Observation of enhanced photoluminescence in erbium-doped semiconductor microdisk resonator

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(Received 24 October 1994; accepted for publication 10 March 1995)

We report experimental results from an erbium-doped gallium phosphide microdisk resonator pumped by a Ti-sapphire laser at 980 nm. Fabrication and characterization of the microdisk resonator are discussed. Enhanced Er^{+3} intra-4f-shell photoluminescence was observed in the microdisk resonator due to microcavity effect and compared to a thin film sample. At low pumping power intensity, the photoluminescence from erbium-doped gallium phosphide microdisks is an order stronger than that from a thin film sample. © *1995 American Institute of Physics.*

Recently, rare-earth doped semiconductors have attracted much attention due to the sharp and strong intra-4f-shell luminescence from the rare-earth centers.[1,2] The erbium-doped (Er-doped) semiconductors are of particular interest, because its strong emission at 1.54 μm coincides with the minimum transmission loss of the silica-based optical fibers. Emission from different types of Er-doped semiconductors, such as Er-doped InP,[3] GaAs,[4] Si,[5,6] AlGaAs,[7] and GaP[8] has been demonstrated and studied with optical excitation. For most Er-doped semiconductors, the luminescence intensity decreases by more than two orders of magnitude as the temperature increases from 10 K to room temperature.¬ However,¬ Wang¬ and¬ Wessels[8] recently demonstrated that the emission intensity from Er-doped GaP is only weakly temperature dependent and strong emission from Er centers was observed at room temperature. This observation indicates that Er-doped GaP is potentially promising to be an optical material for light-emitting or lasing devices operating at 1.54 μm at room temperature.

In order to asses further the feasibility of using Er-doped GaP in a lasing resonator, microcavity structures were chosen for their promise for realizing low-threshold light-emitting or lasing devices. Among microcavity structures, microdisk resonators in different material systems with optical pumping have been studied extensively.[9–11] The thin disk resonator supports optical modes in the form of a whispering gallery mode where photons skim around the disk circumference being continually totally reflected.[12] Due to the high contrast of refractive indices between the thin semiconductor disk ($n=3.4$) and the surrounding low index medium, e.g., air ($n=1$), the optical mode is strongly confined inside the disk and coupled to the active medium.[13]

Because of its enhanced optical confinement and strong coupling with the active material, the microdisk resonator is of particular interest for us to study Er-doped semiconductors as lasing materials. Although strong luminescence have been observed from Er-doped GaP thin film material, there has been no study of the luminescence from a resonating structure in this material system. In this letter we demonstrate, for the first time, the fabrication of Er-doped GaP microdisk resonators, and compare the photoluminescence from the microdisk resonator and thin film of Er-doped GaP. The cavity effect on the luminescence from Er-doped GaP microdisk resonators was observed.

The structure for the Er-doped GaP microdisk resonator consists of a pedestal layer and a disk layer as shown in Fig. 1. The AlGaP pedestal layer was grown by gas source molecular beam epitaxy (GSMBE) and the Er-doped GaP disk layer was grown by atmospheric pressure metalorganic vapor phase epitaxy (MOVPE). Prior to the growth, the (100) GaP substrate was first chemically etched and cleaned, and then rinsed with de-ionized water. After oxide desorption, a thin GaP buffer layer (200–300 nm) was grown on the substrate followed by a 0.9 μm thick $Al_{0.6}Ga_{0.4}P$ pedestal layer using GSMBE with elemental Al, Ga, and cracked phosphine. Then another thin layer of GaP with several hundred angstroms was deposited on top of the AlGaP pedestal layer to prevent oxidation. The Er-doped GaP microdisk layer with 0.2 μm in thickness was then grown by MOVPE on top of the pedestal layer. Trimethylgallium (TMGa) and phosphine (PH3, 10% in hydrogen) were used as reactants. Palladium diffused H_2 was used as the carrier gas. The microdisk layer

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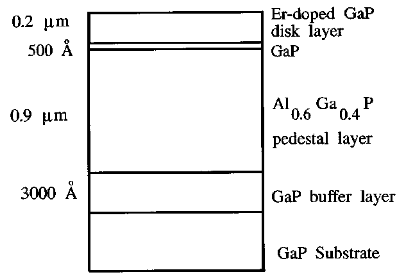


FIG. 1. The schematic of the Er-doped GaP microdisk layer structure, mainly consisting of an AlGaP pedestal layer and an Er-doped GaP disk layer.

was doped with erbium during growth by sublimating tris-tetramethylheptanedionate erbium $[Er(thd)_3]$ and transporting the vapor to the reaction zone with H_2 gas. The doping concentration of erbium is approximately 10^{17}–10^{18} cm^{-3}.

A standard photolithographic technique was used to fabricate the Er-doped GaP microdisk resonator with a 10–20 μm diameter. The circular disks were patterned using an AZ-1350J photoresist. Reactive ion etching (RIE) was then used to vertically etch ($\sim$0.5 μm) into the pedestal layer to form the cylinders. In RIE, we used a gas mixture of methane, chlorine, and argon with a ratio of 4:5:9 and an etching speed of 40 nm per minute. After the cylinders were formed, a highly selective hydrofluoric acid (HF) etchant was then used to etch the remaining $Al_{0.6}Ga_{0.4}P$ pedestal layer horizontally to form a supporting pillar. Figure 2 shows a scanning electron micrograph of the side view of an Er-doped GaP microdisk resonator with 10 μm diameter.

The emission of the Er-doped GaP microdisk resonator was analyzed by optical excitation using a Ti-sapphire laser. The Ti-sapphire laser was tuned to 980 nm with a birefringent plate, and modulated by an acousto-optic modulator. The peak pumping power was varied using neutral density filters. The pump laser beam was then focused to a spot size covering the entire area of the microdisk structure via an objective lens. The microdisk samples were cooled down to liquid-nitrogen temperature using a MMR cryogenic Joule–Thompson refrigerator. The luminescence scattered out from the top surface of the microdisk resonator was collected by the objective lens and dispersed by an optical grating spectrometer. The luminescence was then detected by a liquid-nitrogen-cooled germanium detector using lock-in technique. The photoluminescence of a planar Er-doped GaP thin film sample, which microdisk resonators were fabricated from, was also examined using the same method to study the microdisk effects.

In Fig. 3, we show the emission spectra at 1.54 μm from a planar Er-doped GaP thin film sample (dashed line) and from an Er-doped GaP microdisk resonator with 20 μm in diameter (solid line). Both samples were pumped with the same peak pumping power ($\sim$1.6 mW), where the pumping power intensity was about 520 W/cm^2, and the diameter of the pump laser was maintained around the diameter of the microdisk, i.e., 20 μm. From this particular pumping power, peak emission power of the Er-doped GaP microdisk P_{disk} is enhanced about three times higher than that of Er-doped GaP thin film sample P_{film}. The pump laser was modulated by the acousto-optic modulator to produce 10 μs pump pulse width with an ON/OFF ratio of 1:10 throughout the experiment. The 10 μs pump pulse width allows erbium ion centers to be fully excited, since it is longer than the 0.5 μs transition time for the 980 nm transition of an erbium ion in semiconductors.[7] From similar microdisk structures, we found that the thermal time constant is longer than the pump pulse spacing used in our experiment, i.e., 100 μs. Thus we note that a 1.6 mW beam chopped with 10% duty cycle heats the microdisk less than a 0.16 mW beam steadily illuminating the microdisk. The 1:10 pump chopping reduces average pumping power and thermal heating effect while maintaining the same peak pumping power.

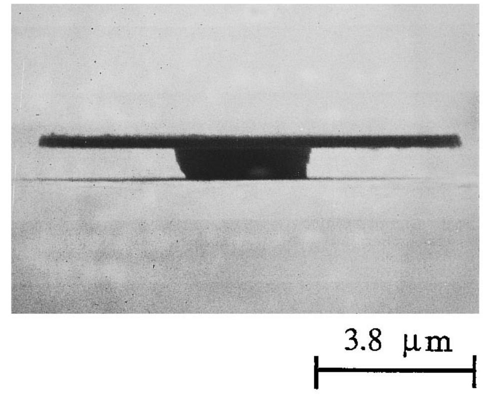


FIG. 2. The scanning electron microscope image of the side view of an Er-doped GaP microdisk resonator with 10 μm diameter.

We have measured P_{disk} and P_{film} as a function of the pump intensity I_p. The dependence of P_{disk} and P_{film} on I_p are shown in Fig. 4(a). In Fig. 4(b) we plot the dependence of the ratio $P_{\text{disk}}/P_{\text{film}}$ on pump intensity I_p. The figure shows that as the pumping intensity decreases below 100 W/cm^2, the ratio $P_{\text{disk}}/P_{\text{film}}$, which represents the cavity enhancement of the emission, increases steeply. At such low

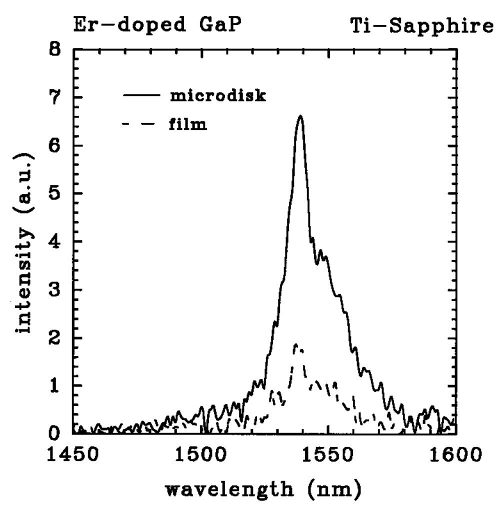
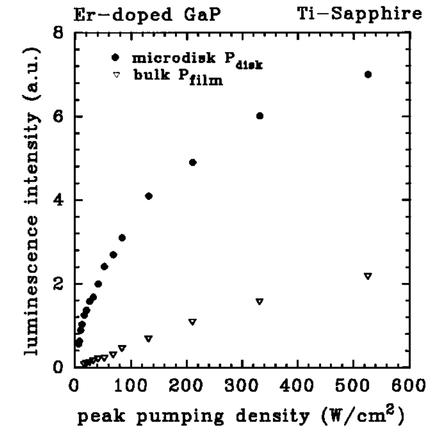
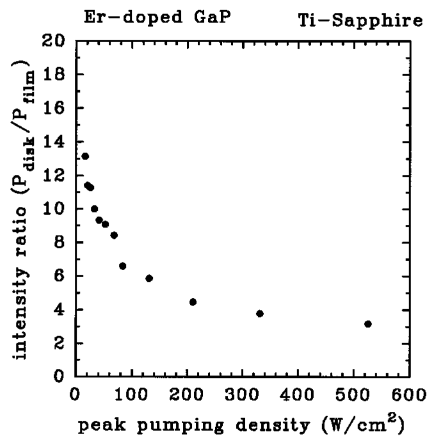


FIG. 3. Photoluminescence of an Er-doped GaP microdisk resonator given by the solid line, and the spectrum of an Er-doped GaP planar thin film sample given by the dashed line. Both measurements were obtained at the same peak pumping power and pumping intensity.



(a)



(b)

FIG. 4. (a) The emission power of the Er-doped GaP microdisk resonator P_{disk} (shown in solid circles) and the thin film sample P_{film} (shown in triangles) vs the pumping intensity, respectively. (b) The ratios between emission power of the Er-doped GaP microdisk resonator P_{disk} and the planar thin film sample P_{film} vs various pumping intensity.

pumping intensity the peak pumping power is below 0.3 mW, and the average pumping power is lower than 0.03 mW (30 μW). We note that under such low pumping condition the thermal heating effect is negligible, and the enhancement of the photoluminescence from the Er-doped GaP microdisk resonator is due to the strong confinement of the optical mode inside the microdisk resonator. Thus the observed emission enhancement is mainly due to the cavity effect. As the pump intensity increases the emission ratio decreases and becomes saturated. The reduction of the emission enhancement at high pumping intensity is probably due to the thermal heating effect.

The increase in the emission intensity ratio at low pumping level may be attributed to the fact that high Q cavity can store photons leading to an enhancement of the light intensity in the cavity. The enhancement of the light intensity in the cavity subsequently causes more photons to be scattered out from the top of the disk. It also causes more excited ions to decay via stimulated emission. A detailed model is currently being studied to further understand the phenomena.

In summary, the Er-doped GaP microdisk resonator has been fabricated, and its emission intensity was studied as a function of peak pumping intensity. Enhanced emission due to the microcavity effect was observed from the Er-doped GaP microdisk resonator compared to the bulk sample. At low pumping intensity, the emission from Er-doped GaP microdisks can be an order stronger than that from a planar thin film sample.

This work was supported in part by the National Science Foundation Ceramics and Electronic Materials Program under Grant No. DMR-9302357. Use of MRL Central Facilities supported by National Science Foundation, at the Materials Research Center of Northwestern University, under Award No. DMR-9120521 is acknowledged. Work at University of California San Diego is supported by National Science Foundation Grant No. DMR-9202692.

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