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A Novel Pt-AlGaN/GaN Heterostructure Schottky Diode Gas Sensor on Si

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SUMMARY Schottky gas sensors of CO were fabricated using high quality AlGaN/GaN/Si heterostructures. The CO sensors show good sensitivity in the temperature range of 250 to 300°C (530%, at 160 ppm CO in N_2) and fast response comparable with SnO_2 sensors. A two-region linear regime was observed for the dependence of sensitivity on CO concentration. GaN sensors on Si substrate offer the possibility of integration with Si based electronics. The gas sensors show slow response with time, the change of material properties possibly in the presence of large thermal stress.

key words: *AlGaN/GaN, gas sensor, Schottky diode, sensitivity*

1. Introduction

GaN-based wide-band-gap semiconductors have become one of the most extensively studied materials and rapid progress has been demonstrated in both optical and electrical devices. Due to their wide band gap and good thermal and chemical stability, GaN based semiconductor materials are also very promising for high-temperature gas sensor devices. In addition the small Fermi level pinning characteristics of GaN are also an important features that may lead in high gas sensitivity.

Recently, Pt-GaN Schottky diodes [1] and AlGaN/GaN transistors [2] have been shown to respond to hydrogen and hydrocarbon species. These devices were found to operate in similar way that hydrogen sensitive field effect sensors operate on Si and SiC [3]–[5]. In sensors of this type, hydrogen atoms diffuse through the Pt and are adsorbed at the metal-semiconductor interface, where they cause electrical polarization, which then changes the electrical properties of the diode. It is well known that the AlGaN/GaN interface has a large polarization field related to piezoelectricity and spontaneous polarization [6] that causes a high-density two-dimensional electron gas to be formed at the AlGaN/GaN interface. The intrinsic polarization fields on the AlGaN/GaN surface are accepted to play an important role in determining the gas sensitivity and response speed. In this study, a Pt-AlGaN/GaN Schottky diode gas sensor on Si (111) substrate was investigated in the temperature range of 250°C to 300°C. The results indicate that the investigated Pt-AlGaN/GaN Schottky diode sensor has good sensitivity to CO. The use of Si substrates for the development of the proposed gas sensors provides a low cost solution, which at the same time permits sensor integration with electronics for signal treatment.

2. Experimental

The AlGaN/GaN sensor material was grown by MOCVD. A cross section of the sensor structure is shown in Fig. 1. Hall measurement on this sample yielded an electron mobility of 1500 $\mathrm{cm^2/Vs}$ and a sheet electron concentration of $6\text{–}7\times10^{12}\,\mathrm{cm^{-2}}$ at room temperature. The high sheet carrier concentration and electron mobility indicate the presence of a two-dimensional electron gas formed at the AlGaN/GaN interface. 70 nm Pt dots of 300 μm in diameter were evaporated on the AlGaN/GaN surface to form Schottky contacts. Ohmic contacts were fabricated by evaporating an Au (100 Å)/Ti (100 Å)/Al (3000 Å) mutilayer on the AlGaN/GaN surface.

The structural and interface quality of the sample were determined using a high-resolution X-ray diffractometer (Bede Scientific Instruments Ltd., Bede D1) through rocking curves and grazing incidence X-ray reflectivity (GIXR) measurements. The details of the obtained results are given in Table 1.

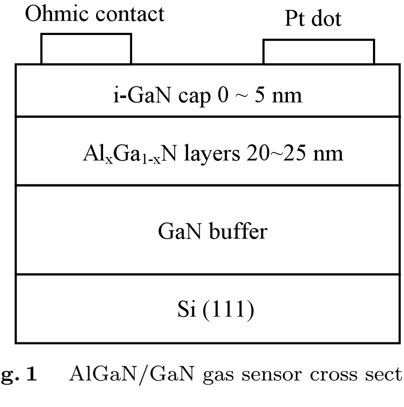

Fig. 1 AlGaN/GaN gas sensor cross section.

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Table 1 Samples structure.

Layer	Materials	Thickness (nm)	Al composition	Interface roughness (Å)
6	AlGaN	25.5	0.21	9.9
5	GaN	720.3	0	1.6
4	AlGaN	45	0.35	2.0
3	AlGaN	40	0.55	/
2	AlGaN	60	0.87	/
1	AlN	110	1	/
Substrate	Si (111)	N/A	N/A	/

3. Results and Discussions

Figure 2(a) shows the (0002) rocking curve with full width at half maximum (FWHM) of 1087 arcsec. The large FWHM is due to large thermal mismatch (56%) between GaN and Si, and indicates the presence of tensile stress and dislocations. Experimentally obtained GIXR results are shown together with simulated characterization in Fig. 2(b). Good agreement was observed between measured and simulated results and the interface roughness of AlGaN and GaN buffer layer of was found to be 0.16 nm. The small interface roughness between GaN and AlGaN supports possibility of obtaining high quality “HEMT”-sensor devices.

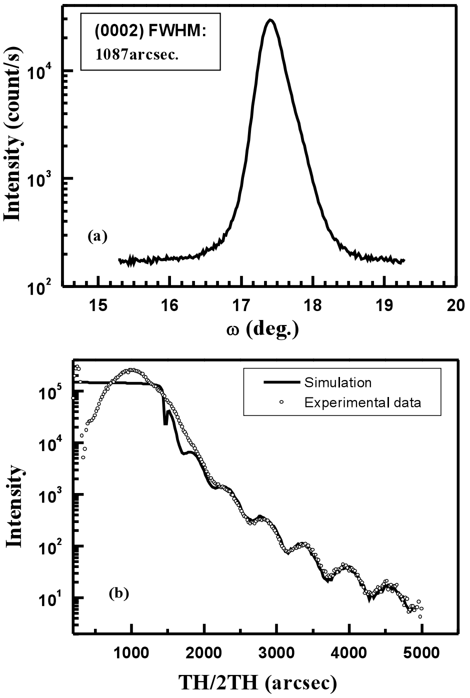

Fig. 2 X-ray diffraction rocking curves and grazing incidence X-ray reflectivity measurements. (a) (0002) rocking curve; (b) grazing incidence X-ray reflectivity.

Gas sensing experiments were performed in a heated quartz tube reactor. The quartz tube gas inlet was connected to a gas manifold, which provided pure N_2 as carrier gas and a 0.18% mixture of carbon monoxide (CO) in nitrogen. The operation temperature was controlled by the furnace temperature controller. The total gas flow rate used in the experiments was 2 SLM. The experiments were carried at a temperature of 250°C and 300°C while the CO gas concentration ranged from 8 to 160 ppm.

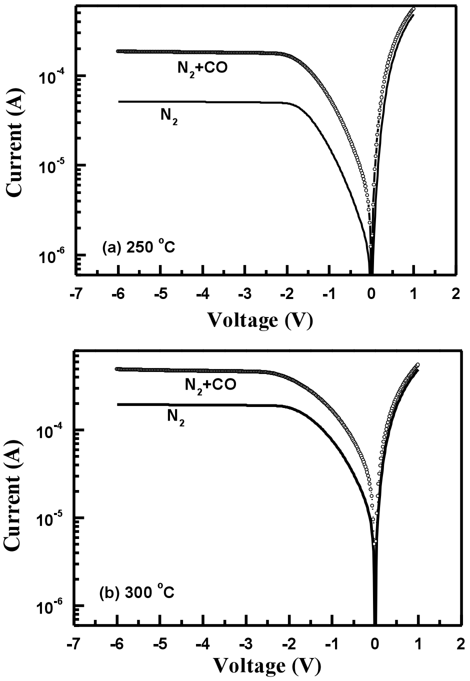

Fig. 3 Logarithmic I-V characteristics in N_2 and 8 ppm CO at (a) 250°C; (b) 300°C.

The current versus voltage (I-V) characteristics and the CO response were measured at 250 and 300°C. Typical I-V characteristics obtained in N_2 and 8 ppm CO in N_2 are shown in Fig. 3. The sensor showed low leakage current and high sensitivity, which open the possibility of use in commercial applications such as domestic gas detection due to low operation current and high sensitivity. It is interesting to notice that higher sensitivity is observed at reverse rather than forward bias operation, which is contrary to the finding of Luther [1]. This is in support of good quality material being used for the sensors and may also indicate a difference in response to CO used in this work versus H_2 used by Luther [1]. The change of barrier height may be extracted from current-voltage characteristic and a value of 1.01 V was found in N_2 at 250°C. When the diode was exposed to 8 ppm CO in N_2, the effective barrier height was decreased from 1.01 to 0.95 V. Moreover, the barrier height was decreased from 1.12 V under N_2 to 1.09 V in 8 ppm CO when the sensor was operated at 300°C. The barrier height variation can be explained by hydrogen atoms diffusing through the Pt and adsorbed at the metal-semiconductor interface, where they cause electrical polarization, which then changes the electron affinity. The temperature dependence of the barrier height indicates inhomogeneous character-

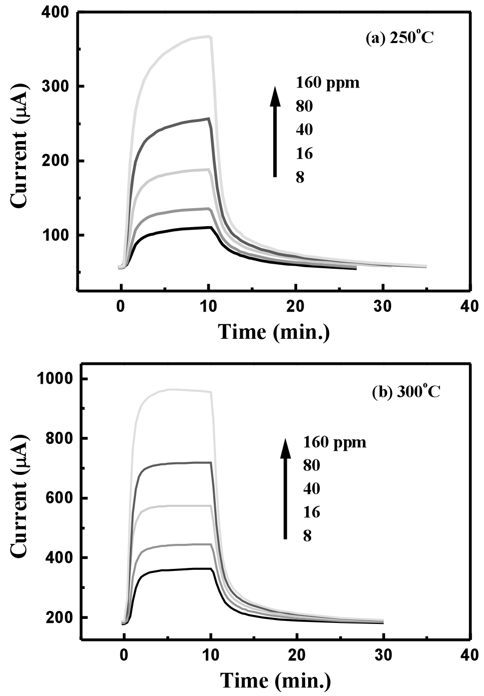

Fig. 4 Response characteristics to different CO concentrations at (a) 250°C and (b) 300°C.

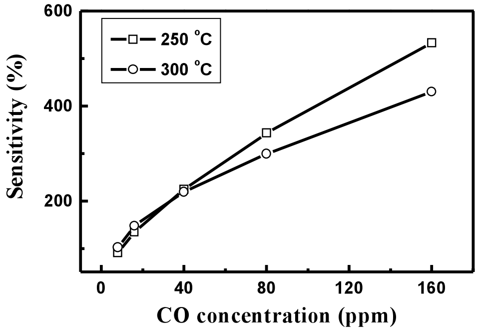

Fig. 5 Sensitivity as a function of CO concentration at 250°C and 300°C.

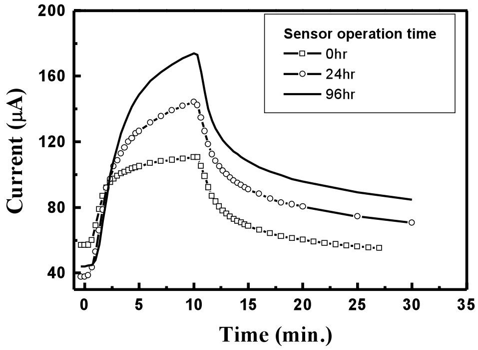

Fig. 6 Change of response characteristic with time at 250°C.

istics for the Schottky contact. Possible reasons include material surface imperfections [7].

The transient response characteristics of the gas sensor in the presence of CO manifest a reverse current increase with CO concentration and are shown in Fig. 4 for the case where the voltage was kept constant at −5 V. As shown by the characteristics of Fig. 4, the gas sensor shows a fast response and short recovery time. The response varied from 2 to 4 min. as defined by the time to reach 90% of the saturation current, which depends on operation temperature and CO concentration. The recovery time of the sensors varied from 10 to 20 min as estimated by the time necessary for the current to return to 10% of its original value. As seen in Fig. 4, both response and recovery (decay) characteristics were improved as temperature increases. A change from 4 to 2 min. for response time and 20 to 10 for recovery time were estimated for a change of operation temperature from 250°C to 300°C. The sensors have very slow response and long recovery time when operated at 200°C, and no sensitivity was observed at room temperature.

The sensitivity $S = (I_{\mathrm{CO}} - I_0)/I_0 \times 100\%$ of the sensor is shown in Fig. 5 for different CO concentrations at two operation temperatures. The results show that the Pt-AlGaN/GaN sensor demonstrates sensitivity varying between 100% and 530% at 250°C and 300°C depending on the CO concentration. The sensor sensitivity is even better than that of $\mathrm{SnO_2}$ sensors ($\mathrm{S_{SO_2}}$=25% at 100 ppm CO [8]). In addition, the sensitivity changes from one linear regime to another as the CO concentration increases. The response time appears to become longer with time of operation as seen in Fig. 6, possibly due to the degradation of material quality caused in the presence of thermal stress.

4. Conclusion

Schottky gas sensors were fabricated using high quality AlGaN/GaN/Si heterostructures. A two-region linear regime was observed for the dependence of sensitivity on CO concentration. The CO sensor shows good sensitivity (530%, at 160 ppm CO) and fast response (2–4 min.), the sensitivity is even better than $\mathrm{SnO_2}$ sensors. The AlGaN/GaN sensor opens the possibility of commercial applications such as domestic gas detection due to low operation current and high sensitivity. Increase of sensor response was observed, after extended operation, possibly due to large thermal stress.

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