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Effect of the Active Layer Thickness on the Electrical and Electroluminescent Properties in Silicon Rich Oxide Based Light Emitting Capacitors

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Abstract*—This work presents the electrical and electroluminescent properties of light emitting capacitors (LECs) using silicon rich oxide (SRO) films as active layer. Metal-insulator-semiconductor-like structures were fabricated with n^+ polysilicon and aluminum as gate and substrate electrodes, respectively. SRO films were thermally annealed at high temperature to induce the silicon agglomeration. The effect of SRO thickness (t_{SRO} = 24, 53 and 80 nm) on the electrical and electro-optical properties of LECs is analyzed. A high conduction state (HCS) is observed at low electric fields (E) for SRO films with 24 and 53 nm of thickness. The current drops from that HCS to a low conduction state (LCS) when a certain electric field is reached. The HCS at low E is not observed as the SRO thickness is increased. A broad visible electroluminescent spectrum is observed on LECs when the electric field is larger than 7.5 MV/cm^2 through the Fowler-Nordheim mechanism. Moreover, an intense infrared (IR) electroluminescent peak is observed in LECs when the SRO film is decreased. This IR EL peak could be related with the silicon substrate emission.

Keywords—Light emitting capacitors (LECs), Silicon nanoparticles, Electroluminescence.

I. Introduction

Silicon (Si) photonics has attracted much attention for the last decades [1, 2]. One of its goals is to develop Si-based light-emitting devices that are compatible with Si technology. Nanometre-sized silicon particles (Si-nps) embedded in a dielectric matrix have shown a strong and stable luminescence at visible and near infrared wavelengths seeming as an alternative for light emitting devices [3]. Band-edge infrared emission has also been observed in metal-insulator-semiconductor (MIS) structures and its origin has been explained as a result of the electron and hole radiative recombination in the silicon substrate [4]. Here, we report about the effect of the SRO thickness (24, 53 and 80 nm) on their electrical and electro-optical properties when used in light emitting capacitors (LECs). LECs with SRO thickness about 80 nm behave like a normal MIS capacitor. However, a high current flow at low electric fields (E) is observed in SRO based LECs where the thickness is below 53 nm. A resistance switching (RS) behavior from the high conduction state (HCS) to a low conduction state (LCS) is observed when the thickness of the SRO films is lower than 53 nm. The electro-optical properties observed in these LECs and the conduction mechanism are also studied.

II. Experiment

MIS structures were fabricated to study the electrical and electro-optical properties of Si-nps embedded in silicon-rich oxide films when the oxide thickness is varied, as shown in figure 1 a).

SRO films with thickness of about 25, 53 and 80 nm were deposited on p-type silicon substrates ((100)-oriented) with resistivity of 0.1-1.4 Ω-cm by low pressure chemical vapor deposition (LPCVD) at 720°C. Nitrous oxide (N_2O) and 5%-nitrogen (N_2) diluted silane (SiH_4) were used as the reactant gases, as reported in [5]. The estimated silicon content for SRO films used in these structures is ~39 at.% as measured by x-ray photoelectron spectroscopy (not shown here). After deposition, the SRO films were thermally annealed at 1100°C for 3 h in nitrogen atmosphere in order to induce the silicon agglomeration.

The thicknesses of annealed SRO films are ~ 24.1±3.2, 53.4±2.6 and 80±2.1 nm, as measured with a Gaertner L117 ellipsometer (@632.8 nm). A ~350 nm thick semitransparent n^+ poly-crystalline silicon (poly) gate was then deposited onto the SRO film surface by LPCVD.

After a lithography process step, square shaped gates of 2.304×10^{-3} cm^2 area were defined, as observed in figure 1 b). Finally, the backside contact was formed with 1 μm thick Al/Cu layer deposited by sputtering.

The presence of Si-nps within the active layers was observed in SRO films deposited under the same conditions by energy filtered transmission electron microscopy (EFTEM). Cross-sectional view images were obtained using an electron microscope JEOL JEM 2010F and Si plasmon of 17 eV. The average Si-np size was 2.7±0.4 nm, as shown in figure 1 c).

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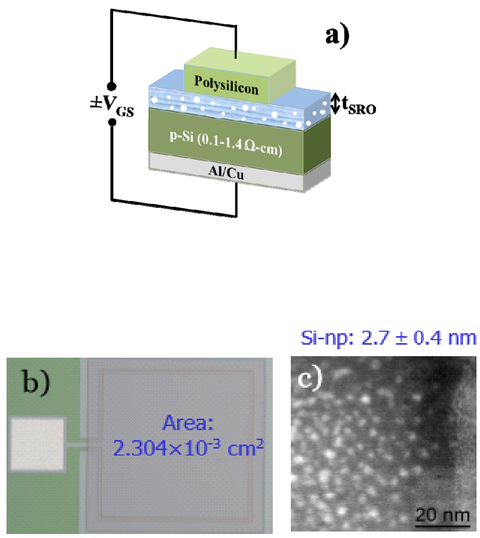

Fig. 1. a) Schematic cross-view, b) surface image of the LEC devices and c) EFTEM of SRO film.

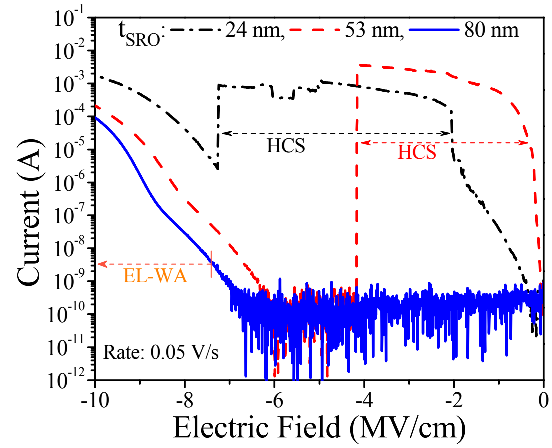

Fig. 2. I-E curve of the LEC with different SRO thickness.

III. Results and Discussions

The presence of defects including the Si-nps, either crystalline or amorphous, and their density and size in silicon rich dielectric materials affect clearly the current transport, and therefore the EL, as in the SRO case. Figure 2 shows the current-electric field (I-E) curves of SRO-LECs with different active layer thickness. SRO-LECs are forwardly biased (accumulation mode) considering the substrate as reference. A HCS is observed at low E values for the SRO thickness ⩽ 50 nm. The HCS switchs to a LCS after a threshold E is reached, which depends on the SRO thickness. The E value required to obtain the resistance switching increases as the SRO thickness reduces, as observed in figure 2. The resistance switching behavior was observed by our group before in SRO films with ~38 at.% of silicon content and it was related to the creation and annihilation of the preferential conductive paths generated possibly by adjacent stable Si-nps and unstable silicon nanoclusters (Si-ncls) through structural changes and by the possible creation of defects (breaking off Si-Si bonds) [5-7]. As we know, preferential conductive paths can be established between adjacent Si-nps allowing a high charge flow through the SRO film.

Once the HCS disappears, through the electrical annealing, the current behavior stabilized and EL on the whole area (EL-WA) is observed at higher electric fields (⩾7.5 MV/cm), as shown in figure 3. On the other hand, the HCS is not observed in the electrical behavior of SRO-LECs with 80 nm of thickness. The later could indicated that the creation of preferential conductive paths is not possible for SRO films thicker than 50 nm.

Therefore, a uniform network of conductive paths becomes posible instead, allowing a uniform charge flow through the whole capacitor area at high electric fields, as reported in [8].

Figure 3 shows the EL spectra from the SRO-LECs. Broad visible spectra with several maximum peaks at ~455, 490, 540, 650 and 800 nm are observed for all SRO thickness. The most intense EL peak almost remains at 650 nm for all SRO film thickness. Emission bands at 455, 540 and 650 nm have been observed before and have been widely related to the neutral oxygen vacancy (NOV), the E'$_\delta$ center and the nonbridged oxygen hole center (NOBHC) defects, respectively [6, 9]. An emission band at ~800 nm has also observed before and it has been related to quantum confinement in silicon nanocrystals [10]. However, this behavior of several peaks has been mainly related to the transmittance spectrum of the top polycrystalline silicon electrode, as observed in [11]. An additional IR band appears for the thinnest SRO film. This emission has been reported as a silicon substrate emission [4]. Therefore, this EL is a result of radiative recombination of holes confined at the interface with electrons that tunnel from poly to the Si substrate through the thinnest film.

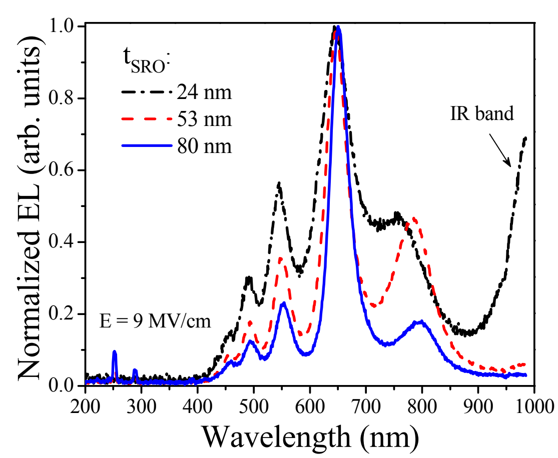

Fig. 3. EL spectra from LECs biased at 9 MV/cm for SRO thickness = 24, 53 and 80 nm.

For all the devices, the EL power intensity increases with the increase of current density with an almost linearly behavior, as shown in figure 4 a). As observed, the EL power is enhanced when the thickness increases from 53 to 80 nm.

To understand the conduction mechanism of the carriers in the devices, different conduction models usually discussed in silicon oxide as Fowler-Nordheim tunneling (F-N), Pool-Frenkel emission (PF) and Trap-assisted tunneling (TAT) are assessed [12]. In our case, the current behavior of all the SRO-LECs is best described by the F-N model. That is, the charges are injected from the electrode into the conduction band of the dielectric by tunneling through a triangular potential barrier. Figure 4 b) shows the J-E curve in the F-N representation, i.e., the logarithm of the ratio J/E^2 versus $1/E$. A straight line in a large range of experimental datas can be found for all samples, giving values of the barrier height (ϕ_B) of ~2.6 eV. This kind of mechanism leads to the injection of hot electrons in the active layer.

IV. Conclusion

Preferential conductive paths, created by defect states and silicon agglomerates in SRO films, exist as the SRO thickness decreases. These preferential conductive paths can be electrically annihilated and then a stable electrical behavior in LECs can be obtained.

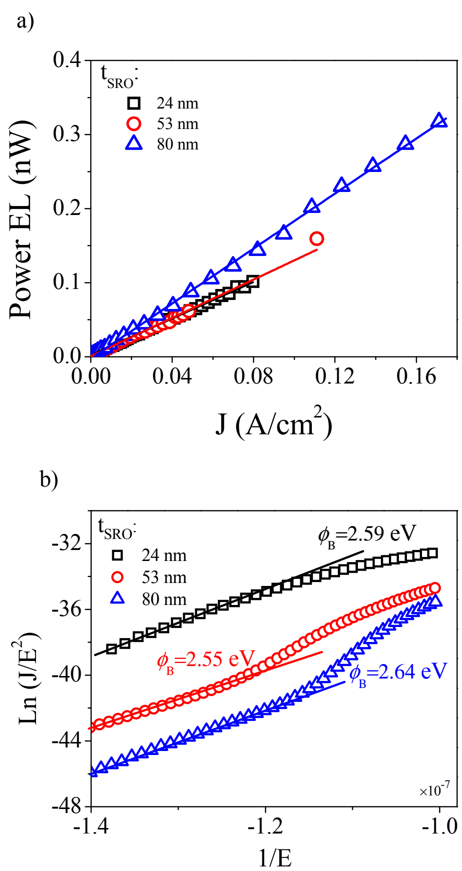

Fig. 4. a) P-J curve, and b) F-N plot for LECs with different SRO thickness.

A broad visible electroluminescent spectrum is observed on LECs when the electric field is larger than 7.5 MV/cm through the Fowler-Nordheim mechanism. An intense infrared electroluminescent peak is observed in LECs when the SRO thickness is decreased.

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