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WHITE ELECTROLUMINESCENCE FROM C- AND SI-RICH THIN SILICON OXIDES

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During the last decade, intense investigations have been devoted to the development of an efficient silicon-based optically active material that could enable integration of photonics with Si microelectronics. For example, silicon nanocrystals (Si-ncs) embedded in SiO_2 emit in the red and near infrared spectral regions. In this system, light emission has been attributed to quantum confinement or surface states [1–3]. Recently, a few studies have reported broad photoluminescence (PL) in the whole visible domain, by doping Si-rich SiO_2 layers with carbon [4, 5]. Blue electroluminescence (EL) emission from such a material has been already reported [6] but efficient EL covering the whole visible spectrum has still to be developed. White light sources compatible with Si technology are interesting for several applications, such as biological and chemical sensors, that need a broad spectral detection, optical interconnectors, or colour display.

Some years ago, we have reported white PL of 400 nm thick SiO_2 layers by co-implanting Si and C [5]. The PL spectrum is the convolution of emission bands located in the red, green, and blue spectral regions. The structural and optical studies attributed the red band to Si-ncs, observed by TEM. The blue and green bands are linked to C-related nanophase such as SiC- or graphitic-like nanoaggregates, detected by Raman spectroscopy and XPS analysis. Furthermore, the green band shows lifetimes of the order of 50–100 ps [7] which gives interest to this system for telecommunication applications where fast modulation is required. This material looks very promising as a CMOS compatible light source once electrical excitation is achieved. This work reports the observation of white EL achieved by adapting the Si and C implantation procedure previously developed [5] for thick materials to thin SiO_2 films (40 nm). Reduction of the thickness of the active layer is required to allow injection and conduction of electrical charge across the dielectric layer at relatively low voltages.

The samples have been prepared by sequential implantation of Si^+ and C^+ in a 40 nm thick SiO_2 layer grown by dry oxidation at 1000 °C on a *p*-type (100) Si wafer. A uniform profile of 10 at. % Si excess in SiO_2 has been obtained by means of a four step implantation including low energy implant (for more details see ref. 8). Subsequently, a single C^+ ion implantation was carried out to a nominal dose of 10 at. % at the peak, i.e., equal to the Si excess. The C implant energy was selected to locate the distribution at the centre of the Si rectangular profile to block the out-diffusion of C, and to favour the formation of SiC and C compounds in the implanted layer. A sample without C^+ implantation was also fabricated as a reference sample. To synthesize the Si and C nanophases, the samples were annealed in a N_2 atmosphere at 1100 °C for some hours. Metal-oxide-semiconductor structures were fabricated by a standard photolithographic process. For the gate electrode, a semitransparent 100 nm thick *n*-type polycrystalline silicon contact was deposited. The device was polarized by applying a negative voltage on the gate, allowing injection of electrons from the gate and hole injection from the *p*-type substrate. EL excitation has been obtained using an Agilent 8114A pulse generator, and the collected signal was processed with a Stanford Research SR830 lock-in amplifier. Current-voltage (*I*-*V*) characteristics were measured using an HP4140B pico-amperimeter. For the structural characterization, Energy filtered transmission electron microscopy (EFTEM) was performed on a field emission TEM, FEI Tecnai™ F20 microscope operating at 200 kV, equipped with a corrector for spherical aberration and the last generation of the Gatan imaging filter series.

Fig. 1. shows PL measurements from both the Si and C implanted sample and the reference sample (without C). The latter shows a PL band centred at 760 nm, characteristic of the light emission coming from Si-nc. For the former spectrum, the two Gaussian peak deconvolution shows that in addition to the band due to the Si-ncs, another band appears, attributed to the C-containing nano-aggregates, similarly to what was observed in thicker layers in previous work [5]. In inset, an EFTEM picture from this sample shows that the active layer in this sample is separated in three regions. The two regions at the border are pure Si-nc embedded in SiO_2, and no C has been detected inside. In the region between the two Si-nc layers a C-rich region is detected, and no Si-nc are observed.

EL has been observed for both samples. The spectra are represented in Fig. 2, from the onset voltage of EL up to breakdown voltage. For both samples, the EL is visible by naked eye. The overall EL power efficiency has been estimated to be around 10^{-4} %. A significant improvement of the external quantum efficiency can be attained by optimizing the transparency of the gate electrode in our devices. In both samples of the present work, the red EL band from Si-nc can be easily identified. Moreover, appearance of bands at higher energies is clearly observed, leading to a white EL. Even though it is difficult to assign the exact microstructural origin of the broad white EL, we can state that this latter is the sum of the emission from Si-nc and from C-related complexes in the matrix. Electrical characterization of both samples was performed in forward polarization. Further details are reported in Ref. 8. For voltage larger than 20 V, the *I-V* curve shows a Fowler-Nordheim dependence. This mechanism is related to the tunnel injection of carriers in the conduction band of the oxide through a triangular shaped barrier. This suggests that the excitation of the luminescent centres is produced by impact ionization.

In conclusion, very thin Si- and C-rich layers have been synthesized by high dose ion beam synthesis. The use of low energy implants has allowed growing a uniform distribution of light emitting nanoparticles. The C-related centres give rise to a significant luminescent contribution in the high energy region of the visible spectrum. Together with the well known red light coming from the Si-ncs, this leads to a white to the eye characteristic emission. The electro-optical characterization of these systems has allowed demonstrating the existence of an intense, white EL emission, which correlates with the PL behavior. Radiative impact ionization of the emitting centers is proposed as the main mechanism responsible for the EL emission. In a further work, we also demonstrated an improve of the power efficiency of at least one order of magnitude, by shifting the distribution of the C-related centres toward the interface region with the substrate and by exciting the Si and C-rich nanoparticles under pulsed excitation conditions [9].

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Figures:

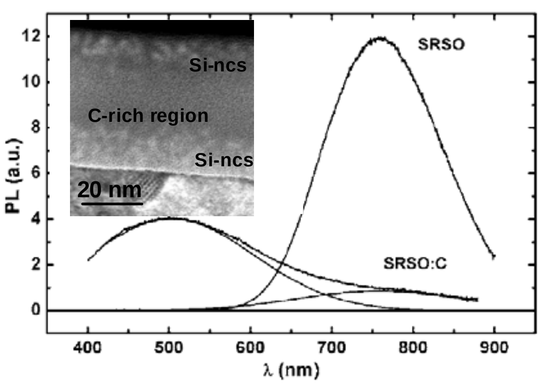

FIG. 1. PL spectra of the the Si and C implanted (SRSO:C) and reference (Si-only, SRSO) samples. Inset shows the EFTEM image of the layer.

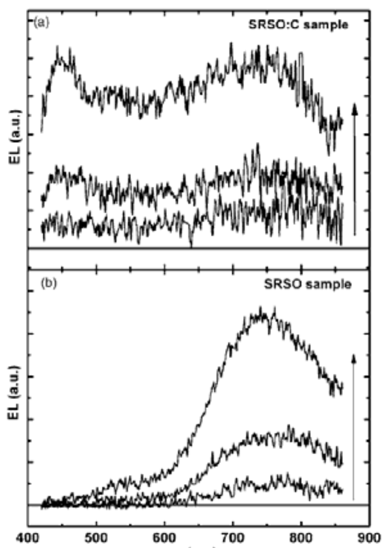

Fig. 2: EL of (a) Si and C implanted and (b) reference (Si only) samples.