TRANSPARENT CONDUCTIVE ELECTRODES FOR GaN-BASED LIGHT EMITTING DEVICE

by

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LIST OF SYMBOLS

α	Absorption coefficient
E_{g}	Band gap energy
ϕ_{B}	Barrier height
ϕ_{Bn}	Barrier height of n-type semiconductor
ϕ_{Bp}	Barrier height of p-type semiconductor
k	Boltzmann constant
$\vec{b}_s^{\,2}$	Burgers vector
n_{b}	Carrier bulk density
ρ_{b}	Carrier bulk resistivity
N_{D}	Carrier concentration of doped semiconductor
μ	Carrier mobility
R_c	Contact resistance
W_{c}	Contact width
S_{Cry}	Crystallite size
θ	Angle
ρ_{e}	Edge and mixed dislocation density
$\mathbf{E}$	Electric field vector
χ	Electron affinity
χ_{s}	Electron affinity of semiconductor
q	Elementary charge (1.602 × 10^{-19} C)
ξ	Energy difference between the Fermi energy and the conduction band
E_c	Energy of the conduction band
E_v	Energy of the valence band
F_{m}	Fermi level of metal
F_{s}	Fermi level of semiconductor
ϕ_{TC}	Figure of merit
v	Frequency
$\Delta\omega_{\mathrm{s}}$	FWHM of XRC curve
V_{H}	Hall voltage or transverse voltage
n_{idl}	Ideality factor
n	Index of refraction
a	In-plane lattice parameters
I_0	Intensity of the incident light
I_{T}	Intensity of the transmitted light
a_{GaN}	Lattice constant of GaN at *a*-axis
a_{Si}	Lattice constant of Si at *a*-axis
Δa	Lattice mismatch
$\mathbf{B}$	Magnetic field vector
T	Optical transmittance
c	Out-of-plane lattice parameters
$\boldsymbol{v}$	Particle velocity
E	Photon energy
h	Planck constant
R_{p}	Resistance between two contact pads
L	Sample thickness

K	Scherrer constant
ρ_s	Screw and mixed dislocation density
n_{sh}	Sheet density
R_s	Sheet resistance
R_{ss}	Sheet resistance of semiconductor
d	Spacing between crystal planes
R_{sp}	Specific contact resistance
R_q	Surface roughness
T	Temperature
t	Thickness
L_T	Transfer length
λ	Wavelength
ϕ_m	Work function of metal
ϕ_s	Work function of semiconductor

LIST OF ABBREVIATIONS

AlGaN	Aluminum gallium nitride
AlN	Aluminum nitride
arb. unit	Arbitrary unit
AFM	Atomic force microscope
CdO	Cadmium oxide
CTE	Coefficient of thermal expansion
CTLM	Circular transmission line model
cps	Count-per-second
EHP	Electron-hole pair
EDXS	Energy dispersive x-ray spectroscopy
EQE	External quantum efficiency
FE	Field emission
FESEM	Field-emission scanning electron microscopy
FWHM	Full-width at half-maximum
GaN	Gallium nitride
HRXRD	High resolution x-ray diffraction
InAlGaN	Indium aluminum gallium nitride
InGaN	Indium gallium nitride
InN	Indium nitride
In_2O_3	Indium oxide
ITO	Indium tin oxide
IR	Infra-red
IDB	Inversion domain boundaries
IPA	Isopropyl alcohol
LED	Light emitting diode
LT	Low temperature
MOCVD	Metal organic chemical vapor deposition
MOVPE	Metal organic vapor phase epitaxy
MBE	Molecular beam epitaxy
ML	Multi layer
MQW	Multi-quantum well
PAXRD	Phase analysis x-ray diffraction
RTA	Rapid thermal annealing
rlu	Reciprocal lattice unit
RSM	Reciprocal space mapping
RMS	Root-mean-square
rpm	Rotation-per-minute
SiC	Silicon carbide
SF	Stacking fault
sccm	Standard cubic centimeter per minute
SLS	Strain-layer superlattice
TE	Thermionic emission
TFE	Thermionic field emission
TD	Threading dislocation
SnO_2	Tin dioxide
TiO_2	Titanium dioxide

TCE	Transparent conductive electrode
TCO	Transparent conductive oxide
TA	Triple axis
UV	Ultra-violet
UV-Vis	Ultraviolet-visible
XRD	X-ray diffraction
XRC	X-ray rocking curve
ZnO	Zinc oxide

ELEKTROD PENGALIR LUTSINAR UNTUK PERANTI PEMANCAR CAHAYA BERASASKAN GaN

ABSTRAK

Sesentuh elektrik yang berkeupayaan sebagai pengalir arus elektrik yang tinggi dan lutsinar optik yang baik dalam panjang gelombang cahaya nampak adalah sangat penting untuk kecekapan peranti optoelektronik. Kajian ini difokuskan ke atas elektrod pengalir lutsinar (TCE) yang dimendapkan ke atas templat berasaskan GaN untuk aplikasi struktur diod pemancar cahaya (LED) InGaN. Templat GaN jenis-p dan jenis-n digunakan sebagai templat pemendapan untuk tujuan pengoptimuman TCE. Indium tin oksida (ITO) digunakan sebagai sesentuh lapisan atas kerana ITO menawarkan kerintangan arus elektrik yang rendah (~10^{-4} – 10^{-3} Ω-cm), lutsinar optik dalam panjang gelombang cahaya nampak yang tinggi (> 80 %), mempunyai kepekatan pembawa yang tinggi (~10^{21} cm^{-3}) dan kelincahan pembawa yang baik. Untuk memperbaiki kerintangan arus elektrik lapisan ITO, lapisan-bawah logam tipis dimendapkan di antara lapisan ITO di atas dan templat GaN. Bagi templat p-GaN, lapisan-bawah Ni dan Ag dimendapkan di bawah lapisan ITO, manakala bagi templat n-GaN, lapisan-bawah logam tipis Ti dan Al digunakan. Sampel-sampel TCE dikenakan proses sepuh lindap untuk memperbaiki ciri-ciri struktur TCE yang seterusnya akan memperbaiki ciri-ciri elektrik dan optik TCE. Daripada proses pengoptimuman, keadaan sepuh lindap yang terbaik untuk TCE adalah pada suhu 600°C di bawah aliran gas N_2 2 L/min dengan tempoh sepuh lindap selama 15 min. Kerintangan elektrik dan kebolehpancaran optik pada 470 nm bagi lapisan TCE Ni/Ag/ITO (5 nm / 5 nm / 80 nm) di atas p-GaN setelah melalui sepuh lindap selepas pemendapan telah diukur sebagai 3.65×10^{-5} Ω-cm dan 97 %, masing-masing.

Bagi lapisan TCE Ti/Al/ITO (5 nm / 5 nm / 80 nm) yang dimendapkan di atas n-GaN, kerintangan elektrik dan kebolehpancaran optik pada 470 nm telah diukur sebagai 8.61×10^{-5} Ω-cm and 95 %, masing-masing. Daripada pengiraan, angka merit (FOM) bagi TCE Ni/Ag/ITO and Ti/Al/ITO tersepuh lindap ialah $9.51 \times 10^{-2}\ \Omega^{-1}$ and $5.91 \times 10^{-2}\ \Omega^{-1}$, masing-masing, yang mana adalah lebih baik berbanding sampel TCE sedia ada. Di samping pengoptimuman TCE, perigi kuantum berbilang (MQW) LED InGaN yang ditumbuhkan dengan pemendapan wap kimia logam organik (MOCVD) di atas substrat Si (111) dicirikan berdasarkan sifat-sifat struktur dan optik. Didapati bahawa kepadatan kehelan bebenang (TDD) berkurang dengan sisipan n-$Al_{0.06}Ga_{0.94}N$/n-GaN superkekisi lapisan terikan (SLS) di atas tindanan lapisan tengah n-AlN/n-GaN dan menghasilkan lapisan GaN di atas Si yang bebas daripada retak. Daripada keputusan fotoluminesen, tenaga foton yang dipancarkan daripada LED dengan lapisan-bawah SLS ialah 2.97 eV yang bersepadanan dengan panjang gelombang 417 nm. Pada arus 20 mA, voltan nyalaan bagi LED InGaN dengan TCE Ni/Ag/ITO di atas lapisan p-GaN dan lapisan sesentuh Al di bawah substrat n-Si ialah 7.4 V. Voltan pincang hadapan yang tinggi adalah disebabkan oleh kerintangan daripada substrat Si dan lapisan penimbal berasaskan AlN di bawah kawasan aktif.

TRANSPARENT CONDUCTIVE ELECTRODES FOR GaN-BASED LIGHT EMITTING DEVICE

ABSTRACT

Electrical contacts which possess high electrical current conductivity and good optical transparency in visible wavelength are very important for the efficiency of optoelectronic devices. This study focuses on transparent conductive electrode (TCE) deposited on GaN-based templates for the application on InGaN light emitting diode (LED) structure. P-type and n-type GaN templates were used as depositing templates for optimization purposes of the TCE. Indium tin oxide (ITO) is used as a top contact layer since ITO offers low electrical current resistivity ($\sim 10^{-4} - 10^{-3}$ Ω-cm), high optical transparency in visible wavelength (> 80 %), has high carrier concentration ($\sim 10^{21}$ cm^{-3}) and good carrier mobility. In order to improve the electrical current resistivity of the ITO layer, thin metal under-layer was deposited between the top ITO layer and the GaN templates. For the p-GaN templates, Ni and Ag thin metal under-layer were deposited under the ITO top layer, whereas for the n-GaN templates, Ti and Al thin metal under-layer were used. The TCE samples were subjected to post-annealing process in order to improve the structural characteristics of the TCE which consequently will improve the electrical and optical characteristics of the TCE. From the optimization process, the best post-annealing condition for the TCE is at temperature of 600°C under N_2 gas flow of 2 L/min with annealing period of 15 min. The electrical resistivity and optical transmittance at 470 nm of the Ni/Ag/ITO (5 nm / 5 nm / 80 nm) TCE layer on p-GaN after post-deposition annealing were measured as 3.65×10^{-5} Ω-cm and 97 %, respectively. For the Ti/Al/ITO (5 nm / 5 nm / 80 nm) TCE layer deposited on n-GaN, the electrical

resistivity and optical transmittance at 470 nm were measured as 8.61×10^{-5} Ω-cm and 95 %, respectively. From calculation, the figure of merit (FOM) of the post-annealed Ni/Ag/ITO and Ti/Al/ITO TCE is 9.51×10^{-2} Ω^{-1} and 5.91×10^{-2} Ω^{-1}, respectively, which is better than the as-deposited TCE samples. Besides the TCE optimization, multi quantum-well (MQW) InGaN LED grown by metal organic chemical vapor deposition (MOCVD) on Si (111) substrate was characterized based on its structural and optical properties. It is found that the threading dislocation densities (TDD) is reduced with the insertion of n-$Al_{0.06}Ga_{0.94}N$/n-GaN strain-layer superlattices (SLS) on stack of n-AlN/n-GaN intermediate layer and producing crack-free GaN epitaxial layers on Si. From photoluminescence results, the emitted photon energy from the LED with SLS under-layer is 2.97 eV corresponding to wavelength of 417 nm. At 20 mA current, the turn-on voltage of the InGaN LED with Ni/Ag/ITO TCE on top of the p-GaN layer and Al contact layer at the bottom of the n-Si substrate is 7.4 V. The high forward voltage is mainly due to the resistance from the Si substrate and AlN-based buffer layer under the active region.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Transparent conductive electrodes (TCE) offer significant impact to the optoelectronics device technology such as GaN-based light emitting and light absorbing devices due to its unique properties of good optical transparency and high electrical conductivity. The TCE can be deposited on optoelectronic device structure as a single layer or multilayer depending on the device applications. The versatile characteristics of this TCE including high optical transparency, low electrical resistance and high thermal conductivity make it suitable as a current spreading layer and light input/output layer for optoelectronics devices [1]. In general sense, the TCE can be applied to automotive and architectural windows that act as a ultra-violet (UV) and infra-red (IR) blocking layer.

1.1.1 Problem statement of the transparent conductive electrodes

Over decades, researchers have studied on the contact material and its properties for the applications to the optoelectronic devices. Non-oxides or metal-based contact electrodes with single layer structure such as platinum (Pt), titanium (Ti), argentum (Ag), aluminum (Al), nickel (Ni) and Aurum (Au), as well as multilayer thin films such as nickel/aurum (Ni/Au), nickel/argentum (Ni/Ag) and Ti/Al has been deposited on various types of substrates such as silicon (Si) and gallium nitride (GaN) [2-4]. These metal-based contacts provide good electrical current conductivity due to the low electrical resistivity of the bulk metal. However these metal-based electrodes pose low optical transmittance or semitransparent characteristics due to the opaque properties of the metal as well as light reflectance at the interfaces.

Meanwhile, oxides-based TCE or also known as transparent conductive oxide (TCO) such as cadmium oxide (CdO), zinc oxide (ZnO), titanium dioxide (TiO_2), indium oxide (In_2O_3), tin oxide (SnO_2) and indium tin oxide (ITO) offer higher optical transmittance of more than 80% as compared to the metal-based TCE (<80%) [5, 6]. The electrical resistivity is relatively higher than the metal-based contacts with one order of magnitude, but still considered as low resistivity ($\sim 10^{-4} \Omega$-cm) especially for light emitting device applications. An approach to increase the electrical resistivity is by inserting metal under-layer or sandwiched metal layer. Some group of researchers have conducted study on the multilayer TCO-metal such as ZnO/Cu/ZnO, $TiO_2/Ag/TiO_2$, ITO/Ag/ITO, ITO/Ni/ITO in order to increase the electrical conductivity of the TCO [7-10]. However the additional metal layer degrades the optical transmittance characteristics. Therefore the metal layers must be made very thin enough of less than 10 nm thickness in order to increase the light transmittance, but this result in degradation of the electrical properties. Optimizing the TCO-metal multilayer structures such as its thickness, TCO-metal material, deposition conditions as well as pre and post deposition heat treatment can greatly improve the optical and electrical properties of the TCE.

TCE can be deposited on substrates by many techniques such as electron beam deposition and sputtering. The quality of the TCE depends on the target material and conditions during deposition processes. However, most of the deposited TCE such as ITO structures are amorphous in nature [11]. The amorphous nature of the ITO reduces the electrical conductivity, increasing electrical resistivity and reducing optical transmittance of the thin films. In addition, the substrate material used also affects the TCE properties. Substrates with high carrier concentrations such as n-type GaN (>10^{18} cm^{-3}) helps in lowering the electrical resistivity of the TCE as compared to the p-type GaN (<10^{18} cm^{-3}) with lower carrier concentration [12].

Since most of the room temperature deposited TCE produces amorphous thin films, performing post deposition annealing of the TCE thin films can improve the crystalline quality of the films consequently enhancing the electrical current conductivity and increasing light transmittance characteristics. Some parameters such as post-annealing temperature, duration and gas flow need to be carefully optimized in order to get high quality TCE thin films.

1.1.2 Problem statement of the GaN-based light emitting diode

GaN-based materials have been extensively investigated over the past two decades since found for its practical use in light emitting diodes (LED) technology. GaN with its binary cousins, aluminum nitride (AlN) and indium nitride (InN), as well its ternary, aluminum gallium nitride (AlGaN) and indium gallium nitride (InGaN), along with their quarternary indium aluminum gallium nitride (InAlGaN), is considered as one of the most important semiconductors after Si. This is due to their unique structural, electrical and optical characteristics such as direct and large bandgap (E_g ~ 0.7 eV-6.0 eV for InN→GaN→AlN), high carrier mobility, high breakdown field, high thermal conductivity, chemical inertness and good mechanical stability [13].

GaN-based LED offer an ultimate light sources in lighting technology since it covers spectrum from UV to IR. Since found for practical use by Nakamura in the early 1990s, many researchers have put numerous efforts to realizing high quality and high efficiency GaN-based LED. Many approaches were used to hetero epitaxial grow the LED such as by using metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). The hetero structure LED is epitaxially grown on silicon carbide (SiC), sapphire (Al_2O_3) or silicon (Si) substrate.

One of the major challenges in growing the hetero structure GaN-based epitaxial layer on third party substrates are the crystal defects such as lattice and thermal expansion defects [14]. Highly crystal defects may deteriorates device performance, reduce device lifetimes and alters the optical properties. The majority defects within the nitrides epitaxial structure are threading dislocations generated due to the lattice mismatch and differences in thermal expansion coefficient between the epitaxial layer and the substrate. Threading dislocations can be classified into edge dislocation, screw dislocation and mixed dislocation. The epitaxial stress occurs due to the parameter mismatches between the substrates and the epitaxial layer that can generate cracks through the epitaxial layer. Besides the lattice mismatches, differences in coefficient of thermal expansion, CTE of the substrates and the epitaxial layer will results in thermal stress. This stress can be a serious problem as it causes some cracks through the epitaxial layer during cooling.

The most common substrates used for heteroepitaxial growth of III-nitrides are sapphire, 6H-SiC and Si. Lattice mismatched between sapphire and GaN epitaxial layer is higher than the SiC. In addition, the sapphire is thermally and electrically insulating. SiC in the other hand have high thermal conductivity and very good electrical conductivity. However the sapphire and SiC were limited in size to no more than 4 inches as well as demanding high manufacturing cost. Si substrate on the other hand offer larger wafer sizes with diameter up to 12 inches, dramatic cost reduction as compared to the other substrates, have good thermal management as compared to sapphire and easy integration with well-established Si-based manufacturing technologies.

There are several significant challenges in growing GaN-based heteroepitaxial structure on Si substrate with InGaN quantum wells active region. Two major difficulties impeding the growth of high quality InGaN-based LED are the large lattice mismatch (-17%) and thermal coefficient mismatch (116%) between the GaN-based epitaxial layer and Si substrate [15]. These lattice and thermal mismatch can generate structural defects including cracking, threading dislocation (TD) and cloudy surface morphology through the entire device. TD generated from Si substrate up to the InGaN-based multi-quantum well (MQW) active region can act as a non-radiative recombination center by disrupting the light emission process, resulting in the production of heat rather than light thus reducing the optical emission efficiency of the LED [16].

Several approaches were proposed to overcome the inherent heterostructure challenges of Si as a substrate for the GaN-based epi-layer. The lattice mismatched and thermal stress in GaN-based epi-layer on Si can be controlled with the use of buffer and intermediate layer. Many research groups have been investigated on these buffer and intermediate layer for GaN growth on Si such as AlN buffer layer, AlGaN buffer layer, AlGaN/GaN superlattice, AlN/GaN strain superlattices (SLS) buffer interlayer on AlGaN/AlN nucleation layer, AlN/AlGaN low temperature (LT) buffer layer [17], which will be discussed in detail in the next chapter. The lower lattice parameter of AlN forces the GaN-based epi-layer to be grown under compression stress, accordingly counteracting the thermal tensile stress acting from the Si substrate.

Besides optimizing high quality structure of the GaN-based LED, good quality ohmic contact with high optical transparency also plays an important role for producing high external quantum efficiency, EQE. TCE with good optical characteristics and high electrical conductivity can be used as contacts on top of the p-GaN and n-GaN layer to spread the electrical current uniformly. In addition, with high optical transparency, visible light generated from the active region can be transmitted out through the TCE efficiently.

1.2 Research Objectives

The objectives of this research are to

(i) Study the improvement of the electrical and optical properties of transparent conductive electrodes based on ITO and Ni/Ag metal thin films sputter deposited on p-type GaN.

(ii) Study the improvement of the electrical and optical properties of transparent conductive electrodes based on ITO and Ti/Al metal thin films sputter deposited on n-type GaN.

(iii) Investigate the InGaN LED structure properties grown on Si (111) substrate based on its structural, optical and electrical properties.

1.3 Research Originality

The main originality in this study lies on the combination of Ni and Ag thin metal layer with the ITO layer deposited on p-GaN, and the combination of the Ti and Al thin metal layer with the ITO layer deposited on n-GaN for transparent conductive electrodes (TCE) with specific structural, morphological, electrical and optical properties, deposited as a TCE contact layer on p-GaN, n-GaN and InGaN light emitting device structure that was grown on Si (111) substrate by MOCVD, that to the extent of our knowledge, have not been reported by other research groups. The combination of ITO TCO with under-layer metal thin films will enhance the electrical properties of the TCE as a current spreading layer. Moreover, detail study on the effect of post-annealing on the TCE layer is expected to improve the TCE properties with excellent ohmic behavior and excellent optical characteristics, consequently increases the LED efficiency.

1.4 Research Scope

This study will focus on the deposition and optimization of ITO-based transparent conductive electrodes with the insertion of Ni and Ag thin metal films under the ITO on p-GaN; and Ti and Al thin metal films under the ITO on n-GaN. Furthermore, this study will characterize the InGaN LED structure with the insertion of strain layer superlattices under-layer and finally deposition of transparent conductive contacts on p-GaN layer of the InGaN LED and Al contact layer on Si (111) substrate.

1.5 Thesis Outline

The content of this dissertation is organized as follows:

Chapter 2 encompasses the literature overview of the metal contact and transparent conductive electrodes technology on p-GaN, n-GaN and semiconductor optoelectronic devices especially GaN-based light emitting device. The overview on GaN-based light emitting device development especially related to the InGaN LED structure development is also included.

Chapter 3 is related to the basic principles of the TCE including metal-based and TCO-based transparent contact, principles of InGaN-based light emitting device structure with multi-quantum-well (MQW) active region and basic concept of some of the characterization techniques.

Chapter 4 explains the methods for sample preparations, depositions, growth and characterizations. This includes the cleaning procedure, TCE deposition process, post-deposition annealing, InGaN LED growth process followed by the characterization of the TCE and InGaN LED structure based on its structural, morphological, electrical and optical characteristics.

Chapter 5 presents the results of the ITO-based TCE on p-GaN with Ni and Ag metal thin layer under the ITO. The post-annealing effects on the TCE based on the structural, morphological, electrical and optical properties are discussed.

Chapter 6 presents the results of the ITO-based TCE on n-GaN with Ti and Al metal thin layer under the ITO. The post-annealing effects on the TCE based on the structural, morphological, electrical and optical properties are discussed.

Chapter 7 presents the structural and optical characterization results of the InGaN light emitting device grown on Si (111). The results on the implementation of TCE on p-type layer of the InGaN LED structure are also briefly discussed.

Finally in Chapter 8, conclusion on TCE and InGaN LED characterization results covered in this thesis with recommendations for further research work will be given.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Transparent conductive electrodes including non-oxide (metal only conductor contact) and oxide (oxide metal) either single layer or multilayer has been investigated for its structural, electrical, optical and morphological properties for semiconductor optoelectronic applications. Good ohmic contact and high optical transmittance characteristics of the TCE on semiconductor devices such as GaN-based light emitting devices can improve the power and optical efficiency of the device. This chapter overview on the transparent conductive electrodes technology from the non-oxide metal contacts (eg. Ni, Ag, Ti and Al), transparent conductive oxide (eg. CdO, ZnO and ITO) and ITO-metal TCE (eg. Ni/ITO, Ag/ITO and Ti/ITO). Further sections will overview on the technology development of the InGaN light emitting structure.

2.2 Overview of contact technology

Improvements in metal-semiconductor contacts have become a critical factor for better technology along with the advancing properties of the semiconductor devices. In recent years, GaN itself has been proven to be excellent choice for light-emitting devices especially for white light and high power device applications. The successes of all GaN related devices for high brightness and high efficient LED application depend largely on having excellent contact properties to these devices. Contact to semiconductor basically consists of region of semiconductor surface just below first metal layer, metal semiconductor interface and few layers of contacts metallization above the semiconductor. Invariably the as-deposited contact does not give the desired properties (either low resistance or high Schottky barrier). So the contacts were undergone treatment such as plasma and heat treatment which results in formation of different complex inter-metallic compounds by way of solid state reaction among metal layers and semiconductor surfaces.

2.2.1 Metal-contact technology on GaN

GaN has received much attention due to its unique properties of wide and direct energy band gap which makes it suitable for high efficiency light-emitting device applications. Good ohmic metal-semiconductor contacts may enhance the device efficiency. High quality metal-semiconductor ohmic contact with low electrical resistance is vital to ensure the high efficiency electrical current flow through the contact to the GaN-based devices. In addition, the development of multilayer contact has been utilized to obtain low resistance ohmic contact performance. Furthermore, thermal annealing can be used in order to get ohmic characteristics of the metal contacts, besides improving the thermal stability and electrical characteristics. Some research groups have deposited metal-based thin film contact such as Ti/Al [18] and Ti/Al/Ni/Au [19, 20] on semiconductor substrates.

Chen and his group introducing Ni/Au on Ti/Al in order to preventing inter-diffusion of Ti, Al, Au and also as an anti-oxidation of the contacting layer [21]. They performed two-step annealing process at 900°C under N_2 for 30s to lower specific contact resistance, ρ_c to 9.65×10^{-7} Ω-cm^2. Other group of researcher reported on the improvement of the specific contact resistance as low as 3×10^{-6} Ω-cm^2 with multilayer metallization ohmic contact of Ti/Al/Ni/Au on AlGaN/GaN after three steps rapid thermal annealing, RTA from 400°C to 830°C [19]. Greco *et.*

al. reported on Ti/Al ohmic contact on AlGaN/GaN/Si with electrical resistivity of 3.33×10^{-5} Ω-cm and 1.23×10^{-5} Ω-cm for the high defect density (12×10^{9} cm^{-2}) and the low defect density (4×10^{9} cm^{-2}) in the epitaxial structure, respectively [18].

Metal contact on p-GaN

The high contact resistance of p-GaN is one of major problems in the realization of long-lifetime and reliability operation of GaN-based devices. It is due to the difficulty to grow heavily p-type doped in GaN ($>10^{18}$ cm^{-3}) and to get an appropriate metal having work functions larger than that of p-GaN (~7.5 eV) [22]. The difficulty to form low ohmic contact on p-GaN is also due to the extremely large Schottky barrier height formed at metal/p-GaN interfaces. The performance of InGaN LED such as the operation voltage is strongly affected by contact resistance. Power dissipation due to voltage drop at the p-GaN/metal contact interface generates Joule heat, thus causes high junction temperature which could degrade the performance of the device. It is thus crucial to develop high-quality ohmic contact on p-GaN to enhance device performance.

However it is difficult to obtain ohmic contact on p-GaN with specific contact resistance of less than 10^{-4} Ω-cm^{2} due to the low activation energy of Mg dopant and the tendency of GaN surface to preferentially lose N during processing [23]. Various metallization method including surface preparation methods, metallization layer, deposition techniques and annealing treatments have been investigated to obtain low specific contact resistivity and low energy barrier between the metal contacts and p-GaN [24-26]. Single layer, bi-layer, and multilayer metallization contacts based on high work function metals such as Ni, Pt, Au and Pd have been investigated for ohmic contact formation. Thus multilayer metallic films with high work function such as Ni/Au [27] and Ni/Ag [28, 29] have been used as a contact on p-GaN.

Cao has reported on the improvement of electrical and optical characteristics with the fabrication of Ni/Au current spreading layer on p-GaN after annealing in air at 550°C for 5 min [27]. The high conductivity and transparency in visible regime of the Ni/Au make it a good candidate as a current spreading layer for InGaN LED. The low contact resistance was attributed to the formation of intermediate NiO (band gap ~ 4 eV) embedded with Au-rich and Ni-Ga-O islands which was believed to be low barrier contact to p-GaN. Annealing process also helps in reducing the contact resistance due to the hydrogen atoms bonded with Mg or N in p-GaN are removed during the annealing process, which in conjunction increases the hole concentration in p-GaN layer.

Qin studied on Ni/Au ohmic contact on top p-GaN layer of InGaN/GaN MQW blue LED [30]. They found that the Ni layer play a role of reducing the Schottky barrier while the Au layer play a role of spreading the injection current. They also found that the three steps annealing can improves the contact properties significantly. Since Ni has a relatively high metal work function as well as good adhesion to nitrides, it was utilized as an intermediate film [31]. Hassan reported on the Ni/Ag metal contacts on p-GaN instead of Au since Ag is cheaper than Au, has low electrical resistivity (1.59×10^{-6} Ω-cm) and good thermal conductivity (1 cal/cm-s-°C). They achieved specific contact resistance of 9.9×10^{-2} Ω-cm^2 after undergone thermal annealing at 700°C for 15 min with subsequent cryogenic cooling treatment for another 10 min [32]. Further research by Jang and Lee was reported on the improved specific contact resistance of 5.2×10^{-5} Ω-cm^2 with the fabrication of Ni/Ag/Ru/Ni/Au multilayer metal contacts on p-GaN after annealing at 500°C for 1 min in O_2 ambient. Ru was used in order to act as a diffusion barrier for Ag out-diffusion to the surface, resulting in excellent thermal stability [33]. They also reported on Ni/Ag metal contacts on p-GaN with achieved specific contact resistance of 5.2×10^{-5} Ω-cm^2 after annealing at 500°C for 1 min in O_2 ambient. Out-diffused of Ga atoms from GaN could dissolve in the Ag layer to form Ag-Ga solid solutions, leaving Ga vacancies below the contact. Ga vacancies could increase the net hole concentration and reduce the surface band bending, resulting in the ohmic contact formation [34].

Cho used Pd/Ni/Au multilayer metallization contact on p-GaN and achieved ohmic characteristics after thermal annealing at 500° for 1 min in N_2 [35]. Pd was used for its high work function and high reactivity, besides the Pd properties that act as an acceptor in GaN, causing the near surface region to be highly doped. In addition, the transformation of Ni to NiO during thermal annealing at the interface of Ni and GaN produce a layer with high hole concentration which led to the reduction of contact resistance. Hong-Xia reported on a novel Ni/Ag/Pt ohmic contact on p-GaN [36]. The specific contact resistance improves to 26×10^{-6} Ω-cm^2 after thermal annealing at 500°C for 3 min in O_2 ambient. Pt layer can improve the surface morphology and thermal reliability, Ag plays a key role in achieving good ohmic contact due to the out-diffusion of Ga into Ag forming vacancies which increase the hole concentration while the surface contamination of p-GaN is reduced by Ni. Chang reports on Ni/Ag/Au ohmic contact on p-GaN which achieved specific contact resistance of 4.35×10^{-4} Ω-cm^2 after thermal annealing at 500°C for 10 min in O_2 ambient [37]. Ni/Au and Ag are combined in order to form low resistance and high reflective contact.

Chou *et. al.* show that the addition of 10 at.% of Al with Ag in Ni/Ag contacts reduce the specific contact resistance to 10^{-2} Ω-cm^2 after thermal annealing at 500°C for 10 min in air [38]. The addition of a small amount of Al additives in Ni/Ag can effectively prevent the formation of Ag agglomeration on the p-GaN surface, consequently improves the properties of the annealed contacts. De-Sheng *et. al.* shows an improvement of the Ni/Ag ohmic metal contact with specific contact resistance of 2.5×10^{-4} Ω-cm^2 on p-GaN after annealing at 550°C for 1 min in O_2 [28]. Kim fabricated Ni-Co solid solution/Au on p-GaN with thermal annealing process at 550°C for 1 min in air [39]. The annealing process improves the ohmic characteristics of the contact as well as the optical transmittance of ~70%. The Co used might contribute to increase in the carrier concentration by extracting hydrogen from p-GaN thus lowering the contact resistance.

Ag films have poor adhesion to the substrate and easily agglomerate at elevated temperature in air. Son *et. al.* reported on low specific contact resistance of 8.2×10^{-6} Ω-cm^2 of the Ni/Ag/Ni multilayer metal contact on p-GaN after annealing at 450°C for 1 min in air [24]. They deposited thin Ni over-layer on top of the Ag contact layer in order to prevent surface diffusion of Ag atoms during annealing, leading to smoother surface morphology and low contact resistivity. The Mg doping concentration is generally about 10^{20} cm^{-3}, but only 0.1-1% of the Mg atoms are activated, due to high activation energy (~170 meV) and the formation of Mg-H complexes decreasing the number of active carrier which lead to carrier density to ~ 10^{17} cm^{-3} [24]. Chuah *et. al.* reported the Ni/Ag metallization scheme on p-GaN achieving specific contact resistance of 1.74000×10^{-1} Ω-cm^2 after thermal annealing at 700°C for 10 min under N_2 flow [29]. They deduce that high Mg doping may lead to the creation of a large number of deep level defects in p-GaN, leading to the reduction of the depletion region in p-GaN near the interface and increases the probability of thermionic filed emission. Further investigation by Chuah *et. al.* also reported their study on different metallization of Ir/Ag [40]. They used Ir due to its ability to diffuse through the oxide contamination at the metal/p-GaN interface layer. They achieved lower specific contact resistivity after the same thermal annealing process as compared to the reported Ni/Ag contacts. Song *et. al.* studied on the role of diffusion barrier metals (Pt and Ti) on the Ni/Ag/Pt or Ti/Au deposited on p-GaN for flip chip LED [41]. They found that the Pt diffusion barrier shows lower specific contacts resistance of 3.8×10^{-3} Ω-cm^2 as compared to the Ti of 8.1×10^{-3} Ω-cm^2, respectively, after thermal annealing at 380°C for 1 min in air. Youngjun *et. al.* investigated on the carrier transport mechanism of Ni/Ag/Pt contacts to Mg-doped p-GaN [42]. They prove through experiment and calculation that the contact behavior was found to strongly depend on the Mg doping concentration.

Further study was conducted by Huang *et. al.* on the effect of hydrogen treatment on ohmic contact to p-GaN [26]. The interfacial oxide layer on the p-GaN surface was found to be the main reason for causing the nonlinear I-V behavior for the H_2 untreated p-GaN films. Surface inversion of p-GaN layer was successfully achieved by H_2 treatment at high temperature of 1000°C. This consequently increase nitrogen vacancy density, pinned the surface Fermi level close to the conduction-band edge, reduce the Schottky barrier height that allows the electrons to flow easily over the barrier from the metal contact to p-GaN, lowering the metal contact resistance and thus improve the I-V characteristics to the linear behavior. Other group of researcher used graphene with the insertion of thin Ti/Al metal layer to improve the contact resistance although loss ~20% of the optical transmittance [43]. Graphene is used as a contact layer since it is highly transparent, high electrical, high thermal conductivities and high mechanical flexibility. After thermal annealing, the I-V characteristics of the Gr/Ti/Au contact become ohmic as compared the nonlinear of the as-deposited contact. Kim *et. al.* reported on a low specific resistance (6.1×10^{-5} Ω-cm^2) of Pd/Zn/Ag metal contacts after annealing at 500°C for 1 min in air [44]. The Pd interlayer is used to enhance the adhesion of the Zn on p-GaN. In addition, Pd was expected to form ohmic contact on p-GaN since Pd has a large work function. InGaN LED with Pd/Zn/Ag contacts exhibited a forward voltage of 3.01 V at 20 mA.

Metal contact on n-GaN

Ti- or Al-based metallization contacts such as Ti/Al [45], Ti/Au [46] and Ti/Al/Ni/Au [21] had been widely used as contacts to n-GaN as it is widely recognized as the ohmic contact yielding the lowest resistivity. Among many contact metallization schemes on n-GaN, Ti/Al-based contacts are widely utilized. Ti metallization schemes reduces contact resistance by forming a low work function TiN alloys with the under GaN layer. In such metallization contacts, low specific contact resistance ranging from ~ 10^{-5} – 10^{-8} Ω-cm^2 have been reported, which are good enough for the operation of the optoelectronic devices.

Recent results have shown that the additional layers on the Ti/Al contact layers such as Ni/Au, Pt/Au, Ti/Au can reduce the contact resistivity especially after undergone heat treatment or post-annealing process. Al reduces the reaction between Ti and GaN. Ti /Al contact on AlGaN/GaN annealed at low temperature have a resistivity of 1.67-5.45 Ω-cm [47]. Placidi *et. al.* has conducted a study on the effects of cap layer on Ti/Al ohmic contact on n-GaN [48]. They have shown that the specific contact resistance of the Ti/Al with top protected layer of SiO_2 is lower than the unprotected top contact layer. Kim *et. al.* deposited Ta-based ohmic contact with Ti/Al upper-layer and Ni/Au over-layers on AlGaN/GaN [49]. After post-annealing at 700°C for 1 min, they achieved ohmic contact of Ta/Ti/Al/Ni/Au with specific contact resistance of 7.5×10^{-7} Ω-cm^2 and root-mean-square surface roughness of 28.8 nm. Ti/Al (40/160 nm) contacts exhibited linear current-voltage characteristics after post-annealing at 300°C and 400°C, and remained nearly linear after post-annealing at 700°C with barrier height, φ_B of 0.35eV [45].

Further study by Dobos *et. al.* that reported on the structural effects of Ti/Au ohmic contact on n-GaN before and after thermal annealing [46]. They showed that the Au diffused through Ti layer and Au rich grains were formed under Ti layer. TiN was also formed at the metal-GaN interface. The annealed contact shows very smooth surface morphology. Jeon *et. al.* studied on Cr/Al ohmic contact on N-polar n-GaN for vertical LED [50]. They found that the annealed specific contact resistance of the Cr/Al contacts increases by one order of magnitude than the as-deposited samples. Cr layer may serve as a diffusion barrier to the out-diffusion of Ga atoms during annealing. Ga atoms are dominantly out-diffused into the metal electrodes because of lower formation energy of Ga vacancy compared to that of N vacancy in n-GaN. The acceptor-like defects could give rise to electrical compensation in the N-polar n-GaN, resulting in a decrease in the electron concentration and hence increase in the effective Schottky barrier heights. Furthermore, Dobos *et. al.* investigated the effects of the Cr/Au contacts to the n-GaN for its electrical, structural and morphological characteristics [51]. After annealing in vacuum at temperature of 700°C and 900°C, the I-V characteristics of the contact become linear. The Cr was selected as the first contact layer because it has a work function (4.5 eV) which is close to the n-GaN, and because of its reactive nature, it also acts as an oxide reducing agent. Further study was performed by Dobos *et. al.* on Ti/Cr/Al contacts on n-GaN and post-annealing process at 400, 700 and 900°C for 10 min in vacuum [52]. Annealing process at 700 and 900°C yielded inter-diffusion, lateral diffusion and alloying of the metal contacts and the GaN. The diffusion of Cr into the epi-layer of GaN led to ohmic behavior and increase series resistance at 700°C.

Borysiewicz *et. al.* studied on thermal stability of the Ti/Al/TiN/Ti/Al/TiN/Ti/Al/TiN ohmic contact to n-GaN [53]. The contact remains ohmic and morphologically unaltered after aging annealing at 300, 400 and 500°C in ambient air for 100h but the specific contact resistance increases by one order of magnitude as compared to the as-deposited samples. A thin Ti oxynitride layer was found to form after the aging process that most probably leads to the observed rise in the specific contact resistance. By employing the Ti/Al/Ti/Al/Ti/Au (30/30/30/30/30/60 nm) multi-layered structure, better ohmic characteristics were demonstrated, significantly reduced contact resistance and enhanced surface morphology of the contact electrodes [54]. The current transport characteristics facilitated at 39.35 mA at $V = 1$V, with specific contact resistanceρ_c of 4.52×10^{-6} Ω-cm^2 and contact resistance of 0.52 Ω mm [54].

2.2.2 Transparent conductive oxide

As discussed in section 2.2.1, different types of metal-based contacts were deposited on p- and n-type GaN for the application on GaN-based devices. Types of contacts on p-GaN and n-GaN need to be optimized carefully in order to improve the device performance. For LED, low resistance ohmic contact either on p-GaN or n-GaN are very important for optimum device performance. However, the metal-based contacts are almost opaque or semi-transparent that less light from the device can be emitted out even though with low input power. In order to achieve high optical transparency, the metal contacts need to be made very thin (less than 20 nm) which results in non-uniform surface morphology and consequently degrades the electrical characteristics.

Contact or electrode with good optical transparent characteristics and low electrical resistance are very essential for efficient LED. The low electrical contact resistivity can acts as a good current spreading layer as well as allow less power input to the device, whereas the high optical transparency contact allows the light generated emitted out with very minimum optical loss. Doped oxide-based thin film contact with much better transparency and good electrical characteristics has been studied and continuing to be developed. These highly transparent and conductive thin films contact, also known as transparent conductive oxide (TCO) were achieved by introducing native defects such as oxygen vacancies, or by doping with higher doping elements [55]. Many types of TCO such as CdO, ZnO, In_2O_3, SnO_2 and ITO have been studied extensively for their unique properties as well as for the optimum device performance.

Historically, CdO is one of the first examples of a TCO reported in 1907 [56]. CdO thin films contact were achieved by DC magnetron reactive sputtering [57, 58], thermal evaporation [59], spray pyrolysis [60], atmospheric-pressure chemical vapor deposition [61] and electrochemical deposition technique [62]. CdO thin films have attracted much attention because of their high Hall mobility values and high electron concentration (10^{19}- 10^{21} cm^{-3}) [56, 61]. This n-type conductivity CdO has a face centered cubic (FCC) crystal structure with lattice constant of 4.694 Å. It has wide direct band gap between 2.2 and 2.7 eV and narrow indirect band gap of 2.1 eV [61, 62]. It has high transmittance in the visible spectral region of 80-95% [63], high electrical conductivity and low electrical resistivity of ~1.4×10^{-4} Ω-cm makes it useful for various optoelectronics applications [63]. Although the CdO TCO have the desired good electrical and optical characteristics, they face tremendous obstacles in penetrating the market due to the high toxicity of Cd [55].

Besides CdO, ZnO is II-VI semiconductor and is one of the promising TCO that offer good electrical conductivity and highly transmittance especially for wide bandgap optoelectronics and microelectronics device applications. ZnO thin films have been deposited on GaN by many techniques such as RF magnetron sputtering [64, 65], atmospheric-pressure metal-organic chemical vapor deposition (AP-MOCVD) [66], metal-organic chemical vapor deposition (MOCVD) [67] and pulsed laser deposition (PLD) [68, 69]. ZnO is used with GaN to grow ultraviolet (UV) light emitters [70]. ZnO is n-type semiconductor with direct band gap energy of 3.37 eV [71] and carrier concentration of ~10^{17} cm^{-3}. It offers some advantages including large 60 meV exciton binding energy at room temperature [72], low cost, non-toxicity, etch ability with wet chemicals, high temperature stability and abundant material resources [6]. The ZnO TCO have similar refractive indices with GaN in the range of 2.1-2.5 which have the advantages of reducing internal light reflections especially for the GaN-based light-emitting devices [73]. In addition, the ZnO has relatively small lattice mismatched with GaN of less than 2% and small difference between the in-plane linear thermal expansion coefficients ($\alpha_{ZnO} = 6.51 \times 10^{-6}$ K^{-1} and $\alpha_{GaN} = 5.59 \times 10^{-6}$ K^{-1}) [66]. However the ZnO-based TCO degrade much faster than other TCO such as ITO when exposed to damp and hot environment. The as-grown ZnO naturally exhibits n-type characteristics due to the oxygen vacancies, growing p-type ZnO are difficult due to the self-compensation mechanism involving oxygen vacancies, zinc interstial and low solubility of dopant [74]. Since most of ZnO is used with GaN to produce light emitters in UV region, doping the ZnO films with group III-elements such as Ga, Al and In have been realized with very attractive electrical and optical applications as a TCO for electrode applications. Ga-doped ZnO (GZO) have been extensively studied due to several advantages such as has high resistance to oxidation and less lattice deformation as compared to other materials [68]. GZO has been reported to have the lowest resistivity of 8.12×10^{-5} Ω-cm and high transmittance ~90% in the visible spectrum ranges [75]. The dopant concentration of the GZO is more often in the range of $10^{20} – 10^{22}$ cm^{-3} with Hall mobility of 14-40 cm^2/V-s [68, 76, 77]. Other research groups reported on the Al-doped ZnO thin films forming AZO. The AZO reaches optical transmittance of 80-90% at visible spectrum. The reported carrier concentration of the AZO thin films is in the range of 10^{20}-10^{21} cm^{-3} with the lowest resistivity of 8.54×10^{-5} Ω-cm.

In_2O_3 is a wide band gap semiconductor showing direct band gap of about 3.7 eV can be used for various applications in optoelectronics such as light-emitting and detector devices [78]. Various techniques have been used to prepare the In_2O_3including pulsed electron beam deposition (PED) [79], thermal oxidation [78], pulsed DC magnetron sputtering [80] and pulsed laser deposition (PLD) [81] . Many types of substrates such as c-cut sapphire [79], glass [80], Si[82], GaAs and quartz [81] were used for the deposition of the In_2O_3. Adurodija *et. al.* reported on low resistivity of 3.5×10^{-4} Ω-cm of the In_2O_3 thin films deposited on Si (100) with thickness of 100 nm [82]. Tripathi *et. al.* shows average optical transmission of ~96% of the 200 nm thick In_2O_3 thin films deposited on quartz and glass substrate [81]. They also successfully shows the optical band gap values of In_2O_3 thin films of 3.64 eV and 3.79 eV deposited on quartz and glass substrates, respectively.

SnO_2 belongs to TCO family that combining the unique properties of low electrical resistivity and high optical transmittance in the visible ranges. It is n-type semiconductor with a wide band gap of 3.6 eV and composes of a tetragonal rutile crystal structure [83]. Many methods used to deposit the SnO_2 such as spray pyrolysis [84], thermal evaporation [85], DC and RF magnetron sputtering [86, 87]. SnO_2 is a low cost and multifunctional materials that show high electrical conductivity, high exciton binding energy of ~ 130 meV, mechanically strong, chemically stable and have good adhesion to most of the substrate [86-88]. SnO_2 thin films deposited by DC magnetron sputtering on glass shows electrical resistivity of 4.3×10^{-2} Ω-cm with Hall mobility of 15 cm^2/V-s and carrier concentration of 2×10^{19} Ω-cm for ~150 nm thick thin films [87]. Amma *et. al.* reported on low electrical resistivity of 2.92×10^{-3} Ω-cm for 170 nm thick SnO_2 thin films [84] whereas Alhuthali *et. al.* reported on high optical transmittance of 66 nm thick SnO_2 thin films of ~94% at visible spectrum [86]. Study conducted by Yu *et. al.* shows very low electrical resistivity of 6.5×10^{-5} Ω-cm and optical transmittance of ~73% at ~470 nm with the multilayer structure of SnO_2/Cu/ SnO_2 [89]. Further investigation by Yu *et. al.* by using multilayer SnO_2/Ag/SnO_2 shows improved optical transmittance as high as 94.8% at ~470 nm and low electrical resistivity of 1.0×10^{-4} Ω-cm [90].

Although CdO is the first TCO thin films realized more than a century ago and have good electrical and optical transmittance characteristics, the CdO has a relatively narrow band gap and high toxicity. Despites the advantageous properties of ZnO especially for the application in short wavelength LED and LD, but the ZnO-based TCO degrade much faster than other TCO such as ITO when exposed to damp and hot environment. Even though the band gap energy of In_2O_3 is lower than the

SnO_2, a compound of both of them exhibit excellent electrical and optical properties. As compared to other TCO including CdO, ZnO, In_2O_3 and SnO_2, ITO is the predominant TCO used in optoelectronic devices due to the ease of its processing [55].

2.2.3 ITO-based transparent conductive electrode

ITO is preferred as a contact layer on optoelectronic semiconductor devices as it offers good electrical conductivity, highly transparent to visible light, high reflection in infrared region, strong absorption in UV region, mechanically hard, chemically inert transparent material and have good adhesion to GaN [91, 92]. The ITO also serves as a good current spreading layer when connected to the external potential for application in visible light emitting diode. The additional current spreading layer on p-GaN and n-GaN is important to achieve uniform current distribution and light emission. For top emitting InGaN LED structure, the top transparent conductive layer which acts as a window layer is important for efficient light extraction. Electrical current from the external potential is spread uniformly by the TCO layer to the active region through the p-type semiconductor layer consequently producing photon in term of visible light. This visible light is transmitted out through the transparent TCO contact layer without losing much of its intensity and optical spectrum to the contact layer.

ITO can be deposited on the substrates by many techniques including sol-gel processes [93, 94], thermal evaporator [95, 96], electron beam evaporation [97, 98], pulsed laser deposition (PLD) [99], RF/DC sputtering [100, 101], plasma enhanced chemical vapor deposition (PECVD) [102], metal-organic chemical vapor deposition

(MOCVD) [103] and atmospheric pressure chemical vapor deposition (APCVD) [104].

Many substrates have been used for ITO deposition depending on the application such as Si [105], Si (100) [106], p-Si (100) [107] glass [108-110], quartz glass [101, 111, 112], polyethylene terephtalate (PET) [106, 113], p-GaN [97, 114, 115] and n-GaN [116-118]. The ITO is widely used for applications including solar cells [119], flat panel display [120], gas sensor [121, 122], organic light emitting diodes (OLED) [123], GaN-based vertical light-emitting diodes (VLED) [124] and InGaN/GaN LED [125, 126].

Sol-gel method (or wet chemical method) offers several advantages including simplicity, low cost, easily controlled doping level, no need for vacuum in the deposition chamber and feasible preparation of large area films [94]. But this method involved wet chemical that need delicate processes. In addition, organic solvents used in this deposition process like ethylene glycol and ethanol are often flammable and harmful to the environment [93]. Thermal evaporation offer easy preparation for deposition, low cost of target material and less radiation damage to the substrates [105]. Electron beam evaporation has the advantages of low cost, high purity and high deposition rate [91]. However the evaporation process produces lower quality of thin films as compared to the sputtering methods due to the evaporation process itself. Sputtering method in turn, including RF and DC magnetron sputtering provides high deposition rate, large deposition areas, high purity of the target materials, clean deposition environment, low vacuum environment, controllable thin films stoichiometry, less damaged areas, good films adhesion, simplicity of the growth process, relatively low sputtering energy particle generation and high plasma density [127]. Although other thin films technique such as the chemical vapor