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Polarization-Dependent Emission from [112]-Oriented GaAs/(Al, Ga)As Quantum Wells:A Manifestation of Anisotropic Optical Matrix Elements

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Experimental evidence of optical anisotropy in GaAs/(Al,Ga)As quantum wells grown on the (112) GaAs surface is presented. It is found that the photoluminescence emission intensity of the fundamental $e \rightarrow hh$ transition is anisotropic for incident excitation light polarized along the two orthogonal $[\bar{1}10]$ and $[11\bar{1}]$ directions. Simple theoretical optical matrix element calculations also predict the anisotropy observed in the experiments.

The experimental investigation of anisotropic optical effects in quantum well structures is becoming increasingly relevant because of the ability to grow these structures on substrates oriented in crystallographic directions different from the [001] [1, 2]. Recently for example, it has been determined that in certain directions of the general crystallographic orientation denoted by $[11\ell]$, where ℓ can be 0 or any positive integer, a valence band anisotropy induced by band mixing in quantum well structures can lead to anisotropic matrix elements [3, 4]. For values of ℓ larger than 7, the properties of the surfaces approach those of the conventional (001). Optical emission, as well as absorption, by quantum well structures grown on substrates oriented in the [110] orientation has been found to be anisotropic [3, 5]. The reported anisotropic effects have encouraged the design and demonstration of a polarization-sensitive optical modulator [6] and the investigation of the use of this anisotropy in the anticipated control of the polarization eigenstates of vertical-cavity surface-emitting lasers [7].

For the Miller index ℓ=2, the substrate surface denoted by (112) is obtained. It is relatively straight forward to grow high quality optical III-V heterostructures by the technique of molecular beam epitaxy on the (112) GaAs surface. We have done so and wish to report our investigations of the anisotropic effect on this particular orientation. The structures grown were studied by photoluminescence excitation (PLE) spectroscopy using a tunable Ti:sapphire laser. Optical matrix elements for the interband transitions in the GaAs/(Al,Ga)As quantum well structures on the (112) GaAs substrate were computed using the effective mass approximation at the Brillouin zone center.

The structures investigated consisted of five GaAs(8 nm)/$Al_{0.45}Ga_{0.55}As$ quantum well structures grown on top of a GaAs buffer layer. The quantum wells were capped with a 200-nm-layer of GaAs. An identical structure on the (001) GaAs substrate was grown alongside the (112) sample for purposes of comparison. The photoluminescence excitation spec-

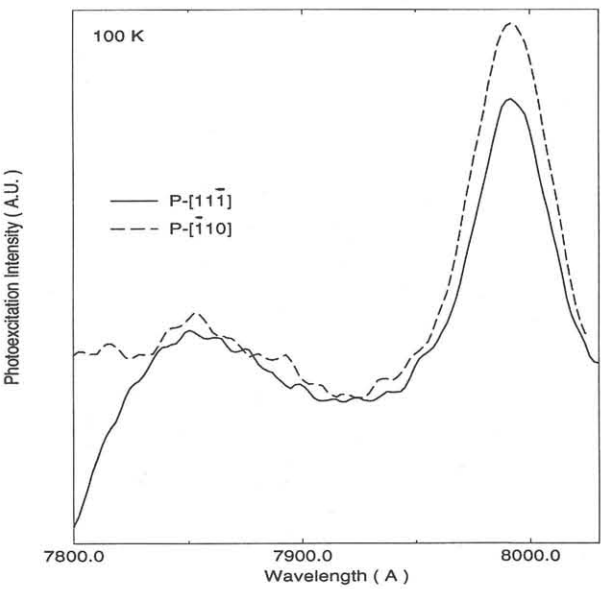

Fig. 1: Photoluminescence excitation spectra of GaAs/$Al_{0.45}Ga_{0.55}As$ QWs oriented in the [112] direction for incident light with polarization aligned along the $[11\bar{1}]$ and the $[\bar{1}10]$ direction.

tra from the [112] and [001] quantum well structures are shown in Figs. 1 and 2. The spectra shown are for two orthogonal polarizations of the incident light. The emission intensity for incident excitation light polarized parallel to the $[\bar{1}10]$ crystallographic direction and then to the $[11\bar{1}]$ direction is shown in Fig. 1. These spectra show that the transition from the conduction band ground state to the heavy-hole ground state is anisotropic for light polarized along the two orthogonal directions. The anisotropy of the light-hole related transition is not evident from our experimental data although this transition is clearly resolvable. This could probably be due to the lower signal level recorded for this transition. The spectra shown in Fig. 2 for the structures grown on the (001) GaAs surface show no anisotropy—as expected from qualitative symmetry arguments.

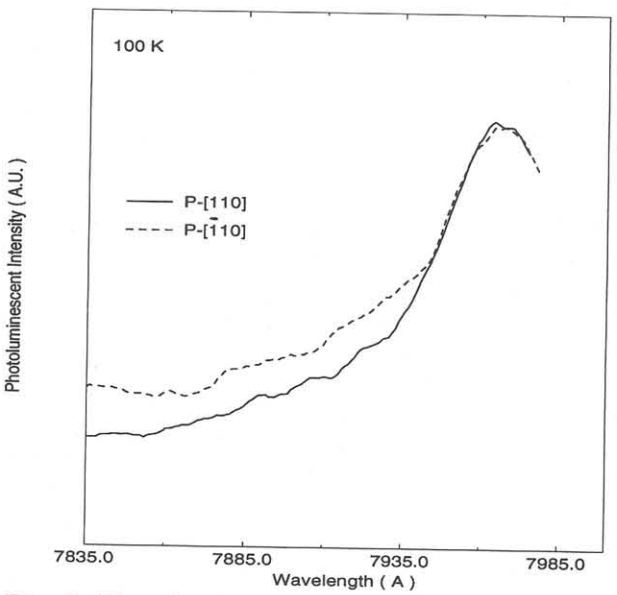

Fig. 2: Photoluminensce excitation spectra of [001]-oriented QWs for light polarized along the [110] and $[\bar{1}10]$ directions.

The optical matrix elements along any two orthogonal directions on the (112) surface can be calculated from the general expression

$$M = < c|\hat{\mathbf{e}} \cdot \frac{\hbar}{i}\nabla|v >, \qquad (1)$$

where $|c>$ and $|v>$ are the wavefunctions of the conduction and valence band states; $\hat{\mathbf{e}}$ is the unit polarization vector of the electric field associated with incident light used for the excitation. The two orthogonal directions of interest on the (112) surface are the $[11\bar{1}]$ and the $[\bar{1}10]$; they are chosen to form a triplet of mutually orthogonal axes when considered together with the [112] direction. This choice of axes is justified on the basis of the fact that the triplet includes the unit normal to the $(\bar{1}10)$ surface which is the only natural cleavage plane associated with the (112) surface. This surface is important in the formation of naturally cleaved laser facets for devices fabricated on the (112) surface.

A coordinate transformation from the conventional system where z is pointing in the [001] crystallographic direction to a new system (x',y',z') with z' pointing in the [112] direction must be performed in order to obtain the 4×4 Luttinger [8] Hamiltonian, $H_{[112]}$, for the [112] orientation. The appropriate transformation matrix for this operation is

$$U = \begin{pmatrix} \cos\phi\cos\theta & \sin\phi\cos\theta & -\sin\theta \\ -\sin\phi & \cos\phi & 0 \\ \cos\phi\sin\theta & \sin\phi\sin\theta & \cos\theta \end{pmatrix}. \qquad (2)$$

The angles ϕ and θ are the azimuthal and polar angles spanned by the new coordinate system. They are defined as in Fig. 1 of Ref. [9]. The 4×4 Luttinger Hamiltonian obtained from these considerations, valid for the [112] orientation at the Brillouin zone center (k'_x=k'_y=0) for $J = \frac{3}{2}$ in the $|J, J_z>$ representation, is

$$H_{[112]}(k_z) = \frac{\hbar^2 k_z^2}{2m_o}\gamma_1 I_4 + \frac{\hbar^2 k_z^2}{2m_o}\begin{bmatrix} -a & b & c & 0 \\ b & a & 0 & -c \\ c & 0 & a & b \\ 0 & -c & b & -a \end{bmatrix} \qquad (3)$$

where $a = \left(\frac{\gamma_2+3\gamma_3}{2}\right)$, $b = \left(\frac{\gamma_3-\gamma_2}{2\sqrt{3}}\right)$, $c = \sqrt{\frac{2}{3}}(\gamma_2 - \gamma_3)$, I_4 is the 4×4 identity matrix, $k_z = -i\frac{d}{dz}$, and the $\gamma_{i's}$ are the Luttinger valence band parameters. Note that the angular momentum representation, J, used here is obtained by a rotation of the one given by Luttinger in eq. (57) of Ref. [8]. The valence band wavefunctions, $|v_{[112]}>$, are obtained as eigenvectors of $H_{[112]}$.

Because of the spin-degeneracy of both the heavy- and light-hole valence bands, the momentum matrix elements are calculated from the expression

$$M = \sum_{\sigma=\pm} < c_{[112]}|\hat{\mathbf{e}} \cdot \frac{\hbar}{i}\nabla|v^{\sigma}_{[112]}> \qquad (4)$$

within the effective mass approximation. We have further assumed that the quantum wells have barriers with infinite potential energy. The expressions for the ratios of the squared interband matrix elements

for the two orthogonal directions of interest on the (112) surface relative to the bulk matrix element are tabulated below.

	c→hh	c→lh
$\hat{e} \parallel [\bar{1}10]$	$1+\frac{\gamma_3}{\sqrt{\gamma_2^2+3\gamma_3^2}}$	$1-\frac{\gamma_3}{\sqrt{\gamma_2^2+3\gamma_3^2}}$
$\hat{e} \parallel [11\bar{1}]$	$1+\frac{\gamma_2+\gamma_3}{2\sqrt{\gamma_2^2+3\gamma_3^2}}$	$1-\frac{\gamma_2+\gamma_3}{2\sqrt{\gamma_2^2+3\gamma_3^2}}$

If we take the numerical values of the Luttinger parameters for the GaAs quantum well layer to be $\gamma_2 = 2.1$ and $\gamma_3 = 2.9$, then the ratio of the matrix elements for the two polarizations of interest can be determined to be

$$\frac{|M|^2_{c\rightarrow hh}(\hat{e} \parallel [\bar{1}10])}{|M|^2_{c\rightarrow hh}(\hat{e} \parallel [11\bar{1}])} = 1.05 \qquad (5)$$

for the conduction band to heavy-hole ground state transition and

$$\frac{|M|^2_{c\rightarrow lh}(\hat{e} \parallel [\bar{1}10])}{|M|^2_{c\rightarrow lh}(\hat{e} \parallel [11\bar{1}])} = 0.86 \qquad (6)$$

for the conduction band to light-hole ground state transition. These ratios predict an anisotropy in the optical transitions. This anisotropy is clearly evident from our PLE experiments on the quantum well samples grown on the (112) substrates. It is, however, absent in structures grown on the (001) surface as demonstrated by the experiments discussed here.

In summary, we have theoretically shown and experimentally confirmed that quantum well structures oriented in the [112] direction exhibit an optical anisotropy. This anisotropy may have potential applications in novel optoelectronic devices.

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