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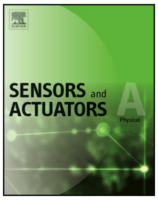

Enhancing emission and conduction of light emitting capacitors by multilayered structures of silicon rich oxide

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ABSTRACT

This work reports the morphological, electrical and luminescent characteristics of Light Emitting Capacitors (LECs) composed by Silicon Rich Oxide (SRO) multilayers. These multilayers alternate four conductive SRO layers (silicon excess of 12 or 14 at%) with three light emitting SRO layers (silicon excess of 6 at%). Transmission electron microscopy reveals that multilayers present well-defined nanoscale layers and interfaces in the multilayers. Furthermore, it is found that layers with high silicon content induce the formation of bigger silicon nanocrystals in the emitting layers as compared to single layers. When LECs are biased through a current-voltage measurement, an electroforming effect, where the current increases abruptly, is observed. This electroforming effect produces conductive trajectories arrays with high silicon content in the conductive SRO layers. These conductive paths allow to the LECs achieve higher current values with lower voltages preserving the luminescent characteristics of the emitting SRO layers. Consequently, it is demonstrated that silicon nanocrystals also act as sources of electro-hole pairs increasing the radiative recombination in the SRO defects. LECs that combine conductive and light emitting SRO films in a multilayered structure allow to enhance brightness and electrical characteristics compared to single layers. Depending on the conductive SRO layer preferential electroluminescence is produced in red or blue region.

1. Introduction

Currently, the power consumption, the crosstalk and capacitive effects between metallic and oxide layers are becoming a limitation for modern integrated circuits. Silicon photonics, whose goal is to fabricate electro-optical (or electrophotonic) integrated circuits on silicon substrates, represents a technological alternative to overcome the mentioned restrictions [1]. These electrophotonic devices should be able to emit and detect light, manipulate it and combine with electrical functions. Already, it has been reported different integrated systems that include different optical and electronic components. For example, the integration of a silicon-based light source with an optical waveguide was recently addressed [2]. In Ref. [3], the optical propagation and refraction phenomena in various complementary metal-oxide-semiconductor (CMOS) structures at 750 nm wavelength were studied. Also, the monolithical integration on Si of a system composed of a light emitter, a waveguide and a photodetector was reported in Ref. [4]. Nevertheless, the silicon-based light sources remain unreliableness because of their low emission intensity, high turn-on voltage and a small operating range, between others features. The operating range is defined as the electrical polarization values (voltage or current) that produce emission without dielectric breakdown.

Silicon is not intrinsically suitable for light emission due to its indirect band gap, and that makes the silicon-based light source the most challenge device for all silicon electrophotonic integrated circuits. One approach is to make Light Emitter Capacitors (LECs) using Silicon Rich Oxide (SRO). Even though SRO-based LECs are fully compatible with silicon technology and fabricated in a simple way [5,6], these devices still have the mentioned limitations. SRO films with silicon excess between 5 and 7 at%, deposited by Low Pressure Chemical Vapor Deposition (LPCVD) and thermally annealed at 1100 °C for 3 h in N_2 ambient has proved to produce the highest luminescence [7]. If silicon excess is above of 7%, then the light emission is quenched and more conductive films are achieved [5]. On the other hand, if silicon excess is less than 5%, the material

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tends to be stoichiometric silicon oxide, thus its emission property is lost [6]. The silicon excess in the SRO-LPCVD is controlled by the ratio of the reactant gases (R_0) during the deposition process, which is defined as $R_0 = [P_{N2O}]/[P_{SiH4}]$, where P_{N2O} and P_{SiH4} are the partial pressures of nitrous oxide and silane, respectively [6].

The first attempt to obtain SRO-based LECs was through the use of singles layers [6]. However, the main limitation in these kind of devices is the turn-on voltage whose value is near to the dielectric breakdown voltage, and once this value is exceeded the device is damaged.

In this regard, different options have been reported to improve the LECs performance. In Ref. [8] was demonstrated that LECs using SiO_x with Si buried in a high density and deposited over Si nano-pillar arrays allow enhancing emission intensity and power conversion. Also, the optical power and the efficiency of LECs can be improved by controlling the size of silicon nanocrystals buried in a SiO_x host [9]. In both cases, the SRO film was obtained by plasma-enhanced chemical vapor deposition (PECVD) exhibiting a high silicon content. Similary, silicon carbide films have been used as active material in Metal-Oxide-Semiconductor Light Emitting Diodes (MOSLEDs), whose performance was improved modifying the deposit conditions [10]; however, this kind of material is non-compatible with a CMOS fabrication process. Additionally, LECs using nanometric multilayers (MLs) also have demonstrated to improve their performance [11–13]. For example, in Ref. [11] was shown that structures alternating SRO layers with different silicon excess allow obtaining LECs with properties that combine those of each layer. In Ref. [14], the performance of LECs was improved by engineering nano-structures into the silicon substrate. However, the same improvement was obtained fabricating multilayers (MLs) of Si and SiO_2 [12,13], and also through implanting ions into the SiO_2 matrix [15–17]. Therefore, it is mandatory to understand the influence of the morphological characteristics on the electro-optical behavior of SRO-based light sources.

In this work, we describe the fabrication of LECs composed of SRO multilayered structures (SiO_x/SiO_y) exhibiting high conduction and light emission, as well as low probabilities to damage the devices. Also, a statistical analysis of TEM images is included in order to determine sizes and density of the silicon nanocrystals (Si-NCs) embedded in each layer of the MLs. These morphological features are related with the electrical and luminescent characteristics of the LECs. It is found that emission is mainly due to defects, while Si-NCs have a significant impact on the LEC conductivity, and depending on the conductive layer used in the MLs, the main electroluminescence peak is centered in the blue or in the red region.

2. Experimental procedure

LECs using SRO multilayers (SRO-MLs) as active material were fabricated on p-type (100) and 2.5–4 Ω-cm silicon substrates. Initially, substrates were cleaned in trichloroethylene, acetone, and deionized water in an ultrasonic bath. Afterwards, the native oxide was removed using a HF buffer solution. Finally, the samples were rinsed with deionized water and spin-dried. Two types of SRO-MLs were deposited by LPCVD at 736 °C. The first structure (labeled M-$LEC_{5/25}$) alternates four conductive layers of $R_0 = 5$ (SRO_5) with three light emitting layers of $R_0 = 25$ (SRO_{25}) of approximately 10 nm and 25 nm thick, respectively. The second structure (labeled M-$LEC_{10/25}$) combines the same number and thickness of layers, but uses $R_0 = 10$ (SRO_{10}) as conductive layer instead of SRO_5. Additionally, an extra sample of SRO_{25} single layer was deposited to compare the photoluminescence response between single layers and multilayers. After deposition, the samples were thermally annealed at 1100 °C for 180 min in N_2 ambient. The LECs were completed depositing a semitransparent 250 nm thick doped n-type polysilicon (N+-Poly) layer. Square gates of $4.056 \pm 0.017 \times 10^{-2}$ cm^2 were formed by photolithography and etching processes. Finally, a 600 nm thick Al film was deposited in the backside of the wafer and the structure was thermally annealed in forming gas. Fig. 1 shows an illustrative scheme of the LEC.

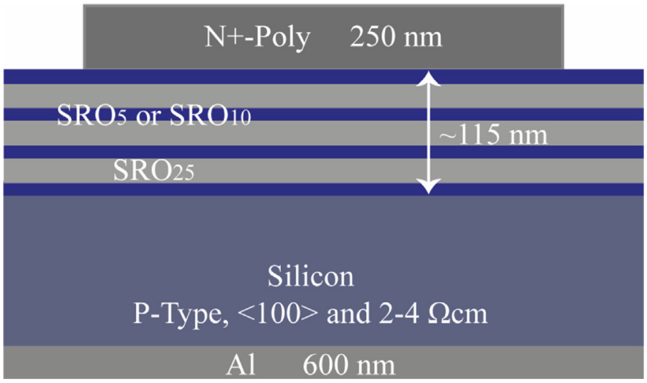

Fig. 1. Scheme of the LEC composed by a multilayered structure of SRO.

A JEOL JEM 2200 transmission electron microscope and Gatan Micrograph software were used to observe the presence of Si-NCs within the samples and to inspect TEM images, respectively. This software identifies the Si-NCs, the electron diffraction pattern of the Si-NCs by Fast Fourier Transform (FFT) analysis, and measures the image area. Additionally, the Si-NCs density was calculated counting the number of Si-NCs, measuring the area of the TEM images, and obtaining the ratio between them. Current versus voltage (I–V) curves were measured with a Keithley source-meter model 2400. Photoluminescence (PL) spectra were obtained with a Fluoro-Max3 spectrometer of Horiba Jobin Yvon. The excitation wavelength (λ_{exc}) was 300 nm and the emission was recorded from 370 to 1000 nm, with a resolution of 1 nm. Electroluminescence (EL) spectra were obtained using the 2400 source-meter and the detection module of the Fluoro-Max3. Emission was detected from 370 to 1000 nm with a resolution of 3 nm.

3. Results

Fig. 2(a) and (b) correspond to TEM images where well-defined nanoscale layers and interfaces are observed for both MLs. A magnification of the images corresponding to the conductive SRO layers in the central zone of the MLs shows a high density of Si-NCs as well as the presence of silicon nano-islands (Si-NIs) at Si/SRO interface. The dark and clear regions correspond to SRO_5 or SRO_{10} and SRO_{25}, respectively (both indicated in the figure). TEM Images were analyzed using Gatan Micrograph software. Si-NCs with size of 2 nm or higher were clearly observed; however, Fast Fourier Transform (FFT) analysis was used to find and assure the existence of Si-NCs smaller than 2 nm. The FFT analysis produce electron diffraction patterns that are related to specific crystalline planes. Electron diffraction patterns of the Si-NIs are related to the (400) orientation. The Si-NIs grows epitaxially from the silicon substrate, such that crystallographic planes in the Si-NIs are similar to that of the substrate [18]. The Si-NCs in the SRO layers are associated to (311), (511), (440) and (531) orientations. The variety of these crystallographic planes could be attributed to the wide range of silicon nanoclusters formed during the deposition process [19].

Fig. 2(c) displays the size distribution of Si-NCs in the SRO_5 layers of M-$LEC_{5/25}$, whose size and density have average values of 4.1 nm and 10^{12} cm^{-2}, respectively. However, it is important to remark that Si-NCs size range from 1.5 nm to 11.5 nm. While, SRO_{25} layers (in M-$LEC_{5/25}$) present Si-NCs with an average size and density of approximately 2.1 nm and ~10^{11} cm^{-2}, respectively.

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