Optical sensitivity of Al/SRO/Si MOS diodes

Z. Yu and M. Aceves
Departamento Electronica, INAOE,
Apartado Postal 51, Puebla, Pue., 72000, Mexico,
e-mail: zyu@inaoep.mx

J. Carrillo
Centro de Investigaciones en Dispositivos Semiconductores,
Benemérita Universidad Autónoma de Puebla,
Puebla, Mexico.

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In this work, the I-V characteristics of an Al/SRO/Si MOS-like diode under illumination were studied. A strongly illumination-dependent photocurrent was observed although the structure was opaque on both sides. The possible mechanisms that create the photocurrent were studied. We believe that the photo-carriers generated in a region surrounding the surface depletion layer dominate the photocurrent. The carriers generated by light in this region can diffuse into the depletion layer, and contribute to the photocurrent.

Keywords: Silicon-rich oxide; MOS-like structure; photosensitive; optical sensor.

En este trabajo, estudiamos las características I-V de una estructura Al/SRO/Si tipo MOS bajo iluminación. Se observo una gran fotocorriente aunque la estructura tiene Al que opaca por ambas superficies. Los posibles mecanismos que producen la fotocorriente fueron estudiados. Creemos que los foto-portadores generados en una región que rodea a la región de agotamiento dominan la fotocorriente. Los portadores generados en esta región difunden hacia la región de agotamiento y contribuyen a la gran fotocorriente.

Descriptores: Óxido de silicio rico en silicio; estructuras tipo MOS; foto-sensibilidad; sensores ópticos.

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1. Introduction

Silicon-rich oxide (SRO) is a multi-phase material that contains sub-stoichiometric SiO_x and excess Si atoms or Si nano-clusters. This material can be easily fabricated using different techniques [1–4] such as Si implantation into the thermal oxide, sputtering, and chemical vapor deposition (CVD). The research on SRO has attracted a great deal of attention since the observations of the strong visible light emission [5] and variable electrical properties that depend on the excess Si concentration [6,7]. It has been suggested that SRO is a promising material for the visible-light emitting devices and some other microelectronic devices, for example: non-volatile memories [8], surge suppressors [9], and even single-electron devices [10]. On the other hand, transparent conductive oxide coating (TCO)/SRO/Si MOS-like structure has showed some optical sensitivity [11] that makes this kind of device a promising structure for optical sensors. This optical sensitivity has been explained by the carrier generation in the depletion layer of the induced PN junction under the gate electrode [12].

In this work, the optical sensitivity of an Al/SRO/Si MOS-like structure is reported under white light illumination, and an effort to understand this phenomenon is made. The result shows that it is possible to develop an optical sensor that can detect the illumination intensity based on this Al/SRO/Si MOS-like structure.

2. Experiments

Samples used in this study have an Al/SRO/Si MOS-like structure. The SRO layer was deposited by low temperature chemical vapor deposition (LPCVD) using nitrous oxide and siliane as reactive gases. The deposition temperature was 700°C and Ro (defined as the partial pressure ratio of N_2O and SiH_4) was 10, 20 and 30, respectively. The thickness of the SRO layer was varied from 20 nm to 365 nm. N-type Si wafers with orientation of $\langle 100 \rangle$ and resistivity of 3-6 Ω-cm were used as substrates. Details of the fabrication have been reported elsewhere [10,13]. I-V measurements were taken at room temperature in the dark and under illumination with different light intensities. For the measurements under illumination, a white light source was used and the incident light was normal to the samples' surface. In order to modify the light intensity, a shutter was used and the light source was near or moved away from the sample. The shutter was completely or partially open, or closed. The optical power density was estimated using a Si photodiode. I-V measurements were taken using a Keithley 2400 SourceMeter controlled by computers. While taking the measurements, the voltage was always swept from negative to positive, with a sweeping rate of about 1.7 V/s.

3. Results and discussion

Figure 1 shows the typical dark and illuminated (photo) I-V curves of the samples with different illumination intensities.

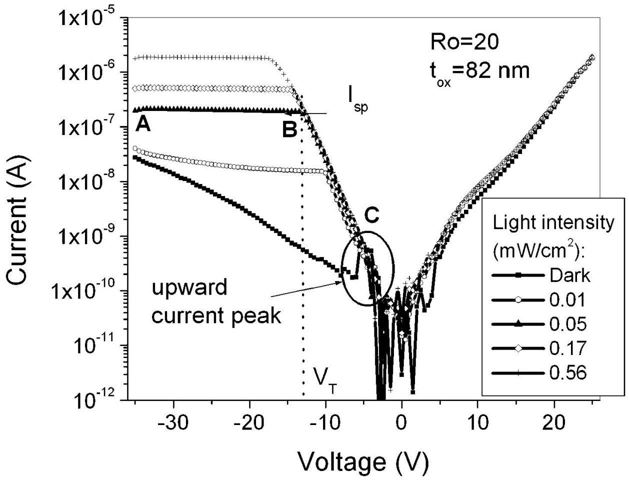

FIGURE 1. Typical dark and photo I-V curves of Al/SRO/Si devices.

Samples with a different R_o and SRO layer thickness (t_{ox}) showed similar I-V characteristics. A dark reverse current shows a very clear upward current peak that is indicated in the figure. This has been reported and discussed in a previous study [10].

For the photo I-V curves, two regimes can be identified under reversed biased conditions: AB and BC. In regime BC where V_g is small (where V_g is the absolute value of the applied reverse gate voltage), the photocurrent increases with V_g, and finally reaches saturation. Also, the photocurrent is almost the same for different illumination intensities. This means that the current is determined by the carrier transportation through the SRO layer instead of the carrier concentration available for conducting the current. The threshold voltage (V_T) at which the photocurrent reaches saturation varies with the illumination intensity and SRO layer thickness t_{ox}. As can be observed in Fig. 1, V_T increases with illumination intensity for a constant t_{ox}. For constant illumination intensity, V_T increases with t_{ox}. Figure 2 shows the plot of (V_T - V_s) as a function of t_{ox}, where V_s is the surface potential of the Si substrate, and (V_T - V_s) is the voltage drop on the SRO layer. It can be seen that (V_T - V_s) increases linearly with t_{ox}. This indicates that the electrical field strength (equal to the slope of the curve) across the SRO layer at which the photocurrent reaches saturation is the same for devices with different SRO layer thicknesses. This electrical field strength is about 2.13×10^6 V/cm for a light intensity of 10 μW/cm^2, and it increases to 2.77×10^6 for light intensity of 0.56 mW/cm^2, as shown in the inset of Fig. 2.

In regime AB, the photocurrent (I_{sp}) reaches saturation; however, it is a function of light intensity. Figure 3 shows the photocurrent as a function of illumination intensity. Photocurrent increases almost linearly with light intensity. This provides a possibility of giving a quantitative detection of the incident light source even though the incident light intensity is very low (10 μW/cm^2 or lower).

A photo- to dark- current ratio of 10^3 has been obtained for an illumination intensity of 0.56 mW/cm^2 for device with Ro=20. It was also found that the photocurrent increases with excess Si concentration in SRO layer. Thus, the detection resolution can even be improved by optimizing the SRO layer, usually decreasing Ro for deposition of this layer.

The transportation mechanism of photocurrent in this Al/SRO/Si MOS-like structure has been discussed elsewhere [13]. Here we try to understand the optical sensitivity as shown by this opaque structure. There are three possible regions where the light can produce photo-generated carriers: the lateral extension region of the depletion layer (width W_L); a region surrounding the depletion layer where the photo-generated holes can diffuse into the depletion layer (width L_p); and the SRO layer around the Al electrode. Figure 4 shows the regions mentioned.

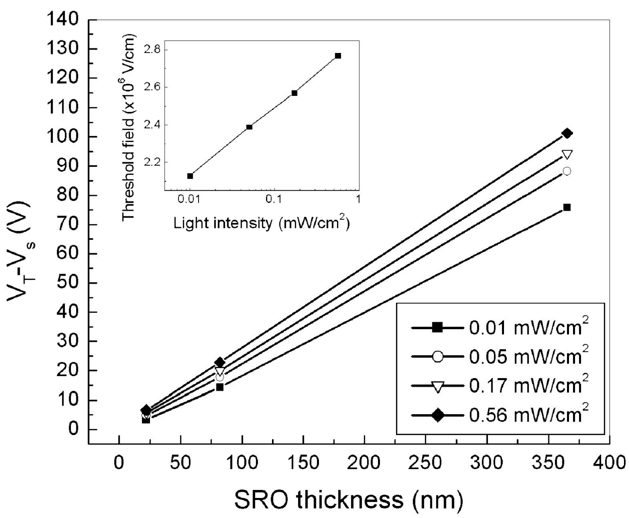

FIGURE 2. Threshold voltage versus the SRO layer thickness. Ro=20. The inset shows the threshold electrical field strength as function of light intensity.

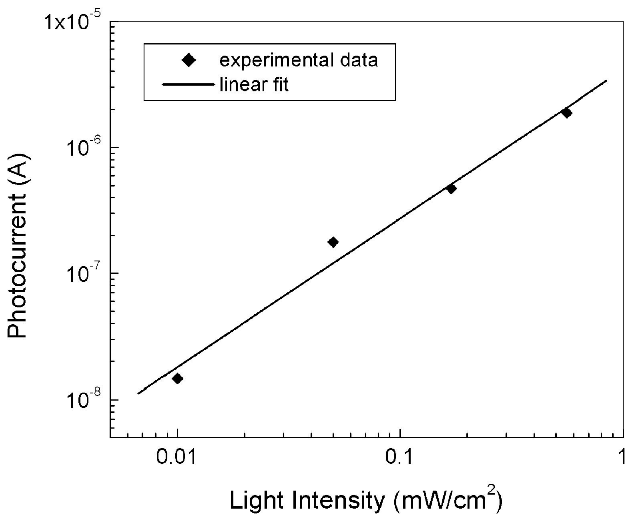

FIGURE 3. Saturated photocurrent (I_{sp}) as function of light intensity.

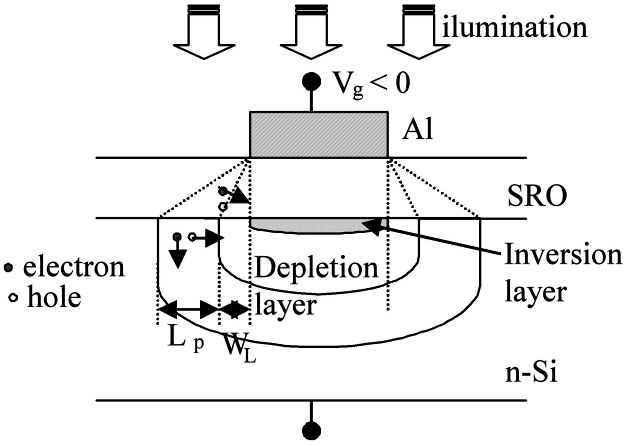

FIGURE 4. Schematic view of the photo-carrier generation zones in Si substrate and SRO layer. Three regions can be classified: SRO layer around the Al gate, lateral depletion region and the diffusion region surrounding the depletion layer.

The width of the lateral extension of the depletion layer W_L can be estimated to be very small (some microns or smaller). The hole's diffusion length L_p can be estimated in the order of 35 μm (For n-type Si, hole mobility μ_p=470 cm^2/V-s, $\tau_p = 10^{-6}$ s) for our samples. Thus the contribution from the lateral extension of the depletion layer is negligible compared with that from the diffusion region.

Another possibility is the combination of charge trapping in the SRO layer and the induced lateral extension of the depletion layer underneath. The light excites electrons and holes in the Si surface between the gap between the gate electrodes, and the excited electrons could tunnel into the SRO layer and be trapped by the Si nanoclusters embedded in SRO layer. This would result in the lateral extension of the depletion layer and a large photocurrent would be expected. The structure showed very high optical sensitivity to visible light, implying that it is possible to use this structure as optical sensor which can be easily integrated into the Si ICs.

4. Conclusion

The Al/SRO/Si MOS-like devices were fabricated and characterized electrically under white light illumination. Pronounced optical sensitivity was obtained by this structure, although the light intensity was very low and its gate electrode was opaque. Two conduction regimes in the surface depletion condition were observed. A linear relation between the photocurrent and incident light intensity was found that suggests the possibility of developing a quantitative low intensity optical detector. A simple model based on the surface depletion and carrier diffusion near this depletion region was proposed in order to understand the optical sensitivity.

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