1.54 μm Er doped Light Emitting Devices: Role of Silicon Content

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Abstract — Thin erbium implanted silicon rich oxides films have been used as active layer in light emitting devices. Electroluminescence has been observed and analyses as a function of the silicon content.

Power Efficiency; Silicon Nanocrystals; Erbium Sensitizer

I. INTRODUCTION

Recently, silicon photonics has been proven to be a mature technology and a suitable platform for optoelectronic circuitry development. However, the monolithic integration of an efficient all silicon light source still remains to be an issue. A promising path towards light amplification in silicon is based on Er^{3+} ions sensitization by silicon nanoclusters [1]. In this work thin (50 nm) erbium implanted silicon rich oxides film suitable for light emitting applications are studied by means of opto-electrical characterization.

The nanocomposites could have single layer or multilayer structure. A multilayer approach in the growth of the nc-Si composite material allows the independent control of nanocrystals size and density. After a high-temperature annealing, the thickness of the SRO layer in the multilayer structure determines the nanocrystals size, while the excess silicon content of the SRO layer determines the nanocrystal density. In addition, a tight control over the silicon oxide layer quality and thickness which separates silicon nanocrystals in the multilayer structure is possible. These features are enough to create an easy recipe in order to engineer the band gap energy of Si-NCs via thickness/composition profiling of a multilayer SRO/ SiO_2 structure.

Comparison between light emitting diodes based on single and multi-layer structures, with different silicon content, in terms of light emitting power efficiency of erbium ions is presented.

II. SAMPLE DESCRIPTION

The device structure is a MOS capacitor where alternating stoichiometric SiO_2 and silicon-rich oxide (SRO). In addition,

Figure 1. Device description: the cross-section is a CMOS capacitor in which the gate oxide is replaced by Er^{3+} ions sensitized silicon-rich oxide.

all the samples were implanted with Er^{3+} ions (Fig. 1). The samples were grown by low-pressure CVD processes, LPCVD. The silicon nanocrystals were formed by annealing the layers at 900 °C for 1 hour in a nitrogen atmosphere.

The erbium ion concentration in the studied composites was around $4 \times 10^{20} \text{ cm}^{-3}$, obtained by Er implantation with a fluence of $10^{15} \text{ ions/cm}^2$ and energy equal to 20 keV. Post implantation annealing was performed at 800 °C for 6 hours, in order to recover the matrix after the ions implantation. Details of the samples fabrication are reported in [2].

The basic geometry of the device is a 300 μm x 300 μm square with n-type polysilicon gate.

The devices presented in this work are summarized in Table 1. Samples P1, P2 and P3 have as active layer a multilayer structure, formed by an alternance of SRO and of silicon oxide layers. The three devices chosen for this work only differ in the silicon content and are used to evaluate the effect of the silicon excess on the power efficiency of the devices. Sample P4 is a single layer device, with a thickness of 50 nm and silicon excess equal to 12%. This latter one was selected in order to compare single thick layer with multilayer devices, while the silicon content excess is constant.

Device	Structure	Er-implanted matrix	Si excess
P1	Multilayer	LPCVD (2 nm 0% + 3 nm 20%) x 10	11.5 %
P2	Multilayer	LPCVD (2 nm 0% + 3 nm 25%) x 10	14.4%
P3	Multilayer	LPCVD (2 nm 0% + 4 nm 25%) x 8	16%
P4	Single Layer	LPCVD 50 nm	12%

Table 1. Summary of the devices under study

III. RESULTS AND DISCUSSIONS

A. Single layer vs. Multilayer

The light emitting diodes under study have low silicon excess and hence low conductivity, which means high operating voltages. In direct current (DC) regime, the Er ions are excited by impact excitation, as high energy transitions of erbium were clearly observed in the visible region of the spectra.

Figure 2 shows the integrated electroluminescence intensity of the peak at 1.54 μm as a function both of the injected current and of the applied voltage. It is reported for P1, which is the best multilayer under study, and P4, in order to do a comparison between the single and the multilayer light emitting devices. Both P1 and P4 active materials have the same thicknesses (50 nm) and about the same average silicon excess, but voltages are larger for the multilayered device. This is due to the different distribution of nanocrystals inside the active layer, providing higher injection energy barriers for multilayered devices compared with the single ones. However, both devices under study show very similar EL intensities.

Figure 2. Electroluminescence behavior vs. injected current and applied voltage for a multilayer (blue) and a single layer (red) light emitting diode.

Starting from this, the power efficiency in the infrared was evaluated and Figure 3 shows it as a function of the injected

current. In the figure, only P1 and P4 are reported. The most important result is that the multilayers have allowed increasing the power efficiency of the devices of about 1.5 times with respect to the single layer device. The maximum value of power efficiency achieved is $1.5 \times 10^{-2} \%$, referred to P1 at an injected current equal to 100 nA.

Figure 3. Power efficiency as a function of the injected current for a multilayer (blue) and a single layer (red) light emitting diode. In the inset, an example of the EL spectrum for P1 is shown (injected current of 50 μA).

B. External Quantum Efficiency of different Multilayers

Figure 4 shows the external quantum efficiency (E.Q.E.) as a function of the injected current for multilayer LEDs with different thicknesses of oxide and SRO, different concentration of silicon nanocrystals and different silicon content excess.

Figure 4. External quantum efficiency as a function of the injected current for P1, P2 and P3, multilayers with different average content of Si excess.

The maximum value of E.Q.E. is achievable with P1, and it is equal to 0.4%. This value is once again higher than the one achieved with the single layer light emitting diode. The best result was obtained on the multilayer with lowest silicon

excess and this suggests that more studies need to be performed on the role of the silicon excess in the multilayered devices.

C. Silicon excess study

Figure 5 shows the infrared electroluminescence intensity as a function of the silicon excess in different multilayer devices, with silicon excess in the range between 9 and 16 %.

Extrapolating the EL intensity dependence on silicon excess (Figure 5) to zero value gives higher value of the EQE than the one measured in Er-doped LPCVD and thermal silicon oxide. The same value of EQE is reached at about 6% of silicon excess. This figure also shows (right axis, red symbols) that lower operating voltages are achievable with higher silicon excess and/or thinner silicon oxide scaffold that confines Si-NCs. Such LEDs that operate at voltages below 5 V and emit light at the wavelength of around 850 nm have been demonstrated [3,4].

Figure 5. Electroluminescence intensity at 1.54 μm (left axis, blue symbols) at a fixed injected current of 1 μA as a function of average content of silicon excess for a series of multilayer LEDs (squares) and single layer LEDs (stars) and corresponding driving voltages (right axis, red symbols).

The electroluminescence behavior as a function of the silicon content confirms that, increasing the silicon excess, the IR emission decreases.

Anyway, from this plot, is observed that for the same silicon content the multilayers light emitting devices show higher power efficiency regarding to the single layer ones. However, there is still the problem of the high operating voltages both for the single and multilayers devices.

IV. CONCLUSIONS

In conclusion, we presented infrared emission in light emitting diodes, with silicon nanocrystals and Er ions embedded into the active layers. In particular, we had shown and discussed the differences between LED with single or multilayer composition of the active layer and the role of the silicon content excess.

Both multilayer and single layer LEDs operate at high voltages, where impact excitation of Er and unipolar injection are the main excitation mechanisms.

The multilayers have allowed increasing the power efficiency roughly 1.5 times regarding with respect to the single layer devices. The value of the power efficiency at a fixed injected current decreases with the increase of the silicon content.

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