SENSITIVITY OF ION ABSORPTION OF ROOM TEMPERATURE OPERATING SINGLE ELECTRON TRANSISTORS

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ABSTRACT

Nanoelectronic devices form the building blocks of the nanoscaled systems and require innovative technologies for their realization. Single Electron Transistors (SET) is a novel class of nano transistor which operates on the principle of Coulomb blockade. Coulomb blockade effects become dominant when the device dimensions approach few nano-meters. The SET devices are potential candidates for applications in nano sensing, and data storage. Because of the smaller dimensions of the SET devices coupled with their low power requirements for their operation, these devices render a significant advantage in terms of total power required for these sensors and could potentially cut down the weight, the land warrior carries. They enable potentially novel applications to the Future Force Warriors (FFW) and in particular provide revolutionary capabilities to the Land Warrior. The present paper described the application of the room temperature operating SET device towards nano-sensing and the effect of the passivating oxide layer on the sensitivity of the SET device. The sensitivity of the SET gas sensor could be controlled by the thickness of the passivating oxide. The speed of response of the SET sensor was 450 m sec. The applications of SET towards nano-sensing would allow for the realization of nano scaled devices for the Future Combat Systems (FCS).

INTRODUCTION

The capabilities of the Land Warrior can be improved by the reduction of weight carried by the land warrior. Minimizing the power requirement of different electronic instruments and sensing devices can lead to the reduction of the weight carried by the land warrior. One of the possible solutions to the problem of weight reduction is by harnessing the power of nano electronics by suitable design and fabrication of nano-scaled devices and systems that would consume low power and require smaller substrate area. Single electron transistor (SET) devices have device dimensions in the nano scale range and use quantum effects for their operation. SETs are touted as prime candidate for the next generation nano-scaled devices [Grabert, et al., 1992]. SET devices have capabilities like high speed of operation, smaller device dimensions [Likharev, et al., 1999] and ease of integration into the existing CMOS platform, which make them a prime candidate for future nano-scaled systems. Single Electron Transistors (SET) were fabricated using FIB deposition technology. The fabricated SET device was used as a gas sensor.

The gate terminal of the SET device was used as a sensing element. The sensing mechanism of the gas sensor is dependent on the ion absorption of the gas molecules on the gate electrode of the SET device. Depending on the gas molecules being sensed, the polarity of charge on the gate electrode changes and would decide the device behavior of the SET. The SET device shows a clear Coulomb blockade and Coulomb oscillations in the device characteristics at room temperature. The introduction of the gas molecules was sensed by the SET device through the modulation of the device characteristics. The adsorption of gas molecules allows for the electron transfer to the gate terminal and applies an additional charge on the gate electrode proportional to the number of gas molecules adsorbed to the gate terminal. The SET based gas sensor was successfully used to sense the N_2O gas molecules. The sensitivity of the ion absorption can be modulated by the variation of the thickness of the passivating oxide used. The thicker passivating oxide resulted in higher sensitivity of the ion absorption and hence higher reduction in the drain current of the SET device. The increase in sensitivity of the gas sensor with the thick oxide of 45 nm was 286% larger than the sensitivity of the device with 15 nm thick passivating oxide. The reduction in the drain current was 14 pA more when a thick passivating oxide was used. The increased sensitivity of the device allows to measure low gas concentrations of the incoming gas molecules and hence would allow for the integration of the SET based sensors into the armor of the land warrior making them portable.

I. DEVICE FABRICATION

The SET device used as a gas sensor was fabricated using FIB deposition technology. The device is composed of multiple island SET system. The SET device was fabricated on a 300nm thick insulating layer, deposited on a Si substrate. The 300nm thin film of Al_2O_3 was deposited on a clean silicon wafer using radio frequency (RF) sputter deposition in a Perkin Elmer 2400-8J parallel plate sputtering system. The Al_2O_3 is

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used as a high quality isolating layer. Following the deposition of Al_2O_3, nano-islands having an average size of 10nm were deposited in tungsten using the FIB deposition. The nano-islands were deposited on an area of 16µm x 16µm on the isolation layer. The depositions of nano-islands were followed by the oxidation of nano-islands in peracetic acid to form the tungsten oxide on the surface of the nano-islands to form the tunnel junctions.

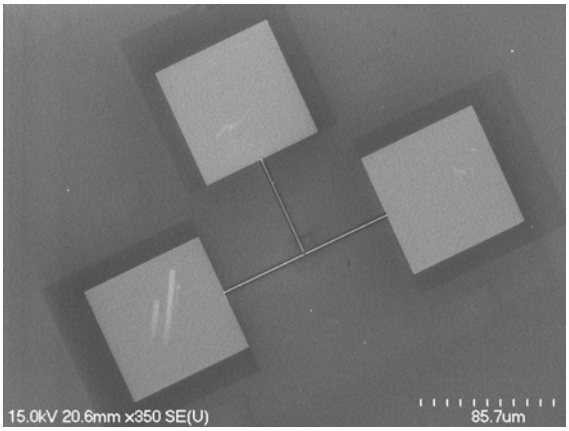

Figure 1: SEM micro graph of the SET device, the source, drain and gate terminals of the SET device are clearly shown.

The nano-scaled leads connecting the active area of the device were fabricated in tungsten using FIB deposition, the nano leads were of 250nm in width and 50 µm in length. The deposition parameters for the tungsten nano leads were adjusted to yield a continuous thin film contrary to the deposition of tungsten nano islands. The probing pads connecting nano leads were deposited in tungsten using FIB deposition [Karre, et al., 2007]. The deposited probing pads were having the dimensions of 100µm x 100µm in size. The fabricated SET device was passivated using a 30nm thick Al_2O_3 layer.

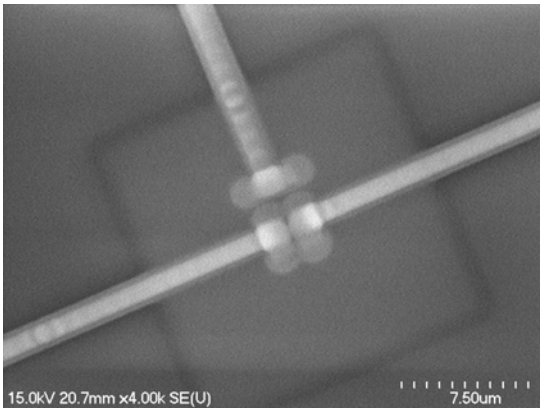

Figure 2: SEM micro graph of the active area of the SET device fabricated using Focused Ion Beam deposition technology as shown through the Al_2O_3 passivation layer.

The source, drain and gate terminals were exposed by etching the thin passivating layer. The gate electrode acts as a sensing element for the gas sensor. The SEM micrograph of the fabricated SET device is shown in Fig. 1, where the source, drain and gate terminals and the connecting nano leads are shown after the removal of the passivating layer on top of the source, drain and gate terminals. The active area of the SET device seen through the passivating layer is shown in Fig 2.

II. GAS SENSING USING SET

The sensing of absorbed gas molecules is mediated through ion-adsorption. The incoming gas molecules interact with the tungsten gate pad and are adsorbed to the gate terminal. The adsorption of the gas molecules results in the modulation of charge on the gate due to the electron transfer between the incoming gas molecules and the gate terminal. The charge on the gate terminal is modulated according to the number of gas molecules adsorbed on the gate. As an interesting permanent gas demonstration, the charge on the gate would increase or decrease depending on the interaction of the gas molecules with the tungsten oxide layer present on top of tungsten gate electrode. The N_2O gas was used in the present investigation. The interaction of one N_2O gas molecule with tungsten oxide results in electron transfer to the tungsten oxide, thus building up the negative potential on the gate electrode. The experimental setup used for the gas sensing is shown in the Fig. 3.

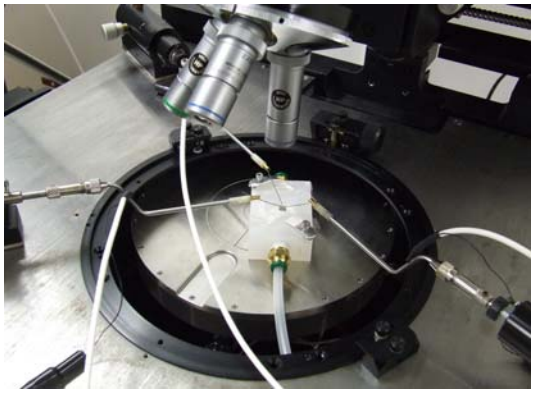

Figure 3: Photograph showing the setup of the gas flow cell and experimental setup for device probing.

The SET device is placed in a flow cell, one end of it is connected to the supply of N_2O gas and the other end is used to purge the N_2O gas. The flow cell was covered except for the area to allow the probing terminals to interact with the probing pads of the device. The source, drain and gate electrodes of the device were connected to the probing terminals. Keithely 4200 SCS semiconductor

characterization system was used to probe the device. The drain current of the device is monitored using the Keithley 4200 SCS system. The SET device shows clear Coulomb blockade and Coulomb oscillations at room temperature. The SET device is biased in the Coulomb blockade region of the device characteristics, where there is no increase in the drain current. The introduction of the N_2O gas in to the flow cell results in the ion adsorption of the gas molecules and hence, results in additional charge on the gate electrode of the device [Karre, et al., 2008]. The additional gate electrode charge modulates the device characteristics and results in the reduction of the drain current of the device. The reduction in the drain current is proportional to the number of N_2O gas molecules interacting with the gate terminal and is a clear signature of the incoming gas species. The drain current reduction could be used to identify the concentration of the gas species interacting with the SET device. The drain current reduction with the introduction of the N_2O gas is clearly seen in the Fig. 4. With the introduction of the gas molecule the drain current is reduced and then normalizes to the base value, due to the leakage of the drain current due to the presence of multiple island between the source, drain and gate terminals. The removal of the gas molecules from the flow cell results in the removal of the extra charge on the gate terminal and shows a clear increase in the drain current. The sensing of incoming gas molecules can be sensed rapidly as seen in Fig. 4. The drain current was in the range of few tens of pA. The reduction in the drain current was few pA.

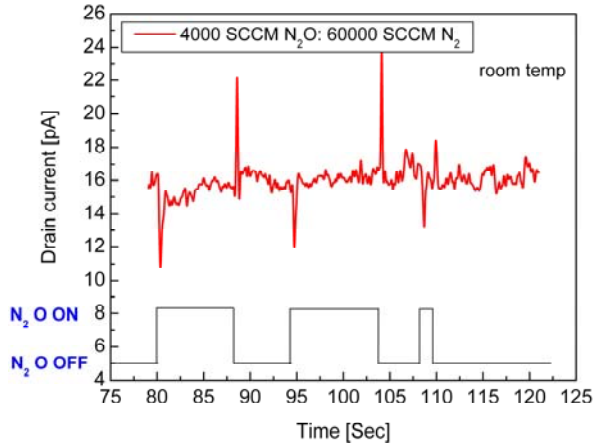

Figure 4: Sensing of N_2O gas by SET device.

The response time for sensing the incoming gas molecules is in the range of ~10^2 ms. The SET device shows clear Coulomb oscillations in the differential conductance of the device, showing the charging and discharging of the device. The Coulomb oscillations in the differential conductance of the SET device are shown in the Fig. 5. The aperiodic Coulomb oscillations are due to the non uniformity of the conducting nano-islands present between the source and drain terminals in a multi dot SET system [Ohkura, et al., 2005]. The variation in the actual dimensions of the conducting nano-islands are responsible for the differences in the charging and discharging of the nano islands [Muller, et al., 2005].

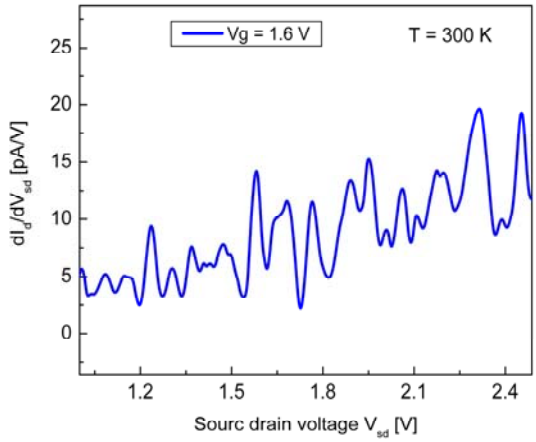

Figure 5: Differential conductance of the SET device at room temperature for a fixed V_G.

III. SENSITIVITY OF ION ABSORPTION

The drain current reduction with the introduction of the gas species was also found to depend on the thickness of the passivating layer. The effect of two different thicknesses, 15nm and 45nm was investigated. The thin passivating oxide allows the gas molecules not only to interact with the sensing gate terminal but also with the active area of the device and hence disperses the total charge seen by the gate terminal. The reduction in the total charge seen by the gate terminal allows for the smaller reduction of the drain current. The thick passivating oxide does not allow for the interaction of the incoming gas molecules with the active are of the device.

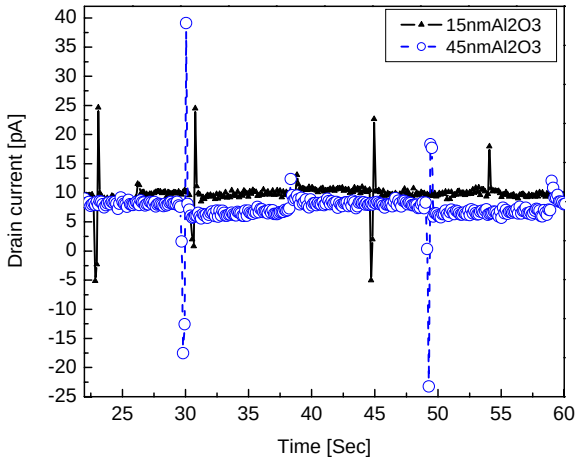

Figure 6: The response of the SET showing the selective ion absorption of the N_2O gas on the gate terminal for different passivating oxide thickness.

The thicker oxide concentrates the gas molecules to interact with the gate terminal improving the sensitivity of the device, because of increase in molecular interaction [Kashkarov, et al., 2007]. The charge seen by the gate electrode is much higher when a thick passivating oxide is used, thus allowing for a higher reduction in the drain current of the device. The results for the different thickness of the passivating oxides having the thickness of 15nm and 45nm are shown in Fig. 6. It can be seen that the thin oxide with 15nm thickness showed a reduction in the drain current of 7pA, whereas the thick passivating oxide with 45nm thickness showed a reduction of 20 pA, the percentage improvement in the drain current reduction with thick passivating oxide was 286%. The thick passivating oxide could be used to improve the sensitivity of the gas sensor. Different concentrations of the N_2O gas can be identified using the reduction in the drain current. For the particular thickness of the passivating oxide layer the SET device shows a reduction in the drain current based on the concentration of the incoming gas molecules. The SET devices can measure lower concentrations of gas molecules with higher sensitivity. The higher concentration of N_2O gas shows a smaller reduction in the drain current.

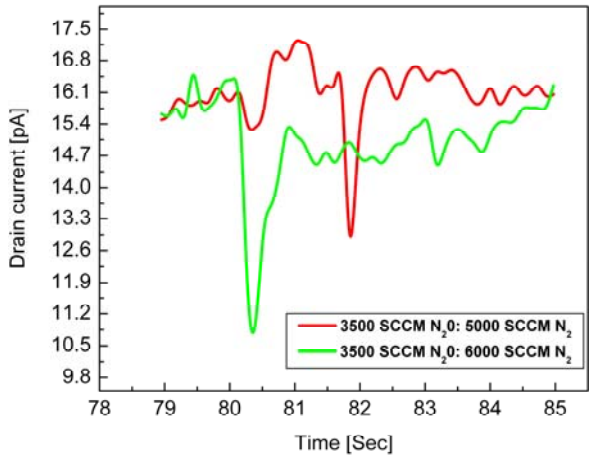

Figure 7: Drain current reduction of the SET device at room temperature for a fixed V_G and different gas concentrations.

It can also be seen that the speed of response for sensing the gas molecules also depends on the concentration of the incoming gas species. The speed of response for a larger concentration of 70% N_2O was found to be was 300 m sec and the speed of response for the 58% N_2O gas was found to be 450 m sec. The SET device is capable of rapidly sensing a wide range of concentrations of the gas molecules as shown in Fig. 7.

CONCLUSIONS

The SET device operating at room temperature fabricated using FIB deposition was used as a gas sensor. The gas sensing mechanism of the SET device depends on the ion adsorption. The dependence of thickness of the passivating oxide layer was shown to impact the sensitivity of the gas sensor. The thick passivating oxide layer was show to be more sensitive to the incoming gas molecules. The drain current reduction of the SET device is a clear signature of the number of sensed gas molecules. The reduction in the drain current for a thick passivating oxide of 45nm was found to be 20 pA, compared to the thin passivating oxide of 15nm showed a reduction in the drain current of 7 pA. There was a 286% improvement in the sensitivity of the sensor with a thick passivating oxide. The speed of response for the gas sensors was found to be dependent on the concentration of the incoming gas molecules and speed of response was in the range of ~10^2 ms.

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