Silicon-based light sources: En route to the first injected Silicon laser emitting at 1.54 µm

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***Abstract*— Metal-oxide-semiconductor light emitting devices were fabricated by means of a Si-rich silicon oxide layer with Er^{3+} ions implanted. The electroluminescence of different materials was studied. Active ring resonators electrically pumped were fabricated and tested.**

Keywords-silicon nanocomposites; erbium; carrier injection; electroluminescence; power efficiency.

I. INTRODUCTION

In the last years, Silicon-based light sources have been a matter of interest for the scientific community [1]. They provide several improvements and breakthroughs towards the electro-photonic all-silicon implementation by means of the Complementary Metal Oxide Semiconductor (CMOS) technology. Following this idea, some works insisted on the possibilities of exploiting the emission of the first excited level of Er^{3+} ions to achieve reliable and efficient light sources electrically pumped emitting at 1.54 µm. Among a number of materials used as erbium hosts, the SiO_2 with silicon nanoclusters (Si-ncs) has demonstrated to be the most successful because of the optimum environment for Er^{3+} ions, its non-resonant large bandgap (9 eV) and the higher carrier injection provided. Moreover, superior electro-optical performances can be obtained by using a multilayered structure of SiO_2 and non-stoichiometric (SiO_x) layers with Er^{3+} ions [2]. Optical gain under electrical pumping should be possible if an optimized active material is inserted in a high quality resonant cavity. Such a device has never been presented in the literature, because i) the active material has still to be optimized to obtain the inversion population of Er^{3+} by electrical pumping, ii) the SiO_x:Er material is a low refractive index material. Therefore a suitable photonic structure has to be designed in order to confine the light inside. A previous work [3] has managed to get round this difficulty by demonstrating theoretically how to confine the light in this material by using a slot structure. Such a proposal to guide the light is shown as a promising candidate to get a Si-based injection laser. In this paper, we show the work done toward the fabrication of such device and preliminary characterization.

II. EXPERIMENTAL AND RESULTS

A. *Fabrication*

Multilayered NMOS capacitors were fabricated with a standard CMOS technology, where the control oxide has been replaced by an active multilayer structure. Fig. 1a shows the device structure. Each layer was deposited by Low Pressure Chemical-Vapour Deposition (LPCVD). The silicon excess was introduced either by deposition of SiO_x layers or by Si ion implantation after the deposition of the SiO_2. In particular, two different Si excess were nominally defined for each single layer (20% or 25%). Table I summarizes the composition of the multilayered structures.

TABLE I

MULTILAYERS	
((2 nm 0 % + 3 nm 20 %) x10)+2 nm 0 %	***M1***
((2 nm 0 % + 3 nm 25 %) x10)+2 nm 0 %	***M2***
((2 nm 0 % + 4 nm 20 %) x8)+2 nm 0 %	***M3***
((2 nm 0 % + 4 nm 25 %) x8)+2 nm 0 %	***M4***
((3 nm 0 % + 3 nm 20 %) x8)+3 nm 0 %	***M5***
((3 nm 0 % + 3 nm 25 %) x8)+3 nm 0 %	***M6***
((3 nm 0 % + 4 nm 20 %) x7)+3 nm 0 %	***M7***
((3 nm 0 % + 4 nm 25 %) x7)+3 nm 0 %	***M8***
Dry thermal SiO2	***M9***

Detailed multilayer composition.

Then, a conventional annealing for 1 hour at 900ºC was done in order to obtain the Si-ncs segregation. Finally, an Er^{3+} implantation of about $1x10^{20}$ at/cm^3 was done at 25 keV of energy in all layers. The activation of erbium ions was achieved applying a post-annealing treatment at 800ºC for 6 hours. Notice that there is one device which is not a multilayer structure (M9). This device was fabricated as a Si-ncs free single SiO_2 layer (dry thermal oxide), and used as a reference. A phosphorous-doped polysilicon layer ($1x10^{20}$ at/cm^3) 100 nm thick was deposited on top of the active layers and used as semitransparent electrode. Finally, a new set of devices consisting on optically active ring resonators (µ-cavities) coupled to passive slot waveguides (WG) was designed and fabricated. A slot WG cross-section was required in order to accomplish both the guidance of the light and the effective electrical pumping inside the resonant structure. The new batch was split in LPCVD multilayers (with the best fabrication parameters obtained from the NMOS capacitors) and Plasma Enhanced Chemical-Vapour Deposition (PECVD) multilayers, for comparison. The total thickness of the multilayer structures was inferred from TEM images (Fig. 1b), showing a good agreement between the nominal (50 nm) and experimental values (53 nm).

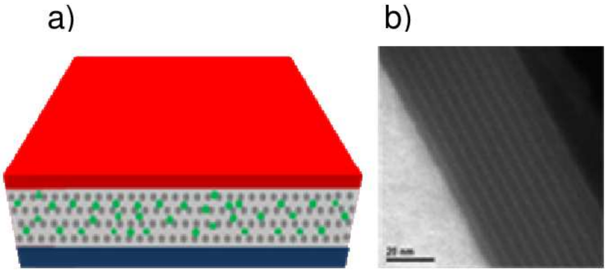

Figure 1: (a) schematic view of the multilayered structure. (b) EFTEM image of a PECVD multilayer obtained by filtering for the c-Si plasmon signal (17 eV).

B. Material optimization

An electro-optical characterization was carried out in all devices. The electroluminescence (EL) spectrum in the infrared was obtained when polarizing under accumulation regime for all devices (see inset of Fig. 2). Essential parameters such as the layer resistivity, the threshold voltage or the optical power at 1.54 μm were obtained. Another interesting feature is the power efficiency (PE), which takes into account the ratio between the injected electrical power and the optical power generated. Fig. 2 shows the averaged PE of devices as a function of the Si excess. Two series of devices have been identified depending on their SiO_2 layer thickness (2nm thick oxides have been marked with black squares and the ones 3nm thick with red circles). A maximum value of the power efficiency is observed in the sample with the lowest Si excess and the thinnest oxide layers, obtaining values around 0.045%. In addition, the PE value for the pure SiO_2 layer has been highlighted with a horizontal blue dashed line.

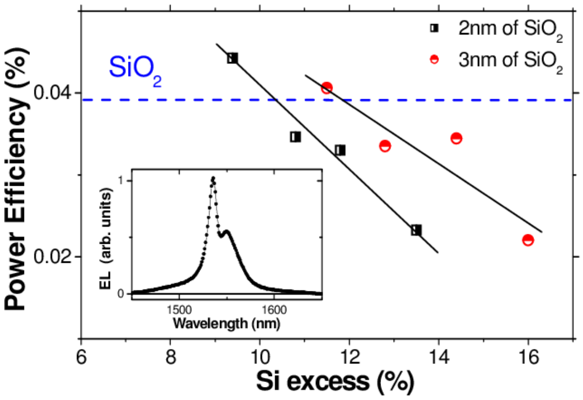

Figure 2: Power efficiency values as a function of the Si excess for the multilayer structures. Two different trends are observed, depending on the SiO_2 layer thickness. Straight lines are guides to the eye. The inset shows a typical EL spectrum at 1.54 μm.

C. Slot structures characterization

Propagation loss measurements have been performed at 1532 nm on the slot WG structures by means of the cut-back technique. It is worth to notice that the cross section of the WG structure in which we performed the losses measurements is the same of that of the resonators. For those set of samples, average losses values of 35 dB/cm have been found.

In order to get more insight on the μ-cavities, transmission measurement have been performed through the ring resonators, using a tuneable laser in a wavelength range around 1535 nm. A maximum Q factor of 2.5 x 10^4 has been found for a resonance at 1546.2 nm (see Fig. 3). These values are comparable with the ones present in literature for similar electrically active slot structures [4].

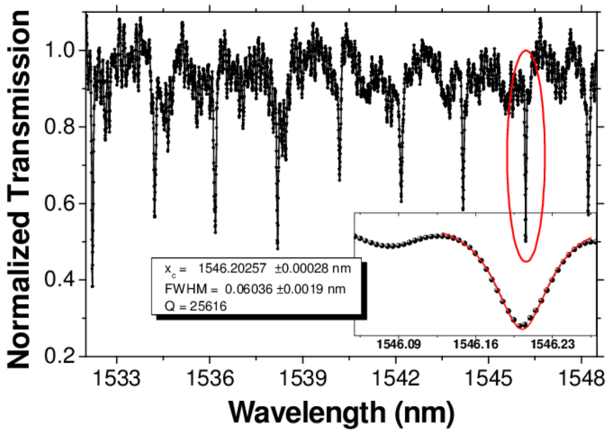

Figure 3: TM polarized transmission spectrum of a 50 μm radius ring, coupled with a 1μm wide waveguide and coupling distance of 220 nm. The inset shows a Lorenzian fit of one particular resonance (red line) at 1546 nm.

III. CONCLUSIONS

Erbium doped multilayer structures were fabricated and embedded in NMOS like capacitors for the electro-optical characterization. An optimization of the material was done in terms of the layer resistivity, voltage threshold, optical power and power efficiency. The best layers were chosen in order to fabricate electrically driven and optically active resonant cavities (slot WG ring resonators). The passive characterization of the structures showed good Q factors and losses comparable with the literature, suggesting a good scenario for the development of the first injected Si laser at 1.54 μm.

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REFERENCES

[1] Y. Berencén, O. Jambois, J. M. Ramírez, J. M. Rebled, S. Estradé, F. Peiró, C. Domínguez, J. A. Rodríguez, and B. Garrido; Optics Letters, vol. 36 (2011) 2617.

[2] A. Marconi, A. Anopchenko, M. Wang, G. Pucker, P. Belluti, and L. Pavesi; *Appl. Phys. Lett.* Vol. 94 (2009) 221110.

[3] V.R. Almeida, Q. Xu, C.A. Barrios, and M. Lipson; Optics Letters, vol. 29 (2004) 1209.

[4] K. Preston and M. Lipson; Optics express, Vol 17 (2009) 1527.