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Polarization-Dependent Optical Gain and Gain Saturation in Vertical-Cavity Surface-Emitting Lasers

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1. Introduction

The polarization switching of semiconductor lasers, especially optical switching and bistable operations based on two orthogonal linearly polarized optical states, are extensively studied in view of future fast optical communications. The optical pulse modulation by the polarization switching is expected to be fast because, compared with the switching by current injection, only a small fraction of the real carrier distributions both in real and momentum space must change in the switching of this kind. There are several theoretical and experimental reports [1-3] on the polarization switching, showing the feasibility of increasing the modulation speed.

We have already calculated the gain saturations in bulk lasers [4]. With regard to the fact that the polarization-switching operations are experimentally demonstrated especially in vertical-cavity surface-emitting lasers (VCSEL), we would like to extend our previous analysis to the QW lasers with VCSEL structures.

In the present study we consider $In_{1-x}Ga_xAs_yP_{1-y}$ semiconductor QW lasers operating at 1.3 μm region with VCSEL structures. A single quantum well, 7 nm in width and composed of InGaAsP, is grown on the (001) plane of InP without lattice mismatch. The light propagates in the [001] direction. We assume in the present study that the two orthogonal optical fields are in the [110] (denoted by H mode) and in the $[\bar{1}10]$ (denoted by V mode) direction. We need two parameters describing the gain saturations; the self-saturation coefficients, $\varepsilon_{sh}(\omega_h)$ for H mode and $\varepsilon_{sv}(\omega_v)$ for V mode (We should mention that $\varepsilon_{sh} = \varepsilon_{sv}$ in VCSEL), and the cross-saturation coefficient for the two fields with orthogonal polarizations, $\varepsilon_{xhv}(\omega_h, \omega_v)$ ($= \varepsilon_{xvh}(\omega_h, \omega_v)$). They show peak at the resonance ($\omega_h = \omega_v$), which are important in determining the bistability conditions. The rate equation analyses show that the polarization bistability appears when the product of two cross saturation coefficients is larger than the product of self saturation coefficients; $\varepsilon_{xhv}(\omega,\omega) \times \varepsilon_{xvh}(\omega,\omega) > \varepsilon_{sh}(\omega) \times \varepsilon_{sv}(\omega)$.

2. Calculations

Linear gains and gain saturation coefficients are given by the imaginary parts of linear and third-order susceptibilities, respectively, which are calculated perturbationally in the quantum mechanical Liouville equation for the density matrices [4, 5]. The dipole transition matrix elements required in the Liouville equation are given by the electron wavefunctions and the band dispersions, which are calculated by diagonalizing Luttinger's Hamiltonian. In the present study we included heavy and light hole bands.

3. Results and discussions

The Ga and As concentrations are chosen so that the well material is lattice matched to InP. The material parameters are taken from [6]. The intraband relaxation times are fixed at 0.1 ps in the present study.

We first show linear gains as a function of photon energy in Fig. 1 for the carrier sheet densities from 1.8 to 3.0×10^{12} cm^{-2} at 300 K. The gain in H mode (g_h) and V mode (g_v) are identical in VCSEL. The gain spectrum shows two peaks; one at 1.028 eV and the other at 1.052 eV. The first one corresponds to the electron-heavy hole transition, and the second one corresponds to the electron-light hole transition.

We show in Fig. 2 the photon energy dependence of the self-saturation coefficients and the cross-saturation coefficients for orthogonal polarizations with the sheet density 3.0×10^{12} cm^{-2} at 300 K. We observe that they strongly depend on the photon energy, in contrast to the results of bulk lasers [10]. This is due to the fact that the density of states

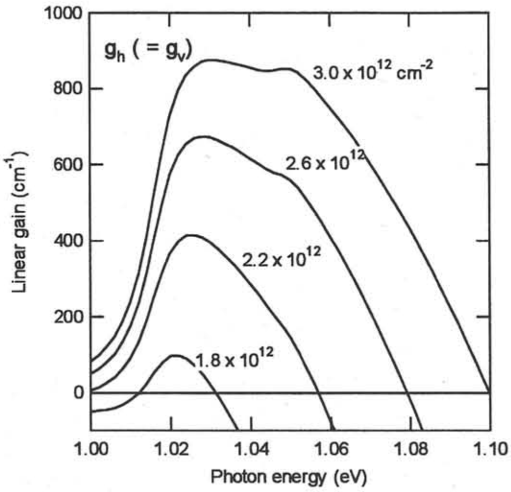

Fig. 1 Linear gain of QW VCSEL at 300 K.

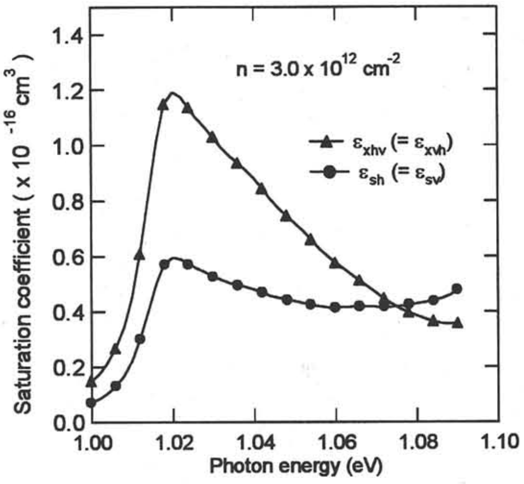

Fig. 2 Self- and Cross-saturation of QW VCSEL

becomes sharper and the hh-lh degeneracy is lifted in 2D system.

To examine the potential bistable operations of the QW VCSEL, the products of the self-saturation coefficients, $\varepsilon_{sh} \times \varepsilon_{sv}$, and the products of the cross-saturation coefficients (peak values), $\varepsilon_{xhv} \times \varepsilon_{xvh}$, are plotted as a function of the photon energy at the density 3.0 x 10^{12} cm^{-2} in Fig. 3. The condition for the bistable operation is satisfied in most of the spectral region, including the peak of the linear gains. This fact, together with the balance of linear gains in the two orthogonal modes, implies that the polarization-bistable operation could be observed in QW VCSELs. Actually there are several experimental reports on the polarization-bistable operations in QW VCSELs [1]. We have also calculated the same quantities of the *bulk VCSEL* (in the limit of infinite well width) as shown in the inset of Fig. 3 at 4.29 x 10^{18} cm^{-3}. $\varepsilon_{xhv} \times \varepsilon_{xvh}$ and $\varepsilon_{sh} \times \varepsilon_{sv}$ are dependent on the photon energy only slightly, and the bistable operation condition is satisfied at all the photon energies. When the QW VCSEL and the bulk VCSEL are compared, the difference between $\varepsilon_{xhv} \times \varepsilon_{xvh}$ and $\varepsilon_{sh} \times \varepsilon_{sv}$ is more significant in the former case.

4. Conclusions

We have calculated self- and cross-saturation coefficients in the VCSEL InGaAsP semiconductor lasers with *bulk* and *QW* structures. The bistable condition is fulfilled at the region of high linear gain both in bulk and QW structures. We notice the larger difference between $\varepsilon_{xhv} \times \varepsilon_{xvh}$ and $\varepsilon_{sh} \times \varepsilon_{sv}$ in the QW laser than in the bulk laser.

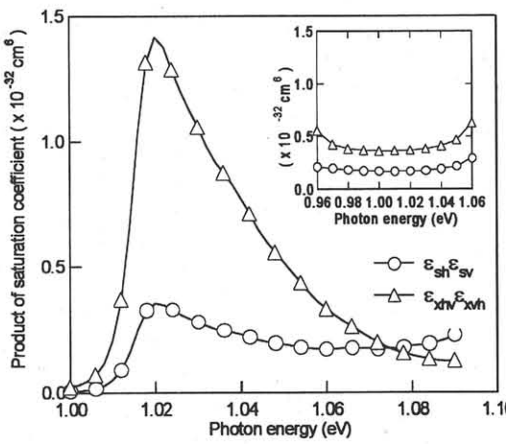

Fig. 3 $\varepsilon_{xhv}\varepsilon_{xvh}$ and $\varepsilon_{sh}\varepsilon_{sv}$ of QW and Bulk (inset) VCSEL.

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