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Sensors and Actuators B 108 (2005) 501–507

SENSORS AND ACTUATORS B CHEMICAL

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Influence of gate bias of MISiC-FET gas sensor device on the sensing properties

Shinji Nakagomi[a,*], Akira Fukumura[a], Yoshihiro Kokubun[a], Susan Savage[b], Helena Wingbrant[c], Mike Andersson[c], Ingemer Lundström[c], Mikael Löfdahl[d], Anita Lloyd Spetz[c]

[a] *School of Science and Engineering, Ishinomaki Senshu University, Ishinomaki, Miyagi, Japan*
[b] *ACREO AB, Electrum 236, SE-164 40 Kista, Sweden*
[c] *S-SENCE and Div. of Applied Physics, Linköping University, SE-581 83 Linköping, Sweden*
[d] *AppliedSensor AB, Teknikringen 6, SE-583 30 Linköping, Sweden*

Received 12 July 2004; received in revised form 11 November 2004; accepted 19 November 2004
Available online 11 January 2005

Abstract

The influence of gate bias on the gas sensing properties of SiC-based field effect transistors with catalytic gate and a buried short channel has been studied. The drain current–voltage (I_d–V_D) characteristics of the device reveal non-saturation property, which is a consequence of the short channel design. The drain current is larger in hydrogen ambient than in oxygen ambient at the same drain voltage. The threshold voltage decreases with increasing positive gate bias, and increases with increasing negative gate bias. When a positive bias is applied to the gate, the I_d–V_D characteristics reveal a tendency to saturate. A positive gate bias increases the drain voltage response to hydrogen, as compared with a negative applied gate bias. However, a positive gate bias decreases the stability of the device signal. A change in the channel resistivity is the main reason for the change in the electrical properties when a positive gate bias is applied. A physical model that explains the influence of the gate bias has been studied, and the behavior of the barrier height in the channel was estimated by using the temperature dependence of the I_d–V_D characteristics.

Keywords: Current–voltage; JFET; MISiC-FET; Gate bias; Buried short channel

1. Introduction

Research into a field effect gas sensor device with a catalytic metal gate started when Lundström et al. reported a hydrogen gas sensor device based on a silicon-based field effect transistor in 1975 [1]. Since that time, much research has been carried out, as reviewed in Ref. [2].

The generation of electron-hole pairs in the silicon-based device increases as the temperature rises, and intrinsic semiconductor electric properties appear at about 250 °C. Therefore, the device based on silicon cannot work at higher temperatures [3].

A gas sensor device based on silicon carbide, SiC, with a band-gap of about 3–3.4 eV, has been developed in order to realize a high-temperature gas sensor device. This work started in 1992. For reviews see Refs. [4,5]. This gas sensor device can be operated up to 700 °C. The sensor can detect saturated hydrocarbons that decompose at higher temperatures. Also, a very fast response time of a few milliseconds has been achieved [6,7]. There are several groups who carry out research on gas sensor Schottky devices or capacitors based on SiC [4,5,8–12]. Also, catalytic metal insulator SiC field effect transistor, MISiC-FET, gas sensor devices have been developed in a co-operative effort between S-SENCE at Linköping University and Acreo AB [4,5]. Several applications regarding combustion monitoring in exhaust and flue gases have been demonstrated using this device [13–15].

* Corresponding author. Tel.: +81 225 22 77 16; fax: +81 225 22 77 46.
E-mail address: nakagomi@isenshu-u.ac.jp (S. Nakagomi).

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doi:10.1016/j.snb.2004.11.057

Two problems that now have to be solved by software in order to realize long term operation in a harsh environment are base-line drift and deterioration of the gas sensitivity.

Nakagomi et al. have studied the electrical properties of the device regarding the influence of substrate bias on the I_d–V_D characteristics [16,17]. It has been demonstrated that a negative substrate bias could be used to control the base-line of the sensor device and improve the response to hydrogen. This provides a method for base-line and gas sensitivity control. Also, a physical model has been proposed by the use of a modified SIT equation [18].

In this paper, the influence of gate bias is studied. The current–voltage characteristics have been measured in hydrogen and oxygen ambients at several temperatures up to 600 °C. The gate bias dependence of the time resolved response of the sensor is also shown. The physical model that was used in Refs. [18,19] is applied, in order to estimate and explain the behavior of the channel barrier between the source and the drain.

2. Experimental

The sensor is based on a catalytic metal–insulator–silicon carbide field effect transistor, MISiC-FET, with buried source, drain and channel regions (see Fig. 1). These regions are buried in order to improve the high-temperature performance of the device. In effect, the MISiC-FET is a lateral junction FET with a buried short channel.

The electronic transistor device has been designed and processed by Acreo, while the catalytic metal electrode that transforms the electronic device into a sensor device has been developed and processed by S-SENCE at Linköping University. The source and drain regions were formed by the implantation of nitrogen. The MOS gate was formed by the deposition of a bi-layer of tantalum silicide and Pt on an insulator of $SiO_2/Si_3N_4/SiO_x$ film. Ohmic contacts to source, drain and backside substrate were formed by Ni, which was subsequently annealed and covered by a bi-layer of tantalum silicide and Pt. Fig. 1 shows a schematic cross-section of the structure and the wiring of the device in order to measure the electrical properties. The sensor chip is mounted on a ceramic heater on a 16 pin holder, together with a temperature sensor (Pt-100 element). An air gap is maintained between the heater and the holder, The holder was placed in an aluminum block with a small cavity and 500 ppm H_2 or 0.5% O_2 with argon as the carrier gas was passed at a flow rate of 100 ml/min. Drain current–voltage (I_d–V_D) characteristics of the device were measured at several values of gate bias using a Keithley source measurement unit 236. Response curves while switching between ambient gases 4000 ppm H_2/N_2 and 0.5% O_2/N_2 in a gas-mixing system were recorded.

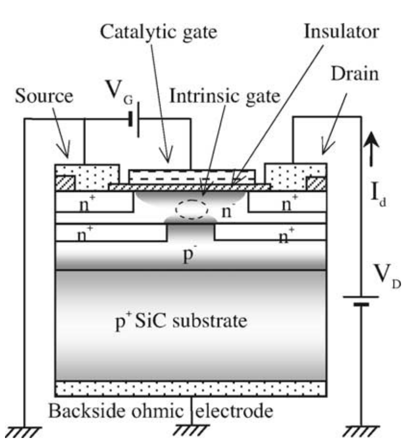

Fig. 1. Structure of a MISiC-FET gas sensor device and wiring.

3. Results and discussion

3.1. Current–voltage characteristics

Fig. 2 shows the dependence of the I_d–V_D characteristics on the gate bias in H_2 and O_2 ambients at 200 and 400 °C, respectively. The gate bias is varied in 1 V steps between +4 and −4 V.

The drain current flowing in hydrogen ambient is higher than that in oxygen ambient at a fixed gate voltage. The gas response of the device is thus defined as the drain voltage change, at fixed drain current and gate bias, when switching between the gas ambients. The drain threshold voltage is seen to increase as the gate bias becomes more negative, and vice versa. This behavior makes it possible to control the baseline of the sensor. The I_d–V_D characteristics at negative gate bias show non-saturation properties. But at higher positive gate biases, the I_d–V_D characteristics do tend towards saturation.

The saturation property at positive gate biases only appears at temperatures above 100 °C. This indicates that the drain current at positive gate biases becomes suppressed at higher temperatures. This is due to the behavior of the channel conductance as described later.

The drain current axis of the I_d–V_D characteristics at 200 °C in Fig. 2 was changed to a logarithmic scale in order to enlarge the low drain current region, see Fig. 3. In the low drain voltage region, the drain current increases exponentially with increasing drain voltage when a negative gate bias is applied. With increasing positive gate bias, the drain current in the low drain voltage region increases drastically. This can be explained by the increasing positive gate bias causing a lowering of the barrier height. The behavior of the barrier height will be examined in the next section, through an investigation into the temperature dependence of the I_d–V_D characteristics in the low drain voltage region.

The drain voltage difference, ΔV, between the H_2 and O_2 ambients at a constant drain current was calculated from the I_d–V_D characteristics. Fig. 4 shows the dependence of ΔV on the drain current at several gate biases and a temperature of 200 and 400 °C as an example. The absolute value of ΔV is less than 0.25 V over almost the whole drain current range at