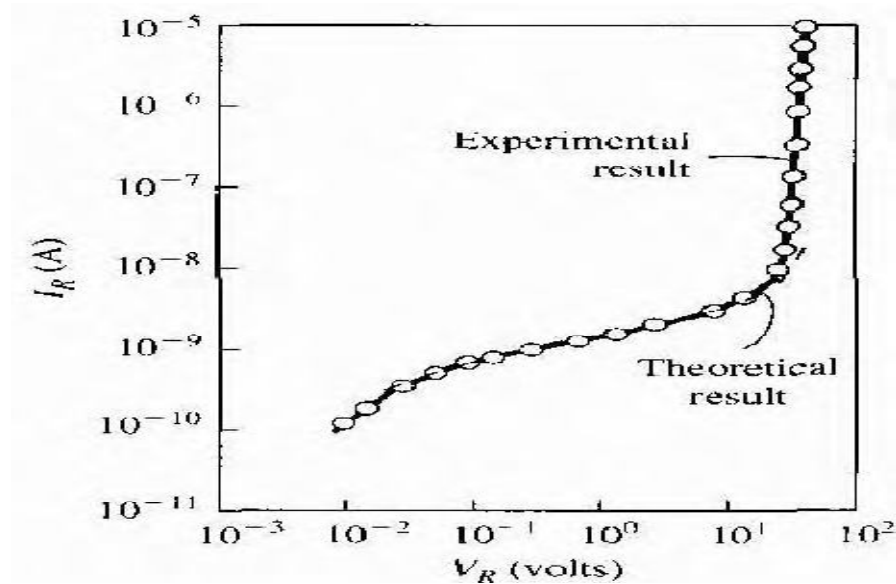


Fig. 3.8. Experimental and theoretical reverse-bias currents in a PtSi-Si diode[25].

3.2.6. Comparison of the Schottky barrier diode and the pn junction diode

Although the ideal current-voltage relationship of the Schottky barrier diode given by Equation (3.14) is of the same form as that of the pn junction diode, there are two important differences between a Schottky diode and a pn junction diode: The first is in the magnitudes of the reverse-saturation current densities, and the second is in the switching characteristics.

The reverse-saturation current density of the Schottky barrier diode was given by Equation (3.15) and is

$$J_{ST} = \left[A^* T^2 \exp\left(\frac{-e\Phi B_n}{KT}\right) \right] \quad (3.17)$$

The ideal reverse-saturation current density of the pn junction diode can be written as[32]:

$$J_S = \frac{eD_n n p_o}{L_n} + \frac{eD_p p_{no}}{L_p} \quad (3.18)$$

The form of the two equations is vastly different, and the current mechanism in the two devices is different. The current in a pn junction is determined by the diffusion of minority carriers while the current in a Schottky barrier diode is determined by thermionic emission of majority carriers over a potential barrier. The figure 3.9 show compare of forward bias between Schottky diode and pn junction diode.

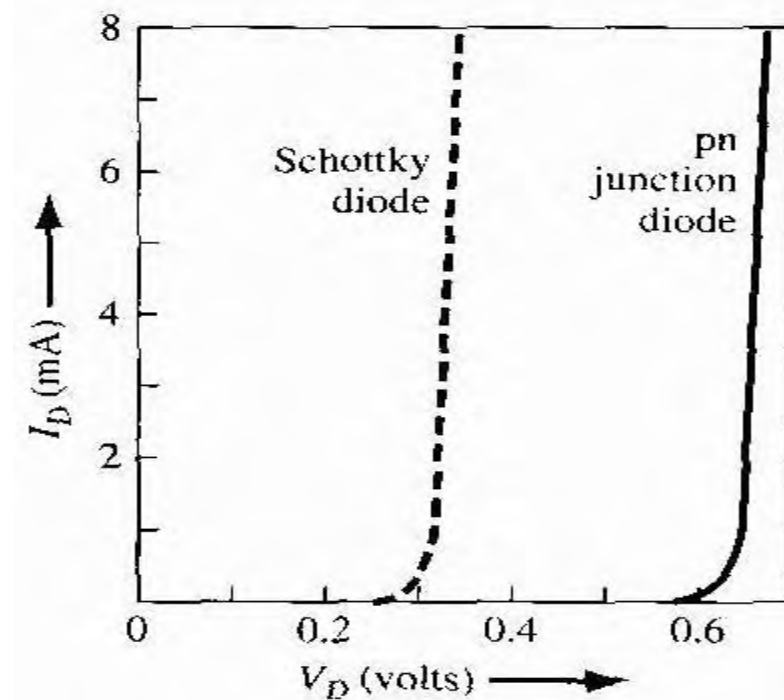


Fig. 3.9. Comparison of forward bias I-V characteristics between a Schottky diode and a (pn) junction diode[25].

Since $J_{ST} \gg J_S$ the forward-bias characteristics of the two types of diodes will also be different. Figure 3.8 shows typical I-V characteristics of a Schottky barrier diode and a (pn) junction diode.

3.3 Metal-semiconductor ohmic contacts

Contacts must be made between any semiconductor device, or integrated circuit, and the outside world. These contacts are made via ohmic contacts. Ohmic contacts are metal-to-semiconductor contacts, but in this case they are not rectifying contacts. An ohmic contact is a low-resistance junction providing conduction in both directions between the metal and the semiconductor. Two general types of ohmic contacts are possible: The first type is the nonrectifying barrier, and the second is the tunnelling barrier [25].

3.3.1. Ideal nonrectifying barriers

We considered an ideal metal-to-n-type semiconductor contact in Figure 3.1 for the case when $\Phi_m > \Phi_s$. Figure 3.1 shows the same ideal contact for the opposite case of $\Phi_m < \Phi_s$ is an ohmic contact ideal nonrectifying as shown in figure below

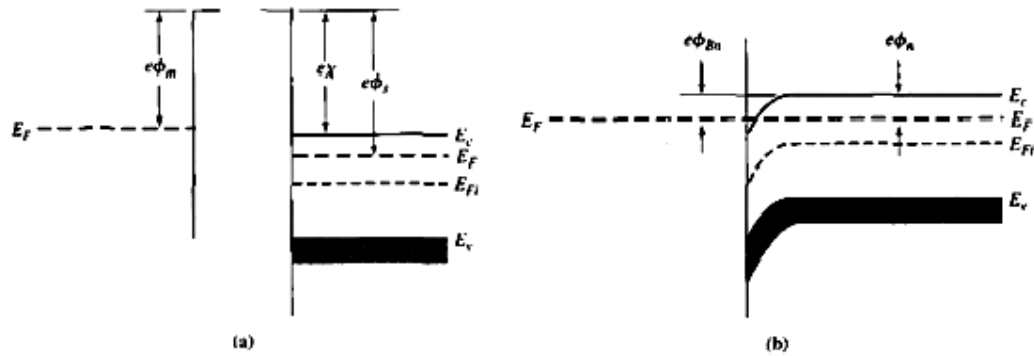


Fig. 3.10. Ideal energy band diagram (a) before contact and (b) after contact for a metal-n-semiconductor junction for $\Phi_m < \Phi_s$ [25].

3.3.2 Tunnelling barrier

The space charge width in a rectifying metal-semiconductor contact is inversely proportional to the square root of the semiconductor doping. The width of the depletion region decreases as the doping concentration in the semiconductor increases thus, as the doping concentration increases, the probability of tunnelling through the barrier increases. Figure 3.11 shows a junction in which the metal is in contact with a heavily doped n-type epitaxial layer.

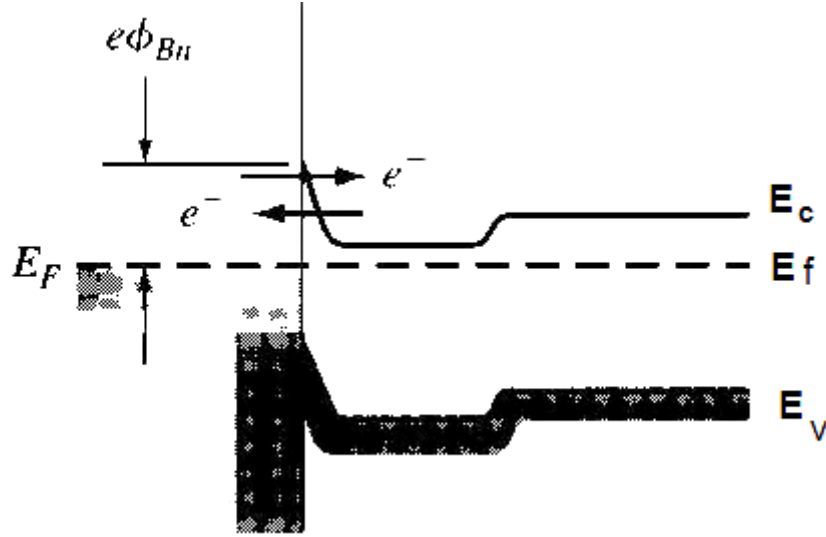


Fig. 9.11. Energy band diagram of a heavily doped n-semiconductor-to metal Junction [25].

3.3.3 Specific contact resistance

A figure of merit of ohmic contacts is the specific contact resistance. R This parameter is defined as the reciprocal of the derivative of current density with respect to voltage evaluated at zero bias. We may write:

$$R_c = \left(\frac{\partial j}{\partial v} \right)^{-1}_{v=0} (\Omega \cdot \text{cm}^2) \quad (3.19)$$

We want R_c to be as small as possible for an ohmic contact.

For a rectifying contact with a low to moderate semiconductor doping concentration the current-voltage relation was given by equation (3.12) as:

$$J_n = \left[A^* T^2 \exp \left(\frac{-e\Phi B_n}{KT} \right) \right] \left[\exp \left(\frac{ev_a}{KT} \right) - 1 \right] \quad (3.20)$$

The specific contact resistance for this case is then

$$R_c = \frac{(KT/e) \exp(+e\Phi B_n/KT)}{A^* T^2} \quad (3.21)$$

The specific contact resistance decreases rapidly as the barrier height decreases. For a metal-semiconductor junction with a high impurity doping concentration the tunnelling process will dominate.

Figure 3.12 shows a plot of the theoretical values of R_C as a function of semiconductor doping

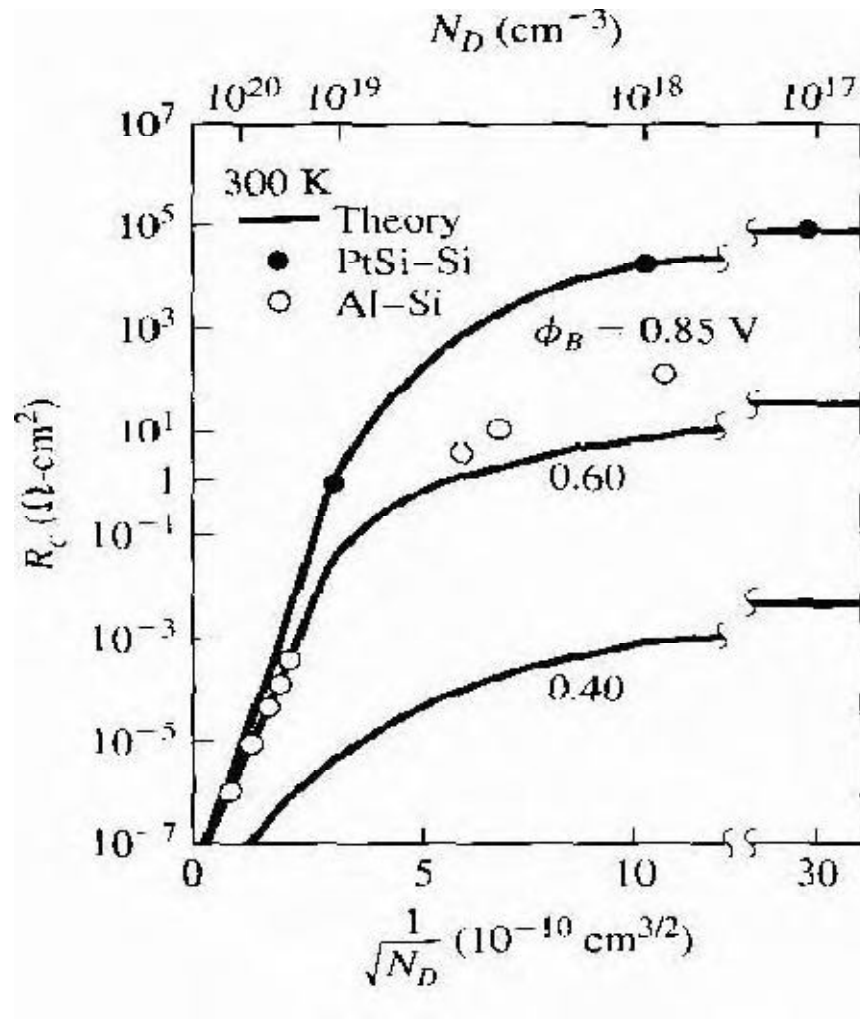


Fig. 3.12. Theoretical and experimental specific contact resistance as a function of doping[25].

Contacts on wide-band gap materials. In general, low barriers are not possible on these materials, so a heavily doped semiconductor at the surface must be used to form a tunnelling contact.

Chapter four

Calculations of Schottky barrier height and built in potential (Φ_B , V_{bi}) for some metals

4.1. Introduction

In this section we discussed some equations and figures presented in chapter three to calculate the values of schottky barrier height Φ_B and built in potential barrier V_{bi} from the work functions of some metals and semiconductors and electron affinity reported in that chapter. To determine the best metal contact with semiconductor on an n-type for the high work function of metal.

4.2. Discussion

From figure 3.1. and Eqs: 3.1 and 3.2 we get:

Electron in the metal must pass over potential barrier of height $\Phi_B = \Phi_m - \chi_s$.

Electron in the semiconductor must pass over built in potential $V_{bi} = \Phi_m - \Phi_s$.

$$\Phi_s = \chi_s + \Phi_n \quad (4.1)$$

$$V_{bi} = \Phi_m - \Phi_s \quad (4.2)$$

From potential barrier height we get:

$$\chi_s = \Phi_m - \Phi_B \quad (4.3)$$

From equation (4.1)

$$\chi_s = \Phi_s - \Phi_n \quad (4.4)$$

From equations (4.3) and (4.4)

$$\Phi_m - \Phi_B = \Phi_s - \Phi_n \text{ hence}$$

$$\Phi_m - \Phi_s = \Phi_B - \Phi_n \quad (4.5)$$

From (4.2) and (4.5) we get:

$$V_{bi} = \Phi_B - \Phi_n \quad (4.6)$$

$$\Phi_B = V_{bi} + \Phi_n \quad (4.7)$$

From (4.1)

$$\Phi_n = \Phi_s - x_s \quad (4.8)$$

Also from figure 3.1 the separation distance between the conduction band and Fermi level after contact with an n-type semiconductor is the increasing with the decreasing electron concentration. But on a p-type semiconductor is the decreasing with the increasing electron concentration.

According to the values of the work functions of some metal and semiconductors and electron affinity are given in tables (3.1), (3.2) and (3.3) respectively we calculated potential barrier and recorded in table (4.1). We applied the equation

$$\Phi_B = \Phi_m - x_s.$$

Table 4.1. Values of Φ_B metal to n-type semiconductor for high work functions.

Metal	Semiconductor				
	Si	Ge	GaAs	Cu_2O	AlAs
Au	1.09	0.97	1.03	1.64	1.60
Ni	1.14	1.02	1.08	1.69	1.56
pd	1.64	1.52	1.58	2.19	2.12
Pt	1.11	0.99	1.05	1.66	1.62
Rh	0.97	0.85	0.91	1.52	1.48

If we applied equation (4.8) we get the values of Φ_n :

Table 4.2. Values of Φ_n metal to n-type semiconductor for high work functions.

Element	Potential Φ_n
Si	0.72
Ge	0.65
GaAs	0.62
Cu_2O	0.70
AlAs	1.30

If we applied equation (4.6) we get the values of V_{bi} :

Table 4.3. Values of V_{bi} metal to n-type semiconductor for high work functions.

Metal	Semiconductor				
	Si	Ge	GaAs	Cu_2O	AlAs
Au	0.37	0.32	0.38	0.94	0.30
Ni	0.42	0.37	0.46	0.99	0.35
Pd	0.92	0.87	0.96	1.49	0.82
Pt	0.39	0.34	0.43	0.96	0.18
Rh	0.25	0.20	0.29	0.82	0.32

To refer to the values of Φ_B and V_{bi} in tables 4.1 and 4.3 respectively if we substituting in equation 3.12. $J = \left[A^* T^2 \exp\left(\frac{-e\Phi_{Bn}}{KT}\right) \right] \left[\exp\left(\frac{ev_a}{KT}\right) - 1 \right]$ we can get greater current when the Φ_B is smaller and smaller current when the Φ_B is greater. In other hand the electron carrier concentration increasing by decreasing the potential barrier height in an n-type semiconductor materials.

4.3. Conclusions

Based on the results of this work, the following conclusion could be drawn. The novel Rh rhodium contacts with germanium semiconductor were successfully

increasing the majority carrier concentration of the semiconductor instead of gold, nickel and platinum.

The Au, Ni and Pt are also increasing the electron carrier concentration for contacts with n-type Ge, Si and GaAs but the rhodium is better.

For p-type semiconductor. If we want to contact semiconductor with metal must to be looking for metal with low work function because required $\Phi_m < \Phi_s$.

Unfortunately, it is often impossible to find a metal of sufficiently high or low work function to arrange the electron flow in the correct direction to obtain an ohmic contact, especially to wide-gap semiconductors.

4.4. Recommendations

The applications of gold silicon semiconductor contacts in multi different electronic devices were found to successful potential, but gold is high cost.

As metal semiconductor contacts considered in this work gold is not the only metal found to enhance the majority carrier concentration of semiconductors, there is existence other metals low cost and available elements must be also recommended.

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