Er-doped Polycrystalline Silicon for Light Emission at $\lambda = 1.54$ $\mu$m

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We deposited amorphous silicon films, implanted them with erbium/oxygen, and then recrystallized them with a series of thermal treatments. Recrystallization is necessary to remove implantation damage and optically activate Er/O complexes for light emission at 1.54 $\mu$m. Photoluminescence and glancing angle x-ray diffraction were used to characterize the polycrystalline Si:Er. Following 30-minute isochronal anneals and isothermal anneals at 575$^\circ$C and 600$^\circ$C, the erbium luminescence intensity was observed to increase in direct relation to the degree of recrystallization during the anneal. Hydrogen passivation of dangling bonds further increased the luminescence intensity to about one half of the intensity found in a comparable single crystal material. The optically active Er is shown to be located within the recrystallized grains, and it exhibits a de-excitation (backtransfer) mechanism similar to that of single crystal Si:Er.

Key words: Si microphotonics, Er-doped polysilicon, photoluminescence, crystallization, energy backtransfer

INTRODUCTION

Erbium-doped silicon (Si:Er) has been widely studied as a light emitting material ($\lambda = 1.54$ $\mu$m) for integrated silicon microphotonics technology. 1–5 As one injects electron-hole (e-h) pairs by photo-excitation or the forward biasing of a pn-junction, Er centers are excited by a multi-step energy transfer process that is optimized by reducing lattice defects and other nonradiative pathways. 6 The emitted light originates from an intra-shell 4f transition within the Er ion. The sharp emission bands of the luminescence spectrum (<10 nm) do not change position with temperature. The spectral features are influenced by the ligand field that surrounds each Er center. For example, co-doping with oxygen produces an oxygen ligand field that yields a particular Si:Er spectrum. 7 Oxygen co-doping is also commonly done to enhance the luminescence intensity and to increase the solubility of the Er ions in silicon. 2,8

Erbium-doped silicon does not have a high external, luminescence quantum efficiency at room temperature. A nonradiative energy backtransfer pathway, which increases with temperature, has been found to compete with the radiative emission pathway. 6,9,10 Attempts to optimize the luminescence intensity of Si:Er have centered on maximizing the concentration of optically active Er and minimizing the amount of implantation defects through a variety of heat treatments.

Previous Work in Er-doped Amorphous Silicon

Although single crystal Si:Er has been the focus of many studies in recent times, Er-doped amorphous silicon (a-Si:Er) has been produced by various methods and has shown room-temperature luminescence at 1.54 $\mu$m. 11–14 Instead of the sharp luminescence peaks found in single crystal Si:Er, a-Si:Er typically has one broad peak that is shifted to slightly higher wavelengths. Because of the disordered atomic arrangement in a-Si, the oxygen ligand field for each Er center is likewise disordered, and the luminescence manifests an inhomogeneously broadened PL spectrum, not the characteristic sharp-line spectrum found in single crystal Si:Er. Since a-Si is a defective, glassy phase, it has a higher Er solubility limit than its crystalline counterpart. Nonetheless, the high defect
concentrations of amorphous material result in lower quantum efficiencies and lower PL intensities. Usually, a-Si is hydrogenated to passivate dangling bonds that act as light absorbers and nonradiative recombination centers. The hydrogen passivation usually improves the quantum efficiency.

Early studies demonstrated room temperature Er luminescence in Er/Si co-sputtered amorphous films without any additional anneals. Some papers have reported results on hydrogenated a-Si:Er as a function of post-deposition thermal treatments and codopant (e.g. O, N) concentration. Shin et al. implanted Er into a-Si and found a maximum in emission intensity after doing an anneal at a temperature of 300–400°C. However, they did not observe luminescence above 500°C. Zanatta et al. co-sputtered Er with hydrogenated a-Si and observed a maximum luminescence intensity following a 500°C anneal. These films were deposited in hydrogen atmospheres, but they did not undergo post-anneal hydrogenation.

**Erbium Incorporation and Defect Reduction by Forming Er-doped Polysilicon**

By crystallizing a-Si:Er into polysilicon (poly-Si:Er), one may incorporate metastable, high concentrations of Er through the crystallization process and, at the same time, reduce the defect concentration. Polysilicon, by nature, contains recombination centers such as grain boundaries and intragranular defects. However, it is a better electrical and optical material than a-Si and a more flexible material in terms of processing than single crystal silicon. For example, the carrier mobilities and optical transmission losses in poly-Si outperform those of amorphous silicon. Moreover, by using poly-Si:Er, one can fabricate structures where the light emitting material is not constrained to the substrate plane. Polysilicon can be deposited in multiple planes above the substrate without the constraint of epitaxy. Because poly-Si can be deposited in this multi-level fashion, one can conceivably incorporate poly-Si light emitting devices within dielectric contrast structures to enhance performance. For instance, using Si/SiO₂ resonant structures, one can enhance the spontaneous emission of a light emitting material or improve the photon capture efficiency of a detector.

Ion implantation is a common means of introducing Er into silicon. As mentioned earlier, oxygen is usually co-implanted to improve the luminescence. For low Er/O doses a post-implantation damage anneal is typically performed at 800–900°C for 30 min, and erbium concentrations above the thermodynamic solubility limit (~10¹⁶ cm⁻³) have been observed. Typical peak concentrations of optically active Er are in the range of 10¹⁸–10²⁰ cm⁻³. Erbium peak concentrations of 10²⁰ cm⁻³ can be achieved by (a) first amorphizing the silicon with a high-implantation Si and/or Er dose and then (b) recrystallizing it by solid phase epitaxy (SPE). Si:Er LEDs which exhibit room temperature luminescence have been fabricated by using this pre-amorphization/incorporation technique.

**EXPERIMENTAL PROCEDURE**

In our study amorphous films were deposited at 560°C by low-pressure chemical vapor deposition (LPCVD) on silicon wafers with a surface layer of thermal oxide of 1.8 μm thickness. Polysilicon films were deposited on the same substrates at 625°C. The LPCVD films were 0.2 μm thick and nominally undoped. Erbium and oxygen were implanted to a mid-film depth of 0.1 μm at peak concentrations of 5 x 10¹⁷ cm⁻³ and 2 x 10¹⁸ O cm⁻³. This sample had a standard post-anneal at 800°C for 30 min. The a-Si:Er, annealed at 575°C for 30 min, shows a single, broad peak. Annealing at 575°C for 18 h, followed by a RTA at 900°C for 20 sec, the film is crystallized into poly-Si. The similarity in PL spectra (indicated by arrows) for single crystal and poly-Si:Er show that the Er in the poly-Si is incorporated into the crystalline grains of silicon during the anneal.

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**Fig. 1. PL spectrum (T = 4.2 K) of (a) single crystal Si:Er, (b) high implant, crystallized poly-Si:Er, and (c) high implant, a-Si:Er. The single crystal specimen was implanted at 400 keV, 5 x 10¹⁷ Er cm⁻³ and 2 x 10¹⁸ O cm⁻³. This sample had a standard post-anneal at 800°C for 30 min. The a-Si:Er, annealed at 575°C for 30 min, shows a single, broad peak. Annealing at 575°C for 18 h, followed by a RTA at 900°C for 20 sec, the film is crystallized into poly-Si. The similarity in PL spectra (indicated by arrows) for single crystal and poly-Si:Er show that the Er in the poly-Si is incorporated into the crystalline grains of silicon during the anneal.**

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