Carrier pinning by mode fluctuations in laser diodes

J. O'Gorman
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

S. L. Chuang
Department of Computer and Electrical Engineering, University of Illinois at Urbana-Champaign, 1406 W. Green Street, Urbana, Illinois 61801

A. F. J. Levi
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

We show that fluctuations into cavity modes give rise to substantial subthreshold carrier pinning in laser diodes. These fluctuations, which extract a current I^{fl} from the device, play an increasingly important role with increasing temperature.

Recently we reported that photons fluctuating into cavity modes of a laser diode at subthreshold drive current contribute to the temperature dependence of the device.[1] We also demonstrated that, contrary to popular belief, Auger recombination does not play a dominant role in determining the temperature dependence of threshold current in long wavelength ($\lambda = 1.3$ μm) laser diodes.[2] This assertion has been independently confirmed.[3] In this letter we report the results of experiments in which we systematically explore the relationship between carrier pinning and emission from index guided edge emitting laser diodes (LDs) and light emitting diodes (LEDs) at different temperatures.

Our experiments make use of the fact that spontaneous emission experiences amplification while propagating along the index guide. In contrast, nonguided light, which is measured after passing through a window in the substrate, does not experience gain. By comparing the ratio of measured emission spectra from the facet (F) and the window (W) of a LED with calculated spectra, we extract carrier density n, for various drive currents I, and temperatures T. Despite the presence of amplified spontaneous emission, we find that the overall temperature sensitivity of the I–n relationship in the LED is weak. Using the *same* device structure, but introducing facet mirrors to form a laser cavity, we find substantial carrier pinning for the device when the drive current is *below* lasing threshold. This significant carrier pinning arises due to subthreshold fluctuations into the laser cavity modes. These fluctuations, which extract a current I^{fl} from the LD, play on increasingly important role with increasing temperature.

The LD and LED devices used in the experiments have identical geometry and structure, apart from antireflection (AR) facet coatings on the LED. We use a standard bulk active region buried heterostructure design. The active region consists of an InGaAs layer of thickness $d = 0.14$ μm with a room temperature band gap of $E_g^0 = 968.6$ meV lattice matched to an n-type InP substrate and capped by a layer of p-type InP. After a two step regrowth process, the active region has a width $w = 1$ μm and is surrounded by InP. The device is cleaved to a length of $l = 260$ μm and bonded p-side down onto a BeO submount. A gap or window in the metallization making elec-

trical contact to the back of the n-type InP substrate allows collection of nonguided light generated in the active region. As-cleaved devices lase at wavelength $\lambda = 1.31$ μm with room temperature threshold currents in the range 9 mA $< I_{th} < 10$ mA. In the temperature range $298 < T < 328$ K the temperature dependence of threshold current is well characterized by an activation temperature $T_0 = 42$ K.

Figure 1 shows the measured window spontaneous emission spectrum L^W of an edge emitting LED. This consists of light collected through the substrate and corrected for losses due to free carrier absorption in the n-type substrate. Also shown in Fig. 1 is the amplified spontaneous emission spectrum for light collected from the facet L^F of the LED. The difference between the two spectra clearly indicates the effect of gain experienced by light traveling along the length of the index wave guide.
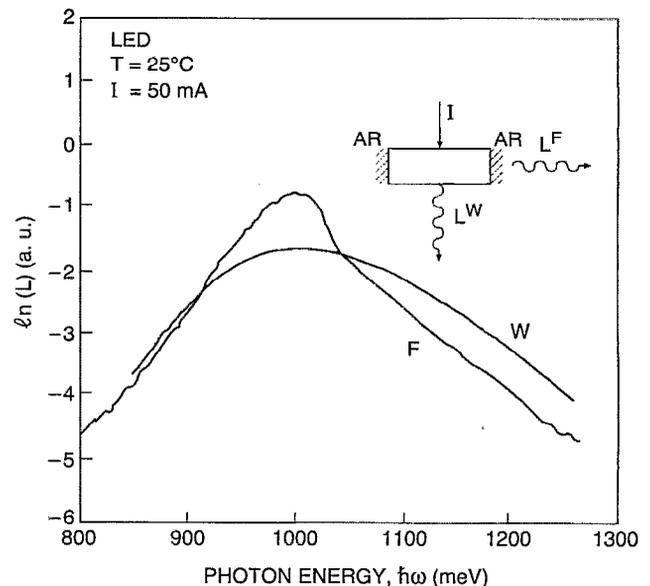

FIG. 1. Measured emission spectrum of TE-polarized facet light L^F and unpolarized window light L^W of an antireflection coated light emitting diode at an injection current $I = 50$ mA and temperature $T = 298$ K (25 °C). L^W has been corrected for free carrier absorption in the n-type InP substrate.
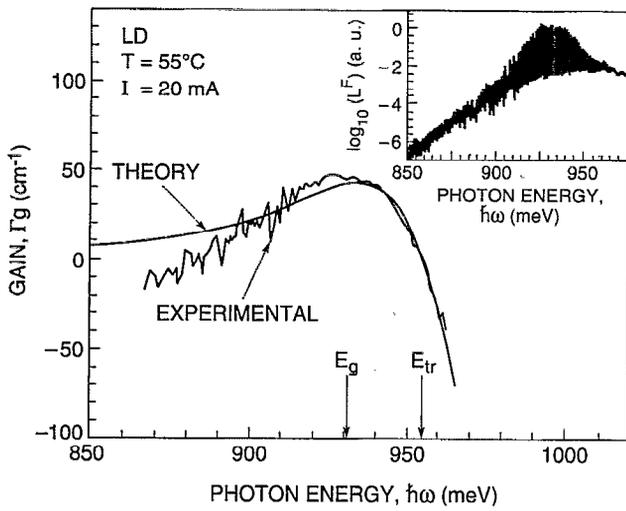
FIG. 2. Experimental and theoretical TE-polarized gain spectrum of a laser diode for injection current $I = 20$ mA at temperature $T = 328$ K (55 °C). This comparison provides an estimation of carrier density $n = 1.7 \times 10^{18}$ cm^{-3}. From n we obtain $\Delta E_g = -26.3$ meV and given $E_g^0 = 956.8$ meV, we obtain $E_g = 930.5$ meV. The inset shows the Fabry–Perot modulated emission spectrum for facet light.

The window light intensity L^W is proportional to the spontaneous emission rate per unit volume per unit energy interval $R_{sp}(\hbar\omega)$ multiplied by the volume of the cavity, wld, and a factor which accounts for free carrier absorption α_{fc} in the n-type substrate of thickness d_s. We may write

$$L^W = \hbar\omega R_{sp} wld A^W \exp(-\alpha_{fc}d_s)\Delta\epsilon, \quad (1)$$

where $\Delta\epsilon$ is the energy resolution of the spectrometer and A^W is the window aperture function. Gain as a function of photon energy, $\hbar\omega$, is calculated from the spontaneous emission spectrum making use of the relationship[4]

$$g(\hbar\omega) = \hbar\left(\frac{c\pi}{\omega n_g}\right)^2 [1 - \exp\beta(\hbar\omega - \Delta\mu)] R_{sp}(\hbar\omega), \quad (2)$$

where $\beta = 1/k_B T$, c is the speed of light, and n_g is the refractive index. R_{sp} is calculated taking into account conduction band non-parabolicity and the presence of both heavy- and light-hole valence bands.[5]

The facet light intensity experiences gain or loss described by an amplification factor $[\exp(g'l) - 1]/g'l$.[6] Hence,

$$\ln\left(\frac{L^F}{L^W}\right) = \ln\left(\frac{[\exp(g'l) - 1]}{g'l}\right) + \ln\left(\frac{A^F}{A^W}\right) + \alpha_{fc}d_s. \quad (3)$$

In this expression A^F is the aperture function for the facet and gain, g', includes the influence of the confinement factor.[5] From a logarithmic plot of L^F/L^W, we determine the transparency energy E_{tr} which we then use to extract the carrier concentration n using our gain model.

For the laser diode we independently measure gain spectra over a wide energy range using the Hakki–Paoli method.[7] Typical results of doing this are shown in Fig. 2.
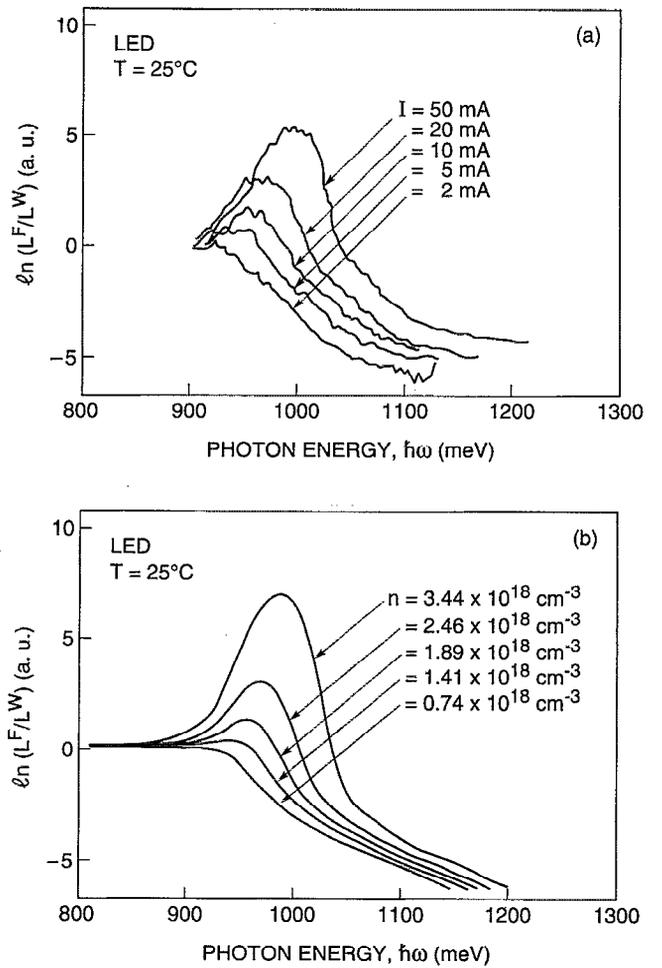

FIG. 3. (a) Measured ratio of TE-polarized facet and unpolarized window LED light, L^F/L^W, corrected for free carrier absorption in the substrate. Injection currents are $I = 50$, 20, 10, 5, 2 mA at temperature $T = 298$ K (25 °C). (b) Theoretical results for experimental conditions in (a). Carrier density for the corresponding current in sequence in (a) is indicated.

As may be seen, apart from low-energy scattering or Urbach band tailing effects[8,9] our theoretical model agrees well with experiment. Using this model, we determine the carrier density from the overall gain spectrum and the transparency energy $E_{tr} = E_g^0 + \Delta E_g + \Delta\mu$, where $\Delta E_g = -\zeta n^{1/3}$ is the approximate carrier induced band gap shrinkage,[10] $\zeta = 2.2 \times 10^{-5}$ meV cm, and $\Delta\mu$ is the difference between the chemical potential μ_e for the conduction band and μ_h for the valance band, measured from the band edges. Furthermore, the value of E_{tr} is independently confirmed by using a wavelength tunable laser to measure the photon energy at which net gain is zero.[11]

In Fig. 3(a) we show the results of plotting the natural logarithm of the ratio of facet light to window light for various LED injection currents. Figure 3(b) gives results of calculating this ratio using our gain model. The agreement between experiment and model is very good considering the lack of reported data on the interband matrix elements for InGaAsP materials. Here we take a linear interpolation using the E_p (energy equivalent interband momentum matrix element) values of InAs, InP, GaAs,
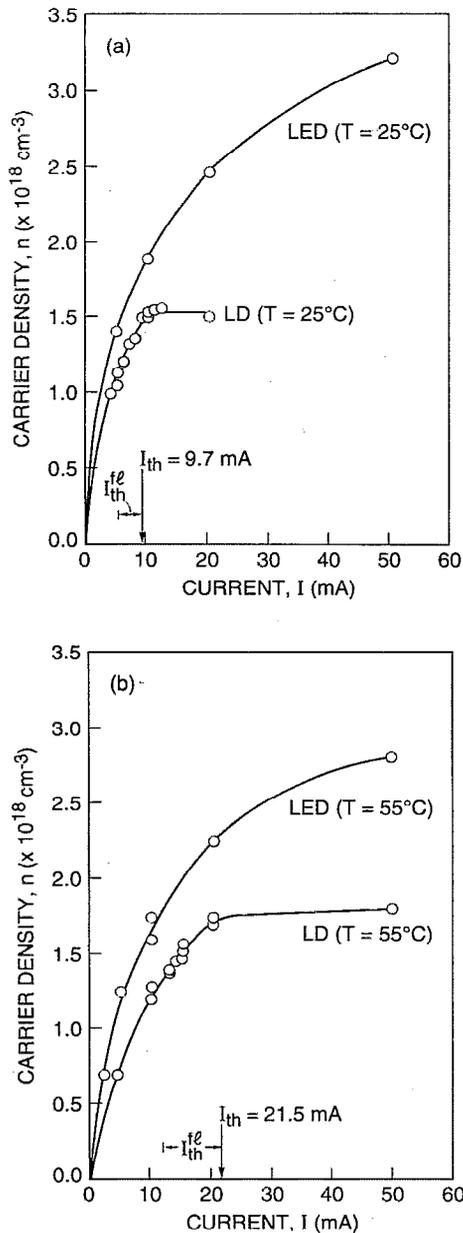
FIG. 4. Carrier density for LED and LD as a function of injection current determined from experiment and theory. In (a) temperature is $T = 298$ K (25 °C), laser diode threshold current is $I_{th} = 9.7$ mA, and $I_{th}^{fl} = 4$ mA and in (b) temperature is $T = 328$ K (55 °C), laser diode threshold current is $I_{th} \simeq 21.5$ mA, and $I_{th}^{fl} = 10$ mA.

and GaP.[12] It can be seen from Figs. 2 and 3 that there is a sharp decrease in gain near the transparency energy E_{tr}. This behavior, when combined with our band structure calculation, allows an estimation of carrier density.

In Fig. 4 we show carrier density n vs current for LD and LED for two different temperatures. It is apparent from the data that carrier pinning in the LED is both less substantial and less temperature sensitive than in the LD. Photons fluctuating into cavity modes of the laser cause carrier density to be pinned more effectively than in the corresponding LED device. Thus, to reach lasing threshold, it is necessary to provide an extra current I_{th}^{fl} to overcome the effects of this pinning. We define I_{th}^{fl} as the difference in drive current between LED and LD to reach the laser diode's threshold carrier density, n_{th}. Scrutiny of Fig. 4 shows that I_{th}^{fl} accounts for almost half the LD threshold current, I_{th}. At elevated temperatures carrier density at threshold increases so that the relative importance of fluctuations is enhanced and I_{th}^{fl} increases. Naturally, such subthreshold fluctuations act as a feedback mechanism which cause laser threshold current I_{th} to increase with increasing temperature.

The above results imply that I^{fl} plays an important role in determining the temperature dependence of threshold current in long wavelength laser diodes. Presumably, it is necessary to use multimode rate equations[13,14] to approximately take into account the temperature dependence of I^{fl}. In addition to photon mode fluctuations, any such calculation must correctly deal with amplified spontaneous emission and the carrier density dependence of the fraction of spontaneous emission coupling into a given mode.

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