理學博士 學位論文

RF magnetron co-sputtering 방법을 이용한 다결정 MgZnO/ZnO 박막 트랜지스터의 연구

A study of polycrystalline MgZnO/ZnO thin-film transistor using the RF magnetron co-sputtering method



2013 年 8月

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本 論文을 李鍾勳의 理學博士 學位論文으로 認准함.



2013 年 8月

韓國海洋大學校 大學院



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Abstract

RIMEUN

최근 ZnO 기반의 트랜지스터 연구가 활발히 진행이 되고 있다. 이와 같은 이유는 저온 성장된 박막임에도 불구하고 1 cm²/Vs 이상의 높은 이동도를 가지며, 가시광영역에서 높은 광 투과성을 가지기 때문에 고성능의 투명전 자소자 개발을 가능하게 한다. ZnO 물질은 박막형 트랜지스터, 발광소자, 투 명전극, 수광소자, 가스센서, 태양전지 등 다양한 분양에 적용 가능하다. 다 양한 활용이 가능한 이유는 ZnO가 가지는 우수한 물성 때문이다. ZnO 는 3.37 eV 의 광밴드갭을 가지기 때문에 가시광영역에서 투명하다. 또한 Mg이 ZnO에 합금될 경우 광밴드갭이 늘어나기 때문에 UV 영역까지 발광소자 및 수광소자로써 활용이 가능하다. 또한 상온에서 60 meV의 여기자 결합에너 지를 가지고 있으며, 직접천이형 밴드갭이기 때문에 발광소자에 큰 각광을 받는 물질이다. 또한 박막형 트랜지스터에도 많은 연구가 진행이 되고 있다. 박막형 트랜지스터는 기존의 비정질 실리콘 기반의 디스플레이의 백플레인 소자를 대체하기 위한 연구가 활발히 진행이 되고 있다. 평판형 디스플레이 는 대면적화 고해상도, 뿐만 아니라 빠른 주파수를 요구함에 따라 기존의 비정질실리콘의 이동도로는 한계에 도달하게 되었다. 이를 해결하기 위해 LTPS (low-temperature polycrystalline silicon)이 필요로 하나 레이저 열처리



등의 후속 공정이 필요로 하게 되어 공정단가가 상승하며, 대면적화에 문제 가 제기되고 있기 때문이다. 하지만 ZnO 박막은 저온 성장한 박막임에도 불 구하고 기존의 비정질 실리콘의 이동도를 넘으며, 공정단가 또한 LTPS 공정 보다 저렴하며, 기존의 비정질 실리콘공정 기반시설을 이용할 수 있기 때문 에 산화물 기반의 트랜지스터를 디스플레이의 백플레인용 소자를 개발하기 위해 많은 연구가 진행되고 있다. 이와 같은 ZnO 기반의 전자소자를 구현하 기 위해서는 금속과 반도체 특성에 대한연구, 반도체 물질의 구조적 및 조 성에 대한 연구, 또한 절연체에 대한 연구가 필요로 하다. 또한 ZnO 기반의 트랜지스터를 스위칭 소자로 활용하는 방법에는 MISFET (metal-insulator-semiconductor field effect transistor) 으로 구현 가능하다. 이와 같은 박막형 트랜지스터를 디스플레이의 백플레인 소자로 활용하기 위 해서는 높은 이동도, 낮은 subthreshold swing, 해상력을 향상시키기 위한 높 은 ON전류 및 전력소모를 줄이기 위한 낮은 OFF전류를 가지는 소자가 요 구된다. MISFET 소자의 경우 절연체층이 필요로 하다. 절연체층의 특성요구 조건으로는 낮은 전압에서 작동가능하기 위해 높은 유전율 상수를 가져야 하며, 또한 낮은 누설전류를 가지며 피로파괴전압에 높은 저항성을 가지는 물질특성이 요구 된다. 또한 반도체에 캐리어를 주입하기 위해서는 오믹접 합 특성이 필요로 하다. 반도체 층 물질로써는 ZnO에 Mg이 첨가될 경우 밴 드갭 증가 및 자유전자의 캐리어를 감소시킨다. MgZnO의 경우 ZnO 기반의 산화물반도체에서 발생할 수 있는 산소공공에 의해 야기되는 소자의 불안정 성을 해결할 수 있는데 이와 같은 이유는 Zn-O 결합 보다 Mg-O 결합에너 지가 더 강하기 때문에 산소공공과 같은 결함 생성을 줄일 수 있다. 또한 ZnO 와 MgZnO 의 이종접합시에는 접합 경계면에 높은 전자 밀도를 형성이 가능하여 빠른 전자이동도를 얻을 수 있기 때문에 전자소자의 성능 향상을 가져 올 수 있다.

본 논문에서는 ZnO 와 Mg_xZn_{1-x}O를 이용한 박막형 트랜지스터에 대해서 연구 하였다. Mg_{0.3}Zn_{0.7}O와 오믹접합을 얻기 Ni/Au 와 Ti/Au 물질을 사용하 여 Mg_{0.3}Zn_{0.7}O 박막과 오믹접합을 확인하였으며 97.6 Ω·cm² 의 접촉비저항 을 얻었다. ZnO 박막에 Mg 합금 비율이 1 과 10 at.% 박막을 증착하여 Mg_xZn_{1-x}O 단 일 채널을 가지는 박막형 트랜지스터를 제작하였으며, Mg_xZn_{1-x}O-TFT 의 소 자 평가가 이루어 졌다. Mg 첨가량이 증가함에 따라 Mg_xZn_{1-x}O-TFT의 이동 도는 감소하였으며, SS 값도 ZnO에 비해 증가하였다.

ZnO와 Mg_xZn_{1-x}O 이종접합 박막형 트랜지스터가 제작하였으며, ZnO 박 막의 두께에 따른 소자 평가가 이루어졌다. Mg_xZn_{1-x}O/ZnO TFT는 ZnO-TFT 보다 빠른 이동도를 가지며, 낮은 SS 값을 가지는 트랜지스터의 제작이 가 능하였다. Mg_xZn_{1-x}O/ZnO TFT에서 ZnO 박막의 두께는 ~10 nm 일 때 가장 우수한 특성을 보이는 것을 확인하였다. 또한 ZnO, Mg_xZn_{1-x}O, Mg_xZn_{1-x}O/ZnO TFT의 게이트 바이어스 스트레스 측정 및 히스테리시스 측 정을 통해 소자의 신뢰성을 평가 하였다. Mg_xZn_{1-x}O/ZnO TFT 이종접합으로 제작된 트랜지스터는 게이트 바이어스 스트레스 실험에서 ZnO 소자보다 낮 은 전류 이동특성 및 낮은 히스테리시스 폭을 보이는 것을 확인하였다.

마지막으로 MgO박막을 절연체로 하는 ZnO 트랜지스터를 제작 하였다. MgO 경우 9.8의 유전체 상수를 가지기 때문에 저 전력의 소자로 기대할 수 있다. MgO 경우 증착 중 산소분위기 비율을 달리 하여 증착하였으며, 산소 분위기가 증가함에 따라 유전체 상수가 11.35 까지 증가하는 것을 확인 하 였다.

KEY WORDS: ZnO 산화아연; MgZnO 산화마그네슘 아연; Thin film transistor 박막 형 트랜지스터; Heterojunction 이종접합



Chapter 1. Introduction

The ubiquity of information access and transmission, and the greater use of a wider range of devices have revealed the importance of lightweight and flexible display terminals. ZnO-based materials are promising for use in the next generation of transparent and flexible electronic devices because they can be cheaply grown at low temperature; they are also highly transparent at visible wavelengths [1–4].

The superior properties of ZnO lend it applicability in diverse devices such as thin film transistors (TFTs), light-emitting diodes (LEDs), transparent electrodes, photo detectors, gas sensors, and solar cells [5, 6]. Visible transparency arises from a material having an optical band gap (Eg) greater than 3.1 eV. ZnO has a suitable optical band gap of 3.37 eV [7]. This can be increased through the incorporation of Mg, making the material suitable for use in LEDs or photodiodes with expanded ultraviolet wavelengths [8]. ZnO is potentially applicable in LEDs due to its high exciton binding energy (60 meV) and direct band gap [8-10]. ZnO-based TFTs are of interest due to their potential use in flexible and lightweight display devices. ZnO materials are expected to have varied applicability across a range of electronic devices. Efforts to overcome the drawbacks of conventional amorphous silicon (a-Si)-based TFTs-which are currently used in such as backplane devices to control each pixel of a flat panel display-have included the development of oxide semiconductors, with ZnO-based TFTs appearing particularly attractive [11]. Flat panel displays require high resolutions and high frequencies over large areas, and the mobility of conventional a-Si TFTs has reached its limit [12]. To solve this problem, low-temperature polycrystalline silicon (LTPS) could be used, but it requires additional post-fabrication processing such as laser crystallization that increases the cost of the material [2]. However, ZnO-based transistors with mobilities greater than those of a-Si TFTs can be fabricated by growing ZnO film at low temperature. The fabrication of ZnO TFT-based backplane devices would be simpler and cheaper than that of comparable LTPS-TFT-based devices.



Switching in ZnO-based TFT devices can be achieved using metal-insulator semiconductor field-effect transistors (MISFETs). The ZnO layer in a TFT acts as a channel for current flow. Its conducting properties can be modified by doping. For example, the substitution of Zn^{2+} with In^{3+} creates free electrons that will increase electronic conductivity [13]. Defects such as oxygen vacancies and interstitial Zn can also generate free electrons. Multi-component ZnO-based TFTs have also been studied; e.g., TFTs have been fabricated using indium zinc oxide (IZO), zinc tin oxide (ZTO), and gallium indium zinc oxide (GIZO) [14-16]. In polycrystalline silicon, electrons move across the p-orbital. Amorphous GIZO has high electron mobility through the superposition of the s-orbital of the (n-1)d10ns0 $(n \ge 4)$ [17, 18]. The high conductance of the channel layer causes high off-current and negative on-voltage; it can be reduced through lowering the carrier concentration to <10¹⁵ cm⁻³ or controlling the thickness of the channel layer. IZO and ZTO TFTs have shown instability and high conductance; therefore, a suppressor such as Mg, Ga, Hf, or Zr is required to control carrier concentration and to suppress oxygen vacancies in the channel layer [19-22]. However, such multi-component materials are difficult to control precisely, and small differences of composition ratio can greatly affect a device's electrical properties. Additional components (e.g., In and Ga) can be rare and expensive; the avoidance of such materials in high-mobility alternative materials such as ZnO poly-crystal structures, which can be easily grown at room temperature, makes them particularly attractive [23]. The incorporation of Mg into ZnO increases its optical band gap, and the use of MgZnO can reduce oxygen vacancies caused by gate bias stress because the binding energy of Mg-O is stronger than that of Zn-O. The increased band gap of MgZnO thin films allows the formation of MgZnO/ZnO heterostructures with fast electron transfer at the interface. At the heterojunction of Mg_{0.15}Zn_{0.85}O and ZnO, the band-gap offset ratio of $\Delta E_{\rm C}/\Delta E_{\rm V}$ is about 3/2 to 7/3 [24]. Two-dimensional electron gas (2DEG) has been reported to generate high electron density at the junction interface of MgZnO/ZnO epitaxial thin films grown by molecular beam epitaxy (MBE) or pulsed laser deposition (PLD) [25-27]. 2DEG can be used to form III-V



semiconductors such as AlGaAs-GaAs and AlGaN-GaN into high-electron-mobility transistors (HEMTs) [28]. The use of 2DEG with MgZnO/ZnO has been reported, but only in a few studies. This work reports the characteristics of MgZnO/ZnO heterojunctions implemented in high-speed electronic devices. Commercial devices require simple and consistent fabrications methods; therefore, assessment of the deposition technique is necessary. Sputtering can yield uniform ZnO thin films over large areas. ZnO and MgZnO thin films deposited by sputtering should be characterized in addition to the fabricated device, and any problems identified in the heterojunction structure should be investigated and resolved. ZnO deposited by radio-frequency (RF) sputtering is generally polycrystalline at low temperatures [29]. In the case of MgZnO/ZnO thin films, a consistent RF sputtered poly-crystal structure is difficult to achieve due to the effects of the 2DEG. However, MgZnO/ZnO heterostructures with enhanced electrical properties have been achieved by the screening of defects and grain boundary potential to achieve a large number of carriers induced by polarization effects [30-32]. Electron gas in the quantum well-which is triangular due to spontaneous polarization and piezoelectric polarization-of heterojunction devices can have sufficiently high electron mobility and density for application in next-generation displays and high-frequency wireless communication devices. Much research has focused on conventional AlGaN-GaN and AlGaAs-GaAs heterojunctions, while MgZnO/ZnO heterojunction devices remain comparatively less well explored. If MgZnO/ZnO-based high-mobility electronic devices were sufficiently developed, their commercialized would be rapid because ZnO and its processing offer many advantages. The 2DEG in a heterojunction transistor can reduce the power consumption of devices because such devices can be depleted easily using a small gate voltage. The electron pathway formed at the heterojunction interface decreases electron traps and scattering, and so allows the stability to be improved. Devices are also likely to operate at high frequencies with low noise and quick signal responses [33].

To achieve effective ZnO-based devices, their various aspects must be studied and optimized. These include the junction interface between the metal and the semiconductor, the fabrication of channel materials and their structures, and the insulator layer. Silicon dioxide (SiO₂) films made by the thermal oxidation of silicon wafers have very smooth surfaces among the commercially available materials. A smooth surface is important for thin-film transistors because it reduces electron scattering. TFTs formed on SiO₂/Si substrates are useful for the evaluation of channel performance over a wide range of gate voltages, regardless of the gate leakage current. SiO₂ thin film can endure several tens of gate voltage with low leakage current. The insulator in a MISFET device needs a low leakage current and a high dielectric constant. The conventional insulators used with SiO₂ and/or SiN_x materials are deposited by chemical vapor deposition. However, if insulators could be deposited by RF sputtering, the fabrication process would be simplified. MgO can be deposited by RF magnetron sputtering; it has a high dielectric constant of about 9.8 [34].

This dissertation investigates the characteristics of thin-film transistors with singleand bi-layer channels formed with ZnO, $Mg_xZn_{1x}O$, and $Mg_xZn_{1x}O/ZnO$. The possibility of using RF-magnetron-sputtered MgO as an insulator was also studied. The first chapter reviews literature reporting the applications of oxide TFTs and the properties of ZnO, MgO, and MgZnO materials. The second chapter presents the physical, optical, and electrical properties of ZnO, $Mg_xZn_{1x}O$, and $Mg_xZn_{1x}O/ZnO$ heterostructures. The experimental methods are also described. This chapter also reports the ohmic contact properties of $Mg_{0.3}Zn_{0.7}O$ with Ni/Au, Ti/Au, Al, and In/Au metals. TFTs of ZnO, $Mg_xZn_{1x}O$, and $Mg_xZn_{1x}O/ZnO$ are described in this chapter. The effects of deposition time on ZnO thickness and the heterostructures of $Mg_xZn_{1x}O/ZnO$ TFTs are also reported here. The third chapter explores the MgO insulator. MgO layers were deposited by RF magnetron sputtering using different oxygen concentrations in the inert gas. The dielectric constant was investigated for capacitance–voltage measurements. A ZnO TFT with MgO insulator was also



fabricated and characterized. The final chapter contains the conclusion and summary of this dissertation.





1.1 Oxide TFT application

In the last decade, metal-oxide semiconductors have attracted considerable attention for the next generation of flat-panel backplane displays. Because of the demands associated with flat panel displays, the need for flexible, transparent displays that can be manufactured using low-temperature processes at low cost has continually increased [35, 36]. First, oxide materials have high transparent due to the high energy band gap > 3.1 eV. Second, oxide materials can be deposited at low process temperature. This means that the flexible substrate like as plastic material can be used for substrate. Third, oxide TFTs have high mobility, although amorphous structure. The display is developing for large size and high resolution, thus the high mobility is required.

There are some of requirements for achieving a high-performance flexible display: e.g., (i) stable and uniform phase, (ii) high carrier mobility (> 10 cm²/Vs), (iii) low carrier concentration ($<10^{15}$ cm⁻³), (iv) the uniformity of thin film under at low temperature [2].

Figure 1.1 shows the application of new functional display with oxide TFT for smart windows, concept of transparent mobile phone, E-paper, and flexible, bendable, and foldable displays.

What is the world you dream ? Fransparency + + + + + Commercy + + Commercy + Commercy + Commercy + Commercy + Commercy Com

Fig. 1.1 Application of newly functional display with oxide TFTs



1.2 Comparison of Oxide-based TFT with Si-based TFT

The basic function of TFT is switch. The display devices are essentially required the switching device to control the on/off at the each pixels. The thin film transistor used in the current display is amorphous silicon (a-Si)-TFT. Although conventional a-Si TFT has low mobility ($< 1 \text{ cm}^2/\text{Vs}$), this devices have good uniformity and high reproducibility. In order to obtain a high mobility, the phase of silicon has to poly crystal state, additional process is required such as excimer laser annealing (ELA). However, oxide TFT has not only high mobility but low process cost. Compare to low temperature poly-silicon, the oxide-based TFT is simple process and it is able to use the conventional a-Si TFT line. Comparison of oxide-based TFT with Si-based TFT has shown in table 1.1.

 Table 1.1 Comparison of oxide-based TFT with Si-based TFT for number of process step, cost, mobility, and etc [37]

	ITEM	ELAp-Si	Non-laser p-Si TFT	μc-Si	a-SiTFT	Oxide TFT
Mobility (cm ² /Vs)		50~200 50	20~100	1~20	0.5~1	~100
TFT type		PMOS, CMOS	PMOS, CMOS	0 NMOS	NMOS	NMOS
TFT uniformity		Worse	Medium	Better	Better	Better
Process Step		PMOS : 5~6 CMOS : 9~10	PMOS : 5~6 CMOS : 9~10	5~6	4~5	4~5
Equipment investment		High	Medium	Low	Low	Low
Compatibility with a- Si TFT line		Not	Medium	ок	OK	OK
	TFT	High	Medium	Low	Low	Low
cost	Module	Low (Integrated Driver)	Low (Integrated Driver)	High (non- integrated)	High (non- integrated)	Medium (non- integrated)
	Total	Profitable (small size panel)	Medium	High (Large size panel)	High (Large size panel)	Profitable (Large size panel)
Cu	rrent Stability	Stable	Stable	Stable	Unstable	777



1.3 Metal oxide material

There are transparent materials to use for the semiconductor such as ZnO, SnO₂ , and In₂O₃ [38]. These materials had initially developed for transparent conduction oxides (TCOs). The oxide materials can be alloyed each other for high transparency and high electrical conductivity. For example, an indium tin oxide (ITO; In₂O₃:SnO₂ = 90%:10% ratio) was used widely for transparent electrode at the solar cells, flat panel displays, and other commercial devices. There are other compositions such as, ZnO-In₂O₃(IZO) and ZnO-SnO₂(ZTO) [13]. The electrical conductivity of IZO and ZTO material is high. Moreover these materials easily form the amorphous phase at the low temperature growth condition. The electrical properties of the IZO and ZTO are unstable at the operation of devices with gate voltage biased. In addition, the carrier concentration is high, it is unsuitable to apply as the channel material. The number of carrier concentration has to control [37].

In 2004, the Nomura group [39] reported the amorphous structure of an indium-gallium-zinc-oxide material that incorporated quaternary elements as a channel layer; the mobility of the TFTs fabricated using this material was reported as over 10 cm²V⁻¹s⁻¹. Following this study, the use of multi component elements to create the channel layer was actively investigated. If the *ns*-orbitals ($n \ge 4$) overlap, the mobility is known to be high, even if the crystal is amorphous. As shown in Fig. 1.2, the electrons can move along to the *ns*-orbitals. However, some studies used Sn to replace the expensive indium elements and found that mobility values of a few cm²V⁻¹s⁻¹ could be achieved [36, 40, 41].

For improved stability, TFTs incorporating Mg, Hf, Ga, or Zr in a ZnO-based active layer have been reported to reduce the voltage shifts produced by bias stress because of a strong binding energy with oxygen that reduces the number of oxygen vacancies [19, 42-44]. In a similar study, Jeong et al. [45] reported that improved stability resulted from the Ga doping of zinc tin oxide. Ga ions have stronger binding energy than Zn, which decreases the number of oxygen vacancies, and as a result, electron traps at the active layer and/or between the insulating and the active



layers are reduced [45].

Table 1.2 shows the standard electrode potential (SEP). The value of Mg is -2.37 E^{o}/V , this means that the combine of Mg-O does not easily lose oxygen and Mg can be oxidized more easily than Zn-O. At the Mg incorporation into the ZnO thin films, the electron traps generated by oxygen vacancy can be reduced, thus the stability of thin film transistor will be improved.



Fig. 1.2 Schematic orbital drawing for (a) covalent semiconductors (b) post-transition-metal oxide semiconductors [39]



Oxidant	E°/V
Sn (n=5)	-0.14
In (n=5)	-0.34
Zn (n=4)	-0.76
Ga	-0.56
Zr	-1.45
Hf roll	-1.55
Mg	-2.37
1115 04	

Table 1.2 Standard electrode potential (SEP) for adatoms



1.4 Physical properties of ZnO and MgO

ZnO and MgO materials are II-VI binary compound semiconductor. Most of this group crystallized in either hexagonal wurtzite or cubic zinc blende structure as shown in the Fig 1.3. The ZnO normally form in the hexagonal crystal structure with a = 3.24 Å and c = 5.12 Å. The Zn atoms are tetrahedrally coordinated to four O atoms, where Zn *d* electrons hybridize with the O *p* electrons [46].

MgO materials generally is rock salt structure which is often the most stable form for highly ionic solids, and has been prototype for experimental and theoretical studies of neutral and polar oxide surfaces. The structure consist of two interpenetrating fcc lattices of oxygen anions and metal cations in a +2 oxidation state, making these oxides even more ionic than prototypical ionic NaCl. The lattice constant of MgO is a = 4.21 Å.



Fig. 1.3 The crystal structure (a) cubic rock salt, (b) cubic zinc blende, and (c) hexagonal wurtzite structure [46]



The ZnO typically has the hexagonal wurtzite structure in which each Zn or O atom is surrounded by four neighbors of the other type [46]. The band structure of ZnO for zinc blende phase is shown in Fig. 1.4. The band gap width is 3.37 eV and direct, and the conduction band minimum is again a single broad minimum formed from Zn *s* states [7, 47]. The band gap of ZnO can be tuned via divalent substitution on the cation site. For example Mg substitution leads to an increment in the band gap up 4.0 eV while still maintaining the wurtzite structure. Contrastively, Cd substitution caused a reduction in the band gap to ~ 3.0 eV [48].



Fig. 1.4 Band structure for ZnO [47]



The properties of ZnO are summarized in Table 1.3. Table 1.4 shows the properties of MgO. The band gap of MgO is 7.8 eV and the dielectric constant is 9.83. This material can be used for gate insulator due to wild band gap and high dielectric constant.

Properties	Value	
Lattice parameter at 300K	0.20405	
ao	0.32495 nm	
	0.52069 nm	
Co	1.602 (ideal value = 1.6333)	
<u>co/ao</u>		
u	0.345	
Density	_5.606 g/cm ³	
Stable phase at 300K	Wurtzite	
Melting temperature	1975 °C	
	$a_0: 6.5 \times 10^{-6}$	
Linear expansion coefficient (/*C)	c_0 : 3.0 x 10 ⁻⁶	
Static dielectric constant	8.656	
Refractive index	2.008, 2.029	
Energy gap	3.4 eV, direct	
Intrinsic carrier concentration	$<10^{6} \text{ cm}^{-3}$	
Exciton binding energy	60 meV	
Electron effective mass	0.24	
Electron Hall mobility at 300K for	200 cm ² /Vs	
n-type conductivity		
Hole effective mass	0.59	
Hole Hall mobility at 300K for low	0.35	
	$5-50 \text{ cm}^2/\text{Vs}$	
p-type conductivity		

Table 1.3 Properties of ZnO material [5]



Properties	Value
Lattice constant	a = 0.4216 nm
Crystal structure at 300K	cubic rock salt
Band gap energy	7.8 eV
Density State	3.576 g/cm^3
Melting point	2.852 °C
Boiling point	3,600 °C
Thermal conductivity at 300K	$45-60 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$
Refractive index	941.736
Dielectric constant	9.83
Linear expansion coefficient (/°C)	10.5×10^{-6}

Table 1.4 Properties of MgO material



1.5 Application of ZnO

Since the ZnO has direct and wide band gap, it is suited to application in blue and UV optical devices. Moreover, the ZnO optical device was expected more effective to the emitting efficiency than to the GaN optical devices because the ZnO has large exciton binding energy about 60 meV (GaN; ~22 meV) [8, 49].

The ZnO has large piezoelectric constant, it is able to adopt for voltage generates, sensors, transducers and actuators. Since the ZnO has the strong sensitivity of surface conductivity to the presence of adsorbed species, it can be used for sensor devices [50].

The ZnO can be applied for making transparent electric devices. The ZnO easily shows the n-type electrical properties due to the defect such as oxygen vacancy and/or interstitial zinc ion. Highly doped ZnO thin film with trivalent cation shows a high electrical conductivity, and it is able to apply for transparent conducting oxide. This material has some of advantage such as, a possibility of synthesis from solution method, availability of large single crystals, and amenability to wet chemical etching, and abundant resources, as shown in Fig. 1.5 [51].



Fig. 1.5 Properties of ZnO material



1.6 Properties of MgZnO

Mg_xZn_{1-x}O thin film is essential to make a heterostructure with ZnO thin films. Moreover Mg incorporation into the ZnO can be tuned the optical band gap for using optical devices to emit or to receive the light. The Mg_xZn_{1-x}O alloys with the wurtzite structures and the magnesium molar fraction as large as 40% makes it possible to fabricate heterojunction and adjust the bandgap in the range from 3.2 to 4.0 eV. The conduction band off-set (ΔE_C) and the valence band offset (ΔEv) ratio is between 3/2 ~ 7/3 at Mg_xZn_{1-x}O/ZnO (15 at.%) heterostructure [24]. The increase of ΔE_C causes increase of activation energy, therefore the number of free electron will be decreased.

The theoretical formation energy of oxygen vacancy in MgO (rock salt) and ZnO (wurtzite) are 5.8 eV and 3.1 eV, respectively. The standard electrode potential of Mg is -2.37 E^{O}/V , while Zn is -0.76 E^{O}/V . The Mg-O bind does not form easily the oxygen vacancies and Mg could be more easily oxidized than ZnO. Firstly principles calculations shown that the oxygen vacancy in ZnO has the lowest formation energy among the donor-like defects with deep electronic state. We speculate that the Mg incorporation into the ZnO could be reduced the formation of oxygen vacancies. Generally, the oxygen vacancy in the ZnO is in the neutral state (Vo). However, under negative gate voltage, the band bending can crease the electron depletion region in the TFT active layer. In this case, the V_O could be excited to doubly the ionize state (Vo²⁺) and releases electrons into the conduction band. Mg might be a good candidate to suppress the oxygen vacancy in the ZnO átive layer. Moreover, the Mg²⁺ substitution in the Zn²⁺ site does not cause large lattice distortion because of their similar ionic radii (Zn²⁺: 0.60 Å and Mg²⁺: 0.57 Å).



1.7 Heterostructure of MgZnO/ZnO thin films

The ZnO material due to having a wide band gap (3.37 eV) that can be changed from 3.0 to 4.0 eV by using doping method with Mg and Cd atom into the ZnO material. The quantum-confinement effects have shown at the MgZnO/ZnO and ZnO/CdZnO heterostructure in the conduction band offset as shown in Fig. 1.6. Especially, the application to the high electron mobility transistor (HEMT) by using electron transport properties of a 2-dimensional electron gas (2DEG) has been studied. Figure 1.7 shows the (a) 2DEG concentration and (b) Hall mobility of ZnO/MgZnO single heterostructure depend on temperature [26]. The 2DEG can be The polarization mismatch between the MgZnO/ZnO described as follows. heterojunction structures from the interfaces of the junction causes the positive charge which induces the polarization, and the 2DEG is formed at the ZnO junction interface. The experimental results showed a strong dependence of the mobility by the 2DEG concentration. At the theoretical results, the interface roughness scattering (IRS) is the major cause of the scattering at high electron concentration. Recently, A Thongnum et al. theoretically investigated the MgZnO/ZnO junction roughness effects by considering the concentration of positively charged electron and the polarization-induced built into the model, and the 2DEG mobility was affected by the effect of scattering electrons which used the model of the roughness-induced fluctuation of the in-plane direction.

In particular, the formation of a 2DEG in a high electron mobility transistor can improve the mobility properties for high speed. Both the ZnO and the MgZnO derive the spontaneous polarization. The experimental results about the MgZnO spontaneous polarization is not reported, while the theoretical and experimental results about the phenomenon of spontaneous polarization are reported. However, the amount of MgZnO spontaneous polarization is larger than ZnO, and it can be estimated with increasing by the increasing amount of Mg. Therefore, if the Oxide face of the MgZnO, the ZnO is Zn face, the 2DEG would be formed only single heterojunction interface. The simulation results reported for modulation doping and



polarization effects at the polycrystalline MgZnO/ZnO thin film in the 2010 [30, 31]. At this results, the Modulation doping structure have shown a high mobility to suppress the impurity potential and grain boundary potential in spite of the polycrystalline of the ZnO layer. Although MgZnO/ZnO heterostructure have polycrystalline, it shows the enhancement in electrical properties for screening of defects and grain boundary potential by a large number of carriers induced by the polarization effect [30, 32].



Fig. 1.6 A calculating band offsets of MgO/ZnO heterostructure at wurtzite structure





Fig. 1.7 (a) 2DEG concentration and (b) Hall mobility of ZnO/MgZnO single heterostructure [26]



1.8 Evaluation of performance for MISFET

1) Field effect mobility

The field effect mobility is determined by measuring of the transconductance (g_m) , defined by

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} | V_{DS} = constant \tag{1.1}$$

The drift component of the drain current with $Q_n = C_{ox}(V_{GS-}V_T)$ is

$$I_D = \frac{W}{L} \mu_{eff} C_{ox} \left(V_{GS} - V_T \right) V_{DS}$$
(1.2)

When the filed-effect mobility is determined, the transconductance is usually taken to be

. DITIME

$$g_m = \frac{W}{L} \mu_{eff} C_{ox} V_{DS}$$
(1.3)

When this expression is solved for the mobility, it is known as the field-effect mobility

$$\mu_{FE} = \frac{Lg_m}{WC_{ox}V_{DS}} \tag{1.4}$$

2) Saturation Mobility

Sometimes the MOSFET mobility is derived from the drain current-drain voltage curves with the device in saturation. The saturation drain current can be expressed



$$I_{DS,sat} = \frac{W\mu_{sat}C_{ox}}{2L}(V_{GS} - V_T)^2$$
(1.5)

When this equation is solved for the mobility, this mobility called the saturation mobility, is

$$\mu_{sat} = \frac{2Lm^2}{WC_{ox}} \tag{1.6}$$

where *m* is the slope of the $\sqrt{I_{DS,sat}}$ versus (V_{GS} - V_T) plot.

3) Threshold voltage

The threshold voltage can be estimated from $\sqrt{I_{DS,sat}}$ versus $(V_{GS}-V_T)$ curve at $V_{DS} > V_{GS}-V_T$ (saturation region). The V_T are obtained by plotting $\sqrt{I_{DS,sat}}$ as a function of V_{GS}. For $V_{GS}-V_T$, this curve would become linear and the x-intercept gives V_T .

4) Subthreshold swing

Subthreshold swing (SS) is the slop of linear increased region at the $log(I_{DS})$ verse V_{GS} curve. It is typically expressed by the inverse subthreshold slope given by the equation:

$$SS = \frac{dV_{GS}}{d(\log I_{DS})} \tag{1.7}$$

The large SS values indicates a large trap density (N_t^{max}) of tail states because the SS value is related to trap density by the equation:

$$N_t^{\max} = \left[\frac{SSlog(e)}{kT/q} - 1\right]\frac{C_i}{q}$$
(1.7)

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where k is Boltzmann's constant and C_i is the gate insulator capacitance.

5) On-off current ratio

 I_{ON}/I_{OFF} ratio is derived from maximum I_{DS} and minimum I_{DS} ratio at the I_{DS} verse V_{GS} curves. For higher resolution displays, TFT are required to have a large on current to drive imagine pixels and a small off current to reduce the power consumption [52]. Consequently, the TFT have to large on-off current ratio.





1.9 TFT structures and princess

Figure 1.8 shows four basic structures of thin film transistor according to the position of the electrodes, channel layer, and the insulator. Staggered structure is that source and drain contacts are placed on the opposite side of the gate. Coplanar structure is that all electrodes are located on the same side of the active. For batter control of the channel layer, coplanar bottom-gate structure (invert) has been proposed. According to the gate position, the structures of TFTs are called top-gate or bottom-gate [52].

Figure 1.9 shows ideal energy band diagrams for a n-type devices as viewed through the gate biasing conditions. The energy band diagram under flat band, 0 V applied to the gate, source, and drain, has shown in Fig. 1.9 (a). Figure 1.9 (b) shows an energy band diagram under the positive gate bias ($V_G > 0$ V). The applied positive potential attracts the mobile electrons in the channel layer, forming an accumulation region near the insulator-channel interface. This accumulation region leads to an increase of conductance in the channel layer. Figure 1.9 (c) shows an energy band diagram under negative gate bias ($V_G < 0$ V) in n-type channel layer. The applied negative potential repels the mobile electrons from channel layer, leaving depletion region near insulator-channel interface. The conductance under depletion condition is higher than under equilibrium condition due to the reduced mobile electrons in the channel layer [53].





Fig. 1.8 TFT structures (a) staggered bottom-gate (invert), (b) coplanar bottom-gate (invert), (c) staggered top-gate, and (d) coplanar top-gate [52]




Fig. 1.9 Energy band diagrams for a n-type devices under (a) flat band (equilibrium), (b) accumulation ($V_G > 0$ V), and (c) depletion ($V_G < 0$ V) conditions



Chapter 2. MgZnO and Mg_xZn_{1-x}O/ZnO MISFET

2.1 Experiment method

2.1.1 Deposition of ZnO and Mg_xZn_{1-x}O thin films

 $Mg_xZn_{1-x}O$ alloy films were deposited by RF magnetron co-sputtering onto thermally oxidized silicon substrates, as shown in Fig. 2.1. Silicon substrates yield a resistivity of 0.005 Ω cm in conjunction with an *n*-type carrier. The co-sputtered commercial targets, ZnO and Mg_{0.3}Zn_{0.7}O (4 inches in diameter, Mg/Mg+Zn, 30 at.%), had purities of 4N (99.99%). The SiO_2/Si substrate was cleaned with acetone, methanol, and de-ionized water in an ultrasonicator for 5 min. The cleaned substrate was positioned in the sputtering chamber. The base pressure was less than 10^{-6} Torr, and the work pressure was 5 mTorr. Argon gas was introduced at a flow rate of 20 sccm, controlled by a mass flow controller. The ZnO and MgZnO targets were sputtered at 300 °C. The RF-power of the ZnO target was 100 W, which remained unchanged, whereas the power applied to the MgZnO target was set to 50 or 100 W. The deposition condition is summarized in Table 2.1. For convenience, each Mg_xZn_{1-x}O alloy sample is numbered as follows, as shown in Table 2.2: the ZnO (100 W) TFTs co-sputtered with MgZnO (50 or 100 W) are designated MZO50 and MZO100, respectively. The using single ZnO (100 W) or MgZnO (100 W) targets are designated ZnO and MgZnO, respectively.





Fig. 2.1 Schematic representation of RF magnetron co-sputtering system









Sample name	Deposition Conditions
ZnO	Single ZnO target
MZO50	ZnO 100W + Mg0.3Zn0.7O 50W
MZO100	ZnO 100W + Mg0.3Zn0.7O 100W
MgZnO	Single Mg _{0.3} Zn _{0.7} O target
of of th	

Table 2.2 The sample names according to the deposition conditions



2.1.2 Fabrication of TFT devices

The flow chart for process steps was shown in Fig. 2.2. First, the n^+ -type silicon wafer was cleaned with acetone, methanol, and de-ionized water, sequentially. The native oxide on the silicon wafer was removed by diluted HF solution.

Second, the cleaning single crystal silicon wafer was located on the center position of horizontal furnace. The wafer was oxidized with O_2 gas at 900 °C. The thickness of SiO₂ thin films grown for 10h was confirmed about 60 nm by transmission microscopy.

Third, ZnO, $Mg_xZn_{1-x}O$, and $Mg_xZn_{1-x}O/ZnO$ materials are deposited on the SiO₂/Si substrate by using an RF magnetron co-sputter system. The thickness of ZnO and $Mg_xZn_{1-x}O$ were controlled by deposition ratio.

Forth, the ZnO and $Mg_xZn_{1-x}O$ were selectively etched with diluted HCl solution for channel patterns.

Fifth, the samples were patterned by photolithography to form source and drain pads. Ti (10 nm) and Au (100 nm) layers were deposited using an e-beam evaporation system to form electrodes.

Sixth, the gate metal was silver, which was deposited on the back side of the silicon substrate.

Seventh, the TFTs formed on SiO₂/Si were measured by using semiconductor parameter analyzer such as, HP4145B and Keithley 4200-scs.

Figure 2.3 (a) shows an image of the source and drain electrodes on a MgZnO/SiO₂/Si TFT, as measured by using optical microscopy. The channel width and length were 100 μ m and 10 μ m, respectively.

Figure 2.3 (b) shows a schematic diagram of a $Mg_xZn_{1-x}O$ -TFT top contact and bottom-gate structure. The single layer $MgxZn_{1-x}O$ -TFTs were formed on the SiO₂ thickness about 90 nm.

Figure 2.4 shows (a) MZO50/ZnO and (b) MZO100/ZnO heterostructure. The

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thicknesses of SiO_2 are 70 nm (MZO50/ZnO) and 40 nm (MZO100/ZnO), respectively. The difference of SiO_2 thickness was contributed to thermal oxidation condition.



Fig. 2.2 Flow charts of the ZnO and MgZnO TFT devices for process





Fig. 2.3 (a) Top view image of MgZnO-TFT measured by optical microscopy (b) Schematic diagram of the MgZnO TFT structure





Fig. 2.4 Schematic diagram of the (a) MZO50/ZnO TFT structure and (b) MZO100/ZnO TFT structure



2.2 Results and discussion

2.2.1 Evaluation of MgZnO thin films

2.2.1.1 Structure properties

Figure 2.5 shows X-ray diffraction patterns from ZnO, MZO50, and MZO100 films on SiO₂/Si substrates. Rather than growing epitaxially, the films were deposited on the amorphous substrates. The ZnO (002) peak was 34.35° whereas the MZO50 and the MZO100 samples displayed hexagonal (*h*)-MgZnO (002) peaks at 34.35° and 34.45°, respectively. In general, Mg-doped ZnO (002) peaks appeared beyond 34.4° (which was shifted relative to the 34.65° peak observed for the single MgZnO target, not shown here) as a result of the ionic radius difference between Zn^{2+} (0.60 Å) and Mg²⁺ (0.57 Å) [54]. As the power applied to MgZnO was increased, the *h*-MgZnO (002) peaks showed preferential growth in the *h*-MgZnO (002) direction without inducing formation of a rock-salt structure (MgO), which would have resulted in phase separation. Other peaks corresponding to MgZnO-ZnO were not observed in the XRD results. Moreover, the ZnO, MZO50, and MZO100 thin layers had the full widths at half maxima (FWHM) of 0.38, 0.38, and 0.47°, respectively, which values were fitted by using a Gaussian.

Figure 2.6 shows the Θ -2 Θ measurement results of MZO50/ZnO hetero-structure on the SiO₂/Si substrate. The MZO50/ZnO thin films shows 2 Θ = 34.3 ° at the all samples, which peaks are correspond with (002) out plan direction of hexagonal wurtzite ZnO or MgZnO. The full width at half maximum (FWHM) of the (002) peak of those thin film have similar values about 0.4 °. In this result all sample are not shown with phase separation or defect related peaks. The XRD results evaluate that all samples have shown with similar crystallinity.

To evaluate the crystallinity, we measured the X-ray rocking curves. Figure 2.7 (a) shows the X-ray rocking curves of the ZnO, MZO50 and MZO100 peaks for all samples and the FWHM values for (002) peaks. Comparing the FWHM values for samples the ZnO, MZO50 and MZO100, the FWHM values calculated at the



rocking curves method have similar values at the ZnO(002) and Mg_xZn_{1-x}O(002) peaks. These are ~ 2700 arcsec. This result means that the crystallinity of the co-sputtering MgZnO thin films has similar compare with the ZnO thin films. The reason of similar FWHM values are because ionic radii differences between Zn^{2+} (0.60 Å) and Mg²⁺ (0.57 Å) is small.

Figure 2.7 (b) shows the X-ray rocking curves of the MZO50/ZnO(10nm) and MZO100/ZnO(10nm) bi-layer samples. The FWHM values for the MZO50/ZnO (002) peaks are 2608 arcsec and for the MZO100/ZnO (002) peaks are 2636 arcsec, respectively. These values are slightly small values, as compared to previous single layer. The bi-layer thin films show the more improvement of crystallinity than single layer thin films due to a using thin ZnO layer.



Fig. 2.5 XRD θ -2 θ results for ZnO, MZO50, and MZO100 alloy films





Fig. 2.6 XRD 0-20 results ZnO and MZO50/ZnO alloy films





Fig. 2.7 XRD rocking curves taken from (a) single layer and (b) $Mg_xZn_{1-x}O/ZnO$ bi-layer



The surfaces of the ZnO, MZO50, and MZO100 films on the SiO₂/Si substrates were investigated by using AFM measurements. The surface of the Mg_xZn_{1-x}O alloy film reveals grain-shaped islands as shown in Fig. 2.8. The grain sizes of ZnO, MZO50, and MZO100 are 80.6, 70.6, and 79.5 nm, respectively. The value of the root-mean-square (RMS) roughness is from 2.7 nm to 3.2 nm. At the AFM results, the surface images are similar as compare with ZnO and Mg_xZn_{1-x}O thin films.

Figure 2.9 shows AFM results of MZO50/ZnO(10nm) and MZO100/ZnO(10nm) bi-layer thin film. The surface is similar with single layer of ZnO and Mg_xZn_{1-x}O. The grain sizes of MZO50/ZnO(10nm) and MZO100/ZnO(10nm) are 77.1 and 78.9 nm, respectively. The RMS roughness of MZO50/ZnO is 2.8 nm, while MZO100/ZnO is 3.2 nm over 2 x 2 μ m².

The recorded SEM images (50,000 x magnifications) of all the $Mg_xZn_{1-x}O$ samples deposited at different co-sputtering power onto the SiO₂/Si substrate are shown in Fig. 2.10. The all $Mg_xZn_{1-x}O$ thin films have shown the grain-shaped islands







Fig. 2.8 AFM image (2 \times 2 $\mu m^2)$ of the ZnO and Mg_xZn_1-xO thin films grown on a SiO_2/n^+ -Si substrate





Fig. 2.9 AFM image $(2 \times 2 \ \mu m^2)$ of the MZO50/ZnO(10nm) and MZO100/ZnO(10nm) thin films grown on a SiO₂/n⁺-Si substrate





Fig. 2.10 Top view SEM images of $Mg_xZn_{1-x}O$ alloy films



2.2.1.2 Optical properties

Figure 2.11 shows the optical transmittance spectra of the ZnO, MZO50, MZO100, and MgZnO films, on a double-polished Corning glass substrate. The wurtzite structure and the Mg content in these films were the same as those present in the MgZnO films deposited on SiO₂/n-Si substrates because the surface of Corning glass is similar to that of SiO₂, both being amorphous. ZnO, MgZnO, and Mg_xZn_{1-x}O alloy films showed a high optical transmission exceeding 80% in the visible region. The inset in Fig. 2.11 shows a plot of $(\alpha hv)^2$ versus hv, which indicates the position of the optical band gap (E_g) , where α and hv are the absorption coefficient and the photon energy, respectively. The band gap energy in the MgZnO alloy films was evaluated according to $\alpha (hv) = A (hv - E_g)^{1/2}$. The band gaps of the ZnO and MgZnO films were 3.27 and 3.93 eV, respectively, whereas the band gaps of the MZO50 and MZO100 alloy films were 3.34 and 3.52 eV. These results indicate that the Mg content increased with increasing power applied to the Mg_{0.3}Zn_{0.7}O target. The Mg compositions (x) in the Mg_xZn_{1-x}O films were found to be x = 0 (ZnO), 0.01 (MZO50), 0.10 (MZO100), and 0.305 (MgZnO), according to the relationship between the Mg content and the band gap in the hexagonal phase [55].





Fig. 2.11 UV-Vis results for ZnO, MZO50, MZO100, and MgZnO alloy films. The inset shows a plot of $(\alpha hv)^2 - hv$



2.2.1.3 Electrical properties

Figure 2.12 shows the electrical properties measured by using the TLM method with a series of Au/Ti contacts (200 µm × 200 µm) with different spacings ($d_i =$ 5, 10, 20, 40, and 80 µm). A schematic of the measurement method is shown in Fig. 2.12 (d). According to the TLM model [56], a specific contact resistivity (ρ_c) and a bulk film resistivity (ρ) can be evaluated by using the formula $\rho_c =$ $R_c^2 W^2 R_s^{-1}$ and the slopes in Figs. 2.12(a)–(c), respectively, where R_c denotes the contact resistance, W the width of the contact, and R_s the sheet resistance of the semiconductor layer outside the contacts. The ρ of ZnO is 4.13 × 10³ Ω ·cm while those of the MZO50 and the MZO100 thin layers are 1.29 × 10⁴ Ω ·cm and 2.88 × 10⁴ Ω ·cm, respectively. With increasing Mg content, the bulk resistances of the samples increased as a result of the increasing donor ionization energy [57]. In this result, the resistance of ZnO is higher than other reported results for undoped ZnO thin films (resistivity: ~10⁻² Ω ·cm, carrier concentration: ~10¹⁸ cm⁻³) [57]. The carrier concentrations of ZnO, MZO50, and MZO100 are expected to be about 10¹⁴ ~ 10¹⁵ cm⁻³.





Fig. 2.12 Plots of the resistance as a function of the contact pad spacing for (a) ZnO, (b) MZO50, and (c) MZO100. (d) Schematic diagram of the TLM measurement



2.2.2 Ohmic Contact of MgZnO

2.2.2.1 Motivation

Over the past few years, Zinc Oxide (ZnO) materials have been seeking the application to adopt various electronic devices. This material can be used to light emitting diode, photodetector, solar cell, and transparent thin film transistor due to the superior physical properties. ZnO has a wide band gap (3.37 eV) and direct band gap [7]. Moreover, the ZnO has superior properties at the light emitting diode due to the high exciton binding energy (60 meV). In addition, the ZnO can have potential application on the display device because of the high transmittance (<80%, at the visible wavelength region). Recently, the drive circuit of display of AMOLED (active matrix organic light emitting diode) is changing from LTPS (low temperature poly silicon)-TFT to IGZO(indium gallium zinc oxide)-TFT due to some of advantages such as the low temperature process and fast electron mobility. However, there are some disadvantages at the ZnO material like as unstable electrical properties and degradation of device performance by defect from derived oxygen vacancy. To solve this problem, the study of improving stability develops with using the Mg incorporation into the ZnO. The free carrier concentration at the MgZnO thin films is decreasing due to increasing band gap which cause the increasing activation energy. As shown in Fig. 2.13, the carrier concentration decreased by increase of activation E is difficult to formation of Ohmic contact because of thick barrier. Therefore, the formation of Ohmic contact between metal to semiconductor is difficult at the wide band gap material. In this study, we investigate the Ohmic contact with various metal electrodes. The work function of Ti, In, Al, and Ni are 4.33, 4.12, 4.28, 5.04~5.35 eV, respectively. The metal work function was shown in Fig. 2.14. Generally, for achieving Ohmic contact, it is required low work function of metal at the n-type semiconductor. The Ohmic properties of MgZnO thin film was investigated with various metal electrode, and the characteristics of source-drain according the metal electrodes at thin film transistor has been studied.





Fig. 2.13 Ohmic contact formation by function of doping at the semiconductor





Fig. 2.14 The metal work functions depend on atomic number



2.2.2.2 Experimental detail

The Mg_{0.3}Zn_{0.7}O thin films were deposited by using a RF-co sputter system with the Mg_{0.3}Zn_{0.7}O (Mg : Zn atomic ratio = 3 : 7) and the ZnO targets. First of all, to confirm Ohmic properties, the MgZnO thin film was deposited by using single Mg_{0.3}Zn_{0.7}O on the c-Al₂O₃ substrate for 2 h at the 5 mTorr (Ar 20 sccm) by applying 100 W. The thickness was 180 nm and the deposition temperature was 300°C. Prior to deposition, the substrate was cleaned with common organic cleaning process. After deposition, the patterns of transmission line model (TLM) as shown in Fig. 2.15 formed by using a photolithography method. Ti(10 nm)/Au(100 nm), Al(100 nm), In(10 nm)/Au(100 nm), and Ni(10 nm)/Au(100 nm) metals were deposited by using an E-beam evaporation, and after that the patterns were finally completed by using a lift-off method.

The electrical properties were measured with semiconductor parameter analyzer (Hewlett-Packard HP4145B). The structure characteristics were investigated by using the X-ray diffraction (PANalytical X'pert Pro) and the Atomic force microscopy (Seiko SPA400).



2.2.2.3 Results and Discussion

Figure 2.15 shows a metal contact pattern of TLM on a MgZnO/SiO₂/Si TFT, measured by SEM. The width and lengths were 200 μ m and 5, 10, 20, 40, and 80 μ m, respectively. The width and length measured by SEM are 4.2 and 208.7 μ m due to limitations in the photolithography process.



Fig. 2.15 A metal contact pattern of transmission line model on the MgZnO thin

film



Figure 2.16 (a) shows the XRD (X-ray diffraction) spectrum of $Mg_{0.3}Zn_{0.7}O$ thin film. The MgZnO thin film predominantly shows the (002) direction with hexagonal wurtzite structure. In addition, by substituting of Mg^{2+} ions for Zn^{2+} ions, the lattice constant of c-axe direction was decreased due to the strong interaction between Mg^{2+} ions with O^{2-} . This phenomenon was confirmed at the more increased $2\Theta = 34.75^{\circ}$ of MgZnO (002) direction than $2\Theta = 34.4^{\circ}$ of ZnO (002).

Figure 2.16 (b) shows the surface image of $Mg_{0.3}Zn_{0.7}O$ thin film by using an atomic microscopy. The root-mean-square roughness is 3.9 nm and the grain-size is 38.0 nm.

Figure 2.17 shows the results of current-voltage measurement with different distances of contact metals. The Ni/Au, Ti/Au, and Al show the linear I-V curves, while the In/Au displays non-linear curve. The linear curve means the Ohmic contact between metal and semiconductor.

Figure 2.18 shows the resistivity according to the distances between metal to metal by using transmission line model (TLM). The Ni/Au metal electrode shows lowest contact resistance about $9.76 \times 10^1 \ \Omega \cdot cm^2$, while the Ti/Au electrode shows contact resistance of $1.27 \times 10^2 \ \Omega \cdot cm^2$. Generally, the low contact resistance can be obtained by using a Ti/Au electrode with ZnO thin films. However, in this experiment, it is difficult to injection of carrier into the MgZnO thin films due to low carrier concentration. In other words, the barrier exists between metal and semiconductor interface that the barrier-width widely forms. Under this condition, the flow of carrier tunneling rather than thermally excite is dominant. The Al metal show the linear current-voltage characteristics at the Mg_{0.3}Zn_{0.7}O thin film forming Ohmic contact. However, the In/Au metals shows unstable current-voltage curve because there are defects at the metal-semiconductor interface.





Fig. 2.16 (a) XRD and (b) AFM surface morphology of the $Mg_{0.3}Zn_{0.7}O$ film





Fig. 2.17 The resistivity-distance of (a) Ni/Au, (b) Ti/Au, (c) Al, and (d) In/Au contact metals by transmission line model





Fig. 2.18 The resistivity-distance of (a) Ni/Au and (b) Ti/Au contact metals by transmission line model with Mg_{0.3}Zn_{0.7}O thin films



2.2.2.4 Conclusion

We have investigated the characteristics $Mg_{0.3}Zn_{0.7}O$ thin film transistor according to Ohmic properties between the metal and the semiconductor. The Ni/Au and the Ti/Au metal electrodes have shown Ohmic properties. The contact resistance of Ni/Au is $9.76 \times 10^1 \ \Omega \cdot cm^2$, while the Ti/Au electrode is $1.27 \times 10^2 \ \Omega \cdot cm^2$. The contact properties of Ni/Au and Ti/Au electrodes are similar. However, the Al and In/Au metal contact reveals non-linear increase of resistance according to the distance. Generally, the metal electrode for Ohmic contact with ZnO thin films is Ti/Au metal. Moreover the difference of contact properties up to Mg 30 at.% compare to Ti/Au and Ni/Au metal electrode was small, in our experiment. Thus, the metal electrode for formation of source and drain at the thin film transistor was selected with Ti/Au metals.





2.2.3 Single channel layer of MgZnO MISFET

2.2.3.1 Motivation

ZnO is a II-VI-group semiconductor with high transparency in the visible range (400-700 nm) and a high mobility, and the material may be processed at low temperatures [35, 58]. ZnO-based thin-film transistors (TFTs) show promise for use in the active devices of flat panel displays. ZnO-based materials, such as In-doped ZnO, Ga-doped ZnO, zinc tin oxide, and In₂O₃-Ga₂O₃-ZnO, have been extensively studied [43, 59-61]. For these reasons, oxide-based TFTs have higher mobilities than amorphous silicon based-TFTs. The properties of oxide semiconductor-based TFTs strongly depend on those of the TFT's active layer, which can be varied by introducing dopants, applying thermal annealing, altering the layer thickness, and varying the growth parameters [62, 63]. Al-, Ga-, and In-doped ZnO yield a high carrier concentration and are suitable for applications that require transparent conducting materials. However, In-doped active layers of ZnO TFTs suffer shifts in the threshold voltage during on-state bias stressing. To overcome this problem, doping of Ga, Hf, Zr, and Mg atoms in the In-doped ZnO active layer has been tested as a method for controlling the net electron carrier concentration by suppressing carrier generation via oxygen vacancy formation in the active layer [19, 22, 64]. Especially, for Mg incorporation into ZnO, the conduction band edge in the energy band gap has been reported to be increased, potentially away from the intrinsic shallow donor state [65]. The activation energy for preparing defect donor states thereby increased, and the effect donor carrier concentration decreased. Moreover, Kim et al. [19] expected Mg incorporation to bring about not only improved stability but also stable performance by reducing formation of oxygen vacancies in the channel layer under bias or thermal stress condition. Moreover, Mg-O does not easily lose oxygen and Mg can be oxidized more easily than Zn because MgO has a higher oxygen vacancy formation energy (9.8 eV) than ZnO (3.8 eV) and a lower standard electrode potential (-2.37 V) than Zn (-0.76 V).

In this work, we report on Mg incorporation into the ZnO active layer of TFTs



by using a co-sputtering method with ZnO and $Mg_{0.3}Zn_{0.7}O$ (Mg 30 at.%) targets. Furthermore, we describe properties of MgZnO TFTs as functions of the Mg content in the ZnO active layer and structural characteristics of the MgZnO active layer fabricated by using the co-sputtering technique.

2.2.3.2 Experimental detail

allov deposited by RF co-sputtering $Mg_xZn_{1-x}O$ films were onto thermally-oxidized silicon substrates. Silicon substrates have a resistivity of 0.005 Ω cm and *n*-type carriers. The SiO₂ thickness was 90 nm. The co-sputtered commercial targets, ZnO and Mg_{0.3}Zn_{0.7}O (4 inches in diameter, Mg/Mg+Zn, 30 at.%), had purities of 99.99%. The SiO₂/Si substrate was cleaned with acetone, methanol, and de-ionized water in an ultrasonicator for 5 min each. The cleaned substrate was positioned in the sputtering chamber. The base pressure was less than 10^{-6} Torr, and the working pressure was 5 mTorr. Argon gas was introduced at a flow rate of 20 sccm, which was controlled by using a mass flow controller. The ZnO and the MgZnO targets were sputtered for 30 min at 300°C. The RF power of the ZnO target was 100 W, which remained unchanged, whereas the power applied to the MgZnO target was set to 50 or 100 W. After deposition, the ZnO and the $Mg_xZn_{1-x}O$ thin films were etched; then, the samples were patterned by using photolithography to form source and drain pads. Ti (10 nm) and Au (50 nm) layers were deposited using an e-beam evaporation system to form electrodes. The gate metal was silver, which was deposited on the back side of the silicon substrate. Passivation was not included in the processing. The electrical properties were evaluated by using a semiconductor analysis (HP4145B, Hewlett-Packard) in the dark and at room temperature.



2.2.3.3 Results and Discussion

ZnO-based TFTs were prepared using Mg_xZn_{1-x}O alloy films, and their properties were measured. The output curves $(I_{DS}-V_{DS})$ of those TFTs are shown in Fig. 2.19. All measurements were conducted on devices with channel widths and lengths of 100 and 10 μ m, respectively. A drain-to-source voltage (V_{DS}) of 0–10 V was applied, and the gate voltage (V_{GS}) was increased in steps of 10 V up to a total of 40 V. The output curves for ZnO, MZO50 and MZO100 TFTs show typical output characteristics. The drain-to-source current abruptly increases as the drain-to-source voltage increases at a positive gate bias, indicating that mainly electron carriers are generated in the channel. The ZnO TFTs show a high IDS of about 0.44 mA at $V_{DS} = 10$ V and $V_{GS} = 40$ V while the values of the I_{DS} of the MZO50 and the MZO100 are slightly decreased, about 0.39 and 0.12 mA, respectively, under the same conditions. Because I_{DS} depends on the mobility degradation and the series resistance [17], these degradation of the I_{DS} values are thought to be caused by the increase in the series resistance with increasing Mg incorporation, corresponding to Figs. 2.19 (a)-(c). Moreover, with increasing Mg contents in the active layer, we believe that the ionized carriers are decreased.

Figure 2.20 shows the transfer curve $[log(I_{DS})-V_{GS}]$ and $\sqrt{I_{DS}}$ as functions of V_{GS} for ZnO, MZO50, and MZO100-TFTs. The field-effect mobility (μ_{FE}) induced by the transconductance (g_m) at low drain voltage ($V_{DS} = 2.5$ V) is determined by

$$\mu_{FE} = \frac{Lg_m}{WC_i V_{DS}},\tag{2.1}$$

where W is the channel width, L is the channel length, and C_i is the capacitance per unit area at gate insulator. The threshold voltages (V_T) were calculated by fitting a straight line to the plot of $\sqrt{I_{DS}}$ versus V_{GS} in the saturation region. The sub-threshold slope (S.S.) from the linearly increasing region of the transfer curve can be extracted using the equation



$$S.S. = \frac{dV_{GS}}{d(\log I_{DS})}.$$
(2.2)

The V_T , μ_{FE} , and on/off ratio of the ZnO TFT were 11.84 V, 9.12 cm²V⁻¹s⁻¹, and ~10⁹, respectively. The MZO50 and the MZO100 samples show slightly degraded values of the μ_{FE} , about 8.08 and 3.11 cm²V⁻¹s⁻¹, respectively. In this case, the mobility was found to decrease with increasing Mg incorporation. Matsubara et al. [66] suggested that these phenomena were caused by three possibilities: i) grain boundary scattering, ii) impurity scattering by Mg, and iii) increased electron effective mass due to band-gap widening. The XRD results showed the FWHMs of ZnO and MZO50 to be similar, whereas the MZO100 thin films had higher values. The grain boundary can capture conduction electrons to form a double Schottky barrier [23, 67]. This cause of the decreased mobility is still not certain, but it is a candidate for all these phenomena.

Moreover, the phenomenon of charge traps is present not only in semiconductor channel layer but also in the channel/dielectric interface. To confirm the density of traps caused by Mg incorporation in the ZnO channel layer, we calculated the density of the interfacial and the semiconductor bulk traps (N_t) from the experimental *S.S.* values by using following equation:

$$N_t = \left(\frac{S.S.\log e}{kT/q} - 1\right)\frac{Ci}{q},$$
(2.3)

where k is the Boltzmann constant, T is the temperature, and q is the electron charge. The N_t value was 3.1×10^{12} cm⁻²eV⁻¹ for the ZnO TFT while the MZO50 and the MZO100 TFTs showed values of about 7.5×10^{12} and 5.5×10^{12} cm⁻²eV⁻¹, respectively.

Also, the V_T increased from 11.84 to 16.58 V with increasing Mg content. The increased V_T could be caused by the channel carrier concentration being decreased by increasing the Mg content. In general, V_T will be higher in devices where the



channel carrier concentration is less because a higher gate voltage is required to accumulate charges in the semiconductor-dielectric interface [68].



Fig. 2.19 Output curves ($I_{DS}-V_{DS}$) for (a) ZnO, (b) MZO50, and (c) MZO100 TFTs




Fig. 2.20 Transfer semi-log plots of $I_{DS}-V_{GS}$ for (a) ZnO, (b) MZO50, and (c) MZO100 TFTs



2.2.3.4 Conclusion

In conclusion, $Mg_xZn_{1-x}O$ alloy films were deposited via RF co-sputtering onto thermally-oxidized silicon substrates to form the active component in TFTs. The Mg content in the $Mg_xZn_{1-x}O$ alloy films could be controlled by varying the RF power, and the band gaps were found to be 3.27-3.93 eV. The mobility and the on/off ratio of the ZnO-TFTs were $9.12 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and $\sim 10^9$, respectively. The properties of the ZnO-based TFTs are summarized in Table 2.3.

Table 2.3 Threshold voltage (V_T), field effect mobility (μ_{FE}), subthreshold swing (S.S.), I_{ON}/I_{OFF} , and trap density (N_t) ratio in the ZnO and the Mg_xZn_{1-x}O TFTs

	V_T (V)	$\mu_{FE.}$ (cm ² V ⁻¹ s ⁻¹)	S.S. (V·decade ⁻¹)	I _{ON} /I _{OFF}	N_t (cm ² eV ⁻¹)
ZnO	11.84	9.12 19	45 0.83	~10 ⁹	3.1×10^{12}
MZO50	13.40	8.08 04	1.93	~109	7.5×10^{12}
MZO100	16.58	3.11	1.42	$\sim 10^{8}$	5.5×10^{12}



2.2.4 Heterostructure of MgZnO/ZnO-MISFET

2.2.4.1 Motivation

Zinc oxide is a promising material for use in the next generation of flat panel displays and transparent electronic devices because of, for example, its high transparence, low-temperature processing, and higher field-effect mobility than shown by a-Si:H-TFTs [4]. An additional advantage is its formation of a 2DEG when employed in an MgZnO/ZnO bi-layer. An epitaxial ZnO thin film on MgZnO is under tensile strain due to the different a-axis lattice constants at the ZnO layer [69]. It can form high electron densities on the ZnO/MgZnO interface by piezoelectric and spontaneous polarization effects [69, 70]. However, the fabrication of epitaxial thin films requires MBE or PLD [59, 71]. To grow epitaxial thin films, a thick MgZnO or ZnO buffer layer is needed to reduce lattice mismatch. MISFETs of lattice-matched MgZnO/ZnO/MgZnO thin films can show higher mobility; however, they show low on/off ratios ($\sim 10^3$) due to low off-currents caused by the buffer layer allowing current leakage [72, 73]. Recent simulation modeling and Hall measurements by Huang et al. [31] led to the observation of a localized 2DEG, which formed in an RF sputtering system and improved the mobility of MgZnO on ZnO heterostructures. They also suggested modulation doping design. Chin et al. [30] also found MgZnO/ZnO structures deposited by RF sputtering to show improved Hall mobility, despite having polycrystalline structures.

The transistor properties of MgZnO/ZnO bi-layer TFTs are reported here. Field effects are rarely reported in devices with polycrystalline structures at the channel layer. RF co-magnetron sputtering was used because it is more compatible with the commercial fabrication of large-area devices than the growing of epitaxial thin film by such as PLD or MBE. The thickness of ZnO in a TFT is important as it forms an insulating layer. If the MgZnO/ZnO interface is far from the insulator, it cannot effectively accumulate electrons for use in the channel region. A thin ZnO layer puts the interface too close to the insulator, and poor crystallinity and surface morphology result with the consequences of increased scattering by grain boundaries



and ionized impurities; phonon scattering is also increased. The concentration of Mg in the ZnO is also important because it increases both the band-gap and resistivity. The incorporation of single-layer Mg (6 at.%) in ZnO has been shown to improve thermal stability and mobility [74]. Koike et al. [75] fabricated an $Mg_{0.3}Zn_{0.7}O/ZnO/Mg_{0.3}Zn_{0.7}O$ heterostructure field-effect transistor that showed high mobility but also a low on/off ratio (~10³) due to the MgZnO layer forming a pathway for leakage current. The thin MgZnO (30 at.%) film fabricated in the current work showed high resistance and high contact resistance with metals. A high on/off ratio and high mobility for drain–source current was obtained using a low Mg content in the alloyed ZnO layer. The characteristics of MZO50/ZnO and MZO100/ZnO bi-layer TFTs are reported here.

2.2.4.2 Experimental detail

(Mg_xZn_{1x}O) films were sequentially deposited by RF ZnO and MZO50 co-sputtering onto silicon substrates that had been thermally oxidized in an O₂ 0.005 Ω cm). Α Nanospec system and cross-sectional ambient (resistivity transmission electron microscopy (TEM) images confirmed the SiO₂ thickness to be 70 nm. Prior to deposition, the substrates were cleaned by acetone methanol, and de-ionized water in an ultrasonicator for 5 min, before being placed in the sputtering chamber. The base pressure was $\sim 10^6$ Torr, and the working pressure was 5 mTorr with 20 sccm argon gas. Deposition was at 300 °C using commercially obtained ZnO and MgZnO (Mg 30 at.%, 4 inches) targets. Deposition was controlled to form bi-layer structures of MZO50 and ZnO with respective thicknesses of 54 and 6 nm, 48 and 12 nm, 42 and 18 nm, and 30 and 30 nm. In each case, the total thickness was 60 nm. Pure ZnO was first deposited with 100 W RF power. Under continued 100 W ZnO sputtering, the second layer was deposited by co-sputtering a MgZnO (30 at.%) (MZO50) target at 50 W for Mg incorporation into the ZnO material.



MZO100 and ZnO thin films were deposited under similar conditions onto the SiO_2 (40 nm)/ n^+ -Si substrate. Deposition was controlled to form bi-layer structures of MZO100 and ZnO with respective thicknesses of 45 and 5 nm, 40 and 10 nm, 30 and 20 nm, and 20 and 30 nm. In each case, the total channel thickness was 50 nm.

The MZO50/ZnO and MZO/100 bi-layer channel layers were etched by conventional photolithograpy. Ti (10 nm) / Au (50 nm) metals were electron-beam deposited, and electro pads as source and drain electrodes were formed by lift-off. A silver gate electrode was attached at the back side of the silicon substrate. The structures were investigated by X-ray diffraction (XRD) and TEM. Their electrical properties were measured by semiconductor analysis apparatus (HP4145B and Keithley 4200-SCS) and their optical properties were measured by UV–Vis spectrometry.

2.2.4.3 Results and Discussion

The bright field cross-section TEM image of the MZO50 (48 nm)/ZnO (12 nm)/SiO₂/Si structure (Figure 2.21 (a)) shows the c-directional columnar structure of the ZnO and MZO50. The components of the bi-layer are difficult to distinguish because it maintained a hexagonal wurtzite structure throughout and the Mg content was low. Selective area electron diffraction (SAED) (Fig. 2.21 (b)) shows ZnO or MgZnO (0002) spots near the Si (002) spots, which indicate that the ZnO thin films were deposited in a direction parallel to ZnO(0002)//Si(002). SAED showed the MZO50/ZnO thin films to have a poly-crystalline structure. Mg contents were confirmed by energy dispersive X-ray (EDX) spectroscopy: line scanning (Fig. 2.21 (c)) and spot measurements (Fig. 2.21 (c)) were undertaken. The analyzed areas are labeled in Fig. 2.21 (c) as A, B, C, and D. At areas A, B, and C, 2.5 at.% Mg was measured; at area D no Mg-K α peak or Mg-related peak was detected. This result indicates that the MZO50/ZnO bi-layer was well formed





Fig. 2.21 (a) Bright field TEM image and (b) SAED pattern of MZO50/ZnO(18nm)(c) EDX-line scanning of HS-ZnO and (d) EDX-spot spectrum



Figure 2.22 (a) shows the band diagram with the derived optical band gap at the equilibrium state of an ideal metal-insulator semiconductor (MIS) with MZO50/ZnO/SiO₂/metal structure. The ratio of the conduction band offset (ΔE_C) and the valence band offset (ΔE_V) between MgZnO and ZnO has been previously estimated to be about 3:2 [24]. At the junction interface of MZO50/ZnO (i.e., the conduction band site), localized high electron density is able to form through the attraction of electrons by the potential arising from spontaneous and/or piezoelectric polarization. Figure 2.22 (b) shows the band gap of the MZO50/ZnO heterostructure under an applied positive gate bias. In a metal-insulator semiconductor, electrons accumulate at the insulator-semiconductor interface to form the channel region. However, electron accumulation is also expected at the conduction band edge of the junction interface of ZnO and MZO50 in the bi-layer structure.

The source–drain current (I_{DS}) versus the gate–source voltage (V_{GS}) for ZnO (Fig. 2.23 (a)) and MZO50/ZnO(18 nm) (Fig. 2.23 (b)) TFTs are shown for devices of channel length (L) 10 µm and width (W) 100 µm. V_{DS} was biased from 0 to 10 V, and the gate–source voltage (V_{GS}) was incrementally increased in 5 V steps from 0 to 30 V. As gate voltage increased, I_{DS} increased with clear pinch-off properties. Figures 2.23 (c) and (d) respectively show the I_{DS} versus V_{GS} curves of ZnO and MZO50/ZnO(18 nm) TFTs. Field-effect mobility (μ_{FE}) was determined at low $V_{DS} = 0.5$ V by the following equation [76]:

$$\mu_{FE} = \frac{Lg_m}{WC_i V_{DS}},\tag{2.4}$$

where g_m is transconductance and C_i is the capacitance per unit area at the gate insulator. The field-effect mobility of the ZnO TFT is 5.38 cm² V¹ s¹; while the bi-layer TFTs showed higher values of 6.77–7.56 cm² V¹ s¹. This was due to the low trap density in the drain–source current path localized in the conduction band region of the MZO50/ZnO junction interface. Figures 2.23 (c) and (d) show no gate leakage currents.



The field-effect mobility, sub-threshold swing (SS), threshold voltage, and I_{on}/I_{off} ratio are compared for MZO50 TFTs with different ZnO thicknesses (Figs. 2.24 (a) –(d), respectively). Increasing the ZnO thickness to ~10 nm led to increased mobility; mobility was not increased as thickness further increased. This was due to less effective carrier confinement in the MZO50/ZnO junction interface due to the attenuation of the electric field at greater distances from the insulator–semiconductor junction interface. The SS of the bi-layer TFTs was lower (0.57–0.69 V decade¹) than that of the ZnO TFT (about 0.86 V decade¹). All devices showed high on/off ratios of I_{DS} (>10⁸) at a high V_{DS} of 10.5 V.

Figure 2.25 shows I_{DS} versus V_{DS} curves for ZnO and MZO100/ZnO bi-layer TFTs; each had a channel with $W = 100 \,\mu\text{m}$ and $L = 10 \,\mu\text{m}$. V_{GS} was biased from 0 to 20 V in 5 V steps, while the applied V_{DS} increased form 0 to 10 V. The curves measured under increasing V_{DS} show clear saturation properties. The I_{DS} at the saturation region increased with increasing ZnO thickness.

Figure 2.26 shows I_{DS} versus V_{GS} curves for ZnO and MZO100/ZnO bi-layer TFTs. Field-effect mobility was calculated using the previous equation at a low V_{DS} (0.5 V). The field-effect mobility of the ZnO TFT was 5.74 cm² V¹ s¹; the MZO100/ZnO bi-layer TFTs showed values from 2.42 to 7.40 cm²/Vs, with the highest value shown by the MZO100/ZnO(10 nm) TFT. The thickness of the ZnO layer had a strong effect on the TFTs and it was optimized here at ~10 nm. A thinner ZnO layer of 5 nm resulted in a TFT that showed the lowest μ_{FE} . SS values of the MZO100/ZnO bi-layer TFTs decreased to 0.22 V·decade⁻¹, compared with the SS of 0.44 V/decade shown by the ZnO TFT. The lower SS suggests that the MZO100/ZnO bi-layer TFT had a lower trap density. The lower bulk trap density was achieved by the MgZnO channel layer due to reduced oxygen vacancies.





Fig. 2.22 (a) Band diagram of MZO50/ZnO hetero-structure and (b) band bending by applying a positive voltage at the metal





Fig. 2.23 Output plots for (a) ZnO and (b) MZO50/ZnO(18nm) and Transfer semi-log plots of I_{DS}-V_{GS} for (c) ZnO and (d) MZO50/ZnO(18nm)





Fig. 2.24 (a) Field effect mobility, (b) sub-threshold swing, (c) threshold swing and (d) On/Off ratio of ZnO-TFT and MZO50/ZnO-TFT parameters





Fig. 2.25 Output plots for (a) ZnO, (b) MZO100/ZnO(5nm), (c) MZO100/ZnO(10nm), (d) MZO100/ZnO(20nm), and (e) MZO100/ZnO(30nm) devices





Fig. 2.26 Transfer semi-log plots of I_{DS}-V_{GS} for (a) ZnO, (b) MZO100/ZnO(5nm),
(c) MZO100/ZnO(10nm), (d) MZO100/ZnO(20nm), and (e) MZO100/ZnO(30nm) devices



2.2.4.4 Conclusion

MgZnO/ZnO bi-layer TFTs were shown to have higher mobilities and lower SS values than a similar single-layer ZnO TFT. The optimal bi-layer structure had a localized conduction band-gap region that formed a current pathway for improved mobility and low SS. The thickness of the ZnO layer affected the TFT parameters; ZnO thickness was optimized at about 10–20 nm. The parameters of the ZnO, MZO50/ZnO, and MZO100/ZnO TFTs fabricated in this study are summarized in Tables 2.4 and 2.5.

Table 2.4 Threshold voltage (V_T), field effect mobility (μ_{FE}), sub threshold swing (S.S.), and I_{ON}/I_{OFF} in the ZnO and MZO50/ZnO TFTs

	V_T (V)	$\mu_{FE}(cm^2V^{-1}s^{-1})$	S.S. (V·decade ⁻¹)	I _{ON} /I _{OFF} ratio
ZnO	11.12	5.38	0.86	$\sim 10^{8}$
MZO50/ZnO(6nm)	10.60	6.77	0.57	$\sim 10^{9}$
MZO50/ZnO(12nm)	10.00	7.56	0.69	$\sim 10^{8}$
MZO50/ZnO(18nm)	9.73	7.38	0.68	$\sim 10^{8}$
MZO50/ZnO(30nm)	10.12	7.10	0.57	~109

Table 2.5 Threshold voltage (V_T), field effect mobility (μ_{FE}), sub threshold swing (S.S.), and I_{ON}/I_{OFF} in the ZnO and MZO100/ZnO TFTs

	V_T (V)	$\mu_{FE}(cm^2V^{-1}s^{-1})$	$\frac{S.S.}{(V \cdot decade^{-1})}$	I _{ON} /I _{OFF} ratio
ZnO	7.39	5.74	0.44	$\sim 10^{8}$
MZO100/ZnO(5nm)	9.33	2.24	0.72	$\sim 10^{7}$
MZO100/ZnO10nm)	7.25	7.40	0.24	$\sim 10^{8}$
MZO100/ZnO(20nm)	7.20	4.35	0.22	$\sim 10^{8}$
MZO100/ZnO(30nm)	7.71	5.04	0.27	$\sim 10^{8}$



2.2.5 Stability properties of MgZnO TFT and Mg_xZn_{1-x}O/ZnO TFT

2.2.5.1 Hysteresis properties

Figure 2.27 shows the hysteresis behavior of ZnO, MZO50, and MZO100 single layer TFT. The clockwise hysteresis (ΔV_{GS}), which is defined by the difference of the V_{GS} at the I_{DS} of 10⁻¹⁰A between the V_{GS} sweeps of off-to-on and on-to-off with $V_{DS} = 0.5$ V. The phenomenon of clockwise hysteresis is known because of negative charge trapping in an oxide semiconductor and/or in an oxide semiconductor/insulator interface. The ZnO TFT shows $\Delta V_{GS} = 3.04$ V, while the ΔV_{GS} of MZO50 and MZO100 TFT are 3.53 and 6.70 V, respectively. In this result, the increase of Mg incorporation in to the ZnO reveals the increase of Δ V_{GS} . This reason is thought due to increase of bulk trap in MgZnO thin film and/or increase of interface traps derived by Mg_xZn_{1-x}O/SiO₂.

However, the hysteresis behavior of MZO50/ZnO TFT shows decrease, as shown in Fig. 2.28. The ΔV_{GS} of ZnO is 3.14 V, while MZO50/ZnO(12nm) is 1.65 V. All MZO/ZnO bi-layer TFT display the decrease of ΔV_{GS} . The shift of transfer curve in hysteresis loops is attributed to the interface states. For forward sweeping, the interface states discharge the trapped carriers initially and then begin trapping carriers while gate bias sweeps. Although the ΔV_{GS} MZO50 single TFT was increasing, the thin ZnO inserted between MZO50 and ZnO TFTs shows low ΔV_{GS} . In this result, we believe that a large number of interface trap at MZO50/SiO₂ could be generated by defects than ZnO/SiO₂ interface, it could be solved by using thin ZnO layer. However, the ΔV_{GS} values of MZO/ZnO bi-layer TFTs more were decreased than ZnO TFT. This reason could be thought by decrease of bulk trap in semiconductor or MZO/ZnO interface derived high electron density.

Figure 2.29 shows the hysteresis behavior of ZnO and MZO100/ZnO bi-layer TFTs. In this experiment, the ΔV_{GS} was decreased from 2.17 V (ZnO TFT) to 1.05 V (MZO100/ZnO TFT). Both MZO50/ZnO and MZO100/ZnO TFT, the ZnO thickness optimized about 10 nm.





Fig. 2.27 Hysteresis behavior of (a) ZnO, (b) MZO50, and (c) MZO100 devices





Fig. 2.28 Hysteresis behavior of (a) ZnO, (b) MZO50/ZnO(6nm), (c) MZO50/ZnO(12nm), (d) MZO50/ZnO(18nm), and (e) MZO50/ZnO(30nm) devices





Fig. 2.29 Hysteresis behavior of (a) ZnO, (b) MZO100/ZnO(5nm), (c) MZO100/ZnO(10nm), (d) MZO100/ZnO(20nm), and (e) MZO100/ZnO(30nm) devices



2.2.5.2 Positive gate bias stress

Figure 2.30 shows the positive gate bias stress (PBS) results with $V_{GS} = +20$ V at the ZnO, MZO50 and MZO100 single layer TFT. In this devices were not passivation layer and measured in the dark box at the room temperature. All devices, the V_{on} shifts for positive direction because the captured electrons screen that it required more gate voltage for on-state. As increase of Mg incorporation into the ZnO, ΔV_{on} was increased from 3.35 to 4.60 V because of increase of interface trap at Mg_xZn_{1-x}O/SiO₂.

Figure 2.31 shows the positive gate bias stress results with $V_{GS} = +20$ V at the ZnO, MZO50/ZnO(6nm), and MZO50/ZnO(12nm). In this result hetero-structure devices show more low voltage shift about Δ 4.8 V than the ZnO single layer TFT has Δ 6.1 V. In this result could be thought two reasons. One is suppressing the oxygen vacancy due to the Mg-O bonding, which are decreasing could be to reduce the formation electron trap by the oxygen vacancy site. Other reason is that initial I_{DS} current is preferentially flow at the MgZnO/ZnO interface later than the ZnO/SiO₂ interface. MgZnO/ZnO junction state could be formed electron current path by polarization effects.





Fig. 2.30 Transfer semi-log plots of (a) ZnO, (b) MZO50, and (c) MZO100 under PBS test. $V_{GS} = +20$ V, $V_{DS} = 10$ V, for a duration of 6400 sec





Fig. 2.31 Transfer semi-log plots of (a) ZnO, (b) MZO50/ZnO(6nm), and (c) MZO100/ZnO(12nm) under PBS test. $V_{GS} = +20$ V, $V_{DS} = 10$ V, for a duration of 6400 sec



Chapter 3. MgO Insulator

3.1 Study of TFTs by using a MgO insulator

3.1.1 Motivation

Oxide semiconductor devices have attracted attention as a replacement for conventional silicon-based devices, and ZnO-based oxide materials are emerging as the next generation of oxide semiconductor materials. ZnO has higher mobility than amorphous silicon-based thin-film transistors (TFTs), and ZnO-based TFTs are suitable for applications that require transparent devices, due to their wide band gap $(E_g = 3.37 \text{ eV})$. High-dielectric constant (k) materials have been suggested for ZnO TFTs, to allow a sufficient number of charges to accumulate, and reduce the operating voltage [77, 78]. The k of MgO is approximately 9.8 [79]. This value can be affected by the growth conditions; specifically, the presence of interstitial oxygen can increase the dielectric constant [34]. MgO thin films grown in an oxygen-rich environment show more oxygen than Mg ions in their composition [34, 80]. The Chen group [34] reported the improved mobility of ZnO TFTs, and explained that the reduction of grain boundaries in the ZnO film on the MgO insulator with the excess oxygen ions. Motivated by this, we attempted MgO deposition using RF (radio frequency) magnetron sputtering, aiming to develop a large-scale process. The maximum process temperature was set not to exceed 300° C. We also controlled the oxygen percentage in the reactive gas mixtures to induce the reaction between the Mg ions and the O_2 .



3.1.2 Experimental detail

The MgO thin layer was deposited on an *n*-type and low-resistivity (0.005 Ω ·cm) Si (100) substrate using an RF magnetron sputtering system. Prior to deposition, the silicon substrate was cleaned using acetone and methanol, where each was applied for 5 min in the ultrasonicator. The native oxide (SiO_2) on the Si substrate was removed via the application of a buffered oxide etchant for 5 min. Finally, the sample was rinsed using deionized water, and blown dry using N₂ gas. The working pressure was 5 mTorr, and the temperature set at 300°C. Mixed Ar and O₂ was flowed into the chamber, and was controlled using a mass flow controller. The total amount of gas (Ar+O₂) was 20 sccm. The total pressure was maintained at 5 mTorr, and the injected gas mixture was changed by varying the O_2 gas flow, with oxygen percentages of 30% [i.e., $O_2/Ar + O_2$ ratio = 6 sccm/(14 sccm + 6 sccm)], 50%, and 70%. A commercial MgO target (4 inch) was used; the target was sputtered for 10 h using an RF power of 300 W, with various Po values. The ZnO was deposited on the MgO/Si substrate using RF magnetron sputtering. To make the channel region, the ZnO was patterned using a metal mask. The deposition temperature was 300°C, with an Ar amount of 20 sccm, and a pressure of 5 mTorr. The ZnO thickness was ~60 nm. Ti (10 nm)/Au (50 nm) were deposited using e-beam evaporation, and were patterned using the lift-off technique, as shown in Fig. 3.1 (a). Ag metal was attached on the back side of the Si substrate. With this Au/Ti/MgO/Au/Ti structure, a metal-insulator-metal (MIM) structure was formed on the Corning glass substrate using the same deposition conditions as those used for MgO; the pattern is shown in Fig. 3.1 (b).





Fig. 3.1 (a) Schematic of the ZnO TFT, (b) top-view optical image of the ZnO TFT, and (c) MIM structure with a square pattern ($w = 200 \ \mu m$)



3.1.3 Results and Discussion

Figure 3.2 shows the θ -2 θ XRD pattern for the fabricated TFT film transistor. A weak MgO (200) peak was observed at $2\theta = 44.4^{\circ}$. The MgO (200) peak intensities were similar, in spite of the different oxygen percentages. Chen *et al.* [81] reported that the crystallinity of MgO thin films was affected by the oxygen partial pressure, showing improved crystallinity at low O₂ pressures. However, our results suggested the formation of an amorphous state under low-temperature conditions. The peaks at $2\theta = 34.4^{\circ}$ and $2\theta = 38.2^{\circ}$ corresponded to ZnO (002) and Au (111), respectively.

Figure 3.3 shows the transmittance of the MgO insulator layer on the glass substrate. The transmittance of the MgO was over 80% in the wavelength range of 300–800 nm. This result revealed the superior transparency in the visual region, regardless of the different oxygen-to-argon percentage deposition conditions.



Fig. 3.2 XRD θ -2 θ spectra for the ZnO TFT with MgO gate insulators grown with oxygen percentages (in the reactive gas mixture) of (a) 30%, (b) 50%, and (c)

70%





Fig. 3.3 Transmittance spectra for MgO thin films deposited on the glass substrate at oxygen percentage of (a) 30%, (b) 50%, and (c) 70% in reactive gas mixtures



Figure 3.4 shows an AFM image of the MgO film grown on the n^+ -Si substrate using an oxygen-to-argon percentage of (a) 30, (b) 50, and (c) 70%. The root-mean-square (RMS) surface roughness of the MgO thin films grown on the n^+ -Si substrate using oxygen percentages of 30%, 50%, and 70% were measured as approximately 3.42, 3.48, and 3.38 nm, respectively. All of the MgO films grown were relatively smooth. The MgO thin film grown with an oxygen percentage of 70% showed the lowest RMS value.

The thickness of the deposited MgO layer was measured using a surface profiler. The measured thicknesses of the MgO thin films grown using oxygen percentages of 30%, 50%, and 70% were 167, 175, and 207 nm, respectively. These results showed that the interaction between Mg^{2+} and O^{2-} was more active in an oxygen-enrich environment, which explains the increase in the MgO thickness.

Figure 3.5 shows the capacitance C-f curve for the MIM structure. At frequencies from 1 kHz to 1 MHz, the capacitance remained almost constant. The capacitance (*C*) was obtained using an *LCR* meter (HP4284A), which was controlled using LabVIEW. To investigate the gate-insulating dielectric properties, capacitance–frequency (*C*-*f*) measurements was carried out using the MIM structure.

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}, \qquad (3.1)$$

where *C* is the capacitance, ε_0 is the dielectric constant in vacuum, ε_r is the dielectric constant, *A* is the area of contact, and *d* is the distance. The values of *C* for the MIM structures with an MgO insulator formed using oxygen percentages of 30%, 50%, and 70% were 15.85, 18.60, and 19.41 pF, respectively, which were measured at f = 1 kHz. Using Eq. (1), the dielectric constants of the MgO thin films grown using oxygen percentages of 30%, 50%, and 70% were determined as 7.48, 9.20, and 11.35, respectively, as summarized in Table 3.1. The dielectric constant increased as the oxygen percentage in the reactive gas mixture was increased. This agreed with results from other research groups [34]. As the oxygen percentage increases, the interstitial oxygen ions generate holes, which produces



quasi-dipoles. As a result, the increased k is thought to result from the presence of interstitial oxygen ions.



Fig. 3.4 AFM image $(2 \times 2 \ \mu m^2)$ of an MgO film grown on an n^+ -Si substrate using an oxygen-to-argon percentage of (a) 30, (b) 50, and (c) 70%





 Table 3.1 Thickness and Dielectric constant of magnesium oxide film

Oxygen percentage (%)) Thickness (nm)	Dielectric constant		
30	167	7.48		
50	175	9.20		
70	207)45	11.35		
off of th				





Fig. 3.5 C-f curves for MIM-structure TFTs with deposited MgO layers grown with the oxygen percentages of (a) 30%, (b) 50%, and (c) 70%



Figure 3.6 shows output plots for the drain-to-source current (I_{DS}) against the drain-to-source voltage (V_{DS}), for a ZnO-TFTs with MgO-layer gate insulators. The current (I)-voltage (V) characteristics were measured using a semiconductor parameter analyzer (HP4145B). The output characteristics revealed that the ZnO-TFTs exhibited saturation properties, as illustrated by the flatness of the I_{DS} curves at high V_{DS} . The saturation current can be expressed as [59]

$$I_{DS} = \left(\frac{C_{i}\mu_{sat}W}{2L}\right) (V_{GS} - V_{th})^{2} \quad \text{for } V_{DS} > V_{GS} - V_{th}, \quad (3.2)$$

where C_i is the capacitance per unit area of the gate insulator, μ_{sat} is the saturation mobility, V_{th} is the threshold voltage, and W and L denote the channel width and length, which were 100 µm and 60 µm, respectively. In the saturation region at $V_{GS} = 10$ V, the I_{DS} for the ZnO TFT created using an oxygen percentage of 70% was three times higher than the values for the other ZnO TFTs (oxygen percentages of 30% and 50%). This was caused by changes in the Ci value that resulted from the increased dielectric constant and the improved mobility, which in turn resulted from the low scattering at the channel/gate insulate interface. As shown by Eq. (2), the saturation current has to increase following $I_{DS} \propto V_{GS}^2$. However, none of the TFT devices showed increases in I_{DS} following Eq. (2), due to the presence of electron traps. This phenomenon could have resulted from the electron injection from the ZnO channel layer into the gate oxide that occurred as V_{GS} increased [82].

Figure 3.7 shows the $[log(I_{DS})-V_{GS}]$, the $\sqrt{I_{DS}}$ as a function of V_{GS} , and the I_G-V_{GS} curves for the ZnO-based TFTs. The ZnO TFTs were measured by sweeping V_{GS} from -10 to 20 V, with a V_{DS} of 5 V. The devices showed a low gate leakage current (I_G) in the V_{GS} range from -20 to 20 V. The field-effect mobility (μ_{FE}) [61] and subthreshold slope (SS) [59] were obtained using

$$\mu_{FE} = \frac{Lg_m}{WC_i V_{DS}},\tag{3.3}$$

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$$SS = \frac{dV_{GS}}{d(\log I_{DS})},\tag{3.4}$$

where g_m is the transconductance. The obtained μ_{FE} values for the ZnO TFTs with MgO insulators grown at oxygen percentages of 30%, 50%, and 70% were approximately 0.0121, 0.0126, and 0.0235 cm²·V⁻¹·s⁻¹, respectively. The μ_{FE} values for the ZnO TFTs with MgO insulators grown using oxygen percentages of 30% and 50% were similar, whereas the μ_{FE} for the 70% device was approximately two times larger than for the other oxygen percentages. The improved mobility was likely due to two factors: increased dielectric constant, which would have increased the accumulation of electrons in the ZnO channel layer, and decreased trap density, which occurred because of compensation effects; i.e., the effects of the oxygen vacancy defects in the channel layer were compensated for by the injection of excess oxygen ions into the MgO insulator at the ZnO/MgO interface. The total equivalent trap state (N_T) can be calculated as follows [59]:

$$N_{t}^{\max} = \left[\frac{SS\log(e)}{kT/q} - 1\right]\frac{C_{i}}{q},$$
(3.5)

where k is the Boltzmann constant, q is the electron charge, e is the base of the natural logarithm, and T is the temperature. Following Eq. (4), the SS values of the ZnO TFTs with MgO insulators grown using oxygen percentages of 30%, 50%, and 70% were approximately 1.63, 1.26, 1.18 V decade⁻¹, respectively, as displayed in Fig. 3.7. Using Eq. (5), the N_t^{max} values for the ZnO TFTs with MgO insulators grown at oxygen percentages of 30%, 50%, and 70% were calculated as 6.52×10^{12} , 5.85×10^{12} , and 5.69×10^{12} cm⁻², respectively. These values are similar to those reported in previous studies for high k dielectric materials [43, 59]. Decreases in N_t^{max} can affect the mobility; the mobility of the 70%-oxygen-percentage ZnO TFT was superior to that of the other ZnO TFTs with MgO insulators grown with lower oxygen percentages. The turn-on voltages of the ZnO TFTs with MgO grown under oxygen percentages of 30%, 50%, and 70% were -2.9, -3.4, and -2.2 V, respectively. These values were derived from the linearly increasing $I_{DS}^{1/2}$ region,



which is shown in Fig. 3.7. The I_{ON}/I_{OFF} ratios of the ZnO TFTs with MgO insulators grown using oxygen percentages of 30% and 50% were similar (approximately 10⁴), while the 70%-oxygen-percentage ZnO TFT device showed a value of ~10⁵, because of the higher current generated compared with the other devices.



Fig. 3.6 $I_{DS}-V_{DS}$ curves for ZnO-based TFTs with deposited MgO layers grown using oxygen percentages of (a) 30%, (b) 50%, and (c) 70%





Fig. 3.7 $log(I_{DS})-V_{GS}$ (red circles), $\sqrt{I_{DS}-V_{GS}}$ (green squares), and I_G-V_{GS} (black lines) curves for ZnO-based TFTs with MgO insulators grown with oxygen percentages of (a) 30%, (b) 50%, and (c) 70%



3.1.4 Conclusion

In summary, ZnO TFTs with MgO insulators were successfully fabricated with different oxygen percentages in the reactive gas mixture, using RF magnetron sputtering. The dielectric constant increased from 7.48 to 11.35 as the oxygen percentage was increased. The ZnO TFT with an MgO insulator grown using an oxygen percentage of 70% showed a field-effect mobility of 0.0235 cm²·V⁻¹·s⁻¹, an I_{ON}/I_{OFF} ratio of ~10⁵, and an SS value of 1.18 V·decade⁻¹. The MgO insulator properties were controlled by changing the oxygen percentage in the reactive gas mixture.





Chapter 4. Summary & Conclusion

This dissertation explores the characteristics of thin film transistors containing ZnO or MgZnO. $Mg_xZn_{1x}O$ and ZnO thin films were deposited by RF magnetron co-sputtering on SiO₂/Si substrates. The Mg composition of the ZnO thin films was controlled using ZnO and $Mg_{0.3}Zn_{0.7}O$ targets co-sputtered under variable applied RF power. The thin films showed similar crystallinity with c-axes orientated perpendicular to the thin films. Increased Mg incorporation into the ZnO thin film increased its resistivity. $Mg_xZn_{1x}O$ also showed an increased optical band gap compared with that of ZnO.

The ohmic contact of $Mg_{0.3}Zn_{0.7}O$ was investigated using the metals Ni/Au, Ti/Au, Al, and In/Au. Ni/Au and Ti/Au showed ohmic behavior with the $Mg_{0.3}Zn_{0.7}O$ thin film; the contact resistance was 97.6 Ω cm² (Ni/Au).

ZnO thin film was deposited with Mg incorporated at 1 at.% and 10 at.%. The resulting MgZnO TFTs (MISFETs) were evaluated. The mobility of the TFTs decreased with increasing Mg content. However, the transistor incorporating a heterojunction of MgZnO and ZnO thin film showed greater mobility than a single-layer ZnO TFT. The performances of Mg_xZn_{1x}O/ZnO bi-layer TFTs with varying ZnO thicknesses were evaluated; they showed more stable characteristics than a ZnO TFT device.

Finally, a ZnO TFT with an MgO insulator was fabricated. MgO is expected to decrease power consumption due to its high dielectric constant of 9.8. The MgO insulator layer was deposited under different oxygen concentrations; higher levels of ambient oxygen increased the dielectric constant to 11.35.


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