Co-Implantation of Carbon and Protons: An Integrated Silicon Device Technology Compatible Method to Generate the Lasing G-Center

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The optically active carbon related G-center is attracting great interest because of evidence that it can provide lasing in silicon. Here a technique to form the G-center in silicon is reported. The carbon G-center is generated by implantation of carbon followed by proton irradiation. Photoluminescence measurements confirm the controlled formation of high levels of the G-center that, importantly, completely dominates the emission spectrum. Unlike previous methods of introducing the G-center the current approach significantly is truly fully compatible with standard silicon ULSI (ultralarge scale integration) technology.

1. Introduction

Silicon photonics is an important, rapidly developing field that offers a route to fast computer chips and telecommunication by integration of optical components with electronics. An urgent requirement is to develop a silicon-based optical emitter compatible with standard ultralarge scale integration (ULSI) technology. Despite silicon's dominance in electronics, it still lacks key properties needed for fully integrated silicon photonics because of its indirect band gap which limits its performance as an efficient optical emitter. However, various approaches have been tried to circumvent this limitation and achieve light emission, such as the introduction of optically active point defect centers,[1–4] Raman conversion,[5–7] dislocation engineering[8,9] and nanocrystals in silicon dioxide with or without rare earth doping.[10–13]

Light emission from silicon can be achieved by manipulating point defects to produce emission at wavelengths of interest, which depend on the nature of the defects.[1] A promising light-emitting point defect in silicon is the carbon related G-center, due to its sharp luminescence peak at 1280 nm, matching the important optical communications wavelength of 1300 nm, coupled with evidence that it can support optically pumped lasing.[3,4] The G-center emission is due to the optically-active form of the substitutional - interstitial carbon (C_s–C_I) complex, enabled by mobile silicon interstitials (Si_I). The main methods used to generate the G-center are by electron irradiation[1,14] and by modification of the silicon surface.[3,4,15,16] The earlier reports resulted from fundamental defect studies of high energy electron irradiated as-grown silicon, where the G-center emission was identified as due to residual carbon from the crystal growth.[1] Subsequently, the deliberate incorporation of additional carbon to increase the G-center activity was investigated.[15] More recently, nanopatterning of the silicon surface was incidentally found to introduce carbon impurities and lattice damage to enable G-center formation.[3] This approach has been developed further by doping with high concentrations of carbon using solid-phase epitaxial re-growth followed by nanopatterning.[4] However, this method results in severe lattice damage and is not suitable to be produced on large scale within CMOS (complementary metal oxide semiconductor) technology. The formation of the G-center by chemically modifying the silicon surface with hexamethyldisilazane followed by laser annealing has also been reported recently.[16] Whilst of considerable scientific interest, it is doubtful if any of these current methods of G-center generation could be practicably applied in integrated silicon device production. For any realistic prospect of adoption by industry, it is paramount to develop a method of generating high concentrations of the G-center using tools truly compatible with standard ULSI technology. The electron irradiation approach to activate the G-center is efficient and at first sight would appear promising but, because of their light mass, electrons of the required energy scatter laterally in the silicon surface by tens of microns at the energies needed–far-too-far to be practicable given current device dimensions.

Here we report on the generation of the G-center by ion implantation of high doses of carbon followed by proton irradiation. Because of the 1800 times greater mass compared to

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Table 1. Sample details.

Sample	Carbon Energy [keV]	Carbon dose [ions/cm^2]	C Concentration [cm^{-3}]
A1	30	2.0×10^{12}	2×10^{17}
	10	5.5×10^{11}	
A2	30	2.0×10^{13}	2×10^{18}
	10	5.5×10^{12}	
A3	30	2.0×10^{14}	2×10^{19}
	10	5.5×10^{13}	
A4	30	2.0×10^{15}	2×10^{20}
	10	5.5×10^{14}	

electrons, the proton induced silicon interstitial profile has negligible lateral scattering in the top surface region of the silicon where devices are fabricated. This method, unlike previous approaches, is truly compatible with CMOS technology.

2. Sample Preparation

N-type silicon wafers (100) with resistivity ~10 Ω cm and manufacturer-specified residual carbon content of 2.5×10^{16} cm^{-3} were implanted with different carbon doses at 30 keV (first implant) and then 10 keV. The double implantations give a reasonably flat carbon profile ensuring better concentration uniformity along the depth of samples. The volume concentration ranges from 2×10^{17} to 2×10^{20} C cm^{-3} calculated using SUSPRE.[17] Samples were subsequently rapid thermally annealed at 1000 °C for 20 seconds in nitrogen ambient to repair the lattice damage and incorporate C on substitutional lattice sites. Proton irradiation of the annealed samples was then carried out from 500 keV up to 2 MeV at fluences ranging from 5×10^{10} to 5×10^{15} cm^{-2}. Un-irradiated carbon samples as well as proton irradiated samples without carbon implants were also kept as references. Details of the implant parameters are given in **Table 1**.

3. Results and Discussion

Figure 1 shows the photoluminescence (PL) spectra for samples of 2×10^{19} C cm^{-3} concentration and proton irradiated at 2 MeV at different doses. The main features in the various spectra, annotated on the figure, are the silicon band-edge related emission at ~1130 nm, the W-center at ~1220 nm (due to the aggregation of silicon self-interstitials),[1,2] the G-center (zero phonon line at 1282 nm with associated local phonon replicas extending to ~1500 nm) and the carbon-oxygen C-center at ~1580 nm.[1] The relative intensities of these features vary strongly with process conditions. The inset in Figure 1 is a higher resolution (0.32 nm) spectrum taken across the G-center zero phonon line which shows a full width at half maximum (FWHM) of 2.35 nm, which is expected at this measurement temperature (80 K).[14] The G-center is not present in the sample without proton irradiation, where the dominant features are the silicon band-edge emission and the C-center. Once samples are proton

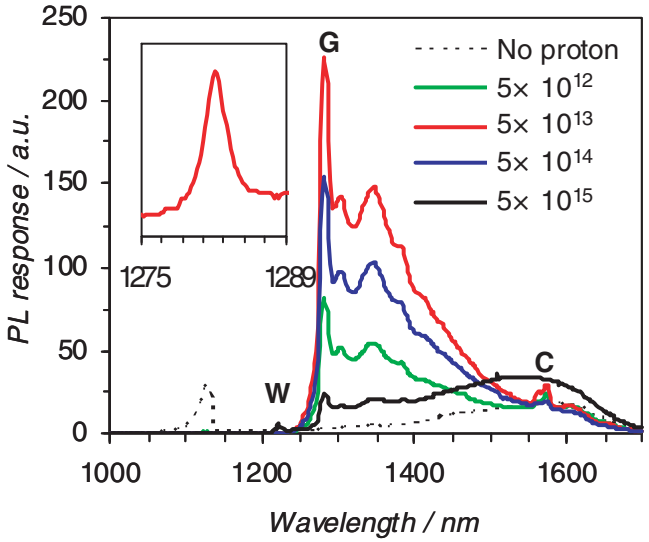

Figure 1. Photoluminescence spectra measured at 80 K of silicon samples implanted to 2×10^{19} C cm^{-3} and annealed at 1000 °C for 20 s, followed by 2 MeV proton irradiation at different doses. The proton doses (cm^{-2}) are indicated. The positions of the W-, G- and C-centers are also shown. The inset is a higher resolution spectrum across the G-center zero phonon line, also taken at 80 K; its FWHM is 2.35 nm.

irradiated, even at the lowest doses, the G-center emission completely dominates the spectra and the competing silicon band-edge emission is negligible. The G-center peak intensity increases up to a proton dose of 5×10^{13} cm^{-2} and subsequently decreases. At the highest proton irradiation dose (5×10^{15} cm^{-2}) we start to see the W-center, thus confirming the production and presence of excess silicon interstitials in this sample, and a broad PL emission band also emerges. The C-center was observed in all samples except at the highest proton fluence; its peak intensity, however, is weak when compared to the G-center and saturates quickly, once all the residual oxygen impurities are fully complexed with the carbon.

Figure 2 shows the PL response for samples implanted with different carbon doses and irradiated with the same proton fluence of 5×10^{13} cm^{-2} at 2 MeV. The G-center dominates in all carbon implanted samples; its peak intensity increases with carbon concentration up until 2×10^{19} C cm^{-3} after which it decreases. The G-center is also observed in the un-implanted carbon sample, due to the residual carbon impurities present in CZ silicon wafers, typically ~10^{16} C cm^{-3}.

Figure 3, showing the G-center peak intensity plotted as a function of proton dose (2 MeV) for all C implanted samples, summarizes the results. From inspection of the full set of complete spectra for each combination of carbon and proton doses we can explain the basic behaviour summarized in Figure 3. In general, G-center formation is enhanced by providing additional carbon by implantation and annealing and additional silicon interstitials from the host lattice disruption due to proton irradiation. For all carbon concentrations except the lowest, the G-center peak intensity increases steadily with the proton fluence up to a dose of ~5×10^{13} cm^{-2} after which it drops rapidly. The general trends can be explained by considering the several

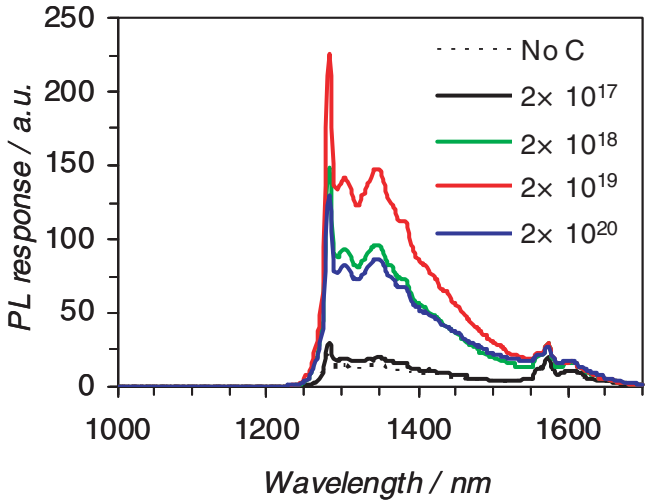

Figure 2. Photoluminescence spectra measured at 80 K of silicon samples implanted with different carbon doses and annealed at 1000 °C for 20 s, followed by proton irradiation at 5×10^{13} cm^{-2} at 2 MeV. The carbon concentrations (cm^{-3}) are indicated.

parallel processes occurring. The initial increase in the G-center peak is due to the increase in the silicon interstitials required for G-center generation created by the proton irradiation. The peak intensity of the G-center emission in the lowest carbon dose sample is reached earlier, as a function of proton dose, as all the available carbon is incorporated in the G-center. Higher proton irradiation in this sample then reduces the G-center intensity as a result of increased non-radiative recombination from proton related damage centers. The higher carbon concentration samples require a higher proton dose to provide sufficient silicon interstitials to complex with the carbon. The decrease in intensity above the 5×10^{13} cm^{-2} proton fluence results from competition from silicon interstitials which form clusters with each other, lowering the probability of them contributing to forming the G-center complex. The weak G-center emission in all the samples irradiated with 5×10^{15} cm^{-2} protons is associated with the emergence of a broad (1400–1700 nm range) defect related competing emission. Its presence in all the carbon doped samples suggests that it is due to proton induced damage. Interestingly there is no evidence from the PL results of carbon clustering or SiC precipitation in the proton irradiated samples even at the highest 2×10^{20} C cm^{-3} concentration.

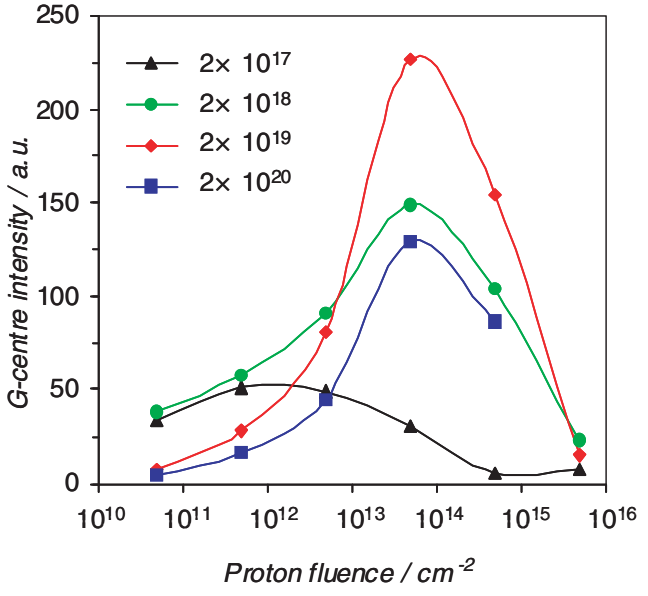

Figure 3. G-center PL peak intensity measured at 80 K as a function of proton dose (all implants at 2 MeV) for different carbon concentration samples. The carbon concentrations (cm^{-3}) are indicated.

4. Conclusions

In conclusion, we have investigated and presented a new approach to incorporate high levels of the emissive G-center peaking sharply at 1282 nm. We obtain optimum G-center generation at a carbon concentration of 2×10^{19} cm^{-3} under a proton irradiation of 5×10^{13} cm^{-2} at 2 MeV. The absence of any competing silicon band-edge emission for even the lowest carbon concentrations once irradiated with protons directly evidences the highly efficient generation, in this work, of the G-center compared with several of the previous approaches where the silicon band-edge emission still dominates by at least an order of magnitude[3,16] or is of the same order[4] as the G-center emission, indicating much lower concentrations of the G-center was achieved. Significantly this technique utilizes fully ULSI technology compatible processes such as ion implantation and high temperature annealing.

5. Experimental Section

Photoluminescence measurements were carried out to characterize the G-center generation as a function of carbon concentration and proton irradiation dose. The PL experiments were performed at 80 K across the 1000–1700 nm spectral region (spectral resolution of 4.8 nm) using above band gap laser excitation (514 nm at ~5 mW mm^{-2}). Additional spectra (from 1275 to 1289 nm) around the sharp G-center zero phonon line were taken at a higher resolution of 0.32 nm. The samples were mounted in a continuous-flow liquid nitrogen cryostat placed in front of a conventional half-meter spectrometer. Light was detected by a liquid nitrogen cooled Ge p-i-n diode and processed by a conventional lock-in amplifier.

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