

Optoelectronics properties of FTO/SRO/Si radiation sensors

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Abstract

In this paper, we describe the optoelectronic properties of new metal-insulator-silicon optical sensors, in which the silicon rich oxide layer is used as a leaky insulator. Over a leakage current through the insulator layer, two possible operating modes have been found for sensors. At certain voltage bias, the sensor is likewise photodetector with an abrupt p-n junction. At lowered bias the sensor reveals the properties of “usual” metal-oxide-semiconductor (MOS) capacitor. If a stepwise voltage bias is applying to structure, new optoelectronics properties of sensor have been obtained due to a transient process taking the place at change of voltage. We assume this process as a basis for designing of new optical sensors with an essential internal signal gain.

1. Introduction

Non- stoichiometric silicon oxides (or Silicon Rich Oxide, SRO) are a variation of silicon dioxide (SiO_2), in which the content of either silicon or oxygen is changed. These oxides are no longer SiO_2 , and have to be represented by SiO_x , where x is between zero and two. When x is equal 2, the dielectric is SiO_2 , whereas x is zero, then it is amorphous or polycrystalline silicon. For any value of x between 0 and 2, the dielectric is non-stoichiometric silicon oxide. Silicon rich oxide (SRO) presents small silicon islands embedded in silicon dioxide matrix. This circumstance drastically changes it electric property relatively to silicon dioxide.

SRO can be deposited by low-pressure chemical vapor deposition (LPCVD) in an evacuated furnace through which there is a flow of silane (SiH_4) and nitrous oxide (N_2O) [1]. The excess silicon can be judged by the ratio of these gases $R_0 = \text{N}_2\text{O}/\text{SiH}_4$.

In the SRO, electrons can move between the silicon islands by tunneling [2]. Thus, the SRO layer at certain value of R_0 is likewise to a leaky insulator that exhibit considerable steady state current flow even at relatively small applied electric field. If such SRO layer is sandwiched between a metallic electrode and semiconductor (metal-insulator-semiconductor (MIS) structure), new physical effects can be achieved. It has

been show [3] that the d. c. current through the insulator introduces deviation of this structure from a standard MOS capacitor. The application of a substrate-depleting d. c. voltage establishes a steady-state non-equilibrium depletion regime [3,4]. This regime is characterized by equality of the current representing generation of the minority carriers (in the bulk of the substrate and at the interface with the insulator) and the thorough current across the insulator to a metallic gate. At that, the current will depend on the voltage drop across the leaky insulator and the excess surface minority carriers density because of the charge accumulated in the space charge region. Any change in the generation current will produce new currents equality at a new value of the charge in the space charge region. If the majority-carrier current through the insulator is small and the bias voltage is sufficient to main the steady-state non-equilibrium depletion regime, the electrical characteristics of such structure are likewise to those of an abrupt p-n junction. For the first time, this operating mode in Al/SRO/Silicon structure was investigated by Aceves M. et al [5]. However, opacity of Al contact presented the possibility to obtain only a qualitative information about the real value of photocurrent. Quantitative assessment of the photocurrent in steady-state non equilibrium mode was done in [6], when Al non-transparent contact was changed on the layer of conducting transparent fluorine-doped tin oxide.

At lower bias, the transport of generated minority carriers through the insulator is limited, and a stable inversion layer will form at the semiconductor surface. At this bias the structure will operate in an equilibrium MOS capacitor mode. If two-level stepwise voltage bias is applied to structure, it's possible to obtain two current components related to above-mentioned operating modes: the generation current from the depletion region and the displacement current related to a transient process in MOS capacitor due to a change of voltage.

Recently, we show, at the first time, that this transient process can be used as a basis for designing of new optical sensors with essential internal gain [7]. The effect obtained does not peculiar only to the structures with semi-conducting SRO layer. This effect takes place also in metal-insulator-semiconductor structures with other type of “leaky” insulator as a metal phthalocyanine organic semiconductor [8], for example. Thus, the

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approach to use the transient process in MIS structures with “leaky” insulator is interesting for designing high-sensitive optical sensors with internal gain.

The main goal of this article is to present additional new experimental details obtained in FTO/SRO/Si structures. This information gives us further comprehension of the physical processes in such type of sensors.

2. Samples fabrication

The FTO/SRO/Si sensors were prepared by depositing SRO layer on high-resistive n-type silicon substrate with the carrier concentration about of 10^{12} cm^{-3} . The SRO with the silicon excess of 8.5 at.% was deposited in a hot-wall LPCVD reactor. Silane, diluted to 5% in nitrogen, and nitrous oxide were used as reactants at $R_0 = 20$. Samples were sintered in a nitrogen ambient at $T = 1000^\circ\text{C}$ for 30 minutes following the deposition of SRO. The thickness of the SRO layer was determined both by ellipsometry with a Gartner 117 ellipsometer and by profiling with a Tencor Surface Profilometer Alphastep 200. In both cases, the average of the measurements was taken to be the value for the thickness of the SRO film. Transparent conducting n-type fluorine-doped tin oxide (FTO) layer as the gate electrode was deposited on the surface of SRO by spray technique [9]. The conducting properties of optimized FTO film is likewise a metallic layer due to a big carrier concentration ($\sim 10^{20} \text{ cm}^{-3}$). Moreover, high transparency of FTO in visible and near infrared spectral range (more than 80%) allows an effective light penetration inside silicon.

FTO film was subsequently etched to a rectangular shape of $6 \times 10^{-2} \text{ cm}^2$.

3. Measurements details

Quasi-static current-voltage (I-V) and capacitance-voltage (C-V) characteristic were obtained with a Wavetek pulse/function generator as a d. c. / pulse voltages source and recorded with a Tetronix TDS-3012 oscilloscope.

The capacity (C) of FTO/SRO/Si sensor together with a load resistor ($R_L = 50 \text{ k}\Omega$) forms a derivation circuit. An output signal is

$$U_{out}(t) = -R_L C \left| dU(t)/dt \right| ,$$

where $U(t)$ is an input time-dependent voltage bias applied to structure. At a linear voltage sweep $U(t) = U_0 \pm \alpha t$, the output signal is proportional to the capacity of the structure:

$$U_{out} = \left| \alpha R_L C(t) \right| \text{ or } I(t) = \left| \alpha C(t) \right| \quad (1)$$

Thus, using a linear sweep voltage, it is possible to obtain a low-frequency C-V characteristic.

The photoelectric measurements were carried out with a monochromator or light-emitting diode (LED).

4. Photoelectric characteristics in non-equilibrium mode

This type of operating mode is obtained when a certain d. c. voltage applied to the structure causes appreciable current through the SRO layer. Due to the insulator at that is “leaky”, photogenerated holes can not accumulate at the surface of the silicon and will recombine with electrons from a metallic gate. The structure is in non-equilibrium state, and the quasi-Fermi level of holes does not coincide with the electron Fermi-level in the depletion region. It stays at position nearer to the conducting band as shown in Fig. 1. The quasi-Fermi levels of the majority (ϕ_e) and minority carriers (ϕ_h) split by quantity of $V_a - \phi$, when V_a is applied voltage and parameter ϕ is a potential difference between the metal (gate) Fermi-level and the surface hole quasi-Fermi level.

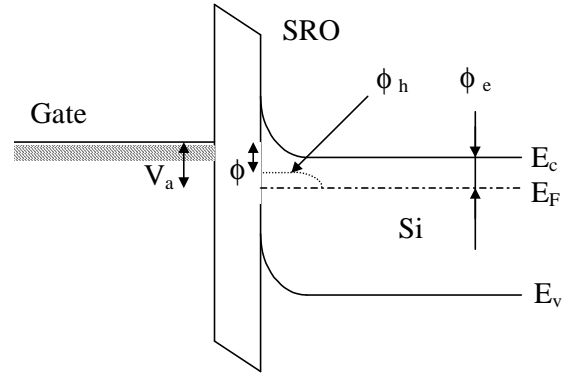


Figure 1. The energy band diagram for the structure in non-equilibrium depletion mode.

If the structure is illuminated by a square-wave modulated monochromatic light, the time-dependent photoresponse does not have the same form at different light power (Fig. 2).

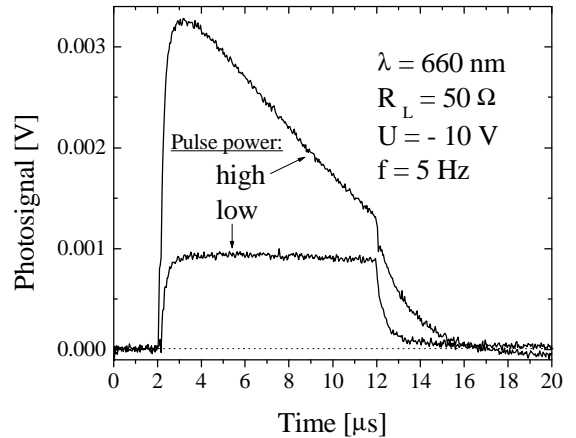


Figure 2. Time-dependend photosignal obtained in FTO/SRO/Si structure illuminated by a 12 μs light pulse at repetition frequency of 5 Hz.

Photo-signal at low incident light power is likewise to one from a standard silicon photodetector. However, the signal form at certain light power suffers a drastically changes. These changes of signal connect with limited carrier transport possibility of the SRO layer.

At high generation rate of holes, their ability to recombine with electrons from the FTO gate is limited by the tunneling probability of electrons between the silicon islands within the SRO layer. At given silicon excess, the current through SRO layer (J_{tun}) depends on the voltage drop on this layer. Increasing of the holes generation rate at given voltage bias occurs their accumulation in the potential wall at SRO/Si interface. This causes transition of the structure in quasi equilibrium state that is typical for MOS capacity. In this operating mode, the photo-signal (J_{ph}) has the alternating differential form. One can see the signal polarity changing at high light intensity. Below, we will show this detail more thoroughly.

Due to a limited capacity of the potential wall, the differential form of the output signal appears when the potential wall is filled by photogenerated holes. This circumstance, together with limited tunnel current through SRO layer, limits at given voltage bias (U) a dynamic range of sensor operating in depletion mode at illumination from a pulse-modulated light source. The width (τ) of the light pulse to have non-differential output signal needs to be less then) $(C \times U) / (J_{\text{ph}} \equiv J_{\text{tun}})$. Here, C is the MOS capacity in an inversion mode.

5. Quasi equilibrium MOS operating mode

To obtain more details about the carrier transport mechanism in FTO/SRO/Si sensors operates in the mode likewise to MOS capacitor, a quasi-static C-V (I-V) characteristics have been examined.

Fig. 3 shows the current signal in the dark (a) and illuminated conditions (b) recorded when a linear voltage sweep bias from -20 V to 0.5 V with $\alpha = 400$ V/s is applied to the sensor.

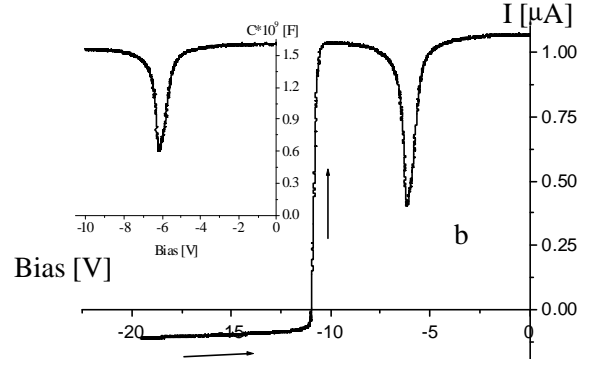
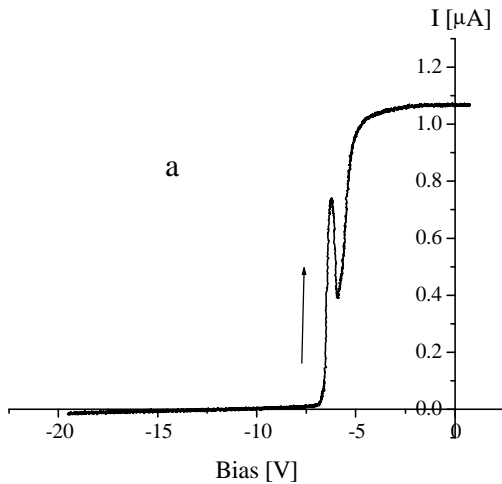


Figure 3. The current signal recorded at a linear sweep bias applied to the FTO/SRO/Si sensor: a – in the dark; b – at illumination.

From this figure one can see that at high voltage bias the thorough dark current (Fig. 3a) and a steady photocurrent take place. At voltage bias below -7 V (in the dark) and -11 V (at illumination), the I-V characteristics undergo an essential changes, and to become identical with C-V characteristic of MOS capacitor. These voltage biases correspond to the transition from the non-equilibrium MIS operating conditions to quasi-equilibrium MOS capacitor mode.

The value of current on Fig.3 can be recalculated accordingly (1) at known value of α to obtain the C-V characteristics (insertion on Fig. 3b). At that, the thickness of the SRO layer is determined as $0.16 \mu\text{m}$ that coincides well with the measured thickness by ellipsometric and profilometric methods.

In Fig. 4 we present the I-V characteristics of the sensor that is obtained at linear sweep voltage. To see the difference between two operating modes, a square-wave modulated light from the LED illuminates the sensor.

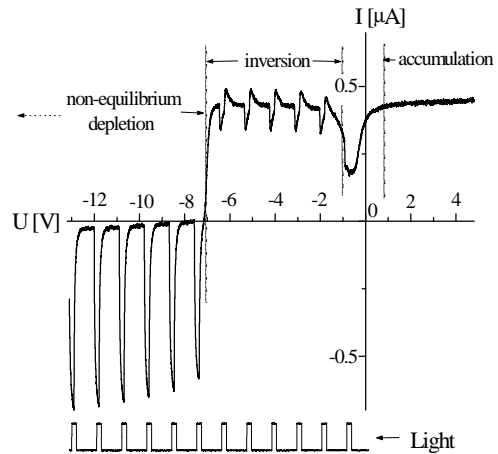


Figure 4. The I-V characteristic of FTO/SRO/Si sensor recorded at a linear sweep bias and a square-wave modulated light.

At bias less than -7 V, the structure goes from a non-equilibrium depletion mode to quasi equilibrium MOS capacitor mode, when the photo-signal has a differential form. That is why, the signal on Fig. 2 at high light intensity has this distinctive form.

The voltage threshold corresponds to this transition depends on illumination level (Fig. 5). The curve 1 relates to a dark condition, and 2-6 result at illumination.

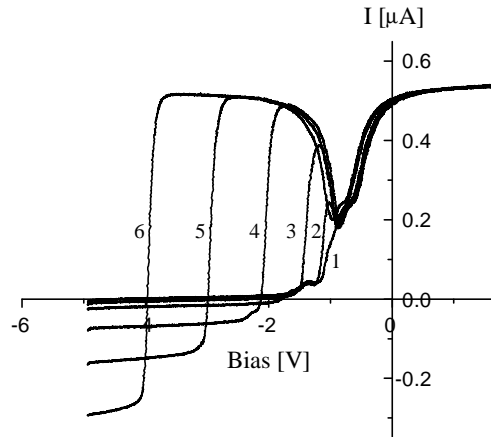


Figure 5. The I-V characteristic of FTO/SRO/Si sensor recorded at a linear sweep bias and at different illumination levels.

Figure 6 shows the result obtained for the FTO/SRO/Si photodetector when a stepwise two-level voltage bias is applied to the device.

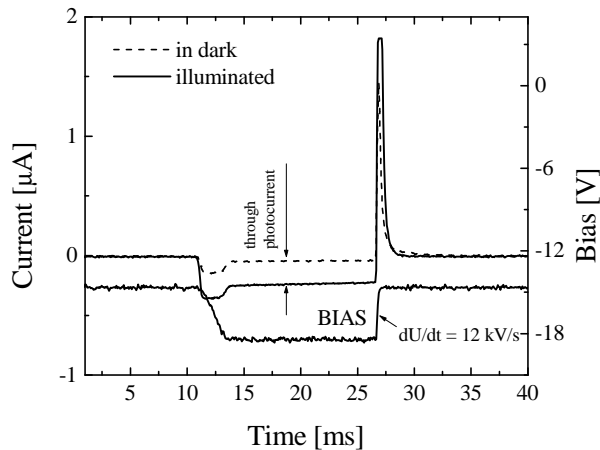


Figure 6. Time-dependent current characteristics of FTO/SRO/Si sensor at two-level stepwise voltage bias applied to structure.

Low and high level of a stepwise bias corresponds to two above-mentioned operating modes. The transition portion between two voltage levels presents a linear sweep voltage. At that, the displacement current appears at fast changing of bias. The amplitude of current peak depends on the light intensity. It is significantly bigger

than a value of thorough photocurrent in depletion non-equilibrium operating mode. In that way, we have internal photocurrent amplification. It was estimated that the magnitude of internal gain is in the order of 100. More technical details about electrical and optoelectronic characteristics of FTO/SRO/Si photodetectors the reader can find in [7].

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