Enhanced spectral power density and reduced linewidth at 1.3 μm in an InGaAsP quantum well resonant-cavity light-emitting diode

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The active region of an InGaAsP single-quantum well light-emitting diode (LED) emitting at 1.3 μm has been placed in the antinode of a resonant cavity consisting of a 32-period distributed Bragg reflector (DBR) and a top silver mirror, with reflectivities of 92% and 95%, respectively. The dominant feature of the 300 K electroluminescence emission at all current levels is a 3 nm (2.8 meV) wide spontaneous emission peak centered on the cavity resonance wavelength. The spectral power density of the structure is more than one order of magnitude higher as compared to a structure without cavity. The resonant-cavity LED operates without gain yet the extremely narrow spectrum indicates that the structure is suitable for wavelength division multiplexing applications.

Recently, microcavities have received much attention with respect to demonstrating fundamental changes in the spontaneous emission lifetime[1,2] and spontaneous emission rates[3] of oscillators within the cavity. Theoretical studies also investigated the coupling of spontaneous emission into the lasing modes in vertical-cavity surface-emitting lasers.[4] These laser structures consist of high reflectivity ($>99\%$) distributed Bragg reflectors (DBRs) above and below a planar active region, providing sufficient feedback for net gain and lasing to be achieved. Enhanced light-emitting diode (LED) emission from single mirror structures has been investigated,[5–7] but so far most demonstrations of cavity enhancement or inhibition of spontaneous emission has occurred in optical pumping experiments.[2,3] Most work in semiconductors has involved AlGaAs DBR mirrors [8] with either AlGaAs, InGaAs, or GaAs quantum active areas.

In this letter we demonstrate for the first time an emission at room temperature with very high spectral purity in a resonant-cavity light-emitting diode (RCLED) structure operating at 1.3 μm. While the problems associated with growing thick, highly-reflective 1.3 μm DBRs on InP have so far prevented the demonstration of a 1.3 μm semiconductor vertical cavity laser, the reflectivity requirements for a microcavity LED structure are much relaxed. The RCLED structure typically requires reflectivities less than 95%. While a laser uses stimulated emission to channel the pump energy into a set of discrete optical modes, a microcavity can affect the spontaneous emission rate into different optical modes without any requirement for gain.[9] At certain wavelengths and angles, the optical mode function exhibits a resonance within the cavity,[3,10–12] and couples strongly to the emitting dipole provided the dipole is in an antinode position of the mode. This resonance effect causes a large increase in the spectral power density at 1.3 μm, as well as a spectral narrowing in our RCLED device.

Two LED structures, A and B, were grown by organometallic vapor-phase epitaxy (OMVPE) in back-to-back runs. The bottom mirror of growth A is a 32-period InGaAsP/InP DBR with a measured peak reflectivity of 92%. A diagram of the structure is shown in Fig. 1. A comparison structure, growth B, does not include the DBR but is otherwise identical to growth A. Growths A and B have a single quantum well in the intrinsic region of the *p-i-n* LED. While multiple wells provide better carrier capture and less spectral broadening due to band-filling, a single well reduces the effects of active-region gain and self-absorption. In this way, we can be sure that changes in the emission spectrum are only due to cavity-induced changes in the directional spontaneous emission rate. The top mirror consists of a 60 nm thick silver layer which provides an ohmic contact to the p^+-quaternary cap layer, and has a reflectivity of about 95%. By making one mirror more reflective than the other, the emission out the low-reflectivity side at normal incidence will be increased.[7,8] We have also been careful to place the active quantum well in an antinode of the resonant optical mode, increasing the coupling of the oscillating dipoles to the mode by a factor of two.[5] Judging by the repeatability of layer thickness and emitted power of previous growth runs, we believe that the two wafers are comparable in quality.

The measured reflectivity spectrum of a portion of the as-grown wafer is shown in Fig. 2. While the reflectivity spectrum of a DBR by itself is quite symmetric about the reflectivity maximum, the top cap region is designed to be

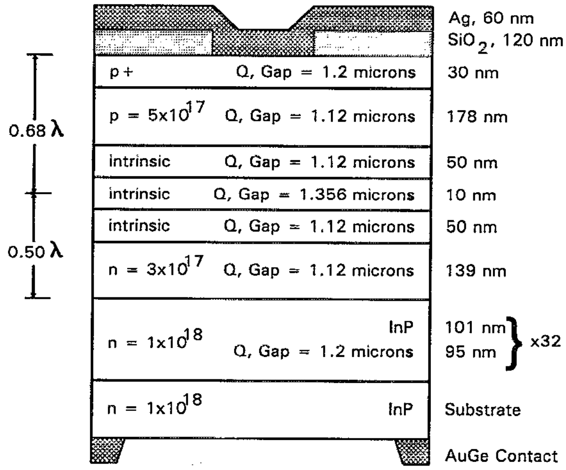

FIG. 1. The structure of growth A, an InGaAsP resonant-cavity light-emitting diode (RCLED) operating at 1.3 μm. Growth B is similar, except without the 32 periods of alternating $\lambda/4$-thickness InP-quaternary layers. The 10 μm diam. top silver contact also acts as a mirror, reflecting the majority of the light out of the substrate.

0.682 wavelengths thick in order that the phase shift at the top silver mirror will result in an antinode occurring at the position of the quantum well. The theoretical peak reflectivity is 94% for a perfectly-grown DBR as calculated from the quantum well position. The calculation assumes an InP index of 3.21, a quaternary index of 3.43 (for $E_g = 1.032$ eV), and a confinement and active region index of 3.33. Actual measurements indicate that the reflectivity of the DBR is 92 ± 2 percent.

A matrix method was used to determine the change of DBR reflection phase with wavelength near the reflectivity maximum. Once this is done, one can find the penetration length of light into the DBR as a multiple of the light wavelength. This can be defined as the distance from the first DBR interface at which one could replace the DBR by a perfect mirror in a material with average index n and wavelength $\lambda (=\lambda_0/n)$ to obtain the identical change of phase ϕ with vacuum wavelength λ_0. The penetration length L_{pen} is then:

$$\frac{L_{\text{pen}}}{\lambda} = -\frac{\lambda_0}{4\pi} \frac{d\phi}{d\lambda_0}. \tag{1}$$

In our mirrors, $d\phi/d\lambda_0$ is calculated to be $-0.0353\ \text{nm}^{-1}$ which gives $L_{\text{pen}} = 3.65\lambda$. Therefore the effective penetration length is 7.3 periods of the DBR mirror, and the effective length of the resonant cavity L_{cav} is about 4.83λ. For emission along the optical axis through one of the reflectors, and assuming that either mirror has high reflectivity, the emission rate enhancement factor F for a dipole in the resonance antinode is given by:

$$F = \frac{A_{\text{spon}}(\lambda_0) d\Omega}{A_0(\lambda_0) d\Omega} = 2 \left(\frac{1+\sqrt{R_1 R_2}}{1-\sqrt{R_1 R_2}} \right) \left(\frac{2-2R_{\text{out}}}{2-R_1-R_2} \right). \tag{2}$$

Here R_1 and R_2 are the mirror reflectivities, and $d\Omega$ is a narrow solid angle around normal incidence exiting from the mirror R_{out} (which is either R_1 or R_2). For structure A, assuming mirror reflectivities $R_1 = R_{\text{out}} = 0.92$ and $R_2 = 0.95$, the maximum intensity enhancement factor through the substrate calculated from Eq. (2) is $F_A = 73$. This result ignores the effects of the substrate to air reflection. Note that F is really an emission rate enhancement for a single dipole, and not an intensity enhancement factor. Energy conservation requires that one must multiply F by the ratio of the lifetimes with and without cavity τ_{cav}/τ_0, to get the true intensity enhancement factor.

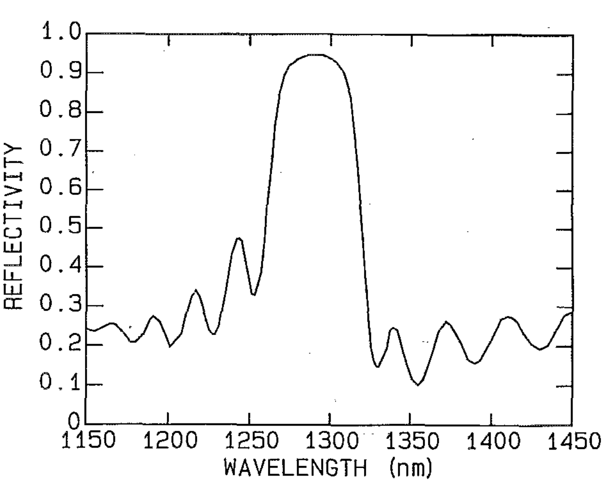

FIG. 2. A normal-incidence reflectivity spectrum of growth A, corresponding to the same position on the wafer that was used to measure the final emission spectra of the processed LEDs.

For growth B without a DBR mirror, the top silver reflector still sets up a standing wave resonance for the dominant optical mode. The enhancement factor F_B for a single $R = 95\%$ reflector with the quantum well in a resonance antinode is 3.8. The ratio of maximum enhancement in the two structures is then $73/3.8 \approx 19.2$. Unlike growth A, the enhancement for the single mirror structure will change only slightly over the spectrum of the LED due to a shift in the antinode position. If the silver mirror were farther away from the active region, this change would be more pronounced.

The test device design is partly shown in Fig. 1. A 120 nm thick SiO_2 layer was electron-beam evaporated on the semiconductor surface for protection and electrical insulation. The substrates of the materials were thinned and polished with mechanical action and a bromine-methanol etch. An AuGe-Ni-Au ohmic contact was evaporated on the substrate, a window opened using lift-off photolithography, and the contacts annealed at 400 °C. A 10 μm diameter hole, aligned with the substrate window, was etched in the SiO_2. About 60 nm of silver was evaporated on the surface and then patterned to isolate individual devices. Because of the high sheet reflectivity of the p layers (>1 kΩ/sq), current injection will only occur directly under the silver-semiconductor interface. There is some resistive current leakage observed from in the current-voltage curves.

A comparison of the spectra of the two structures, measured in a solid angle within 7° of normal incidence is given in Fig. 3. The injection current was 1.0 mA, not including 0.2 mA of leakage, resulting in a current density

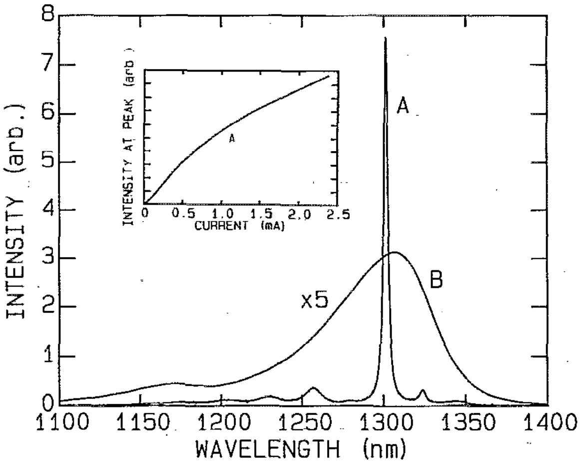

FIG. 3. The substrate-emission spectra of light-emitting diodes processed from growths A and B with a pump current density of 1.3 kA/cm^2 at room temperature. The spectrum of growth B is shown amplified by five for clarity. The inset shows the peak intensity of spectrum A vs injection current.

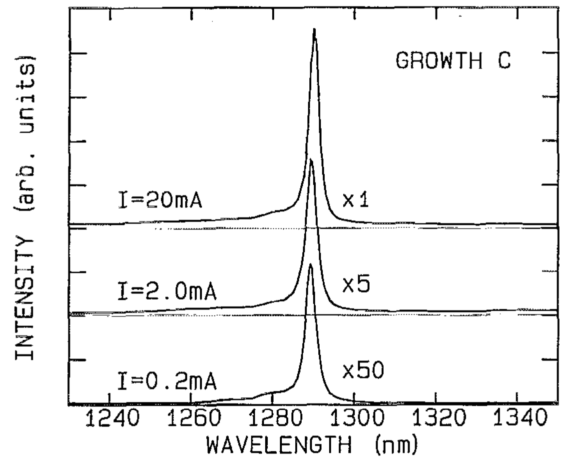

FIG. 4. The room-temperature emission spectra of a single quantum well, top emitting, 40 μm diam. RCLED fabricated from growth C for injection current levels of 0.2, 2.0, and 20 mA.

of 320 A/cm^2. There is a drastic enhancement of the spectral power density of growth A of a factor of 12 compared to that of growth B. While the spectral width of material B is not affected significantly by the mirror, material A exhibits a high spectral purity with a full width of 3.0 nm (2.8 meV). This is the narrowest 300 K spontaneous emission spectrum reported from a truly spontaneously emitted device. This width of 0.11 kT is observed at all pump levels, and is much smaller than the 3.3 kT width seen in structure B. While narrower spectra have been observed in superluminescent vertical cavity structures,[13,14] they do not exhibit spectral purity at all pump levels, and achieve some of their narrowing through the effects of gain. While a structure with gain exhibits super-linear increase of peak height with current, the inset of Fig. 3 shows that the resonance peak of material A initially grows linearly with current, although becoming sub-linear due to band filling at higher pump.

A demonstration of the insensitivity of the spectrum to current is shown in Fig. 4 for a top-emitting 40 μm diam RCLED made from growth C. The bottom mirror is 95% reflecting, while the top is 90%-reflecting semi-transparent silver. At actual injection levels of 0.2, 2.0, and 20 mA, the spectra exhibit identical widths of 3.2±0.2 nm. This demonstrates that the linewidth is determined only by the resonance of the cavity, and indicates that RCLED devices would be favorable for wavelength multiplexing applications.

The theoretical width can be derived from the quality factor Q of the cavity, assuming the resonance antinode does not shift significantly for the spectral range in question (which is true for material A). One must also assume that the natural emission spectrum does not change drastically in the calculated spectral width. The resonant enhancement with $\Delta\lambda_0$ is then given by:

$$\frac{\Delta\lambda_0}{\lambda_0} \approx \frac{1}{Q} = \frac{\lambda}{2L_{\mathrm{cav}}}\left(\frac{1-\sqrt{R_1R_2}}{\pi\sqrt[4]{R_1R_2}}\right). \qquad (3)$$

Given the calculated value of $L_{\mathrm{cav}}=4.83\ \lambda$ for structure A, Eq. (3) gives $\Delta\lambda_0=2.89$ nm, which is in good agreement with our measured 3.0 nm.

The discrepancy between the calculated spectral-power-density enhancement ratio between materials A and B of 19.2, and the measured one of 12 can be accounted for by the uncertainty in the DBR and silver mirror reflectivities, the fact that the resonance occurs slightly to the long-wavelength side of the DBR reflection maximum, and by some small self absorption within the quantum well. The spectral intensity enhancement factor seen in material A as compared to B did not depend on pump intensity, indicating that absorption or gain effects were not significant in our device.

The next question is whether the resonant cavity structures give a power gain over conventional LEDs. The spectra of materials A and B shown in Fig. 3 exhibit the same overall power to within a few percent. This means that the overall power of both structures is approximately equal to the enhancement factor F_B, which is calculated to be 3.8. Even greater powers may be achieved with improved mirrors (with shorter penetration depth L_{pen}), and more asymmetric mirror reflectivities, i.e., $R_2 \gg R_{\mathrm{out}}$, so that more power couples through the substrate. Even with our large value of L_{cav}, however, we get 51% of the optical power of material A within a 9 nm range about the 1.3 μm emission peak.

In conclusion, an InGaAsP resonant-cavity light-emitting diode (RCLED) operating at a wavelength of 1.3 μm has been realized for the first time. The electroluminescence emission from the OMVPE-grown device exhibits high spectral purity with a linewidth of 2.8 meV. Furthermore, an enhancement of more than one order of magnitude in spectral power density is observed in the structure when compared to noncavity structures at all current injection levels. The spectra indicate that the RCLED is a purely spontaneous emitting device which is suitable for wavelength division multiplexing applications. The RCLED therefore has novel device characteristics which are not found in lasers or conventional LEDs.

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