Enhanced photoluminescence by resonant absorption in Er-doped SiO_2/Si microcavities

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Si/SiO_2 Fabry–Perot microcavities with an Er-implanted SiO_2 active region resonant at the Er excitation wavelength of 980 nm have been realized. Room-temperature photoluminescence measurements reveal that the Er luminescence intensity increases by a factor of 28 as compared to a structure without cavity enhancement. We show that the experimental enhancement of the luminescence intensity agrees with theory if optical absorption of the 980 nm light in the Si layers of the cavity and reduced mirror reflectivities are taken into account.

The spontaneous emission characteristics in condensed matter structures can be changed in microcavity structures which were first proposed by Purcell in 1946.[1] Studies of spontaneous emission from Er-doped Si/SiO_2 microcavities[2,3] have demonstrated changes in the emission intensity, the spectral purity, and the emission lifetime. The microcavities were grown on Si substrates and consist of a Si/SiO_2 distributed Bragg reflector (DBR), a SiO_2 active region, and a Si/SiO_2 top DBR. The center SiO_2 region is doped with the rare-earth Er incorporated by ion implantation and subsequent annealing, which yields optically active Er atoms in SiO_2.[4] The alteration of the spontaneous emission properties has also been observed in other material systems including semiconductors[5–8] and dyes.[9] Although Purcell[1] predicted large spontaneous lifetime changes, the experimental lifetimes in planar microcavities do not change dramatically[3] due to many unaltered optical modes orthogonal to the cavity mode. However, the spontaneous emission *intensity* along the cavity axis and the *spectral purity* of the emission can be changed drastically.[2,3]

In this letter we demonstrate for the first time that *absorption* properties of an optically active medium can be changed drastically by a microcavity. Er-implanted SiO_2 is used as the optically active medium. SiO_2:Er has an absorption band at 980 nm and an emission band at 1.55 μm due to $4f$ intra-atomic transitions of Er^{3+} ions. The Fabry–Perot cavity is designed to be resonant with the 980 nm absorption band of SiO_2:Er. We demonstrate that the luminescence efficiency of the cavity structure is much higher as compared to a no-cavity structure, while the spectral features of the active SiO_2:Er *emission* are unaltered.

A schematic illustration of the experimental photoluminescence setup of the microcavity is shown in Fig. 1. The latter was grown on a Si substrate and consists of 4 pairs of a SiO_2/Si (1700 Å/730 Å) distributed Bragg reflector (DBR), the Er-doped SiO_2 (3400 Å) active region, and 2 1/2 pairs of a Si/SiO_2 (730 Å/1700 Å) DBR. The thickness of the active region is half the 980 nm absorption wavelength of Er divided by the refractive index of SiO_2. The calculated reflectivities of the bottom and top DBR are 99.8% and 98.5%, respectively. The growth conditions, the Er implantation dose, and the post-implantation annealing conditions were reported previously.[2–4] A 100 mW 980 nm semiconductor laser (Spectra Diode Labs) was used as an excitation source. The angle between the optical excitation and the optical axis of the cavity Θ can be systematically varied, as indicated in Fig. 1. A Fourier-transform infrared spectrometer was used as an optical detection system. Additional reflectivity measurements of the bottom DBR and the microcavity were carried out using a tungsten halogen incandescent lamp and an optical spectrum analyzer (Anritsu). A silver mirror served as a reflectivity standard. The reflectivities were measured at an incident angle of 9.5°. The top mirror of the cavity was etched off to evaluate the luminescence enhancement of the microcavity structure. Buffered oxide etchant was used to etch SiO_2 (rate 100 Å/min) and KOH dissolved in water heated to 80 °C was used to etch Si (rate 300 Å/s). All optical measurements were carried out at room temperature.

The reflectivity spectra of the 4 pair SiO_2/Si bottom reflector clad by the Er-doped SiO_2 active region and of the entire Fabry–Perot microcavity are shown in Fig. 2. The reflectivity spectrum of the bottom reflector displays a broad band of high reflectivity in the wavelength range 0.75–1.25 μm. The magnitude of the reflectivity near the center wavelength of 1.0 μm exceeds 98%. The reflectivity spectrum of the complete cavity, shown in the lower part of Fig. 2, also displays the broad reflectivity band. In addition, the reflectivity exhibits a dip at 0.995 μm which is the fundamental resonance mode of the cavity. The trans-

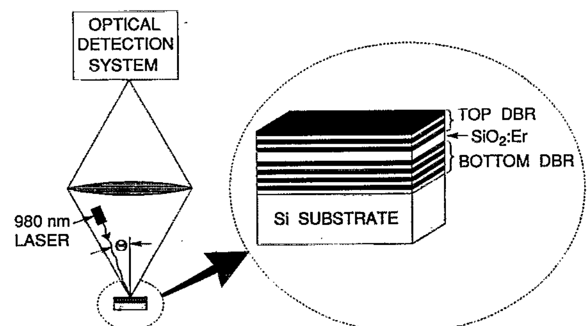

FIG. 1. Experimental configuration of Er-doped Si/SiO_2 microcavity optically pumped by a 980 nm semiconductor laser.

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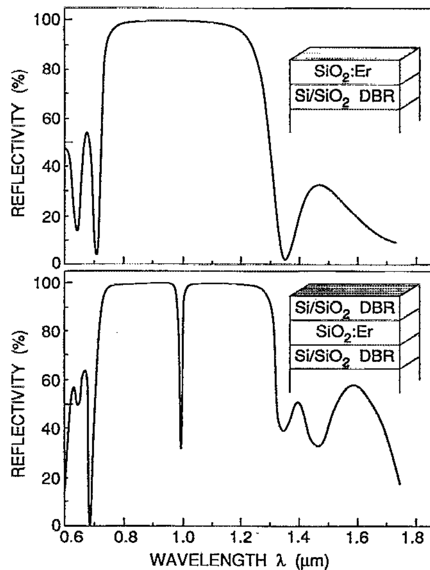

FIG. 2. Reflectivity of a Si/SiO_2 distributed Bragg reflector (DBR) clad by a $(\lambda/2)$ SiO_2:Er active region and of a DBR/SiO_2:Er/DBR microcavity resonant at 995 nm.

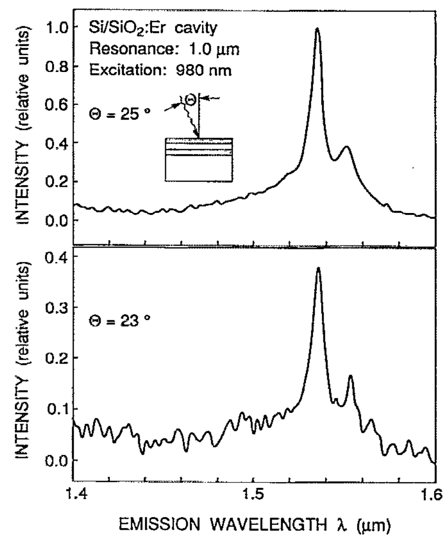

FIG. 3. Room-temperature photoluminescence spectrum of an Er-doped Si/SiO_2 microcavity which is, at $\Theta=25°$, resonant with the excitation wavelength of 980 nm. Slightly off resonance, at $\Theta=23°$, the Er intensity is lower.

mission of a Fabry–Perot cavity approaches unity at the resonance wavelength. The full width at half-minimum of the resonance mode is 9 nm which translates into a *cavity quality factor* of $Q=\lambda/\Delta\lambda=110$. This is a remarkably high value since the Si used in the bottom and top DBR absorbs light at $\lambda<1.1$ μm due to interband transitions. The sharp cavity resonance shown in Fig. 2 demonstrates, however, that the Si/SiO_2 material system is well suited for high Q microcavities resonant at $\lambda\cong 1$ μm.

The reflectivity spectra were measured in the Er-implanted part of the wafer as well as in unimplanted parts of the wafer. We found no noticeable difference in the reflectivity spectra between the two regions. The resonance wavelength varied weakly across the 2.5 cm$\times$2.5 cm wafer between 0.995 and 1.05 μm.

The room-temperature photoluminescence measurements were carried out with the exciting 980 nm semiconductor laser at an angle of Θ from the optical axis of the cavity, as shown in the inset of Fig. 3. The off-normal excitation of the cavity allows us to tune the resonance to 980 nm, since the resonance wavelength depends on the angle Θ.[2,3] The luminescence signal from the Er emission line at 1.535 μm has maximum intensity at an excitation angle of $\Theta=25°$. The corresponding Er luminescence spectrum is shown in Fig. 3. The intensity of the $\lambda=1.535$ μm peak of the Er spectrum is normalized to unity (1.0) and serves as a reference intensity for all other intensities presented in this publication. Also shown is a luminescence spectrum obtained at an excitation angle of $\Theta=23°$ where the intensity is less than half the intensity of the $\Theta=25°$ spectrum. Note that the Er spectra exhibit the typical double-peak structure with the major line at 1.535 μm and a secondary line at 1.55 μm.[4,10] Thus, the *shape* of the optical emission spectrum is not influenced by the microcavity, since the 1.5 μm Er emission band is well outside the DBR reflectivity band and off the cavity resonance.

The excitation-angle dependence of the 1.535 μm Er emission line is shown in Fig. 4. The dashed line represents a fit to the experimental points. The peak intensity exhibits a narrow maximum at $\Theta=25°$. The cavity, which is resonant at approximately $\lambda=1.0$ μm for $\Theta=0°$, is resonant at $\lambda=980$ nm for an excitation angle of $\Theta=25°$. The full width at half-maximum of the dashed curve is 4°.

Next we discuss the absorption enhancement due to the resonant absorption effect of the cavity. Without a cavity and a bottom reflector, the exciting light passes through the active region only once and a very small fraction of photons excites Er atoms. In the presence of a bottom reflector, the 980 nm light traverses the active region twice. In the presence of a cavity, photons traverse the active region of the cavity many times and the enhancement of the absorption is given by[11]

$$G_a=\frac{2(1-R_1)}{(1-\sqrt{R_1R_2})^2}\cong\frac{4}{\pi}F=\frac{4}{1-\sqrt{R_1R_2}}, \quad (1)$$

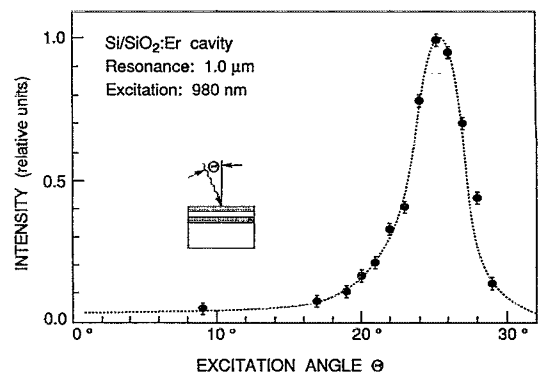

FIG. 4. Photoluminescence intensity of an Er-doped Si/SiO_2 cavity resonant at the excitation wavelength vs excitation angle.

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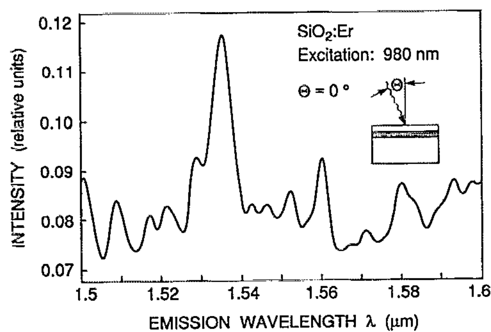

FIG. 5. Room-temperature Er luminescence spectrum of a SiO_2:Er layer excited at $\lambda=980$ nm.

where R_1 and R_2 are the reflectivities of the top and bottom reflector, respectively, and F is the finesse of the cavity. For the derivation of Eq. (1) it was assumed that $R_2 \cong 1$, and $(1-R_2) \ll (1-R_1)$, that the 980 nm Er absorption per single pass is very small, and that the Er is homogeneously distributed in the SiO_2 active layer. Furthermore, the absorption of 980 nm light in the Si layers is neglected. Using $R_1=99.8\%$ and $R_2=98.5\%$, we calculate $F=368$ and an enhancement factor of $G_a=468$. Assuming an absorption coefficient of $\alpha=900$ cm^{-1} for Si at 980 nm, the enhancement factor is calculated to be 282. If compared to a structure with a bottom mirror (which has a calculated enhancement of 2.74 over a no-mirror structure), the expected enhancement is $G_a=103$. Furthermore, lower-than-calculated mirror reflectivities reduce the finesse and thereby the enhancement factor. Including the absorption in the Si layers, we calculate the width of the resonance dip to be 2.8 nm wide. Using the measured width of 9 nm, the calculated enhancement reduces to $G_a=32$. We next compare the experimental intensity enhancement of the cavity structure and the structure with only a bottom reflector (the two structures are schematically shown in the insets of Fig. 2).

The photoluminescence spectrum of an Er-doped SiO_2 layer grown on top of a 4 pair SiO_2/Si mirror is shown in Fig. 5. The structure, which is schematically shown in the inset, was fabricated by etching off the top DBR of the cavity structure. The main Er related peak at 1.535 μm has an intensity of 0.036 relative units, which is a factor of 28 weaker as compared to the cavity structure. Comparison of the experimental enhancement with the calculated enhancement ($G_a=32$) yields very good agreement. The comparison further indicates that the experimental mirror reflectivities are lower than the calculated ones and that some 980 nm pump light is absorbed in the Si layers of the DBRs. The luminescence spectra shown in Fig. 5 displays noise of average intensity 0.08 relative units, which is due to defect luminescence from the Si substrate. The defect luminescence can be clearly separated from the Er signal.

The strong luminescence enhancement observed in the absorption-resonant microcavity has potential applications in optical devices. As an example, we consider optical amplifiers for 1.55 μm communication systems.[12] It is desirable that the signal light propagation direction and the pump light direction be orthogonal. Such orthogonality is not feasible in conventional amplifiers[12] due to the weak oscillator strength of the 980 nm Er absorption transition. The enhanced efficiency of Er excitation offered by the resonant absorption cavity may be useful for optical amplifiers.

In conclusion, we have realized resonant-absorption microcavities in the Si/SiO_2:Er material system. The cavity is resonant with the 980 nm absorption band of Er, has a calculated finesse of 370, and a measured quality factor of 110. A strong luminescence intensity enhancement is observed with this cavity structure, with efficiencies of 28 times higher as compared to a no-cavity structure. The theoretical efficiency enhancement is determined to be $(4/\pi)F$, where F is the finesse of the cavity, if the Si layers of the DBR were transparent to 980 nm light. The experimental enhancement agrees with theory, if absorption of 980 nm light in the Si layers of the DBR and reduced mirror reflectivities are taken into account. Potential applications of the structure include planar optical waveguide amplifiers and optically pumped lasers.

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