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Three-dimensional wavelength-scale confinement in quantum dot microcavity light-emitting diodes

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We introduce a microcavity light-emitting diode (LED) structure that uses submicrometer oxide aperture and a quantum dot active region to achieve strong three-dimensional confinement of both the carrier distribution and the optical field. Light–current curves show optical emission for devices as small as 400 nm in diameter. Spectroscopy on electrically pumped LEDs, with apertures ranging from 2.5 down to 0.7 μm, show several spectral lines corresponding to cavity modes. A strong blueshift of the resonant modes for smaller apertures demonstrates the role of the oxide aperture in confining laterally the optical wave in a volume comparable to $(\lambda/n)^3$. Due to the high quality factors and low mode volumes, the devices could be good candidates for the demonstration of the Purcell effect under electrical pumping. *© 2004 American Institute of Physics.*
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Implementation of quantum cryptography protocols relies on devices capable of generating single photons on request with high count rates at telecom wavelengths (1.3–1.55 μm). The optical properties of single quantum dots (QDs) have the potential for satisfying the requirements of a single photon source.[1–3] The typical extraction efficiency from a quantum dot embedded in GaAs semiconductor material is of the order of ~2%, where the losses are mainly due to total internal reflection at the air–GaAs interface. This limits the count rate, and is particularly detrimental at telecom wavelength where single photon detection technology is in its infancy. It is clear that there is a need to develop and improve methods for increasing the extraction efficiency of the semiconductor source. Current research is directed, among other methods,[4] at improving the extraction of spontaneous emission from single QDs through the optimization of the optical density of states around the emitter. By coupling the QD emission to the fundamental mode of a wavelength-sized microcavity with high quality factor (Q), the spontaneous emission (SE) rate can be increased over the bulk volume, as originally predicted by Purcell.[5] This effect has been observed in ensembles of QDs,[6,7] and more recently in single QDs,[8] embedded in pillar-like semiconductor structures under optical excitation. This SE increase implies that most photons are emitted in the microcavity mode, which can be easily extracted and leads to a much improved efficiency and higher repetition rates. The consequent reduction in exciton lifetime also helps to counteract dephasing in applications where coherence of the emitted single photons is required.[9] However for practical applications, electrical pumping would be much preferred to avoid the need of pulsed pump lasers and micro-photoluminescence apparatus. Achieving at the same time electrical injection and high Q optical confinement in a wavelength-sized cavity is extremely challenging. The use of etched pillars is not very convenient in this case, because of nonradiative recombinations at the etched sidewalls, high series resistance, and mechanical instability. Electrically pumped single QD emission has been demonstrated by postfiltering,[10] with a small metal aperture, with no carrier and no optical confinement. Control of carrier injection, in a submicrometer area, has been proposed[11] and achieved[12] using an oxide current aperture surrounded by a weakly confined optical cavity. On the other side, vertical cavity surface emitting lasers, (VCSEL), which commonly employ distributed Bragg reflectors (DBR) and oxidized current apertures, achieve electrical and optical confinement with much larger dimensions (typically >2 μm). In this article, we present a microcavity QD light-emitting diode (LED) structure that uses an oxidized aperture and DBRs to confine at the same time the carrier injection and the optical mode in a submicrometer volume. We present measurements of electro-optical characterization of the efficiency, spatial mode energy, and quality factors. We also show that this approach is promising for the realization of efficient, electrically pumped single photon sources.

The structures have been processed from a planar microcavity grown by solid source molecular beam epitaxy on (001) oriented n-doped GaAs substrate. The active region consists of a single array of self assembled QDs formed from 3 monolayers of InAs and capped with a 5 nm strain-reducing $In_{15}Ga_{85}As$ layer to extend the emission into the near infrared. The density is estimated to be 3×10^{10} dots/cm^2 from atomic force microscopy on similar uncapped samples. The QDs are embedded in undoped GaAs. Lateral current and optical confinement is provided by an $Al_{0.85}Ga_{0.15}As$ layer, deposited on the top (p-side) of the GaAs layer, which is laterally oxidized resulting in an insulating, low-index ($n\sim1.6$) aperture. An optical cavity with a target Q (from a one-dimensional simulation neglecting lateral loss) of ~1000 is obtained by embedding the active region between a top mirror composed of 5 $Al_{0.75}Ga_{0.25}As$/GaAs quarter-wave pairs plus a top Au layer, and a bottom (output) mirror composed of three pairs of oxidized AlAs/GaAs and three pairs of $Al_{0.9}Ga_{0.1}As$/GaAs. Using optical lithography and reactive ion etching we fabri-

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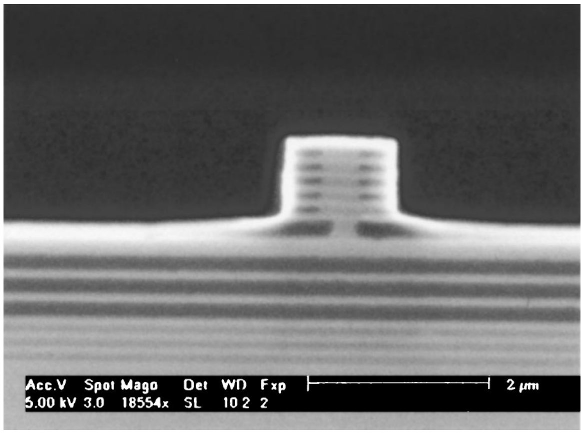

FIG. 1. SEM cross-sectional image of an aperture of 360 nm. The darker regions represent the oxidized AlGaAs and AlAs layers.

cated cylindrical mesa structures with diameters ranging from 10.5 down to 1.2 μm. The etching was stopped in the $Al_{0.85}Ga_{0.15}As$ aperture layer, which was then oxidized, at 400 °C for 90 min in an H_2O atmosphere. In the same oxidation step the AlAs layers were laterally oxidized from trenches etched at 20 μm distance from the mesa. The etched surface was electrically insulated with a Si_3N_4 layer deposited by plasma-enhanced chemical-vapor deposition. Au pads were deposited on the mesas to form the *p*-contact and a layer of Au on the substrate was used as *n*-contact. In order to determine the aperture area, a first estimation of the lateral oxidized distance was obtained on etched stripes from cross-sectional scanning electron microscope (SEM) images, as shown in Fig. 1. The aperture diameter in the mesa was further verified by measuring the scaling of the current–voltage characteristic for different nominal device diameters. As shown in Ref. 12, we expect current spreading and carrier diffusion to be negligible in this structure. Despite a high turn-on voltage (due to unoptimized *p*-doping in the top mirror), all curves can be fitted with a single oxidized length parameter that is also consistent with the SEM estimate.

Figure 2 reports light versus current characteristics at room temperature for a range of devices with different oxide apertures, showing that light is extracted from devices as small as 400 nm in diameter. The measured efficiency is 3.1×10^{-4} for the largest devices (9.5 μm) and decreases to 1.4×10^{-4} for the 400 nm LEDs. The low efficiency is mostly due to the mismatch between the cavity linewidth and the source spectral width: the QD emission is limited by the inhomogeneous broadening. The QD LEDs are designed to be efficient devices only for the one or few QDs that are

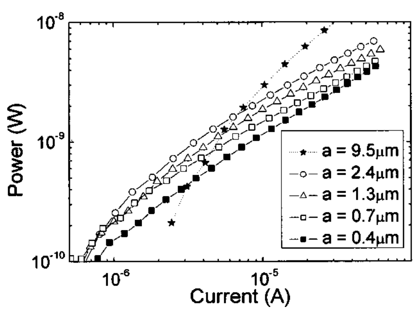

FIG. 2. Light vs current characteristic (293 K) curves for devices with different aperture diameter *a*.

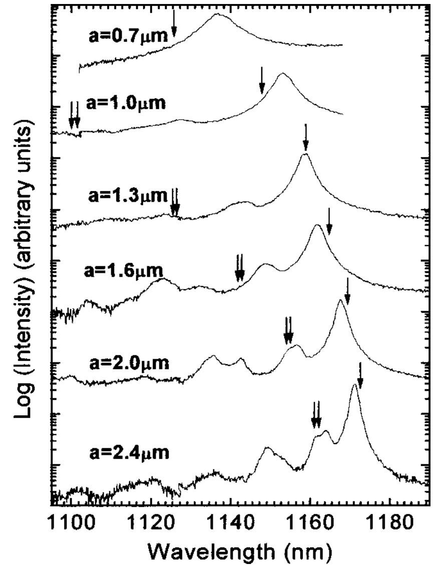

FIG. 3. Electroluminescence spectra (293 K) of microcavities with different oxide apertures (aperture diameter is indicated for each spectra). The blueshift of the resonant line and the increased mode separation for smaller diameters are characteristic of strong optical confinement in 3D. The arrows indicate the positions of the modes predicted by the effective index model. The modes indicated on each spectrum are, respectively, from right to left: HE_{11}, HE_{21}, and EH_{01}, according to the standard convention (Ref. 14).

resonant with the cavity mode: the ultimate goal is to demonstrate enhancement of spontaneous emission from a single emitter which requires high quality factors and small mode volumes. Optimization of these parameters compromises the efficiency[12] for the QD ensemble.

The cw electroluminescence spectra at 293 K are presented in logarithmic scale in Fig. 3 for devices with decreasing oxide apertures. The devices were individually contacted on the Au pads and the luminescence was collected with a 100 μm core optical fiber in contact with the substrate side, and dispersed into a spectrometer equipped with a liquid nitrogen cooled InGaAs near infrared detector. The individual measurements are characterized by several spectral lines corresponding to the resonant cavity modes. When compared to the single peaked spectra of the planar cavity at 1180 nm, this is evidence of strong optical confinement. The ground state transition of the QD is centered at 1245 nm (at 293 K), the cavity modes are therefore pumped by the excited states of the QDs. The inhomogeneous broadening of the QD emission (measured to be 18 nm on similar samples without cavity) ensures that the narrow spectral features are related to the cavity modes and not to QD electronic states. As the diameter of the current aperture is reduced we observe a blueshift of the cavity ground state transition (Fig. 4) and an increase in the splitting between cavity modes consistent with the conventional theoretical trend for increased lateral confinement. We stress that the energy shift (45 meV for the 0.7-μm-diam devices) is much larger than the shift commonly measured in VCSELs and comparable to the shift observed in micropillars.

The standard approach[13] used for quantitatively analyzing the optical confinement in cylindrical dielectric structures is based on the assumption that the transverse component of the resonant electromagnetic field is independent of the longitudinal component, an assumption usually correct for planar cavities or three-dimensional (3D) cavities with dimen-

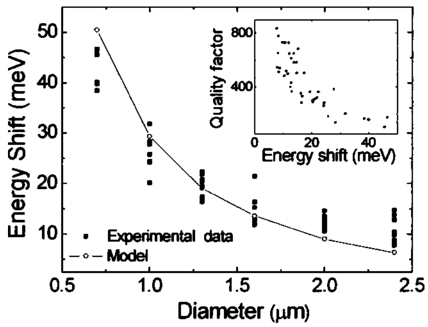

FIG. 4. Comparison of the experimental shift of the fundamental cavity resonance (dots) and prediction by the effective index model (continuous line). Inset: cavity quality factor is plotted as a function of the shift in energy with respect to the planar cavity emission.

sions larger than the wavelength.[14] In this *effective index* approach,[13] the cavity is treated as a two-dimensional circular waveguide with core and cladding indexes given by an effective index weighted by the standing field in the axial direction. In this framework, we solved numerically the eigenvalue equation for the longitudinal standing wave in the core (unoxidized region) approximated to a planar cavity. The resonant wavelength obtained was 1193 nm while the averaged refractive index weighted with the standing field intensity was 3.053. For the cladding (oxidized region) the refractive index was calculated to be 2.757 from the relation:[13] $\Delta\lambda/\lambda=\Delta n/n$. Using these values we applied the numerical methods used for evaluating the confined modes for a step index optical fiber[14] (shown as arrows in Fig. 3 and as a continuous line in Fig. 4). Good agreement was found between experimental evidence and calculated modes for apertures down to 2.0 μm, see Fig. 3, below which the cavity dimensions become comparable to the resonant wavelength and we observe a significant difference between the experimental and theoretical splitting of the cavity modes, thus confirming that the confinement of the transverse component becomes substantial in the smaller devices where the approximation in the effective index model is no longer valid. It is interesting to note that model predicts single mode propagation when the normalized frequency falls below 2.405 (the first zero in the Bessel J_0 function) which corresponds to an oxide aperture of 690 nm in our devices. In Fig. 3 the QD LEDs with apertures estimated at 0.7 μm indeed do not show any evidence of multimode confinement, at least within the broad emission spectrum of the ODs. We observe a significant spread in the resonant energies for devices with the same nominal diameter. This can be attributed to variations in the mesa diameters and oxidized length.

The design quality factor for the QD cavity is 1000, however this value can be reduced in practice due to scattering and diffraction at the oxide interfaces in small devices and waveguiding in the bottom DBR. Because actual diameters can vary among nominally identical devices we plot in the inset to Fig. 4 the quality factor measured in over 40 devices as a function of the resonant energy shift. Beside the variations in the Q value, probably due to the fluctuating quality of the mesa etching (the dimensions being comparable to the resolution of our optical lithography), a clear trend of decreasing Q for increasing lateral confinement is observed. The bests Q values are 850 for large (planar) structures, down to 150–200 for the smallest (0.7-μm-diam apertures. Using electron beam lithography to improve resolution in mesa etching, and by optimizing the shape and position of the oxide aperture, we expect to improve the Q factor to the value needed to observe the Purcell effect ($Q>1000$ in a 1 μm-diam device).[6]

In summary, we have demonstrated that electrical and strong optical confinement can be achieved at the same time in a cavity defined laterally by a thick oxide layer. The dependence of the cavity resonant modes on the oxide aperture is in agreement with the trend predicted by the effective index model. The results are promising and show that with sufficiently low QD densities and improve Q factors, these devices can be good candidates for the realization of very efficient, electrically pumped single photon sources.

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[1] P. Michler, A. Kiraz, C. Becher, W. V. Schoenfeld, P. M. Petroff, L. Zhang, E. Hu, and A. Imamoglu, Science **290**, 2282 (2000).
[2] C. Santori, M. Pelton, G. Solomon, Y. Dale, and Y. Yamamoto, Phys. Rev. Lett. **86**, 1502 (2001).
[3] V. Zwiller, H. Blom, P. Jonsson, N. Panev, S. Jeppesen, T. Tsegaye, E. Goobar, M. E. Pistol, L. Samuelson, and G. Bjork, Appl. Phys. Lett. **78**, 2476 (2001).
[4] W. L. Barnes, G. Björk, J. M. Gerard, P. Jonsson, J. A. E. Wasey, P. T. Worthing, and V. Zwiller, Eur. Phys. J. D **18**, 197 (2002).
[5] E. M. Purcell, Phys. Rev. **69**, 681 (1946).
[6] J. M. Gérard, B. Sermage, B. Gayral, B. Legrand, E. Costard, and V. Thierry-Mieg, Phys. Rev. Lett. **81**, 1110 (1998).
[7] M. Bayer, T. L. Reinecke, F. Weidner, A. Larionov, A. McDonald, and A. Forchel, Phys. Rev. Lett. **86**, 3168 (2001).
[8] G. S. Solomon, M. Pelton, and Y. Yamamoto, Phys. Rev. Lett. **86**, 3903 (2001).
[9] C. Santori, D. Fattal, J. Vuckovic, G. Solomon, and Y. Yamamoto, Nature (London) **419**, 594 (2002).
[10] Z. Yuan, B. E. Kardynal, R. M. Stevenson, A. J. Shields, C. J. Lobo, K. Cooper, N. S. Beattie, D. A. Ritchie, and M. Pepper, Science **295**, 102 (2002).
[11] H. Huang, and D. G. Deppe, IEEE J. Quantum Electron. **36**, 674 (2000).
[12] A. Fiore, J. X. Chen, and M. Ilegems, Appl. Phys. Lett. **81**, 1756 (2002).
[13] G. R. Hadley, Opt. Lett. **20**, 1483 (1995).
[14] A. Yariv, *Optical Electronics* (Sounders College Publishing, San Francisco, 1991).