CHAPTER 7

OVERVIEW OF METAL CONTACTS TECHNOLOGY ON SEMICONDUCTOR

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7.1 INTRODUCTION

Over the past decades, researcher confronts new difficulties and breakthrough due to semiconductor innovation and these chances are evident in the endeavours that have been laid by semiconductor and optoelectronic devices. Semiconductor defined as a material which conducts electricity conditionally, hence making it useful in controlling for optoelectronic devices. It possesses intermediate conductivity, ranging between a conductor and an insulator. The superiority of metal-semiconductor plays a significant role in the performances of semiconductor devices and it is a powerful tool for improving performance in many areas of modern life.

7.2 OVERVIEW OF SEMICONDUCTOR

To dates, a semiconductor material is important due to its superior characteristics including high efficiency electrical and optical properties. Semiconductor is a materials that possess properties between conductor and insulator. In 1940s, semiconductor industry was still young and started with radio devices in 1901, but not purposely used as medium public information until 1920 [1]. Semiconductors are important in electronic devices manufacturing such as diodes, transistors, laser diodes (LD) and light emitting diodes (LEDs). Semiconductor devices have been found to be highly economical because of their miniaturization and reliability. The discovery of rectification makes a big breakthrough in conversion of alternating current (AC) to direct current (DC). This makes semiconductor essential to the creation of diode. Diode typically made from a p-n junction, it has two terminals that allow current to flow in one direction only. While transistor can be used as a switch, which makes it as a basis of computer processors that contain billions of tiny switches. The first major steps in the development of semiconductor transistors today was the invention by Bell Telephone Laboratories in 1948, which process the information in binary code. In the late 1950s, integrated circuits (ICs) were invented by Robert Noyce [2]. Geoffrey Drummer was the first to conceive of an idea, but it was Jack Kilby in 1958 who first bonded three transistors together. In the 1970s, smaller chips of ICs was developed allowing for the creation and development of powerful electronic devices such as computers, laptops, and smartphones in 1990s and 2000s.

The first developed laser diode in the 1960s becomes popular in optoelectronic fields, such as atomic and molecular spectroscopy, interferometry, atomic optics and metrology [3]. The advantages of LD are owing to its small in size, compactness, low power consumption and low cost [4]. The basic technology behind the development of light emitting diodes dates back to 1960s when scientists working with a chip of semiconductor material that was doped to create a p-n junction [5]. The development of LED was prompted in the early 1990s by the invention of the blue LED [6]. Since that, LED performance has improved significantly especially in the optoelectronic industry. LED is the light source that can operate when an electron moves through a semiconductor material. The color of light emission from LED depending on the composition of material of the LED.

There are many semiconductor materials including elemental Si and Ge, and compound, gallium arsenide (GaAs), gallium nitride (GaN), gallium phosphide (GaP). In addition, III-V compounds semiconductor such as GaAs, GaP and GaN offer better electrical and optical characteristics as compared to the elemental semiconductor due to its direct band bandgap that allows for efficient absorption and emission of light [7]. Nowadays, thin films have received tremendous attention because of numerous application of thin films in various fields including electronic semiconductor devices, magnetic recording media, optical coatings and LED. The development of semiconductor science and technology is increasing in the direction of devices utilizing thin film material. Thus, thin films technology has been spurred by the growing importance of the microelectronic industry.

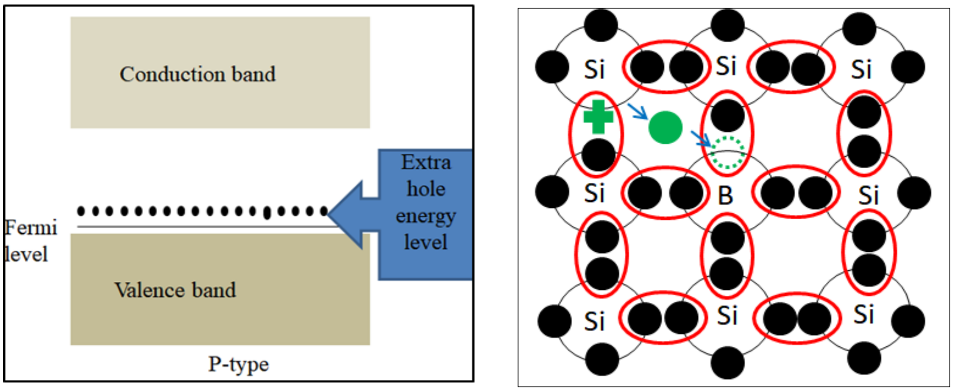
Apart from the elemental semiconductor, compound semiconductor has the advantages due to its band gap and unique properties as shown in Table 7.1. The band gap of GaAs, GaP and GaN are 1.42 eV, 2.26 eV, 3.4 eV, respectively [8]. GaN shows larger band gap as compared to GaAs and GaP. GaN is a direct and wide band gap semiconductor that recently used as a material for violet-blue-green LED and LD. However, the manufacturing cost of GaN is high as compared to Si due to the expensive raw materials and growth equipment. This makes GaN hard to obtain for LED production. Semiconductors have two type, p-type and n-type. In n-type material, there are electrons energy levels near top band gap so that they can be easily excited into the conduction band. The electrons are the majority carrier for current flow in this n-type semiconductor. In p-type, the majority carriers are holes.

Table 7.1 Some widely used elemental and compound semiconductor with band gap values.

Semiconductor		**Group**	**Band gap (eV)**
Elemental	**Si**	IV	1.1
	Ge	IV	0.67
Compound	**CdS**	II-VI	2.4
	CdSe	II-VI	1.8
	ZnSe	II-VI	3.6
	GaN	III-V	3.4
	GaAs	III-V	1.42
	GaP	III-V	2.16
	SiC	IV-IV	3.0

7.2.1 p-type Semiconductor

p-type semiconductor is one that has been doped with trivalent element (has three valence electron). Since there are no excess electrons/hole, the number electrons and holes present at any given time will equal. One of the atom in semiconductor lattice is replaced by an element with three valences electron such as Group 3 (e.g. boron or gallium), the electron-hole will changed as shown in Fig. 7.1. This impurity only able to contribute three valence electron to lattice, therefore leaving one excess hole. Since hole will “accept” free electron, a Group 3 is called acceptor. The holes are majority carriers, while the electrons are minority carriers.

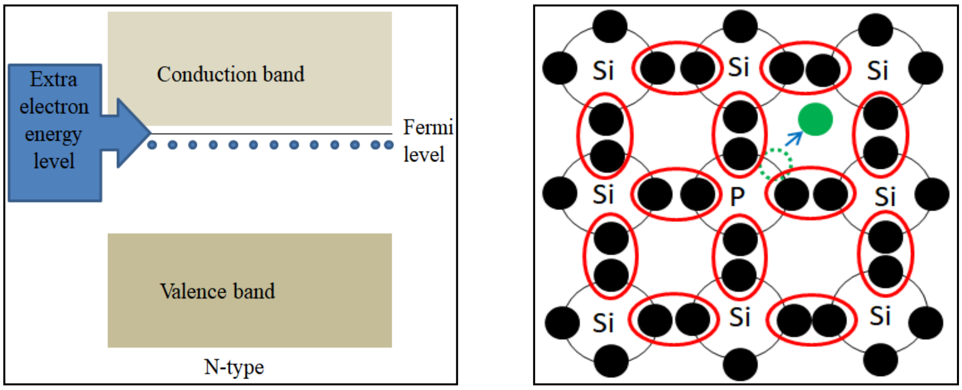


(a) (b)

Fig. 7.1 (a) p-type semiconductor and (b) The free place in boron atom is filled with electron, therefore new hole generated.

7.2.2 n-type Semiconductor

N-type semiconductor is one that has been doped with pentavalent element (has five valence electron). The impurity adds five valence electrons, such as Group 5 (e.g. arsenic and phosphorus) to the lattice where it can only hold four as shown in Fig. 7.2. Therefore, there is now one excess electron on lattice. This free electron requires much less energy to be exited from valence band to conduction band, than the electron which cause the intrinsic conductivity of Si. The dopant which produces an electron, is known as an electron donor. Donor impurities donate negatively charged electrons to the lattice, so a semiconductor has been doped with donor are called n-type semiconductor. The electrons are the majority carrier and holes are minority carriers.



(a) (b)

Fig. 7.2 (a) n-type semiconductor and (b) Phosphorus atom donate its fifth valence electron, acts as free charge carrier.

7.3 Application domain of metal layer

Table 7.2 compares material properties of Si and GaN. These material have major influences and benefits to the fundamental performances characteristic of semiconductor devices. GaN has a wide band gap which is 3.4 eV, meanwhile Si has a 1.1 eV narrow band gap. GaN is an attractive wide band gap semiconductor for ultraviolet optoelectronic, as well as high temperature electronic [9].

Table 7.2 Properties of Si and GaN material [10].

Material property	Si	GaN
Band gap (eV)	1.1	3.4
Critical field (10^6 V/cm)	3	3.5
Electron mobility (cm^2/V-s)	1450	2000
Electron saturation velocity(10^6 cm/s)	10	25
Thermal conductivity (W/cm^2 K)	1.5	1.3

High power electronic needs a good thermal conductivity, however the crystalline quality of GaN was inferior [11]. Reddy *et al*, 2005, reported in research that for GaN, it still difficult to obtain high quality Ohmic contact with low resistance. This is due to the difficulty in achieving high carrier concentration and absences of suitable metal with high work function. Researchers are working toward lowering the cost of GaN development and manufacturing. Since then, Si captures market in various domains application including electronic, communication and medical. Recently, Si has been backbone of technology industry.

Previous study reported that impurity control was major concern for Si material. Various study developed to reduce a metal impurity concentration in Si. Silicon widely has been used in electronic devices such as solar cells, LEDs and piezoresistive. All devices were benefit considerably if grown on cheap and readily semiconductors. The piezoresistance of Si is a great significance because it have been widely used in microsystem [12].

In solar cells production, the majority of Si wafer used today are dope with boron and hence are p-type semiconductor. In component view, the difference between n-type and p-type can be explained by the electron mobility versus hole mobility. Typically, electron mobility and hole mobility of Si at room temperature was 1400 cm^2/(V.s) and 450 cm^2/(V.s). Initially p-type was preferred due to its greater tolerance of radiation damage [13]. p-type has uniform resistivity profile along their length, and has been thought have higher minority carrier mobility which leads to improved solar cells current. However, this last point has been incorrect, since the mobility is usually more than outweighed by lower carrier lifetime. More recently, n-type has some significant advantages over p-type Si. Firstly, n-type Si have higher carrier lifetime, primarily caused by the absence of boron-oxygen defect [10]. In photovoltaic issue n-type Si has no light induced degradation effect and resulted a high carrier lifetime. Meanwhile, p-type Si strongly degrades under illumination. Furthermore, n-type Si highly tolerable to harmful impurities like iron in Si [14]. Thus n-type had better semiconductor properties compared to p-type due to its high and stable efficiency.

7.4 Metal Semiconductor Contacts

Metal-semiconductor (M-S) contacts are the most important component in the structure of the semiconductor devices. There are two types of the metal-semiconductor junction which are often present in semiconductor devices and involved in the fabrication of solid state devices. The two types are Schottky and Ohmic contacts as shown in Table 7.3. A Schottky barrier contact exhibits an asymmetrical current–voltage (I–V) characteristic when the polarity of a bias voltage applied to the M-S contacts is changed. On the other hand, Ohmic contact shows a linear I–V characteristic regardless of the polarity of the external bias voltage. Good Ohmic contact is referred to the case in which the voltage drop across a metal–semiconductor contact is negligible compared to that of the bulk semiconductor material.

Table 7.3 The comparison between Schottky and Ohmic contacts.

Contacts	Schottky	Ohmic
Types	Rectifying	Non-rectifying
Direction of current	Allow currents to flow in one biasing directions and block current in opposite biasing direction.	Allow current to flow in both biasing direction equally well.

In semiconductor devices, contacts must be made between metal and semiconductor. These contacts are made via Ohmic contacts. Ohmic contacts are an integral part of all semiconductor devices. It is used to apply external voltages as well as supply current from external sources. To measure the properties of semiconductor devices, the implementation of Ohmic contacts are essential. Ohmic contacts are metal-to-semiconductor contact, which are non-rectifying contacts. This contact is a low resistance junction which allows current to flow in both directions between metal and the semiconductor. The current through the Ohmic contact should be small. There are two types of Ohmic which are possible. The first one is the ideal non-rectifying barrier, and the other one is tunnelling barrier.

Rectifying properties of metal-semiconductor contact arise from the presence of electrostatic barrier between the metal and semiconductor. The existence of barrier is due to the difference in work function of two materials. If work function of metal, $\emptyset_m$ exceed of semiconductor, $\emptyset_s$ electron pass from semiconductor into metal to equalise the Fermi level, leaving behind depletion region in semiconductor in which the band bend upwards. If $\emptyset_m > \emptyset_s$ (n-type) the band bend upward, it will produce barrier which electron have to surmount in order to pass from semiconductor to metal, which leads the rectifying properties.

The ideal an Ohmic contact is the one that passes required current without dropping any voltage. Metal is excellent for contacts due to their low resistivity. A metal contact is a crucial factor for better technology along with the advancing properties of the semiconductor devices. The metal contacts are important parts in fabricating the semiconductor devices and application to have a better and excellent performance. There is a difference between the single, bi-layer and multilayer of metal contacts. The researcher considered bi-layer and multilayer compared to the single layer due to its lack of properties. Single metal layers are found to be not suitable to form low resistance Ohmic contacts due to properties [15]. To form an excellent Ohmic contact, the barrier must narrow and small furthermore the interface should not reflect the electrons. In addition, the way to make good contacts for semiconductor devices based on their adhesive contact and resistivity measurements in the form an ideal and good Ohmic contact. In semiconductor devices, the metal contacts occurred to make sure the efficiency of the devices used. Several methods have been used to improve the efficiency of the contact properties.

7.4.1 Single layer metal contacts

Single layer metal contacts mean only one metal coated onto the surface of the sample. The previous study reported by single Au was deposited on Si and glass substrate using diode sputtering at room temperature. The thickness and morphology were studied by Rutherford backscattering and AFM measurement. Results show that it consists of tiny gold grains, but on a glass substrate gold cluster of different size are clearly observed [16]. The investigation of optical and mechanical Al thin films varied by the parameter of sputtering deposition was done. It is shown that the surface of roughness increases with the increased of argon flow from 4 to 21 nm. Meanwhile, for optical it indicates higher reflectance for all films in a range of wavelength 250-2500 nm. Cadmium selenide (CdSe) is one compound that has been widely investigated during these years. CdSe can be deposited on glass substrate by thermal evaporation method for the application of solid state device such as solar cells [17]. The grain size increases after irradiation by Transversely Excited Atmospheric (TEA) N_2 laser at different energies from 190-800 nm and a big cluster were formed. The optical absorption spectra of these thin films are increasing after laser irradiation which the colour of thin films changes from red to dark red and band gap decreases after laser radiation. Palladium was prepared on GaAs by resistive heating method [18]. The barrier heights were increased by 0.26 eV that distinguished with atomic hydrogen.

7.4.2 Bi-layer contact thin film

Many researchers reported on double layer or bi-layer metal contacts such as nickel, platinum, aurum, argentum, iridium and aluminium. Ni/Ag contacts on p-type GaN at various annealing temperatures have been investigated. In their research, cryogenic cooling after heat treatment was performed to determine the effects of this treatment to the contacts. This treatment can reduce the specific contact resistivity Ohmic contacts [19]. In addition, there's another research about Ni/Ag bilayer and resulted from the as-deposited contacts exhibit non-linear Ohmic behaviour. The improvement of Ohmic could be due to the high work function of Ni and interfacial reaction between Ni and Ag. This study has resulted in producing the lowest specific resistivity of 0.174 Ω-m^2 [20]. Ni/Cr thin films were deposited on pre-treated polyimide (PI) substrate by ion beam assisted deposition. Effects of Cr buffer layer thickness on structural, mechanical and electrical properties on Ni films were investigated. The surface roughness of Ni was influenced by the thickness of Cr buffer layer. The decrement of roughness will improve in the enhancement of mechanical properties [21].

The thermal annealing on Pt/Ag of a photo-detector device for 400℃, 500℃ and 700℃ was investigated. The lower surface roughness was achieved at a thermal temperature of 700℃ (0.0182 µm). The surface morphology and roughness are considered important factors which could affect the electrical properties and hence affecting the photo-detector performance [22]. Pt/Ni thin films were fabricated using electron beam evaporation on Si substrate. The thickness for Pt was 5-6 nm and Ni was 40 nm. The good performances of Pt for methanol oxidation make its ideal used in a direct methanol fuel cell (DMFC) due to high intensity, ease handling of liquid and low operating temperatures. This study concluded that it can be used systematic modelling of alloy nanoparticles in DMFC [23].

Bi-layer contact Ti/Al metallization have studied the formation of a rough surface after annealing which widely used in technology of GaN based devices by using chemical vapour deposition (CVD) technique. After annealing, the surface roughness increase. This roughness can scatter the light and produce matte appearances [24]. The previous study of the effects of sputter deposited of bilayer Ni/Ti thin film during annealing was investigated. The deposition time of bilayer thin films was varied and undergone annealing treatment at 300℃ – 600℃. The surface roughness increases as the annealing temperature increases [25].

A bi-layer of Au/Pd was deposited by RF magnetron techniques. The result shows the minimal surface roughness with optical band gap 3.1 eV. The average grain size was found to be in the range of 20-25 nm [26]. The Ag/Au bilayer thin films with total thickness around 20 nm were studied. The improvement figure-of-merit (FOM) for plasmonic application are reported and discussed [25]. For Ti/Au contacts, it's annealed from 400°C to 900°C for 10 min in nitrogen (N_2) ambient.

The interaction between the contacts and GaN was investigated by electron microscopy and X-ray diffraction (XRD) [27]. Ir/Pt was annealed in oxygen (O_2) to improve the performance of devices. This study shows that these layers enhance the photocurrent to a dark current contract could all achieved via annealing Ir/Pt film [28]. The surface and interface scattering of conduction electron in Au/In double layer were investigated. As result, the electrical resistance of double layer is sensitive to the structural changes in the Au/In when the indium over-layer is heated for the first time above 120 K [29].

7.4.3 Multilayer metal contacts

Multilayer is the layer which is three or more layers were inserted on thin films metal contacts. The photoelectric application industry was rapid growth today and the enhancements of this device were investigated. The material such as platinum, palladium, magnesium, and nickel recently used as metal contacts for multilayer metal contacts. For previous study, Paillier et al., 2016 investigate of four-layered films (Pd/Mg/Pd/Mg) that leads to an increase in the amount of absorbed hydrogen due to the formation of hydride layer at each Pd/Mg interface although two of these interfaces are buried in films so that hydrogen must go through a Mg layer to reach them. These multilayers offered advantages for the H-storage properties [30].

Ti/Al/metal/Au, where metal is Ti, Mo, Pt, Ir, Ni, Ta has been studied to identify the role of the barrier layer on contact formations and surface morphology. It can be concluded that low-resistance Ohmic contacts can be obtained for all at different annealing temperatures. For surface morphology, it has shown various contacts scheme, where Ir, Pt and Mo show the least changes in gap spacing but the rest show a significant change, while Ti being the worst [31]. Reddy *et al.*, 2015 studied the electrical and structural properties of low resistance Pt/Ag/Au Ohmic contacts to p-type GaN. After annealing, the low specific contact resistance $1.70 \times 10^{-4}\ \Omega\text{-cm}^2$ at 800°C for 1 min resulted. The surface morphology was degraded compared with the as-deposited [32].

In summary, it shows the various results are based on different properties of metal. The types of layer play an important key in metal-semiconductor contact thin films. Based on the previous study, a single layer of Au show the different size of cluster, meanwhile for Al meta single layer, it shows the increment of surface roughness. For bi-layer thin films, its show the improvement of Ohmic contact due to high work function of metal and enhancement of lowest resistance. Furthermore, the lower surface roughness can be achieved after treatment.

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