GaAs multiple-quantum-well reflector modulators with 4:1 contrast ratios on Si

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Considerable modulation ratios are achieved for GaAs multiple-quantum-well reflector modulators grown on Si by inserting an AlAs/AlGaAs dielectric mirror into the device structure. Modulation ratios of up to 4:1 is attained as the external bias voltage is increased to 9 V and the 1C-1HH exciton absorption peak undergoes quantum-confirmed Stark shift. Measurements also indicate that cavity effects arising from the front surface reflection and that of the imbedded dielectric mirror strongly modify the reflectivity spectra.

Growth of GaAs-based optical devices on silicon have important implications on the monolithic integration of the highly developed Si-based electronic devices with important III-V semiconductor based optical devices. It is thought that the light emitter in such an integration would be external to the chip and that the on chip modulators would be used for coding the optical signal. Although there have been numerous investigations on GaAs reflector modulators grown on GaAs,[1-4] reports of GaAs optical modulators grown on Si are rather limited. Demonstration of such a device on Si substrates with respectable modulation ratios have far reaching applications in the fields of bidirectional communication, optical switching, and the practicality of GaAs optical interconnects in Si circuits. In an earlier work,[5] we reported the performance of a GaAs/AlGaAs multiple-quantum-well (MQW) reflector modulator grown on Si. A 7% modulation ratio was attained for that particular device as the bias voltage was increased from 0 to 6 V. In this communication, we report on the performance of a similar device with much-improved contrast ratios by incorporating a stack of quarter wave AlAs/$Al_{0.15}Ga_{0.85}As$ dielectric mirror, similar to those used for conventional structures[6] on GaAs substrate, in the *n* region of the *p-i-n* structure employed.

The samples, A361 and A381, used in this study were grown in a Perkin-Elmer 430 molecular-beam epitaxy system. For the A361 layer, a 2-μm GaAs n^+ buffer layer was grown on top of a Si substrate. This was followed by ten pairs of alternating 723-Å AlAs and 614-Å $Al_{0.15}Ga_{0.85}As$ quarter-wave dielectric stack. A 723-Å AlAs layer separates the mirror from the MQW structure. The entire mirror was doped with Si to 3×10^{18} cm^{-3} and was designed to have peak reflection at 8600 Å. The index of refraction for AlAs and $Al_{0.15}Ga_{0.85}As$ at this wavelength are 2.975 and 3.50, respectively.[7,8] The MQW structure formed the intrinsic region of the *p-i-n* diode and consisted of fifty 90-Å GaAs/$Al_{0.3}Ga_{0.7}As$ quantum wells with 100-Å $Al_{0.3}Ga_{0.7}As$ spacer layer separating the quantum wells from each other. A 0.2-μm $Al_{0.3}Ga_{0.7}As$ (3×10^{18} cm^{-3} beryllium doped) was grown on top of the MQW layer and the sample was capped with 50-Å p^+ GaAs. Sample A381 had a similar structure except that the *i* region consisted of fifty pairs of 90- and 50-Å GaAs quantum wells coupled by a thin 25-Å $Al_{0.3}Ga_{0.7}As$ barrier with 100-Å $Al_{0.3}Ga_{0.7}As$ spacer layers separating the pairs from each other.

Mesas were etched on the sample using standard photolithographic techniques and Ti:Au metalization patterns were provided for electrical contacts. Measurements were done by focusing a 1-mW light beam from a halogen lamp source onto the device at normal incidence. The reflected light was redirected by a 51.5% neutral density filter and focused onto the entrance slit of a 1.26-m Spex monochrometer. Phase sensitive detection techniques were used to amplify the signal measured by a Ge detector cooled to liquid-nitrogen temperature. In order to normalize and extract the absolute reflectivity from the data reflection from an Al-coated mirror was used as a reference. The reflectivity of the Al-coated mirror is nearly constant at 85% in the 6000–9000 Å range.

Figure 1 shows the reflectivity spectra of the A361 device with the reference signal from the Al-coated mirror superimposed. Resonant cavity modes arising from the front surface (reflectivity = 0.3) reflection and that of the buried dielectric mirror are prominent in the reflectivity spectra. The excitonic absorption peak corresponding to the 1C-1HH transition is clearly seen at 8525 Å (1.44 eV) while the reflection dip at 8620 Å is attributed to a resonant cavity mode. For labeling purpose this cavity mode is called the active resonant Fabry–Perot mode. It is interesting to note that the 1C-1LH transition is not seen in the spectra. The expected location of the 1C-1HH excition peak for a 90-Å GaAs quantum well, assuming a 10-meV exciton binding energy and considering the decrease in the band-gap energy of GaAs due to strain,[9] is at 8567 Å (1.443 eV). The increased reflectivity at wavelengths greater than 9000 Å is also attributed to the nonuniformity of the spectral output of the light source used.

Figure 2(a) shows the reflectivity spectra of the A361 device at the region of interest for various bias voltages. Considerable modulation is achieved as the 1C-1HH exciton

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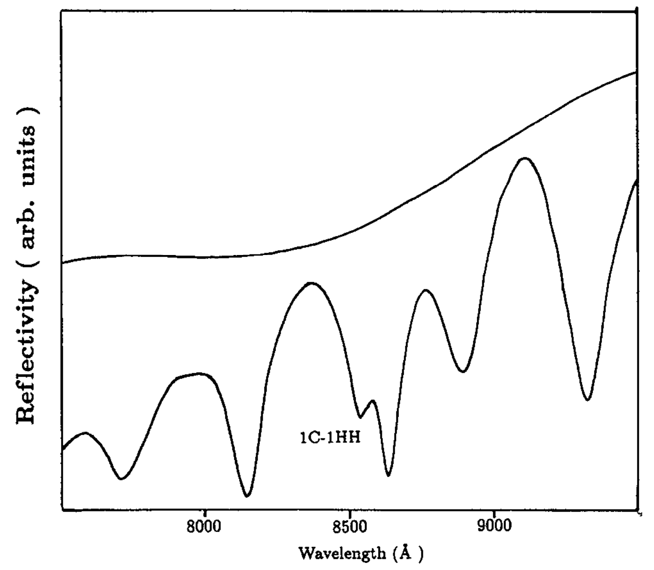

FIG. 1. Reflectivity of the device at normal angle of incidence. The reflected signal from an Al-coated mirror is superimposed for reference.

peak moves to lower energies, the so called quantum-confined Stark effect,[10,11] when the bias voltage is increased. The reflection dip at 8620 Å does not undergo Stark shifts which is consistent with its assignment as a resonant cavity mode. At a 6.0-V reverse bias a modest 31% decrease in the reflectivity is observed for the 8575-Å line. This is further decreased to 51.4% when the bias voltage is changed to 8.5-V reverse bias. The change in the reflectivity at this wavelength is due to the redshifting of the 1C-1HH exciton peak, initially located at 8525 Å at 0-V bias, to the 8575-Å line. On the other hand, the reflectivity at 8620 Å increases by 40% as the bias voltage is increased to 6 V. At a bias voltage of 8.5 V the reflectivity at this particular wavelength is increased by 95%. Very little modulation is achieved at 8525 Å as the bias voltage is increased.

There are two noticeable features in the reflectivity spectrum as the bias voltage is applied which are primarily due to changes in the absorption spectrum of the cavity. The most obvious is the redshifting of the well-resolved 1C-1HH absorption peak which leads to a reduction in the reflectivity at the location at the exciton peak. Modulation at this particular wavelength is further enhanced by taking advantage of the decreasing reflectivity due to the nearby active Fabry–Perot mode. The changes in the reflectivity at this active Fabry–Perot mode are brought about by the increase in the absorption coefficient of the cavity at energies below the 1C-1HH transition and by the change in the refractive index of the cavity which leads to the shifting of the Fabry–Perot mode.[2–4] Thus tuning of the absorption peak and the Fabry–Perot mode is important to achieve large modulation at reasonable bias voltages. To demonstrate the above-mentioned discussion, the cavity length was varied by recessing the top surface using a GaAs selective etch. This led to the shifting of the resonant cavity modes. Figure 2(b) shows the reflectivity spectra for a device with roughly 150 Å of the top surface etched. Very little modulation is attained at the 1C-1HH exciton peak because the increase in absorption at the exciton transition is counteracted by the increased reflectivity in the vicinity to the Fabry–Perot mode. The location of the active Fabry–Perot mode is too far from the 1C-1HH transition that no change in the absorption coefficient at this particular wavelength is expected. Hence no modulation in this region occurs.

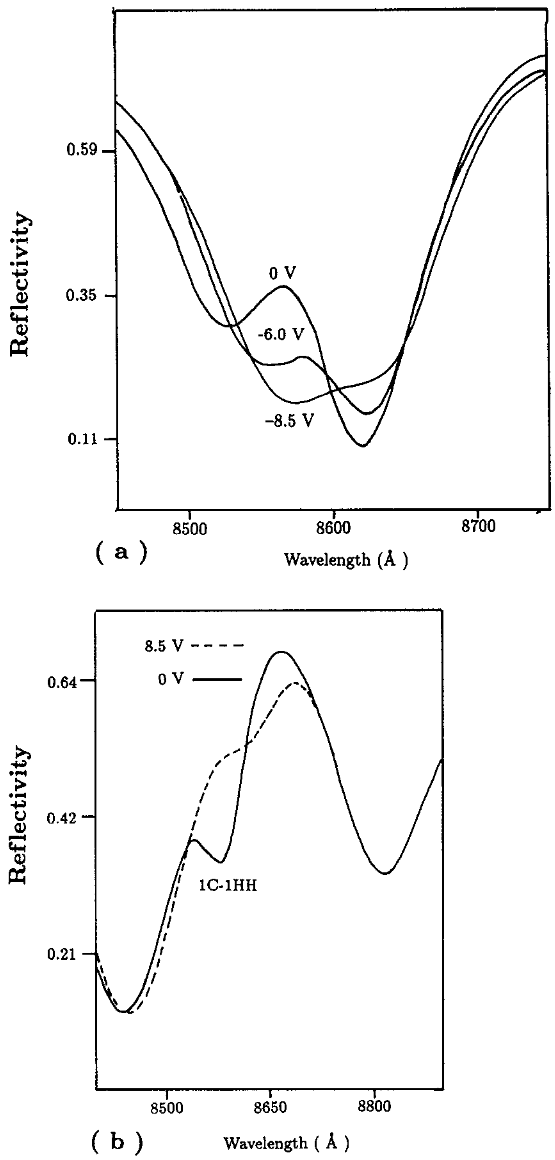

FIG. 2. (a) Reflectivity of the device at various reversed bias voltage. (b) Reflectivity of the same device, at 0- and 8.5-V reverse bias, with the front surface etched. The Fabry–Perot modes have shifted and little modulation occurs at the 1C-1HH exciton peak.

The reflectivity of the coupled quantum-well reflector modulator device, which has been tuned, is shown in Fig. 3. A larger modulation ratio of 4:1 at 8660 Å is achieved as the excitonic absorption peak approaches the active Fabry–Perot mode. Furthermore, contrast ratios of 2:1 and better are achieved over the 8620–8680 Å range. Significant changes in the absorption spectrum of coupled quantum wells compared to that of uncoupled wells at lower applied electric fields have been shown[12] and could be the reason

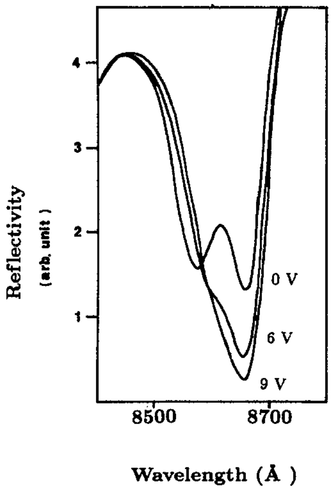

FIG. 3. Reflectivity of the coupled quantum-well reflector modulator at various bias voltage. A 4:1 contrast ratio at 8660 Å is obtained for this structure.

why increased modulation ratio is attained for this particular layer.

In conclusion, we have shown improved performance for a GaAs MQW reflector modulator grown in Si by incorporating a dielectric mirror into the device. Good contrast ratios of up to 4:1 at reasonable bias voltage is achieved, which makes these structures attractive as optical modulators and useful for the high-speed optical interconnection of Si circuits. Cavity effects were shown to greatly modify the reflectivity spectra and should be considered in the design of these devices. Further improvement in the device performance is expected by utilizing structures employed in GaAs optical modulators on GaAs (Refs. 3 and 4) substrates.

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[1] G. D. Boyd, D. A. B. Miller, D. S. Chemla, S. L. McCall, A. C. Gossard, and J. H. English, Appl. Phys. Lett. **50**, 1119 (1987).

[2] R. J. Simes, R. H. Yan, R. S. Geels, L. A. Coldren, J. H. English, A. C. Gossard, and D. G. Lishan, Appl. Phys. Lett. **53**, 637 (1988).

[3] R. H. Yan, R. J. Simes, and L. A. Coldren, Appl. Phys. Lett. **55**, 1946 (1989).

[4] K. K. Law, R. H. Yan, J. L. Merz, and L. A. Coldren, Appl. Phys. Lett. **56**, 1886 (1990).

[5] W. Dobblelaere, D. H. Huang, M. S. Ünlü, and H. Markoç, Appl. Phys. Lett. **53**, 94 (1988).

[6] P. L. Gourley and T. J. Drummond, Appl. Phys. Lett. **49**, 489 (1986).

[7] A. N. Pikhtin and A. D. Yas'kov, Sov. Phys. Semicond. **14**, 389 (1980).

[8] H. C. Casey, Jr., D. D. Sell, and M. B. Panish, Appl. Phys. Lett. **24**, 63 (1974).

[9] W. Stolz, F. E. Guimaraes, and K. Ploog, J. Appl. Phys. **63**, 492 (1988).

[10] E. E. Mendez, G. Bastard, L. L. Chang, H. Morkoç, and R. Fischer, Phys. Rev. B **26**, 7101 (1982).

[11] D. A. B. Miller, D. S. Chemla, T. C. Damen, A. C. Gossard, W. Wiegman, T. H. Wood, and C. A. Burrus, Phys. Rev. B **32**, 1043 (1985).

[12] A. Salvador, J. Reed, N. S. Kumar, M. S. Ünlü, and H. Morkoç, Surf. Sci. **288**, 188 (1990), and references therein.