

*Full Length Research Paper*

# Enhanced oxygen gas sensor by surface-etched gallium oxide

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**Surface-etched Pt/gallium oxide semiconductor structure has been successfully fabricated and studied for the sensing of oxygen gas. The effects of the sandwich oxide structure with larger sensing area on the oxygen gas sensing property are investigated. In the existence of the etched V-groove gallium oxide geometry, its electrical and sensing properties, that is, high sensitivity, significant increase in output current and short response time are characterized. Under the equipment temperature of about 860°C and changeable oxygen gas in nitrogen, a large variation of dynamic resistance 63 KΩ is obtained. From experiment, good stability and repeatability of the oxide sensor are demonstrated when tested under different oxygen concentration. These properties show that the oxide structure has a good potential for high sensitivity oxygen sensor.**

**Key words:** Gallium oxide, oxygen gas sensor, sensitivity, response time.

## INTRODUCTION

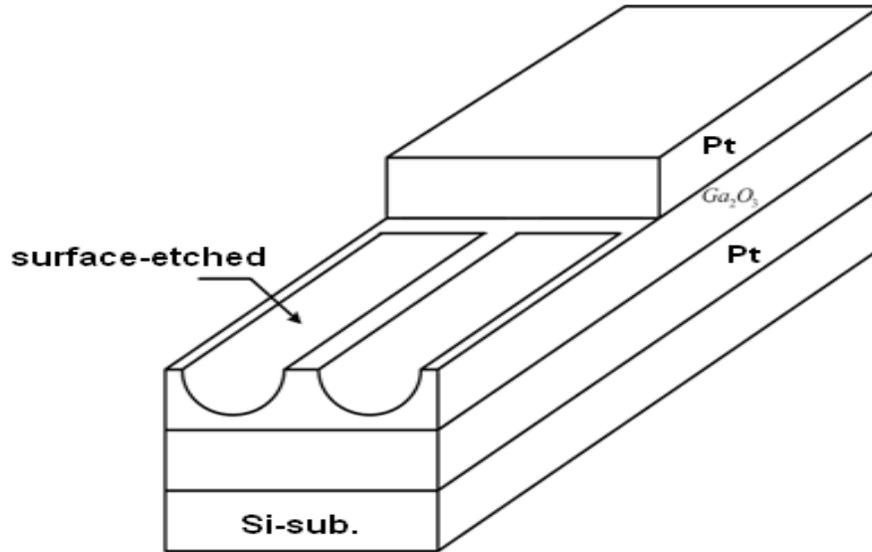
Recently, the current interest is focused on the growth in simple structures to fabricate oxygen sensors for applications in several areas, such as exhaust gas sensors in the automotive or monitoring furnace installations. In addition, oxygen sensor is an important topic because it can prevent the inflammation of explosive gases and also important in medical areas for ventilation assistance. Among several different processes for detecting oxygen, the electrical resistance changes due to oxygen adsorption on the oxide surface based on the semiconductor materials, is the most commonly used one (Tan et al., 2004; Taurino et al., 2003; Cosandey et al., 2000). Most research has been done by using other metal oxide semiconductors, especially tin oxide (SnO<sub>2</sub>) and zinc oxide (ZnO) which have shown a high potential application as oxygen sensors (Henrich and Cox, 1994; Rantala et al., 2000; Al-Hardan et al., 2010). Gallium oxide (Ga<sub>2</sub>O<sub>3</sub>) is one of the most promising oxides as a metal oxide gas sensor. It exhibits a high temperature sensing and stable property (Castaneda, 2007; Tiburcio-Silver and Sanchez-Juarez, 2004) to oxygen gas due to the

deficiency of oxygen in the crystal lattice. But, there are still some blind spots needed to be solved on how composition of gallium oxide and response characteristics of oxygen gas may not keep stable when changing the growth condition (Ogita et al., 2003). Therefore, it is important to find the method for the improvement of the response characteristics of an oxygen sensor based on gallium oxide material. In this work, we report the fabrication of Pt/gallium oxide by reactive RF sputtering technique. The effect of the use of surface-etched gallium oxide with larger sensing area and the response of this kind of oxygen gas sensor is presented which to our knowledge has not been studied elsewhere.

## MATERIALS AND METHODS

The cross section of Pt/gallium oxide oxygen sensor to be studied is schematically shown in Figure 1. This structure consists of Pt-Ga<sub>2</sub>O<sub>3</sub>-Pt layers which were grown on a Si substrate by RF sputtering system (Ogita et al., 2003). The samples were prepared at different temperatures using pure Ga<sub>2</sub>O<sub>3</sub> as powder target and Ar as the sputtering gas. A 0.15 μm thick platinum (Pt) metal layer was deposited by using RF sputtering unit with the power of 200 W. After metal growth, a 0.3 μm thick gallium oxide layer was sputtered on the Pt metal with the pure Ga<sub>2</sub>O<sub>3</sub> target under 950 °C to play as the

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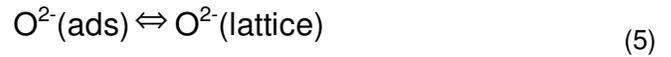
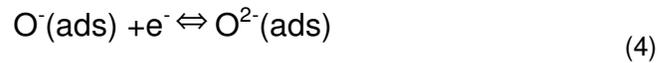
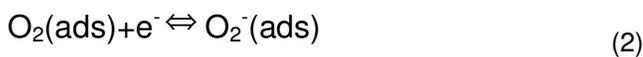


**Figure 1.** Schematic cross-section of the surface-etched Pt-Ga<sub>2</sub>O<sub>3</sub>-Pt oxygen sensor.

oxygen sensing layer. The top view V-groove geometry on the surface of gallium oxide was then formed by the oxide etching solution with photolithographic technique. After etching process, the Pt electrode contact was evaporated by using the lift-off technique. The dc characteristics were measured by using a semiconductor parameter analyzer Agilent E5263. The oxygen sensing properties were also measured in a controlled stream of oxygen and nitrogen mixture gas continuously flowing through the quartz tube. Different concentrations of oxygen and nitrogen mixture gas through the quartz tube with adjustable temperature controller were employed in this study. The oxygen percentages are related to the flow rate and represent an approximation for the partial pressure of the oxygen gas.

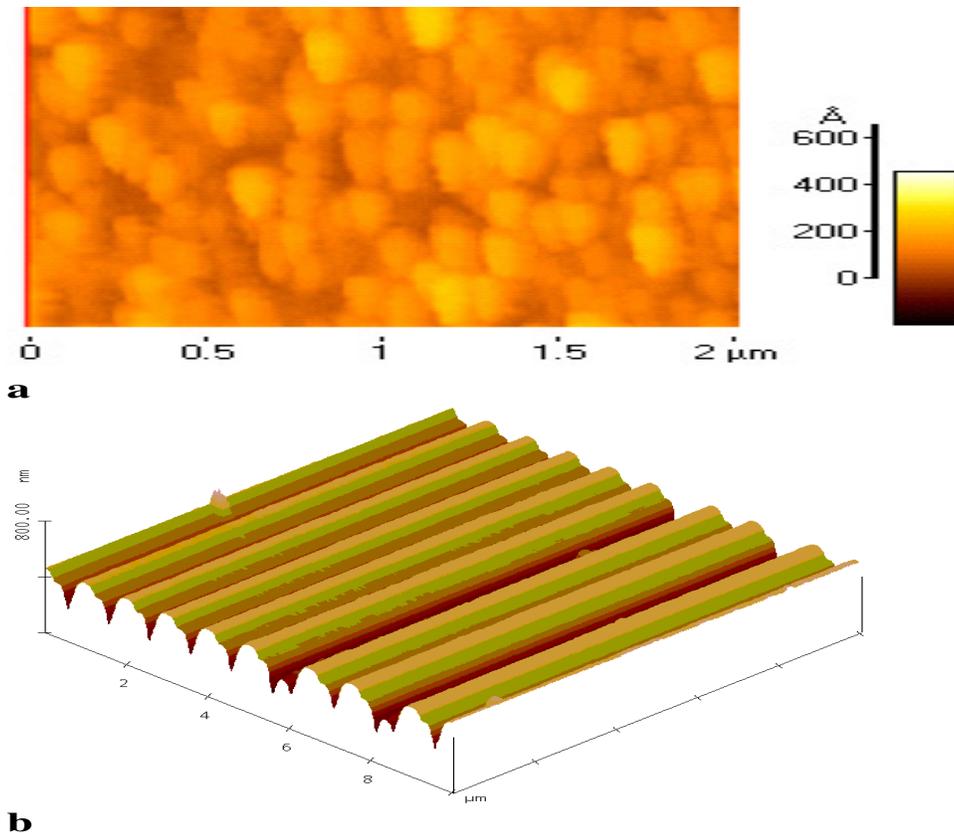
## RESULTS AND DISCUSSION

Here, the gas-sensing properties of the V-groove Pt/gallium oxide structure were characterized for oxygen gas sensing. First, the oxygen sensing mechanism can be simply explained as follows: When oxidizing gases occupied the atmosphere near the sensor surface, more oxygen atoms will be adsorbed at the surface, which would result in attracting much more electrons from the conduction band. Consequently, it will result in the decrease of the surface conductivity (Adamowicz et al., 2008). The corresponding chemical reactions are as follows:

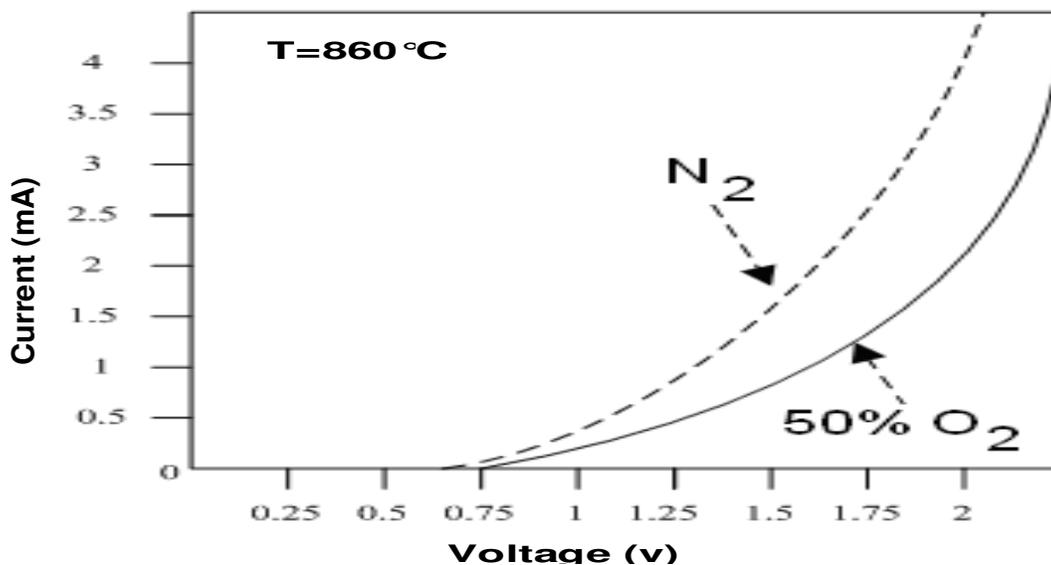


Among the oxide-based oxygen sensors, the film quality is the dominant factor to affect the properties of the response characteristics to oxygen gas. An amorphous Ga<sub>2</sub>O<sub>3</sub> oxide film may be utilized as a good gas sensor with oxygen deficiency (Ogita et al., 2001). The improved electrical conductivity can be considered that the existence of many unoccupied bonds which are induced by oxygen vacancy. Based on the physical understanding of the principle of oxygen sensor, we propose that the surface-etched Ga<sub>2</sub>O<sub>3</sub> oxide may exist much more unoccupied bonds and high sensitivity to oxygen gas can be expected in our work. To check the Ga<sub>2</sub>O<sub>3</sub> oxide film quality, the AFM measurement is executed. Figure 2a shows the AFM micrograph of Ga<sub>2</sub>O<sub>3</sub> film deposited at the sputtering pressure of 5Pa. From experiment, it was found that the deposited film at lower sputtering pressure will have larger grain size than that of deposited film at a higher pressure and result in a fast rising response. Thus, the gas sensitivity is dependent on the sputtering pressure which affects the grain size of the Ga<sub>2</sub>O<sub>3</sub> oxide.

The 3D surface roughness of the proposed V-groove etched Ga<sub>2</sub>O<sub>3</sub> oxide film by photolithographic technique which is measured by AFM is also shown in Figure 2b. The average etched depth is 195 nm. Figure 3 shows the corresponding current-voltage (I-V) characteristics of the surface-etched Pt-Ga<sub>2</sub>O<sub>3</sub>-Pt structure measured under 50% O<sub>2</sub> at 860°C and N<sub>2</sub> at room temperature. The corresponding turn-on voltages are 0.75 and 0.635 V,



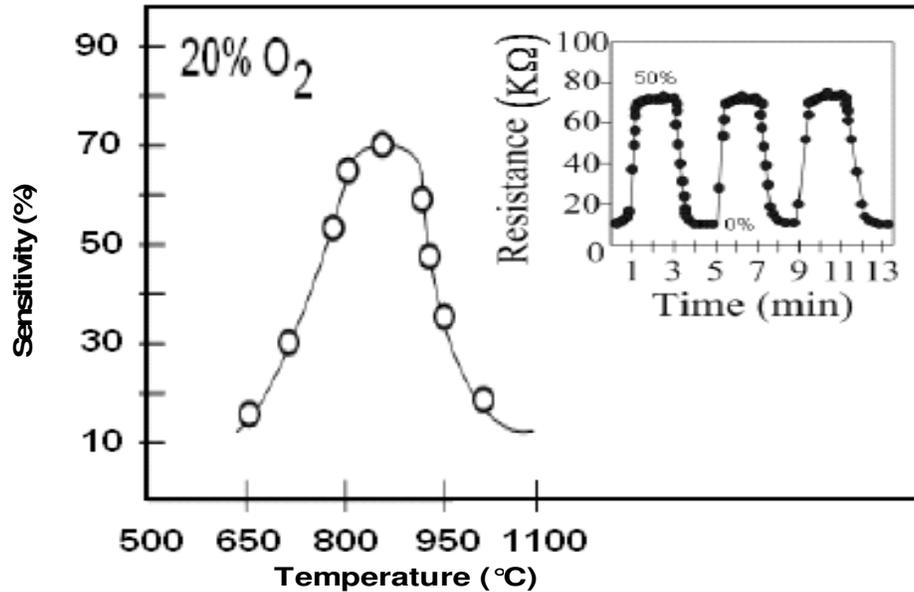
**Figure 2.** (a) AFM 2D image of the RF sputtering  $\text{Ga}_2\text{O}_3$  film prepared at  $950^\circ\text{C}$ ; (b) AFM 3D image for surface of the V-groove  $\text{Ga}_2\text{O}_3$  film.



**Figure 3.** Typical I-V characteristics of the proposed sensor measured in  $\text{N}_2$  and 50%  $\text{O}_2$  environment.

respectively. The relatively lower turn-on voltage of the proposed oxygen sensor is mainly attributed to the insulated oxide layer. The larger turn-on voltage at 50%

$\text{O}_2$  condition is attributed to the higher sensor resistance resulted from the formation of oxygen vacancy. A typical dynamic response time for the surface-etched oxygen



**Figure 4.** Dependence of the proposed sensor on the operating temperatures at 20% O<sub>2</sub>. The dynamic response of the proposed sensor with a 50 to 0% oxygen range at 860°C is in the inset.

sensor which is easy to be changed in the O<sub>2</sub> gas composition between 50 and 0% is demonstrated in the inset of Figure 4. The increased sensor resistance while increasing O<sub>2</sub> concentration indicates that the electrical conduction is due to electrons. On the contrary, the decreased sensor resistance while decreasing O<sub>2</sub> concentration indicates that the electrical conduction is due to the formation of oxygen vacancy and releasing electrons. The variation sensor resistance between the maximum and minimum is up to 63 KΩ at temperature 860°C.

In addition, the calculated average response time ( $\tau$ ) which is defined as the sensor resistance from zero to 90% of its saturation value, for the proposed oxygen sensor, a response time of 12.5 s is obtained. The shorter response time can be explained by the larger interface oxygen vacancy and a larger electron relation rate. It is also found that the sensing temperature is lower than that of previous report (Ogita et al., 2003). The deviation in temperature may be as a result from the different measurement system and the larger sensing area in the proposed structure. In addition, for an oxygen sensor, the sensitivity is defined as follow:

$$S (\%) = \frac{R_g - R_a}{R_a} \times 100\% \tag{6}$$

where R<sub>g</sub> and R<sub>a</sub> represent the resistance in the oxygen gas and atmosphere, respectively. The dependence of sensitivity t a fixed 20% O<sub>2</sub> concentration at different

temperature is shown in Figure 4. From the experiment, it was found that the enhanced sensitivity is up to 72% at lower temperature (840°C) and is attributed to an increase of surface area in this proposed structure (Baban et al., 2005; Moseley, 1992).

**Conclusion**

A new metal-oxide oxygen sensor with larger area V-groove Ga<sub>2</sub>O<sub>3</sub> surface structure is fabricated tested and described. The good quality Ga<sub>2</sub>O<sub>3</sub> layer is employed to obviously modulate the direct current turn-on voltage and oxygen detection sensitivity. The short rising response time of 12.5 s is observed for the 50% O<sub>2</sub> and 0% O<sub>2</sub> conditions. From the experiment, it is found that the proposed structure owns good electrical property and is sensitive in a wide temperature range due to the larger sensing surface area. This kind of new oxygen sensor is also sensitive for the low oxygen concentration detection. Therefore, the studied new structure shows great promise for high sensitivity, fast response and exhibits potential for sensor circuit applications.

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