Strong polarization-sensitive electroabsorption in GaAs/AlGaAs quantum well waveguides

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We report the first measurements of perpendicular field electroabsorption (quantum confined Stark effect) in GaAs/AlGaAs quantum wells for light propagating parallel to the plane of the layers. This geometry is well suited for integrated optics. The absorption edge shifts to longer wavelengths with increasing field by as much as 40 meV, giving a modulation depth > 10 dB. The strong dichroism present in this geometry is retained even at high fields, making polarization-sensitive electro-optical devices possible. We also demonstrate in the waveguide geometry optical bistability due to the self-electro-optic effect with 20:1 on/off ratio.

Recently, there has been great interest in the properties of room-temperature excitons in multiple quantum well structures (MQWS's).[1,2] When an electric field is applied perpendicular to the plane of the layers, a new, strong electroabsorptive effect is observed[3,4] which has no analog in bulk semiconductors. This effect, known as the quantum confined Stark effect (QCSE), has been applied to high-speed modulators,[5] self-linearized modulators,[6,7] optically bistable switches,[7,8] and wavelength selective detectors.[9] So far, however, all measurements have been made using light propagating perpendicular to the plane of the layers. We report the first measurements of QCSE for light propagating parallel to the plane of the layers.

This configuration is of interest both for its physics and for its practical applications. In this geometry, light can propagate with its electric field vector ($\hat{e}$) either in the plane of the layers or perpendicular to the plane. The latter polarization is inaccessible to light propagating perpendicular to the layers and shows different selection rules.[10] Specifically, the heavy hole (hh) excitonic absorption effectively vanishes, and its strength is transferred to the single remaining light hole (lh) peak at higher photon energy. Consequently, the absorption (without field) is strongly dichroic for light propagating in the plane of the layers. The spectra with $\hat{e}\perp$ plane also offer a unique opportunity to study the broadening and changes in oscillator strength of the lh exciton and continuum without the added complication of the hh transitions. We find that the dichroism is retained even as we move the exciton peaks by many times their room-temperature linewidth by applying electric fields perpendicular to the layers; hence electrically controllable polarization-sensitive devices are possible using the QCSE.

The experiments were performed using waveguide samples with only two quantum wells, centered in the guide. This structure eliminates the field inhomogeneity problems of previous MQWS samples.[3,4] The resulting spectra are particularly clear, and permit more quantitative assessments of exciton broadening and absorption strength with field. The waveguide configuration is attractive from a practical standpoint as it is ideal for application to integrated optoelectronics. It permits very long optical path lengths, and hence much greater modulation depths, which would require prohibitively thick MQWS growth if the light propagated perpendicular to the layers. The work that we report here is designed both to test the novel physical processes in this geometry and to demonstrate their practical feasibility.

In order to make the samples sufficiently long that they could be readily cleaved to length, yet still not be too absorbing, we used only two quantum wells centered in a waveguide structure. It is important to control the modes of the guide to avoid artifacts in absorption measurements. Light coupled to higher order guided and radiation modes which have intensity minima at the position of the quantum wells will only be weakly absorbed and must be eliminated before reaching the detector. In order to do this we used a leaky waveguide structure as described previously.[10,11]

The sample design is shown in Fig. 1. Two 94 Å quantum wells were embedded in a 3.6-μ-thick superlattice which formed the waveguide core; this superlattice was surrounded by GaAs cladding layers. The sample was doped as a *p-i-n* diode which was then reverse biased to apply an electric field perpendicular to the quantum wells in the intrinsic region. The structure was designed so that a 150-μm-long sample would exhibit 10 dB modulation depth (based on the previous QCSE measurements[4]) and 3 dB attenuation due to the

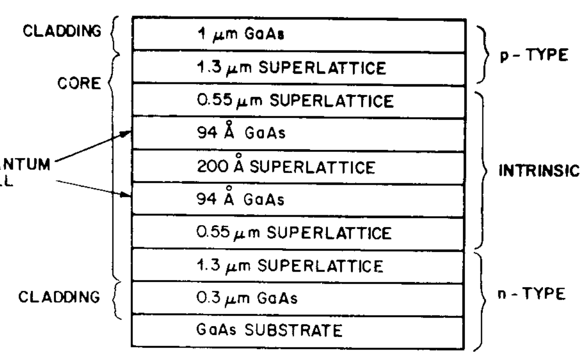

FIG. 1. Sample structure. The superlattice consists of alternate 28 Å GaAs and 50 Å $Al_{0.3}Ga_{0.7}As$ layers. The *n* and *p* doping levels are 10^{18} cm^{-3} except for the top 0.1 μm of GaAs which is *p*-doped 10^{19} cm^{-3}.

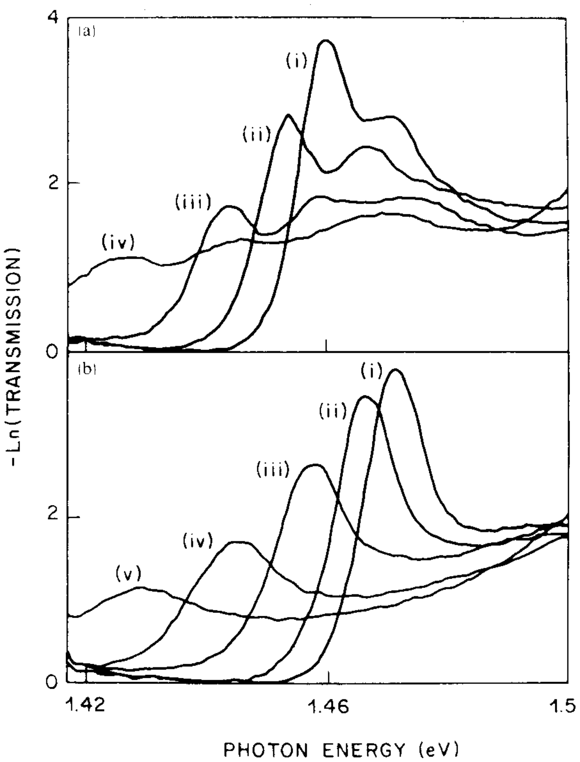

FIG. 2. Absorption spectra of a quantum well waveguide as a function of electric field applied perpendicular to the layers. (a) Incident polarization parallel to the plane of the layers for fields of (i) 1.6×10^4 V/cm, (ii) 10^5 V/cm, (iii) 1.3×10^5 V/cm, and (iv) 1.8×10^5 V/cm. (b) Incident polarization perpendicular to the plane of the layers for fields of (i) 1.6×10^4 V/cm, (ii) 10^5 V/cm, (iii) 1.4×10^5 V/cm, (iv) 1.8×10^5 V/cm, and (v) 2.2×10^5 V/cm. The fields were calculated from C-V measurements.

lossiness of the lowest order leaky mode.[10] The lowest order leaky mode is deliberately chosen to have significant loss so that the higher order modes would be extremely lossy and would not cause artifacts. The maximum loss experienced by the first-order mode should therefore be 13 dB. This is comparable to the loss experienced by the second-order mode due to the leaky waveguide losses alone; hence, careful alignment will ensure that the transmitted light due to coupling to higher order modes is negligible.

An LDS 821 dye laser was used for the experiments. The beam was spatially filtered to improve its quality, and the light was end fired into (and collected from) the samples using laser diode collimating objectives. A portion of the transmitted light was imaged into a television camera to permit observation of the mode structure. In all cases only a single bright line was observed corresponding to the lowest order mode of the slab guide.

Figures 2(a) and 2(b) show the absorption spectrum at different electric fields for $\hat{e}\|$plane and $\hat{e}\perp$plane, respectively. The zero-field spectra exhibit the polarization anisotropy previously observed.[10] For $\hat{e}\|$plane both the hh and lh excitons appear. For $\hat{e}\perp$plane the hh exciton disappears and the lh exciton increases in strength.

When an electric field is applied perpendicular to the layers, a very large shift to lower energy of the absorption edge in both polarizations is seen in the experimental spectra. This is a result of the QCSE in which the perpendicular electric field pulls the electrons and holes to opposite sides of the wells, resulting in a net reduction in the energy of an electron-hole pair. The spectra are taken up to even higher fields than in the previous MQWS case,[3,4] yet the exciton peaks remain well resolved, the absorption edge remains sharp, and the dichroism persists. The maximum shift observed was 40 meV for the lh exciton with $\hat{e}\perp$ plane at a field of 2.2×10^5 V/cm. This is 10 times the bulk exciton binding energy and occurs at an applied field 100 times the classical exciton ionization field. It is remarkable that at such high fields the exciton resonances are still clearly resolvable, with very little broadening. The large shifts observed have application to wavelength selective devices.[9]

We have made calculations of the lifetime broadening due to tunneling of the carriers out of the quantum wells. We used the same tunneling resonance methods as previously reported.[4] The basic assumption is that the exciton only field ionizes (reducing its lifetime and broadening its absorption) when the carriers tunnel out of the wells. For a 60:40 conduction band-valance band mismatch, the increased experimental linewidths are approximately consistent with the calculated values. This implies that the additional broadening previously observed in MQWS is due to field inhomogeneities across the depletion region as suspected.[4] Considerable loss in oscillator strength is expected theoretically for the exciton absorption peak as it shifts with increasing field. This is for two reasons. (i) The electron and hole have reduced overlap in the direction perpendicular to the layers because they are pulled respectively to opposite sides of the well. (ii) The exciton orbit in the plane of the layers is expected to expand[4] because the exciton binding energy is reduced. (This reduces the electron-hole overlap in the plane as well.) This qualitative prediction of the loss of exciton absorption is in agreement with the experiments reported here, and a quantitative comparison will be the subject of future work.

Two other features of the spectra are noteworthy. The first is that we find empirically that there is no significant overall loss of area in the absorption spectra over the spectral range measured; we are not aware of any theoretical model of this at the present time. The second is that there is relatively little change in the "interband" optical absorption at the higher photon energies of our spectra. This is surprising because a simplistic model in which the optical absorption is proportional to the electron-hole overlap in the eigenstates would predict loss of interband absorption as the electron and hole wavefunctions are separated by the field; hence a more sophisticated model is required for the interband absorption.

The device was operated as a modulator by tuning the laser to a fixed incident photon energy below the zero-field absorption edge. With incident photon energies of 1.458 and 1.443 eV for the perpendicular and parallel polarizations, we were able to obtain modulation depths of 10.2 and 9.2 dB, respectively. The measured device insertion loss was 6 ± 2 dB. 3 dB is due to reflection from the faces. This could be eliminated with antireflection coatings. 3 dB is due to the leaky waveguide loss. It should be noted, however, that the leaky waveguide structure is used only for experimental purposes, whereas actual integrated optical devices could be fabricated as real waveguides and would not suffer this built-in

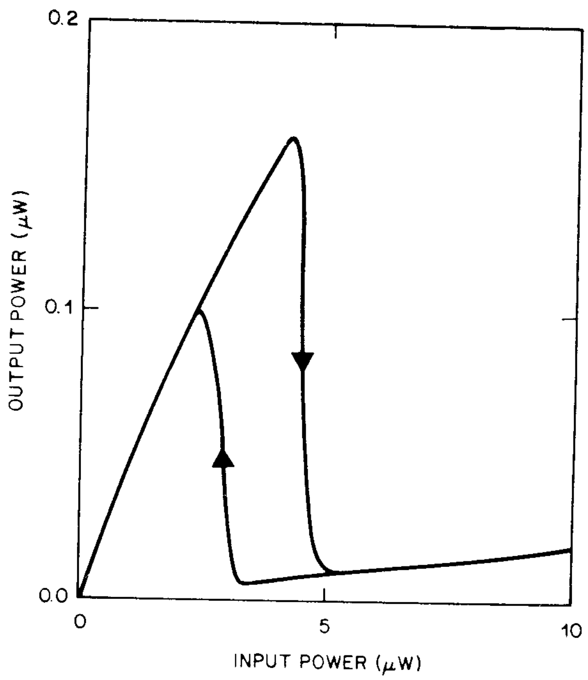

FIG. 3. Measured input/output characteristic at 1.471 eV using a constant current source to bias the device. The incident optical polarization was perpendicular to the layers.

insertion loss. We have also demonstrated a number of self-electro-optic-effect devices[6–8] (SEED's) in the waveguide geometry. Here the device is used simultaneously as a detector and a modulator. For our bistability experiments, a current source is used as a bias[7] and the laser is set to the zero-field position of the exciton. With no incident light the exciton is shifted to lower energy by the applied bias. As the incident light intensity is increased the photocurrent in the device increases. When the photocurrent exceeds the set current, the current source decreases the applied voltage, shifting the exciton back toward its zero-field energy and resulting in increased absorption. The increased absorption then produces increased photocurrent, and hence positive feedback and switching.

We have demonstrated optical bistability in both polarizations. Figure 3 shows the transfer function for $\hat{e}\perp$plane using an incident photon energy of 1.471 eV. We obtain a large on/off ratio of 20:1. This could be increased by either increasing the sample length or adding more quantum wells. Due to the large absorption edge shifts at which excitons can still be resolved, optical bistability can be observed for incident photon energies of 1.455–1.5 eV for $\hat{e}\perp$plane and 1.45–1.49 eV for $\hat{e}\|$plane.

We have also demonstrated other SEED devices such as optical level shifters and self-linearized modulators and also high-speed modulation[12] in the waveguide geometry. This work will be discussed elsewhere.

In conclusion, we have demonstrated the QCSE electroabsorption for the first time in a waveguide geometry. We find that the contrast between the absorption in the two optical polarizations is retained as the excitons shift with field. The resulting clear spectra show several physical phenomena in linewidths and absorption strength that could not be clearly resolved in previous experiments. We have demonstrated that these waveguide structures are applicable to a number of polarization-sensitive, high-contrast devices including modulators and SEED's.

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