Antifuse injectors for SOI LEDs

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***Abstract* - A novel carrier-confinement structure is proposed and realized to generate light in a silicon diode. A significant enhancement of the external power efficiency is observed compared to reference silicon diodes on SOI**.

I. Introduction

SILICON's indirect band gap makes an efficient Si LED difficult to make. Yet, such an LED would bring the integration of electronics and photonics a major step further, explaining the significant research interest on the subject [1, 2].

The efficiency of a silicon LED is in practice determined by the ratio between radiative and non-radiative recombination. The radiative recombination rate in silicon is low (as an indirect, phonon-assisted process is necessary). Efforts to improve the efficiency focus on enhancing the radiative recombination through chemical or structural modifications of silicon [3-6], or by confining the carriers [7, 8]. Meanwhile, the nonradiative recombination rate must be kept low, implying high purity silicon (to suppress SRH recombination), good quality Si-SiO_2 surfaces and an injection level below a few times 10^{17} cm^{-3} (to suppress Auger recombination) [9, 10]. A high concentration of carriers is though needed both to obtain an intense emission and to achieve good ohmic contact in electrically driven devices. The proximity of the contacts (where nonradiative recombination takes place) to the active volume can therefore also play a role in devices without carrier confinement. To overcome this obstacle, one can replace the large junctions between the contacts and the active region (i.e., 3D injectors) with smaller injectors (e.g. 2D and 1D) that confine strongly the carriers in the emitting volume. A tight confinement can result in high concentration of carriers without the need to force large currents through the device, leading to increased power efficiency. As the 2-D injectors have already proved to be beneficial [8], we therefore propose to carry out the next step and investigate the effectiveness of 1-D injectors.

Our studies focus on a compact, fast-switching silicon LED made with standard CMOS manufacturing techniques and operated at room-temperature. In this work, we investigate the light emission from a small SiO_2-encapsulated Si volume (around 100 μm^3), using antifuses as 1-D injectors for electrons and holes. We report a significant enhancement of the band-to-band radiative recombination as compared to the reference p-i-n SOI-LED with classical 3D injection from junctions, supporting the carrier confinement method.

II. Experimental

Our devices consist of a lowly p-doped central region, electrically isolated by a 10-nm thick thermally grown SiO_2 from an n+ and a p+ polysilicon electrode (see Fig. 1 and Fig. 2a). The electrical isolation is meant to spatially confine electrons and holes in the central region, to increase the probability of their recombination inside this volume (as in [8]). The electrical conduction between the polysilicon electrodes through the mono-Si region was achieved by forcing a breakdown current through the thin dielectrics. Thus, a nanoscopic link, called antifuse, is formed [11], which is then trimmed by forcing a well-defined stress current to obtain the desired conductivity. It appears that the size and resistance of the link-antifuse can be properly adjusted by the programming current.

Provided that the programming current is not exceeded, the link is stable and its resistance can hardly be changed by a frequent use of the device. Exceeding the programming current results in a larger link and, therefore, a lower link resistance.

The devices were fabricated from a high quality p-type SOI substrate with a resistivity of 14-22 Ω·cm. Firstly, the central regions were patterned by dry etching the 300-nm thick SOI layer with a plasma etcher based on Cl_2 chemistry. Secondly, 10 nm of thermal oxide were grown at 900°C in dry oxygen atmosphere. Subsequently, a 340-nm thick LPCVD polysilicon layer was deposited (T=610°C) and then patterned to realize the electrodes. A dose of 5×10^{15} cm^{-2} of P^+ and B^+ was implanted to dope the n+ and p+ regions respectively. Dopants were activated by a 30 minutes anneal at 850°C. Metal contact areas were realized by sputtering and patterning Ti/W, as barrier layer, and Al (+1 % Si). A variety of reference n+-p-p+ diodes was fabricated on the same wafer. The reference diodes have standard junctions as injectors, monosilicon p+ and n+ regions instead of polysilicon, and no isolating oxide,

The devices were characterized on wafer level both electrically and optically. Their electroluminescence (EL) was measured using a Karl Suss probe station equipped with a spectral XenICs camera with an InGaAs sensor for IR detection. The measurement data were corrected for the losses in the optical system (as in [12]), to obtain the absolute emission.

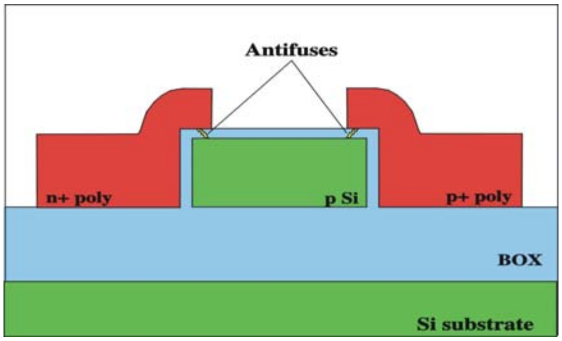

Figure 1. A schematic cross-section of the device with 1-D injectors.

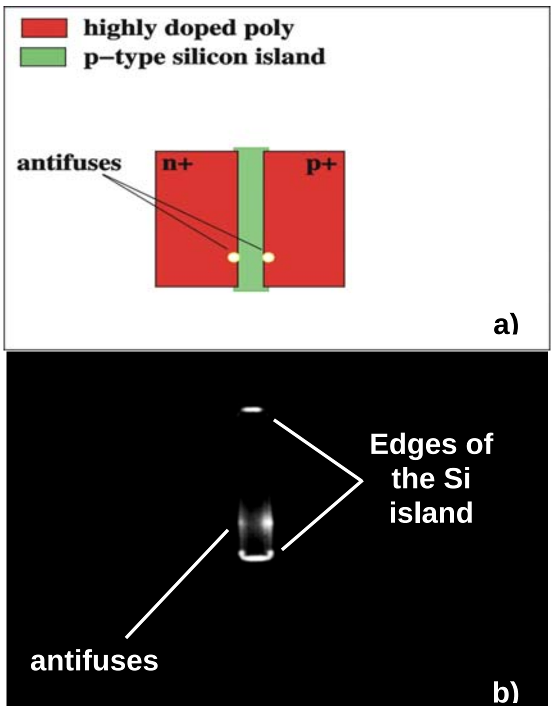

Figure 2. Top view of the device: schematic (a); image obtained with the IR camera (b) under a current of 1.2 mA

III. Results and Discussion

Under forward bias the devices exhibit an intense emission in the NIR spectral region. The light appears localized at the antifuse spots and at the edges of the silicon island (the latter due to waveguiding in the silicon island) (Fig. 2b). The image illustrates that the devices have a small emitting area if compared to standard silicon LEDs (i.e., 3D injectors) which emit also from the whole top surface: such a less scattered light may be beneficial to an efficient coupling with detectors or guiding structures. The shape and position of the EL spectrum correspond to the reference n+-p-p+ diode, pointing to the same emission mechanism based on the phonon-assisted band to band recombination (Fig. 3).

We found that the intensity of the device with 1-D injectors is almost 4 times higher than that of the reference device at a 10 times lower force current (voltage applied is 6.15V and 3.12V respectively). This results in an external power efficiency of

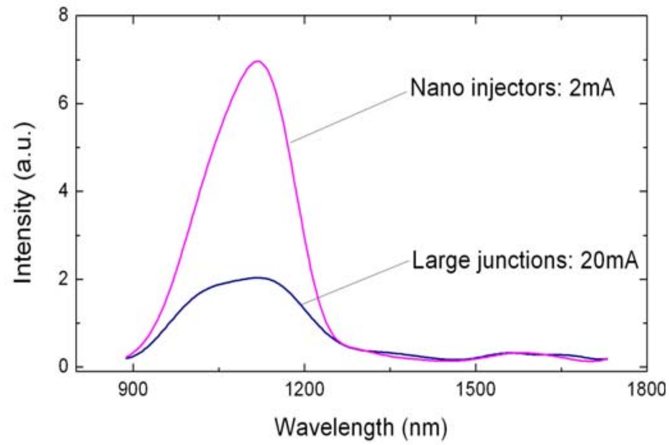

Figure 3. EL spectra of a reference SOI LED with large junctions as carrier injectors, operated at a current of 20 mA, and a device with nano injectors at a current of 2 mA. The data have been acquired with the same exposure time of 5 s.

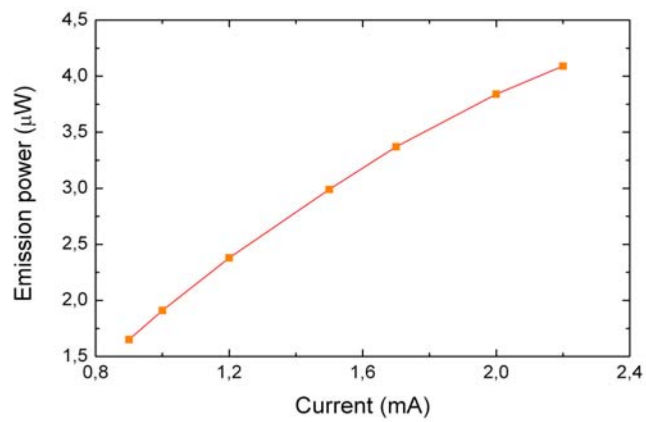

Figure 4. Integrated EL emission power plotted versus applied current for a device programmed to 2.5 mA.

almost 20 times higher than that of the reference diode, clearly pointing to the role of the injectors' size. The lower intensity of the spot on the n+ side, as shown in Fig. 2b, is consistent with a lower concentration of holes due to the lower mobility of holes in silicon compared to electrons. Figure 4 illustrates the dependence of the integrated EL intensity on the injected current, measured for a device programmed at 2.5 mA: the observed less-than-linear increase in emission intensity suggests that the local concentration of carriers inside the active volume is high enough to overwhelm the SRH component (linear with the carrier concentration) but has not yet reached a level where the Auger recombination would become dominant (i.e., the emission would reach its maximum intensity). Moreover, the external quantum efficiency plotted versus applied power (Fig. 5) clearly indicates that a larger injector size (i.e., a higher programming power) results in lower emission efficiency. This fully confirms the role of the injectors' size, thus of the carrier confinement, for the radiative recombination.

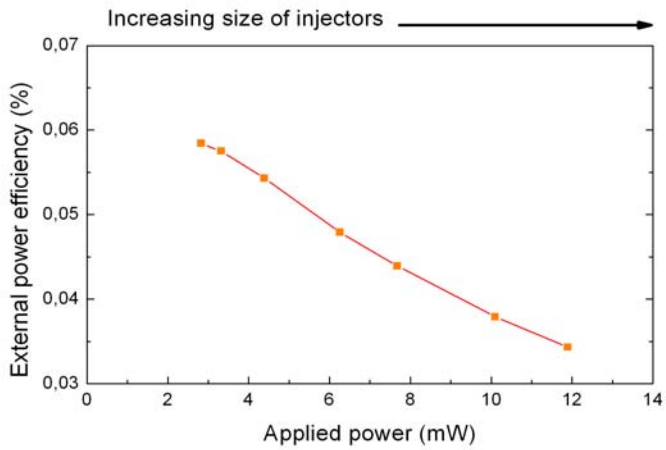

Figure 5. Dependence of the power efficiency on the power applied during the programming step. The latter determines the antifuse size.

IV. CONCLUSIONS

The influence of contact area size on the light emission efficiency from silicon was investigated using antifuse-based silicon LEDs. An external power efficiency of 0.06% was observed, which corresponded to approximately 20× enhancement compared to reference SOI LEDs. Experimental evidences ascribe such an improvement to the better carrier confinement of 1D injectors, in complete accordance with our hypothesis.

ACKNOWLEDGMENTS

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