Intrinsic multiple quantum well spatial light modulators

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Large improvements are reported in the sensitivity of optically addressed multiple quantum well spatial light modulators. In prior work with these materials the quantum well region has been made semi-insulating. It is shown that this is unnecessary and in fact detrimental to performance. By placing layers containing high trap concentrations at the ends of the structure and leaving the active quantum well layers intrinsic the speed of the device at a given illumination is improved by more than four times, diffraction efficiency is enhanced and spatial resolution is almost the same. © *1995 American Institute of Physics.*

Recent demonstrations of perpendicular geometry GaAs/AlGaAs multiple quantum well (MQW) structures as optically addressed spatial light modulators (OASLM) have shown that these devices can offer high speed[1] and high resolution.[2]

These devices use multiple quantum wells that have been made semi-insulating by ion implantation[2] or chromium doping.[1] An ac electric field is applied perpendicular to the plane of the wells at a rate faster than the dark screening time of the material. The surface of the quantum well is then exposed to a write beam that creates photocarriers which screen the applied field in the illuminated regions. The result is an internal electric field which is modulated in the same pattern as the write beam. The optical properties of the quantum well are then changed through the quantum confined Stark effect, and readout with a beam that is nearly resonant with the heavy hole exciton.

All MQW OASLMs to date have had deep traps distributed throughout the MQW region. These ''bulk'' traps have been thought necessary to decrease the dark conductivity of the MQW layers so that screening is largely due to photogenerated, and not background, carriers. In addition, the bulk traps were included to restrict the lateral diffusion of carriers which degrades OASLM resolution. Both these motivations are valid for parallel field geometry MQW OASLMs where photogenerated carriers drift and are trapped within the quantum well layers.[3]

This thinking may not, however, apply to the perpendicular geometry for two reasons: First, materials grown by molecular beam epitaxy (MBE), can have an unintentional doping on the order of 10^{14} carriers/cm^3. This doping concentration is sufficient to screen only about 10% of the high fields applied to these materials in the perpendicular geometry (~50 kV/cm). Any further screening must be by photocarriers or thermally generated carriers, of which there are few due to the large band gap of GaAs. Thus, background carrier screening may not be a problem in good quality materials.

Second, recent work also suggests that bulk traps may not be necessary to maintain OASLM resolution. Theoretical calculations indicate that the screening carriers accumulate in an extremely thin (5 nm) region at the semiconductor-insulator interface.[4] In addition, experimental measurements of MQW OASLMs indicate that the transit time of the carriers across the quantum well region is ~300 ps,[5] so the carriers spend most of each voltage cycle at the interface. These results indicate that the resolution performance of MQW OASLMs in the perpendicular geometry may be largely controlled by the trap concentration of thin layers at either end of the MQW region.

In this letter, we examine the hypothesis that MQW OASLMs with surface, but no bulk, traps can show similar resolution to those with bulk traps. We show that these intrinsic MQW OASLMs offer superior performance to semi-insulating devices.

Three OASLMs were fabricated from two wafers. The MQW region in both wafers was grown by MBE to the same specification: 75 periods of 10 nm GaAs wells separated by 3.5 nm of $Al_{0.3}Ga_{0.7}As$ barriers. Wafer 1 had, in addition, high resistivity cladding layers at both ends of the MQW region. These cladding layers consisted of 30 nm of low-temperature (LT) grown $Al_{0.3}Ga_{0.7}As$. These LT layers were grown at a substrate temperature of 300 °C and annealed at 580 °C. Low-temperature AlGaAs grown under similar conditions to our own has shown dark resistivities of 10^{12} Ω cm and trap densities higher than 10^{18} cm^{-3}.[6] Wafer 2 had no LT cladding layers. Both wafers also had a thin sacrificial AlAs layer to be used for the liftoff process.

The wafers were fabricated into three devices. For each we used epitaxial liftoff[7] to remove the 1 μm MQW from its growth substrate. It was then attached, using solid phase bonding,[7] to a quartz substrate coated with a transparent Cr/Pd/Au electrode. A 0.4 μm silicon nitride dielectric layer was then deposited on the top of the MQW followed by a Cr/Au transparent electrode. The details of the fabrication process are reported elsewhere.[8]

Two devices were fabricated from wafer 1. The first device, designated SI/LT, was proton implanted to provide bulk traps and had low temperature AlGaAs layers to provide surface traps. A multiple step implantation process was used to generate a uniform defect density of $\sim 4\times 10^{16}$ cm^{-3} throughout the 1μm depth of the quantum well material. The second device, designated, INT/LT, was not proton implanted and thus had only surface traps due to the low-temperature AlGaAs layers present in this wafer. The third

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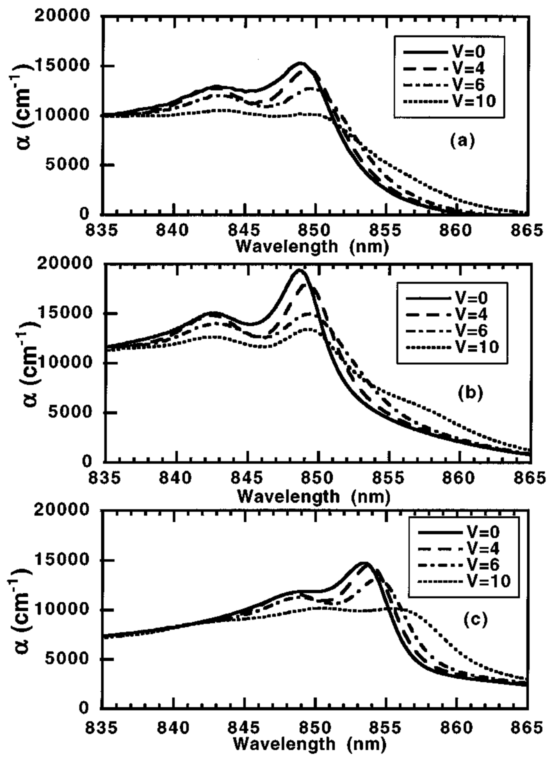

FIG. 1. Room-temperature electroabsorption spectra for (a) SI/LT, (b) INT/LT, and (c) INT devices.

device was fabricated from wafer 2. It was not proton implanted and had no low-temperature AlGaAs layers. It was designated INT.

Electroabsorption was measured in all three devices at room temperature in a Fourier transform spectrometer at voltages that varied from 0 to 10 V. The spectra are shown in Fig. 1. The SI/LT sample has its heavy hole exciton peak at 849 nm and shows a peak electroabsorption of 5000 cm^{-1} at this wavelength with 10 V applied. The INT/LT sample came from the same wafer and thus also shows a heavy hole and electroabsorption peak at 849, but has narrower exciton linewidths and a higher peak absorption modulation of 6000 cm^{-1}. This is because the proton implantation that the SI/LT device was subjected to broadens the exciton features and hence reduces the electroabsorption. This damage to the exciton is a disadvantage to ion implantation of the quantum wells. The INT sample came from a separate wafer and thus shows a slightly different absorption spectra. Its heavy hole peak is at 852 nm and its peak electroabsorption there is 4800 cm^{-1}.

Since all three devices show strong electroabsorption, their ability to store a space charge determines their diffraction efficiencies and resolution. We evaluated their performance as spatial light modulators using a tunable titanium sapphire laser and a self-diffraction experiment. A ± 10 V square wave was applied to the MQW OASLM. To produce the grating interference pattern we used an achromatic grating arrangement.[2] The first order diffraction of one of the pump beams was measured using a silicon *pin* photodiode.

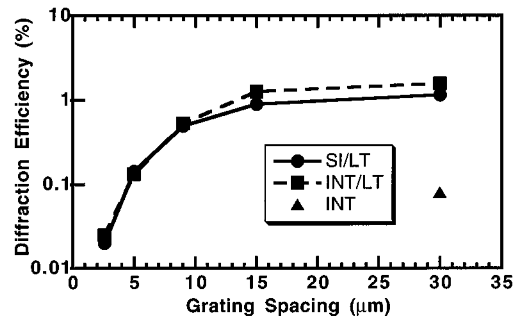

FIG. 2. Diffraction efficiency dependence on grating period for SI/LT, INT/LT, and INT devices.

The spatial resolution of the devices was determined by measuring the diffraction efficiency as a function of grating period. We define diffraction efficiency as the ratio of the peak power in the diffracted order to that in the transmitted pump beam. For the SI/LT and INT/LT samples, diffraction was measured at 852.5 nm, near the peak of the diffraction. For the INT sample the diffraction was measured at 856 nm because the peak diffraction fell at this slightly longer wavelength. Figure 2 shows diffraction efficiency for all three samples. At the longest grating period, the diffraction efficiency of the INT/LT device is approximately 50% larger than the SI/LT device. This is due to the larger electroabsorption this sample exhibits because it has not been proton implanted. As we demonstrated in an earlier work[2] the SI/LT maintains relatively high diffraction efficiency down to periods as short as 5 μm. However, as the figure shows, the INT/LT device's diffraction efficiency falls off only slightly faster with smaller grating period even though it contains no intentional traps in the MQW region. The INT sample which has no intentional traps in either the bulk or at the surface shows only a very weak diffraction at the longest grating period, and no measurable diffraction below 30 μm. This constitutes strong evidence that the resolution of MQW OASLMs operated in the perpendicular geometry is determined predominantly by traps at the interface between the MQW region and the dielectric and that the traps in the bulk MQW play little part. The weak diffraction from the INT sample may be due to unintentional trap sites or surface traps.

Next, we evaluated the temporal performance of the devices. In a perpendicular mode MQW OASLMs each voltage flip of the applied ac field constitutes a new cycle for the device. The speed at which the device can be run is determined by the time for the diffraction to reach its peak value. After a voltage flip, the diffraction efficiency begins to buildup, reaching a peak at approximately the time when the illuminated regions of the sample have completely screened the applied voltage. This time is determined not by the transit time of carriers across the well, which is extremely short,[5] but rather by the photogeneration rate of carriers into the conduction band. The time to peak is thus directly proportional to the illumination level. However, several photons must be absorbed to produce one carriers worth of screening. Presumably, most of the carriers produced by these photons

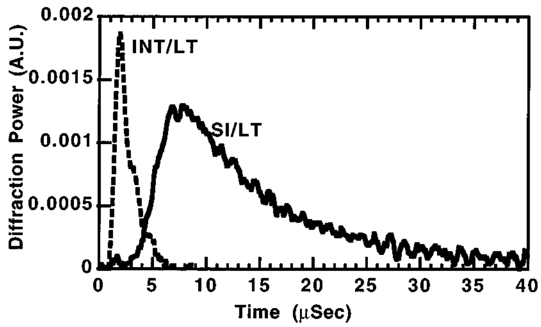

FIG. 3. Diffraction pulses for the SI/LT and INT/LT devices.

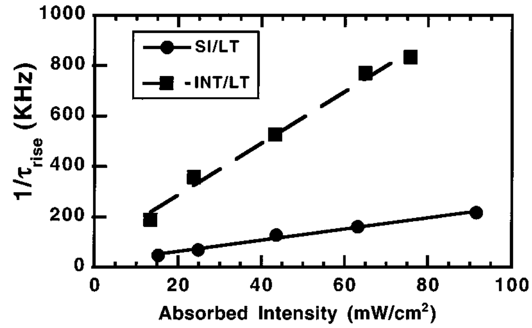

FIG. 4. Inverse of the rise time vs absorbed intensity for the SI/LT and INT/LT devices.

recombine or are trapped in defects within the MQW region before they can travel to the interface and produce the maximum amount of screening.

After peaking, diffraction begins to decline as screening occurs in the darker regions. Eventually a uniform space charge is accumulated at the interface, contrast in electroabsorption is lost, and the diffraction signal drops to zero. The result is a transient diffraction pulse. The rise and fall times of this diffraction pulse are proportional to each other.

Figure 3 shows the diffraction pulses for both the SI/LT and INT/LT samples for the same absorbed power of 43 mW/cm^2. The field was flipped every 100 μs after the diffraction pulse had completely decayed away. The INT/LT device rises and decays approximately 4 times faster than the SI/LT yielding a proportionally higher sensitivity. With no traps in the MQW region of the INT/LT sample it is much more likely for a photogenerated carrier to make it all the way across the wells and fully participate in screening.

Figure 4 shows the inverse of the rise time of diffraction pulses in both the SI/LT and INT/LT samples as a function of absorbed pump intensity. The amount of absorbed energy, averaged over one grating period, needed for the SI/LT sample to reach peak diffraction is 0.35 $\mu J/cm^2$. The amount of energy for the INT/LT sample to reach peak diffraction is 0.08 $\mu J/cm^2$. This means that the SI/LT sample needs approximately 8 photons to produce one carrier worth of screening, while the INT/LT sample needs only about 2 photons. The maximum efficiency possible would be 0.5 photons per carrier since each absorbed photon produces an electron-hole pair.

Contrary to prior work on MQW OASLMs we have shown that bulk traps are not necessary and are in fact detrimental to the performance of these devices. Samples with the MQW region left as-grown and with highly resistive LT AlGaAs layers show comparable resolution performance, larger diffraction efficiencies, and more than 4 times the sensitivity of materials with bulk traps and LT layers. This high sensitivity should allow these materials to work at lower light levels and at speeds higher than 1 MHz without the heating problems that would be present in less sensitive devices.

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