Oscillator strength enhancement for [110]-polarized light in compressively strained GaInP ordered crystals used in AlGaInP lasers

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This letter studies the effect of compressive strain on the polarization-dependent oscillator strength in GaInP CuPt-type ordered crystals. The hole eigenstates are obtained by diagonalizing the total Hamiltonian consisting of the Hamiltonian for ordered GaInP and a perturbed term caused by the strain. Our calculation reveals that the strain squeezes the hole wave function and that the oscillator strength between an electron and the upper-valence-band hole increases for [110]-polarized light. The oscillator strength for [110]-polarized light increases with the strain, reaching 14% at +0.98% strain.

Following the successful growth of high-quality GaInP and AlGaInP epitaxial layers by metalorganic vapor phase epitaxy (MOVPE),[1] much research has focused on red-light-emitting AlGaInP lasers[2,3] for high-density optical-disk memories, laser printers, and bar-code readers. The MOVPE-grown GaInP crystal used as the active layer for the laser has a peculiar structural property:[4] $Ga_{0.51}In_{0.49}P$ grown on a (001) GaAs substrate in a certain range of growth conditions shows CuPt-type sublattice ordering. The reduction in its band gap energy caused by the sublattice ordering, which can be as large as 80 meV, has attracted much attention. A recent report on the polarization dependence of photoluminescence intensity in ordered GaInP showed results consistent with the selection rule that the oscillator strength for $[\bar{1}11]$-polarized light is zero.[5,6] We previously reported that the polarization-dependent radiation due to the anisotropy of oscillator strength results in a strong stripe-direction dependency of a threshold current density for an AlGaInP laser with an ordered-GaInP active layer.[7]

AlGaInP lasers with compressively strained GaInP active layers were recently found to show a low threshold current density[8] and high-power operation.[9,10] The +0.30% strained $Ga_{0.47}In_{0.53}P$ quantum well used as the active layer for the high-power laser,[9] grown on a (001)-oriented GaAs substrate at a growth temperature of 660 °C and a V/III ratio of 150, showed strong sublattice ordering. The (001) in-plane strain reduced the crystal symmetry for the ordered GaInP to monoclinic C_{1h}. Although the reduction should have modified the polarization dependency of the optical gain, the oscillator strength for the C_{1h}-symmetric crystal has never been studied. This letter reports that the oscillator strength for +0.98% strained ordered GaInP for [110]-polarized light is 14% larger than that for both unstrained ordered GaInP and strained disordered GaInP. This increase in oscillator strength is expected to enhance the optical gain in an AlGaInP laser with a GaInP active layer.

Figure 1 shows a view of compressively strained $Ga_xIn_{1-x}P(x<0.51)$ CuPt-type ordered crystal grown on (001)-oriented GaAs. Sublattice ordering is formed in the $[\bar{1}11]$ direction. The compressive strain, caused by the lattice mismatch to the GaAs substrate, is applied in the (001) plane. The symmetry for this crystal structure is monoclinic C_{1h}, which is the lowest symmetry of all III-V compound semiconductor crystals. The symmetry operation for C_{1h} is only a reflection against the $(\bar{1}10)$ plane. According to group theory,[11] C_{1h} has only one double-valued representation $\Gamma_{3,4}$. Thus, the quartet-degenerated hole states under T_d (zincblende) symmetry split into two doublet $\Gamma_{3,4}$ hole states. The doublet electron state is also $\Gamma_{3,4}$. An optical transition is therefore allowed between each hole state and the electron state.

We represented the two doublet hole eigenstates as linear combinations of $|J, J_z\rangle = |3/2, \pm 3/2\rangle$ and $|3/2, \pm 1/2\rangle$ by diagonalizing the total Hamiltonian

$$H_t = H_0 + H', \tag{1}$$

where H_0 is the Hamiltonian for unstrained ordered GaInP and H' is a perturbed term caused by lattice-mismatch-induced strain. The split-off bands are neglected because the spin-orbit energy is sufficiently large. After the symmetry assignment for C_{3v}-symmetric ordered GaInP,[5,6] H_0 was diagonally represented as

$$H_0 = \begin{pmatrix} E_v(\Gamma_8) & 0 \\ 0 & E_v(\Gamma_8) \end{pmatrix} + \begin{pmatrix} \Delta E(\Gamma_{4,5}) & 0 \\ 0 & \Delta E(\Gamma_6) \end{pmatrix}, \tag{2}$$

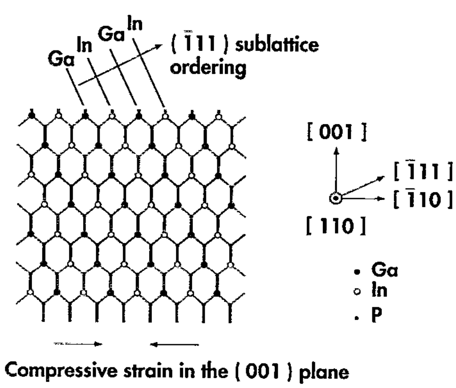

FIG. 1. View of compressively strained GaInP ordered crystal grown on (001)-oriented GaAs. The sublattice ordering is formed in the $[\bar{1}11]$ direction and the strain is applied in the (001) plane. The strain reduces the crystal symmetry for the ordered GaInP to monoclinic C_{1h}.

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TABLE I. Parameters used for the calculation; ϵ refers to the lattice-mismatch-induced strain.

	Energy (meV)
$E_c(\Gamma_6)-E_v(\Gamma_8)$	1916.9[a]
$\Delta E(\Gamma_{4,5})$	+98.9[b]
$\Delta E(\Gamma_6)$	+54.9[b]
$\Delta E(HH)$	$+12.4\times\epsilon$[c]
$\Delta E(LH)$	$+7.9\times\epsilon$[c]

[a]At room temperature for unstrained disordered GaInP grown by liquid phase epitaxy in Ref. 13.
[b]For unstrained ordered GaInP grown by MOVPE at a growth temperature of 650 °C and a V/III ratio of 160 in Ref. 6.
[c]For strained GaInP grown on a GaAs substrate by MOVPE in Refs. 14 and 15.

where $E(\Gamma_8)$ is the hole energy for T_d-symmetric disordered GaInP and $\Delta E(\Gamma_{4,5})$ and $\Delta E(\Gamma_6)$ are the energy shifts for the split hole states. The symmetry-adapted hole functions are $-|3/2,+3/2\rangle \pm i|3/2,-3/2\rangle(\Gamma_{4,5})$ and $|3/2,\pm 1/2\rangle(\Gamma_6)$,[12] where the z axis is along $[\bar{1}11]$. The D_{2d}-symmetric perturbed Hamiltonian H' was represented as

$$H'=\begin{pmatrix} \Delta E(HH) & 0 \\ 0 & \Delta E(LH) \end{pmatrix}=\begin{pmatrix} a\epsilon & 0 \\ 0 & b\epsilon \end{pmatrix}, \quad (3)$$

by using another set of basis functions: $|3/2,\pm 3/2\rangle$ (Γ_7: heavy hole) and $|3/2,\pm 1/2\rangle$ (Γ_6: light hole), where the z axis is along [001]. In case of GaInP in a very thin quantum well, energy shifts by quantum confinement should be added to the diagonal elements. In order to add H' to H_0 in Eq. (1), H' was represented using the same basis functions as H_0 by applying Euler's rotation transformation and another unitary transformation. The parameters[6,13–15] used for calculation are listed in Table I. Figure 2 shows the calculated transition energies between the electron and the hole eigenstates for strained ordered GaInP (solid lines) and for strained disordered GaInP (dashed lines). In contrast with disordered GaInP, the hole states in ordered GaInP interacted with each other, as shown by the splitting of the transition energies C-V_1 and C-V_2.

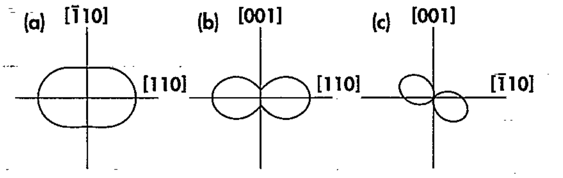

FIG. 3. Polarization dependence of oscillator strengths between the electron and the upper-valence-band hole at the Brillouin zone center for +0.98% strained ordered GaInP on (a) (001), (b) ($\bar{1}$10), and (c) (110) polarization-direction planes. The oscillator strength for [110]-polarized light increases due to the strain.

Figure 3 shows the anisotropic features of the polarization dependence of the oscillator strength between the electron and the upper-valence-band hole at the Brillouin zone center for +0.98% strained ordered GaInP on (a) (001), (b) ($\bar{1}$10), and (c) (110) polarization-direction planes. The oscillator strength is defined as the norm for the dipole matrix element. The transition between the electron and the lower-valence-band hole was neglected because the splitting energy of 62 meV (Fig. 2) is sufficiently larger than k_BT. Our calculation revealed that the oscillator strength for [110]-polarized light increases due to hole wave function squeezing caused by the strain. A quantitative understanding of the reason for the oscillator strength increase is that only the [110]-polarized optical transition is allowed for both the ordered-GaInP C_{3v}-symmetry selection rule and the strained-GaInP D_{2d}-symmetry selection rule. Strained quantum-well lasers with ($\bar{1}$10)-cleaved mirror facets emit [110]-polarized laser light, so the oscillator strength increase therefore contributes to the optical gain for the lasers.

Figure 4 shows the oscillator strengths for [110]-, [$\bar{1}$10]-, and [001]-polarized lights. An increase in compressive strain drastically affects the oscillator strengths. At a strain of +0.98%, as large as that shown in Fig. 3, the oscillator strength for [110]-polarized light reaches a max-

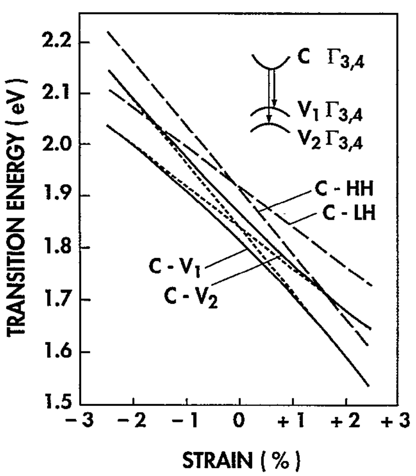

FIG. 2. Transition energies between an electron and the hole eigenstates for ordered GaInP (solid lines) and for disordered GaInP (dashed lines). The two hole states in strained ordered GaInP interact with each other.

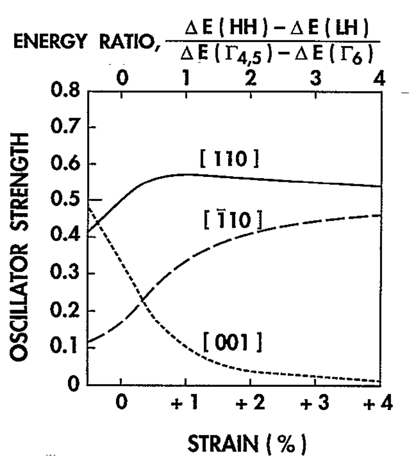

FIG. 4. Normalized oscillator strengths for [110]-, [$\bar{1}$10]-, and [001]-polarized lights for ordered GaInP. An increase in strain drastically affects the oscillator strengths. At +0.98% strain, the oscillator strength for [$\bar{1}$10]-polarized light reaches a maximum value of 0.57, which is 14% more than oscillator strengths for unstrained ordered GaInP and for strained disordered GaInP.

imum value of 0.57. It should be noted that the oscillator strengths derived from Eqs. (1)–(3) depend only on the ratio of $\Delta E(\Gamma_{4,5})-\Delta E(\Gamma_6)$ to $\Delta E(HH)-\Delta E(LH)$, and at $+0.98\%$ strain $\Delta E(\Gamma_{4,5})-\Delta E(\Gamma_6)$ equals $\Delta E(HH)-\Delta E(LH)$. In comparison, the [110] oscillator strengths for unstrained ordered GaInP and for strained disordered GaInP are 0.50, because [110] is normal to their respective forbidden polarization directions of $[\bar{1}11]$ and [001]. Therefore, the maximum oscillator strength for the strained ordered GaInP is 14% more than those for unstrained ordered GaInP or strained disordered GaInP. This result shows that the optical gain for [110]-polarized lasing light should increase by 14% and, thus, should reduce the threshold current.

In summary, we reported on the polarization-dependent oscillator strength between the electron and the upper hole eigenstate for compressively strained ordered GaInP crystals. The hole eigenstates were obtained by diagonalizing the total Hamiltonian consisting of the Hamiltonian for the CuPt-type ordered GaInP and the perturbed term caused by lattice-mismatch-induced strain in the (001) plane. Our calculation revealed that the oscillator strength is maximum for [110]-polarized light. The oscillator strength for [110]-polarized light increased as the strain increased, reaching 14% for a $+0.98\%$ strain. This increase in oscillator strength is expected to enhance the optical gain in AlGaInP lasers with GaInP active layers and should reduce the threshold current.

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