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Fabrication of Pt-Circular Schottky Diode on Undoped AlGaN/GaN HEMT

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Abstract: In this study, Pt-circular Schottky diode is successfully fabricated for gas sensor application. The fabricated Schottky diode shows good rectification characteristics. The device which shows improvement in term of wiring connection for electrical characterization is fabricated. The DC I-V curves of fabricated Schottky diodes show low series resistance of 210 Ω and 330 Ω. The Schottky barrier height (SBH) in the range of 0.458-0.708 eV are experimentally obtained and the discrepancy with the calculated SBH is discussed. A measurement setup that has a capability to allow measurement at high temperature, high hydrogen gas density and low vacuum pressure is also presented. The fabricated device is expected to be suitable for gas sensing application.

Key words: HEMT, gas sensor, Schottky diode, AlGaN/GaN, wide bandgap

INTRODUCTION

Recent trends toward the so-called ubiquitous network era combined with the progress of nanotechnology are rapidly opening up a new horizon for application areas of III-V nanoelectronics, combining information technology, nanotechnology and biotechnology. III-V materials such as GaAs, InP, GaN and their heterostructures are good platforms for such applications, since they are industrially proven materials for constructing high performance communication devices and high speed signal processing integrated circuits. Additionally, their superb transport properties are surface sensitive for sensing physical, chemical and biochemical information (Hasegawa and Akazawa, 2007).

In view of increased use of fuel cells as a new clean and viable energy source to replace petroleum, hydrogen sensors are strongly demanded to avoid hazardous explosion. Since, the so-called sensor networks are making a rapid progress, the sensor material from semiconductor group is preferable since on-chip integration with other micro and nanoelectronic devices can be easily realized (Usami and Ohki, 2003). There have been many reports on chemicals sensors using metal-oxide compound semiconductors, such as SnO_2 and ZnO (Yamazoe and Miura, 1992; Morrison, 1982). However, the sensing mechanism of these compound semiconductors is related to various defects such as oxygen vacancy and metal vacancy. In addition, these materials are also not suitable for high temperature operation.

There is a strong interest in GaN-based material gas sensor for applications including fuel leak detection in automobiles and aircraft, fire detectors, exhaust diagnosis and emissions from industrial processes (Luther *et al*., 1999). This material is capable of operating at much higher temperatures than many of the conventional semiconductors such as Si because of its large bandgap. It was also reported that sensor with Schottky diode structures or field-effect transistor (FET) structures fabricated on GaN and SiC (Casady *et al*., 1998) are sensitive to a number of gases, including hydrogen and hydrocarbons (Kim *et al*., 2003).

This study presents the fabrication of a Pt-circular Schottky diode on undoped-AlGaN/GaN high-electron mobility-transistor (HEMT) structure for hydrogen gas sensor applications. The fabricated Schottky diode shows good rectification characteristics. A measurement setup that has a capability to allow measurement at high temperature, high hydrogen gas density and low vacuum pressure is also presented. The sensing response is presented elsewhere (Mohamad *et al*., 2010).

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MATERIAL AND DEVICE STRUCTURES

AlGaN/GaN heterojunction has been shown to form a potential well and a two-dimensional electron gas (2DEG) at the lower heterointerface. These structures are well known for possessing high electron mobility in the 2DEG channel, highest sheet carrier concentration among III-V material system, high saturation velocity, high breakdown voltage and good thermal stability.

A schematic of undoped AlGaN/GaN HEMT structure is shown in Fig. 1. The undoped-AlGaN/GaN substrates are grown by metal organic chemical vapor deposition (MOCVD) on 430 μm c-plane sapphire substrates. The epitaxial structure consists of a 25 nm undoped-AlGaN, a 2 μm thick undoped-GaN and a buffer layer. A sheet carrier concentration and mobility of this epitaxial substrate determined by Hall measurement at room temperature are 6.61×10^{12} cm^{-2} and 1860 cm^2/V sec, respectively. The mobility for undoped-AlGaN/GaN material used in this study is two times higher than the Si-doped AlGaN/GaN reported by Matsuo *et al.* (2005). Therefore, it is expected that this material structure can produce faster response which can be determined from current-time transient (I-t) measurement.

SiO_2 layer is applied as a mask for the dry etching process. Before the deposition of SiO_2 film on the surface of undoped-AlGaN/GaN, the native oxide is removed using BHF solution. Next, 100 nm of SiO_2 layer is deposited using Plasma-Enhanced Chemical Vapor Deposition (PECVD). Then, the unwanted SiO_2 layer is etched out using buffered hydrofluoric acid (BHF) solution. The mesa patterns is formed by applying dry etching process for 30 sec using an inductively-coupled plasma reactive ion etching (ICP-RIE) system with gas mixture of BCl_3 (20 Sc cm) and Cl_2 (10 Sc cm). The etching parameter and depth for the samples is shown in Table 1. The impact of DC bias voltage on the undoped-AlGaN/GaN etch depth is shown in Fig. 2. It can be clearly seen that lower DC bias shows deeper etch depth.

After ICP-RIE, the SiO_2 mask is removed using BHF solution and organic solvent treatment to clean the samples before being proceeded to ohmic formation. Ohmic contacts are formed by e-beam deposition and lift-off process. The metals and thicknesses of ohmic contact are Ti/Al/Ti/Au and 20/50/20/150 nm, respectively. Following that, rapid thermal annealing process at 850°C for 30 sec is carried out. Figure 3 shows the I-V characteristics of ohmic contact of sample B and

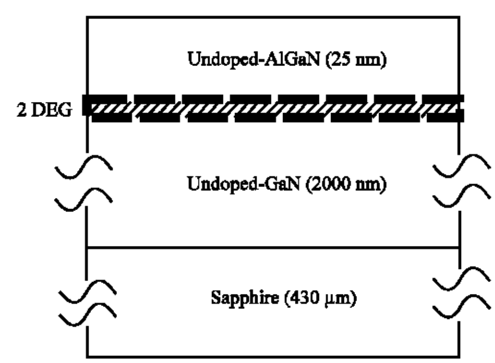


Fig. 1: The material structure

Table 1: The condition of etching and etched depth

Sample	Pressure (mTorr)	Power of RIE (W)	Power of ICP (W)	DC bias (V)	Etch depth (nm)
A	5	200	500	220	142.75
B	5	200	500	219	152.42
C	5	200	500	216	154.68
D	5	200	500	215	162.98

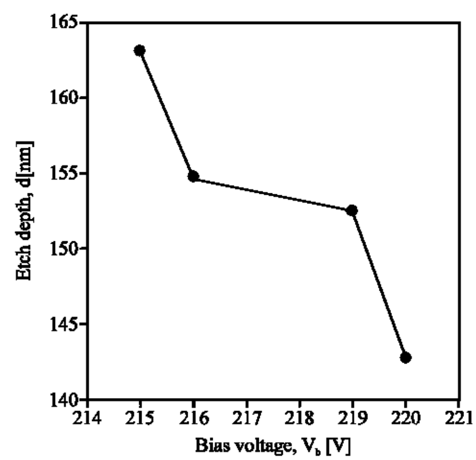


Fig. 2: Undoped-AlGaN/GaN etches depth as a function of bias voltage

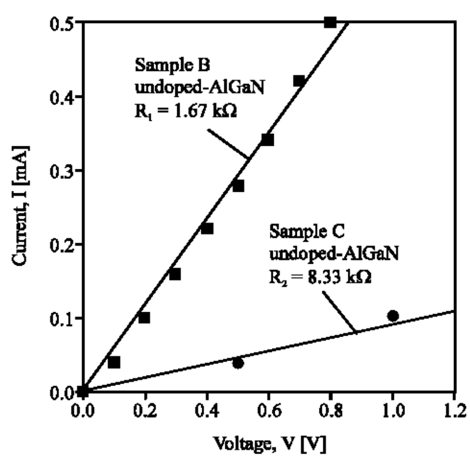


Fig. 3: The current-voltage for ohmic characteristic

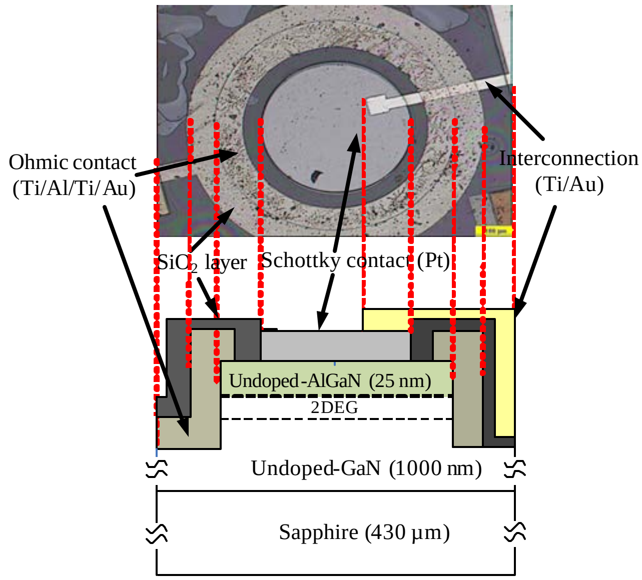


Fig. 4: Fabricated device and cross sectional of circular Pt/AlGaN/GaN Schottky diode

sample C after annealing process. The series resistance for sample B, R_1 is estimated to be 1.67 kΩ and sample C, R_2 is 8.33 kΩ.

Finally, the Schottky contact is formed by evaporating a 5 nm thick catalytic Pt metal. The transient time of current is expected to be faster if the thickness of Schottky contact decreases (Hudeish *et al*., 2005). Figure 4 shows a fabricated device and cross sectional of circular Pt/AlGaN/GaN Schottky diode.

In this preliminary study, the devices with Schottky contact diameter, d of 400 and 600 µm are fabricated. The device with diameter, d of 400 µm is named Schottky diode S1 and the device with diameter, d of 600 µm is named Schottky diode S2. Schottky diode S1 and Schottky diode S2 are the fabricated devices on the sample B.

RESULTS AND DISCUSSION

DC I-V characteristics of circular Schottky diode: In this study, the Pt-undoped-AlGaN/GaN Schottky diode is successfully fabricated. The DC I-V characteristics are measured using Agilent Parameter Analyzer Model 4145B and Micromanipulator Probe Station. As shown in Fig. 5, the DC I-V curve of a fabricated Schottky diode S1 and Schottky diode S2 shows a diode I-V curve with a 210 Ω and 330 Ω series resistance, respectively, defined at the slope between 2 and 4 V.

The trend in the variation of current with applied bias appears to follow the thermionic emission (Sharma, 1984). Measurements of the reverse saturation currents of the devices are used to calculate the Schottky barrier heights (SBHs) from the Richardson-Dushman equation for the thermionic current. I_s given by:

$$\phi_B = V_t \cdot \ln\left(\frac{A \cdot A^* \cdot T^2}{I_S}\right) \tag{1}$$

In Eq. 1, ϕ_B is the barrier height in volts, I_s is the reverse saturation current, V_t is the thermal voltage, A* is the effective Richardson constant, A is the area of the metal-semiconductor contact and T is the absolute temperature. The reverse leakage current for device S1 is 69.99 µA and SBH is calculated to be 0.458 eV, while the reverse leakage current for device S2 is 9.9 nA and barrier height is calculated to be 0.708 eV. These SBH values are much lower than the ideal calculated value which is 1.55 eV.

The discrepancy of Schottky barrier height is may due to the fabrication process, i.e., annealing process, where it can result in the decrease in barrier height as suggested by Zhang (1999). They have reported Schottky contacts of different metals to the n-type AlGaAs/GaAs structures and proposed a model, which involves quality of the contact and defect formation at the semiconductor surface due to interdiffusion and/or penetration of metal to the semiconductor. This model can qualitatively explain the difference in barrier heights and degradation of barrier due to certain process.

In addition, it was also reported by Mustafa *et al*. (2010) where the work functions of the metal and the semiconductor are determined by the process. The actual

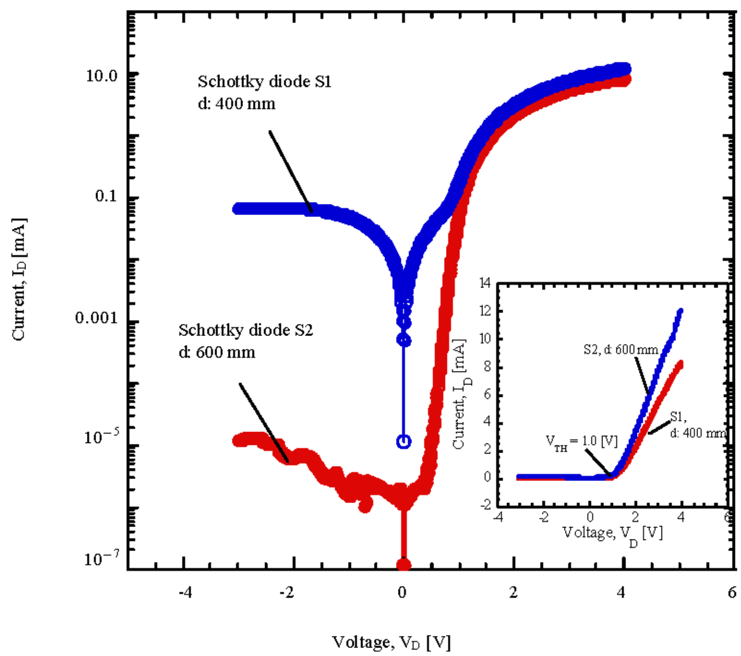
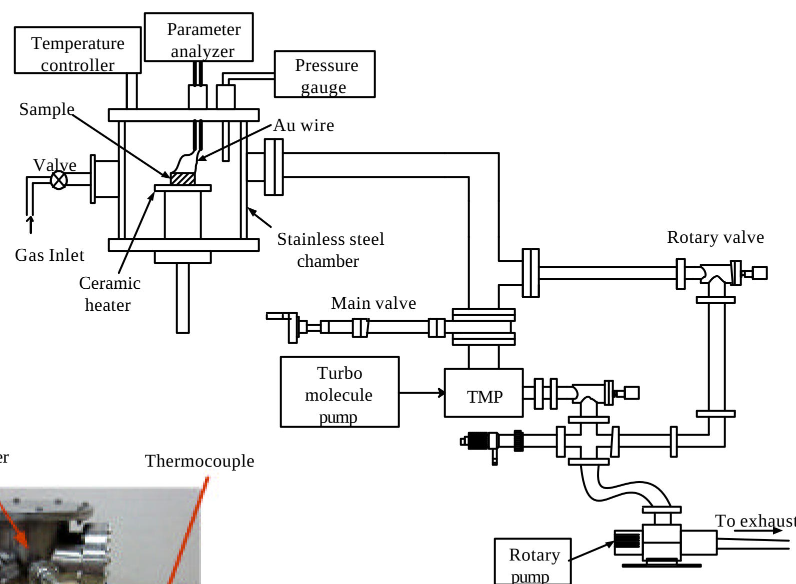


Fig. 5: DC I-V curve of fabricated Schottky diode S1 and S2

(a)



(b)

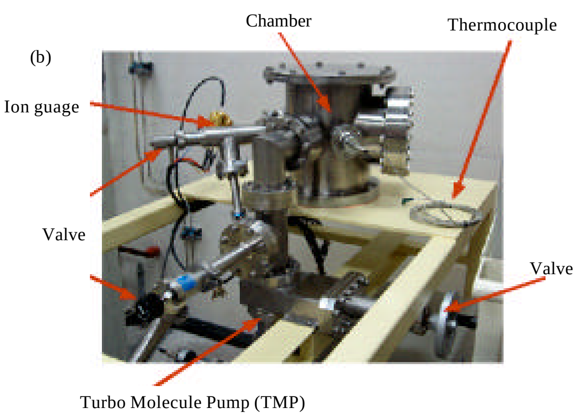


Fig. 6: (a) Schematic and (b) photo of measurement system

nature of the metal-semiconductor contact is not controllable and in fact may vary substantially from one process to another.

Sensing measurement system: A schematic and photo of sensing measurement system is shown in Fig. 6a and b, respectively. The system can be used for measurement at low vacuum pressures, high temperatures and also high hydrogen gas density. With the capability to vacuum the chamber down to 10^{-6} Torr, high concentration of hydrogen gas can be introduced into the vacuum chamber without any possibility of explosion during high temperature measurement. The results of current-voltage (I-V) characteristics and time transients of current (I-t) of the Schottky diodes exposed to hydrogen gas is reported elsewhere (Mohamad *et al*., 2010).

CONCLUSION

Pt-circular Schottky diode was successfully fabricated for gas sensor application. The fabricated Schottky diode showed good rectification characteristics. The DC I-V curves of fabricated Schottky diodes showed low series resistance of 210 and 330 Ω. The SBH in the range of 0.458-0.708 eV were experimentally obtained and the discrepancy with the calculated SBH was discussed. A measurement setup that has a capability to allow measurement at high temperature, high hydrogen gas density and low vacuum pressure was also presented.

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