REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 70, NUMBER 2 FEBRUARY 1999

New microhumidity field-effect transistor sensor in ppm$_v$ level

Supratic Chakraborty[a)]
Department of Physics, University of Kalyani, Kalyani 741 235, West Bengal, India

Kazuhiro Hara
Department of Electrical Engineering, Tokyo Denki University, 2-2 Kanda-Nishikicho, Chiyodaku, Tokyo 101-8457, Japan

P. T. Lai
Department of Electrical and Electronic Engineering, University of Hong Kong, Pokfulam Road, Hong Kong

(Received 14 September 1998; accepted for publication 17 November 1998)

An integrated humidity sensor able to detect and measure a very low humidity concentration and higher relative humidity (RH) levels as well with the possibility of industrial application has been designed and fabricated using very large scale integration technology where thin porous Al_2O_3 film acts as humidity sensing material. The porous structure of Al_2O_3 has been obtained by anodic oxidation of a thin film of Al in sulfuric acid. During anodic oxidation, a few top atomic layers of Ta are also oxidized into Ta_2O_5 whose properties affect the normal sensing properties of Al_2O_3 and a better quality of sensor with higher sensitivity and speed is obtained. The gate insulator structure of the field-effect transistor is $SiO_2/Si_3N_4/Ta/Ta_2O_5/Al_2O_3$. The device is basically an enhancement mode metal–oxide–semiconductor field-effect transistor. The drain current I_D of the device is measured at constant gate and drain voltages at 25 °C and found to be sensitive up to less than ~1 ppm$_v$ moisture concentration. The response time of the sensor in ppm$_v$ level is less than 1 s. The device is also found to be very sensitive at higher RH levels and shows a linear dependency on RH. The response and recovery times of the sensor are 2 and 6 s, respectively. © *1999 American Institute of Physics.* [S0034-6748(99)05202-8]

I. INTRODUCTION

Anodically oxidized thin porous Al_2O_3 films have been used as dielectric material in the fabrication of humidity sensors, which are widely used in the measurement and control of relative humidity.[1–3] Normally, it is difficult to design and fabricate a humidity sensor which is very stable and sensitive in extremely low humidity level. In order to detect a very small amount of water vapor (less than 10 ppm$_v$), the device must have to be very sensitive and the porosity of Al_2O_3 has to be controlled.[4,5] An attempt has been made to design a humidity sensor in ppm$_v$ level.[6]

In this article, an attempt is made to design and fabricate a humidity sensing field-effect transistor (FET) which will be able to measure a moisture concentration as low as in ppm$_v$ level. A *n*-channel metal–oxide–semiconductor field-effect transistor (MOSFET) has been fabricated with SiO_2 and Si_3N_4 as gate insulators. Thin layers of Ta and Al are respectively deposited on Si_3N_4 and Al is later anodically oxidized to get the porous structure of Al_2O_3. A few top atomic layers of Ta are also oxidized into Ta_2O_5 during oxidation. The device is found to be sensitive ~1 ppm$_v$ level. The drain current (I_D) and response time of the device are measured with humidity concentrations. These sensor parameters are also measured at different relative humidity (RH) levels and the response time of the sensor is found out.

[a)]Electronic mail: supratic@klyuniv.ernet.in

II. EXPERIMENTAL TECHNIQUES

Figure 1 shows a cross-sectional view of the humidity sensing device. This is basically a normally off *n*-channel MOSFET. SiO_2 and Si_3N_4 layers are acted as gate insulators. The channel length and width of the FET are 10 and 8300 μm, respectively. The Si_3N_4 layer covers the whole surface area except contact windows to keep FET properties constant in ambient condition. Thin films of gold (Au) deposited on Si_3N_4 act as source (S) and drain (D) electrodes. A thin film of Ta (thickness=20 Å) is deposited on Si_3N_4 layer which covers the channel area of the FET and another thin film of Al (thickness=2000 Å) is deposited on Ta. These films are grown using dc magnetron sputtering system with the substrate held at room temperature. The porous Al_2O_3 film is obtained by electrochemical anodization of Al film. 1.5 M H_2SO_4 acid and a current density of 200 A m^{-2} are used for 7 min during anodic oxidation of Al at 25 °C to get its porous structure which proves to be an important step in the fabrication to get a highly sensitive humidity sensing device. During anodic oxidation, a few top atomic layers of Ta are also oxidized into Ta_2O_5. Finally, a gold film, ~200 Å thick, is deposited on Al_2O_3 as gate electrode (G) by electron beam evaporation system. The device is tilted at 57° with respect to evaporated Au atom coming out during deposition to get its semitransparent nature.

A closed humidity chamber of known volume is designed. A humidity level up to 1 ppm$_v$ is attained by injecting known volume of saturated water vapor into the cham-

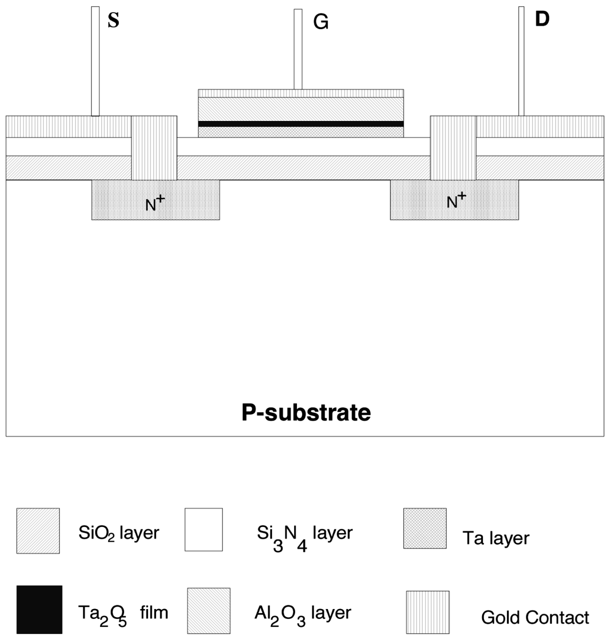

FIG. 1. Cross-sectional view of the FET sensor.

ber. Constant humidity environment is created using some closed chambers containing saturated water solutions of different salts to achieve different RH levels (e.g., 11%, 33%, 44%, . . .). Silica gel and pure water solution are used to get 0% and 100% RH levels. A special arrangement is made to make electrical contacts with the sensor head placed inside the chamber.

III. RESULTS

Figure 2 shows the dependence of I_D, the drain current of the designed FET on moisture concentration. The response characteristics of the sensor is measured at 25 °C at constant gate voltage ($V_g=3.4$ V) and constant drain voltage ($V_{DD}=4.5$ V). An ac signal of 1 kHz is superimposed on V_g at the gate. It is found that the variation of I_D is consistent with moisture concentration which indicates the special feature of this structure at low humidity concentration, particularly at ppm$_v$ level. It is a completely new structure having much higher sensitivity and faster response time than conventionally anodized Al_2O_3. The reason may be due to partial anodization of a few atomic layers of Ta film, the layers just below Al_2O_3 layer, into Ta_2O_5. Rutherford backscattering spectrometry (RBS) also confirms the development of Ta_2O_5 layer. The response and recovery times of the sensor are less than 1 s when moisture concentration changes from 10 ppm$_v$ level to 1000 ppm$_v$ level and back to 10 ppm$_v$ level, respectively.

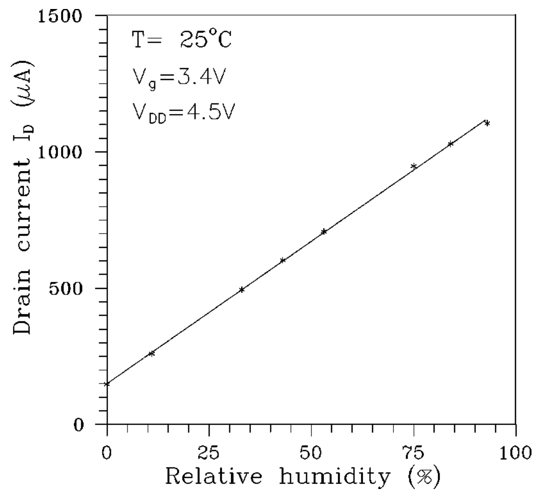

FIG. 3. Variation of drain current (I_D) of the FET sensor with relative humidity at constant gate and drain voltages.

Figure 3 shows the variation of I_D with relative humidity (RH). The variation is linear with RH up to 93% RH level. The sensor has got a very small hysteresis loop at higher RH level (beyond 84% RH level).

The response and recovery times of the sensor are shown in Fig. 4 which come out to be 2 and 6 s, respectively, when observations are carried out between 0% and 93% RH levels. The recovery time of the sensor will be ~10 s when observations are carried out between 0% and 100% RH levels.

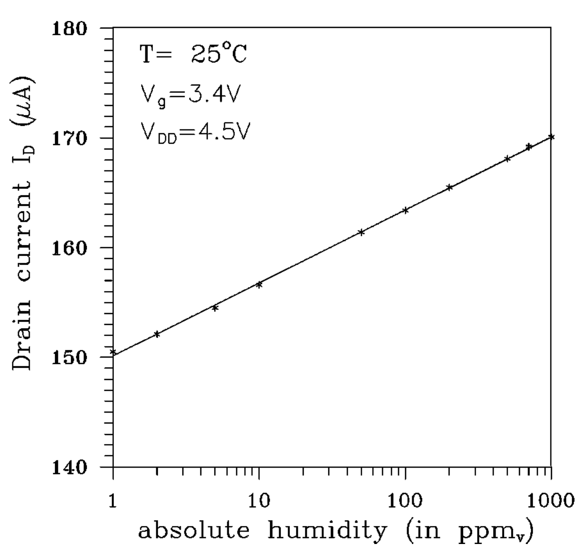

FIG. 2. Plot of drain current with absolute humidity.

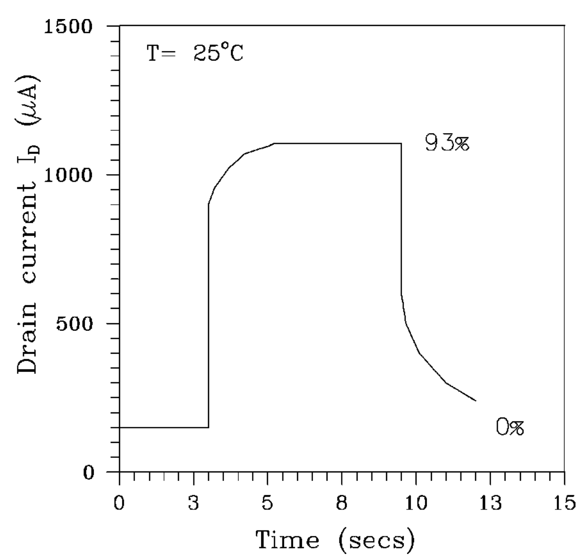

FIG. 4. Transient response of the FET sensor.

The higher recovery time in the later case is due to pore condensation which takes place at 100% RH level.

IV. DISCUSSION

A moisture sensitive field-effect transistor sensor having a stable and reliable output in ppm_v level is designed and fabricated using very large scale integration technology. It is a new structure which is very sensitive and much faster than conventional porous Al_2O_3 sensor. The sensor is small in size (area $5\,mm^2$) and compatible to *in situ* fabrication with other circuitry. A large number of sensor heads can be produced commercially at the same time which reduces its cost.

[1] R. K. Nahar and V. K. Khanna, Int. J. Electron. **52**, 557 (1982).
[2] G. Sberveglieri, R. Anchisini, R. Murri, C. Ercoli, and N. Pinto, Sens. Actuators B **32**, 1 (1996).
[3] Y. Sadaoka, Y. Sakai, and S. Matsumoto, J. Mater. Sci. **21**, 1269 (1986).
[4] Y. Shimizu, H. Ichinose, H. Arai, and T. Seiyama, Nippon Kagaku Kaishi 1270 (1985).
[5] H. Arai and T. Seiyama, in *Humidity Control Sensors*, edited by W. Göpel, J. Hesse, and J. N. Zemel (VCH, Weinheim, Germany, 1992), Vol. 3, Chap. 20.
[6] M. G. Kovac, D. Chleck, and P. Goodman, Solid State Technol. **21**, 35 (1978).