Enhanced Luminescence of Erbium Doped Silicon Due to Hydrogen

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Erbium- and oxygen-doped silicon was additionally doped with hydrogen, using plasma-enhanced Chemical Vapor Deposition. Samples treated with solid-phase epitaxy (SPE) before hydrogen doping and annealing at 900 °C after show a large enhancement of the photoluminescence yield. Secondary Ion Mass Spectroscopy gives evidence for an enhanced diffusion of both oxygen and erbium at this temperature towards the surface. This change in local concentration leads to a dominance of the cubic center that is usually only found for lower Er concentrations. Controlled etching shows that the PL does stem from a deeper region with lower erbium concentration. The luminescence yield in the hydrogenated samples is significantly higher even if compared to samples prepared to optimize the cubic center luminescence. We thus conclude that hydrogen can enhance the solubility of the cubic center in Si:Er,O.

Introduction

Erbium (Er) doped semiconductors have attracted a lot of attention as they seem to indicate a way to obtain temperature stable emission at a well defined wavelength [1] – [7]. Furthermore, the wavelength close to 1.5 µm of this emission stemming from an intra-4f-transition coincides nicely with the absorption minimum in conventional optical fibers. The main problem for applying this material system to devices working at room temperature is the temperature induced quenching of the luminescence efficiency. Investigations showed that co-doping of Si with Er and light elements, in particular oxygen (O), leads to a reduction of this quenching [3] and room temperature electroluminescence (EL) and photoluminescence (PL) [4], [5] were subsequently reported.

The low solubility limit of Er in Si necessitates the use of non-equilibrium methods like ion implantation for its incorporation. Because of the required high doses for Er and O, a thermal annealing step for re-crystallization is necessary. To achieve room temperature EL, Er has to be incorporated in $SiO_{2-\delta}$ precipitates, which are formed at high annealing temperatures (> 950 °C) [6]. Both Er and O stay relatively immobile even at temperatures that high. The shallow dopants required for a diode structure, however, show substantial diffusion already at this temperature. [7]

Hydrogen is a very common impurity in all semiconductor materials. Focusing on its positive characteristics – gettering of metal impurities and passivation of residual defects – as well as on the known enhancement of the diffusion of interstitial oxygen [8] and the formation of Er-O complexes and precipitates [9], we expected an overall positive effect on the performance of our structures. We also hoped that hydrogen might decrease the necessary annealing temperature for precipitate formation thus helping to prevent diffusion of the dopants.

Results and Discussion

Samples were prepared from boron doped (10 Ohm·cm) Cz-Si (100) with an oxygen content of approx. 2 x 10^{18} cm^{-3}. Er was implanted at 300 keV with a dose of 1 x 10^{14} cm^{-2} resulting in a peak concentration of 5 x 10^{18} cm^{-3} in 100 nm depth. Oxygen was implanted at 40 keV with a dose of 1 x 10^{15} cm^{-2} resulting in a peak concentration of 5 x 10^{19} cm^{-3}. Both profiles overlap spatially according to TRIM code simulation and SIMS. Two sets of samples were prepared – one treated by SPE (600 °C/15 min. in N_2 atmosphere), the other "as implanted" – and hydrogenated for 1 hour at 260 °C by a hydrogen plasma (110 MHz, 200 sccm hydrogen flux, 400 mTorr pressure) which leads to a hydrogen concentration of about 10^{19} cm^{-3} throughout the wafer [10]. The samples were then annealed at various temperatures in the range between 450 °C and 1000 °C.

In samples not treated with SPE, the effect of hydrogen is rather limited. The Er-related line spectra closely resemble those in samples without hydrogen treatment, although the intensity due to Er-O complexes is smaller in respect to the cubic lines than in non-hydrogenated samples at elevated annealing temperatures. In samples previously treated with SPE, the PL-intensity is slightly higher than in the reference samples at first. The peak PL-intensities of the annealed samples are shown in Fig. 1 as a function of annealing temperature. The difference becomes significant at higher annealing temperatures (800 and 900 °C), where the luminescence yield is about five times bigger than in the non-hydrogenated samples.

Furthermore, we observe a change in the PL spectra. For samples with hydrogen and annealing temperatures larger than 700 °C, the so-called "cubic" center becomes more and more prominent, and it dominates the spectra after annealing at 900 °C. This center is attributed to Er on an interstitial site and was previously only observed in samples with a low concentration of Er, i.e., when the implantation doses are below the amorphisation limit [11]. The lines due to Er-O complexes are completely absent for samples annealed at 900 °C.

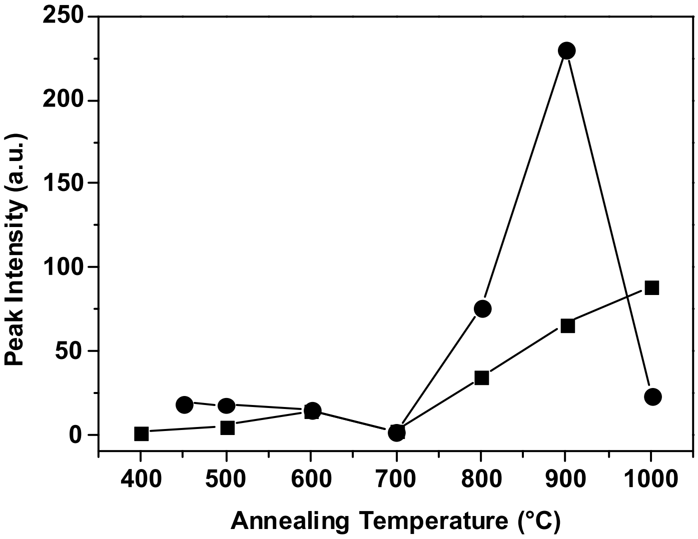

Fig. 1: Peak intensities versus annealing temperatures. Circles show the intensities for the hydrogenated samples, diamond symbols represent the reference samples.

We applied SIMS to gain information on possible changes in local concentration. The results show that hydrogen does not only enhance the diffusion of oxygen but also affects erbium. The usual Gaussian profile is broadened and an accumulation of both species near the surface can be clearly seen. Most of the Er is concentrated within 50 nm of the surface reaching concentrations of up to 1020 cm^{-3}.

To determine the origins of the luminescence we removed 60 nm from the top of the wafer using reactive ion etching. However, although we removed approx. 80 % of the incorporated erbium according to SIMS, the luminescence dropped only by 10 %. This observation points strongly to a PL origin in the region with lower concentration further inside the sample. Using the incorporated doses and the SIMS results as landmarks, we estimate the remaining concentration of erbium in the sample to be approx. 3×10^{12} cm^{-2}. Maximum PL yield for the cubic center is achieved for an implantation dose of 1×10^{13} cm^{-2} and annealing temperatures of 900 °C. Comparing the PL yield to such samples, the intensity is still significantly higher in the hydrogenated samples (Fig. 2). This is an indication for a higher percentage of optically active erbium in our hydrogenated samples.

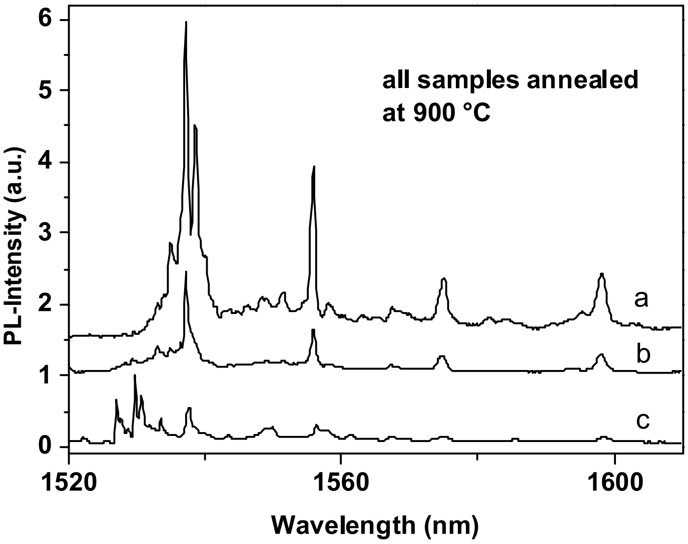

Fig. 2: (a) The cubic lines dominate the PL-spectra in the hydrogenated samples. (b) Spectra of a sample with low Er concentration and (c) of a reference sample (set 4) are shown. The lines at 1.53 µm due to Er-O complexes are absent in the hydrogenated sample. Spectra shifted for clarity.

Studies of power dependence support this interpretation. In the high power regime, the PL-yield I_{Pl} is given by $I_{PL} \propto N_{Er}^{*}/\tau$ with N_{Er}^{*} being the number of optically active erbium and τ being the radiative lifetime. The hydrogenated samples show a higher saturation intensity compared to both the reference sample and samples optimized for cubic center luminescence. The comparison to the reference sample is valid, because although the emitting center is different, the lifetime is identical for both centers [12]. The higher saturation intensity demonstrates a higher number of optically active erbium ions. The “thermal” quenching of the PL intensity with increasing temperature is not influenced by hydrogen. So additional co-doping with hydrogen does not help with room temperature applications. However, it may be advantageous for applications at low temperatures to make use of the higher percentage of optically active erbium and the narrow linewidth [11] of the cubic center.

Conclusion

In summary, hydrogen influences the PL of Si:Er,O indirectly by mobilizing the implanted Er and oxygen. SIMS measurements give evidence for an enhanced diffusion of both species at elevated temperatures towards the surface. Subsequently the local concentration of both dopants is changed. This change in local concentration leads to a dominance of the cubic center, which is usually only found for lower Er concentrations. We find a substantial increase of the luminescence yield for annealing temperatures in the range of 800°C to 900°C. The luminescence yield in the hydrogenated samples is significantly higher even if compared to samples prepared to optimize the cubic center luminescence. Comparing luminescence yield and local concentration, we obtain strong indications for an enhanced solubility of the cubic center in samples co-doped with hydrogen.

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