On the switching speed of SOI LEDs

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1. Abstract
Recently, we presented a novel design for a silicon LED in SmartCUT™ SOI wafers. It exhibits a record quantum efficiency for SOI-based silicon LEDs and opens the way to the integration of light emitters in a VLSI process on SOI. In this paper, we present first experimental and modeling results showing that this new design has the potential to switch on and off faster than 1 MHz – sufficiently fast for several commercial applications such as an integrated optocoupler.

2. Introduction
The design of our LED is presented in Figure 1. The light-emitting central region is a lowly p-type doped silicon volume of 5 x 60 x 0.15 μm³.

Fig.1: Schematic cross-section of the SOI LED under study in this work. Reprinted from [1].

Two highly doped (n+ and p+) regions provide the carriers to be recombined in the lowly doped central region. The highly doped regions are separated from the central region by gated, ultra-thin (down to 5 nm) silicon slabs. These allow the injection of one type of carriers, while they form a barrier for the other type of carrier. As a result, carriers injected in the central region have no other option than to recombine.

Through the use of high-purity silicon with a low doping level, an injection level around \(10^{17} \text{ cm}^{-3}\), and well-passivated silicon surfaces (using thermal oxidation), the non-radiative recombination rate in the central volume is not too high, and the probability for radiative recombination becomes significant.

The device exhibits an external quantum efficiency of 1.4 x 10⁻⁴ at room temperature, for emission around 1150 nm (the silicon B-B peak) – comparable to the best bulk-silicon LEDs when no special surface modifications are made to enhance the outcoupling [2]. This device exhibits a power output up to 0.25 μW [1].

3. Switching speed
For integrated optics, a switching light source has great advantages over a continuous light source that requires an external switching device. Our LED has been designed to be fast-switching (apart from the rather large dimensions of the present prototypes, due to our lab capabilities). However, the LEDs compactness, and its unconventional emission wavelength complicate a direct measurement of the on/off switching behavior of the LED with the instruments at hand. In this section, we present indirect estimates of the switching speed.

On-switching
The on-switching speed is intrinsically determined by the RC-delay occurring in the device, when the diode is switched to forward-bias. (That is, if \(V\) in figure 1 is switched from low to high and back to create light modulation; alternatively, the light can be modulated with \(V_{b1}\) and/or \(V_{b2}\)!) It is not correct to assume that the device will start emitting light as soon as current starts to flow, so electrical measurements are not conclusive to determine the on-switching behaviour. However, we can assume that, once the excess carriers are inside the central region, they will mix almost instantaneously given the device dimensions, the low field in the central region and the thermal velocity.

The total capacitance of the diode sketched in figure 1 consists of three major components: the diffusion capacitance, the gate capacitances, and the capacitance towards the substrate. (The latter is an order of magnitude less than the gate capacitance.)

A rough calculation of the capacitances and resistances involved can give an indication of on-switching speed. When the positive terminal \(V\) is switched from 0 to 1 V, charge needs to be supplied to charge up the gate capacitance \(V_{b1}\) of 1 pF. The external resistance of the device is approximately 1 kΩ. Then, charge is to be supplied to the central region to raise the carrier density. Assuming that the central region has \(np = n_i^2\) in off-state, and \(n = p = 5 \times 10^{17} \text{ cm}^{-3}\) in the on-state, caused by a change of 1 V in the forward bias, the diffusion capacitance is first-order estimated at 7 pF with the device dimensions mentioned in Section 2. Combined with the gate capacitance, this would lead to an on-switching RC-time of 8 ns.
Off-switching

The off-switching can be studied with electrical measurements. As a diode is switched from forward-bias to reverse, a short transient current will be observed originating in the excess carriers flowing out of the depletion region. This so-called reverse recovery current [4,5] of the diode gives a direct indication how long it takes to remove the excess carriers from the central region of our LED. It can be readily assumed that light emission will stop instantly when the dn-product has dropped back to ni [6]. Therefore, the reverse recovery current indicates the speed of off-switching of our LED.

Figure 2 shows the recovery current of our LED, when the forward-voltage of the diode is switched from high to zero volts. The measurement was carried out using a Keithley 4200 with pulsed-IV extension, in oscilloscope mode. The fast decay of the recovery current indicates that the LED will switch off within ~200 ns.

![Figure 2: The off-switching behaviour of an SOI LED and \(|V_{b1}| = V_{b2} = 1 \text{ V}\). The diodes are pumped by a voltage pulse: pulse width of 250 ns; pulse decay of 10 ns. The on-state bias was 3.5 V, off-state 0 V.]

4. Device modeling

The switching behaviour can be systematically investigated using a modeling package such as ATLAS [3]. At the time of writing, we can only report the first results of SOI pin-diodes without the gated, thinned-down access regions. The simulator reproduces the dc I-V characteristics of this diode (fig. 3).

![Figure 3: Simulated and measured I-V characteristics of a lateral SOI pin diode with 30 µm intrinsic region.]

The overall picture of on- and off-switching of such a device is in line with our findings reported in Section 3 (Fig. 4). In accordance with gated-pin-diodes reported earlier [7] the low voltage regime the current of our SOI diode is determined by Shockley-Read-Hall recombination in the bulk and at the Si/SiO2 interfaces. The high voltage regime is determined by series resistance of the charge plasma in the intrinsic region.

We expect to report considerable further progress with both simulations and measurements at the workshop.

5. Conclusions

In this paper we address the switching speed of an SOI-based LED with emission efficiency comparable to bulk Si LEDs. On the basis of calculations, simulations and electrical measurements, we made plausible that the device can reach a switching speed around 1 MHz. Further work will include the direct optical switching measurement, and device improvement (shorter access regions) to further increase the speed.

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References