AlGaAs/GaAs multiple quantum well reflection modulators grown on Si substrates

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We report for the first time large excitonic absorption at room temperature in AlGaAs/GaAs multiple quantum well structures grown on Si substrates in a *p-i-n* configuration, using photocurrent measurements. We demonstrate an optical reflection modulator which is based on the quantum-confined Stark effect and exciton broadening with a reverse bias voltage applied across the *p-i-n* structure. A 7.7% change in the reflectivity of the device with 6 V reverse bias voltage was observed. These results demonstrate clearly that optical device quality AlGaAs/GaAs is obtainable directly on Si substrates which has great implications with regard to the monolithic integration of optical III-V and electronic Si technology.

Multiple quantum well (MQW) *p-i-n* modulators, based on the quantum-confined Stark effect, have been demonstrated extensively for AlGaAs/GaAs MQW's, grown on GaAs substrates by molecular beam epitaxy (MBE).[1-3] MQW electroabsorption modulators have also been reported in the InGaAs/InP[4] material system grown on InP substrates by metalorganic chemical vapor deposition, in the InGaAs/InAlAs[5] material system grown on InP substrates by MBE, and in the GaSb/AlGaSb[6] system grown on GaSb substrates by MBE. Also strained-layer MBE-grown InGaAs/GaAs[7,8] modulators on GaAs have been reported.

The use of Si as a substrate for GaAs epitaxy[9] would allow monolithic integration of GaAs-based optical devices and Si-based electronic devices, taking advantage of the important optical properties of GaAs and the mature processing technology for Si. Optical signals can be generated in such a monolithic system, making optical off chip communication possible. There are two main difficulties associated with the growth of GaAs on Si. The first is that of lattice mismatch: GaAs has a 4% larger lattice constant than Si. This large mismatch will unavoidably cause misfit dislocations. Techniques which confine the dislocations to the bottom of the epitaxial structure are required. The second difficulty is the problem of antiphase disorder. This defect can also be suppressed using special growth techniques.[9]

In this letter we report to our knowledge the first MBE-grown *p-i-n* AlGaAs/GaAs MQW optical reflection modulator,[10] grown on a Si substrate. The modulator operation is based on the electric field effect on the optical absorption of the MQW material. Reflection modulators are of interest for bidirectional communication systems, in parallel arrays of optical switching and processing devices and for optical interconnects.[10] The latter is especially interesting when the reflection modulator is grown on the same substrate alongside a Si very large scale integrated (VLSI) circuit.

A schematic diagram of the device structure investigated is shown in Fig. 1. The samples were grown on an As-doped (100) *n*-Si (0.01 Ω cm) substrate tilted toward (110) by 4° using MBE. Following a monolayer deposition of As to avoid antiphase disorder (using As_2 dimeric source), about 200 Å of *n*-GaAs (Si doped at 3×10^{18} cm^{-3}) was grown at a substrate temperature of 450 °C. The growth rate and temperature were then increased to 1 μm/h and 600 °C, respectively. About 0.5 μm into the buffer layer a five-period 100 Å/100 Å $In_{0.2}Ga_{0.8}As$/GaAs strained-layer superlattice was grown to help bend out some of the dislocations. This was followed by the growth of another 1.5-μm-thick *n*-GaAs buffer layer and 50 periods of GaAs quantum wells of 120 Å thickness with 120 Å $Al_{0.3}Ga_{0.7}As$ barriers (undoped). Finally a 0.5 μm *p*-$Al_{0.3}Ga_{0.7}As$ cap layer (Be doped at 5×10^{18} cm^{-3}) was grown. Large (600 μm diameter) mesa devices were fabricated using AuBe rings as contact on the *p*-material and a AuGe-Ni-Au contact on the *n*-substrate.

The room-temperature photocurrent spectrum for the device described is shown in Fig. 2. The spectrum was obtained by focusing a chopped monochromatic beam on the aperture of the AuBe ring. We used a 100 W tungsten-halogen lamp with a 270 McPherson monochromator to generate the probe light. The photocurrent was detected by conventional lock-in techniques as the voltage dropped across a 1 MΩ resistor in series with the *p-i-n* diode. The determination of the absorption spectrum using transmission measure-

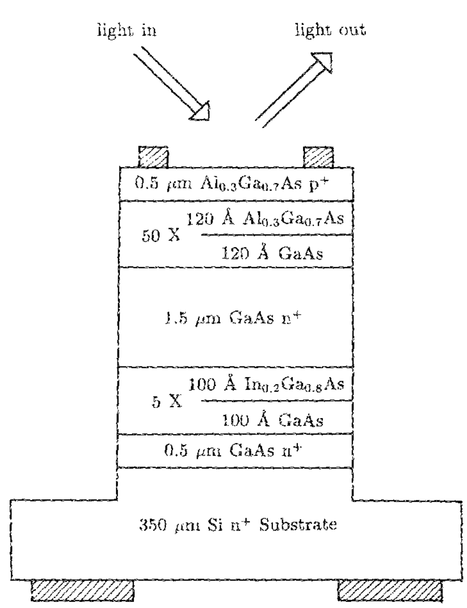

FIG. 1. Schematic diagram of the optical reflection modulator.

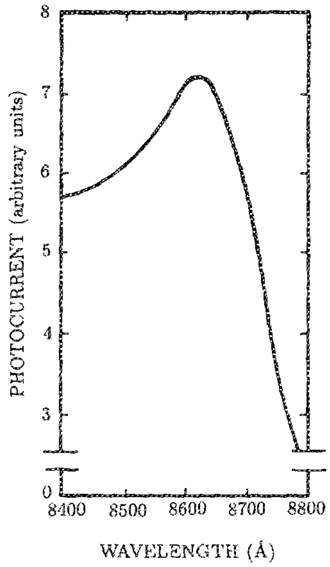

FIG. 2. Photocurrent spectrum of the MQW *p-i-n* structure.

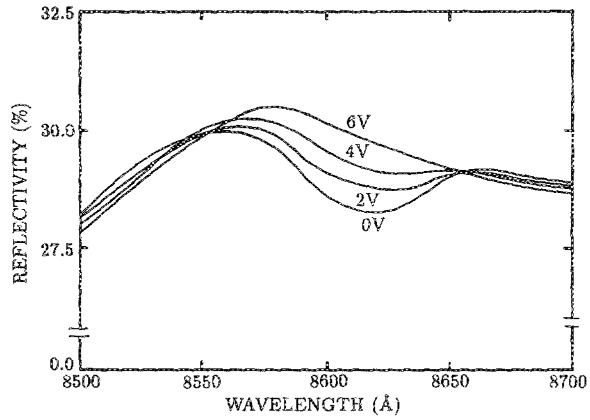

FIG. 3. Reflectivity spectra at different reverse bias voltages.

ments would require for the Si substrate to be removed since it is absorbing at the wavelengths of interest, and the spectrum would be influenced by Fabry-Perot fringes.[11] Photocurrent measurements give similar results as absorption measurements and they eliminate the need for two-sided processing of devices to produce a window in the Si substrate. Therefore we used the photocurrent technique.[11] A clear peak in the photocurrent spectrum at 8610 Å is dominated by the heavy-hole ($C1$-$H1$) excitonic absorption resonance of the MQW material. The light-hole ($C1$-$L1$) excitonic absorption may also contribute to this peak but cannot be resolved since the seperation between $C1$-$H1$ and $C1$-$L1$ is comparable to the linewidth of the resonance peak. In contrast, the same structures grown on GaAs exhibited a double peak associated with heavy- and light-hole transitions.[1] Large excitonic absorption at room temperature allows us to use this MQW material to create a strong optical modulation when an electric field is applied. This was demonstrated on the same sample for a reflection modulator.

The room-temperature reflectivity spectrum of the *p-i-n* MQW devices was measured for varying reverse bias voltages. A broad-band low-power (20 W) tungsten lamp was used as the light source. The light beam was focused on the aperture of the AuBe ring. The beam diameter was reduced to 100 μm using a diaphragm. The reflected light was focused on the entrance slit of a Spex 1.26 m focal length grating spectrometer. The dispersed light was detected by a GaAs photodetector. Typical room-temperature reflectivity curves for the device investigated are shown in Fig. 3. The zero bias equilibrium spectrum shows a reflection dip (absorption peak) at the same energy as the photocurrent peak. This can be explained by the multiple reflections at the internal interfaces and external material edges of the MQW material, so that the total reflected light signal is strongly influenced by the resonant absorption at the excitonic oscillation energy of the MQW.[12] Applying an electric field across the MQW structure, the reflection spectrum changes progressively. A shift of the excitonic resonance could be seen when the voltage was increased. This behavior is well known as the quantum-confined Stark effect. Also a large broadening of the reflection dip is observable. The modulation response with 6 V reverse bias voltage in terms of the relative reflectivity change $\Delta R/R$ is shown in Fig. 4. A change of 7.7% of the reflectivity of the modulator with 6 V reverse bias voltage and at 8610 Å wavelength was measured. An improvement of this result could be achieved by using a multilayer dielectric mirror between the substrate and the modulator structure.[10]

The speed of this type of device is not limited fundamentally by carrier lifetime effects.[1] The limit on the speed is set by how fast the electric field can be applied to the material (RC constant limitation) and how fast the relevant wave functions can respond to the perturbation. The latter effect was proven to be much faster so that the speed will primarily be limited by electrical considerations. Bandwidths of 1 GHz and larger should be possible using scaled devices with

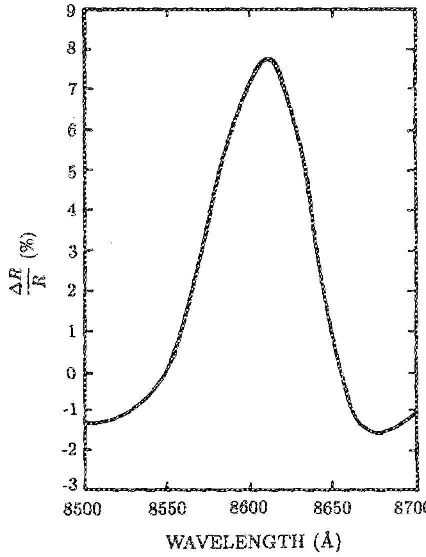

FIG. 4. Relative change of the reflectivity as the voltage is swept from 0 to 6 V.

a minimal parasitic capacitance. Such devices may be very useful for the high-speed interconnection of Si VLSI circuits.

In conclusion, large excitonic absorption at room temperature was observed in AlGaAs/GaAs MQW structures grown on Si substrates and significant modulation of the absorption spectrum near the exciton peak with an applied electric field was used to make optical reflection modulators. We have proven that optical device quality AlGaAs/GaAs is obtainable directly on Si substrates which has great implications with regard to the monolithic integration of optical III-V and electronic Si technology.

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