GaAs-AlGaAs Multiquantum Well Reflection Modulators Grown on GaAs and Silicon Substrates

K. W. GOOSSEN, MEMBER, IEEE, G. D. BOYD, MEMBER, IEEE, J. E. CUNNINGHAM, W. Y. JAN, D. A. B. MILLER, MEMBER, IEEE, D. S. CHEMLA, MEMBER, IEEE, AND R. M. LUM

Abstract—**We present measurements of GaAs-AlGaAs multiple quantum well (MQW) reflection modulators grown simultaneously on GaAs and silicon substrates. Comparable electroabsorption is observed, with contrast ratios of about 4:1 for both modulators at 20 V. The absorption spectrum of the GaAs-on-Si quantum well shows a single exciton peak, which leads to certain improvements in modulator performance. This study is very encouraging for the growth of GaAs MQW modulators on silicon integrated circuit chips for off-chip communication.**

RECENTLY there has been a maturing of the technology of GaAs/AlGaAs multiple quantum well (MQW) quantum confined Stark effect (QCSE) based p-i (MQW)-n modulators [1]-[4] and related self-electrooptic effect (SEED) devices [5]-[7] grown on GaAs substrates by molecular beam epitaxy (MBE). It has been demonstrated that with the incorporation of an MBE-grown dielectric mirror beneath the modulator, they may operate in reflection mode [4] and that these devices can operate at 5.5 GHz [8]. These properties make MQW modulators attractive as devices for optical communication between electronic integrated circuit (IC) chips. Moreover, using modulators for optical interchip communication allows the light source to be off-chip, alleviating associated heating problems. Also, the degradation of semiconductor lasers due to defects can be severe. Modulators may be less sensitive to defects, making them an attractive alternative for achieving optical communication on silicon, which predominates in electronics, and which is lattice mismatched to GaAs. In this study, we will show that GaAs-on-Si modulators can indeed be practical.

Previous investigations of GaAs-on-Si MQW modulators have shown that electroabsorption exists [9], [10]. We present here a direct comparison of MQW high-quality reflection modulators (i.e., devices incorporating a dielectric mirror) grown simultaneously on GaAs and Si substrates.

We measured photocurrent spectra at different bias voltages and found that although there are differences in the shape of the absorption edge of MQW's grown on Si and GaAs, the shifts of the absorption edge with voltage are the same for the MQW grown on the Si substrate. Reflection measurements were performed as a function of bias, and comparable contrast ratios were found for the devices. In fact, it was found that the different shape of the absorption edge of the Si substrate MQW can be advantageous.

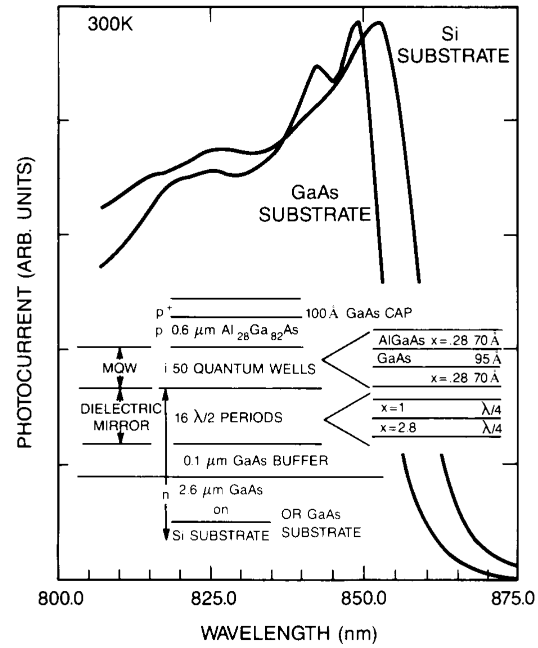

Fig. 1. Photocurrent spectra of GaAs multiple quantum well (MQW) modulators grown on GaAs (left) and Si (right) substrates at 0 bias. Stresses induced by the thermal expansion coefficient mismatch cause the GaAs-on-Si QW excitons to shift so that they coincide.

The structure (Fig. 1, inset) of the devices consists of a 1000 Å n$^+$ GaAs buffer layer grown atop the n$^+$ substrate, followed by a dielectric mirror design consisting of 16 periods of 622 Å n type $Al_{0.28}Ga_{0.72}As$ and 711 Å n type AlAs. Over this are 50 undoped wells consisting of 95 Å GaAs layer between 70 Å $Al_{0.28}Ga_{0.72}As$ barriers. Atop this a 0.7 μm p type $Al_{0.28}Ga_{0.72}As$ layer was grown to complete the diode, and finally a 50 Å cap of p$^+$ GaAs was grown. This growth was performed with gas source MBE [11] on a rotating substrate. We used a commercial GaAs-on-Si substrate (supplied by Kopin Corp., Taughton, MA 02780) with 2.6 μm of n$^+$ GaAs already grown on a 3° off axis ⟨100⟩ n$^+$ silicon substrate.

Devices were fabricated by etching 200 μm mesas on 400

Manuscript received May 23, 1989.
The authors are with AT&T Bell Laboratories, Holmdel, NJ 07733.
IEEE Log Number 8931006.

1041-1135/89/1000-0304$01.00

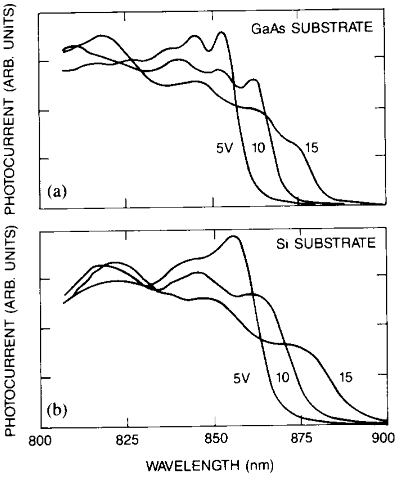

Fig. 2. Photocurrent spectra of the GaAs substrate (a) and Si substrate (b) modulators at 5, 10, and 15 V bias. The shift of the Si substrate QW absorption edge is nearly the same as the GaAs substrate QW.

μm centers and alloying gold contacts onto the mesas. Alloyed indium contacts were made to the back of the substrate. The top surfaces were anti-reflection coated with 1100 Å of SiO. The etching process produced cracks in the GaAs-on-Si, which is common for these strained layers. These did not affect device performance except to limit device area when the crack went through a device. Ultimately island growth of the GaAs modulators will be used on silicon IC's, so there will be no etching needed and then we expect that the cracks will not occur. Ninety percent of the GaAs-on-Si diodes had reverse breakdowns greater than 15 V. Note that in previous MQW modulators made by us [12] without a dielectric mirror this number was only 30 percent, suggesting that the addition of a dielectric mirror significantly reduces defects in the MQW by acting like a superlattice buffer.

Shown in Fig. 1 are the photocurrent spectra for the devices at 0 V bias (all measurements in this paper are at room temperature). For the GaAs substrate device, the heavy and light hole exciton peaks are clear, while for the silicon substrate device only one broader peak is visible, as has previously been reported [9]. The Si substrate device peak is at a slightly lower energy than the GaAs substrate devices' heavy hole peak, as has been seen previously by us [12]. The shift of the exciton peaks is caused by strain induced by the larger coefficient of thermal expansion of GaAs compared to Si. Jagannath *et al.* [13] performed photoluminescence measurements of GaAs-on-Si QW's from which they found that the light and heavy hole excitons cross each other as the well width is increased from 45 to 180 Å. From this we infer that in our samples the heavy and light hole excitons lie on top of each other.

In Fig. 2 are the measurements of photocurrent spectra at 5, 10, and 15 V reverse bias. The shift of the absorption edge of the Si substrate device with bias is about the same as for the GaAs substrate device, although there is greater broadening for the former. For both, the shift is nearly quadratic with voltage as seen previously for the QCSE [2], and previously by us with GaAs-on-Si MQW's [12].

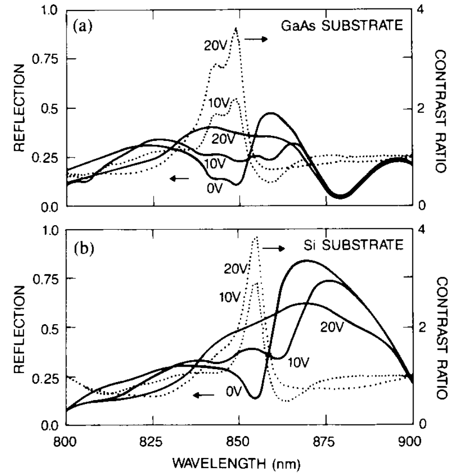

Fig. 3. Reflection spectra at 0, 10, and 20 V (solid lines) and contrast ratio (i.e., reflection normalized to reflection at 0 V) (dotted lines) for the GaAs substrate (a) and Si substrate (b) modulators.

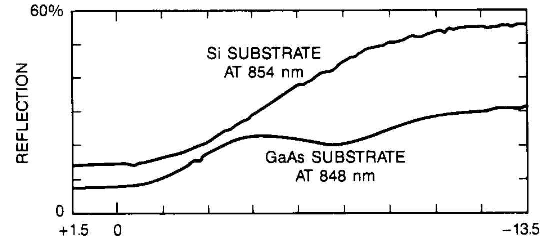

Fig. 4. Reflection as a function of bias for the GaAs substrate and Si substrate modulators at the zero bias heavy hole exciton wavelength (where maximum contrast ratio is obtained). The dip in the GaAs curve near 7 V is caused by the light hole absorption. Therefore, the single-peak nature of the Si substrate QW absorption edge leads to improved performance at medium voltages.

Reflection spectra as a function of bias are shown in Fig. 3 for 0, 10, and 20 V (solid curves). The underlying mirror spectrum is evident in the 0 V curve, with reduced reflection above the band edge of the MQW due to its absorption. The mirror spectrum is shifted slightly to higher energy for the GaAs substrate compared to the Si substrate. This is apparently due to its different placement on the substrate holder of the MBE machine, leading to different growth parameters. This shift leads to a smaller absolute reflection. However, we may still compare the contrast ratio of the two devices, i.e., the ratio of the reflectivity at a certain bias to that at zero bias. The dotted lines in Fig. 3 are the contrast ratios for 10 and 20 V bias. The contrast ratio is about 4:1 for both devices at 20 V.

In both the reflection and the contrast ratio, the heavy and light hole are evident in the GaAs substrate device while for the Si substrate device there is only one peak. This is disadvantageous in that it leads to a smaller bandwidth, but advantageous in another respect. In Fig. 4, we show the reflectivity versus voltage for the two devices at the heavy hole exciton wavelength. For the GaAs substrate device, as one increases the voltage from 0 V there is at first an increase in the reflectivity, but then it decreases because of the light hole absorption. For the Si substrate device, however, there is a monotonic increase in the reflectivity since there is only one absorption peak. Therefore, at mid-voltages one may actually expect better performance from the Si substrate modulator.

In conclusion, we have performed photocurrent and reflection spectroscopy as a function of bias on GaAs MQW reflection modulators grown simultaneously on GaAs and silicon substrates. We observe shifts of the absorption edge only slightly less for the devices grown on the Si substrate. We find contrast ratios of about 4:1 for both our devices at 20 V, and the single-peaked nature of the GaAs-on-Si quantum well absorption actually leads to improved performance at mid-voltages. This is very promising for the growth of such modulators on silicon wafers for application as optical interconnects between IC's.

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