Modulation of light by an electrically tunable multilayer interference filter

G. W. Yoffe, D. G. Schlom, and J. S. Harris, Jr.
Solid State Electronics Laboratory, Stanford University, Stanford, California 94305

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We describe the structure and performance of a new, nonabsorbing, perpendicular geometry light modulator based on an electrically tunable, multilayer interference filter. The device consists of a GaAs/AlAs quarter-wave stack with aluminum contacts, grown by molecular beam epitaxy. A strong, applied electric field changes the refractive indices through the Franz–Keldysh effect, shifting the transmission spectrum and modulating the intensity of light tuned to the edges of the high reflectance band. Modulation ratios up to 2.5:1 have been obtained for photon energies 0.05–0.2 eV below the GaAs band gap. The device has applications in arrays and for modulation of high power light.

Light modulators that operate in perpendicular rather than waveguide geometry are of interest because they can be integrated into two-dimensional arrays, with applications including spatial light modulators and free-space optical interconnect. The perpendicular modulator that has received the most attention is the multiple quantum well electroabsorption modulator.[1] This device suffers from three main problems. First, the saturation intensity is low[2] because the exciton peak is quenched by an optical power density of 600 W/cm^2. Second, the modulation depth is generally only 2–3 dB. Finally, the range of possible operating wavelengths is determined by the material, since the modulator is only effective for light tuned exactly to the exciton peak, and the quantum well width has to be around 100 Å. In this letter we describe a new nonabsorbing modulator based on an electrically tunable, all-epitaxial multilayer interference filter on a GaAs substrate. We report modulation of light tuned just below the band gap.

There have been several demonstrations of optical interferometric elements fabricated with the GaAs/ AlAs material system. The most common[3,4] has been the quarter-wave stack, consisting of alternating layers of two materials, each layer a quarter wavelength thick. The transmission spectrum of this structure exhibits sharp transitions from reflectance to transmittance on either side of a band of high reflectivity. A shift in the spectrum, caused by changes in the refractive indices, will modulate light tuned to the edges of this band.

Application of a strong electric field changes the refractive index of semiconductors through the Franz–Keldysh effect.[5] We have estimated the magnitude of the change by first considering the broadening of the absorption edge[6] and then applying a form of one of the Kramers–Kronig relationships[7] that relates the change in refractive index, Δn, at a certain photon energy, E, to changes in the absorption coefficient $\Delta\alpha$:

$$\Delta n(E) = \frac{ch}{2\pi^2} P \int_0^\infty \frac{\Delta\alpha(E')dE'}{(E')^2 - E^2},$$

where the symbol P signifies the Cauchy principal value. For GaAs, an applied electric field of 200 kV/cm would cause an increase in the refractive index of roughly 0.1% for a photon energy of 1.2 eV, and 0.2% for 1.3 eV. The effect is similar for structures containing GaAs quantum wells of greater than 150 Å width; for this case our calculations took into account quantum size effects and forbidden transitions which become allowed in the presence of a strong field.[8] The use of quantum wells can also increase the maximum transmission and sharpen the spectrum, because the absorption tail is cut off for all energies below the lowest allowed state. To obtain useful modulation with changes in refractive index of this magnitude, we require features in the transmission spectrum that are sharp to approximately 25 Å. Calculations based on an optical transmission matrix method[9] indicated that a 30-period GaAs/AlAs stack on a GaAs substrate would give the required sharpness.

Three device structures were grown on n^+-doped GaAs wafers in a computer-controlled Varian Gen II molecular beam epitaxy (MBE) machine at 0.5 μm/h growth rate, calibrated by reflection high-energy electron diffraction oscillations to ± 5%. All were designed to have a high reflectance band centered at 1 μm. The general structure is shown in Fig. 1. The GaAs buffer layers and multilayer reflector structure were doped n type at

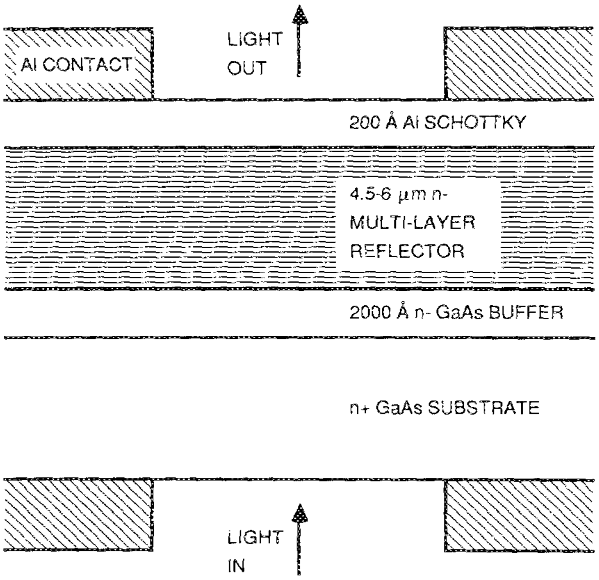

FIG. 1. Schematic diagram of the modulator. The multilayer reflector is a 30-period GaAs/AlAs quarter-wave stack in sample 610, a 30-period three-eighths wavelength GaAs/one-eighth wavelength AlAs stack in sample 611, and a 40-period multiple quantum well/ AlAs quarter-wave stack in sample 504.

$1\times10^{15}/\mathrm{cm}^3$. To ensure high breakdown voltage, the top thin Al Schottky contacts were deposited in the MBE chamber after the substrate had cooled to around 50 °C. Al for electrical contacts was subsequently deposited through shadow masks onto both sides of the wafers. The backside contact to the heavily doped substrate was operated in forward bias and gave a negligible voltage drop compared to the reverse-biased contact to the lightly doped epitaxial material. Sample 610 contained a 30-period 715 Å GaAs/835 Å AlAs quarter-wave stack. Sample 611 contained a 30-period asymmetric stack, with 1070 Å GaAs (three-eighths wavelength) and 420 Å AlAs (one-eighth wavelength) layers. Both of these wafers were grown with a substrate temperature of 680 °C. Sample 504 contained a 40-period quarter-wave stack in which the GaAs was replaced by 745 Å layers containing three 155 Å GaAs quantum wells separated by 70 Å $\mathrm{Al}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As}$ barriers. This wafer was grown at 750 °C to optimize the AlGaAs. We estimated refractive indices at 1 μm wavelength of 3.5, 3.4, and 3.0 for the GaAs, quantum well layers, and AlAs, respectively.[10]

The zero-bias transmission spectra for samples 610 and 611 agreed well with theory, as shown in Fig. 2. All measurements were taken at room temperature. Attenuation of the signal was largely due to the thin Al Schottky barrier layer, which was not antireflection coated. The spectrum for the quantum well sample was similar to that of sample 610, but shifted approximately 300 Å to shorter wavelength because Ga desorption at the high substrate temperature slightly reduced the GaAs growth rate. Note that the high reflectance band has very low transmittance (less than 1%) and sharp edges, especially for sample 610, the symmetric quarter-wave stack. These features are required for high contrast modulators.

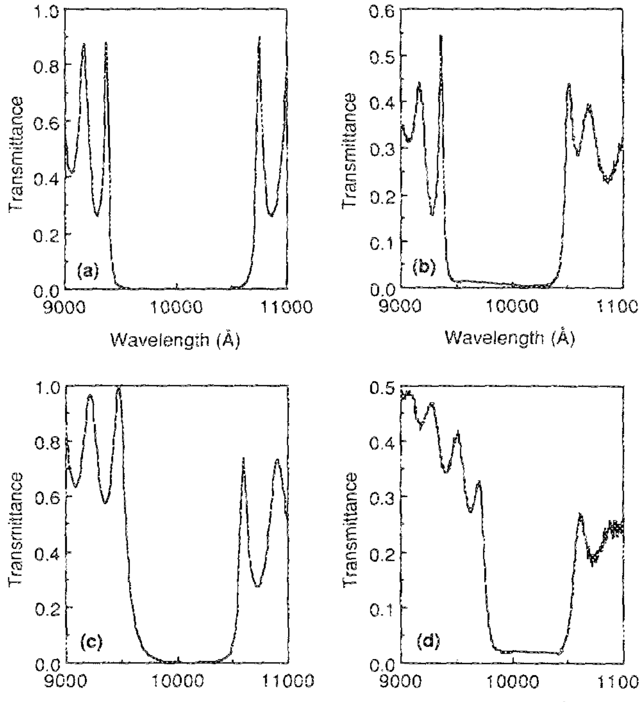

FIG. 2. Calculated and measured transmission spectra for the symmetric and asymmetric stacks, both designed to be high reflectors for 1-μm light: (a) theoretical and (b) experimental spectra for the 30-period symmetric GaAs/AlAs quarter-wave stack, sample 610; (c) theoretical and (d) experimental spectra for the 30-period asymmetric structure, sample 611, consisting of three-eighths wavelength GaAs and one-eighth wavelength AlAs layers.

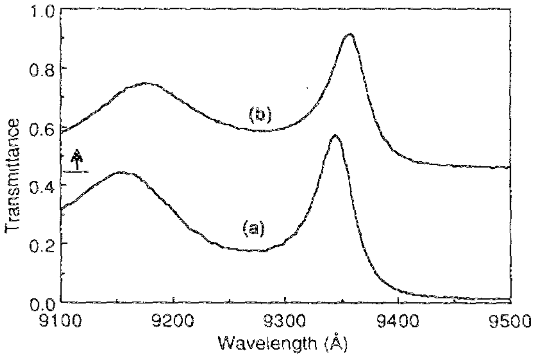

FIG. 3. Transmission spectra at the short wavelength edge of high-reflectivity band of sample 610, quarter-wave stack, at electric fields of (a) 0 V/cm and (b) 220 kV/cm.

Both of the quarter-wave structures, 610 and 504, behaved as predicted under a strong applied electric field. The effect of field on the short wavelength side of the spectrum for sample 610 is shown in Fig. 3. Shifts in the spectrum of up to 20 Å are seen, corresponding to an average change of 0.2% in the refractive indices. The effect is greater on the short wavelength, high-energy side of the reflectance band because the change in refractive index increases with decreasing energy separation from the band gap. Field-induced dampening of the side peaks can be seen. This is due to weak electroabsorption at wavelengths close to the band gap (8720 Å). The shifts and electroabsorption combine to effect modulation, positive or negative depending on the wavelength, as illustrated in Fig. 4. The largest modulation ratio

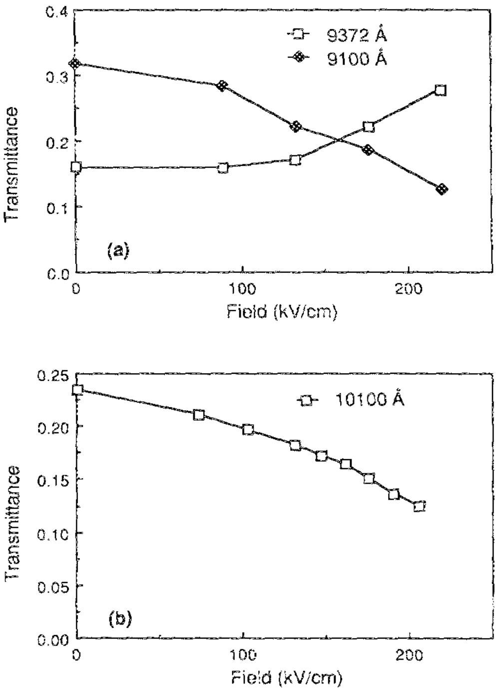

FIG. 4. Transmittance as a function of applied field (a) for sample 610 on the short wavelength side of the high reflectivity band and (b) for sample 505, quantum-well quarter-wave stack, on the long wavelength side. Wavelengths are indicated on the figure.

that was obtained was 2.5:1 at 9100 Å wavelength.

Since very little absorption takes place, this type of device is potentially useful for modulation of high-power sub-band-gap light, such as the 1.06 μm output of a cw Nd:YAG laser. The absence of photogenerated carriers makes it attractive for high-speed applications. With improvements in the modulation ratio it can become a useful device wherever perpendicular geometry modulators are required.

We have described and demonstrated a new nonabsorbing electrically tunable interference modulator. Modulation ratios of greater than 2:1 have been obtained at various sub-band-gap photon energies. The device can be designed to operate at any photon energy between 0.05 and 0.2 eV below the band gap.

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