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New microhumidity field-effect transistor sensor in ppm\(_v\) level

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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\(_2\)O\(_3\) film acts as humidity sensing material. The porous structure of Al\(_2\)O\(_3\) 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\(_2\)O\(_5\) whose properties affect the normal sensing properties of Al\(_2\)O\(_3\) 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\(_3\)N\(_4\)/Ta/Ta\(_2\)O\(_5\)/Al\(_2\)O\(_3\). 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 \(\approx 1\) 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\(_2\)O\(_3\) 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\(_2\)O\(_3\) 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\(_3\)N\(_4\) as gate insulators. Thin layers of Ta and Al are respectively deposited on Si\(_3\)N\(_4\) and Al is later anodically oxidized to get the porous structure of Al\(_2\)O\(_3\). A few top atomic layers of Ta are also oxidized into Ta\(_2\)O\(_5\) during oxidation. The device is found to be sensitive \(\approx 1\) 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.

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\(_3\)N\(_4\) layers are acted as gate insulators. The channel length and width of the FET are 10 and 8300 \(\mu\)m, respectively. The Si\(_3\)N\(_4\) 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\(_3\)N\(_4\) act as source (S) and drain (D) electrodes. A thin film of Ta (thickness=20 Å) is deposited on Si\(_3\)N\(_4\) 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\(_2\)O\(_3\) film is obtained by electrochemical anodization of Al film. 1.5 M H\(_2\)SO\(_4\) 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\(_2\)O\(_5\). Finally, a gold film, \(\approx 200\) Å thick, is deposited on Al\(_2\)O\(_3\) 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 chamber.
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$_2$O$_3$. The reason may be due to partial anodization of a few atomic layers of Ta film, the layers just below Al$_2$O$_3$ layer, into Ta$_2$O$_5$. Rutherford backscattering spectrometry (RBS) also confirms the development of Ta$_2$O$_5$ 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.

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 $\sim$ 10 s when observations are carried out between 0% and 100% RH levels.
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$_2$O$_3$ 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.