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Dislocation-related electroluminescence of silicon after electron irradiation

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ABSTRACT

This letter describes a novel method of introducing controllable dislocations in silicon by electron irradiation. A corresponding dislocation-related light emitting diode with $\sim$1.6 μm emission at room temperature has been fabricated. A new affiliated peak of dislocation-related electroluminescence at $\sim$0.86 eV is observed. The current-dependent electroluminescence proves that the dislocation-related luminescence is derived from several dislocation-induced energy levels which have higher priority in recombination of the injected electrons and holes over the band-to-band recombination. Our work may provide an alternative approach for silicon-based light sources.

1. Introduction

A silicon-based optical on-chip emitter which is compatible with present integrated circuit technology is one of the challenges in silicon photonics. Light emitted from dislocations in silicon is an important source of radiative transitions in the infrared band which fits well with the transparency windows of optical fibers. There are four lines with energies of 0.812 eV (D1), 0.875 eV (D2), 0.934 eV (D3) and 1.000 eV (D4) [1] in the dislocation-related photoluminescence (DRL) of silicon. Usually only the D1 line, having the highest thermal tolerance, is displayed in the electroluminescence (EL) and matches well the interesting 1.55 μm band. The success of dislocation-related EL at room temperature in plastically-deformed silicon, for which external quantum efficiencies of more than 0.1% have been achieved using hydrogen passivation and impurity gettering, makes the D1 line an important candidate in silicon-based light sources [2]. Recently, a MOS-LED based on a dislocation network formed by direct wafer bonding showed a strong EL from the D1 line at low temperature with an internal quantum efficiency of about 0.1% (external of 0.0013%) [3]. It was also reported that a *p*-*i*-n^+ structure is used to get EL from D1 at room temperature based on defects in the nanostructured Si layers composed of Ge island arrays [4,5].

DRL spectra show large variations that depend on the different dislocation formation mechanisms such as plastic deformation [1,2], ion implantation [6,7], precipitation of oxygen [8–10], wafer bonding [11], Ge/Si mismatch [4,12,13] and laser melting [14]. However, most of these methods are not fit for the integrated circuit processing technology, as there is an absence of appropriate technology to control either dislocation density or location well. In this paper, we reported a promising method of inducing dislocations by electron irradiation. By this method, the location and density of "clean" dislocations could be easily modulated. A silicon-based dislocation-related light emitting diode with $\sim$1.6 μm emission at room temperature has been fabricated based on this technique and the mechanism of EL was discussed. We believe our novel technique can help in understanding the physics underpinning dislocation-related EL in silicon and also provide an alternative approach for silicon-based light sources.

2. Experiment

P-type (100) Czochralski (CZ) silicon wafers with resistivity of 2–8 Ω cm were cut into 20×20 mm^2 samples and then scanned with a focused electron beam for 1 min under vacuum of 5×10^{-3} Pa at room temperature. The electron acceleration voltage was 8 keV and the power density of the electron beam was $\sim$1.5 W/mm^2. In preparing the LED structure, *pn* junctions were made by phosphorus diffusion with a surface carrier concentration of $\sim 2 \times 10^{18}$ cm^{-2} and a junction depth of $\sim$0.5 μm. To form Ohmic contacts, an aluminum electrode was evaporated on the n^+ side, and a gold electrode was sputtered on the *p*-type substrate.

Microstructures of the dislocations were studied using a TECNAI G^2 20 field emission transmission electron microscope. Photoluminescence (PL) was excited using a 974 nm laser diode; both PL and EL signals were collected using an Edinburgh FLS920P Spectrometer with a nitrogen-cooled near-infrared photomultiplier tube. The temperature-dependent PL and EL measurements

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were performed over the range 15–300 K using a helium flow cryostat from Advanced Research Systems.

3. Results and discussions

Optical microscopy images of the silicon wafer with electron irradiation after preferential-etching using a Secco etchant are shown in Fig. 1. The electron-scanned area is seen full of dislocations (Fig. 1a) whereas other areas of the sample remained unaffected (Fig. 1b). From this technique, the dislocation density was estimated to be in the order of $10^7\ \text{cm}^{-2}$. Fig. 1c shows a cross-section view of the uniform dislocation distribution of the area after electron irradiation. Dislocations are seen to penetrate the wafer at roughly the same density; this is in contrast to results of Sveinbjornsson and Webber [14] who found the dislocations induced by laser melting only existed on the surface. Moreover, we confirmed in our experiments that the dislocation density was positively correlated with electron irradiation intensity, thus indicating that dislocations could be formed locally and controllably by this technique. The morphology of dislocations is shown in the inset of Fig. 1d. The dislocations are isolated, without cross-gliding and without the formation of dense networks through interaction and multiplication. Indeed, during the fast heating and cooling process under electron irradiation, there is limited time for dislocations to multiply and cross-glide.

A typical PL spectrum obtained at 15 K of silicon wafer just after electron irradiation is shown in Fig. 1d. The four lines labeled D1 through D4 are typical for dislocation-related luminescence in silicon [1,15]. Silicon-wafer EL after electron irradiation is carefully studied at 15 K (Fig. 2). The D1 line dominates the whole spectrum when current injection levels are low. Its turn-on current is quite small, indicating that the D1 center can be activated easily. It is interesting to note a new shoulder peak appearing at ~0.861 eV beside the D1 line which only exists at relatively higher current injection levels. This peak may be affiliated to the D1 line coming through its fine structure. However, the exact origin needs further study. Another thing to be stressed is the D1 line's full widths at half maximum of PL and EL are different (~25 and 70 nm, respectively). It may be due to the different carrier injection mechanisms of photoluminescence and electroluminescence.

The dependence on the forward bias current density of EL intensity and the peak energy of both the D1 and band-to-band (BB) lines at 15 K is shown in Fig. 3. The BB line shows a linear correlation with the current. The observed behavior of BB radiation is consistent with efficiency calculations as a function of the carrier injection level. For the D1 intensity versus the injection level, the situation is more complex. The D1 emission increases sub-linearly with current density whereas the peak position remains the same. In our samples, the dislocations were well-distributed on both sides of the space charge zone of the *pn* junction. It is assumed that the D1 center is composed of several energy levels induced by dislocations [16–18]. A clear positive correlation between the density of dislocations and the intensity of D1 luminescence is observed [1,15]. Thus the D1 center is strongly affiliated with dislocations. The minority carriers injected by the current mainly recombine at the diffusion region and the depletion region. The D1 centers located in these areas are the activated luminescence centers offering physical sites for carriers to recombine by emitting D1 luminescence. The sub-linear behavior of the D1 line intensity with respect to current is due to the reduction of activated D1 centers which is caused by the shrinkage of the depletion region as voltage increases. When the current density reaches around ~0.23 A/cm^2 (while the temperature is still at 15 K), the D1 intensity becomes saturated and starts to shift to lower energy. This may be because the occupancy of the dislocation-induced states gradually becomes saturated under higher injection [7] and Auger

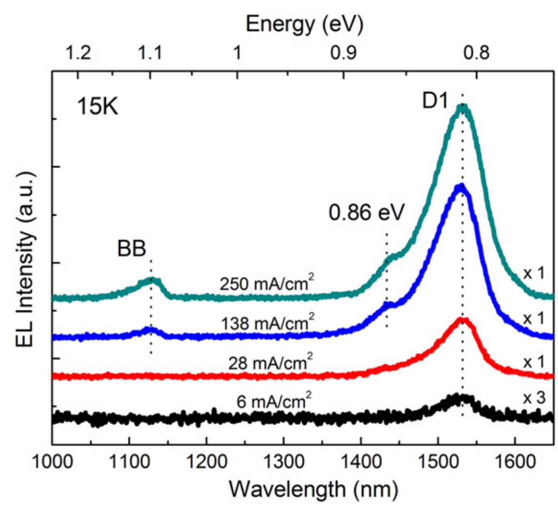

Fig. 2. Typical EL spectra at 15 K of a forward-biased *pn* junction diode with dislocations induced by electron irradiation. The D1 line exists at all levels of current injection, whereas the BB line and the sub line of 0.86 eV only appear at high current injection.

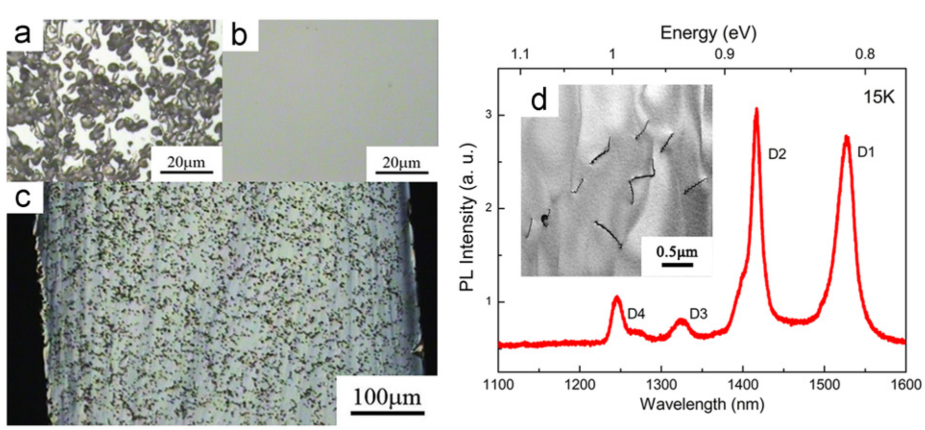

Fig. 1. Optical microscopy of the silicon wafer after preferential etching by Secco etchant: (a) plan view after electron irradiation; (b) plan view of area without electron irradiation; and (c) cross-section view of area with electron irradiation. (d) Typical PL spectrum at 15 K of an electron irradiated area: the quartet of lines (D1 to D4) are related to dislocations in silicon. The inset is a TEM image showing typical dislocation morphology in a silicon wafer after electron irradiation. The bright field image is formed with $B = <001>$, $g = <0-40>$.

recombination is strongly enhanced at high injection levels. The red-shifting of the D1 peak is greatly affected by the built-in electric field, which is due to the Stark effect on the dislocation-related excitonic states [19].

A significant BB line and the D1 line are observed at room temperature (Fig. 4) with the D1 line shifting to ~0.78 eV. To get a stronger signal of D1 line, one needs much higher current injection, because non-radiative recombination is much stronger at room temperature than at 15 K, thus consuming much more injected carriers and suppressing the probability of radiative recombination dramatically.

It is intriguing to observe that BB luminescence does not appear at the same time as D1 luminescence at low temperature. The BB line only starts to become visible at relatively high current injection levels. The PL radiative decay time of D1 line is of order of around 1 ns [12] and the time-resolved EL measurements reveals that the response time of the D1 line is below 1.8 μs [2], which is much faster compared with that of BB luminescence in bulk silicon. The increased density of dislocation will lead to an intensity increase of D1 luminescence and an intensity decrease of BB luminescence [7]. In the bonded wafer, electrons and holes recombine radiatively at the dislocation-related states where the so-called potential well is formed at the charged dislocation network confining the electrons while emitting pure D1 luminescence [3]. However, results to identify these D1 center related levels, using for example DLTS, are complex and unclear. In our cases, the injected electrons and holes are inclined mainly to retain energy levels induced by dislocations whereas most prefer to recombine giving off D1 light emissions at low temperature. At low injection levels, the predominant recombination mechanism is multi phonon Shockley–Read–Hall (SRH) recombination. The internal quantum efficiency will grow with the enhancement of the injection level. Upon increasing current injection, electrons and holes that have recombined through levels induced by dislocations will become saturated and some may recombine through free-carrier transitions. This explains why with increasing current the BB line appears later than the D1 line. The present authors suggest this phenomenon is direct evidence proving the existence of certain levels of D1 centers which offer electron–hole recombination sites. One of these dislocation-related levels is considered at 0.35 eV in the energy band [17]. This also proves that the recombination route of D1 center is competitive with the band-to-band route.

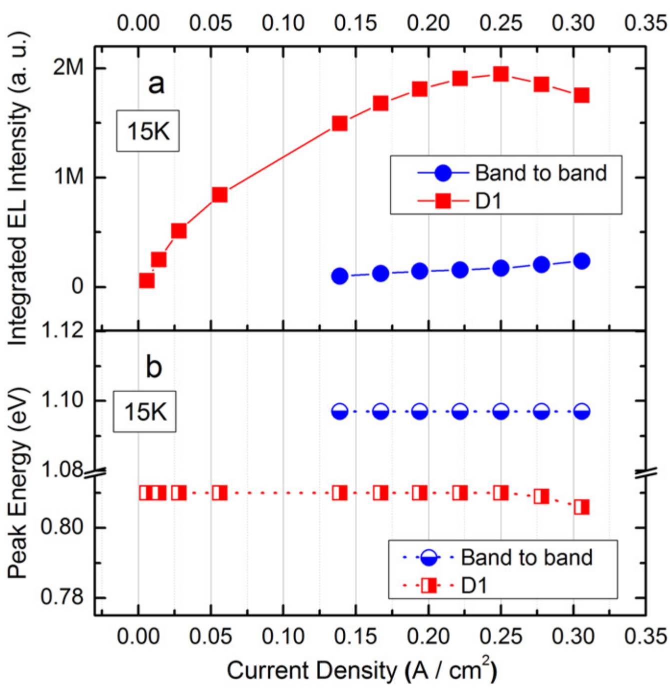

Fig. 3. The dependence of (a) integrated EL intensities and (b) peak energies of D1 and band-to-band transitions on the forward bias current density at 15 K.

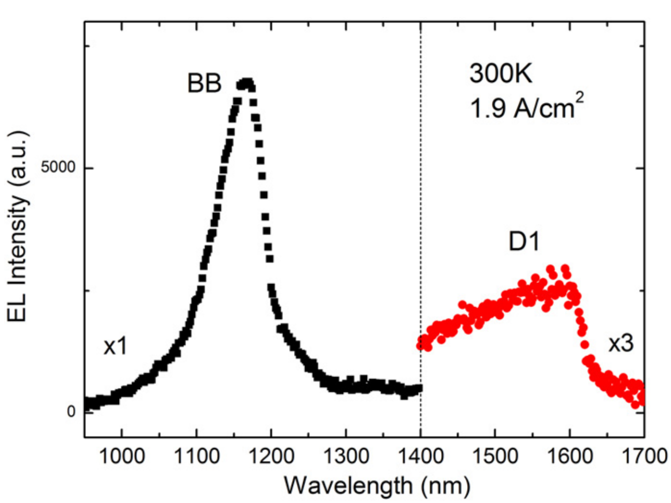

Fig. 4. EL spectra of a *pn* junction diode with dislocations under forward bias at room temperature. The signal at ~1.1 eV is due to the phonon assisted band-to-band transitions, whereas the peak at ~0.78 eV is assigned to the D1 center.

4. Conclusions

We induced dislocations locally and selectively by electron irradiation and successfully obtain DRL in silicon. Significant EL of the D1 line at room temperature was observed. The current-dependent EL showed direct evidence that the D1 center is composited by certain dislocation-induced levels. These have much more priority in recombination of the injected electrons and holes over the band-to-band recombination. It is suggested that by improving the preparation of *pn* junction and decreasing the nonradiative recombination centers, the prospect is good that by using electron irradiation high-efficiency silicon-based light emitting diodes can be produced.

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