The Effect of Temperature to the Formation of Optically Active Point-defect Complex, the Carbon G-centre in Pre-amorphised and Non-amorphised Silicon

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Abstract. The effect of the temperature ranging from cryogenics to room temperature were investigated on the formation of the optically-active point defect called the G-centre. The G-centre as an emissive point defect gained a lot of attention recently due to its sharp zero phonon luminescence peak at a wavelength of 1.28 μm (0.97 eV) with the evidence of lasing occurred in the structure. The emission of the G-centre is attributed to the carbon substitutional–carbon interstitial (CsCi) complex which interacts with silicon interstitials during the damage event. This complex is generated by implantation of carbon and followed by proton irradiation. Prior to the carbon implantation, two of the samples were pre-amorphised by germanium. Photoluminescence (PL) measurements were carried out at temperature ranging from 80 K up to room temperature to observe the intensity of the main peaks. The results confirm that the main peaks of point-defect centre in all of the samples including the G-centre suffer from the temperature quenching. However, the peak intensity for some of the wavelength especially the ones with high FWHM, do perform better at high temperature. The temperature quenching phenomena observed in the point-defect technique is the main problem that needs to be addressed and solved before realizing the method in the all silicon photonic system.

1. Introduction

There is a crucial requirement to create a silicon-based optical emitter, which is compatible with standard ULSI technology used in fabricating integrated circuits [1]. Despite silicon dominance in the electronics industry, it is still lacking key properties in optoelectronics. This is because of the indirect band gap which limits the radiative recombination efficiency. However, in the past decade, various approaches have been introduced to try circumventing the band gap limitation, thus transforming silicon as an optically active material. Among the successful and promising methods of emitting light from silicon are point defect centres [2-5], Raman conversion [6-8] strained silicon i.e. dislocation engineering [9,10] and nanocrystals with or without rare earth doping such as erbium(Er) [11-14]. The first silicon laser was reported in 2004 by Jalali et al using the Raman conversion techniques, however by its nature can only ever be optically pumped [6].

The G-centre as an emissive point defect gained a lot of attention recently due to its sharp zero phonon luminescence peak at a wavelength of 1.28 μm (0.97 eV) with the evidence of lasing occurred...
in the structure [15]. The emission of the G centre is attributed to the carbon substitutional–carbon interstitial (CsCi) complex which interacts with silicon interstitials during the damage event. The G centre emission at 1280 nm is in the spectral range which is vital in long-haul fiber-optic networks and is ideally suited to silicon intra-chip and inter-chip low-power data interconnects. A new method fully compatible with CMOS (Complementary Metal Oxide Semiconductor) technology to efficiently produce the lasing G-centre has been recently reported [16-18]. It combines the implantation of carbon, subsequent heat treatment followed by high-energy proton implantation on bulk silicon substrates to form CsCs complexes and Si interstitials.

The luminescence intensity of the G-centre emission varies with the implant conditions such as the carbon and proton doses. Ion implantation damages the target and displaces many atoms. In CMOS technology, the electrical behaviour after implantation is dominated by deep-level electron and hole traps, which capture the carriers and make the resistivity high. Annealing or rapid thermal process (RTP) is needed after the implantation to electrically activated the implanted atoms while removing the radiation damage. RTP is usually favored among other conventional heat treatment methods because of the shorter processing times and higher electrical activation of the implanted dopants [19]. In the case of pre-amorphized samples, an annealing process is required to allow solid phase epitaxial regrowth (SPER) where the orientation of crystalline region is replicated into the volume that evolves from the amorphous solid with the crystalline region of the wafer serving as the ‘seed’.

In this paper, we report the temperature dependence study of both pre-amorphised and non-amorphised silicon that have been implanted with carbon and irradiated with protons to form the optically active centres especially the G-centres. The amorphisation of the silicon lattice was done by bombarding samples with germanium. Photoluminescence measurements have been carried out at different temperatures to investigate the G centre’s peak and other related luminescence intensity in bulk silicon samples. The measurements confirm temperature quenching problem suffered by employing the point-defect technique to gain luminescence in silicon.

2. Sample preparation and analysis

The experiment was performed using N-type silicon wafers (100) with resistivity of ~ 10 Ωcm and manufacturer-specified residual carbon content of 2.5×10^{16} cm^{-3}. One of the samples were pre-amorphised with 2×10^{15} cm^{-2} of germanium at energy 180 keV. Samples were then implanted with different doses of carbon, first at 30 keV and followed by implantation at 10 keV. The double implantations were done to construct a reasonably flat carbon profile thus ensuring better uniformity of carbon concentration along the depth of samples. After the C implantation, samples were annealed at 1000 ºC for 20 seconds in N2 ambient. This is to allow the solid phase epitaxial regrowth (SPER) of the silicon lattice, repair the lattice damage and to activate while introducing carbons into the substitutional sites. Proton irradiation of the annealed samples was subsequently carried out at different doses. Details of the samples are given in Table 1.

**Table 1.** Sample details. The first carbon implant was at 30 keV and the second implant at 10 keV. All samples were annealed at 1000 ºC for 20 s after the C implants. The average carbon volume concentrations were calculated using SUSPRE [20]. Proton irradiation was performed at 2 MeV after the C post-implant anneal. No further sample processing was done after the proton irradiation.

| Sample | Ge dose (cm^{-2}) | C volume concentration (cm^{-3}) | Proton dose (cm^{-2}) |
|--------|------------------|-------------------------------|-----------------------|
| 1      | -                | 2×10^{19}                     | 5×10^{14}             |
| 2      | -                | 2×10^{20}                     | 5×10^{15}             |
| 3      | 2×10^{15}        | 2×10^{19}                     | 5×10^{13}             |
3. Results and Discussion

Figure 2 shows the photoluminescence spectra of sample 1, measured at different cryogenic temperature ranging from 80 to 120 K, of bulk silicon implanted to 2×10^{19} cm^{-3} volume concentration of carbon, followed by proton irradiation at 5×10^{14} cm^{-2} at energy of 2 MeV. Two optically active point-defect centre observed in these samples, which are CsCs complex, the G-centre at ~ 1.28 μm and C-centre at ~ 1.57 μm. The latter is another zero phonon line luminescence feature attributed to the carbon-oxygen (CsCs) complex intensity while developing a broad peak in the ~ 1.4 to 1.6 μm range. The broader structured luminescence from 1.3 to 1.4 μm observed in both spectra is a familiar feature of the G-line spectra resulting from local phonon modes [21]. At 80 K, the sharp G-line peak is dominating the spectrum but it is quickly decreasing to quarter of its value when temperature is increase to 90 K. The G-line peak intensity continues to drop at higher temperature denoting the temperature quenching problem suffered by the optically active point-defect. At 120 K, the G-centre peak is no longer observed in the spectrum. As for the C-line, the peak intensity can be seen to drop gradually and finally absence at 120 K. It has been suggested that temperature quenching problem by employing point-defect technique is due to non-radiative process by unspecified energy barrier and deep level trap [22].

![Figure 1](image1.png)

**Figure 1.** Shows the a) PL spectra of the sample with the different measurement temperatures from 80 to 120 K and b) luminescence intensity of the G and C-centres’ peaks for non-amorphised sample with 2×10^{19} cm^{-3} of carbon and 5×10^{14} cm^{-2} protons. The luminescence especially of the G-centre peak quenches rapidly when the temperature increased from 80 to 90 K.

Sample 2 is a bulk silicon wafer that has been implanted to 2×10^{20} cm^{-3} volume concentration of carbon, followed by proton irradiation at 5×10^{15} cm^{-2} at energy of 2 MeV. The photoluminescence spectra of this sample at different temperature is shown in Figure 3. There are three main peaks observed...
in the sample which is the G-line, W-line attributed to self-interstitials defect clusters formed after ion irradiations and a broad peak at ~ 1.55 μm [23]. The presence of the W-line indicates the existence of an excess of silicon interstitials created after the proton irradiation, which compete to form various silicon-related radiative and non-radiative centres, including the W- and G-centres. The broad peak at 1.55 μm is clearly dominating the spectrum with a gradual drop of peak intensity from 80 to 120 K. As before, the G-line peak intensity decrease rapidly with the increase in temperature and completely absence at 120 K. Similar to the G-centre, W-line peak has also drop rapidly with temperature and cannot be observed at temperature higher than 95 K. Higher carbon and proton doses in this sample as compared to sample 1 does not give a higher peak intensity of the G-centre. This is because; the excessive amount of the carbon and silicon interstitials in the lattice will tend to agglomerate and forming other radiative and non-radiative centres [17].

Figure 2. shows the a) PL spectra of the sample with different measurement temperature from 80 to 120 K and b) luminescence intensity of the main peaks for crystalline sample with 2×10^{20} cm^{-3} of carbons and 5×10^{15} cm^{-2} protons. The highest peak of this sample is a broad peak at 1550 nm whose intensity decreases uniformly with temperature.

Figure 3 shows the photoluminescence spectra for sample 3 which has been pre-amorphised with ge prior to carbon implantation with volume concentration of 2×10^{19} cm^{-3} and proton irradiation dose of 5×10^{13} cm^{-2}. Three main peaks the G-line, C-line and broad peak at ~1.6 μm are observed in this sample with the C-line at ~ 1.57 μm dominating the spectrum. End-of-range (EOR) defects are common
occurrence in a preamorphised sample and observed at a former amorphous/crystalline (a/c) interface after solid phase epitaxial regrowth (SPER) [17]. EOR defects might trap the majority of silicon interstitials which are vital in the formation of the G-centre thus resulting in the domination of the C-centre luminescence in this sample. We also suggest that the formation of the broad peak at 1600 nm is due to the formation of the interstitials after the SPER. The C-line peak can still be observed at 120 K giving it strong presence and have the potential to emit at room temperature.

![Figure 3](image)

**Figure 3.** shows a) the PL spectra of the sample with different measurement temperature from 80 to 120 K and b) the luminescence intensity of the main peaks for the pre-amorphised sample with 2×10^{19} \text{cm}^{-3} of carbon and 5×10^{13} \text{cm}^{-2} protons. The highest peak of this sample is at 1574 nm (C center) whose intensity decreases gradually with temperature but started to decrease rapidly at 100K.

4. Conclusion
We have investigated the temperature effect on the formation of the optically active point defect while focusing at the G-centre. As predicted, most of the luminating centres suffers from the temperature quenching problem and usually disappear at higher temperature. However, there are some potential point-defect centre such as the carbon-oxygen (CiOi) C-centre when the sample was first pre-amorphised with ge.

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