Microcavity enhanced vertical-cavity light-emitting diodes

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(Received 25 January 1993; accepted for publication 2 April 1993)

We systematically studied microcavity enhancement and mode-coupling effects in photo- and electroluminescence of an AlGaAs/GaAs vertical-cavity light-emitting diode (LED) by continuously changing the microcavity resonance with respect to the quantum well band gap. At mode overlap we obtained maximum photo- and electroluminescence intensities and a minimum emitted linewidth of 4.6 nm at 836 nm with a FWHM divergence of 62°. However, the electrical-to-optical efficiency was less than 1 μW/mA. Application issues for optical interconnects are presented.

Optical interconnects are attractive for high-speed chip-to-chip communication because much of the energy and area in electronic chips is used for communications between logic devices.[1–3] The optical interconnect is either based on an emitter-receiver or on a modulator-receiver link.[4] The modulator based link requires an external optical power supply and generally a more complicated interconnect technology. On the other hand an on-chip laser emitter requires more power on the electronic chip due to the threshold penalty. Recently, lower threshold currents have been demonstrated using microcavity enhanced semiconductor lasers[5–7] which was motivated by previous demonstrations that spontaneous emission of a medium is modified when placed inside a microcavity with has at least one dimension on the order of an optical wavelength.[8–10] So far, threshold powers around 5 mW have been demonstrated[11] for which the key improvement was a low series resistance. To avoid threshold issues altogether, an attractive alternative emitter for optical interconnects seems to be the light emitting diode (LED), or better yet, the microcavity enhanced LED.

Even though conventional LEDs operate without threshold they still suffer from low electrical-to-optical efficiency, isotropic broadband light emission, and low modulation bandwidth. As we show in the present work, microcavity effects are essential to improve LED performance.[12,13] To ensure good overlap of cavity resonance and quantum well exciton peak, despite heating effects, we continuously changed the coupling strength between excitons and cavity modes in a LED microcavity by varying the relative position of the microcavity resonance and the quantum well band gap across the wafer.[14] Our systematic study reveals room-temperature cavity enhancements and mode-coupling effects in both photo- and electroluminescence. At mode overlap we obtain minimum emitted linewidth and divergence.

The microcavity LED design [Fig. 1(a)] is based on a previously demonstrated vertical-cavity surface-emitting laser (VCSEL)[15] but with reduced top reflectivity of $\approx 93\%$ and a quantum well thickness variation of 100 Å to ≈ 60 Å across the wafer. Additional change in the mode coupling is obtained by the typical mirror variation across a full wafer (see Fig. 9 of Ref. 16). The microcavity resonance at room temperature is well defined, and well within the reflectivity band of the mirrors, but due to the lower cavity Q broader than typically observed for VCSEL [Fig. 1(b)].

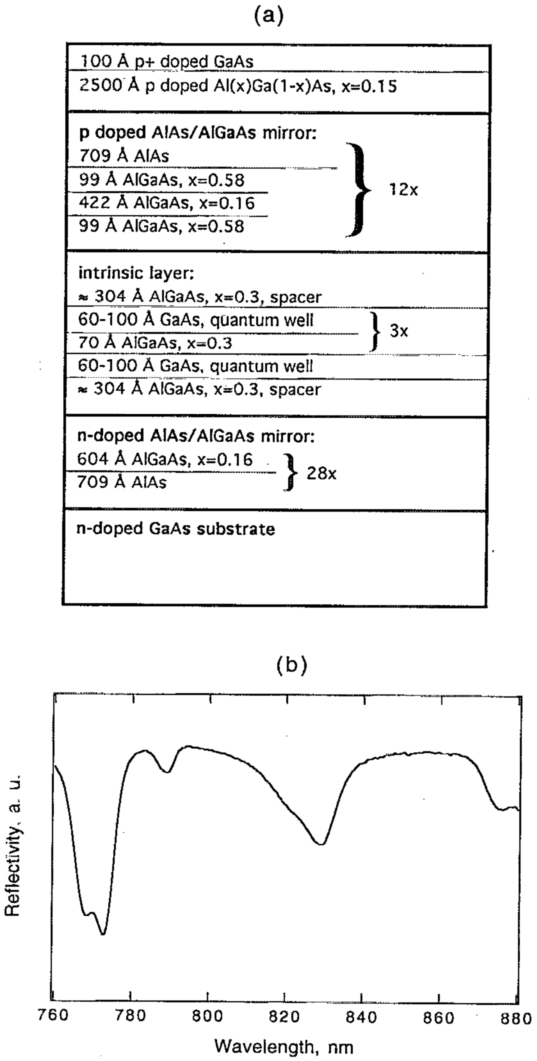

FIG. 1. (a) LED structure, (b) reflectivity curve.

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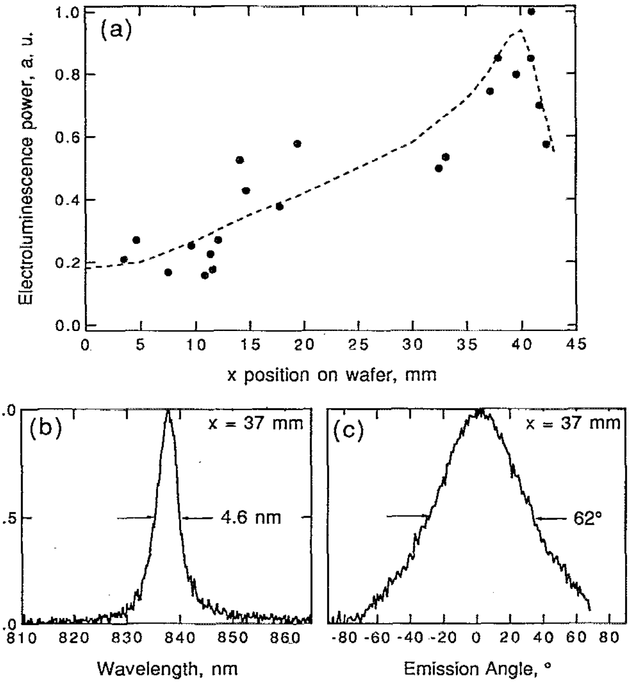

FIG. 2. Electroluminescence of microcavity LED at constant current of ≈3 mA. At maximum power we also observe minimum emitted linewidth (b) and minimal divergence (c). Away from the LED with maximum power the linewidth continuously increases.

Microcavity LEDs with 20 μm diam emitting windows were fabricated in steps of 200 μm along the x axis of the wafer. The patterned deep H^+ implantation has been described before.[15] Peripheral current injection occurs from the metallized contact area into the nonimplanted nonmetallized emission window. The typical diode operation voltage is ≈7 V mainly due to the relatively high resistivity in the p-doped top reflector which can ultimately by improved.[11] An approximately linear dependence for the output power versus current is measured as expected for spontaneous emission.

We obtained good performance regarding divergence and linewidth of the emitted light. At the position where maximum output power was measured for a fixed LED current of ≈3 mA [x=37 mm in Fig. 2(a)], we also obtained a minimum linewidth of 4.6 nm at a peak wavelength of 836 nm [Fig. 2(b)], with a divergence of 65° FWHM [Fig. 2(c)]. As one moves away from the LED with maximum power, the electroluminescence (EL) linewidth continuously increases to 7.5 nm with a peak wavelength of 843 nm at $x \approx 20$ mm. The linewidth was measured using a microscope lens with a numerical aperture of 0.65, and an optical spectrum analyzer with a 0.1 nm resolution. The divergence was measured by moving a detector with an angular resolution of 2.5° on a circular motion centered at the LED. We believe that the maximum power occurs because the exciton coincides with the cavity resonance. At matching conditions, we observe a five-times enhancement of the electroluminescence [Fig. 2(a)], however, the electrical-to-optical efficiency is still less than 1 μW/mA.

Because of the large fluctuations in the measured electroluminescence power [Fig. 2(a)] and to further substantiate microcavity enhancement effects under matched exciton and cavity-resonance condition, we performed photoluminescence (PL) and reflectivity measurements on an unprocessed piece adjacent to the microcavity LEDs. Because there is a built-in field in the LED structure, which is nearly canceled under forward bias, we performed two PL excitation measurements: one preserving the field (excitation at 802 nm) and one at flatband (excitation 488 nm). We show below that the PL intensity also shows a five-times enhancement at matched conditions, confirming the EL results [Fig. 2(a)]. In addition, the PL and the cavity resonance dependence on position demonstrate that the maximum power occurs because the exciton coincides with the cavity resonance.

Using a Ti:sapphire laser at a wavelength of ≈802 nm with a focused beam diameter of 0.5 mm and an average excitation power of 100–200 mW, carriers were only created within the quantum wells. The microcavity resonance was determined from the wavelength dependent reflectivity measurements using a low-intensity white light source. Figure 3 shows both the PL peak wavelength and the microcavity resonance (i.e., at minimum reflectivity) and demonstrates that the PL intensity is maximized where the microcavity resonance and the quantum well exciton peak overlap at $x \approx 44$ mm. As in the case of the electroluminescence (Fig. 2) the cavity induced enhancement at resonance is a factor of ≈5.

When the PL measurements are done with a 488 nm excitation wavelength which is absorbed everywhere in the LED structure we observe maximum PL intensity at $x \approx 30$ mm. The high intensity (≈200 mW from an argon-ion laser focused to a beam diameter of ≈0.5 mm) excitation at a 488 nm produces a flatband condition in the p-i-n LED structure and a broad PL spectrum due to the high carrier density. This results in two peaks in the PL spectrum [Fig. 3(b)] where one is due to the microcavity resonance and the other due to the quantum wells. At matched condition at $x \approx 30$ mm, where the microcavity resonance and the exciton peak overlap, we observe only one PL peak with maximized PL intensity. To determine which peak is due to the quantum well, we measured the PL of a sample with most of the p-doped mirror etched away, which destroyed any significant cavity mode coupling effects. Indeed, we obtain only one PL peak [Fig. 3(b), solid line] which coincides with the short wavelength peak of the PL spectrum of the as-grown sample, where the cavity was intact. The other peak is then due to the cavity resonance.

At $x \approx 44$ mm, where we observed PL enhancement under 802 nm excitation, the cavity resonance is ≈14 nm away from the quantum well exciton as measured in the etched sample [Fig. 3(b)]. This indicates that the QW exciton is shifted from its zero field position. The shift is a consequence of the built-in field, preserved under 802 nm excitation. Because the intrinsic region is rather small with an optical thickness of $\lambda/2$ the field is $\approx 1.3 \times 10^5$ V/cm. Due to the quantum confined Stark effect the built-in electric field produces an estimate red shift of the exciton peak

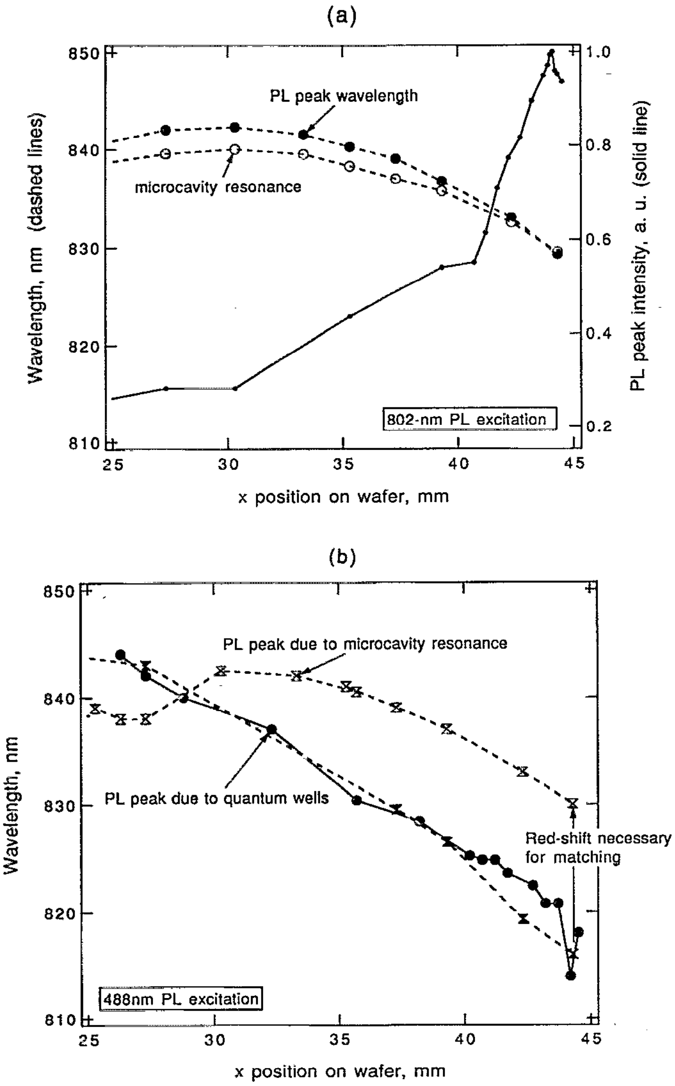

FIG. 3. Photoluminescence (PL) and reflectivity measurements. (a) PL excitation at 802 nm: absorption occurs only in the quantum wells which maintains the built-in field and shifts the point of matched excitons and cavity resonance with maximum PL intensity to $x \approx 44$ mm, (b) PL excitation at 488 nm: absorption occurs everywhere which screens the built-in field. Matched exciton and cavity-resonance condition with maximum PL intensity occurs at $x \approx 30$ mm. Away from matched conditions we observe two peaks on the PL spectra (dashed lines).

wavelength of ≈ 15 nm.[17] This shift produce an overlap with the cavity resonance at $x \approx 44$ mm which is responsible for the PL enhancement observed under 802 nm excitation [Fig. 3(a)].

Because a forward biased *p-i-n* structure is close to flatband we would expect maximum enhancement effects close to $x \approx 30$ mm where the 488 nm excited PL intensity peaks [Fig. 3(b)]. However, we must also take into account the red shift induced by ohmic heating,[18] the residual field still present in a forward biased *p-i-n* junction, and the different positions on the wafer. The fact that the PL measurement was done on a piece adjacent to the processed LED piece is probably the most significant reason for the difference.

It is interesting to note, that at matched conditions we observe a broadened minimum, with a double peak structure in the reflectivity curves [Fig. 1(a)] analogous to Weisbuch's results.[14] However, because of our low-Q cavity we are also able to observe a distinct splitting of the PL spectra away from matched conditions. Further discussions about the mode coupling in the microcavity LED will follow.

In conclusion, we demonstrated a significant enhancement of the electro- and photoluminescence intensity when the cavity resonance is matched to the quantum well exciton. In addition, we observed for the first time room-temperature coupling effects between excitons and cavity photons in LEDs. The light emission properties in terms of linewidth and divergence are sufficient for optical interconnects, the electrical-to-optical efficiency, however, is not. With a typical link loss of ≈ 10 dB the optical power requirement on the emitter side is $> 100\ \mu$W (Ref. 4) which can be generated with lower power dissipation using a microcavity laser[11] rather than a microcavity enhanced LED. If the power requirements of the VCSELs are not further improved the modulator-receiver link might be more advantageous, in which case one may use diode-pumped solid-state lasers[19] as practical high-power compact external optical power supplies.

The authors would like to acknowledge helpful discussions with David A. B. Miller, Mike E. Prise, and Ghulam Hasnain.

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