International Journal of Natural and Engineering Sciences 6 (2) : 49-52, 2012
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Room Temperature Hydrogen Gas Sensor using Ni/Al_2O_3/Ni/n-Si Magnetic Tunneling Transistor

Vahdat NAZERIAN* Alireza SALEHI

Laboratory of Device Fabrication, Department of Electrical Engineering, K.N. Toosi, University of Technology, P.O. Box 16315-1355, Seyed Khandan, Tehran, IRAN

***Corresponding Author**
e-mail: nazerian@eetd.kntu.ac.ir

Received : January 02, 2012
Accepted : February 10, 2012

Abstract

In this paper, the sensing characteristics of Ni/Al_2O_3/Ni/n-Si devices as magnetic tunneling transistor (MTT) hydrogen gas sensors were investigated. The Ni/Al_2O_3/Ni/n-Si sensors were prepared using an electron beam deposition of Ni, Al_2O_3 and Ni layers, respectively with different tunnel barrier (Al_2O_3) thicknesses of 10, 15, 20 and 25 nm onto n-type Si substrates. An appropriate profile of magnetization was used to magnetize the ferromagnetic Ni layers of emitter and base. We measured current-voltage (I-V) characteristics of the sensors in absence and presence of 500 ppm hydrogen gas at room temperature. From I-V characteristics, we obtained the sensing response of the sensors with different tunnel barrier thicknesses when exposed to 500 ppm hydrogen gas. We have found that the MTT sensors showed an excellent response to hydrogen at room temperature so that the response was inversely related to the Al_2O_3 film thickness and a higher response was recorded for thinner tunnel barrier layers which exhibited an excellent agreement with the results obtained from the simulation of the device.

***Keywords**:* Ni/Al_2O_3/Ni/n-Si Devices; Magnetic Tunneling Transistor; Magnetization Profile; Tunnel Barrier; Sensing Response; Hydrogen Gas

INTRODUCTION

Detection of hydrogen gas in different atmospheres is of importance in many environments especially in industrial process control applications such as petroleum industries. Security systems operating in hydrogen environments demand fast and highly sensitive hydrogen sensors. Despite the research efforts already reported in literature [1-3], still many problems deserve to be further investigated and different aspects of gas sensors have to be studied to improve their sensing characteristics. It is well known that in normal electronic the charge of carriers for controlling the electric current is used. However, there are new devices in which the spin of carriers is used for controlling the electric current. The new approach is known as spintronic [4-6] and the phenomenon is used in this study for gas detection. When some gases exposed to the surface of ferromagnetic layers the magnetization properties of the layers are affected significantly [7-9]. In our previous work [10] we fabricated a magnetic Ni/n-Si Schottky diode as hydrogen gas sensor so that the exposure of the gas to the surface of ferromagnetic Ni layer affected the magnetization of the layer significantly and so a considerable improvement in sensing response of the device towards hydrogen gas at room temperature was achieved. Hence, we will be able to detect the hydrogen if the changes of the magnetization characteristics of the layers are measured properly. Therefore, we believe that there is a reason to investigate new structures of ferromagnetic layers for gas detection. It is known that in the spin device of magnetic tunneling transistor (MTT) (see figure 1) containing a magnetic tunneling junction (MTJ) and a Schottky barrier [11-13], little change of the magnetization of each ferromagnetic layer (emitter or base) causes a significant change of output current (collector current) of the device.

It means that the changes of the magnetization characteristics of the layers are converted into the electric current using the MTT structure proposed. So, we report that Ni/Al_2O_3/Ni/n-Si magnetic tunneling transistor can be used as a novel hydrogen gas sensor.

To our knowledge, works on MTT structure as a gas sensor has not been published yet.

EXPERIMENTAL PROCEDURE

In the present study, we investigated the effect of hydrogen gas on magnetization of ferromagnetic Ni thin layers as well as the influence of this process on the functionally important gas sensing response. In order to investigate these aspects, we fabricated Ni/Al_2O_3/Ni/n-Si device, as shown in figure 2 using n-type Si wafer (1 0 0) implanted with a phosphor impurity concentration of 1.0×10^{15} atoms/cm^3. The Si wafer was chemically etched and then cleaned by the standard method. The Si-substrates were cut into a 12 mm × 12 mm size and then loaded in a deposition chamber.

First the ohmic contact of collector was done using AuGe/Au (100 nm/250 nm) by an evaporation system followed by annealing at 400 °C in nitrogen gas for 3 min and then the base contact, tunnel barrier and emitter contact were prepared using an electron beam deposition of Ni (30 nm), Al_2O_3 (10, 15, 20 and 25 nm) and Ni (50 nm) layers, respectively onto the Si substrates. To prepare magnetic Ni/Al_2O_3/Ni/n-Si sensor for gas sensing applications, an appropriate profile [10] was used as a function of magnetic field (*B*) and time (*t*) to magnetize the emitter and base ferromagnetic layers anti-parallel. Using a vibrating sample magnetometer on the magnetized Ni layers, we confirmed the magnetic effect on the layers which was similar to the results reported in [14]. For sensing measurements, after injecting hydrogen into the gas chamber through a mass flow controller, a KEITHLEY source measurement unit was used to measure current–voltage (*I–V*) characteristics of the sensor. It should be noted that all the *I–V* characteristics were measured after receiving stable state in the presence of hydrogen.

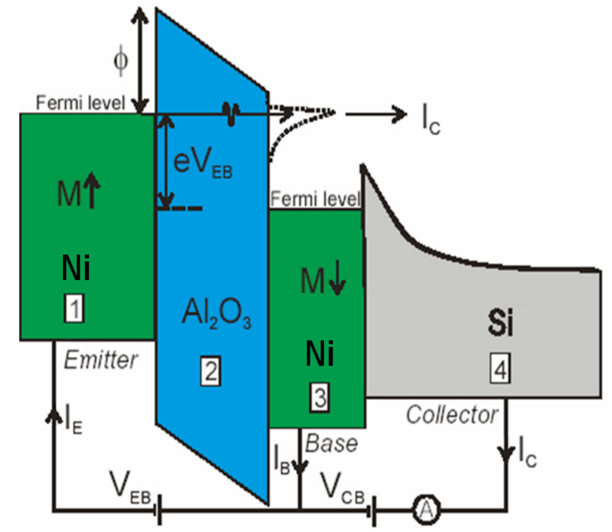


Fig.1. Schematic picture of magnetic tunneling transistor.

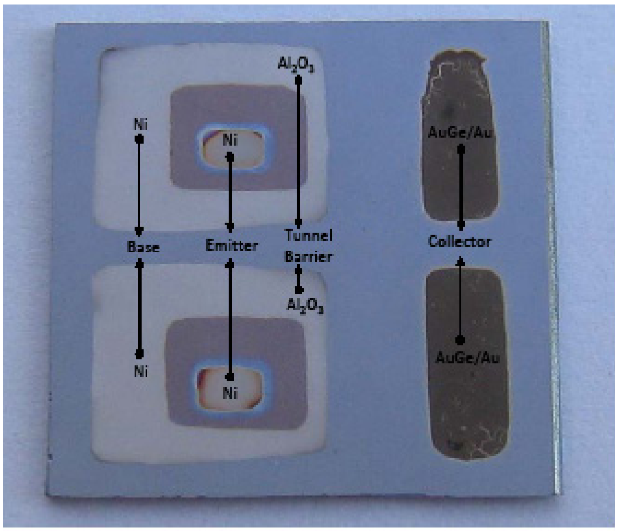
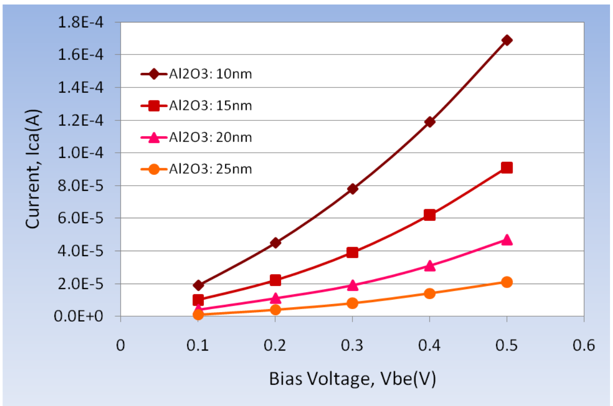


Fig.2. Image of Ni/Al2O3/Ni/n-Si MTT sensor.

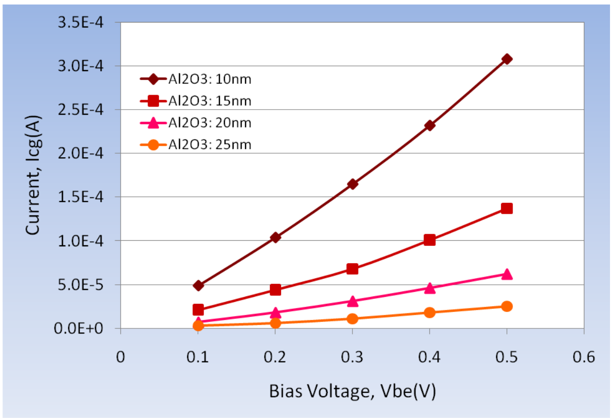
RESULTS AND DISCUSSION

The changes in collector current (I_{ca}) of the MTT sensors with different tunnel barrier thicknesses of 10, 15, 20 and 25 nm versus bias voltage (V_{be}) in clean air are shown in figure 3(a). It is observed that the collector current value of the MTT device increases with decreasing the tunnel thickness at identical bias voltage.

To study the effect of hydrogen gas on the sensing characteristics of the Ni/Al_2O_3/Ni/n-Si sensors, we measured the changes in collector current (I_{cg}) of the sensors with different tunnel barrier thicknesses when exposed to 500 ppm hydrogen gas at room temperature. The results are shown in figure 3(b).



(a)



(b)

Fig.3. I–V characteristics of Ni/Al2O3/Ni/n-Si devices with different tunnel barrier of 10, 15, 20 and 25 nm thick at room temperature (a) before hydrogen exposure and (b) after exposure of 500 ppm hydrogen.

It is exhibited that the collector current of each sensor increases in presence of hydrogen gas compared to the collector current of that sensor in absence of hydrogen at the same bias voltage of V_{be}.

The response time to hydrogen of the magnetic Ni/Al$_2$O$_3$/Ni/n-Si sensors were also measured. A response time of 1.5 s was obtained for the sensor with tunnel thickness of 10 nm when subjected to 500 ppm hydrogen at room temperature. However, the recovery time was observed at a longer time of around 3–4 min. In contrast, the sensor with tunnel barrier of 25 nm thick showed a longer response time of 2.8 s but the recovery time was similar to that of the other sensors.

To characterize the sensing response of the sensors with different tunnel barrier thicknesses towards hydrogen gas, we measured the changes of the collector current at a fixed bias voltage of V_{be} = 0.5 V using the *I–V* curves of figure 3. The sensing response was calculated from (1)

$$S\% = (\frac{I_{cg}}{I_{ca}} - 1) \times 100 \qquad (1)$$

Where I_{cg} and I_{ca} denote the collector current values of the MTT sensor at bias voltage of V_{be} = 0.5V in presence of 500 ppm hydrogen and in clean air, respectively [10]. The results are summarized in figure 4 as a function of tunnel barrier thickness.

Figure 4 shows the sensing response of the MTT sensors. It is obvious that the MTT responses increase considerably with a decrease in tunnel barrier thickness. A very high response of 82 was recorded for the device with tunnel thickness of 10 nm, whereas a response of 19 was obtained for the device with tunnel thickness of 25 nm to the same hydrogen concentration.

This is a more than 4-fold increase of the sensing response of the MTT sensor, exhibiting the high performance of the sensor with thinner tunnel thicknesses for detection of hydrogen at room temperature. For more clarity, we summarized the results of the response to 500 ppm hydrogen gas for the Ni/Al$_2$O$_3$/Ni/n Si sensors in the inset of figure 4. It is observed that the sensing response of MTT sensor to hydrogen was inversely related to the Al$_2$O$_3$ film thickness.

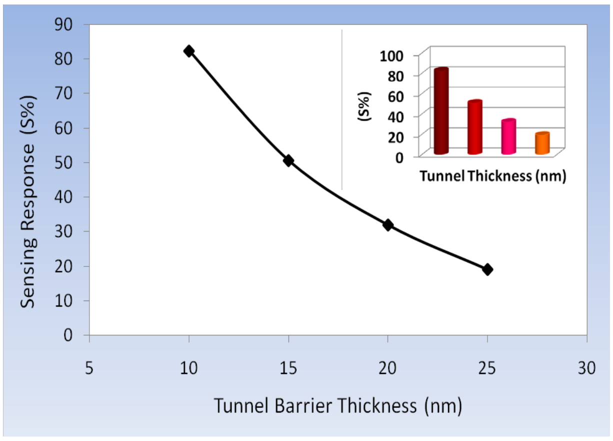


Fig.4. Variations in sensing response of Ni/Al2O3/Ni/n-Si sensors versus different tunnel barrier thicknesses towards 500 ppm hydrogen gas at room temperature. The inset is representative the sensing response of the MTT sensors to 500 ppm hydrogen.

We believe that in the Ni/Al$_2$O$_3$/Ni/n-Si device when exposed to hydrogen gas the change in the arrangement of magnetic clusters can affect the electronic properties of the device [15,16] so that the magnetization of upper ferromagnetic layer (emitter) decreases resulting in a decrease in spin polarization of the electrons in the layer which creates higher collector current in the circuit. This means that the number of spin-polarized electrons from ferromagnetic/semiconductor contact increases at the junction interface. The experimental results exhibited a significant response towards hydrogen. So the MTT device can be used as a gas sensor to promote the sensing response towards hydrogen. The trend shows an excellent agreement with those of the sensing characteristics obtained from the simulation of the MTT sensor [17].

CONCLUSIONS

In summary, we fabricated magnetic Ni/Al$_2$O$_3$/Ni/n-Si sensors in which the effect of tunnel barrier thickness of the emitter-base junction on the response of the sensors towards 500 ppm of hydrogen concentration at room temperature was studied. It is observed that a higher sensing response towards hydrogen was recorded for thinner tunnel barrier layers subjected to similar concentration of hydrogen, exhibiting the high performance of the MTT device for detection of hydrogen at room temperature and we propose it as a good candidate of hydrogen sensor.

Acknowledgments

The authors thank M. M. Lajvardi for his help in samples preparation and gas sensing measurements.

REFERENCES

[1] Yamazoe N. 1991. New approaches for improving semiconductor gas sensors. Sensors and Actuators B. 5:7–19.

[2] Zhang T, Mubeen S, Myung NV, Deshusses MA. 2008. Recent progress in carbon nanotube-based gas sensors. Nanotechnology. 19:332001-1–332001-14.

[3] Satyanarayana L, Reddy KM, Manorama SV. 2003. Nanosized spinel NiFe$_2$O$_4$: A novel material for the detection of liquefied petroleum gas in air. Materials Chemistry Physics. 82:21–26.

[4] Wolf SA, Awschalom DD, Buhrman RA, Daughton JM, von Molnár S, Roukes ML, Chtchelkanova AY, Treger DM. 2001. Spintronics: a spin-based electronics vision for the future. Science. 294:1488–1495.

[5] Grünberg P. 2001. Layered magnetic structures: history, highlights, applications. Physics Today. 54:31–37.

[6] Parkin SSP. 2002. Applications of magnetic nanostructures. Advances in Condensed Matter Science. 3:237-277.

[7] Qiu HS, Gao J, Ma B, Zhang ZZ, Jin QY. 2006. Spin reorientation transition and its gas absorption effect on Ni/fct-Fe films at 110 K. Journal of Korean Physical Society. 49:2095-2098.

[8] Oba Y, Sato T, Shinohara T. 2006. Gas adsorption on the surface of ferromagnetic Pd nanoparticles. e-Journal of Surface Science and Nanotechnology. 4:439-442.

[9] Shinohara T, Sato T, Taniyama T. 2004. Ferromagnetism of gas-evaporated Pd fine particles in mesoscopic size. Journal of Magnetism and Magnetic Materials. 272-276:E1181–E1182.

[10] Salehi A, Nazerian V. 2007. Characterization of magnetic Ni/n-Si Schottky contact for hydrogen gas sensing applications. Sensors and Actuators B. 122:572–577.

[11] Moodera JS, Kinder LR, Wong TM, Meservey R. 1995. Large magnetoresistance at room temperature in ferromagnetic thin film tunnel junctions. Physical Review Letters. 74:3273-3276.

[12] Fuchs GD, Emley NC, Krivorotov IN, Braganca PM, Ryan EM, Kiselev SI, Sankey JC, Katine JA, Ralph DC, Buhrman RA. 2004. Spin-transfer effects in nanoscale magnetic tunnel junctions. Applied Physics Letters. 85:1205–1207.

[13] Yuasa S, Fukushima A, Nagahama T, Ando K, Suzuki Y. 2004. High tunnel magnetoresistance at room temperature in fully epitaxial Fe|MgO|Fe tunnel junctions due to coherent spin-polarized tunneling. Japanese Journal of Applied Physics. 43:L588–L590.

[14] Shalguina EE, Mukasheva MA, Abrosimova NM, Kozlovskii L, Tamanis E, Shalygin AN. 2006. The influence of annealing on magnetic and magneto-optical properties of iron and nickel films. Journal of Magnetism and Magnetic Materials. 300:e367–e370.

[15] Moina CA, Vazader M. 2001. Electrodeposition of nano-sized nuclei of magnetic CO–Ni alloys onto n-Si(1 0 0). Electrochemical Community. 3:159–163.

[16] Sparks PD, Stern NP, Snowden DS, Kappus BA, Checkelsky JG, Harberger SS, Fusello AM, Eckert JC. 2004. Stripe domains and magneto-resistance in thermally deposited nickel films. Journal of Magnetism and Magnetic Materials. 272–276:e1339–e1340.

[17] Nazerian V, Salehi A. 2012. Theoretical analysis of magnetic tunneling transistor as a novel hydrogen gas sensor based on spintronic. International Journal of Natural and Engineering Sciences.