Highly Sensitive and Low Power Hydrogen Gas Sensor Based on FD-SOI PNIN TFET

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Abstract: In this paper, a new H_2 gas sensor based on FD-SOI PNIN TFET with Palladium metal gate is proposed through simulation-based study. The transfer characteristics and the H_2 gas sensitivities of the proposed sensor at various gas pressure are studied. FD-SOI PNIN TFET H_2 sensor exhibits superior sensitivity in contrast with FD-SOI TFET H_2 sensor due to the integration of the narrow N^+ layer at the source side. The effect of substrate bias on the sensitivity of FD-SOI PNIN TFET H_2 sensor also has been studied. It is finally proposed that designers can use the substrate bias to improve the sensitivity of FD-SOI PNIN TFET H_2 sensor.

1. Introduction

Hydrogen(H_2) gas presents itself as one of the best alternative energy for clean and renewable energy source. However, H_2 is colorless, inflammable and explosive. Therefore, it is important to develop a effective method to monitor the concentration of H_2[1-3]. MOSFET based gas sensors has some advantages, such as cheap, easy-made, fast response and recovery, high sensitivity, etc., which give them large potential in usage[4-8]. However, with the length down scaling, MOSFETs suffer from short channel and hot carrier effects. TFETs with steep substhreshold swing were proposed as a alternative to MOSFETs[9-14]. Its basic structure is a reverse biased P-I-N diode. When a positive voltage is applied to the gate of the TFET, the energy bands in the P^-/N^- region are pushed down, and tunneling takes place between the valence band of the P+-source and the conduction band of the P^-/N^- region. However, due to poor tunneling probability of Silicon, TFETs have low on current. In addition, its average substhreshold swing needs to be further decrease, which is important for improve sensitivity sensor.

In this paper, a H_2 gas sensor based on FD-SOI PNIN TFET with Palladium(Pd) metal gate is proposed. The sensitivity of the sensor, which is a crucial parameter, has been studied through numerical simulation. In addition, the effect of substrate bias on the sensitivity of FD-SOI PNIN TFET H_2 sensor also has been studied.

2. Device Structure and Simulation Model

Figure 1 shows the schematic view of the FD-SOI PNIN TFET H_2 sensor. The device consist of Palladium(Pd) gate, SiO_2 gate oxide, P^+ Silicon(Si) source, the narrow N^+ Silicon(Si) layer, P^-/N^-

Silicon(Si) channel, N^+ Silicon(Si) drain, SiO_2 buried oxide and Silicon substrate. In order to reduce ambipolarity effect, the source and the drain are doped asymmetrically in the case of the FD-SOI PNIN TFET H_2 sensor. The source doping is 10^{20} cm^{-3}, the narrow N^+ layer doping is 10^{19} cm^{-3}, the drain doping is 5×10^{18} cm^{-3}, the P^-/N^- doping is 10^{17} cm^{-3}, the gate length is 50nm, the narrow N^+ layer length is 5nm, the gate dielectric thickness is 3nm and the Si layer thickness is 10nm. Pd has a very high selectivity towards H_2 gas, so the Pd gate with a workfunction of 5.1eV is used as the sensing element of the FD-SOI PNIN TFET H_2 sensor. The sensor mechanism concludes dissociation and adsorption of hydrogen molecules at the Pd surface, and then diffusion of some atomic hydrogen into Pd film, which form dipoles at the Pd/insulator interface changing the gate work function. The change in work function of Pd metal gate has been altered to the change in hydrogen gas pressure as reported in ref.[15][16].

The numerical simulation of the FD-SOI PNIN TFET H_2 sensor has been performed on Silvaco Atlas. For accurate simulation, the non-local band-to-band tunneling, band-gap narrowing and the quantum model are applied. All simulations used a very fine mesh across the region where the tunneling took place. Junctions were ideally abrupt.

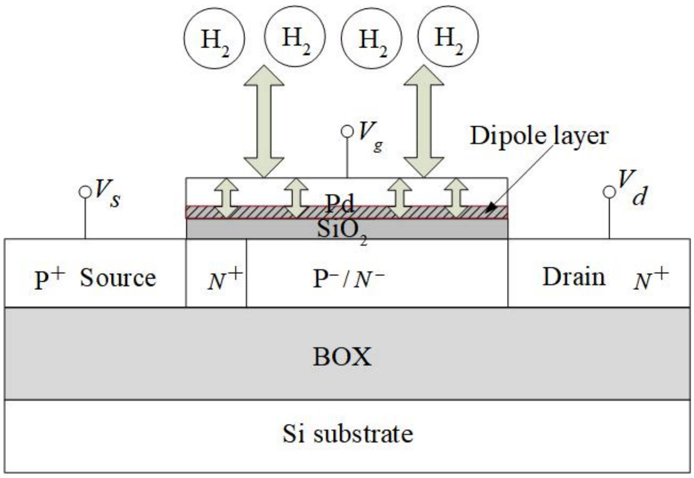


Figure 1: Schematic view of the FD-SOI PNIN TFET H_2 sensor.

3. Results and Discussions

The transfer characteristics of the FD-SOI TFET and FD-SOI PNIN TFET H_2 sensor are presented in Figure 2. FD-SOI PNIN TFET H_2 sensor shows very steeper subthreshold swing and higher on current. To further study the operational principle of the FD-SOI TFET and FD-SOI PNIN TFET sensor, lateral band diagrams at 0.1nm below the SiO_2/Si interface of these two structures at higher H_2 pressures is shown in Figure 3. As can be seen from this figure, the FD-SOI PNIN TFET H_2 sensor shows the steeper band bending. This steeper bending reduces the tunneling path and enhances the injection efficiency of the carriers, and then increases the drain current.

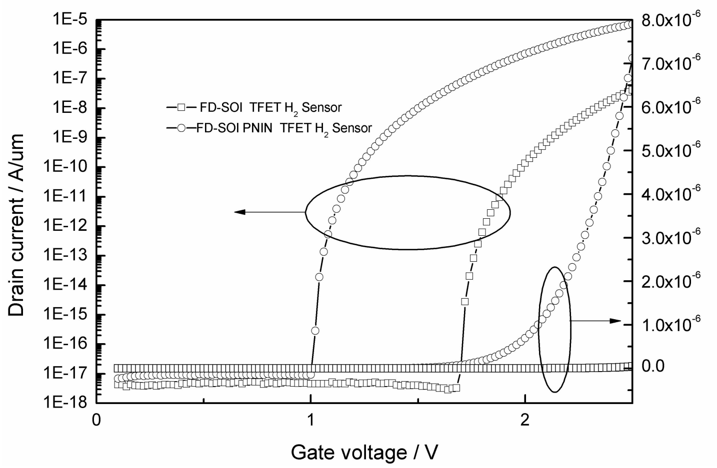


Figure 2: The FD-SOI TFET and FD-SOI PNIN TFET H_2 sensor transfer characteristics. Left axis is log scale, and right axis shows the same data on a linear scale.

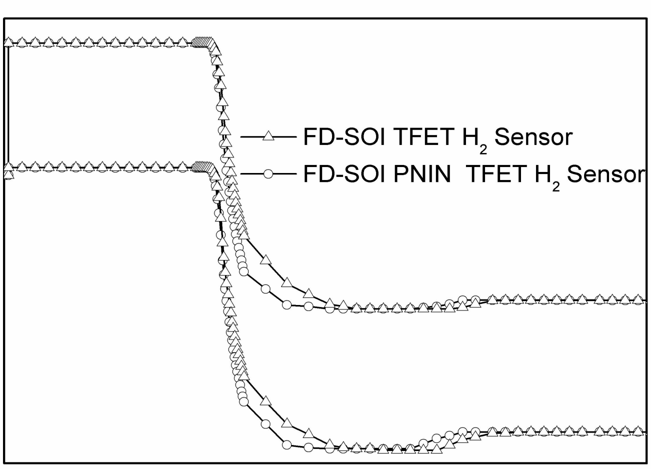
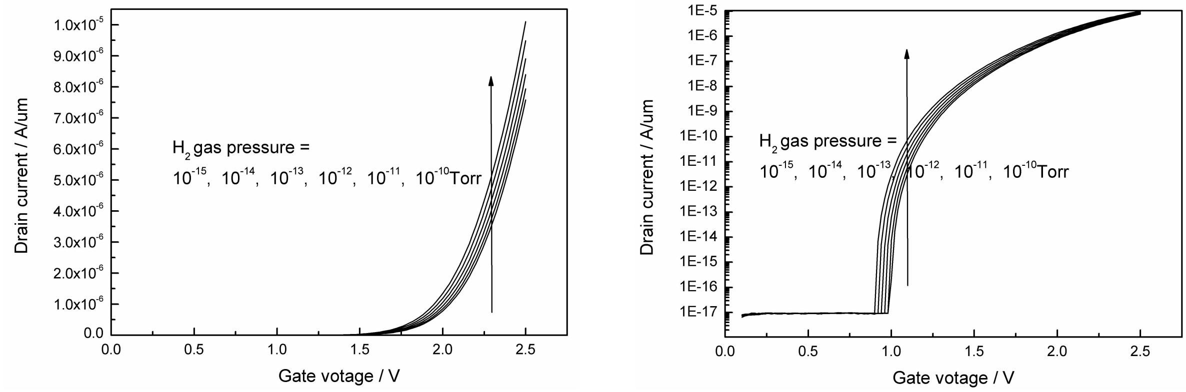


Figure 3: Band diagrams for the FD-SOI TFET and FD-SOI PNIN TFET H_2 sensor.

Figure 4(a) and 4(b) show transfer characteristics of FD-SOI PNIN TFET H_2 sensor for various H_2 gas pressure in linear and log scale, respectively. It shows that the drain current of FD-SOI PNIN TFET H_2 sensor is changed with H_2 gas pressures. As the H_2 gas pressure increases, the sensor drain current increases. This is caused by the fact that the work function of Pd metal gate has been changed with the hydrogen gas pressure.



(a)Linear scale (b)Log scale

Figure 4: Transfer characteristics of FD-SOI PNIN TFET H_2 sensor for various H_2 gas pressure.

Sensitivity(Sn) of the H_2 gas sensor is defined as the ratio of change in current after gas adsorption(I_{after}-I_{before}) to the initial current before gas adsorption(I_{before}) and is given by [17].

$$S_n = \frac{I_{after} - I_{before}}{I_{before}} \quad (1)$$

In Figure 5 and Figure 6, sensitivity is showed as a function of the gate voltage for the FD-SOI TFET and FD-SOI PNIN TFET H_2 sensor, respectively. It is observed that maximum sensitivity is obtained in the subthreshold region. This can be explained by the fact that the highest effect of gate occurs in the subthreshold region of these two H_2 sensor.

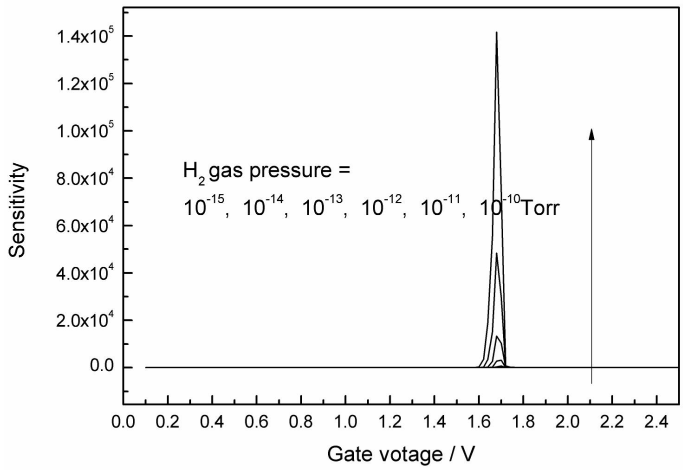


Figure 5: Sensitivity of FD-SOI TFET H_2 sensor for various gate voltage.

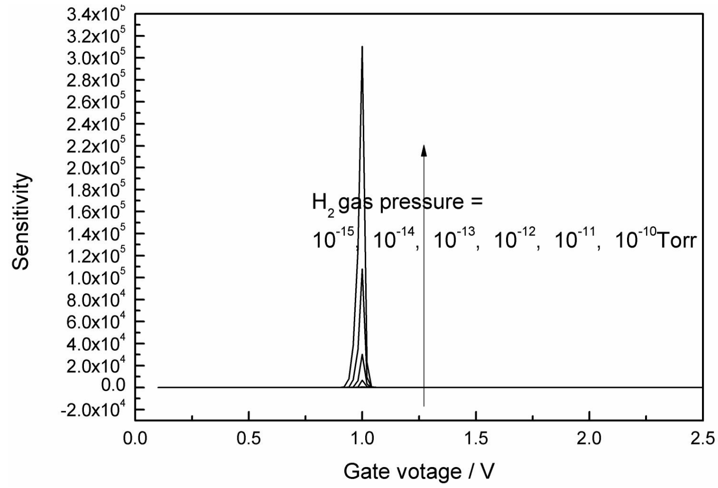


Figure 6: Sensitivity of FD-SOI PNIN TFET H_2 sensor for various gate voltage.

In Figure 7, sensitivity of FD-SOI TFET and FD-SOI PNIN TFET H_2 sensor are plotted w.r.t H_2 gas pressure. It is observed that for T = 300K, with an increase in H_2 gas pressure from 10^{-15} to 10^{-10} Torr, sensitivity of the FD-SOI PNIN TFET H_2 sensor is increased by many orders than that of the FD-SOI TFET H_2 sensor. This increased sensitivity is caused by the steeper band bending at the tunneling junction due to the introduction of the narrow N^+ layer as shown in Figure 3.

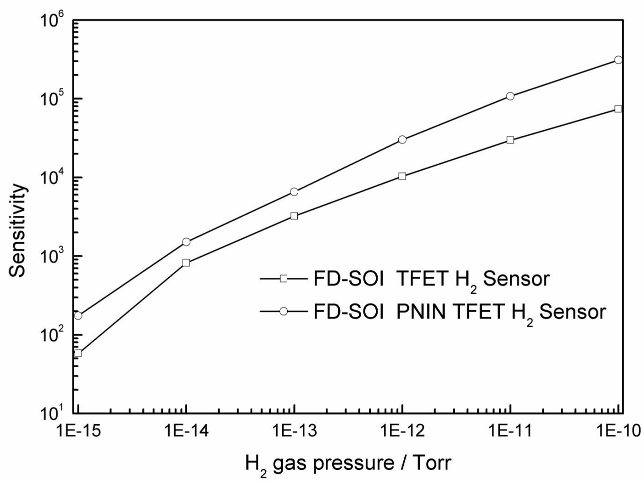
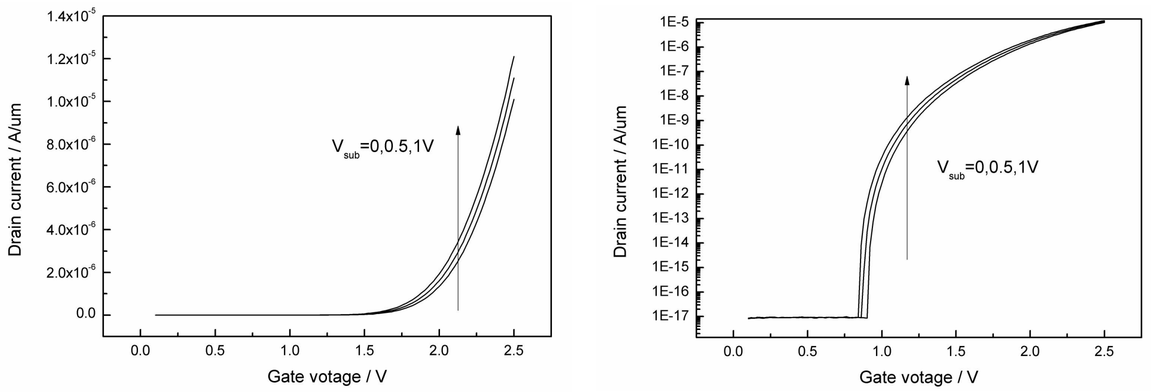


Figure 7: Sensitivity comparison of the FD-SOI TFET and FD-SOI PNIN TFET H_2 sensors as a function of gas pressure.



(a)Linear scale (b)Log scale

Figure 8: Transfer characteristics of FD-SOI PNIN TFET H_2 sensor for V_{sub}=0,0.5,1V at 10^{-10} Torr H_2 gas pressure.

Figure 8(a) and 8(b) plot transfer characteristics of the FD-SOI PNIN TFET H_2 sensor for different substrate bias (V_{sub}) conditions. It shows that the drain current of the FD-SOI PNIN TFET H_2 sensor is increased with V_{sub} increased form 0V to 1V.

Figure 9 plots the variation of sensor sensitivity with H_2 gas pressure at given substrate bias V_{sub} = 0 and V_{sub} = 1. It is observed that the FD-SOI PNIN TFET H_2 sensor biased with positive V_{sub} will be suitable for high sensitivity of operation.

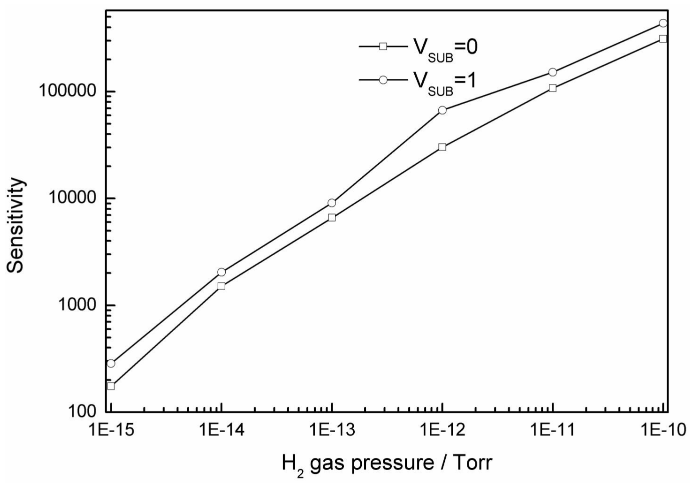


Figure 9: Sensitivity comparison of FD-SOI PNIN TFET H_2 sensor for different set of substrate bias conditions.

Acknowledgments

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