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

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***Abstract*—Remarkably strong infrared light emission was recently observed from silicon p$^+$-n diodes. In several publications a causal relation is proposed between the larger-than-expected light intensity and the existence of lattice damage around the junction. In this letter, we present direct experimental evidence that lattice damage is in fact detrimental to the efficiency of light emission of silicon LEDs. The experiments call for a revision of the explanation for strong light emission in this type of devices.**

***Index Terms*—Dislocation, integrated optics, integrated optoelectronics, light-emitting diodes, light sources, luminescent devices, optoelectronic devices, semiconductor device fabrication, semiconductor devices, silicon.**

I. INTRODUCTION

BULK monocrystalline silicon has an indirect bandgap 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]–[5]. It was shown by Ng *et al.* [1] that the external quantum efficiency of such diodes can reach 2×10^{-4} at room temperature. The authors attribute the high efficiency of light emission to the presence of dislocation loops near the p-n junction.

This explanation of the observed relatively strong light emission has led to debate in literature [2]–[5]. Trupke *et al.* [2] recently showed that high purity silicon may have a much higher light emission efficiency than assumed thus far. 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 letter, we directly compare silicon diodes with different levels of lattice damage. The diodes are formed either by implantation or by diffusion; and extra lattice damage is optionally added using silicon ion implants.

II. EXPERIMENTAL

We fabricated 100×100 μm^2 diodes by forming a shallow p$^+$ region in Cz-grown 5–10-$\Omega\cdot$ cm n-type wafers. The p$^+$ layer was formed by either 40–100-keV B$^+$ ion implantation or by diffusion (with a conventional Silox process). The p$^+$ sheet-resistance and junction depth were controlled to be in the same range by tuning implantation energy and diffusion conditions. The diodes formed by B diffusion were optionally implanted with silicon (10^{15} Si$^+$ atoms/cm^2 at 200 and/or 450 keV) and subsequently annealed to form dislocation loops. The dislocation loops are located either above the metallurgical junction (using 200 keV) or beneath it (with 450 keV). The dislocation loop formation was controlled by varying the temperature of the post-annealing between 850 °C to 1050 °C, for a fixed time of 20 min (as in earlier papers). The silicon implants were carried out on parts of the wafer only. Thus, the implanted and nonimplanted diodes experienced the same process conditions. Aluminum contacts were formed at the back and front-sides of the wafer. The wafers were sintered at 400 °C for 5 min in wet N$_2$.

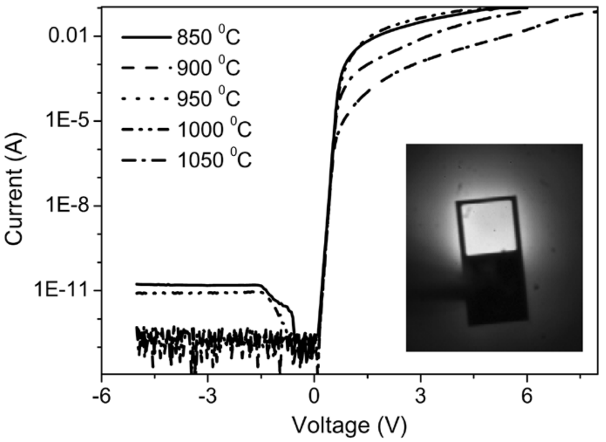

Fig. 1. Current–voltage characteristics of B-implanted LEDs annealed at various temperatures. (Inset) Photograph of a silicon LED device under a forward bias current of 50 mA, taken with an InGaAs (infrared) camera. The inside square is the diode area. The rectangular black feature around it is the aluminum interconnect and bond pad.

Electrical characteristics were measured using a Cascade probe station and an Agilent 4156C parameter analyzer. Emission spectra were obtained at room temperature (unless stated otherwise) with a Spectro 320 scanning spectrometer with an InGaAs detector. An optical fiber (65-μm diameter) on a Cascade Microtech Lightwave Probe was positioned above the LED to guide the light from the LED to the spectrometer.

The external quantum efficiency was estimated from the light collected with this probe. A geometrical correction was made for the limited opening angle of the fiber. The (considerable) emission beyond the diode edges (see inset in Fig. 1) was excluded from this efficiency quantification. The presence of extended defects was verified using HR-XRD and HRTEM measurements. From the TEM pictures we estimate the dislocation

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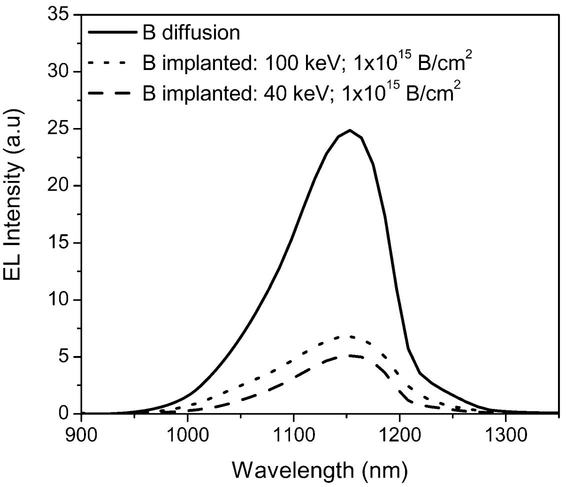

Fig. 2. Silicon LED formed by diffusion exhibits stronger light emission than an ion-implanted LED. A lower implant energy leads also to lower light emission.

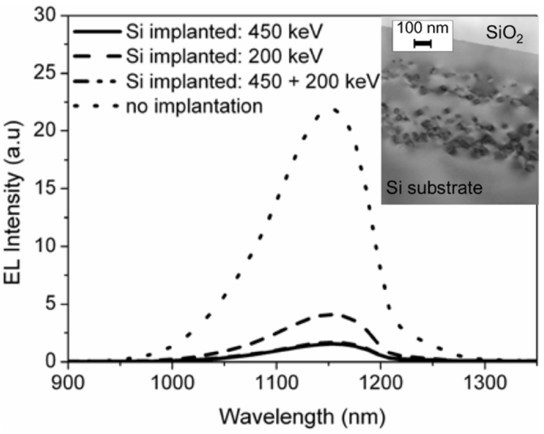

Fig. 3. Comparison of the electroluminescence of B-diffused silicon diodes without, and with, silicon ion implantation to form lattice defects. The device with the least lattice damage emits most light. (Inset) TEM cross section picture of a silicon wafer implanted with 200- and 450-keV Si^{+}, and annealed at 950 °C.

loop density to 5×10^{11} cm^{-2} in the silicon-implanted samples, which is more than three orders of magnitude higher than the density observed in diffused junctions [6].

III. RESULTS AND DISCUSSION

Current–voltage characteristics show normal diode operation, as illustrated in Fig. 1. All devices show a low reverse leakage current, contrary to the result described in [1]. Under forward bias, the dominant contribution to the total current is the diffusion current component. This implies that the recombination takes place outside the space charge region throughout the low injection regime.

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 inset in Fig. 1, and also reported in [1]. The external efficiency of our B-implanted LEDs is estimated to be around 10^{-4} with an uncertainty of a factor 2, in line with [1]. All electroluminescence spectra of the manufactured LEDs give the same emission peak at a wavelength around 1150 nm at room temperature. Spectrum shape and maximum are consistent with [1]. The observed spectrum is associated with phononassisted radiative band-to-band recombination. The highest light emission intensity is found in the device annealed at 1050 °C, consistent with the reported trend in [4]. Identically processed devices showed a 4.3% variation of the electroluminescence.

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 Fig. 2. 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, if the defects created in the silicon (by the boron implant) influence the light emission in the diode, they reduce rather than enhance it.

Fig. 2 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 [2].

In earlier works, it was assumed that the light emission in silicon is enhanced by the presence of dislocation loops, through the formation of a strain field. From the experimental results presented above, however, it seems that the introduction of dislocation loops suppresses the radiative recombination! For an independent confirmation of this remarkable result we set up a second experiment.

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 °C and 30 min) 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.

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 Fig. 3). 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.

Our experiments provide support for the earlier suggestion by Sobolev *et al.* that gettering of recombination centers plays a role, and the recent findings of Trupke *et al.* [2] that clean, monocrystalline silicon may well be a much more efficient light source than generally assumed. Through our experimental method it is however not possible to separate the effects of different defects (point defects, dislocations, stacking faults, etc.) to the emission efficiency, and one type of defect may counteract the contribution of another's.

The temperature dependence of the light emission spectra was investigated by measurements at seven chuck temperatures in the range 253–473 K. Three diodes were characterized: one boron-implanted, and boron-diffused diodes with and without silicon implant. A monotonous increase of the integrated electroluminescence with temperature is found in all diodes. The emission peak shifts to larger wavelengths, qualitatively consistent with the band gap decrease as a function of temperature.

IV. CONCLUSION

Silicon light emitting diodes have been reported to exhibit high quantum efficiency when crystal defects are created near the p-n 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 was observed in a wide experimentation range with varying dislocation loop densities, dislocation loop depth, and annealing temperature. This new finding calls for a revision of the current understanding of light emission from defect-engineered silicon LEDs.

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