Silicon light emitting diodes emitting over the 1.2–1.4 μm wavelength region in the extended optical communication band

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Here, we demonstrate bulk silicon light emitting diodes operating over the 1.2–1.35 μm range. This is achieved by the implantation of the rare earth thulium, incorporated in the trivalent Tm^{3+} state, into silicon p - n junctions. Light emitting diodes operating under forward bias have been obtained by codoping of boron to reduce the thermal quenching. Seven sharp lines are observed, corresponding to known internal Tm^{3+} transitions in the manifold from the $^3\text{H}_5$ to the $^3\text{H}_6$ ground states. This center, together with the basic 1.15 μm silicon emitters and Si:Er devices operating at 1.54 μm , now enables significant coverage of the extended (1.1–1.8 μm) optical communications band in silicon. © 2008 American Institute of Physics. [DOI: 10.1063/1.2916824]

The incorporation of rare-earth (RE) elements into III-V and silicon substrates is a promising contender for the development of optical sources. The RE partially filled inner 4f shell gives rise to sharp transitions, which are highly insensitive to the crystal host and temperature variations. For example, light emission at 1.54 μm , due to the incorporation of Er ions into III-V and Si substrates, were extensively investigated and light emitting devices demonstrated.^{1,2} Another RE also known to function as an optical center is the element thulium (Tm). Transitions between the trivalent Tm (Tm^{3+}) lowest excited states and the ground state can lead to emissions around 0.8, 1.2, and 1.9 μm .³ Here, we investigate the emission at wavelengths between 1.2 and 1.35 μm , the region of lowest dispersion in optical fibers and a required wavelength for several optical communication applications.

Light emission in III-V semiconductors (GaAs, GaInP, GaP, InP, and AlGaAs) incorporating Tm^{3+} has been previously reported.^{3–9} Photoluminescence (PL) spectroscopy at low temperatures was the main technique utilized to optically characterize these materials. Luminescence was observed around 0.8, 1.2, and 1.9 μm and attributed to transitions between the lowest Tm^{3+} crystal-field-split spin-orbit levels ($^3\text{F}_4$, $^3\text{H}_5$, and $^3\text{H}_4$) and the ground state ($^3\text{H}_6$), respectively. For the $^3\text{H}_5$ – $^3\text{H}_6$ transition, the main emission, present in most of the samples, was located around 1.233 μm , although small line shifts between emissions from different host crystals were also reported. Additional lines were also observed near the 1.211, 1.255, 1.278, 1.298, 1.312, and 1.326 μm regions. The only report of Tm^{3+} emission in crystalline silicon was by Pomrenke *et al.*³ $5 \times 10^{13} \text{ Tm cm}^{-2}$ at 390 keV was implanted into n - and p -type Si substrates followed by annealing at 850 °C for 15 min. Their PL measurements, performed at 6 K, showed a set of four relatively sharp but very weak lines, located in the region of 1.2–1.35 μm , superimposed on a very large broad background.

The dislocation engineered method in silicon was employed to fabricate efficient room temperature light emitting diodes operating at around 1.1 μm .¹⁰ In this approach, non-radiative recombination is minimized by the controlled introduction of dislocation loops to form energy barriers for carrier diffusion. This provides spatial confinement of the injected carriers, thus, enhancing the band-to-band recombination. Light emission at other wavelengths can also be achieved by combining the standard dislocation engineering technique with the introduction of optical centers, operating at specific wavelengths, in the device active region. For example, room temperature light emitting diodes operating at $\sim 1.5 \mu\text{m}$ have been fabricated, using this approach, by incorporation of Er (Refs. 11 and 12) and $\beta\text{-FeSi}_2$ (Ref. 11) between the depletion region edge and the dislocation loops array. In this letter, we report on the electroluminescence (EL) of dislocation engineered light emitting devices incorporating Tm ions in the active region.

Dislocation engineered light emitting devices doped with Tm were fabricated by implanting 400 keV Tm ions, at four different doses ranging from 10^{12} to $10^{15} \text{ Tm cm}^{-2}$, into a n -type Si [100] substrate ($2\text{--}7 \Omega \text{ cm}$) previously implanted with $10^{15} \text{ B cm}^{-2}$ at 30 keV. The boron implant, as well as providing the p -type doping to form the p - n junction, also introduced the dislocation loops. Samples were subsequently annealed in nitrogen ambient to electrically activate the dopants. Annealing temperatures ranged from 750 to 950 °C, for times up to 15 min.

EL and PL measurements were carried out at 80 K to characterize the devices. The devices were mounted in a continuous-flow liquid nitrogen cryostat placed in front of a conventional half-meter spectrometer. A liquid nitrogen cooled germanium p - i - n diode was used for detection of the luminescence. The EL measurements were performed under forward bias (current density of 1.25 A/cm^2) extracting the light through a window at the back of the samples. The device geometry is identical to those incorporating Er that were previously reported.¹² Current-voltage measurements were performed on all devices prior to the EL experiments and standard diode characteristics were observed with typical turn-on voltages of around 1 V. The PL experiments were

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FIG. 1. EL response, measured at 80 K, for devices implanted at different Tm doses and annealed at 850 °C for 15 min.

performed using an argon ion laser at an excitation wavelength of 514 nm.

Light emission consisting of seven lines in the characteristic region of 1.2–1.35 μm , attributed to the $^3\text{H}_5$ – $^3\text{H}_6$ transitions of Tm^{3+} , was observed from several diodes. The EL intensity showed a strong dependence on the Tm implanted dose and postimplant annealing conditions. Figure 1 shows the EL spectra from devices implanted at different doses and annealed at 850 °C for 15 min. The EL emission is more pronounced in devices implanted at the lower doses, with the sample implanted with $10^{13} \text{ Tm cm}^{-2}$ giving the maximum intensity. Seven clear emission lines can be observed at 1211.5, 1231.0, 1250.8, 1269.3, 1288.8, 1311.3,

FIG. 2. EL response, measured at 80 K, for devices implanted with $10^{13} \text{ Tm cm}^{-2}$ and annealed at (a) 850 °C for 1, 5 and, 15 min and (b) annealed at 750, 850, and 950 °C for 15 min.

FIG. 3. PL and EL spectra, measured at 80 K, from samples implanted with Tm and incorporating boron induced dislocation loops. Also shown is the PL spectrum of a sample implanted with Tm only. The Tm implant conditions were the same for all samples ($10^{13} \text{ Tm cm}^{-2}$ annealed at 850 °C for 15 min).

and 1326.0 nm (1.024, 1.007, 0.991, 0.977, 0.962, 0.946, and 0.935 eV, respectively) separated by around 16 meV. As the Tm implanted dose increases, the intensity of these lines decreases, being almost absent for devices implanted at $10^{15} \text{ Tm cm}^{-2}$. This is attributed to increased implant damage or precipitation of excess Tm above the solubility limits due to the higher doses.

Figure 2 shows the dependence of the Tm transitions as a function of annealing conditions—time and temperature. Figure 2(a) shows the EL measured from devices implanted with $10^{13} \text{ Tm cm}^{-2}$ and annealed at 850 °C for 1, 5, and 15 min. Figure 2(b) shows the EL from devices implanted at the same dose but annealed at 750, 850, and 950 °C for 15 min. The brightest EL is obtained after annealing at 850 °C for 15 min. No Tm^{3+} related emissions are observed from devices annealed at 950 °C. Intensity of Tm^{3+} emissions falling off with increasing anneal temperature has been observed in the GaAs:Tm system.³ It was suggested that residual impurities in the substrate may become more mobile as the annealing temperature increases and form complexes with the Tm^{3+} , thus, reducing the concentration of optically active Tm ions and quenching the luminescence.

Figure 3 shows the PL spectra of samples implanted with Tm, with and without boron induced dislocation loops. PL emission related to the Tm is only observed in the sample codoped with boron. This shows that the B doping, to form an engineered dislocation loop array, is essential for obtaining high efficiency, high temperature luminescence from the Tm center, as was previously observed for the incorporation of Er in silicon.^{11,12} The EL spectrum of a similar diode is also shown in Fig. 3. In the PL spectrum, eight lines are observed, compared to seven in the EL, due to the splitting of the line at 1288.8 nm into a resolved doublet with lines at 1283.9 and 1290.6 nm.

Table I lists the positions of the Tm^{3+} related emission from our silicon samples as well as the emission peaks ob-

TABLE I. Comparison of Tm^{3+} emission peaks observed on this work and previously reported emissions in Si, GaAs, and AlGaAs.

Si (nm)	Si ^a (nm)	GaAs ^a (nm)	GaAs ^b (nm)	AlGaAs ^a (nm)
1211.5		1211	1224	1220
1231.0	1233	1233	1233	1231
1250.8	1244	1250	1249	
		1256	1256	1255
			1260	
		1262	1261	1260
1269.3	1264			
	1278	1278	1278	
1283.8		1286	1285	1283
1290.6		1290		
		1300	1298	1297
1311.3		1312	1312	1311
1326.0		1326		

^aReference 3.^bReference 4.

served from the only previous study in silicon³ and from a number of III-V (Refs. 3 and 4) semiconductors that have the same tetrahedral symmetry. Comparison of our results with data from Ref. 3 shows that the four lines observed in their work are reproduced here—the slight discrepancy in line position is the result of the poor signal to noise in the earlier data, which were also superimposed on a much larger broad background. In our work, the silicon samples codoped with boron show additional lines, not previously observed in silicon, at 1211.5, 1283.8, 1290.6, 1311.3, and 1326.0 nm. These additional lines have all been reported in the PL of Tm doped GaAs and AlGaAs, as can be seen by comparison to the tabulated results, although some of the lines appear as resolved doublets in the lower temperature, higher resolution, GaAs and AlGaAs results.

As in the previous reports, we therefore attribute the observed emission in our samples to the $4f-4f$ intracenter transitions between the lowest Tm^{3+} crystal-field-split spin-orbit levels ($^3\text{H}_5$) and the ground state ($^3\text{H}_6$), which should

give a maximum of five transitions at low temperatures when only the lowest of the $^3\text{H}_5$ manifold states is occupied.⁴ The additional lines, also observed in the GaAs and AlGaAs systems, were attributed either to some distortion of the Tm^{3+} ion from the simple T_d site to a site of lower symmetry or the contribution of Tm^{3+} complexes. Given that Tm^{3+} complexes are unlikely to identically occur in silicon and GaAs, our results support the first explanation of reduced Tm^{3+} site symmetry.

In summary, we have shown that Tm implantation into silicon can be used to provide both EL and PL emissions in the 1.2–1.35 μm region of the extended optical communication band. The introduction of dislocation loops using B coimplantation is paramount in obtaining high efficiency high temperature operation. We anticipate that further optimization of the process could lead to the elimination of the remaining thermal quenching and room temperature operation, as was previously demonstrated in equivalent erbium based devices.^{11,12}

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