# Multiple quantum well reflection modulator

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We demonstrated a quantum-confined Stark effect electroabsorption modulator consisting of quantum wells of AlGaAs and GaAs on an epitaxial multilayer dielectric mirror, all grown by molecular beam epitaxy. The resulting reflection modulator avoids problems of substrate absorption, and has relatively high contrast ratio (up to ~8:1 with peak reflectivity of 25% at 853 nm) because the light passes twice through the quantum wells. Reflection modulators are of interest for bidirectional communication systems, in parallel arrays of optical switching and processing devices and for optical interconnects. For the latter there exists the possibility of this device grown on the same substrate alongside a GaAs integrated circuit or even on Si substrates.

Multiple quantum well structures of alternate layers of two different semiconductors show interesting optical properties at room temperature. In particular, the optical absorption near the band-gap energy can show exceptional exciton resonances. The abrupt absorption edge can be shifted to longer wavelengths, without destroying the sharp exciton resonances, with an electric field perpendicular to the layers, a phenomenon called the quantum-confined Stark effect (QCSE).[1,2] Because the resulting changes in absorption are large, the modulated light can propagate perpendicular to the surface of the chip, and it is possible to make optical modulators that are only microns thick[3] and that can operate at high speed.[4] The QCSE has also been applied in the related self-electro-optic effect devices (SEED's) to make optical switches, oscillators, and linearized modulators.[5] Recently two-dimensional arrays of QSCE devices have been demonstrated[6] and both physics and applications summarized.[2]

Most QCSE devices have used molecular beam epitaxy (MBE) material with GaAs wells and $Al_xGa_{1-x}As$ barriers grown on GaAs substrates. Since the substrate is opaque at the normal operating wavelengths (e.g., ~850 nm), a window in the substrate is usually opened using a selective etch. For some applications the removal of the substrate may be inconvenient. One solution is to use a material system with a transparent substrate. Recently QCSE electroabsorption has been observed in InGaAs/GaAs strained-layer quantum wells on GaAs substrates near 950 nm where the GaAs is transparent,[7] and also in InGaAs/InP quantum wells on InP substrates,[8] although heavily doped substrates always have some residual absorption.

An alternative approach that makes substrate absorption irrelevant is to incorporate a mirror between the substrate and the QCSE device. The device then operates in reflection, with the light to be modulated making a double pass through the active quantum well region, thereby also increasing the contrast ratio. Such a method is therefore potentially useful with the GaSb/AlGaSb quantum well system[9] on GaSb substrates as well as the AlGaAs/GaAs system, both of which have shown good QCSE electroabsorption. This type of structure is attractive for optical interconnection of integrated circuits, for arrays of SEED's,[5,6] and is also applicable to bidirectional communications systems that require reflective modulators.[10]

Multilayer dielectric mirrors can be grown using the same material system as is used for the quantum wells using molecular beam epitaxy (MBE). This kind of mirror was first demonstrated by Van der Ziel, and Ilegems,[11] and more

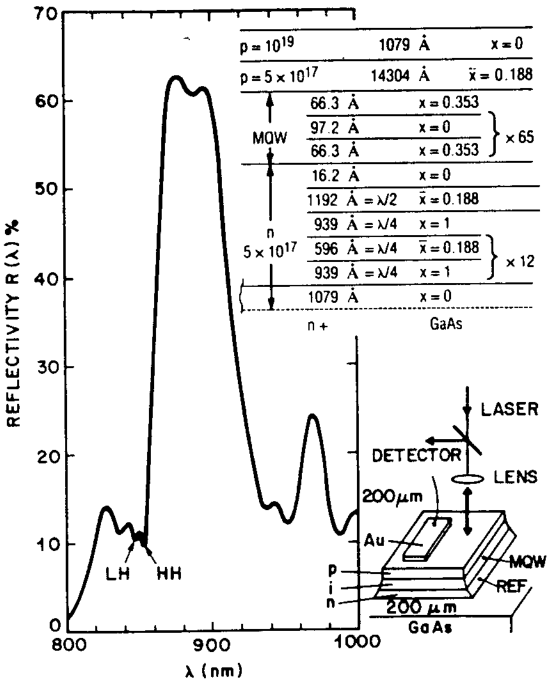

FIG. 1. Structure of the MQW reflection modulator and a typical reflectivity spectrum of the wafer (with antireflection coating). $x$ is the fraction of Al in the $Al_xGa_{1-x}As$. Note that where $\bar{x} = 0.188$ is indicated, that layer represents an average $x$ for a superlattice comprised of alternate layers of 13.9 Å with $x = 0$ and 15.9 Å with $x = 0.353$. 596 Å represents 20 pairs, 1192 Å is 40 pairs, and 14304 Å is 480 pairs. The nominal thicknesses shown are at a point on the circumference of the 2-in.-diam circular wafer (i.e., at the position $X = 1''$, $Y = 0$, where the wafer center position is defined as $X = 0$, $Y = 0$), and are deduced from the thicknesses measured in the growth "shadows" of the mounting clip. The sample location for optical measurements was at the position ($X = -1/4''$, $Y = 0$).

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recently has been discussed by various authors.[12-15] Complete nonlinear Fabry–Perot devices have been fabricated this way using the AlGaAs system[14,15] and also using the ZnSSe system.[16]

The MBE-grown structure is shown in Fig. 1. The dielectric mirror is formed of alternating high and low index layers, each approximately one quarter-wavelength ($\lambda/4$) thick. For the high index material we use a short period superlattice (SL) of $Al_xGa_{1-x}As$ and GaAs. The low index layers are AlAs. The use of SL gives a low average Al context ($\bar{x} = 0.188$) material that will behave approximately like the average alloy. Such SL may give better layer growth, and avoids the necessity of changing the Al oven temperature to give AlGaAs with sufficient Al for the subsequent quantum well barriers. Both SL and AlAs are transparent at the operating wavelengths of the QCSE modulator. The whole mirror structure is *n* doped so that it is conducting. A $\lambda/2$-thick *n*-doped layer separates the last AlAs layer from the undoped quantum wells and barriers. Finally, a *p*-doped SL and a *p*-doped GaAs contact layer are grown to complete the *p-i-n* diode structure of the quantum well modulator. Nominal layer thicknesses are shown in Fig. 1 as derived from programmed deposition times and deposition rates calculated from measured film thicknesses at a shadow mask near one edge of the wafer (see Fig. 1 caption).

A reflection spectrum of the wafer is also shown in Fig. 1. This was taken near the position on the wafer where devices were subsequently fabricated. For this spectrum, the entire wafer was antireflection coated with a $\lambda/4$ layer of silicon oxide. (This layer was removed before further device processing.) The spectrum shows absorption peaks (reflection dips) at 853 nm for the heavy-hole exciton and at 848 nm for the light hole. The main width of the reflection spectrum is narrowed on the short wavelength side by the absorption edge of the quantum wells. The maximum wavelength of the peak reflectivity on the wafer was at 1.04 $\mu$m with a bandwidth of 0.13 $\mu$m. With an index of 2.942 for AlAs and 3.375 for the $\bar{x}$ AlGaAs the calculated bandwidth is 11.4% and the peak reflectivity 88%, compared with an experimental value of 12.5% and 80%, respectively. The spectral position of the reflection peak was very sensitive to position on the 2-in.-diam wafer, more so than was expected based on simple modeling knowing that the Al gun was displaced by 25° from the substrate axis. The wavelength of the reflectivity peak shifted by 16% from the location of the 1.04 $\mu$m peak to the test location whose reflectivity is shown in Fig. 1 in a distance of 0.5 in. It should be noted, however, that the substrate was not rotated during growth, and rotation should significantly reduce nonuniformity.

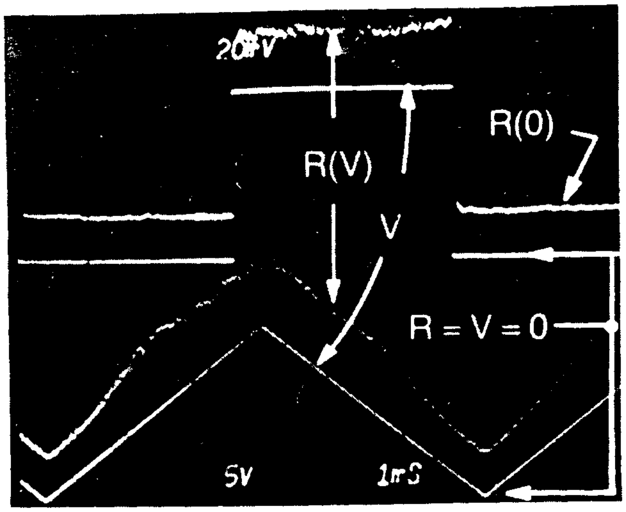

FIG. 2. Reflected optical beam $R$, modulated by an applied voltage $V$, square wave (upper trace) or triangular wave (lower trace). Peak voltage in both traces is 14 V and $\lambda = 853$ nm.

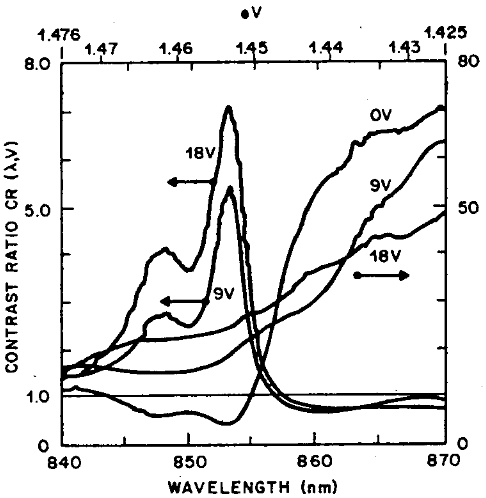

FIG. 3. Measured reflectivity and contrast ratio vs wavelength at several voltages.

The modulator devices are fabricated as an array of $200 \times 200$ $\mu$m mesas with 400 $\mu$m periodicity. Contacts are formed in part of the top *p*-GaAs contact layer, then this layer is etched away everywhere else using a selective etch that stops at the SL. [This GaAs layer is removed because it is slightly absorbing at wavelengths below ~870 nm (~10% per pass), and for these wavelengths the actual modulator reflectivity will consequently be slightly higher than the wafer reflectivity in Fig. 1.] The exposed *p*-SL is antireflection coated with a $\lambda/4$ layer of silicon oxide. A

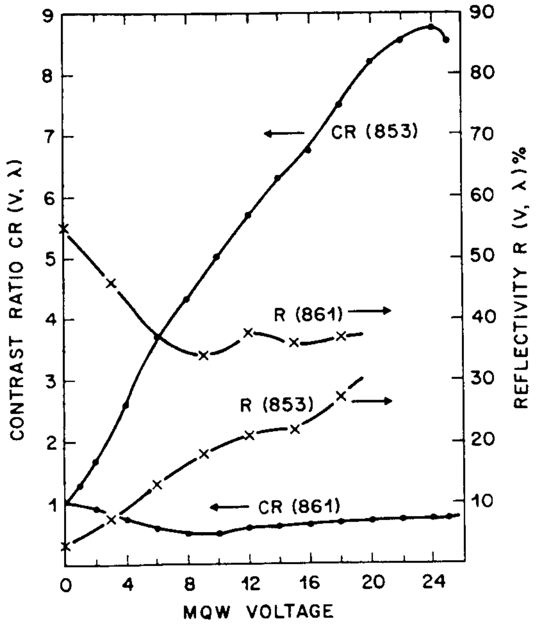

FIG. 4. Reflectivity and contrast ratio vs voltage at two wavelengths.

contact is taken off the $n$-GaAs substrate, and a reverse bias voltage is applied between the top contact of the mesa and this substrate contact to operate the device. Every one of the 192 devices on the array tested had a reverse breakdown $> 33$ V, which implies that this structure is potentially applicable to large parallel arrays of modulators.

The modulator device optical characteristics were measured using a krypton-ion laser-pumped Styrl 9 dye laser running with $\sim 1$ nm bandwidth. In Fig. 2 the device operation is displayed with a square wave modulation of 14 V and a triangular wave modulation, all at 853 nm. Noise is due to dye laser instabilities. Scans of the reflectivity versus wavelength at several voltages are shown in Fig. 3. The QCSE shifts of the optical absorption to longer wavelengths with increasing (reverse bias) voltage can be clearly seen. The apparent broadening of the exciton peak is probably due to nonuniform fields within the depletion region across the different quantum wells.[1,2] As a modulator, there are two distinct modes of operation, either "normally-off" in which increasing voltage gives increasing reflection, or "normally-on" in which increasing voltage results in reduced reflection, with the transition between the two occurring at $\sim 857$ nm. We can define a normally-off contrast ratio of the modulator as the ratio between the reflection with a specified voltage applied to that at 0 V. Such contrast ratios are also shown in Fig. 3. The peaks at 853 and 848 nm in the contrast ratio coincide with the heavy- and light-hole exciton absorption peaks at 0 V, where the absorption is particularly strong. Above $\sim 857$ nm, this contrast ratio decreases to a minimum of about 0.5 at 863 nm, corresponding to a normally-on contrast ratio of about 2.

In Fig. 4 we present data of contrast ratio and absolute reflection coefficient as a function of voltage at optimum wavelengths for normally-off and normally-on operation. In normally-off operation, the modulator offers high contrast ratio (up to $\sim 8:1$) over a relatively small spectral range and with significant loss in its high reflection state. In normally-on operation, the loss is lower and the spectral bandwidth is larger, but contrast between the states is less. We have not tested the high-speed or power-handling limits of this modulator, but we expect it to be similar to previous devices, where speeds of $\sim 100$ ps have been observed[4] and powers $> 1$ mW have been modulated.[5] Saturation of the excitonic absorption in these quantum well modulators is not expected to be a problem for milliwatt continuous wave powers because the carriers are swept out by the field in times $\sim 200$ ps.[17]

In conclusion, we have demonstrated that QCSE devices can be successfully fabricated with internal, epitaxially grown dielectric mirrors. This allows us to make surface reflection modulators with relatively high contrast ratios and to avoid problems caused by absorbing substrates. Such devices may be useful in reflection modulators for bidirectional communications,[10] in reflection modulators for the optical interconnection of integrated circuits, and in parallel arrays of optical switching and processing devices.[6]

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