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SiC-based FET for NO_x gas sensing applications using $InVO_x$ metal oxides as a gate material

Introduction

Demands for exact monitoring of nitrogen oxide gases (NO_x), which are air pollutants released from combustion facilities and automobiles, have become more serious all over the world in recent years. For air quality monitoring or exhaust gas control, NO_x is the main gas to be detected, and the concentration range to be measured is about 0-10 ppm. SiC-based sensors that can be used at high temperature and in corrosive atmosphere have been under development for that purpose. An electronic device based on SiC can function as a chemical sensor with the deposition of catalytic material on a thin insulating layer on its surface. The catalytic material can be a metal such as Pt, Pd, or combinations of these [1-3]. Metal oxides can also used as catalytic layers on devices [4-6]. The field effect transistor (FET) is the most complicated device design tested to date but is a highly reliable design for gas sensors. In the case of FET gas sensor, the small changes induced in the catalytic metal by the reactant gases can cause large changes in the source-drain current, which makes this device a very effective sensor. In this paper the NO_x, O_2, and Deuterium sensing properties of SiC-based FETs with $InVO_x$ metal oxides as a catalytic gate in dependence on the operation temperature have been investigated.

Eperiments

The device fabrication process utilized mainly conventional process steps, including mesa isolation, source and drain implantation, and a field oxide deposition using a thermal oxidation. Ohmic contacts were realized using Ni metal, with rapid thermal annealing process. Finally indium oxide-vanadium oxide was deposited by co-sputtering indium oxide and vanadium oxide simultaneously to form 100 nm gate electrode.

Detailed information on the fabrication process can be found elsewhere [7-8]. For gas sensing tests, the sensors were placed into a quartz tube, which was evacuated to a base pressure of 4 x 10^{-8} mbar. Current/voltage (I-V) characteristics have been carried out at different gas concentrations on sensors, which were heated during operation at different temperatures using a furnace. The temperature was measured by a thermocouple a few millimeters above the sensor. In all cases the applied source drain voltage varied between 0 V and 20 V in steps of 40 mV while the respective values of the current were measured.

Results

In the first step the sensors were tested for the response to NO_x gas with concentrations starting from 2 and going up to 2010 ppm (pure NO_x) in vacuum at temperatures between 230 and 400°C. Fig. 1 shows the I-V characteristics of a SiC-based FET sensor in vacuum and in the presence of 2 ppm of pure NO_x at 300°C. It is obvious that the exposure of the sensor to the oxidizing gas NO_x results in a decrease of the source-drain current. The response to NO_x can be understood by considering the interaction between NO_x and $InVO_x$. NO_x molecules will affect the effective work function of the gate and thus change the current through the transistor.

If NO_x molecules are introduced between the catalyst and insulator, the difference of work function of the catalyst (metal oxide) and the semiconductor, $\Phi_{MS} = (\Phi_M - \Phi_S)$, changes upon chemical reactions on the surface interface, causing a shift in the threshold voltage V_T. This would affect the source-drain current I_{SD} in the linear region of the transistor ($V_G \ll V_{SD}$)

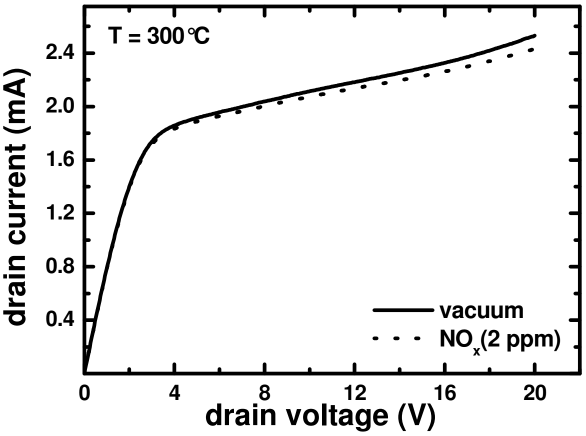

Fig. 1 I-V characteristics of the sensor operated at 300°C in vacuum (solid line) and in the presence of 2 ppm of pure NO_x (dotted line).

according to:

$$I_{SD} = \mu C_i \frac{W}{L}(V_G - V_T)V_{SD} \quad , \qquad (1)$$

where µ is the electron mobility in the channel, C_i is the insulator capacitance per unit area, W/L is the channel width-to-length ratio, V_G and V_{SD} are the applied gate-source and source –drain voltages, respectively, and V_T is the threshold voltage. The increase of work function will cause a decrease in source-drain current. This is because the threshold voltage depends on the difference between the Fermi level in the semiconductor and the catalyst. As the work function increases the threshold voltage increases and the current decreases as the (V_G - V_T) value gets lower.

In the second step the sensors were tested for the response to other gases such as deuterium with concentrations between 12 and 5180 ppm (pure D_2) at temperatures between 25 and 350°C, and O_2 with concentrations starting from 2 going up to 3030 ppm (pure O2) at temperatures between 250 and 400°C.

When the sensor is exposed to D_2, the change of current with time is measured at a constant source-drain voltage of 14 V. Fig. 2 illustrates the plot of transient currents versus time upon introduction and removal of 100, 34, 74, 16, 284, 500, 850, 1600, and 5180 ppm D_2 at a temperature of 100°C. The current increases when D_2 is introduced into the quartz tube due to a decrease in the work function of the catalytic gate and a decrease in the threshold voltage of the FET. As can be seen from Fig. 2, the source-drain current increases with increasing D_2 concentration.

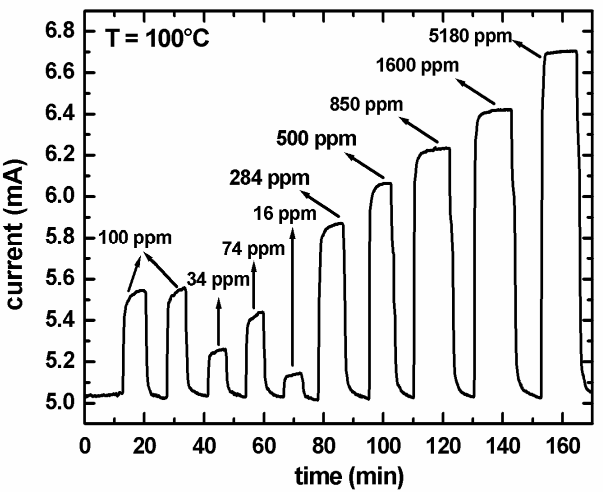

Fig. 2 Source-Drain current versus time upon introduction and removal of 100, 34, 74, 16, 284, 500, 850, 1600, and 5180 ppm D_2 at a temperature of 100°C. The applied source-drain voltage is fixed at 14 V.

The dependence of the sensitivity towards 100, 500 and 1000 ppm of pure NO_x, O_2, and D_2 on the operating temperature is presented in Fig.3. We have defined the sensitivity as the relative current variation at constant voltage expressed in percent:

$$S = \frac{I_g - I_v}{I_v} \times 100$$

Whereby I_g and I_v are the current of the sensor in presence of gas and in vacuum, respectively.

It becomes obvious from Fig. 3 that the optimum detection temperatures occur in the range of 275-325℃ for NO_x. In this range the cross sensitivity to O_2 and D_2 is very low indicating that the sensor is very suitable for selective detection of NO_x. The optimum temperature of operation for detection of deuterium is determined to be between 25-100℃. In this range no significant response to O_2 and NO_x is observed indicating that the sensor is very suitable for selective D_2 detection at very low temperatures.

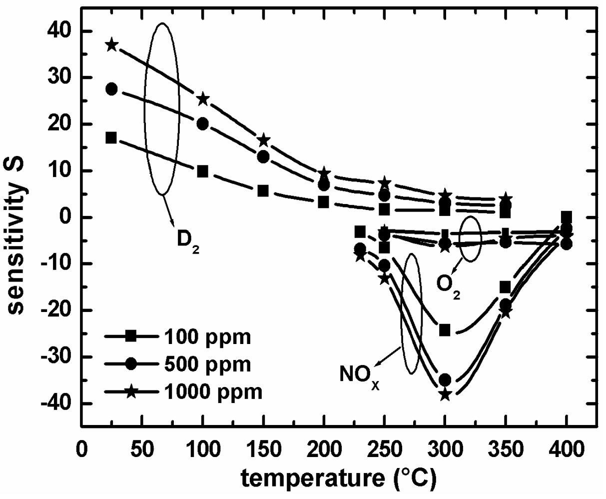

Fig. 3 The dependence of the sensitivity towards 100, 500 and 1000 ppm of pure NO_x, O_2, and D_2 on the operating temperature. The measurements were performed at a constant voltage of 14.V.

Conclusion

4H-SiC FETs were made in the depletion mode, using a metal oxide thin film for a gate electrode. The response to NO_x, D_2, and O_2 gases was investigated as a function of the operating temperature for different concentrations of the test gases. The sensor is very sensitive to NO_x and its performance is strongly dependent on the gas concentrations and operating temperature. The sensitivity to D_2 has been found to be maximal at room temperature. The optimum detection temperatures occur in the range 275-325℃ for NO_x. In this range the cross sensitivity to O_2 and D_2 is very low indicating that the sensor is very suitable for selective detection of NO_x. The optimum temperature of operation for detection of D_2 is determined to be between 25-100℃. In this range no significant response to O_2 and NO_x is observed indicating that the sensor is very suitable for selective D_2 detection at very low temperatures.

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