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Ultrafast carrier trapping in Er-doped and Er,O-codoped GaAs revealed by pump and probe technique

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Abstract

Dynamics of photoexcited carriers in Er-doped GaAs (GaAs:Er) and Er,O-codoped GaAs (GaAs:Er,O) have been systematically investigated by means of a pump and probe technique. A characteristic ps-scale relaxation was clearly observed in transient reflectance (dR/R) and transmission (dT/T) curves. The relaxation was due to the trapping of photoexcited carriers by an Er-related trap, which was closely related to efficiency of Er^{3+} luminescence.

Keywords: GaAs; Erbium; Carrier trapping; Ultrafast phenomena; Pump and probe technique

1. Introduction

Much attention has been paid to rare-earth (RE) doped semiconductors as a promising new class of materials that emit light from the RE 4f shell by means of electrical injection. The intra-4f shell transitions of RE ions give rise to sharp emission lines whose wavelengths are largely independent of both the host materials and temperature. This stability occurs because the filled outer 5s and 5p electron shells screen transitions within the inner 4f electron shell from the interaction with the host. The intra-4f shell transitions from the first excited state ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) of Er^{3+} ions at around 1.5 μm are of special interest because the wavelength matches the minimum loss region of silica fibers used in optical communications.

We have intensively investigated organometallic vapor phase epitaxy (OMVPE) and luminescence properties of Er-doped III–V semiconductors [1]. In Er,O-codoped GaAs (GaAs:Er,O), the Er-related photoluminescence (PL) spectrum was dominated by sharp emission lines under host-excited conditions at a low temperature [2]. The Er center has been identified as an Er atom located at the Ga sub-lattice with two adjacent O atoms (hereafter referred as Er–2O) together with two As atoms [3]. Recently, we have fabricated GaAs:Er,O homostructure and GaInP/GaAs:Er,O/GaInP double heterostructure (DH) light emitting diodes (LEDs) by OMVPE and successfully observed 1.5 μm electroluminescence (EL) due to an Er-2O center under forward bias at room temperature [4–6]. The dependence of the EL intensity on the injection current density indicated extremely large excitation cross-section of Er ions by current injection ($1–2\times10^{-15}$ cm^2) in the LEDs [4]. However, the Er excitation cross-section decreased with increasing active layer thickness in the DH LEDs, suggesting reduced diffusion lengths of injected carriers in a GaAs:Er,O active layer [7].

In this article, we investigated nonequilibrium carrier dynamics in OMVPE-grown GaAs:Er,O as well as Er-doped GaAs (GaAs:Er), which was revealed by a pump and probe technique.

2. Experimental

2.1. Sample preparation

The samples were grown on (0 0 1) semi-insulating GaAs substrates by low-pressure OMVPE. The details of sample preparation were previously described [4].

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For pump and probe transmission measurements, the samples with the thickness of 1 μm were grown on a 0.15 μm GaInP etch-stop layer, followed by chemical etching of the GaAs substrate with H_3PO_4:H_2O_2:H_2O = 3:4:4. The Er concentration of the samples was less than $10^{17}\,cm^{-3}$, which was below the detection limit of secondary ion mass spectroscopy (SIMS) measurements.

2.2. Pump and probe measurements

Dynamics of nonequilibrium carriers in GaAs:Er,O and GaAs:Er have been studied directly by pump and probe reflection and transmission measurements at room temperature. A mode-locked Ti:sapphire laser was used for fs pulses with a pulse width of about 100 fs, a center wavelength of about 840 nm, and a repetition rate of 82 MHz. Optical pulses from the laser were divided to two beams; the first beam excited the sample as a pump pulse, and the second beam was used as a probe pulse. The power of the pump and probe pulses were fixed at 30 and 1 mW, respectively. The pump and probe pulses polarized perpendicularly were focused with a diameter of about 10 μm on the sample surface. The transient of reflectivity and transmittance was monitored as a function of the relative time delay between pump and probe pulses.

3. Results and discussion

3.1. Time-resolved reflectivity

Fig. 1 shows time-resolved reflectivity in two GaAs:Er,O samples (high-concentration sample and low-concentration sample). Er and O concentrations are 9×10^{18} and $3\times10^{18}\,cm^{-3}$ in the high-concentration sample, and 8×10^{17} and $9\times10^{17}\,cm^{-3}$ in the low-concentration sample, respectively. The results in nominally undoped GaAs and GaAs:Er (Er concentration: $1\times10^{18}\,cm^{-3}$) are also shown for comparison. Time-resolved reflectivity in the undoped GaAs is governed by two relaxation components: a fast component (not shown in the figure) and a slow component. They correspond to the carrier transit lifetime from high-energy level to band edge, and the carrier recombination lifetime of approximately 1 ns, respectively.

On the other hand, the reflectivity of GaAs:Er,O reveals an abrupt increase in amplitude, followed by a steep decrease down to negative in less than 1 ps and then a gradual increase in more than 100 ps [8]. The steep decrease is due to bandgap renormalization produced by a large number of nonequilibrium carriers. The recovery from the negative minimum in the time-resolved reflectivity depends strongly on Er concentration. In the high-concentration sample, a rapid recovery is clearly observed at the initial stage.

We have investigated quantitatively the initial recovery observed in GaAs:Er,O. The experimental data were changed to be absolute values and subtracted by a slow background due to carrier recombination between conduction band and valence band. It has been found that there are two components, fast component τ_{fast} at the initial and then slow component τ_{slow}. The Er concentration dependence of τ_{fast} is shown by closed circles in Fig. 2. Experimental results for other samples not cited in this article are also plotted together in the figure. The recovery time is almost inversely proportional to Er concentration.

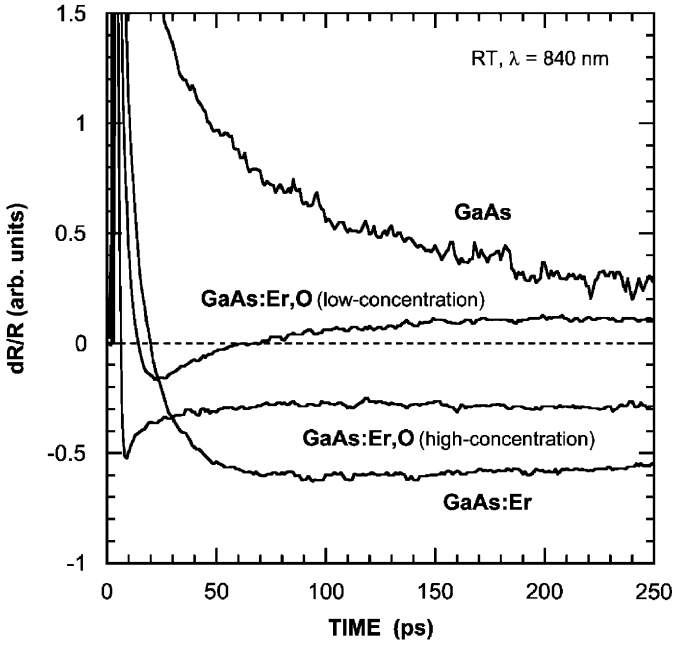

Fig. 1. Time-resolved reflectivity for GaAs:Er,O and GaAs:Er. The result for undoped GaAs is also shown for comparison.

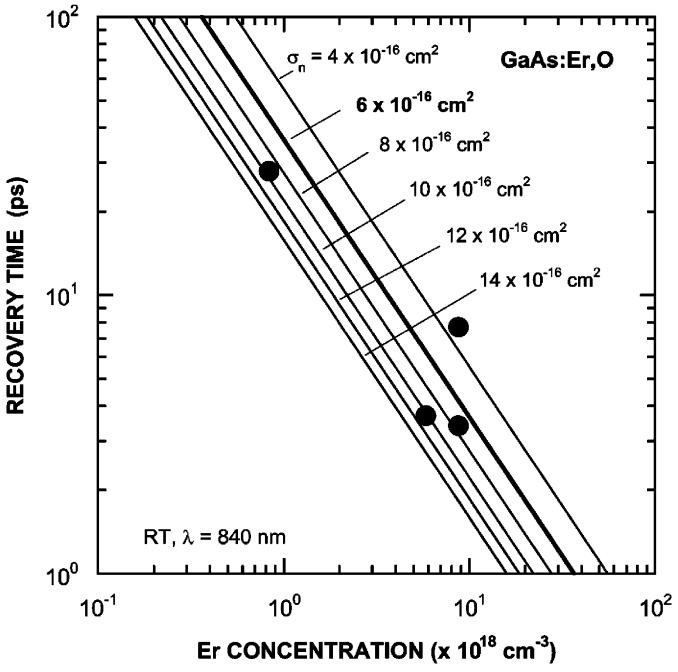

Fig. 2. Er concentration dependence of τ_{fast} in GaAs:Er,O. The results calculated using Eq. (1) are shown by solid lines.