Relaxation of optically excited 4f electrons in Er-doped Ga$_x$In$_{1-x}$P

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Abstract

Luminescence and relaxation properties of optically excited 4f electrons in Er-doped Ga$_x$In$_{1-x}$P ($0 \leq x \leq 1$) have been investigated by time-resolved measurements of photoluminescence (PL) due to intra-4f shell transitions in Er$^{3+}$ ions at 4.2 K. For $x = 1$, the lifetime of Er-related emission falls in the sub-millisecond range. The lifetime of an emission line at 0.805 eV, which is observed throughout the entire range of $x$, decreases with increasing Ga content. These effects are explained by relaxation processes of excited Er ions which are perturbed by a crystal field around the ions. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Erbium; Ga$_x$In$_{1-x}$P; 4f electrons; Lifetime

1. Introduction

Er-doped III–V semiconductors attract increasing attention because they may have a great impact on optical communication systems operating at 1.5 μm, near the minimum of transmission loss in silica-based fibers [1]. The intra-4f shell transition from the first excited state ($^4$I$_{13/2}$) to the ground state ($^4$I$_{15/2}$) of Er$^{3+}$ ion results in emission at 1.5 μm. We have investigated Er-doped phosphorus-based III–V semiconductors such as InP and GaP grown by organometallic vapor-phase epitaxy (OMVPE) and found that characteristics of the Er-related luminescence depend strongly on the host material [2–6]. There have been limited studies made on Er-doped Ga$_x$In$_{1-x}$P (GIP: Er), although knowledge about the behavior of the Er-related luminescence in GIP provides a clue for understanding the mechanism of 4f-shell excitation and relaxation in Er-doped phosphorus-based III–V semiconductors [5,7,8].

In this paper, we report on luminescence and relaxation properties of optically excited 4f electrons in GIP: Er with Ga content varying between 0 and 1, which is investigated by time-resolved PL measurements.

2. Experimental

GIP: Er samples were grown coherently on GaP, GaAs, and InP substrates by OMVPE...
Er was introduced using Er(MeCp)$_3$ (tris(methylcyclopentadienyl)erbium) as an Er source. For time-resolved PL measurements at 4.2 K, the samples were directly immersed into liquid He. A pulsed dye laser operating at 385 nm, pumped by an excimer laser, was used as a photoexcitation source. The luminescence was detected through a 0.32 m monochromator using a GaInAs photomultiplier tube. The PL decay time was measured with a digital oscilloscope.

3. Results and discussion

3.1. Emission lifetime in Er-doped GaP

For Er-doped GaP (GaP: Er), Er-related PL spectrum consists of numerous narrow emission lines [5,6]. Theoretically, if an Er$^{3+}$ ion behaves as a simple ion placed in a crystal field of cubic symmetry, $T_d$, the ground state splits into five states ($I_6$, $I_7$ and $3I_8$), and the first excited state into five states ($2I_6$, $I_7$ and $2I_8$) [9]. For an Er$^{3+}$ ion involved in a complex with a defect, however, a further splitting of the $I_8$ state into two Kramer states occurs due to a crystal field of lower than cubic symmetry, and the corresponding transitions result in eight zero-phonon lines [9]. The appearance of more than eight emission lines in the low-temperature PL spectrum suggests the coexistence of various Er-related luminescence centers with different atom configurations.

Time-resolved PL measurements have been performed on several emission lines in GaP : Er at 4.2 K. A single exponential PL decay is obtained for each emission line. The decay time falls in the sub-millisecond range with values shown in Fig. 1. In the figure, letters from “a” to “i” are identical with those in Ref. [6]. The emission lifetimes are comparable to those reported previously for Er-doped GaAs and InP [10–12]. The variation in lifetimes obtained for GaP : Er reflects the difference in atom configurations between Er-related luminescence centers, since the crystal field around Er ions influences energy intervals and transition probabilities between the 4f states. The intensity for lines b, c, and d is approximately inversely proportional to the lifetime. This indicates that the lines originate from the same luminescence center. This conclusion is supported by the excitation wavelength dependence of the intensity for both the above- and below-band gap excitation conditions [6].

3.2. Emission lifetime in Er-doped Ga$_x$In$_{1-x}$P

Er-related luminescence has been observed in GIP : Er [5,8]. The 4.2 K PL spectra of the GIP : Er samples grown on GaP with $x$ of 0.996 and 0.99 are exactly the same as that of GaP : Er, exhibiting extremely narrow emission lines. The PL intensity gradually increases with increasing Ga content, i.e. increasing band gap. Similar effect is observed in GIP : Er grown on InP. For GIP : Er ($x = 0.51$ and $0.66$) grown on GaAs, on the other hand, three emission lines at 0.8020, 0.8045 and 0.8087 eV are observed. Their relative intensities are dependent on Ga content.

We have investigated an Er-related emission line at 0.805 eV commonly observed in GIP : Er. As shown in Fig. 2, the lifetime decreases with increasing Ga content from 1.5 ms at $x = 0$ to 0.7 ms at $x = 1$. This behavior agrees well with the increase in PL intensity for higher Ga content [5]. This enhancement in probability of the intra-4f shell transitions of Er$^{3+}$ is due to the increased perturbation of wave functions of Er by its first- or
Fig. 2. Ga content dependence of lifetime of the emission line at 0.805 eV.

second-nearest-neighbor atoms, because the lattice constant of host material decreases with increasing $x$.

4. Conclusion

We have investigated relaxation processes of optically excited 4f electrons of Er ions in Ga$_x$In$_{1-x}$P ($0 \leq x \leq 1$) by time-resolved PL measurements at 4.2 K. For GaP : Er, Er-related PL spectrum consists of numerous extremely narrow emission lines. It indicates the coexistence of various Er-related luminescence centers with different atom configurations. The emission lifetime falls in the sub-millisecond range. The comparison of the lifetime with the PL intensity suggests that a few emission lines originate from the same luminescence center. The lifetime of emission line at 0.805 eV, which is observed in Er-doped Ga$_x$In$_{1-x}$P throughout the entire range of $x$, decreases with increasing Ga content. This enhancement in probability of the intra-4f shell transitions of Er$^{3+}$ is due to effective electronic coupling of 4f states of Er ions with the external environment, because the lattice constant of host material decreases with increasing $x$.

Acknowledgements

The authors would like to thank Tri Chemical Laboratory Inc. for the Er source. The work was supported in part by Grant-in-Aids for Scientific Research of Priority Areas, Spin Controlled Semiconductor Nanostructures No. 11125209, for Scientific Research (B) No. 11450119, and for Exploration Research No. 10875070 from the Ministry of Education, Science, Sports and Culture.

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