Polarization sensitive lateral photoconductivity in GaAs/AlGaAs quantum well based structures on low-temperature grown GaAs(001)

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Polarization-resolved lateral-photoconductivity measurements are reported on device structures made of GaAs/Al0.3Ga0.7As quantum wells sandwiched between low-temperature grown GaAs(001) layers. The mesa device structures have long length (3 mm∥y) and narrow width (10 and 20 μm∥x) in the (001) plane. For light incident along [001], the ground state light-hole exciton transition is much stronger for light polarization E∥x, compared to E∥y. The heavy-hole exciton transition shows a weaker polarization anisotropy of opposite sign, being stronger for E∥y. Through calculations based on the Bir–Pikus Hamiltonian, the observed in-plane optical polarization anisotropy is shown to arise from valence band mixing induced by anisotropic strain in the plane of quantum wells. © 2010 American Institute of Physics. [doi:10.1063/1.3479501]

Polarization sensitive detection of light of a particular wavelength finds application in optical logic circuits, including optical computation where the state of polarization defines the high/low bit value. A high-density cost-effective device structure, for probe beam incident along y, is shown. The top inset shows the relative oscillator strength dependence on the polarization angle of the probe beam in the growth plane. We provide an explanation for the occurrence of polarization anisotropy here and verify it through electronic band structure calculations.

The device structures (Fig. 1 inset) were grown on semi-insulating GaAs(001) substrate using molecular beam epitaxy. They consist of 20 pairs of GaAs/Al0.3Ga0.7As QW (well width Lw =11 nm), lying on top of a 250 nm thick 200 °C grown low temperature (LT) GaAs layer and then capped with a similar LT-GaAs layer. Using photolithography, elongated mesas were etched down to the bottom LT-GaAs layer. The mesas had 10 or 20 μm width (∥x) and 3 mm length (∥y), and were coated with Au electrodes on the sides. The insulating LT-GaAs ensures that there is predomi-
nantly a uniform lateral voltage drop, and consequently a constant lateral electric field\(^8\) across the QW structure along \( \mathbf{x} \). For the photoconductivity measurements, the probe beam was obtained by dispersing light from a 100 W quartz-tungsten-halogen lamp with a monochromator (band pass 1 meV) and then linearly polarized using a Glan–Taylor polarizer. Typically a bias of 1 V was applied for measurements in the temperature range from 297 to 11 K.

Figure 1 shows the lateral photoconductivity spectra of a 10 \( \mu \text{m} \) wide device for in-plane polarizations of the probe beam with \( E \parallel \mathbf{x} \) and \( E \parallel \mathbf{y} \) at 11 K. One can identify the sharp resonances at 1.545 and 1.555 eV as the \( n=1 \) confined electron-heavy hole (\( e_1h_h_1 \)) and electron-light hole (\( e_1l_h_1 \)) exciton transitions in the QW. The interesting thing here is the difference in the signal strength between \( E \parallel \mathbf{x} \) and \( E \parallel \mathbf{y} \) polarizations. The \( e_1l_h_1 \) resonance is much stronger (weaker) for \( E \parallel \mathbf{x} \) (\( E \parallel \mathbf{y} \)), while the opposite is the case for the \( e_1h_h_1 \) resonance which is stronger for \( E \parallel \mathbf{y} \). To estimate the relative oscillator strength \( f \) of the transitions we have fitted the sum of a Gaussian and a broadened step function modified by the Sommerfeld factor, representing the exciton and the two-dimensional density of states related absorption, respectively, for each transition. The dashed lines in Fig. 1 show an example of the \( e_1h_h_1 \) and \( e_1l_h_1 \) contributions for \( E \parallel \mathbf{y} \), as obtained from fitting. \( f \) was estimated from the area of the Gaussians. The top inset in Fig. 1 has a plot of \( f \) as a function of the polarization angle of the probe beam in the (001) plane, for the 10 \( \mu \text{m} \) wide device. The functional form \( f = f_x \cos^2 \theta + f_y \sin^2 \theta \), considering \( f_x \) and \( f_y \), as two independent values of the oscillator strength for \( E \parallel \mathbf{x} \) and \( E \parallel \mathbf{y} \) for a particular transition, fits (dark lines) the data satisfactorily.

We define the in-plane polarization anisotropy as \( 100 \times (f_y - f_x)/(f_y + f_x) \). In the 10 \( \mu \text{m} \) wide devices the measured in-plane polarization anisotropy was typically \( \approx 5\% \) for the \( e_1h_h_1 \) and \( 19\% \) for the \( e_1l_h_1 \) transitions at 11 K. In the 20 \( \mu \text{m} \) wide devices [Fig. 2(a)], the maximum measured anisotropy was lower, being \( \approx 10\% \) for the \( e_1h_h_1 \) transition. At room temperature [Fig. 2(b)] the relative difference in the signal between \( E \parallel \mathbf{x} \) and \( E \parallel \mathbf{y} \) at the \( e_1l_h_1 \) exciton resonance was reduced due to increased broadening.

We next consider how in-plane optical polarization anisotropy arises in these QWs. In general, anisotropy can occur if the cubic symmetry in the (001) \( \mathbf{x} \)-\( \mathbf{y} \) plane is disturbed, for example by the lateral electric field along \( \mathbf{x} \). However, the electric field cannot be the source of the polarization anisotropy here, since the measured polarization anisotropy did not change appreciably when the bias voltage was increased by a factor of 5. Here the optical polarization anisotropy occurs due to anisotropic in-plane strain. It is known that the lattice constant of as-grown LT-GaAs can be larger by a factor of more than 0.12\% compared to that of GaAs.\(^9\) The critical thickness beyond which such an LT-GaAs film on GaAs substrate will relax\(^10\) is \( \approx 230 \) nm. Thus our 250 nm thick bottom LT-GaAs layer is partially relaxed and consequently the QW layers on top would be under some tensile strain. The strain anisotropy between \( \mathbf{x} \) and \( \mathbf{y} \) directions arises because of the skewed aspect ratio of the mesa. The QWs are more likely to be coherently strained to the LT-GaAs base along \( \mathbf{x} \) due to the narrow width in that direction. The side Au contacts also add to the average tensile strain and its anisotropy.\(^11\) The wider devices will have relatively less strain anisotropy and consequently smaller optical polarization anisotropy, as observed. We note here that anisotropic strain, generated by incorporating a long and narrow etched trench, has been used previously to help fix the emission polarization of vertical-cavity surface-emitting lasers.\(^12\) We verify the above hypothesis by comparison with theoretically estimated influence of an average strain anisotropy, as sampled by a probe beam wider than the device, on the optical transition energies and oscillator strengths, as follows.

Strain dependent electronic band structure calculations were performed using the Bir–Pikus Hamiltonian for cubic III-V semiconductors.\(^13\) The three valence bands (VBs) of GaAs (heavy, light, and spin-orbit split-off hole band) were considered together, separately from the conduction band (CB). The parameter values used are given in Ref. 14. A value of \( \pi/13.3 \) nm\(^{-1} \) was considered for crystal momentum component \( k_z \) \((k_x=0, k_y=0) \) of both electrons and holes, in order to include the effects of quantum confinement\(^7\) and match the experimentally obtained transition energies. This is consistent with the fact that for the \( n=1 \) confined level in a finite height rectangular potential well, one expects \( k_z < \pi/L_y \). The CB minima of GaAs is made of atomic \( s \) orbitals, while the three VB maxima are formed out of a combination of atomic \( p_x, p_y \), and \( p_z \) orbitals. A transition involving \( s \) and \( p_x \) requires \( \mathbf{p} \) polarized light and so on. Strain mixes the VB and thereby modifies the polarization selection rules. To determine the polarization anisotropy we have calculated \( f_x, f_y, f_z \), the \( \mathbf{x}, \mathbf{y}, \mathbf{z} \) components, respectively, of the relative oscillator strength, for the two transitions. Figure 3 shows them plotted as a function of strain \( \epsilon_{xx} \) and \( \epsilon_{yy} \) in the plane of the QWs. They obey the sum rule \( f_x + f_y + f_z = 1 \). Effective mass dependent quantum confinement alone moves the \( n=1 \) light hole (lh) level below the heavy hole (hh) by 17 meV in these QWs, while biaxial tensile strain tries to do the opposite by pushing the lh band above hh. For \( \epsilon_{xx} = \epsilon_{yy} \approx 0.25\% \), where the plots seem to converge, these two effects cancel exactly resulting in zero splitting between \( e_1h_h_1 \) and \( e_1l_h_1 \) transitions. The plots show that \( f_x = f_y \) for isotropic in-plane strain \( (\epsilon_{xx} = \epsilon_{yy}) \), therefore anisotropic in-plane strain is necessary to observe optical polarization anisotropy.

Figures 4(a) and 4(b) show the calculated transition energy of the \( e_1h_h_1 \) and \( e_1l_h_1 \) transitions, as a function of in-plane strain. Figures 4(c) and 4(d) show the anisotropy between the calculated \( f_x \) and \( f_y \) for these transitions as a function of in-plane strain. They verify that the polarization anisotropy arises when \( \epsilon_{xx} \neq \epsilon_{yy} \) and show that the polarization anisotropy is much larger for the \( e_1l_h_1 \) transitions. Note that for a given in-plane strain anisotropy (shift away from

![Figure 2](https://example.com/Fig2.png)

**FIG. 2.** (Color online) Lateral photoconductivity signal in a (a) 20 \( \mu \text{m} \) wide device at 11 K and the (b) 10 \( \mu \text{m} \) wide device at 297 K for incident polarization \( E \parallel \mathbf{x} \) and \( E \parallel \mathbf{y} \).
the $\varepsilon_{xx} = \varepsilon_{yy}$ line), the optical polarization anisotropy increases with increasing in-plane tensile strain and decreases for increasing compressive strain. By comparison with the measured transition energies we estimate the in-plane strain in the QW layers to be ($\varepsilon_{xx} \approx 0.13\%$, $\varepsilon_{yy} \approx 0.10\%$) and ($\varepsilon_{xx} \approx 0.095\%$, $\varepsilon_{yy} \approx 0.08\%$) for the 10 $\mu$m and 20 $\mu$m wide devices, respectively. For these strain values, the theoretically estimated optical polarization anisotropy magnitude and its sign, for both the $e_1hh_1$ and the $e_1lh_1$ transitions, agree well with our measurements. The LT-GaAs layers, apart from enabling application of a lateral electric field to the QW layers, acts as a stressor layer generating some average in-plane tensile strain in the QW layers, which enhances the optical polarization anisotropy.

In conclusion, we have shown that the combination of an appropriate underlaying insulating stressor layer and a highly skewed metal coated mesa geometry, can be used to generate anisotropic in-plane tensile strain and thereby obtain optical polarization anisotropy in the in-plane photoconductivity of cubic III-V semiconductor QWs. The oscillator strength induced anisotropy will be dominant for angles of incidence up to 18° after which the difference in the reflectivity of the air/LT-GaAs interface between s and p polarizations will begin to influence the polarization anisotropy of the photoconductivity signal. For devices working at infrared/telecommunication wavelengths, conventional III-V growth and processing technology is more mature than for III-nitrides. The present study represents a viable alternative to the use of nonporal III-nitrides currently being investigated in the context of polarization sensitive detection/switching applications. Multiple stripes can provide larger active area, while a desired operating wavelength can be achieved by appropriate QW/stressor layer combination, with the possibility of fine tuning it by adjusting $L_w$.

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FIG. 3. (Color online) Variation in the relative oscillator strength components ($f_x$, $f_y$, and $f_z$) of $e_1hh_1$ and $e_1lh_1$ transitions in a [001] oriented GaAs/Al$_0.3$Ga$_0.7$As QW ($L_w=11$ nm) as a function of in-plane strain $\varepsilon_{xx}$ and $\varepsilon_{yy}$. The dashed lines identify the isotropic strain case when $\varepsilon_{xx} = \varepsilon_{yy}$.

FIG. 4. Calculated energies at 11 K of (a) $e_1hh_1$ and (b) $e_1lh_1$ exciton transitions in a [001] oriented GaAs/Al$_0.3$Ga$_0.7$As QW ($L_w=11$ nm) as a function of in-plane strain $\varepsilon_{xx}$ and $\varepsilon_{yy}$. The dashed lines identify the isotropic strain case when $\varepsilon_{xx} = \varepsilon_{yy}$. Calculated polarization anisotropy, in terms of the difference between $f_x$ and $f_y$, for (c) $e_1hh_1$ and (d) $e_1lh_1$, as a function of in-plane strain. The circles and the squares mark the estimated strain in the 10 $\mu$m and the 20 $\mu$m wide devices, respectively.