Electroabsorption by Stark effect on room-temperature excitons in GaAs/GaAlAs multiple quantum well structures

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(Received 18 January 1983; accepted for publication 4 March 1983)

We report the first observation of electroabsorption in GaAs/GaAlAs multiple quantum well structures. We have been able to induce Stark shifts for room-temperature exciton resonances of ~ 10 meV for applied field $\sim 1.6\times 10^4$ V/cm in a sample with 96-Å GaAs layers, giving large changes in optical absorption (e.g., a factor of 5 or $\sim 4\times 10^3$ cm^{-1} increase). This should permit optical modulators with micron path lengths and potentially very fast operation.

PACS numbers: 78.20.Jq

In this letter we report the first observation of the dependence of the optical absorption on electric field in GaAs/GaAlAs multiple quantum well (MQW) structures. Near the band gap (~ 850 nm) large effects are seen with fields of the order of 10^4 V/cm, due to the shift and the broadening of *room-temperature exciton* resonances.[1] These structures are very attractive for light modulation application, requiring only a few microns optical path, and having potentially small insertion losses. Because of the nature of the microscopic mechanisms responsible for the effect and the very small volume involved, very high speed applications may be possible.

Because of the confinement of carriers in thin layers compared to the bulk exciton diameter (~ 300 Å for GaAs) in MQW structures, strong exciton peaks are observed in the absorption spectra at room temperature.[1] Three contributions to the spectrum can be distinguished[2]: the two peaks of the heavy hole and light hole exciton and an interband continuum associated with the step-like density of states of the quasi-two-dimensional electron-hole gas. Conversely, in

 0003-6951/83/100864-03$01.00

conventional semiconductors such resonances have all but disappeared at room temperature and the electroabsorption is mainly due to the Franz–Keldysh effect giving in general a broadening of the band edge.[3] At low temperature, however, excitonic Stark effect is observed in conventional semiconductors.[4] In MQW structures we find at room temperature large shifts of the exciton resonances to lower energies with applied field; thus, it is possible to move a strong absorption peak into a region that was previously substantially transparent promising deep modulation with short optical path length.

When a uniform electric field E is superimposed on the Coulomb potential which binds an electron and a hole, one side of the Coulomb potential well is lowered and the well width is slightly increased. The first effect changes discrete bound states into continua, resulting for $E < E_I$ is broadening of the lines and in a field ionization for $E \sim E_I$. (E_I is the ionization field $E_I = E_X/ea_X$, where E_X is the exciton binding energy and a_X its radius.) The broadening of the well is associated with the second order Stark shift which lowers the ground state energy.[5] Because of the toroidal structure of the excitons in MQW it is necessary to apply the field in the plane of the exciton orbit, to observe these effects.

The MQW structure used in our experiments was fabricated by molecular beam epitaxy on a GaAs substrate. A 1.45-μm-thick $Ga_{0.72}Al_{0.28}As$ cap layer was first grown, followed by 65 periods of alternate 96-Å GaAs and 98-Å $Ga_{0.72}Al_{0.28}As$ layers to form the 1.26-μm-thick MQW structure and capped by a further 1.45-μm-thick $Ga_{0.72}Al_{0.28}As$ layer. The cap layers are transparent in the MQW gap region. All the materials were undoped with residual carrier concentration $\lesssim 10^{15}\,cm^{-3}$. A $3 \times 3\,mm^2$ sample was cleaved along the (110) and ($1\bar{1}0$) direction and glued, epitaxial layer down, with a transparent epoxy to a sapphire substrate and the entire GaAs substrate selectively etched off. Electrodes of 100-Å Cr followed by 1000-Å Au were evaporated on the sample to give an electrode spacing $d = 300\,\mu m$. A cw tunable oxazine 750 dye laser was used to measure the absorption spectra. The laser beam was focused to a 50-μm-diam spot at the center of the interelectrode gap, with a polarization perpendicular to the static field. The transmission corrected for surface reflection was measured as a function of the laser frequency for applied voltages varying from 0 to 650 V. The laser power was kept as low as ~ 10 μW to avoid carrier generation. The current passing through the sample was 10 μA at 150 V. Examples of the absorption coefficient spectra for 0, 400, and 600 V are shown in Fig. 1. Large shifts and broadening are evident. The shifts are difficult to measure up to $V \sim 200$ V because they are small compared to the linewidth, above this value they show a superlinear dependence on V, as shown on Fig. 2. The light hole-exciton peak was found to shift more than the heavy hole one. The linewidth could be measured only for the heavy hole exciton; it was taken as the half-width at half-maximum on the low-energy side of the peak. The width variation is monotonic and approximately linear with the applied field, varying from 2.8 meV at $V = 0$ to 4.3 meV at $V = 600$ V. The precise value of the field applied to the MQW is difficult to evaluate because of possible space-

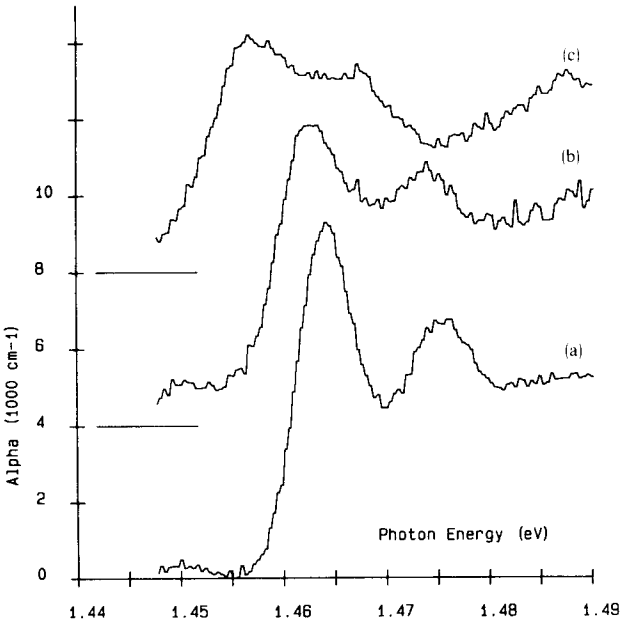

FIG. 1. Absorption coefficient of the MQW sample near the band edge for three static potential applied: (a) $V = 0$; (b) $V = 400$ V; (c) $V = 600$ V. The curves (b) and (c) displaced vertically for clarity.

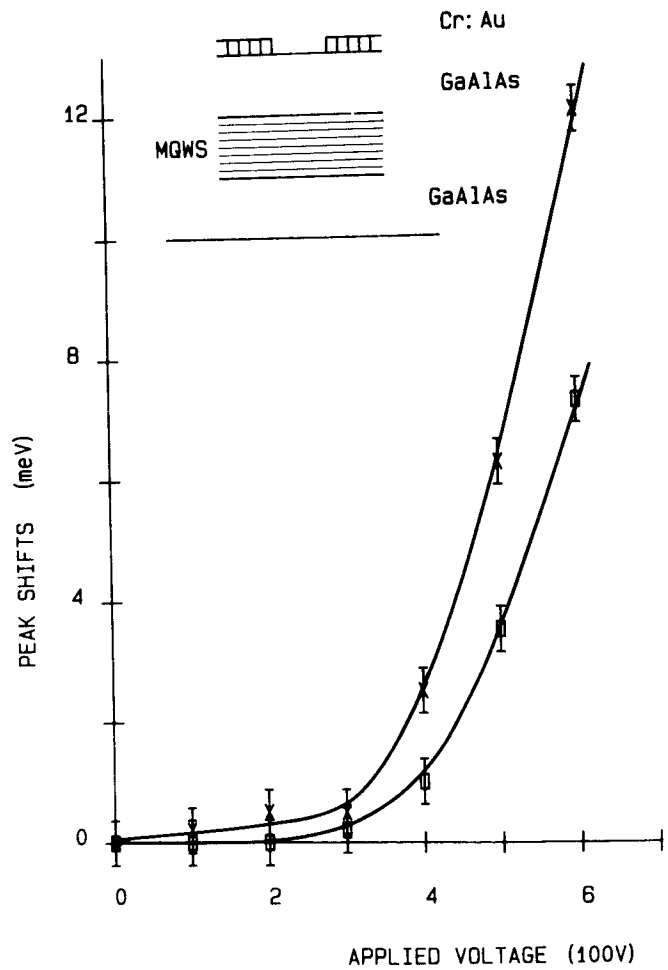

FIG. 2. Variations of the position of the heavy hole electron (□) and of the light hole-electron (×) exciton peaks as a function of the applied static potential. Insert: details of the structure of the sample.

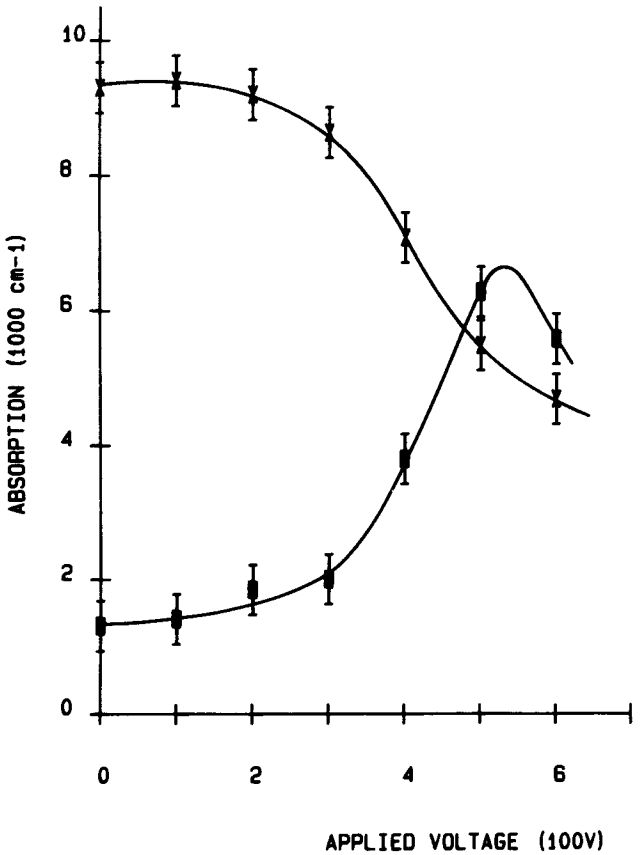

FIG. 3. Variations of the absorption coefficient at the exciton peak (1.46 eV) (×) and 5 meV below (□) as a function of the applied static potential.

charge effects and contact resistances. Assuming that the sample behaves like a simple resistor, at the center of the interelectrode spacing one can take $E = \gamma V/d$, where the correction factor for our geometry is $\gamma \lesssim 0.8$.[4] The spectra [Figs. 1(b) and 1(c)] correspond therefore to $E \sim 10^4$ and 1.6×10^4 V/cm. To evaluate the binding energy of the excitons in MQW 96 Å thick we use the experimental and theoretical results of Miller *et al.*,[6] which give $E_X(Hh - e) = 9$ meV and $E_X(Lh - e) = 10.5$ meV. The radius can be calculated by the relation $a_X E_X \sim$ constant, which gives $a_X(Hh - e) \sim 65$ Å and $a_X(Lh - e) \sim 56$ Å. The corresponding ionization fields, $E_I = 1.4 \times 10^4$ and $E_I = 1.9 \times 10^4$ V/cm, are quite consistent with our measurements. Note that any simple perturbation analysis of our results is invalid because of the high value of the fields, relative to E_I, which we utilize. The apparent contradiction between the larger binding energy of the light hole exciton and its greater sensitivity to static fields should be interpreted with care, as additional complication may occur due to its proximity to the heavy hole interband continuum.

In Fig. 3 the variations of the absorption coefficient are shown as a function of the applied potential at the heavy hole-exciton peak and 5 meV below; positive or negative changes larger than $\Delta\alpha \sim \pm 4 \times 10^3$ cm^{-1} are obtained in the absorption at given photon energies as the field is increased from 0 to 1.6×10^4 V/cm. This result compares most favorably to the case of bulk GaAs[7] where fields up to $(5 \pm 1) \times 10^4$ V/cm are necessary to induce changes of the absorption coefficient $\Delta\alpha \sim 2 \times 10^2$ cm^{-1}, as well as to the case of other III-V compounds[8] where changes $\Delta\alpha \sim 2 \times 10^3$ cm^{-1} are obtained, but only with fields as large as 4×10^5 V/cm. It is important to notice that the speed at which the absorption changes is *not* determined by the exciton lifetime; rather it is related to how fast the energy levels of the crystal can be shifted, which is a very fast process. The speed of a modulator based on this room-temperature excitonic Stark effect will most likely be limited by the speed at which the "static" field can be applied. A number of other interesting effects are associated with this type of electroabsorption. Polarization-dependent effects are expected since the shifts and broadenings depend upon the relative orientation of the static and the optical field as well as upon their orientation with respect to the crystallographic axes. The variation of the absorption is also accompanied by a change of refractive index which can be viewed as a resonant electro-optic effect and may be usable in phase sensitive devices. Work is in progress in our laboratory to study and utilize these effects. In the present letter we have concentrated our report on the Stark effect alone.

In conclusion, we have shown that the Stark effect on room-temperature excitons in MQW produces large variations of the absorption coefficient ($\Delta\alpha \sim \pm 4 \times 10^3$ cm^{-1}) for applied fields of the order of 10^4 V/cm. This effect should be usable in very high-speed optical modulation schemes because of the fast mechanisms involved and the small volume ($\lesssim 100\ \mu$m^3) necessary to achieve large change of transmission.

We wish to thank D. Pearson for his help in the sample preparation.

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