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The effect of Dislocation Loops on the Light Emission of Silicon LEDs

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Abstract

Recently, different and apparently contradicting results were published regarding the influence of crystal defects on the light emission efficiency of silicon LEDs at room temperature [1-6]. In this paper we report our results on light emission of silicon p^+n diodes with various defect engineering approaches. The p^+ region was formed either by ion implantation or by diffusion; and optionally, additional lattice damage was created by silicon ion implantation. The experiments clearly indicate that lattice defects have a detrimental effect on light emission, contrary to the results published in recent years.

1. Introduction

Bulk monocrystalline silicon has an indirect band gap and consequently shows low light emission efficiency. Several techniques are being pursued to produce an efficient light emitter in silicon technology, preferably compatible to standard IC technology. One of these approaches is the fabrication of diodes with a dislocation loop region near the junction by ion implantation [1-6]. It was shown by Ng *et al.* [1] that the internal quantum efficiency of such diodes can reach 10^{-3} at room temperature. Ng *et al.* attribute the high efficiency of light emission to the presence of dislocation loops near the p-n junction; it is argued that these loops spatially confine carriers through a modification of the band structure, thus reducing the probability that carriers are recombined through a non-radiative process at a point defect in silicon.

This explanation of the observed relatively strong light emission has led to debate in literature and may well be invalid [3,4,8]. Moreover, in retrospect no direct evidence has been brought forward that the dislocation loops are in one way or another responsible for the light emission enhancement. In typical experiments, such as reported in [4], the lattice damage is created by the same implant as the pn junction. A variation of the annealing temperature is then used to control the formation and dissolution of dislocation loops; and the strongest emission is observed when the silicon contains extended defects. But the correlation does not necessarily imply a causal relation. The high-temperature anneal causes many changes to occur in the studied device, and therefore many parameters change at the same time during the formation and dissolution of extended defects:

1) The boron solubility limit depends on the anneal temperature. Therefore, lower boron clustering is expected when a higher anneal temperature is used.
2) A higher temperature anneal automatically leads to higher diffusion budget ($\sqrt{Dt}$) for all contaminants (C, O, metals) in the wafer. This can lead to net displacements of such contaminants, leading to a lower recombination rate of carriers around the junction. Also, the pn junction shifts (and becomes more gradual) as a function of temperature by boron diffusion, catching up the end-of-range defects and even surpassing this layer.
3) Dislocation loops may act as local getter sites for contaminants – and for p-type and n-type impurities. Upon dissolution of the dislocations, these contaminants are again liberated.

Trupke et al. [8] recently showed that high purity silicon may have a much higher light emission efficiency, in spite of the indirect band gap, than assumed thus far. We hypothesize (after [4]) that extended defects act as local getter sites and therefore they may enhance the internal quantum efficiency of a silicon LED *when the concentration of recombination centers in the bulk is high.* The experimental approach where the formation of extended defects is controlled by thermal treatments alone is therefore not sufficient to study a *causal* relation between electroluminescence and the dislocation loops.

Stowe et al. [3] report on experiments where boron or silicon is implanted to form defects in silicon. These experiments show that light emission occurs in damaged silicon samples even when no pn junction is present.

In this paper, experiments are presented that separate the formation and dissolution of dislocation loops in the junction region from the other temperature-activated effects occurring in the system under study. The diodes are formed either by implantation or by diffusion; and extra lattice damage is optionally added using silicon ion implants.

2. Experimental

In order to analyze the influence of the dislocation loops in the light emitting process, we fabricated p^+n diodes in Cz-grown 5-10 Ωcm n-type wafers, with the p^+ located near the silicon surface (see Figure 1). The p^+ layer was formed by either B^+ ion implantation (at various energies between 40-100 keV) or by solid-state diffusion (with a conventional Silox process). The diodes formed by B diffusion were optionally implanted with silicon (10^{15} Si^+ atoms/cm^2 at 200 keV and/or 450 keV) and subsequently annealed (at 950 ºC for 30 minutes) to form dislocation loops. Two implant energies of silicon were used to control the depth of the dislocation loops: either above the metallurgical junction (using 200 keV) or below it (with 450 keV). The dislocation loop formation inside the LED was controlled by varying the temperature of the post-annealing between 850-1050 ºC, for a fixed time of 20 minutes (in line with earlier reports).

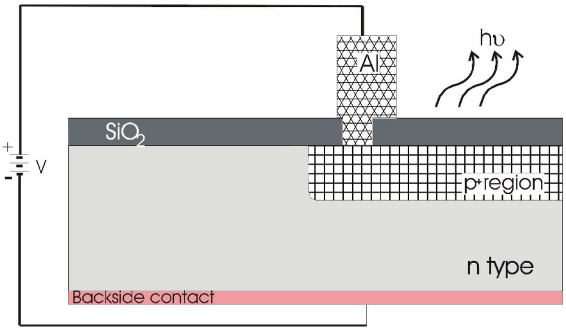

Figure 1: Schematic of structure of the fabricated LEDs.

The silicon implants were carried out on half of the wafer only: the 450 keV implant was carried out on the right half, while the 200 keV implant was carried out on the bottom half, as sketched in Figure 2. In this manner, the comparison between implanted and non-implanted diodes becomes more representative since all diodes are bound to exactly the same process conditions.

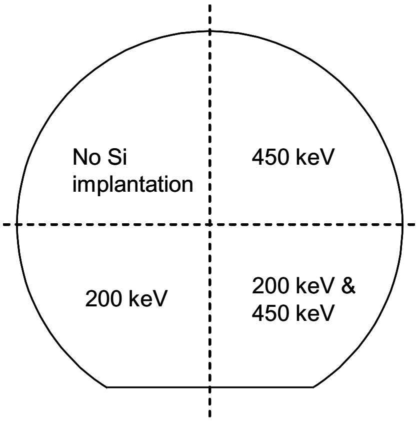

Figure 2: silicon ion implantation experiments on a single wafer containing B-diffused silicon LEDs.

After implanting and annealing, aluminum contact pads were formed at the back- and front-sides of the device. The wafers were then sintered at 400 ºC for 5 minutes in wet N_2.

In order to get comparable diodes, the sizes and structures of the fabricated LEDs were chosen similar. The p^+ sheet-resistance and junction depth were controlled to be in the same range by changing implantation energy and diffusion conditions. The lateral extension of the p^+ region is typically 100x100 μm^2.

Electrical characteristics were measured using a Cascade probe station and an Agilent 4156C parameter analyzer. Emission spectra were obtained with a Spectro 320 scanning spectrometer with an InGaAs detector. An optical fiber (65 μm diameter) was mounted on a micromanipulator and positioned abov the LED to guide the light from the LED to the spectrometer. This detector with sensitivity in the range of 850-1650 nm is very suitable for the emitted spectra centered around ~ 1100 nm wavelength. The presence of extended defects was verified using HR-XRD and HRTEM measurements.

3. Results and discussion

3.1 Electrical characteristics

Current-voltage (*I-V*) characteristics were measured between the back and front contacts to verify normal diode operation and to investigate the level of generation-recombination currents. All devices show a low leakage current, as illustrated for one diode in Figure 3. This is contrary to the result described in reference [1]. Under forward bias, the dominant contribution to the total current is the diffusion current component. It means that the recombination takes place outside the space charge region throughout the low injection regime.

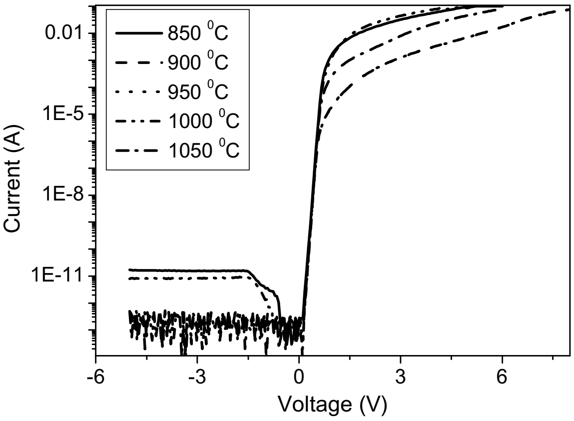

Figure 3: *I-V* characteristics of a B-implanted LED annealed at various temperatures.

3.2 Light emission properties

The electroluminescence measurement of the devices was carried out at room temperature. Electroluminescence was observed under forward bias at a constant current of 100 mA. Light comes out not only straight above the diode itself, but also (with weaker intensity) from the sides, as shown by the photograph in Figure 4, and also reported in [1]. The external efficiency of our LEDs is estimated to be around 10^{-4}, in line with [1]. All electroluminescence spectra of the manufactured LEDs give the same emission peak at a wavelength around 1150 nm, associated with phonon-assisted radiative band-to-band recombination.

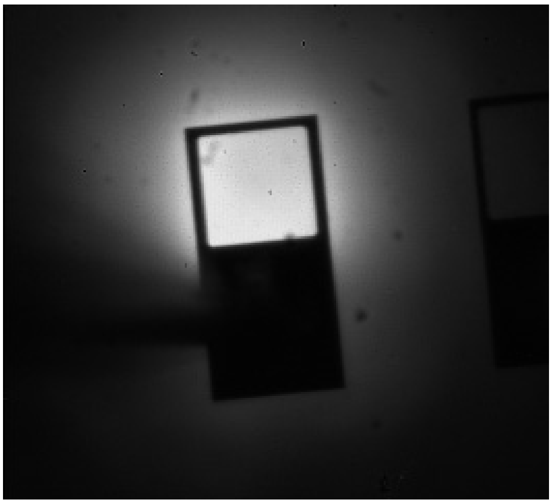

Figure 4: Photograph of a silicon LED device under a forward bias current of 50 mA, taken with an InGaAs (infrared) camera. The inside square is the diode area; the rectangular black feature around it is the aluminium interconnect and bond pad.

The evolution of the dislocation loops depends on the annealing conditions after implantation. In Figure 5 the emission spectra of B-implanted LEDs annealed for 20 minutes at four temperatures are displayed. The highest light emission intensity is found in the device annealed at 1050 ºC, consistent with the reported trend in [4].

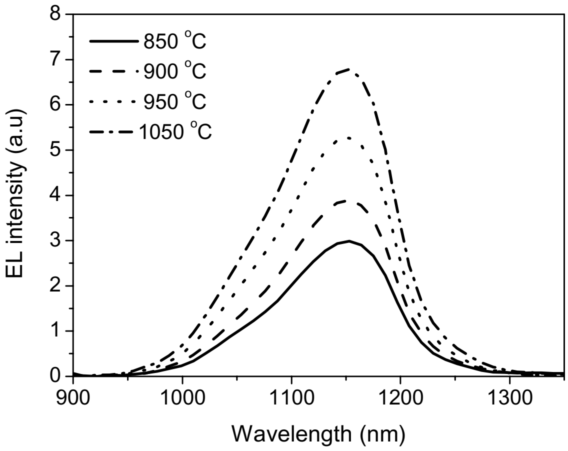

Figure 5: emission spectra of B-implanted LEDs as a function of wavelength, annealed at various temperatures.

A direct comparison of LEDs with the same physical properties but prepared using boron diffusion rather than implantation, shows a surprising phenomenon. The spectra obtained from these compared LEDs are shown in Figure 6. While the light emission spectra from these two types of diodes show the same form, indicating the same root photon emission mechanism, the intensity of electroluminescence is higher for the diffused diodes than for the implanted diodes! This strongly indicates that the defects created in the silicon (by the boron implant) do not enhance light emission in the diode, but rather diminish its probability.

Figure 6 also shows a clear difference between light emission from shallow and deep junctions. The light intensity increases with a deeper boron implant. A higher energy implant leads to a deeper junction, and therefore minority carrier injection will take place deeper in the bulk. As a result, surface recombination is more significant in the shallow junction LED than in the one with the deeper junction. Bulk recombination shows higher photon emission efficiency than surface recombination, as supported by previous reports [8].

Since the result is orthogonal to the existing explanations launched since the publication of Ng et al. [1] on silicon-based LEDs using dislocation loop engineering, we set up an experiment to obtain an independent confirmation of this result.

The same LEDs formed by boron diffusion, i.e. diodes with negligible crystal damage, were exposed to silicon implantations and subsequently annealed (before metallization). An appropriate choice of annealing temperature and time (950 ºC and 30 minutes) results in the formation of extended defects close to the diode junction, as realized in the original paper [1]. TEM micrographs confirmed the existence of the dislocation loops at the appropriate depth, as indicated in Figure 7.

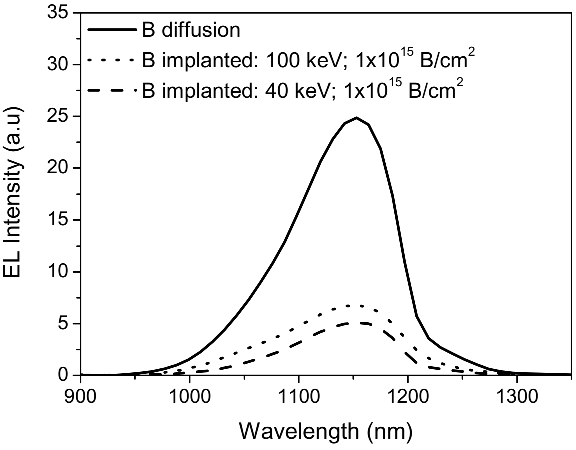

Figure 6: A silicon LED formed by diffusion exhibits stronger light emission than an ion-implanted LED, indicating that lattice defects in fact deteriorate LED efficiency. A lower implant energy leads also to lower light emission.

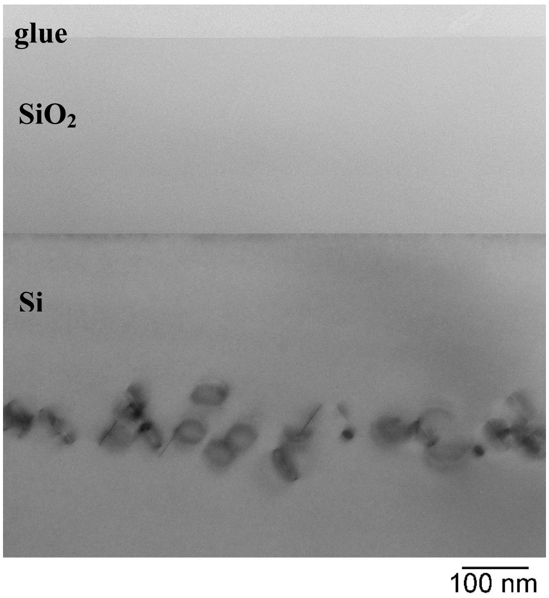

Figure 7: Cross-section TEM image taken along the [100] direction for a diffused LED with Si implantation and annealing at 950 °C for 30 min. {111} prismatic loops and partial faulted Frank dislocation loops can be recognized.

This experimental approach leads to very similar silicon-based LEDs with and without silicon lattice damage. The spectra obtained from these diodes confirm our earlier findings, see Figure 8. Diodes that received no implant exhibit the highest electroluminescence; an implant forming defects above the junction has a detrimental effect to the luminescence, but the deeper defect implantation (450 keV) is clearly the most detrimental to the light emission.

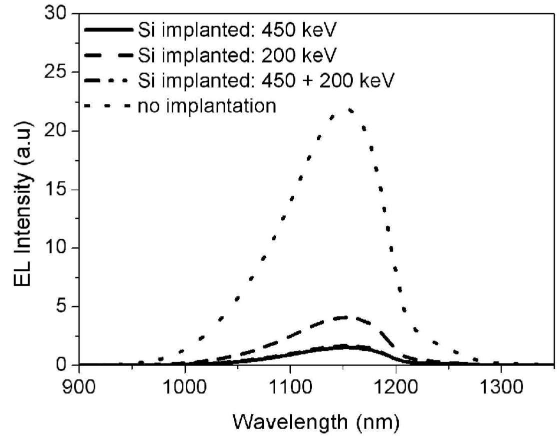

Figure 8: Comparison of the electroluminescence of B-diffused silicon diodes without, and with silicon ion implantation to form lattice defects. The device with the least lattice damage emits most light.

4. Conclusions

Silicon light emitting diodes have been reported to exhibit high quantum efficiency when crystal defects are created near the pn junction. However, with two new experimental approaches we have shown that silicon lattice damage has a detrimental effect to the emission of light in forward-biased silicon p^+n diodes. This new finding calls for a revision of the current theories on light emission from defect-engineered silicon LEDs. It provides support for the earlier suggestion by Sobolev *et al.* that gettering of recombination centers plays a role, and provides support for the recent findings of Trupke *et al.* [8] that clean, monocrystalline silicon may well be a much more efficient light source than generally assumed. The results indicate that to obtain a highly efficient silicon LED, engineering efforts should focus on silicon purity and gettering, rather than the formation of dislocation loops in the LED junction region.

5. Acknowledgements

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