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Measurement of transverse electric and transverse magnetic spontaneous emission and gain in tensile strained GaInP laser diodes

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We have measured the modal gain and spontaneous emission spectra of a 0.8% tensile-strained GaInP laser structure in transverse electric (TE) and transverse magnetic (TM) polarizations by analysis of the single-pass amplified spontaneous emission from the end of a segmented-contact structure. The absolute values of the true spontaneous emission rates have been determined for both polarizations. Data for the TE_y and TM peak gain as functions of the total intrinsic radiative current can be fitted with the usual logarithmic relation with a transparency current density of 99 A cm^{-2} and with the (electron–light-hole) TM/TE_y gains in the ratio 4:1 as predicted from the oscillator strengths. Spontaneous emission into the TM modes accounts for 48% of the total radiative current.
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It is well established that lattice strain can have a beneficial effect on the threshold current of quantum-well lasers through changes in recombination rates and optical gain arising from strain-induced modification of the valence band structure. The strain separates the light-hole (lh) and heavy-hole (hh) valence subbands by up to several (k_BT) at room temperature, such that under compressive (tensile) strain the hh (lh) band is uppermost.[1] Compressively strained and unstrained devices emit in the transverse electric (TE) polarization mode and the effect of compressive strain is to reduce the transverse magnetic (TM) radiative recombination rate, resulting in improved characteristics of TE gain versus total current. With sufficient tensile strain, the gain in the TM modes exceeds that of the TE modes and the devices emit TM polarized laser light. Reductions in threshold current with tensile strain can be achieved due to the lower density of states associated with the lh valence subband which is uppermost. Strain has been particularly beneficial in red-emitting AlGaInP lasers and this material provides a model system for experimental study of strain effects because Auger recombination is negligible and the only intrinsic contribution to the threshold current is radiative recombination.

The influence of strain on the operation of a laser is determined by its effect on both the optical gain *and* the spontaneous recombination rates associated with the TE and TM polarization modes. In practice, the threshold current is also influenced by extrinsic nonradiative processes and the injection efficiency, so to achieve a complete and unambiguous experimental determination of the effects of strain, it is necessary to measure gain and spontaneous emission for both TE and TM polarizations. Optical gain in TE and TM modes can be measured either by the Hakki and Paoli method[2] which utilizes the contrast of the longitudinal modes in the subthreshold amplified spontaneous emission (ASE) spectrum, or by a stripe length method which utilizes the change in the ASE spectrum with pumped stripe length.[3] Both methods rely on observation of ASE from the end facet of an edge-emitting structure. The radiative recombination current is given by the sum of the spectrally integrated spontaneous emission spectra for light of TM polarization [electric field (E-field) vector perpendicular to the plane of the quantum well, i.e., along the z direction] and for TE_x and TE_y polarizations (E-field vector in the plane of the well, along the axis of the cavity and perpendicular to the axis of the cavity respectively). Measurement of true spontaneous emission spectra must be done so as to eliminate modification by optical absorption and gain, for example by making the observations in a direction normal to the axis of the laser cavity, usually by observation normal to the plane of the well (z direction) through a top-contact window[4] or through the substrate. With these geometries, the path length in the gain medium is very short (the width of the well) and other material along the path is nonabsorbing at the wavelengths of interest. However in this geometry, it is only possible to observe light of TE_x and TE_y polarizations. TE_x and TM polarized light can be observed through the side of the laser[5] but to avoid absorption in unpumped material it is necessary to make a high-mesa structure or a buried heterostructure which has a narrow stripe width to avoid amplification. Due to these difficulties, very few measurements of spontaneous emission in the TM mode have been reported. Thus, while it has been possible to study the effects of strain on TE and TM gain, it has not been possible to make a complete study of both TE and TM contributions to the radiative current, and experimental knowledge of the effects of strain on the gain current relation is incomplete.

The purpose of this letter is to describe measurements of both gain and true spontaneous emission spectra in TE and TM polarization modes using an analysis of ASE spectra observed from the facet of a segmented-contact laser struc-

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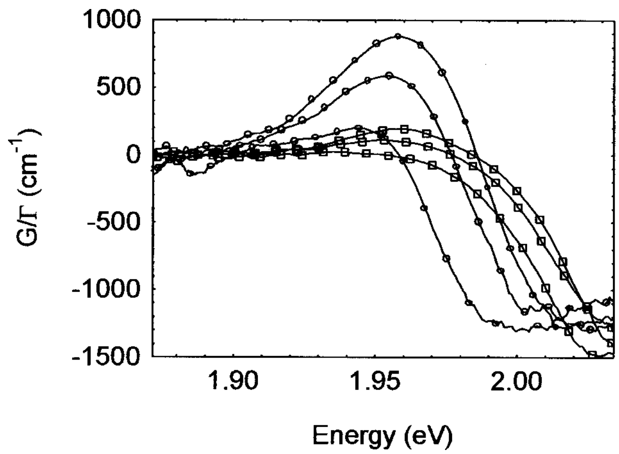

FIG. 1. TM (circles) and TE_y (squares) material gain spectra measured for different drive currents for a tensile strained quantum-well device at 300 K.

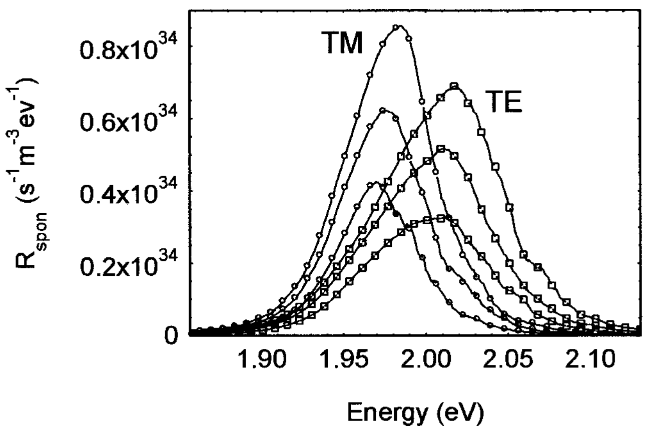

FIG. 2. TM (circles) and total TE (squares) spontaneous emission spectra for the same drive currents as Fig. 1 for a tensile strained quantum-well device at 300 K.

ture, using a technique which we have verified for TE emission.[6] We illustrate the method using red-emitting GaInP lasers where the relative merits of compressive and tensile strain for short wavelength lasers are still the subject of debate. We report results for a 15 nm wide 0.8% tensile-strained single GaInP quantum well with unstrained $(Al_{0.6}Ga_{0.4})InP$ barrier layers. This was fabricated into a 50 μm wide oxide isolated stripe structure with the facets angled by 10° to the plane of the quantum well by growth on an off-axis substrate. The growth conditions and misorientation were chosen to produce disordered material. Misorientaion and the long passive section at the rear of the device, ensured that ASE for only a single pass was observed, without round trip effects. Two electrically isolated contact segments of equal length were produced by etching through the top gold contact layer and GaAs cap layer, providing stripe lengths of 300 μm (I_L) or 600 μm (I_{2L}). A detailed description of the multisection structure is given in Ref. 7. Measurements were performed in pulsed mode at a duty cycle of $\sim$0.03% to avoid self heating effects.

The gain and the true spontaneous emission spectra were obtained from the ASE spectra measured for two pumped lengths.[6] Spectra of the net modal gain are given by the relation

$$G-\alpha_i=\frac{1}{L}\ln\left[\frac{I_{2L}}{I_L}-1\right], \tag{1}$$

where L is the length of one of the equal length segments, G is the modal gain, and α_i is the optical scattering loss. We note that this experiment gives the net modal gain directly in real units. The value of α_i was determined from the asymptotic value of net gain at low photon energy to be $16.5\pm3.0\ \mathrm{cm}^{-1}$ independent of current and polarization. With this value of α_i the material gain, g, was found from the relation $g=G/\Gamma$, where Γ is the optical confinement factor which we calculated to be the same for TE and TM modes for our structure. Figure 1 shows spectra of the material gain for TM (circles) and TE_y (squares) polarizations at 300 K for different drive currents.

True spontaneous emission spectra I_{spon} can also be derived from the same ASE spectra as used for the gain, using the relation[6]

$$I_{\mathrm{spon}}=\frac{1}{L}\ln\left[\frac{I_{2L}}{I_L}-1\right]\frac{I_L^2}{(I_{2L}-2I_L)}. \tag{2}$$

For TE polarization, we have shown that this process gives spectra of the same form as those observed through the top contact window.[6] Equation (2) gives results in arbitrary units as the ASE intensities are also in arbitrary units. We have calibrated the spontaneous emission by calculating the inversion factor

$$P_F=\frac{\gamma_i}{C_i}\frac{1}{\Gamma}\left(\frac{E_{h\nu}^2 n^2}{\pi^2\hbar^3c^2}\right)\left[\frac{G}{I_{\mathrm{spon}}}\right], \tag{3}$$

where C_i is a calibration factor which converts I_{spon} into real units and takes account of the collection geometry and the detector calibration. Equation (3) is based on the usual result for the spontaneous emission rate[8] which is derived for emission into two orthogonal modes propagating in all directions. In a quantum well, it is necessary to distinguish the two TE polarization modes, TE_x, TE_y from the TM_z polarization mode. Consequently, we assign a suffix to the calibration factor C_i where $i=$TE, TM, and allocate a value of $\gamma_i=2/3$ or 1/3 in the TE ($=TE_x+TE_y$) and TM polarizations,

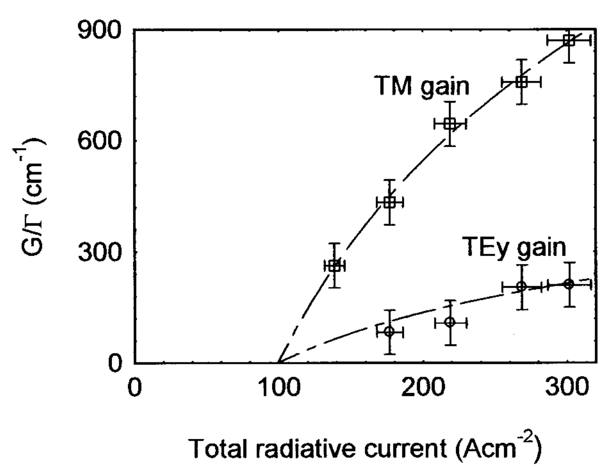

FIG. 3. Plots of experimental data for TM (circles) and TE_y (squares) peak optical gain as functions of the total radiative recombination current for a tensile strained quantum-well device at 300 K. The dash lines show the fitted logarithmic gain–current relations.

respectively. This form of Eq. (3) gives R_{spon} in units of s^{-1} m^{-3} eV^{-1} which assumes that the carriers are totally confined to the width of the quantum well.

The inversion factor is unity when the system is fully inverted irrespective of the form of the occupation probabilities for electrons and holes.[8] From the experimental data, the ratio (G/I_{spon}) tends to the same value at low photon energy for each current measured, indicating that the carrier populations are indeed fully inverted for states near the subband edges. Thus, the spontaneous emission data was calibrated by determining the value of C which makes P_F unity in this low energy regime. The absolute spontaneous emission rate into all TE modes and the TM modes is then given by

$$R^i_{spon}(h\nu) = C_i I^i_{spon}(h\nu). \tag{4}$$

Figure 2 shows results for the TE and TM spontaneous emission spectra at 300 K.

The spectra in Figs. 1 and 2 are consistent with the accepted picture for tensile strained structures. The (lh) subband is the uppermost valence subband and is responsible for emission at ~1.98 eV which is predominantly of TM polarization (Fig. 2). The TE emission spectra show that the electron (e)–hh transition, which is entirely TE polarized, occurs at about ~2.02 eV. This emission occurs because there is partial occupation of the lower-lying hh subband; the subband spacing is about $1.6\,k_BT$. The gain spectra in Fig. 1 similarly show that the TM gain is strongest and that there is a contribution to the TE_y gain at low photon energy from the $(e$–lh) transition.

By integrating the TE $(=TE_x+TE_y)$ and TM spontaneous emission spectra, we can determine the total radiative current and Fig. 3 shows the peak TE_y and peak TM gains versus total radiative current. The TM gain is dominant and these devices operate in the TM mode. The gain spectra in Fig. 1 show that over the range of current studied, the measured TE_y gain arises from $(e$–lh) transitions. Comparison of the areas of the TE and TM emission spectra show that spontaneous emission into the TM modes accounts for $(48\pm 2)\%$ of the total recombination current and this fraction is independent of current over the range studied. Comparison with the drive current density, taking account of current spreading, gives an overall quantum efficiency for spontaneous emission of $(20\pm 4)\%$ at room temperature. At this temperature, carrier leakage makes a contribution to the total current and therefore contributes to the inefficiency. A similar analysis at 200 K gives an overall quantum efficiency of $(42\pm 8)\%$.

The gain–current relation for a quantum well takes a logarithmic form

$$\frac{G}{\Gamma} = g = g_t \ln\left(\frac{J}{J_{trans}}\right), \tag{5}$$

where g_t is a gain parameter and J_{trans} is the transparency current density. We have fitted Eq. (5) to the data in Fig. 3. Since the TE_y and TM gain on this plot arise from $(e$–lh) transitions, we have imposed the requirements that the curves have the same transparency current density and that the TM and TE_y gain parameters are in the ratio of the TM and TE oscillator strengths for the $(e$–lh) transition at the band edge, which is 4:1.[9] Equation (5) provides a good representation of the data with these conditions with $g_t(\mathrm{TM}) = 1795\ \mathrm{cm}^{-1}$ and $J_{trans} = 99\ \mathrm{A\,cm}^{-2}$.

In summary, we have described experimental determinations of modal gain and spontaneous emission in both TE and TM polarizations by analysis of the single-pass ASE from the end of a diode laser structure. We have measured the TE and TM peak gain as functions of the total radiative current in a tensile strained GaInP structure and find that emission into the TM modes accounts for 48% of the total radiative current. The technique provides a complete characterization of the TE and TM contributions to the gain and radiative current necessary for a full analysis of the operation of strained layer structures.

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