A High Efficiency Lateral Light Emitting Device on SOI

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Abstract:

The infrared light emission of lateral p^+-p-n^+ diodes realized on SIMOX SOI substrates show an external quantum efficiency comparable to previous data in the literature [2]. Fabrication of the device in an isolated thin silicon layer has been reported to be a key point to increase the band-to-band recombination probabilities of silicon light emitters [3][4]. In this paper, the device fabrication process, working principle and properties will be discussed. The characteristics of the device with different active region lengths were measured and explained using Silvaco software.

1. Introduction

Since silicon has an indirect band gap, fundamentally it is characterized by substantially lower probability of interband radiative recombination than that of direct band gap materials. The dominant radiative recombination mechanism in silicon is a phonon mediated indirect transition process. Therefore the probability of a photon emission is dependent on the availability of a phonon with appropriate momentum and energy. Meanwhile, in bulk silicon, other non-radiative recombination processes are competing. It is clear that if the non-radiative recombination routes are suppressed, the radiative recombination efficiency can be enhanced consequently. There are some approaches that have been suggested and implemented to tackle the low emission efficiency in silicon; one of them is the use of Silicon On Insulator (SOI) [4][10]. The SOI technology incorporates an insulating layer between the thin single crystal silicon layer and the much thicker substrate of the silicon wafer. Lateral diodes (further called LATODE) have been realized on SOI material. The oxide confines the free carriers in one dimension and therefore increases their interband radiative recombination probabilities.

2. Experimental

The starting material is a 4-inch SIMOX SOI (Separation by IMplanted OXYgen Silicon On Insulator [1]) substrate, with a silicon- and buried oxide (BOX) layer thickness of 190 nm and 350 nm, respectively. The device layer is p-type silicon with a resistivity of 20 Ωcm . Firstly, the device layer is etched by a selective

etching in TMAH into different islands of different sizes, on which lateral diodes with different structures will be realized, by a selective etching in TMAH. After thermal oxidation the highly doped p-type and n-type regions were realized by implantation of BF_2^+ and As^+ with doses of $3.10^{15} \text{ cm}^{-3}$ and $5.10^{15} \text{ cm}^{-3}$, respectively. Dopant activation was processed by furnace anneal in a nitrogen environment at 1000°C for 30 min. A layer of BPSG (Boron-Phosphor-Silicate-Glass) is deposited for good step-coverage. Finally, metal contact areas were fabricated by sputtering of a Ti/W barrier layer and Al (+1% Si) on the wafer after contact holes had been opened in the thermal oxide plus BPSG-CVD oxide layer. A schematic drawing of the LATODE device is shown in Figure 1a, while Figure 1b presents a simulation picture of the device made in Atlas, a device simulation software of the Silvaco code.

Figure 1. Schematic drawing and simulation model of device. The insert shows doping levels in powers of 10.

The light spectra emitted by the devices were measured with a Spectro 320 scanning spectrometer with an InGaAs detector. This detector with sensitivity in the range of 850-1650 nm was very suitable for the emitted spectra centred around ~ 1100 nm wavelength. Occasionally, spectra were also measured with an Avantes Si-CCD spectrometer in order to get information in the visible region. In contrast to the InGaAs spectrometer, the CCD spectrometer was calibrated but could not measure beyond 1000 nm.

3. Results and discussion

A. Electrical characteristics

The LATODE devices were fabricated with various lengths of the lowly doped regions, L , varying from 5 to 20 μm . All the fabricated devices exhibit good current voltage (I - V) characteristics, and show a low leakage current (see Figure 2). A 30 mA forward current can be reached at 8.0 V for $L = 5 \mu\text{m}$ and at 9.8 V for $L = 20 \mu\text{m}$. This is because the resistance increases with length.

Figure 2. I - V characteristics of devices with different active region lengths in linear and semi-log (insert) scales.

B. Optical characteristics

In Figure 3, the spectra of devices emitted at a forward current of 40 mA with various lowly doped region lengths are displayed. The difference in intensity is attributed to the emitting area of each device being seen by the aperture of the optical probe consisting of a 50 μm diameter glass fiber being placed at 45 degrees on the device. It is also worthwhile to note that the top oxide thickness on these devices has not been optimized for maximum transmission and also the collection of photons by the probe is not optimized yet. From the insert we can see that the intensity at the maximum can be given by formula: $I = C + a * L$ where I is intensity; C and a are constants. C can be interpreted as a contribution by the p⁺p and n⁺p junctions while $a*L$ shows the contribution of the lowly doped region. This is also confirmed by Figure 9.

Thermal effect:

The devices as measured and shown in Figure 3 do not have the same temperature because the resistance increases with length L and all the devices were measured at 40 mA current. It was found that the 10 μm

length devices reach their limit at 55 mA at which point the devices are blown up, probably due to melting and evaporation. The 20 μm length devices already reach their critical current value at about 45 mA (see Figure 7).

Figure 3. Emission spectra of lateral diode devices with five different lowly doped region lengths; the maximum intensity as a function of L (inset) given by $I = C + a * L$

In Figure 4, the spectra as function of wavelength for different forward bias currents are shown for a diode with $L = 10 \mu\text{m}$. The intensity of emitted light increases with increasing current from 40 mA to 50 mA. There are several reasons for increased emission. First, due to higher current there is more emission provided that the same fraction of the current results in radiative recombination. Second, a higher current results in a higher temperature of the device (by self heating). External heating was shown to increase the radiative recombination [10]. Third, black body radiation may start to play a role when the device gets very hot. In order to get an impression of the temperature we simulated a short device at 32 mA, see Figure 6. It could be estimated that the device even approaches 1500 K at 40 mA.

Figure 4. Intensity of spectra as function of forward biased currents.

In Figure 5 we show the emitted spectrum of an $L = 20 \mu\text{m}$ device, which "dies" at a current just beyond 45 mA. Here we used the Avantes-CCD spectrometer because it is sensitive in the visible and near IR region. We observe a strong change when increasing the current from 40 mA

to 45 mA. Since the thermal conductivity of Si and of SiO₂ decreases with increasing temperature, it can be estimated that $\Delta T \sim I^3$. Then the 12.5% current increase may easily result in a 300 – 400 degrees temperature rise. The “black body” radiation can then no longer be ignored. The peak observed at ~ 720 nm could be due to interference effects of the 60 nm oxide layer on top of the Si layer. This effect is not visible at 40 mA because there is no radiation yet at 720 nm for this current. The arguments regarding temperature are still qualitative at this stage and require further quantitative analyses but the qualitative discussion is supported by simulation (Figure 6), emission (Figure 5) and blowing up of the device (Figure 7).

Figure 5. The visible emission peak at 720 nm under ultrahigh injection condition.

Figure 6. Temperature distribution of a device when applying a bias current of 20 mA.

Figure 7. The 20 μm length device was blown-up at a 45 mA current

Because of the nature of the measurement system with the optical fiber probe, this does not allow to collect all externally emitted photons. The external efficiency could not be determined exactly. The external efficiency is based on the number of the emitted photons and the number of electrons passed through the neutral region of the device:

$$\eta = \frac{P_{out}}{h\nu} \frac{q_e}{I_f} = \frac{P_{out}}{I_f E_g} \quad \text{and} \quad E_g = \frac{h\nu}{q_e}$$

Where P_{out} is the optical power of the emitted photons collected by optical probe; E_g is the energy of a photon in eV; I_f is the forward bias current. The calculated external quantum efficiency of the LATODE device was $\sim 10^{-4}$ and is comparable to previous studies [2].

The emission distribution of the devices was also pictured by a scientific cooled B/W CCD camera. The emission intensities of a 5 μm length and 20 μm length device are shown in Figure 9a and Figure 9b, respectively, while Figure 8(b) and (c) show top views of the emissions of these devices. We can see that the emitted light intensity at the p⁺/p and n⁺/p edge is higher than that coming out from centre of the lowly doped region of the devices. This results from a higher recombination rate at these boundaries of active region. Simulation, see Figure 10, predict strong recombination at both the p⁺/p edge and at the n⁺/p edge. The simulation data show the maximum recombination rate of 3.8×10^{29} /s cm³ at p⁺/p junction and a lower value of 1.25×10^{29} /s cm³ at n⁺/p junction. A similar qualitative result was obtained in our light intensity measurement. The enhanced emission at the sidewalls of the device is probably related either to multiple reflection of light at this edge, which was isotropically etched, or to current non-uniformity due to mobility deviation (edges are cooler) or due to a non-uniform cross-section of the junction (oxidation profile).

Figure 8. Optical microscope picture of device (a); top-view of emission picture of 5 μm (b) and of 20 μm (c) device taken by a cooled CCD camera

Figure 9. The local intensity of light emission observed by a cooled CCD camera of the 5 μm length (a) and 20 μm length (b) device (simultaneously incident light).

Figure 10. The Simulation of the recombination rate of electrons and holes as function of position along to the active region of the device

4. Conclusions

Lateral p^+pn^+ light emitting diodes have been realized on a SOI substrate. The LEDs show an external efficiency of $\sim 10^{-4}$. It was demonstrated that the self-heating effect can not be ignored and a contribution to the radiative recombination is realistic.

Although the efficiency of silicon LED has increased by the enhancement the radiative band-to-band recombination process, there is room for further

improvement by continuing to reduce the parasitic and optical absorption loss process. A possible way is to use "smart-cut" SOI substrate instead of using the SIMOX SOI substrate in order to increase internal efficiency of the device. Due to effects of the implantation process defects in the silicon layer of an SOI wafer may possibly limit the internal efficiency.

The fabrication of the lateral diode on the high-quality SOI substrate is an approach for realization of efficient silicon LED. This device poses a potential integration of an all-silicon on-chip optical interconnection scheme with light emitter, waveguide, and detector.

Acknowledgments

We are grateful for financial support from STW (the Dutch Technology Foundation) and to the MESA+ Lab. for technical support.

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