PACS numbers: 42.55.Px; 42.60.Lh
DOI: 10.1070/QE2001v031n11ABEH002083

Stimulated emission from GaAs : Er, O at 1538 nm

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***Abstract*. Spontaneous emission and optical gain are studied in MOCVD-grown epitaxial layers of GaAs co-doped with erbium and oxygen. Optimal growth conditions are used to obtain the high erbium concentrations up to 8×10^{18} cm^{-3}. The measurements by the Shaklee – Leheny method revealed the optical gain ~ 45 cm^{-1} at rather low pump intensity ~ 0.1 kW cm^{-2} at 77 K.**

Keywords: *semiconductors with rare-earth ions, stimulated emission, optical gain.*

Semiconductor structures doped with rare-earth ions attract great interest from the point of view of their possible laser applications. The fabrication of erbium-doped semiconductor sources of spontaneous IR radiation at ~ 1.54 μm was reported in Refs [1, 2]. These sources are spectrally matched to erbium-doped fibre amplifiers (EDFA), which operate in the spectral window that is most convenient for the long-distance fibreoptic communication.

From the point of view of solid-state physics, these structures represent an interesting case of the successive energy transfer from an electric subsystem to exciton traps and then to the inner 4f shell of an impurity Er^{3+} ion. The latter finds itself in an excited state from which it can emit photons upon transitions inside the shell. Unlike many other emitting centres in semiconductors, the photon energy in rare-earth ions is almost independent of temperature, resulting in a stable matching of the emission wavelength with a communication line and a photodetector.

Among the best candidates for applications in IR radiation sources, Si or GaAs semiconductors co-doped with erbium and oxygen stand separately. Co-doping with erbium and oxygen results in the formation of Er – 2O centres [3 – 5]. It was shown in papers [3, 5, 6] that the intensity of photoluminescence was substantially higher when an epitaxial GaAs : Er, O layer was grown at the optimal temperature and co-doped under conditions favouring the formation of Er – 2O centres. In this case, the maximum concentration of these centres was as high as $\sim 8 \times 10^{18}$ cm^{-3}. This fact is important for obtaining a suf-ficient optical gain upon the inverse population of emitting centres.

Another important problem concerns the nonradiative depletion of the excited states of the Er ion. This mechanism, which dominates at higher temperatures, is probably the Auger recombination involving free carriers [7, 8].

In this paper, we studied the spectral properties of GaAs: :Er, O from the point of view of possible laser applications. By measuring the optical gain, we managed to observe stimulated emission. To our knowledge, this is the first experimental observation of stimulated emission from GaAs doped with rare-earth ions.

We grew epitaxial layers of GaAs doped with erbium on a (001) GaAs substrate by the MOCVD method at low pressure. The epitaxial layers were grown from TEGa and TBAs. For doping, $Er(C_{11}H_{19}O_2)_3$ was used which contains six oxygen atoms per molecule with one erbium atom. Therefore, this compound provided co-doping of the semiconductor with erbium and oxygen ions. However, it was pointed out in Refs [3, 5] that to optimise doping, it is necessary to introduce oxygen additionally into a gas flow.

The high concentration of erbium (8×10^{18} cm^{-3}) was achieved at the oxygen content sufficient for the formation of luminescent Er – O centres. It was shown in Ref. [6] that there exists the threshold growth temperature (of about 585 °C) above which the formation of Er – O centres is strongly suppressed. The growth was performed at 543 °C. We prepared two structures for experimental studies, whose parameters are presented in Table 1.

Table 1. Parameters of epitaxial structures used in this paper (GaAs : Er, O single layers on a GaAs substrate).

Structure number	Thickness of a Er-doped layer/nm	Concentration* of Er/cm^{-3}
4408	160	8×10^{18}
4215	770	7×10^{18}

*Mass-spectroscopy data for secondary ions.

Photoluminescence was studied at 4.2 and 77 K upon excitation by a cw Ar laser with power of up to 1 kW cm^{-2}. The emission of samples was analysed with a 0.91-m grating monochromator and detected with a germanium liquid-nitrogen-cooled pin-photodiode using a modulator and a lock-in amplifier. The spectral resolution was varied from 0.04 to 0.3 nm.

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Received 29 August 2001
Kvantovaya Elektronika **31** (11) 962 – 964 (2001)
Translated by M N Sapozhnikov

Because the width of the most intense spontaneous emission line is very small (~ 0.04 nm at 4.2 K), the laser cavity should be tuned to this line very precisely. To reduce the mode interval to this linewidth, the cavity length should exceed ~ 1 cm. We measured the optical gain by the Shaklee – Leheny method [9], which does not require a cavity. Amplified spontaneous emission (ASE) was measured at one cleaved face of a sample.

A light spot represented a strip whose length on a sample was varied from zero to L. The ASE intensity depends on the strip length as

$$P_{ase}(L) = P_0[\exp(gL) - 1], \quad (1)$$

where P_0 is a constant and g is the mode gain. When the gain is absent, the spontaneous emission intensity increases with L linearly because the excited volume increases.

Note that expression (1) gives a linear increase ($P_{ase} \sim gL$) for a weak amplification as well. Therefore, it is difficult to identify weak ASE, which can be confused with usual spontaneous emission. ASE can be identified by fitting the experimental dependence of the emission intensity by expression (1) if the experimental dependence differs from a linear function.

Another methodical difficulty is that the edge of the light spot should be sharp. If the spot edge is blurred, its nonrectangular shape will affect the dependence of the ASE intensity on L. This is important upon measuring a high gain when small lengths L are required. In our case, the expected gain is small, so that the initial part of the dependence $P_{ase}(L)$ is not used.

We pumped samples by a cw argon laser at 515 nm. The length of the light spot was up to ~ 1 mm and its width was 0.2 mm, the sample size being 5 mm. The gain was measured at 77 K.

The narrow emission lines of erbium ions were observed in the spectral range from 1538 to 1650 nm, approximately 80% of the total power being emitted in the most intense 1538.1-nm line (Fig. 1). Usually, this power increases sublinearly with the pump power, indicating the tendency to saturation caused by the population of the upper level of the Er ion. The intensity of emission at 1538 nm measured from the sample end is a sum of P_{ase} and background spontaneous photoluminescence P^* caused by pumping by scattered radiation. We measured P^* as a signal that was observed when L approached zero and subtracted this signal from the intensity being measured. The remaining intensity was assumed equal to P_{ase}, and this quantity is plotted as a function of the strip length L (Fig. 2). The curves are shown for samples from two plates for the maximum pump intensity. They were approximately calculated by expression (1) using the gain as a fitting parameter. The solid curves correspond to $g = 8$ cm^{-1} in sample No 4408 and $g = 45$ cm^{-1} in sample No 4215. For a lower pump intensity, the dependence was more close to linear one, which means that the gain was negligible. At greater lengths L, the intensity did not increase, probably because of the gain saturation.

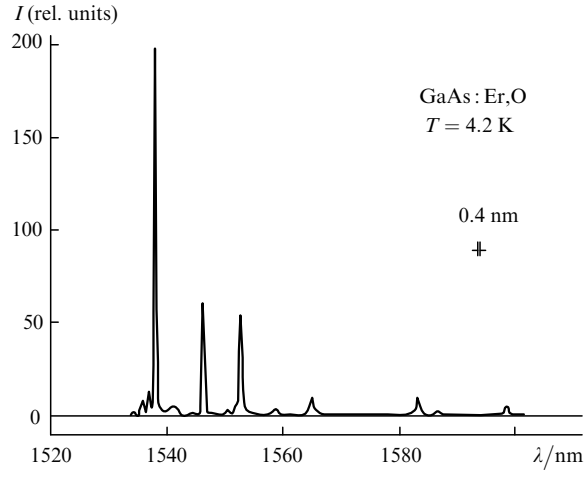

Figure 1. Spontaneous emission spectrum of Er – 2O centres in GaAs excited at 515 nm by a cw argon laser at 4.2 K.

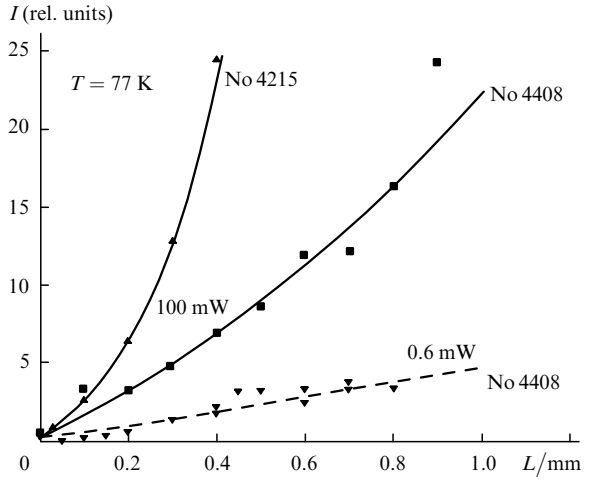

Figure 2. Dependences of the ASE intensity on the length of the illuminated strip on a sample at 77 K upon excitation by a cw argon laser at 515 nm with a total pump power of 100 mW (solid curves; the gain $g = 45$ and 8 cm^{-1} for samples Nos 4215 and 4408, respectively) and with a total pump power of 0.6 mW (dashed curve).

Therefore, we have observed for the first time stimulated emission from GaAs : Er, O at 77 K for the pump intensity above 0.1 kW cm^{-2}. The mode gain of about 45 cm^{-1} was obtained at the length of the illuminated strip up to 0.5 mm. The inversion threshold was exceeded at the pump intensity of ~ 0.1 kW cm^{-2}. The difference between the two samples can be related to the thickness of the GaAs layer doped with erbium, which is greater for sample No 4215 than for sample No 4408. Fore this reason, sample No 4215 exhibits a higher mode gain.

The inversion threshold in our samples proved to be very low compared to other erbium-doped semiconductors. To obtain stimulated emission in nanocrystal silicon fibres doped with erbium, the authors of paper [10] used the pump intensity up to 7 – 10 MW cm^{-2}. Stimulated emission was also observed in amorphous erbium-doped Si upon intense 200-kW cm^{-2} pumping [11]. The higher thresholds observed in these experiments can be explained by a higher concentration of erbium in nanocrystal Si ($\sim 10^{20}$ cm^{-3}) and in amorphous Si ($\sim 2.5 \times 10^{20}$ cm^{-3}), as well as by the facts that pump pulses were short (compared to the upper-state lifetime of the Er ion) and the experiments were performed at room temperature.

Note in conclusion that the 1538-nm photoluminescence band of GaAs co-doped with Er and O proved to be very

narrow. The optical gain of $\sim 45\ cm^{-1}$ was obtained at 77 K upon excitation by a cw argon laser with an intensity of about 0.1 kW cm^{-2}. Therefore, stimulated emission was achieved at least at low temperature. This means that the Auger mechanism of deactivation of Er – 2O centres does not prevent the production of population inversion in these centres.

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