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Influence by Layer Structure on the Output EL of CMOS Compatible Silicon-based Light Emitters

A. A. González-Fernández[1], J. Juvert[1], M. Aceves[2], *Senior Member, IEEE,* A. Llobera[1], C. Domínguez[1]

Abstract—**Fully combined metal-oxide-semiconductor compatible light emitting devices based on nano bi-layer structures were fabricated. The active layers are composed by silicon nitride on top or a silicon-enriched silicon dioxide film with different Si concentrations. Electro and photo luminescence spectra of the devices and the active materials are analyzed and correlated to verify if the origin of the emission is the same. Differences found between electrically and optically stimulated photo-emission in the studied region of the spectra were concluded to be due optical phenomena introduced by the gate and multi-layer configuration, meaning that the same radiative centers are stimulated optically and electrically.**

Index Terms—**Silicon Rich Oxide, Electroluminescence, Photoluminescence, Light Emitting Capacitor**

I. Introduction

THE origin of luminescence from silicon based materials with embedded nano-structures is still a matter of debate. Electroluminescence (EL) from materials compatible with standard combined metal-oxide-semiconductor technology is particularly interesting, as it opens the possibility of creating integrated optoelectronic systems[1], [2], [3]. Devices using polycrystalline silicon (poly) as semi-transparent gate are specially appealing since they present maximum compatibility with standard integrated circuit fabrication processes[4], [5]. A clear understanding of the emission mechanisms taking place in such devices is crucial for their optimization, but the highly doped polysilicon significantly affects the output light of the devices due to its optical characteristics, making the analysis on the origin of EL rather difficult and lacking of precision[4]. Photoluminescence (PL) spectra can also deliver important information regarding the radiative processes taking place in the active layers; nevertheless, it is not yet clear if the mechanisms of EL and PL are necessarily related. Furthermore, the output light emissions of both luminescence types often differ from each other, even when characterizing identical materials[1], [2], [4], [5], [6], [7]. Some authors have attributed the differences to the stimulation of distinct radiative centers[6], but the effect of the gate material in EL tests is not taken into account. Other techniques used to differentiate the origins of PL and EL often rely on indirect measurements, such as temperature dependence on a single wavelength[8], which is useful but very limited if it is considered that luminescence comes from a combination of phenomena as it is now widely accepted[1], [2], [6], [9]; in other studies it is tried to work around the problems caused to spectra analysis by the influence of the gate by taking into account the transmittance of similar materials[4], [5]. However, the results are still not sufficiently accurate since other effects such as interference due to multiple reflections in the layered system may have a significant impact on the spectrum and are difficult to introduce in the corrections[10].

In this work we present the characterization of the PL from bi-layer structures composed by silicon nitride on top of silicon-enriched silicon dioxide (SRO) with different Si concentrations, and the EL of polysilicon gated light emitting capacitors (LECs) fabricated with the exact same material and structure as active layers. Both emission spectra are analyzed and compared with the objective of finding if the origin of the PL of the active material and the EL of the emitting device are both the same, aiming to obtain a broader picture regarding the nature of the influence by the top gate on the output spectra of this type of devices.

II. Experimental

Three sets of samples and devices were fabricated starting with the thermal growth of SiO_2 on p-type silicon wafers with resistivity of $0.1 - 1.4\Omega \times cm$ and crystal orientation (100). On top of the silicon dioxide, a 30 nm silicon nitride film was deposited by Low Pressure Chemical Vapor Deposition (LPCVD) to improve the carrier injection to the electroluminescent devices [11], [12]. The implantations were performed in two steps and the energies were tuned to achieve a Si concentration peak around 25 nm deep in the SiO_2 matrix after simulations with Stopping and Range of Ions in Matter (SRIM) [13]. The first implantation was performed at an energy of 25keV and the second at 50keV. For the first two sets of samples, total doses of 1.2 and 3.0 $\times10^{16}cm^{-2}$, respectively, were implanted in 30 nm thick SiO_2 layers. The third set of samples was fabricated implanting a total dose of 1.5 $\times10^{16}cm^{-2}$ into a thermal SiO_2 layer around 20 nm-thick, hence the peak implantation dose was inside the substrate rather than within the dioxide matrix. All the wafers were then annealed for 240 minutes at 1100 °C to promote Si distribution and nucleation[14], [15]. The silicon excess XS_{Si} values were calculated from X-ray Photoelectron Spectroscopy (XPS, not shown), yielding a respective value of $XS_{Si} \sim 0.41$ and $XS_{Si} \sim 1.43$ at. No silicon excess to consider a typical SRO active layer was found in the third one,

[1]Institut de Microelectrònica de Barcelona, CNM–CSIC, Campus UAB, 08193 Bellaterra, Spain
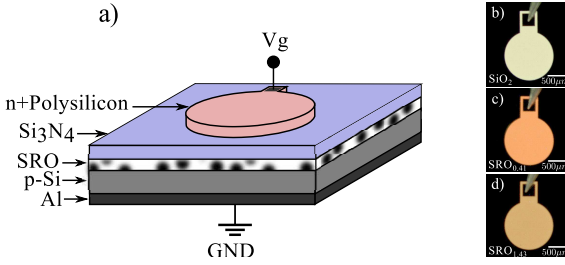[2]INAOE, dpt. of Electronics, PO box 51, Puebla, Pue. 72000, Mexico

Figure 1. (a)Schematic representation of the multi layer and device architecture, not to scale. Top view micro photograph of the device with active layer of (b) Nitride+SiO_2, (c) Nitride+$SRO_{0.41}$ and (d) Nitride+$SRO_{1.43}$ under 100 μA electrical stimulus

and no significant presence of silicon was found in the nitride layer of any sample. Hereafter, the samples will be referred to as $SRO_{0.41}$, $SRO_{1.43}$ and SiO_2, accordingly with their XS_{Si}.

To obtain the LECs a ~350 nm thick polycrystaline silicon layer was deposited by low pressure chemical vapor deposition on top of the active bi-layers, and it was subsequently highly doped with $POCl_3$. Standard photo-lithography and selective wet etching were used to define circle-shaped gates with an area of $1mm^2$. The thermal processes associated to the fabrication of the gates are not expected to introduce significant changes in the active material[15]. Lift-off technique was used to define small aluminum pads to the upper gates to improve electrical stimulus. Figure 1 shows a scheme of the multi-layer and device structure.

The PL and EL spectra were obtained using an OceanOptics QE6500 Spectrometer. For PL, the active bi-layersamples were stimulated with a 325 nm He+Cd laser, and EL spectra was obtained using a Keithley 2400 source meter to stimulate the gate of the devices trough a probe on the pad. Spectra at different current values (from $1\mu A$ to $300\mu A$) were obtained in order to verify if the results suffered variations as it has been reported[2], [7].An expected increase in light emission intensity with applied current was found, but no noticeable changes were observed in the general shape of spectra.

III. RESULTS AND DISCUSSION

The illumination of the gate during electrical stimulus was observed with naked eye. Figures 1(b), 1(c) and 1(d) present micro photographs of the luminescent devices when applying $100\mu A$ to the gates. The normalized PL and EL spectra for the three silicon contents are shown in figures 2(a) and 2(b), respectively.

The PL spectra can be divided in two main bands: one from 380 to around 650 nm, and another from 650 to 850 nm. The higher energy emission (380 to 650 nm) has been reported in SRO and silicon nitrides before[6], [9], [16], and in the case of the samples studied here, it is most likely produced by oxygen related defects present in the SRO-nitride interface, which are known to be , which in turn are probably promoted by the ionic implantation process [6], [9]. Other . Previous studies performed to bi-layers also concluded that this type of emission is caused by nitride presence, rather than by the SRO[16]. This is confirmed in our samples by the fact that
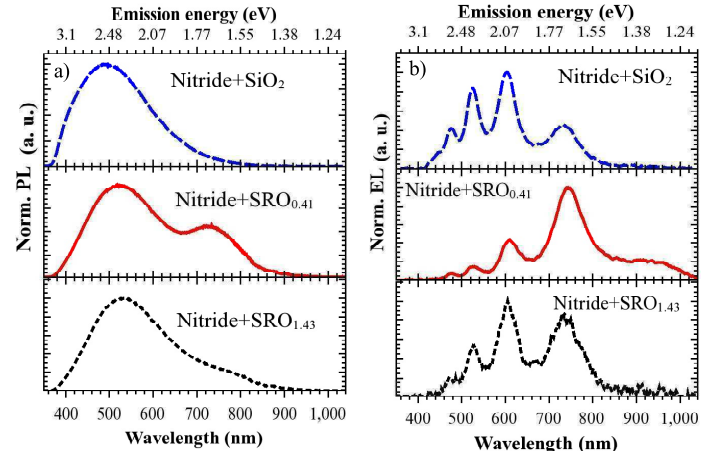

Figure 2. (a)Photo luminescence spectra of the SRO-Silicon Nitride bilayer structures and (b) Electro luminescence spectra of the SRO-Silicon Nitride bilayer devices for samples Nitride+SiO_2, Nitride+$SRO_{0.41}$ and Nitride+$SRO_{1.43}$.

those the samples with no silicon excess (Nitride+SiO_2) only presented the higher energy band. Furthermore, PL spectra obtained from a different set of samples fabricated during the same run, but with the nitride layer removed by selective wet etching did not present any luminescence above 650 nm (not shown).

Regarding the lower energy PL bands (650 to 850 nm), the former analysis allows to conclude that it is produced within the SRO, in accordance to previous reports which relate emission in these range of energies to the presence of silicon nano-structures in SRO[1], [2], [15].

A full analysis of the characteristics of emission is beyond the scope of this manuscript. In any case, and most relevantly for the objectives of the present work , but it is most relevant for the present work to note that there are notorious differences between the PL and EL spectra of the three sets of bi-layered samples (compare figures 2(a) and 2(b)). The objective of the present work is to elucidate if this is caused only by optical effects introduced by the multi-layered structure, or if indeed is due to the differences in the relative intervention of the radiative centers. To achieve this, the relation between EL and PL data will be studied and discussed.

As already mentioned, the EL must be affected by the transmittance of the gate material. Aiming to verify if the radiative centres involved in EL are the same as those causing PL despite the differences in the observed light, an indirect calculus to obtain the real output transmittance was performed. Assuming that EL spectra should present the same shape as the PL affected by the transmittance of the LEC structure, a simple expression for the EL intensity $I_{EL(\lambda)}$ at a wavelength λ would be equation 1.

$$I_{EL(\lambda)} = I_{PL(\lambda)} \times T_{(\lambda)} \qquad (1)$$

Where $I_{PL(\lambda)}$ is the photo-luminescence intensity at the wavelength λ and $T_{(\lambda)}$ the transmittance for such wavelength. Then, the transmittance spectra can be obtained by calculating the ratio of the intensities $T_{(\lambda)} = I_{EL(\lambda)}/I_{PL(\lambda)}$. If indeed the origin of luminescence is the same for both stimulation
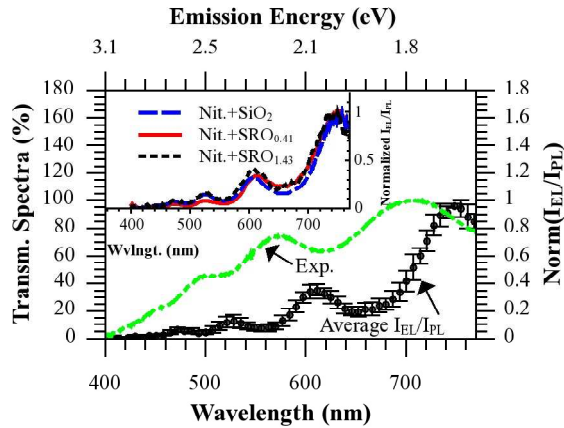
Figure 3. Experimentally obtained transmittance spectra of a non-stimulated doped polysilicon layer deposited on quartz (dotted line), and the average of the result for the luminescence ratio of each sample (circles). The Inset presents the normalized result of EL and PL ratio for the three samples Nitride+SiO_2, Nitride+$SRO_{0.41}$ and Nitride+$SRO_{1.43}$.

mechanisms (electrical and optical), then the normalized ratios should be very similar for the three implantation doses despite the differences in all spectra. The results for these ratios are presented in the inset in figure 3.

Some important considerations must be stated regarding the range in which the resultant transmittance spectra is valid. The intensity of EL observed for wavelengths shorter than 420 nm is too small as to be able to consider reliable the calculi below that point. On the other extreme of the plotted spectra, as PL intensity decays, the $I_{EL(\lambda)}/I_{PL(\lambda)}$ ratio increases. This means that the error of the obtained transmittance also increases as PL diminishes, an this limits the reliability of the calculation for the higher λ. For this work the upper limit for the reliable spectra was considered to be 770 nm, since above this value the average error between three calculated transmittance curves surpasses 10 %. The validity of these considerations is evidenced when observing the remarkable match between the normalization of the three spectra presented in figure 3, which depicts the average of the three calculated transmittance spectra, and the error bars that indicate the deviation from such average. A poly layer on quartz was fabricated to verify the non-stimulated transmittance (discontinuous line in figure 3), and it is worth noting in that this importantly differs from the calculated transmittance, despite the material was fabricated under the exact same conditions as those of the gates. This indicates that the optical effects caused by the multi-layer structure are of great importance to the final observed spectra, and that an inappropriate consideration of such effects can deliver wrong information regarding the true nature of the luminescence extracted from EL measurements. As mentioned before, no changes were observed in EL spectra when varying the applied current from 1 to 300 μA, meaning that the transmittance of the poly do not show variation with current changes in such range.

IV. CONCLUSION

Summarizing, luminescent bi-layered structures and devices based in Si-enriched SiO_2 and silicon nitride were fabricated. The silicon contents on the dioxide matrices was varied. Their photo and electro luminescence were characterized, and noticeable differences were found in all spectra, both with change of silicon contents, and between the two stimulation techniques. The relation between EL and PL was studied, and it It was concluded that regardless of the observed differences in the spectra PL and EL for dissimilar silicon excesses, the ratio of intensities for samples with same silicon contents relation between them was consistent for wavelengths within 420 and 770 nm, indicating that the luminescence in this range is due to the same radiative centers despite the stimulation techniques being different. It was shown that the significant influence of the optical effects introduced by a multi-layered system on the output light emission must be considered to identify the radiative centers on the studied materials. A method is proposed to verify if the centres responsible for EL and PL are the same, which also allows for the reconstruction of the output transmittance of the complete system.

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