FACULTY OF ELECTRICAL ENGINEERING
AND INFORMATION SCIENCE

INFORMATION TECHNOLOGY AND
ELECTRICAL ENGINEERING -
DEVICES AND SYSTEMS,
MATERIALS AND TECHNOLOGIES
FOR THE FUTURE

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391
SiC-based FET for NO\textsubscript{x} gas sensing applications using InVO\textsubscript{x} metal oxides as a gate material

Introduction

Demands for exact monitoring of nitrogen oxide gases (NO\textsubscript{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\textsubscript{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\textsubscript{x}, O\textsubscript{2}, and Deuterium sensing properties of SiC-based FETs with InVO\textsubscript{x} metal oxides as a catalytic gate in dependence on the operation temperature have been investigated.

Experiments

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 $4 \times 10^{-8}$ 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 ($V_G \ll V_{SD}$).
according to:

\[ I_{SD} = \mu C_i \frac{W}{L} (V_G - V_T)V_{SD} \]  

(1)

where \( \mu \) 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 O\(_2\)) 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.

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:

\[ S = \frac{I_s - I_v}{I_v} \times 100 \]

Whereby \( I_s \) 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°C for NOx. In this range the cross sensitivity to O2 and D2 is very low indicating that the sensor is very suitable for selective detection of NOx. The optimum temperature of operation for detection of deuterium is determined to be between 25-100°C. In this range no significant response to O2 and NOx is observed indicating that the sensor is very suitable for selective D2 detection at very low temperatures.

Conclusion

4H-SiC FETs were made in the depletion mode, using a metal oxide thin film for a gate electrode. The response to NOx, D2, and O2 gases was investigated as a function of the operating temperature for different concentrations of the test gases. The sensor is very sensitive to NOx and its performance is strongly dependent on the gas concentrations and operating temperature. The sensitivity to D2 has been found to be maximal at room temperature. The optimum detection temperatures occur in the range 275-325°C for NOx. In this range the cross sensitivity to O2 and D2 is very low indicating that the sensor is very suitable for selective detection of NOx. The optimum temperature of operation for detection of D2 is determined to be between 25-100°C. In this range no significant response to O2 and NOx is observed indicating that the sensor is very suitable for selective D2 detection at very low temperatures.

Acknowledgement

This work was supported by the Thuringian ministry of culture (TKM), project InOzon and the European Union (project GaNano). The authors acknowledge fruitful discussions with John Lemmon a member of GE Global Research.

References:
Actuators, B 77 (2001) 455.


Authors:
Dipl. Ing. Majdeddin Ali
Dr. Volker Cimalla
Dr. Thomas Stauden
Dr. Gernot Ecke
Prof. Oliver Ambacher
Technical University Ilmenau, Center for Micro- and Nanotechnologies, Gustav-Kirchhoff-Str. 7
D-98693 Ilmenau
Phone: +49 3677 69 1172
E-mail: majdeddin.ali@tu-ilmenau.de
Dr. Vinayak Tilak
Dr. Peter Sandvik
General Electric Global Research Center, Micro- and Nano Structures Technologies, 1 Research Circle, Niskayuna, NY 12309, USA