Ultralow threshold laser using a single quantum dot and a microsphere cavity

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We propose a novel semiconductor microlaser, made by capturing the light emitted from a single InAs/GaAs quantum dot in the whispering-gallery mode of a glass microsphere. We demonstrate that such an arrangement allows the laser threshold condition to be satisfied. The corresponding threshold current should be several orders of magnitude lower than is currently possible in semiconductor lasers. [S1050-2947(99)05403-7]

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I. INTRODUCTION

For several years, researchers have been working on designing semiconductor lasers with low thresholds. Laser threshold can be reduced by making the active volume smaller and modifying the density of states for the carriers; so far, the most successful technique to do so has been to use a quantum well in a vertical cavity structure together with selective lateral oxidation [1]. The ultimate limit to this scaling occurs when the active medium consists of only one electron-hole pair with a discrete density of states. This can be achieved by confining the electron and hole in a single quantum dot (QD). We propose the laser with a single quantum dot as a novel, ultralow threshold device, consisting of a single InAs/GaAs self-assembled QD coupled to a high-finesse microsphere cavity. The device would also be a model cavity-QED system, consisting of a single oscillator coupled to a single photon mode. In this sense, it is analagous to the single-atom maser [2], the single-atom laser [3], and the ion-trap laser [4].

II. LASER THRESHOLD CONDITION

To determine whether our device is capable of exhibiting laser action, we cannot use the conventional, macroscopic definition of threshold, that the gain of the optical mode equals the cavity losses. Instead, we follow the alternative definition given by Björk, Karlsson, and Yamamoto, that the mean spontaneously emitted photon number in the laser mode n_{sp} is unity [5]. At this point, stimulated emission overtakes spontaneous emission, and linear amplification is replaced by nonlinear laser oscillation.

We use a simplified photon-flow model to estimate the occupation of the laser mode. First, an electron and hole are pumped into the QD. They spontaneously recombine and emit a photon after an average lifetime τ_{sp}. Afterwards, another electron-hole pair is pumped into the QD, and the sequence repeats. The average spontaneous emission rate will thus be N_A/τ_{sp}, where the inversion parameter N_A is the average probability over time that the QD contains an electron-hole pair. Out of the spontaneously emitted photons, a fraction β will be captured by the laser mode of the optical cavity. The captured photons will remain in the cavity for an average storage time τ_{ph} before leaking out. This photon lifetime is given by Q/ω, where Q is the cavity quality factor and $\omega/2\pi$ is the frequency of the optical mode (assumed to be on resonance with the emission). Combining all the above factors, we obtain a simple expression for the threshold condition:

$$n_{sp} \approx \frac{\beta \tau_{ph} N_A}{\tau_{sp}} \geqslant 1. \tag{1}$$

Only some of the parameters in this expression can be modified in an experiment. The spontaneous emission rate, for example, is set by our choice of the QD. One attractive system is the ensemble of islands formed spontaneously through the Stranski-Krastanow growth of InAs on GaAs by molecular beam epitaxy [6]. Through time-resolved photoluminescence experiments, we determined that these InAs QD's exhibit efficient ground-state luminescence around a wavelength of 960 nm, with a decay time of about 650 ps [7]. Individual QD's can be isolated from the ensemble in micropost structures by a combination of electron-beam lithography and reactive-ion etching [8].

For these QD's, Eq. (1) simplifies to the requirement that $N_A \beta Q \geqslant 2.5 \times 10^5$. In order to reach threshold, then, we require a cavity with very high Q that captures a reasonable fraction of the spontaneous emission.

III. WHISPERING-GALLERY MODES IN MICROSPHERES

The glass microsphere cavity satisfies the criteria of high Q and β. Small fused-silica spheres can by made by melting the tip of an optical fiber with a focused CO_2 laser beam [9]. Surface tension shapes the glass into quasispherical structures with radii of 25 to 100 μm; a fiber stem, useful for positioning, remains connected to the sphere. Among the resonances of these structures are the whispering-gallery modes (WGM's). In a ray-optics picture, these modes correspond to light traveling around the equator of the sphere, constantly deflected back inwards by total internal reflection. Q values as high as 3×10^9 have been observed for these modes [9]. If the sphere is brought close to the surface of the GaAs sample containing the isolated QD, light emitted in appropriate directions will couple by resonant frustrated total internal reflection into a circulating WGM. To couple laser light out of the sphere, a prism or eroded optical fiber can be

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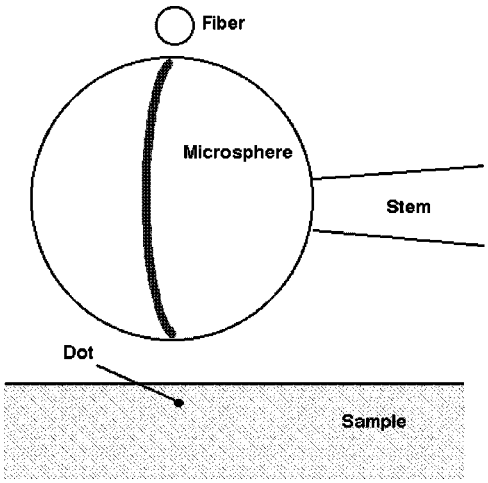

FIG. 1. Schematic of the experimental setup for the microsphere laser with a single quantum dot. The active medium consists of a single InAs quantum dot in a GaAs matrix. A glass microsphere, held by a fiber stem, is brought close to the surface. Light emitted from the dot couples into a whispering-gallery mode of the sphere (represented by the equatorial band). An eroded optical fiber near the other side of the sphere is used to couple out laser light.

brought close to the other side [10]. A schematic of the proposed experimental arrangement is shown in Fig. 1.

Resonances in the microsphere can be described by three mode numbers: a resonance order *n*, an angular mode number *l*, and an azimuthal mode number *m*. WGM's have $n=0$ and $l\approx l_{\max}$, where the maximum angular number $l_{\max}$ is equal to the number of integral wavelengths that can fit around the circumference of the sphere. For each set of mode numbers, there is a transverse electric (TE) and transverse magnetic (TM) polarization mode. The field in one of these modes can be described by a scalar Hertz potential. For example, in a TE mode, the radial electric field is given in terms of an electric potential $\Pi^{(e)}$:

$$E_r=\frac{\partial^2(r\Pi^{(e)})}{\partial r^2}+k_{\text{sph}}r\Pi^{(e)}. \tag{2}$$

In this equation, $\mathbf{r}$ is the radial vector and k_{sph} is the wave vector in the sphere (the free-space wave vector k_0 multiplied by the refractive index $n_{\text{sph}}\approx1.45$). In this notation, the WGM's are simply products of spherical Bessel functions and spherical harmonics:

$$\Pi_{lm}^{(e)}\propto j_l(k_{\text{sph}}r)Y_{lm}(\theta,\phi). \tag{3}$$

The degeneracy between modes with the same *l* and different *m* is lifted in practice by a small ellipticity. We will thus consider coupling into a single TE mode with $m=l=l_{\max}$.

IV. CALCULATION OF PHOTON NUMBER

To determine the number of spontaneous photons in the WGM, we first calculate the capture fraction β using the generalization of Lorentz-Mie scattering theory due to Barton, Alexander, and Schaub [11]. The field inside the sphere is written as a superposition of resonant modes, such as those given by Eq. (3). The electromagnetic radiation field emitted from the dot and incident on the sphere is likewise written as a linear combination of orthogonal spherical modes, as is the field scattered off of the sphere. The coefficients of the three sums are related by application of appropriate boundary conditions. The result is that the amplitude c_o of the WGM in question is related only to the amplitude c_1 of the incident mode with the same mode numbers, as follows:

$$c_0=\frac{h_l'(k_oR)j_l(k_oR)-h_l(kR)j_l'(k_oR)}{n_{\text{sph}}^2 j_l(k_{\text{sph}}R)h_l'(k_oR)-n_{\text{sph}}j_l'(k_{\text{sph}}R)h_l(k_oR)}c_1. \tag{4}$$

In this equation, h_l is the spherical Hankel function, a prime denotes the derivative, and *R* is the radius of the sphere. The coefficient c_1 is given by the overlap of the incident electric field $\mathbf{E}^{\text{inc}}$ with the appropriate spherical harmonic over the surface of the sphere:

$$c_1=\frac{R^2}{l(l+1)j_l(k_oR)}\times\int_0^{2\pi}\int_0^{\pi}\sin\theta\,d\theta\,d\phi\,E_r^{\text{inc}}(R,\theta,\phi)Y_{ll}^*(\theta,\phi). \tag{5}$$

To determine the incident field, we follow the near-field method of Lukosz and Kunz [12]. Because the electric dipole in the QD is randomly oriented, we assume that the emitted field is a spherical wave. The scalar potential inside the semiconductor sample is given by the following Fourier integral:

$$\Pi_o^{(\text{inc})}(\mathbf{r})=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}dk_x\,dk_y\,\psi_o(k_x,k_y)\times\exp(i[k_xx+k_yy+k_{z,\text{sem}}(z-D)]), \tag{6}$$

where the semiconductor-air interface is taken to be at $z=0$, *D* is the distance from the interface to the QD, ψ_o represents a scalar spherical wave, and $k_{z,\text{sem}}=\sqrt{k_{\text{sem}}^2-k_x^2-k_y^2}$. ($k_{\text{sem}}$ is the wave vector in the semiconductor.) This formulation represents the emitted field as a superposition of plane and evanescent waves, corresponding to real and imaginary values of $k_{z,\text{sem}}$. The transmission of each of these waves through the interface is simply given by the appropriate Fresnel coefficient. The scalar potential outside the sample is then given by an integral similar to Eq. (6).

We used the above procedure to calculate capture fractions β for various sphere radii *R* and sphere-sample distances *d*. In the calculations, *D* is taken to be 0.1 μm. Results are shown in Fig. 2. We see that larger spheres have more efficient capture of radiation, and that β generally decreases as the sphere is moved away from the sample. This is consistent with a simple picture, where waves emitted at large angles to the surface normal couple into the WGM directly and by frustrated total internal reflection.

Frustrated total internal reflection also allows light already in the WGM to leak out into the semiconductor sample, leading to a decrease of photon storage time. To calculate the extent of this *Q* degradation, we consider the reverse, equivalent problem of coupling into the sphere of a uniform, homogeneous background of plane waves from the

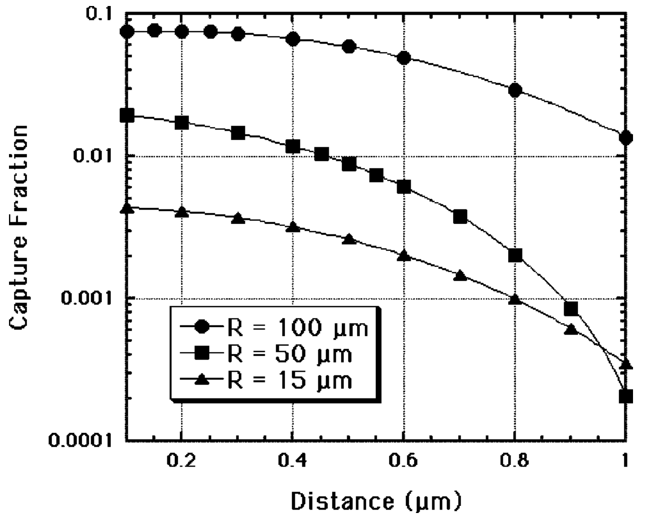

FIG. 2. Calculated capture fractions β for the laser with a single dot, as a function of the microsphere-sample distance. β is the fraction of spontaneous emission from the dot that is captured by the whispering-gallery mode of the sphere. Calculations are done for different sphere radii R assuming that the depth, D, of the dot in the sample is 0.1 μm.

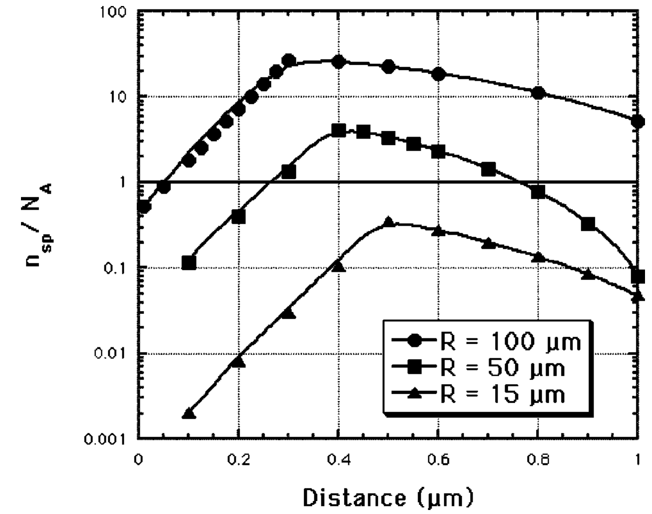

FIG. 4. Calculated number of spontaneously emitted photons n_{sp} in the laser with a single dot, as a function of the microsphere-sample distance. Calculations are done for different sphere radii R, assuming that the depth D of the dot in the sample is 0.1 μm and that the maximum quality factor of the microsphere is 5×10^8. The photon number is normalized by the inversion parameter N_A for the quantum dot, which is the average probability over time that the dot will contain an electron-hole pair.

semiconductor sample. The capture probability for each of these waves is calculated by the modified Lorentz-Mie scattering theory discussed above. By integrating over all waves, we get the total outcoupling probability δ_c per unit pass of the electromagnetic field in the WGM. The quality factor simply follows from this number and the round-trip time T_{rt} in the cavity:

$$Q\approx\frac{T_{\mathrm{rt}}}{|\delta_c|^2}\,\omega=\frac{2\pi R\omega}{c|\delta_c|^2}. \tag{7}$$

In our calculations, we assume that the microsphere, when far from the surface, has a Q of 5×10^8, a value that can be readily achieved in practice [9]. Results are shown in Fig. 3.

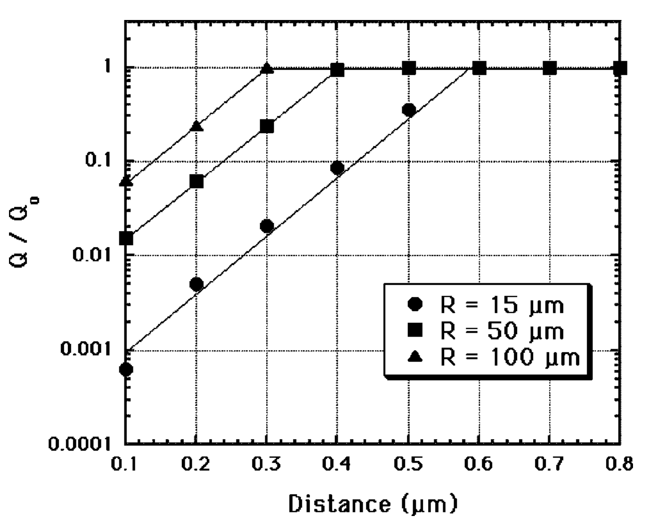

FIG. 3. Calculated quality factor Q of the whispering-gallery mode in a fused-silica microsphere as the sphere is brought towards a GaAs surface. Calculations are done for different sphere radii R as a function of sphere-sample distance. Results are normalized by the maximum quality factor Q_0 of the mode, assumed to be 5×10^8.

When the spheres get closer to the surface than a certain critical distance, the quality factor decreases exponentially. The rate of Q degradation is nearly independent of sphere radius, but the critical distance decreases as R increases. This is mainly due to the longer round-trip time in the larger spheres.

Combining the calculated values of Q and β according to Eq. (1) gives the number of spontaneous photons in the cavity n_{sp}. Results are shown in Fig. 4. It is clear that, for larger

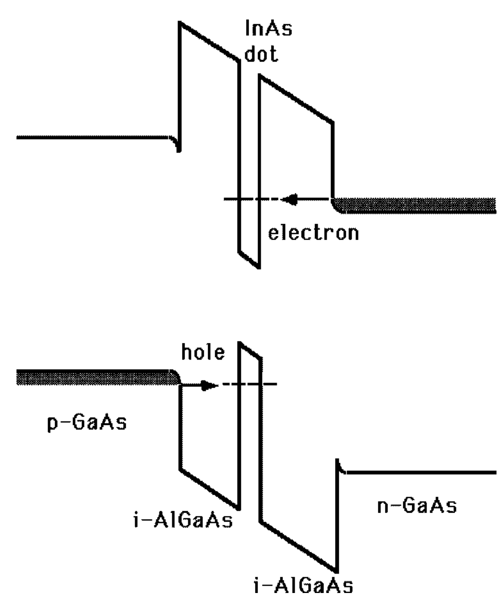

FIG. 5. Schematic energy-band structure of the double-heterojunction resonant-tunneling structure used for pumping a single quantum dot. Carriers tunnel one at a time from the doped GaAs reservoirs, through the intrinsic $Al_xGa_{1-x}As$ barriers, into the isolated InAs dot.

spheres, the threshold condition $n_{sp} \geqslant 1$ is satisfied for a large range of sphere-sample distances d, provided that we have a large enough inversion parameter N_A. Laser action is thus possible in this microsphere laser with a single dot.

V. THRESHOLD CURRENT

The highest calculated value of n_{sp}/N_A is about 27. The threshold pump rate thus occurs for $N_A \approx 1/27$, corresponding to a threshold pump current $I_{th} = eN_A/\tau_{sp} \approx 9$ pA. A more accurate quantum-mechanical calculation based on a master-equation analysis, to be described in a future publication, gives $I_{th} \approx 22$ pA [13]. The somewhat higher value reflects the effects of saturation and self-quenching due to the pumping process [14]. The calculated threshold is still extremely low, being more than five orders of magnitude lower than the current record of 8.7 μA for a microcavity semiconductor laser [15].

In this approximation of threshold current, we have assumed unity internal quantum efficiency, ignoring effects such as leakage current. One way to approach this ideal limit is to incorporate the QD into a double-heterojunction resonant tunneling structure, similar to that used to inject excitons into quantum wells [16]. Figure 5 shows a schematic of an appropriate energy-band structure. Such an arrangement will have a much lower excess current than conventional electrical injection schemes based on capture of hot carriers by QD's. Calculations based on the WKB approximation (the details of which are not given here) indicate that such an arrangement will provide pumping rates high enough to reach threshold.

VI. CONCLUSIONS

We have demonstrated that it is feasible to build a laser by capturing the radiation from a single InAs/GaAs quantum dot in the whispering-gallery mode of a glass microsphere. We calculate a threshold current several orders of magnitude lower than is otherwise achievable in semiconductor lasers. The device is also a model cavity-QED system, and should allow for several unique experiments to study the basic physics of light-matter interaction.

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