Effect of tensile strain/well-width combination on the measured gain-radiative current characteristics of 635 nm laser diodes

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Effect of tensile strain/well-width combination on the measured gain-radiative current characteristics of 635 nm laser diodes

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Polarization sensitive measurements, in real units, of gain and spontaneous emission of GaInP lasers with three strain and well-width combinations allow us to isolate the intrinsic effects of strain when the well width is also adjusted to maintain a fixed output wavelength. Varying tensile strain and well width, for 635 nm operation, have no effect on transverse magnetic polarized recombination at fixed gain, which is consistent with a constant effective mass in the uppermost valence band, but the total transparency current decreases from 116 to 83 A cm^{-2} due to increasing separation of light and heavy hole bands. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1559658]

High performance laser diodes emitting within the 630 nm wavelength band are becoming increasingly important due to the benefits offered to applications such as photodynamic therapy and optical storage. Improvements in the performance of 630 nm lasers are still required and in this letter we address this issue at a fundamental level. We have measured, in real units, the spontaneous emission and gain spectra of laser diodes using our recently reported technique for spontaneous emission,[1,2] a development of the single pass, segmented contact gain measurement.[3] This approach allows us to separately measure TM polarized and TE polarized contributions to spontaneous emission and gain, which are essential to understand the operation of tensile strained lasers. The method has been applied to three single well structures that have different combinations of well width and tensile strain to maintain a constant emission wavelength of 635 nm. The results are consistent with the calculated valence band structure but additionally allow us to quantify the value of the benefits associated with the different combinations revealing that the effects of increasing strain, although useful, are mitigated by the decreasing role of quantum confinement. This experimental data corroborate general arguments we have previously made,[4] based on calculations, to explain the observed performance of the threshold current of 633 nm laser diodes.

The AlGaInP-based samples were supplied by IQE (Europe) Ltd. and were grown by metalorganic vapor phase epitaxy upon off-axis GaAs substrates. The Ga compositions for the compound $Ga_xIn_{1-x}P$ within the single quantum well were $x=0.58$, 0.60, and 0.61 for the three samples investigated, which translate to tensile strains of approximately 0.5%, 0.6%, and 0.7%, respectively. The thickness of the quantum well was different for each sample and was required to be 10, 12.5, and 15 nm, respectively, to achieve 635 nm laser emission. These samples are designated 1, 2, and 3 in order of increasing strain and well width as set out in Table I. This choice of combinations ensures dislocation-free structures as calculated using the Matthews–Blakeslee criterion.[5] Such a calculation shows the strain energy is below that necessary for defect formation for a value of the product of well width and percentage strain of ~200 Å% for these compositions[6] and our samples are all safely below this limit.

The three strain-well width combinations were incorporated into a waveguide and accompanying structure that was identical in each case. Barriers that were lattice matched to GaAs containing $(Al_{0.6}Ga_{0.4})InP$ were used along with AlInP optical cladding layers. The epitaxial material was fabricated into 1500 μm long oxide isolated stripes. Isolation etches were included every 300 μm to produce the contact segments for the measurement of gain and spontaneous emission via the variable excitation length method.[1–3] Gain and spontaneous emission spectra for the three combinations were measured in real units at 300 K using this approach. The radiative current density is defined as the current density necessary to support the spontaneous recombination process and is calculated by integrating the measured spontaneous emission spectrum, to evaluate the total number of photons per unit area per second, and multiplying by the electronic charge. Figure 1 displays the peak TM polarized gain versus total (TM+TE) radiative current characteristics. It can be

TABLE I. Nominal Ga composition (x in $Ga_xIn_{1-x}P$), corresponding strain and well widths for samples 1, 2, and 3 and values of tangential gain, transparency current density, and the proportion of TM polarized spontaneous emission derived from the results.

Sample	1	2	3
Ga composition	0.58	0.60	0.61
Strain/%	0.5	0.6	0.7
Well width/nm	10	12.5	15
G_t /cm^{-1}	51.4±4.5	44.0±1.2	49.0±2.0
J_0 /A cm^{-2}	116±12	87±9	83±8
TM/(TM+TE) spontaneous emission	0.54±0.06	0.61±0.1	0.65±0.08

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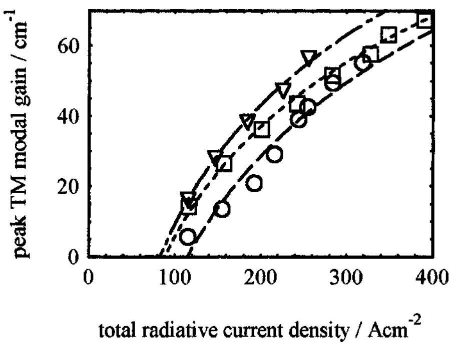

FIG. 1. Peak TM modal gain vs radiative recombination current from samples 1 (circles), 2 (squares), and 3 (triangles).

seen that as an increased tensile strain is incorporated within the quantum well a larger gain is achieved for the same radiative current. Gain-current curves of quantum wells are often described by a logarithmic function

$$G = G_t \ln\left(\frac{J}{J_0}\right), \tag{1}$$

which is characterized by the tangential modal gain parameter G_t and the transparency current J_0. Values of G_t and J_0 derived from the data of Fig. 1 are listed in Table I. There does not appear to be a trend in the values of G_t whereas the transparency current density decreases with increasing strain.

The calculated upper valence bands for the lowest and highest strain-well width combinations (samples 1 and 3) are shown in Fig. 2. All of the higher order energy levels within the well are included in the calculation, which employs a 6×6 Luttinger–Kohn Hamiltonian to take account of the spin-orbit split-off band and interactions between the various subbands that are known to be important in this material.[7] The inputs are the bulk material parameters from the literature.[6] The ideal tensile strained laser material has the upper light and heavy hole bands separated to such an extent that only the upper light hole band is significantly populated.[8] Furthermore, with increasing strain the upper band curvature should approach that of the conduction band so that the quasi-Fermi functions extend equally into conduction and valence band quantum wells reducing the spontaneous recombination current.[9] Previous work has demonstrated that increasing the strain alone (and allowing the wavelength to change) can increase the light hole to heavy hole band separation and increase the valence subband curvature in a way that is beneficial for laser action (e.g., Ref. 7). However,

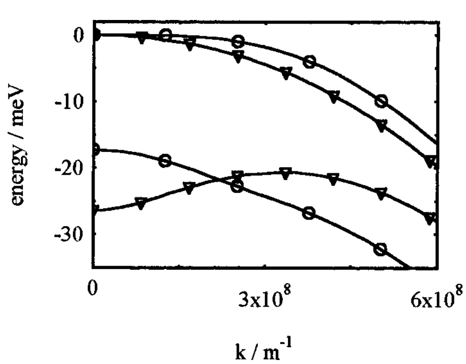

FIG. 2. Calculated upper valence bands for samples 1 (circles) and 3 (triangles).

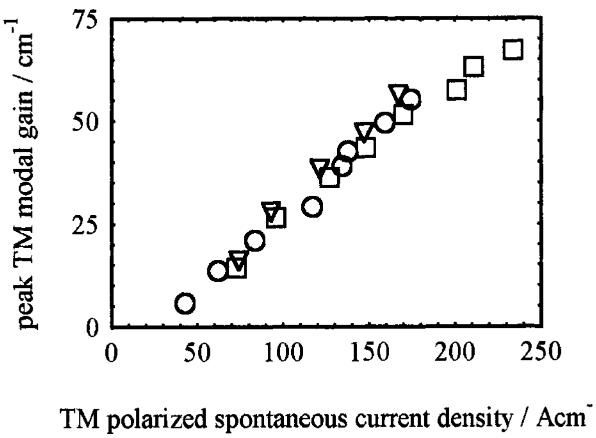

FIG. 3. Peak TM modal gain vs current associated with TM polarized radiative recombination only for samples 1 (circles), 2 (squares), and 3 (triangles).

here, to maintain the fixed emission wavelength, we have also increased the quantum well width as the strain is increased, which leads to a stronger interaction between the subbands. In Fig. 2 the upper, ''light hole,'' subbands are similar for the two structures with only a small increase in $E(k)$ curvature with increasing strain. More noticeable differences occur in the separation of light and heavy hole subbands. At zone center this separation increases by ~ 10 meV as the strain / well width is increased. However, in the widest structure the $E(k)$ curvature changes sign, due to stronger subband interaction, and so light to heavy hole band separation decreases at higher k values. Thus we might expect that the increasing separation of light and heavy hole bands would produce the largest changes in the results providing the bands are not populated out to large k values.

Our experimental technique provides independent measurements of TM and TE polarized spontaneous emission spectra and since electron transitions to the heavy hole subband are primarily TE polarized we can test the validity of the earlier assertions. In Fig. 3 we have plotted the peak TM gain versus the component of the radiative current arising from TM polarized emission. The TM gain versus TM polarized current curves for all three devices are extremely similar suggesting that there is little difference between the curvatures of the upper subband of the three samples in practice. The differences in current density in Fig. 1, and the differences in the transparency current density in Table I, arise due to changes in the TE polarized recombination associated with the second, heavy-holelike subband. This implies that the separation for both higher strain samples is large enough to reduce electron to heavy hole recombination and that only transitions near to zone center are relevant. This latter point is consistent with the relatively large curvature of the conduction band (mass of $\approx 0.114\times$ the free electron mass, m_0,[6] compared to value of approximately $1 \times m_0$ deduced from a parabolic fit to the upper valence bands of Fig. 2). The lack of any trend in the G_t parameter reaffirms that there is little change in the light hole band effective mass [or $E(k)$ curvature] between the three samples.

The proportion of TM polarized spontaneous emission to total (TM+TE polarized) spontaneous emission listed in Table I is an indication of the degree to which strain has reduced the contribution of the heavy hole subband. The proportions for all three samples are independent of total radiative current density, or level of pumping, within the experimental uncertainty. This lack of current dependence presumably arises because the increasing quasi-Fermi level separation is largely taken up by a change in the electron quasi-Fermi level. The relative movement of the quasi-Fermi levels is determined by the relative density of states of valence and conduction bands. Using the same valence and conduction band mass values as described earlier as $1\times m_0$ and $0.114\times m_0$ suggest that ~90% of any change in quasi-Fermi level separation will be taken up by the electron quasi-Fermi level as the pumping is increased. The change in TM/total fraction of spontaneous recombination current in Table I reflects the limited benefit associated with separating the hole subbands when both strain and well width are adjusted to maintain a fixed emission wavelength.

In summary, we have used a variable stripe length method that allowed us to separately measure the TM and TE polarized gain and spontaneous recombination in real units. We have constructed gain-radiative current characteristics of three laser structures that both incorporate differing amounts of tensile strain and have different quantum well widths to maintain a fixed output wavelength. The combination of strain and well width related effects produces a negligible reduction of the TM radiative current with strain because the combination of increasing strain with wider wells cancels any increasing $E(k)$ curvature in the uppermost hole subband with increasing tensile strain. However, a reduced total radiative current at fixed gain and a reduced transparency current was observed with increasing amounts of tensile strain and wider wells, which was attributed to the increased separation of the light and heavy hole valence bands.

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