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Fermi level pinning and differential efficiency in GaInP quantum well laser diodes

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Analysis of spontaneous emission spectra of GaInP quantum well laser diodes above and below threshold show that the quasi-Fermi level separation pins within the quantum wells but not throughout the whole device structure. By reproducing the temperature and cavity length dependence of the external differential efficiency using these measurements it is shown that a value of internal differential efficiency which is nonunity is due to current spreading and incomplete carrier injection and that the temperature dependence is due to the temperature dependence of the efficiency with which carriers are injected into the quantum well. © *1997 American Institute of Physics.* [S0003-6951(97)02409-1]

In semiconductor laser diodes, the carrier density and quasi-Fermi level separation are considered to be ''pinned'' at fixed values above threshold and, although the modal gain only approaches the optical loss asymptotically,[1] above threshold the carrier density exceeds ~99% of its asymptotic value. This pinning has implications for the efficiency with which electrons are converted to stimulated photons within the device active region. Since both the spontaneous emission and nonradiative recombination increase with the carrier density, they also ''pin'' above threshold and the stimulated emission should consume every additional electron leading to an internal differential quantum efficiency of unity.

The internal differential efficiency is usually derived[2] from the linear relation between the external differential efficiency above threshold $(\eta_{ext}^d)^{-1}$ and the device length (L_c):[3]

$$\frac{1}{\eta_{ext}^d}=\frac{1}{\eta_0^d}\left(\frac{\alpha_i L}{\ln(1/R)}+1\right), \tag{1}$$

where α_i is the internal optical mode loss and R is the reflectivity of both laser facets; η_{ext}^d is obtained from the slope of the curve of optical power per facet, P_{ext}, versus current, I:

$$\eta_{ext}^d=\frac{2e}{h\nu}\frac{dP_{ext}}{dI}, \tag{2}$$

for devices of different cavity length ($h\nu$ is the photon energy of the laser light).

Values of internal differential efficiency derived experimentally in this way are routinely found to be less than unity, and in some cases η_0^d is also found to be temperature dependent,[4] which leads to the simple interpretation based on pinning to be questioned. The behavior of η_0^d often seems to follow the behavior of the total threshold current and the overall internal radiative quantum efficiency of the active region, defined as the ratio of the radiative spontaneous recombination rate to the total recombination rate in the active region; consequently the value of η_0^d has come to be regarded as a figure of merit of the ''quality'' of the active material even though sound physical arguments suggests otherwise.

We present an experimental investigation of the factors that determine the value η_{ext}^d measured from the $P_{ext}(I)$ curve in 670 nm GaInP quantum well lasers. These devices have η_0^d of ~0.80 at room temperature and η_{ext}^d per facet decreases from 0.37 in the range 280–320 K to as low as 0.22 at 380 K for a 250-μm-long device. Spontaneous emission spectra measured as a function of current above and below threshold show that the Fermi levels pin within the well but not throughout the whole device structure. From this data we can reproduce quantitatively the values of $\eta_{ext}^d(T)$ for devices of different length, and we show that values of η_0^d less than unity are not in conflict with Fermi level pinning in the gain region and a stimulated emission process which is 100% efficient.

Throughout we are concerned with *differential* efficiencies measured above threshold [Eq. (1)] which we indicate by the superscript ''d'' and which we distinguish from the overall radiative efficiency which is often used as a phenomenological parameter to relate the total device current to the spontaneous recombination current at threshold. The differential nature implies that only those carrier loss processes that increase above threshold contribute to a decrease of the internal differential efficiency.

We write the internal differential efficiency in terms of three components:

$$\eta_0^d=\eta_s^d\eta_i^d\eta_r^d. \tag{3}$$

The term η_s^d is associated with lateral *current spreading* and represents the fraction of the increase in external current which results in an increase in the current entering the active geometrical area producing the optical gain of the device. It is only within the geometrical area of the device that the Fermi levels pin above threshold.

The term η_i^d is the *injection efficiency* representing the fraction of increase in current entering the active area of the device which results in an increase in the total recombination current in the quantum well. It is less than unity if the Fermi levels do not pin outside the quantum well, and it represents current flow associated with recombination in the barrier and drift and diffusion through the cladding layers.

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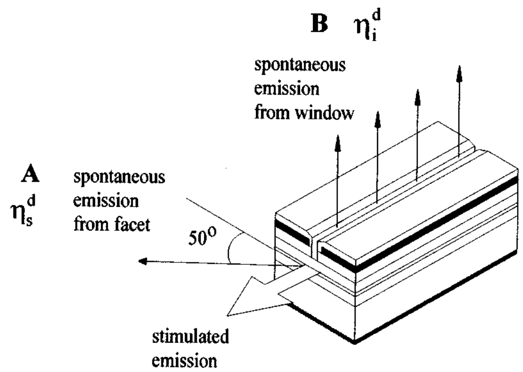

FIG. 1. Schematic diagram showing the experimental arrangement used to measure η_s^d by observing spontaneous emission from the end facet and to measure η_i^d by observing spontaneous emission through a top contact window.

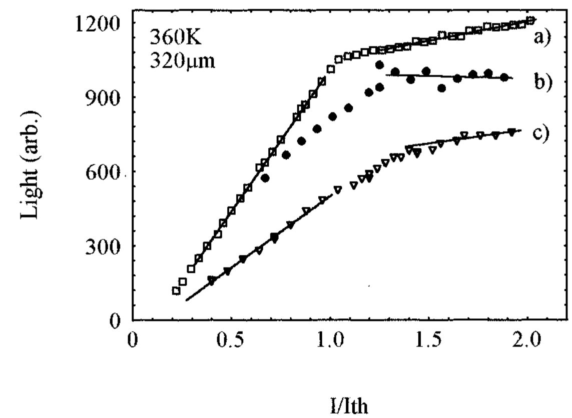

FIG. 2. Spontaneous emission measurements on 320-μm-long lasers at 360 K plotted relative to threshold current. Curve (a) is spontaneous emission from the end facet (measurement A in Fig. 1). (b), (c) Measured as B in Fig. 1 with (b) representing the spectrally integrated light from the quantum well and (c) being that from the barrier/waveguide region.

Finally η_r^d is the differential *radiative efficiency* of the quantum well itself and describes the fraction of the increase in current entering the well which results in an increase in the radiative recombination current within the quantum well. If the Fermi levels in the well pin, the increase in the radiative rate is associated with stimulated emission alone, since both spontaneous and nonradiative rates remain constant, and above threshold η_r^d is very close to unity. We have confirmed by a rate equation analysis[1] that η_r^d is greater than 98% for the lasers used here that have a spontaneous emission factor, $\beta_{\rm spon}$, of about 10^{-3}. Values of η_0^d less than unity, and which are temperature dependent, therefore arise from the behavior of η_s^d and η_i^d and the measurement of these contributions to the efficiency is the subject of this letter.

We make use of two different measurements of the spontaneous emission from a laser device to evaluate η_s^d and η_i^d as illustrated in Fig. 1. The devices were 50-μm-wide, oxide-isolated, striped lasers with cleaved facets operated in a pulsed mode at duty cycle of 5×10^{-4}. To evaluate η_s^d we monitored spontaneous emission from the end facet.[5] To discriminate against the intense stimulated emission at 675 nm we used a monochromator to detect light at 630 nm (within the spontaneous emission spectrum of the well) and detection at an angle of 40° to the laser facet. Figure 2(a) shows this spontaneous emission intensity from the quantum well as a function of drive current. The abrupt reduction of the slope of this curve above threshold corresponds to pinning of the Fermi levels within the gain region, and increases in current above threshold only increase the spontaneous emission rate in the current spreading region where the Fermi levels are not pinned. From the change in slope of light-current curves such as in Fig. 2(a) we deduce values for η_s^d of 0.80, 0.84, and 0.86 for lasers with cavity lengths of 250, 320, and 450 μm, respectively. We find that η_s^d is independent of temperature over the range investigated, 280–400 K.

To evaluate η_i^d we monitored the spectrum of spontaneous emission emerging from a narrow ~4-μm-wide window in the top p contact,[6] as shown diagrammatically in Fig. 1. This emission from the gain-generating region sampled by the window is not affected by current spreading. From the spectra we can spectrally resolve and integrate the spontaneous emission intensity from the well and from the barrier/waveguide core region. Figure 2 curve (b) shows the emission from the well for a 320-μm-long device at 360 K. This increases initially with current then saturates above threshold indicating that the Fermi level separation in the well pins when stimulated emission dominates. The spectrally integrated barrier emission for a 320-μm-long laser at a temperature of 360 K is shown as curve (c) of Fig. 2: Although the slope of the plot decreases above threshold, the barrier emission does not saturate even when the Fermi levels in the well are observed to pin. The absence of Fermi level pinning in the barrier indicates that η_i^d must be less than unity. In fact as the temperature increases, the change in slope from below to above threshold becomes smaller and any tendency of the Fermi levels to pin in the barrier becomes weaker.

The injection efficiency into the well is determined by carrier loss in the barrier and in the cladding layers. If we assume that the relation between the rate of carrier loss through the cladding and that through the barrier is the same above and below threshold, then it can be shown that the ratio of the slopes in Fig. 2(c) above and below threshold is[7]

$$\frac{\left(\dfrac{\Delta P_{\rm ext}}{\Delta I}\right)^{\rm barrier}_{\rm above}}{\left(\dfrac{\Delta P_{\rm ext}}{\Delta I}\right)^{\rm barrier}_{\rm below}} = \frac{(1-\eta_i^d)}{(1-\eta_i)}, \tag{4}$$

where η_i is the injection efficiency below threshold. If η_i does not change significantly with current, then the values of the *differential* injection efficiency and the *overall* injection efficiency are similar; we estimate them to be within 10%. The internal quantum efficiency for spontaneous emission in the well at high injection is close to unity so the efficiency of spontaneous emission from the end facet below threshold is primarily the injection efficiency and current spreading. At low-temperature (<280 K) where $I_{\rm th}$ is linear in T there is no leakage and the current is only affected by current spreading; consequently, extrapolating this linear region to high temperature we estimate values for $\eta_i(T)$ as the ratio of the

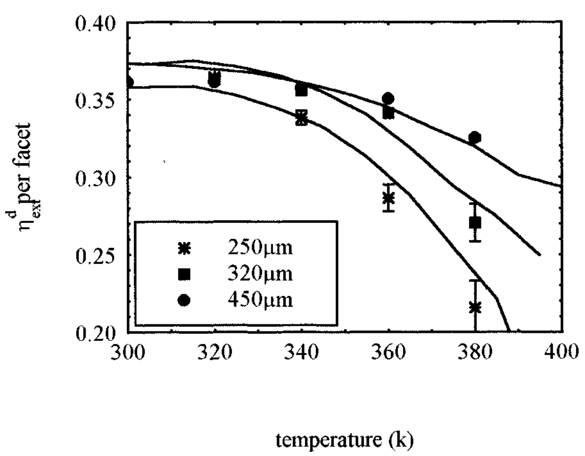

FIG. 3. The external differential efficiency as measured from the slope of the power output vs current characteristic (lines, average of eight devices) and as derived from measurements of the component contributions (solid symbols) plotted as functions of heatsink temperature for devices with lengths of 250 μm (stars), 320 μm (squares), and 450 μm (circles).

linearly extrapolated current to the total current at each temperature. Values of η_i obtained in this way include carrier loss associated with the barrier and cladding regions of the structure. We have repeated our measurements as a function of temperature and for devices 250, 320, and 450 μm in length. We find that the injection efficiency is temperature dependent, with values of η_i^d of about 1 at room temperature decreasing to 0.58 at 380 K in the 250 μm devices (the largest effect).

We have combined our values of η_s^d and $\eta_i^d(T)$ to obtain values of $\eta_0^d(T)$ using Eq. (3) (taking $\eta_r^d=1$) and, taking $\alpha_i=3$ cm^{-1} and $R=0.3$ in Eq. (1), we have calculated experimentally derived values for $\eta_{ext}^d(T)$ shown as the data points in Fig. 3. The lines in Fig. 3 are values of $\eta_{ext}^d(T)$ measured from the slopes of the $P_{ext}(I)$ curves of the same devices according to Eq. (2). The good agreement between the two sets of data as functions of temperature for three different cavity lengths indicates that values of η_{ext}^d less than unity obtained from $P_{ext}(I)$ curves are due to current spreading and incomplete carrier injection into the well. The temperature dependence of η_0^d is due to the temperature dependence of the injection efficiency.

Measurements of spontaneous emission demonstrate that the quasi-Fermi levels pin within the quantum wells but not throughout the whole device structure. From our measurements we have been able to derive values of the external differential efficiency as a function of both temperature and device length that agree with those obtained from the slope of the power output versus current characteristics. We have shown that a value of η_0^d less than unity is not in conflict with Fermi level pinning within the active region and a stimulated emission process that is 100% efficient.

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