Silicon-on-insulator microcavity light emitting diodes with two Si/SiO₂ Bragg reflectors

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Abstract

Light emitting pn-diodes were fabricated on a 5.8 μm thick *n*-type Si device layer of a silicon-on-insulator (SOI) wafer using standard silicon technology and boron implantation. The thickness of the Si device layer was reduced to 1.3 μm , corresponding to a 4λ -cavity for $\lambda = 1150$ nm light. Electroluminescence spectra of these low Q-factor microcavities are presented. Addition of Si/SiO₂ Bragg reflectors on the top and bottom of the device (3.5 and 5.5 pairs, respectively) is predicted to lead to spectral emission enhancement by ~ 270 .

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1. Introduction

Si based light emitters have made tremendous progress over the past few years and even stimulated emission has been claimed by some groups. However, as long as no Si injection laser is available, considerable improvement in device performance can still be achieved by embedding an LED into a resonant cavity (RC). This would lead to enhanced efficiency, spectral purity and directionality, as known from RCLEDs based on III–V compounds [1]. Optically excited Si based RC emitters have been demonstrated before, in SOI wafers [2] and in MOS devices containing nanoclusters and/or Er³⁺ ions [3]. In porous Si also cavity enhanced electroluminescence (EL) has been reported [4]. In more recent attempts, photonic-crystal structures were integrated into Si based LEDs [5–7]. Here we use highly boron doped Si pn junction LEDs, which have been shown to show room-temperature EL at a wavelength of 1150 nm with a reasonably high power efficiency of $>0.1\%$ [8,9]. In continuation of our work using a buried CoSi₂ mirror [10], we present here the design and fabrication of a RCLED with two distributed Bragg reflectors (DBR).

2. Device preparation

Commercial 4 in SOI wafers with a 5.8 μm thick *n*-type (001) silicon device layer were used as the starting material (resistivity 1–20 Ωcm). The device structure is shown schematically in Fig. 1a. The thickness of the buried SiO₂ layer is 515 nm. The pn-diodes were fabricated using standard silicon planar technology and boron implantation into the top *n*-Si. A boron dose of $4 \times 10^{15} \text{cm}^{-2}$ was implanted at an energy of 25 keV. After furnace annealing at 1050 °C for 20 min, Al contacts were lithographically defined and evaporated. In order to test the suitability of the material, we measured the room-temperature EL from these devices, as shown in Fig. 2. Fabry–Perot fringes with a period corresponding to the layer thickness of 5.8 μm are clearly observed. This demonstrates, for the first time to our knowledge, that also SOI material can be used for EL.

For the final device we decided to use a 4λ microcavity (for $\lambda = 1150$ nm), corresponding to a Si layer thickness of about 1300 nm (see Fig. 1b). This thickness has the advantage that exactly one longitudinal mode will be contained in the natural emission spectrum, even if the thickness deviates from the desired value, since the mode spacing is roughly the same size as the natural linewidth ($\cong 100$ nm). This device was fabricated similar to the one described above, but the top Si layer was thinned down by anisotropic KOH etching.

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Fig. 1. Schematic diagram of: (a) LED on 5.8 μm thick SOI; (b) RCLED on 1.3 μm thick SOI.

Fig. 2. Electroluminescence spectrum of Si pn-diode on 5.8 μm thick SOI for different bias currents.

Fig. 3. Electroluminescence spectrum (solid and dashed curves) and simulated reflectance spectrum (dotted curve) of 1.3 μm thick Si pn-diode without Bragg reflectors.

3. Results

Fig. 3 shows the room-temperature EL spectrum of a device with 1300 nm layer thickness, but still without any DBR mirrors. EL is observed for a forward bias > 1.2 V. The maximum of the EL spectra corresponds well to the minimum of the simulated reflectance spectra. For completion of the device, a DBR consisting of 3.5 pairs of 200 nm SiO₂/80 nm Si (reflectivity $R_1 = 98.5\%$) was sputter deposited on top of the diodes. Before deposition of the backside DBR, the substrate has to be etched away under the devices using the buried SiO₂ layer as an etch-stop layer. As the final step a DBR consisting of 5.5 pairs of 200 nm SiO₂/80 nm Si (reflectivity $R_2 = 99.7\%$) will be deposited. The RC is thus asymmetric in order to provide preferential outcoupling of the light from the top.

The expected spectral emission enhancement can be estimated from Ref. [1]

$$G_e \approx \frac{2(1 - R_1)}{2 - R_1 - R_2} \cdot \frac{2F}{\pi},$$

Fig. 4. Simulated reflectance spectrum of LED (dashed line) and RCLED (solid line) on 1.3 μm thick SOI. The resonance width and (twice the) spacing are indicated.

where F is the cavity finesse, i.e. the ratio of mode spacing to resonance width. According to Fig. 4, in our case this is given by $F = 122 \text{ nm}/0.478 \text{ nm} = 255$, and should lead to a spectral emission enhancement of ~ 270 , radiated in a narrow emission cone. The spectrally integrated emission, however, is not expected to be enhanced very much, since it is proportional to G_e times the ratio of cavity-resonance width to natural emission linewidth ($\propto G_e \Delta\lambda_{\text{FWHM}}/\Delta\lambda_n$), the latter being as large as 90 nm in the present case.

4. Conclusions

We have demonstrated efficient electroluminescence (EL) from thin SOI layers, forming the basis for high-finesse resonant cavity (RC) LEDs compatible with Si technology.

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