High-speed optical modulation with GaAs/GaAlAs quantum wells in a *p-i-n* diode structure

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A new type of high-speed optical modulator is proposed and demonstrated. An electric field is applied perpendicular to GaAs/GaAlAs multiple quantum well layers using a "*p-i-n*" diode doping structure of 4-μm total thickness. The optical absorption edge, which is particularly abrupt because of exciton resonances, shifts to longer wavelengths with increasing field giving almost a factor of 2 reduction in transmission at 857 nm with an 8-V reverse bias. The shifts are ascribed to changes in carrier confinement energies in the wells. The observed switching time of 2.8 ns is attributed to RC time constant and instrumental limitations only, and fundamental limits may be much faster.

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In this letter, we report for the first time the observation of large optical absorption changes in GaAs/GaAlAs multiple quantum wells (MQW) due to an electric field applied perpendicular to the MQW layers. This effect is used to make an optical modulator which has desirable electrical properties, operates at room temperature, shows promise of very high speed, and is compatible with laser diode powers, wavelengths, and materials. We apply the electric field perpendicular to the molecular beam epitaxy (MBE)-grown MQW layers in a convenient positive-instrinsic-negative (*p-i-n*) doped structure. The field-induced absorption change is primarily a shift to lower energies of the band-edge absorption, accompanied by some broadening of the edge features, and is greatly enhanced relative to the shifts seen in bulk materials because of the confinement of the carriers in the MQW's. The MQW's also show exceptionally strong room-temperature exciton resonances, which enhance the absorption effects at the band edge. Furthermore, the use of a *p-i-n* doping scheme in this device allows the application of a moderately large electric field to the active layers without high voltage or current drive.

Previous observers[1] of electric field absorption effects in room-temperature MQW's have applied the field in the plane of undoped MQW layers.[2] Measurements have also been made at low temperature[3,4] of the effects of an electric field perpendicular to the layers on luminescence; these observations give much information[3] about impurities and bound excitons,[4] but the information on interband effects at high fields is limited because of quenching of the direct luminescence.

The modulation can be understood in terms of changes in the optical properties of MQW's. The quantization of the motion of electrons and holes in the z direction (perpendicular to the layers) gives rise to discrete subbands starting at energies[5] E_n, $n = 1, 2, 3, \ldots$. This quantization changes the basic nature of the optical interband absorption, giving a series of steps rather than a smooth wavelength dependence. The absorption close to the fundamental edge of direct gap semiconductors is also enhanced by excitonic effects. At room temperature, excitonic resonances are very weak in bulk semiconductors, but the confinement in MQW's enhances the exciton binding energy, and two clear exciton resonances are seen,[6,7] the so-called light-hole and heavy-hole excitons, resulting in a sharp absorption edge. Anything which perturbs the exciton resonances will therefore be particularly effective in changing the absorption near the edge. The energy of an exciton absorption near the edge is

$$E_x = E_g + E_{e1} + E_{h1} - B, \tag{1}$$

where E_g is the energy gap of the bulk semiconductor, B the binding energy of the exciton, and E_{e1} and E_{h1} the confinement energies of the first electron and hole subbands, respectively.

Application of a static field $\mathscr{E}$ modifies all four terms in Eq. (1). The binding energy B is modified when the relative motion of the two particles is affected, as was recently shown by application of a field parallel to the layers.[1,2] The variation of E_g under a static field is the usual Franz–Keldysh effect; it is rather small because it is associated with a modification of the unit cell wave function. Conversely, the variations of the confinement energies E_{e1} and E_{h1} result from the modification of the envelope wave functions within an entire quantum well of length L_z; these wave functions extend over a large number of unit cells and are more sensitive to electrostatic perturbations. Consequently, we expect the variations of the confinement energy to be larger than the Franz–Keldysh effect. Roughly speaking, one expects to see large changes in the absorption when the change in electrostatic potential across a well, $e\mathscr{E}L_z$, is comparable to one of the terms in Eq. (1). For our sample, we have $B \simeq E_{h1} \simeq 10$ meV and $E_{e1} \simeq 50$ meV for the heavy hole exciton. The potential change across a well equals or exceeds these energies for $\mathscr{E} \sim 1$–5×10^4 V/cm, the fields used in this work. It should be noted that these large fields make a perturbation analysis

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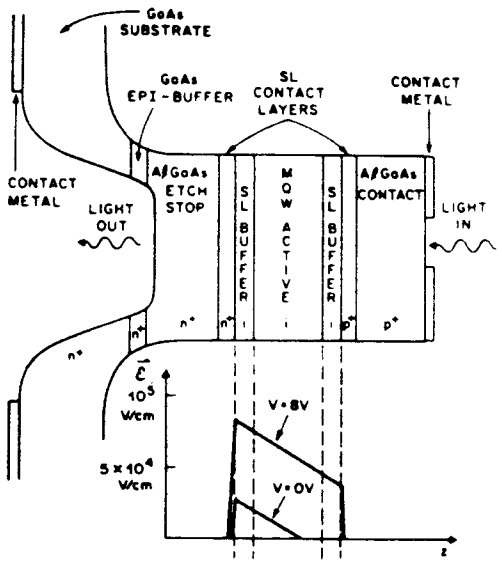

FIG. 1. Schematic view of sample. The semiconductor layers are grown via MBE on a GaAs substrate, and then the diode is defined lithographically. The drawing is not to scale, except that the thicknesses of the epitaxial semiconductor layers are shown in correct proportion. The lower portion of the figure shows the calculated electric field strength $\mathcal{E}$ as a function of position within the device for two applied voltages, using the depletion approximation. Sample parameters are the following: MQW active region: thickness 0.965 μm (50 periods of 95 Å GaAs and 98 Å GaAlAs). Mole fraction of Al in GaAlAs is 0.32. Total thickness 3.9 μm. GaAlAs etch stop and top contact layers each 0.98 μm thick. Superlattice (SL) consists of 28.5 Å GaAs layers alternating with 68.5 Å GaAlAs layers. SL buffers: thickness (each) 0.29 μm (30 periods). SL contacts: thickness (each) 0.19 μm (20 periods). Mesa diameter $\sim 600\,\mu$m. p^+ and n^+ doping $\sim 5\times10^{17}$ cm^{-3}. (These dopings were determined by capacitance-voltage measurements.) i layer doping $\sim 2\times10^{15}$ cm^{-3}. Top contact opening diameter $\sim 175\,\mu$m.

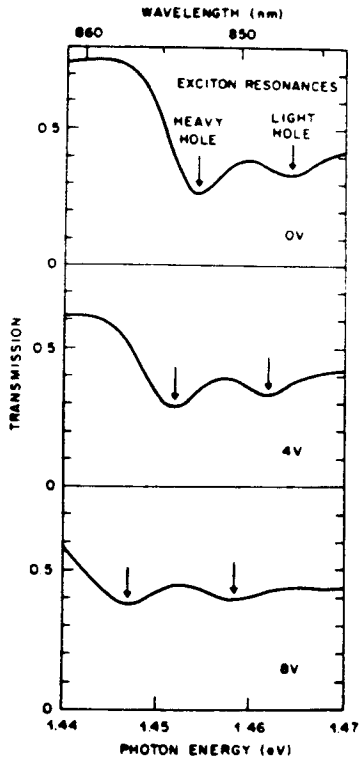

FIG. 2. Transmission spectra of the p-i-n structure with 0, 4, and 8 V applied in reverse bias. The average fields within the MQW region, calculated from C-V measurements, are $\sim 1\times10^4$, 3.4×10^4, and 6.0×10^4 V/cm, respectively, with up to $\pm\,1.4\times10^4$ V/cm variation across the MQW region. See Fig. 1 for field profiles.

of this experiment totally invalid.

The design of our sample is shown in Fig. 1. It is grown on a Si-doped ⟨100⟩ GaAs substrate. The undoped optically active layer, which contains 50 GaAs wells each 95 Å thick, is surrounded by undoped buffer layers and doped contact layers. This creates a p-i-n diode, which is operated in backbiased mode. The buffer and first contact layers are also made of a superlattice of alternating layers of GaAlAs and GaAs. Introducing the thick layers of GaAs into the nominally undoped buffer regions was found to reduce the background doping level by more than an order of magnitude.[8] This reduces the field inhomogeneity across the active region and reduces the drive voltage of the device. The device is defined laterally by an etched mesa 600 μm in diameter which extends into the substrate; a small hole is etched through the opaque substrate by a selective chemical etch. We have made a fairly large initial device for ease of fabrication. Its capacitance is approximately 20 pF.

The p-i-n doping provides many of the advantageous features of this configuration. The lower portion of Fig. 1 shows the internal electric field in the various layers at two different applied voltages, calculated within the depletion approximation, with a p-type background doping level of 2×10^{15} cm^{-3} in the intrinsic layers. The active layer can be switched from low field to approximately 6×10^4 V/cm by the application of 8 V. Because the device is operated as a backbiased diode, its resistance is high and its capacitance is low, which are desirable electrical properties. Finally, the heavily doped contact layers can easily be metallized and contacted.

Optical measurements on the sample were made using a dye laser with either oxazine 750 or LDS 821 dye, pumped by a krypton ion laser. The dye laser could be operated either cw or synchronously mode locked. Figure 2 shows optical transmission spectra of the sample at room temperature at various dc biases. These spectra were taken with ~ 0.5-μW laser power; no significantly different spectra were found for cw or mode-locked excitation. No corrections have been applied to the spectra for surface reflections. The comparatively high absolute transmission ($\sim 75\%$) at ~ 860 nm and 0 V bias is due to the occurrence of a weak Fabry–Perot resonance near this wavelength. The shape of the spectra did not change significantly as the spot size was altered from ~ 5 to $\sim 150\,\mu$m, except for Fabry–Perot effects which are less pronounced for larger spots. In all optical measurements in this letter, average intensities were well below the measured absorption saturation intensities in similar undoped material.[7,9] Absorption spectra taken with up to 1 mW in a ~ 50 μm spot showed no significant change compared to low power spectra.

At zero applied volts, the absorption spectrum is similar to that observed previously at zero field.[7] As the applied dc bias is increased, the exciton peaks are observed to shift to lower energies and broaden. Between 0 and 8 V applied, we see almost a factor of 2 reduction transmission at 1.446 eV (857 nm). (Greater modulation depth should be possible with

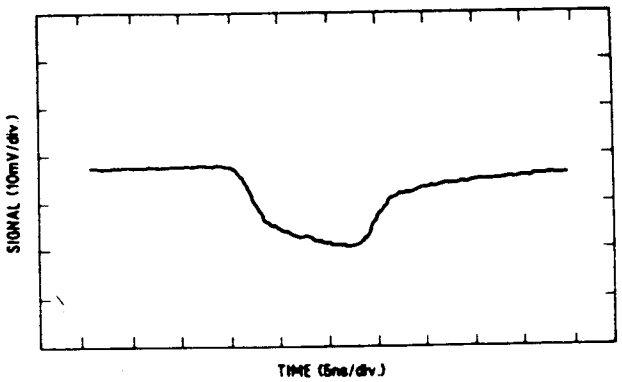

FIG. 3. Detected optical signal as a function of time, recorded on a digital averaging sampling oscilloscope, when the diode was pulsed from 0.5 to 4.0 V. Increased optical signal corresponds to downward deflection. Photon energy was 1.454 eV (~853 nm). The long tails are an artifact of the photodetector used. Optical power was ~100 μW in a ~50-μm diam spot.

thicker samples.) The shift in the exciton absorption can be understood primarily in terms of a shift in the confinement energies of the electron and hole in the quantum well plus some change in the exciton binding energy, as was described earlier. The observed exciton broadening may be due to field inhomogeneity across the MQW's, or the decreased lifetime of the exciton in the presence of the field. The fact that the exciton resonances can be seen at all with a perturbation up to six times the exciton binding energy is remarkable. Our tentative explanation is that the potential barriers at the sides of the quantum wells prevent the electron and hole from being totally separated by the field. It should be noted that if the absorption shifts are indeed due to shifts in electron and hole confinement energies, it should be possible to observe significant absorption changes even in the absence of clear exciton resonances, due to the associated shift of the interband absorption itself. Additional experiments to resolve this and other aspects of the spectra are under way.

To measure the dynamic optical response under cw illumination the diode was bridged with a 50-Ω resistor and driven with a pulse generator with 1.8-ns rise time. The optical output was observed with a Si APD of roughly 1-ns rise time. Figure 3 shows the observed signal recorded on an averaging sampling oscilloscope when the diode was driven between 0.5 and 4 V. The optical wavelength used was 853 nm (1.454 eV). The observed 10%–90% rise time is 2.8 ns. (The slower slopes on this trace are believed to be artifacts of the APD; this was verified by checking the response of the APD with mode-locked laser pulses.) The calculated RC rise time of the device when driven by a 50-Ω load is 2.2 ns. The observed optical rise time is therefore consistent with RC time constant and measurement limitations.

Since optical properties are also affected by thermal effects, we have taken care to assure that the modulation observed is not due to heating. This is demonstrated by the very high speed of the device. In the 2.8-ns rise time of the device, only roughly 3×10^{-4} K of temperature rise are possible in the volume of the illuminated sample spot, even if all the heat from the carriers passing through the device is deposited in this volume. This is much less than the 5 K of heating required to obtain the observed shift in the exciton energies between the 0 and 4-V spectra. Furthermore, the spectra show changes of shape which are not reproduced in zero field spectra at higher temperatures.

In summary, we have demonstrated that the structure in Fig. 1 provides significant optical modulation at room temperature by changes in the absorption due to the shifts in energy levels in the MQW's. The currently observed speed of 2.8 ns can be attributed to instrumental considerations and RC time constants. RC time constants can be reduced by reducing the device size and thus its capacitance.

It is important to realize that the speed of this device is not limited fundamentally by carrier lifetime effects. The limit on speed is set by (a) how fast the electric field can be applied to the material (e.g., RC time constant limitations) and (b) how fast the relevant wave functions can respond to the perturbation. An approximate upper estimate of the latter is given by the uncertainty principle; given the half-width of the absorption features involved ($\gtrsim 3$ meV), the absorption cannot respond faster than ~0.2 ps. Although this estimate is very approximate, it therefore appears that the speed will primarily be limited by electrical considerations. It should be noted, however, that because of the very short optical path (a few microns) we need not match electrical and optical propagation velocities or operate in waveguide configurations with this modulator. At high powers the device will be limited by heat dissipation, absorption, saturation, and the consequences of injecting high densities of carriers; these will be the subject of future work, but none of these has proven to be a major problem so far.

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