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Non-uniform carrier distribution in multi-quantum-well lasers

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We describe an approach to detect the presence of a nonuniform distribution of carriers between the different wells of multi-quantum-well laser diodes by measuring the gain and spontaneous emission spectra and demonstrate its application to a five-well sample that has a nonuniform carrier distribution at low temperatures. © *2003 American Institute of Physics.*
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It is well known that multiple quantum wells (MQWs) can enhance laser performance by increasing the differential gain and by reducing the quasi-Fermi-level (QFL) separation required to achieve threshold gain (assuming optical loss remains the same). This latter benefit is particularly advantageous in short-wavelength GaInP-based devices, in which thermally activated leakage can be reduced by such an approach. However, it is also well established that if carriers are nonuniformly distributed among the wells, then device performance is adversely affected.[1–3] This nonuniform distribution is thought to occur due to poor transport of electrons or, more usually, holes across the multiwell structure, and results in different populations of carriers in different wells, while each well is separately in thermal equilibrium described by its own QFL.[1–3] Evidence of nonuniform carrier distribution between the wells of MQW lasers has been obtained through analysis of special devices fabricated with wells of different widths (e.g., Refs. 4, 5). However, it would be useful to have a technique that could be used with any device structure. In some situations, measurements of the polarization dependence of the modal gain may indicate the presence of a nonuniform carrier distribution.[6] In this work, we present a technique that can be more generally applied, and give an example where a nonuniform carrier distribution is observed in 650-nm-emitting MQW devices, which emit primarily in a single polarization.

The laser structure we use contains five wells of equal widths of 5 nm, with 5-nm separation and, because the wells are compressively strained to achieve the 650-nm emission wavelength, it emits primarily in TE polarization. The barriers and waveguide core of $(Al_{0.55}Ga_{0.45})_{0.5}In_{0.5}P$ are clad with layers of $(Al_{0.70}Ga_{0.30})_{0.52}In_{0.48}P$. The whole structure was grown and supplied by IQE (Europe) Ltd using metal-organic vapor-phase epitaxy upon off-axis GaAs substrates to achieve disordered material.

The use of narrow wells with narrow interwell barriers leads to strong coupling of the electron wave functions and a miniband of allowed electron states as calculated using a simple shooting method and literature values of material parameters.[7] A similar result is obtained for the light-hole (lh) states, whereas the heavy-hole (hh) states are effectively uncoupled due to the significantly larger heavy-hole masses for both well and barriers (see Table I). We evaluate the degree of coupling by calculating the transmission probability spectrum for an electron or hole across the structure, again using a shooting method approach, and determining a tunneling time using $\tau = \hbar/\Delta E$,[8] where ΔE is the half-width at half-maximum of the Lorentzian transmission probability distribution. The times for the electron, lh, and hh states are given in Table I. An equilibrium distribution can be established if the electron–hole recombination time, which is of the order of nanoseconds, is long compared to the tunneling time. This is the case for electrons and lhs, but not for the hhs. The calculations also show that there is a 41-meV energy gap between the hh energy states and the lh miniband. At low temperatures, where the lh miniband is not significantly populated, the distribution of holes can only occur via the drift and diffusion of holes across the wells, reflecting the physics of an uncoupled sample. At higher temperatures, the lh miniband will be significantly populated and will equalize the hole population in the different wells. Thus, within a single sample, we have at different temperatures a set of coupled QWs in which the carriers should be distributed among the wells, and a situation in which the valence wells are effectively decoupled, allowing a nonuniform hole distribution to develop.

To investigate the carrier distribution, we will make use of the measurement of modal gain, QFL separation, and spontaneous emission using the segmented contact method[9] to allow us to monitor the carrier temperature and to calculate a population inversion distribution function.[10] Following Ref. 11, we can write expressions for the modal gain in polarization p per unit length and the spontaneous emission rate per unit area per unit energy in polarization p as follows:

TABLE I. Values of mass as multiples of the free electron mass, m_0 for electrons, lhs and hhs. Calculated tunneling time for the five ground-state solutions of the five-well structure for electrons, lhs, and hhs.

	Mass $\times m_0$		Time, τ/ns Transition number				
	Well	Barrier	1	2	3	4	5
e	0.098	0.127	0.3	0.1	0.07	0.1	0.3
lh	0.148	0.167	0.2	0.06	0.04	0.06	0.2
hh	0.452	0.475	439	146	110	146	439

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$$G^p(h\nu)=\frac{4\pi\hbar}{nc\epsilon_0(h\nu)}\left(\frac{e}{2m_0}\right)^2|M^p|^2\left[\int F_v^{\bullet}(z)F_c(z)dz\right]^2 \times\rho_{\rm red}(h\nu)[f_1(E_1)-f_2(E_2)]\left(\frac{\Gamma}{L_z}\right), \quad (1)$$

$$I^p_{spon}(h\nu)=\left(\frac{1}{3}\right)\frac{16\pi n}{c^3h^2\epsilon_0}(h\nu)\left(\frac{e}{2m_0}\right)^2|M^p|^2 \times\left[\int F_v^{\bullet}(z)F_c(z)dz\right]^2 \times\rho_{\rm red}(h\nu)[f_1(E_1)(1-f_2(E_2)], \quad (2)$$

where $h\nu$ is the photon energy, M^p is the momentum matrix element for transitions of polarization p, F_c and F_v are the envelope functions of the localized states within the QW of width L_z, $\rho_{\rm red}$ is the reduced two-dimensional density of states, f_1 and f_2 are the occupation probabilities of the states at energies E_1 and E_2, where $h\nu=E_1-E_2$, and Γ is the optical confinement factor. By taking the ratio of the gain to the spontaneous emission rate, we can determine the inversion factor[10] defined as

$$P_f(h\nu)=\left[\frac{G^p(h\nu)}{I^p_{\rm spon}(h\nu)}\right]\frac{n^2(h\nu)^2}{\pi^2\hbar^3c^2}\left(\frac{L_z}{\Gamma}\right) =\frac{f_1(E_1)-f_2(E_2)}{f_1(E_1)[1-f_2(E_2)]}. \quad (3)$$

The use of the ratio of the experimentally determined gain and spontaneous emission rate to derive the population inversion factor is correct providing the gain and spontaneous emission at a given energy originate from a single pair of states, and this is true irrespective of whether the probabilities f_1 and f_2 are given by Fermi–Dirac statistics or by some other distribution function. However, more than one pair of states can satisfy k-selection and the condition that $E_1-E_2=h\nu$, where the subscripts 1 and 2 represent upper and lower energy states, respectively, and in this case, the matrix element and density of states of Eqs. (1) and (2) may not cancel. For the case of carriers in quasi-equilibrium, the probabilities are given by Fermi–Dirac statistics and

$$P_f(h\nu)=\frac{f_1(E_1)-f_2(E_2)}{f_1(E_1)[1-f_2(E_2)]}=1-\exp\left(\frac{h\nu-\Delta E_f}{kT}\right), \quad (4)$$

where ΔE_f is the QFL separation. In this quasi-equilibrium case, it can be shown that the measured P_f, which is derived from the sum of the gain and spontaneous emission terms arising from all relevant pairs of states, is given by Eq. (5) and represents the population inversion of each pair of states producing the same transition energy. In this case, the experimental approach to derive P_f is correct irrespective of the numbers of pairs of states involved in the gain and recombination processes:

$$P_{\rm meas}(h\nu)=\left[\frac{\Sigma\, G^p(h\nu)}{\Sigma\, I^p_{\rm spon}(h\nu)}\right]\frac{n^2(h\nu)^2}{\pi^2\hbar^3c^2}\left(\frac{L_z}{\Gamma}\right) =\frac{f_1-f_2}{f_1(1-f_2)} =1-\exp\left(\frac{h\nu-\Delta E_f}{kT}\right). \quad (5)$$

If the carriers are not in quasi-equilibrium, each pair of states with the same transition energy has a different value of P_f. The derived value does not then follow the form of Eqs. (4) and (5), and does not represent the inversion of any particular pair of states.

Measurements of gain and spontaneous emission rate can be used to derive the P_f function and comparison with the form of Eq. (5) used to determine whether a system is in thermal equilibrium. A nonuniform distribution of carriers in identical QWs is a specific form of the nonequilibrium case, in which the distributions of carriers in each well can each be described by a QFL but where this QFL is different for each well and, in this case, the measured P_f function will not be described by Eq. (5). To differentiate between this and a nonequilibrium situation in which the carriers in each well cannot be described by Fermi–Dirac statistics, we examine the spontaneous emission spectrum. The spontaneous emission rate per unit volume at energy $h\nu$ can be written as[12]

$$I^p_{\rm spon}(h\nu)=\frac{n^2(h\nu)^2}{\pi^2\hbar^3c^2}\alpha(h\nu)\exp\left(\frac{\Delta E_f-h\nu}{kT}\right), \quad (6)$$

where the carriers are assumed to be in thermal equilibrium and α is the equilibium absorption at an energy $h\nu$. For measurements at high photon energy, the absorption coefficient should be independent of injection level and in a QW approximately constant with energy, allowing us to determine the carrier temperature T, from a suitable plot of the spontaneous emission versus energy. For measured data that arises from the summation of spontaneous emission from identical QWs that are independent carrier reservoirs, each characterized by a separate QFL separation but the same carrier temperature, the analysis will still provide the carrier

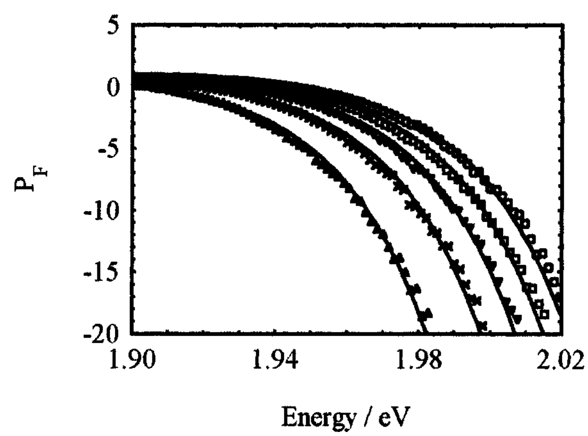

FIG. 1. Experimentally determined population inversion factors (points) at 300 K for drive current densities between 830 and 2500 A cm^{-2}. The lines represent the calculated Fermi–Dirac distribution using the QFL separation derived from the gain spectrum measurement and a carrier temperature of 300 K.

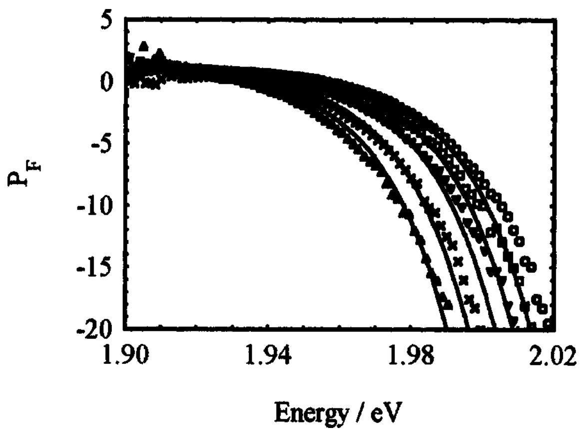

FIG. 2. Experimentally determined population inversion factors (points) at 220 K for drive current densities between 500 and 1170 A cm^{-2}. The lines represent the calculated Fermi–Dirac distribution using the QFL separation derived from the gain spectrum measurement and a carrier temperature of 230 K.

temperature, whereas a nonthermal distribution of carriers will not result in a distribution of the spontaneous emission according to Eq. (6).

The values of P_f as a function of energy derived from the experimental data at room temperature (300 K) and at 220 K are plotted in Figs. 1 and 2, respectively. The 300-K data points follow the lines, calculated for a Fermi–Dirac distribution as given in Eq. (4), as is expected for a uniform thermal carrier distribution. The data taken at 220 K do not agree with those calculated using Eq. (4), the measured QFL separation, and the measured carrier temperature of 230 K (see subsequent discussion), indicating that a simple thermal distribution of carriers is not appropriate. To differentiate between the case of a nonuniform distribution consisting of independent populations of carriers that are separately in thermal equilibrium with the lattice and the case of a nonthermal distribution, we plot the spontaneous emission rate spectra, measured using the segmented contact data, and used previously to derive the values of P_f, for three carrier densities between 500 and 1170 A cm^{-2} in Fig. 3.

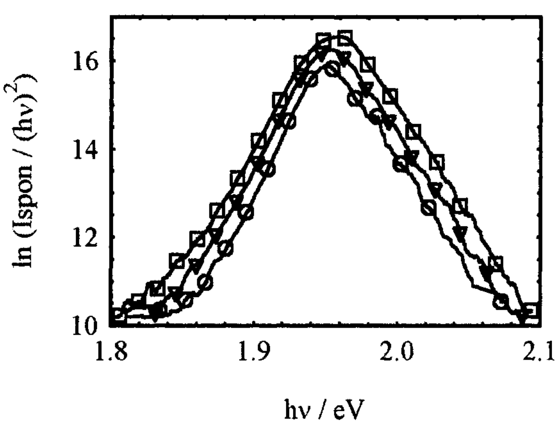

FIG. 3. The spontaneous emission spectra for drive current densities between 500 and 1170 A cm^{-2} at 220 K. The slope suggests that the carrier temperature is 230 K.

The data in Fig. 3 have the dependence expected according to Eq. (6) over the high energy portion from 1.98 to 2.08 eV, and straight line fits over this region yield the same carrier temperature for each current density of (230±5) K, where the uncertainty is two standard errors. The small difference between this temperature and 220 K measured using the cryostat temperature sensor is thought to be due to the thermal gradient between the device and the sensor placed at a distance of 5 cm. The scenario of a nonthermal distribution of carriers within a single QW can be discarded because this would not be expected to produce a spontaneous emission spectrum that could be characterized by a single carrier temperature over a wide energy range or a single carrier temperature that was independent of injection level. Taken in combination, the measurements of spontaneous emission spectra and P_f spectra are consistent with a nonuniform distribution of carriers among the QWs, but with distributions that are in thermal equilibrium within each well.

In summary, we have described a technique that allows us to measure the presence of a nonuniform distribution of carriers in multiple-quantum-well samples. Using a carefully designed structure, we make measurements that demonstrate the presence of a uniform distribution at room temperature and a nonuniform distribution at low temperatures.

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