Self-electro-optic effect device and modulation convertor with InGaAs/InP multiple quantum wells

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We report the first observation of the self-electro-optic effect in InGaAs/InP multiple quantum wells, grown by organometallic vapor phase epitaxy. Clear bistability and switching are observed over a range of 40 nm around 1.61 μm with 20–30 V bias. We demonstrate the operation of a modulation convertor, which converts a modulation from a carrier at 1.6 μm onto a carrier at 0.85 μm and vice versa.

The optical properties of quantum well structures are significantly changed when an electric field is applied perpendicular to the layers. The absorption edge is red shifted, while the excitonic enhancement is maintained even at large fields.[1,2] This effect, known as the quantum confined Stark effect (QCSE), was first observed in the GaAs/AlGaAs material system,[2] and has been applied to make small high-speed optical modulators.[3] These modulators are reverse-biased *p-i-n* diodes, with the multiple quantum wells (MQW's) in the intrinsic region.

It was realized a few years ago that this same structure can function as a logic switching device, the self-electro-optic device (SEED).[4] The general principle of the SEED operation is that photocurrent generated by light absorbed in the diode may change the voltage across it, which in turn causes a change in the absorption of light in the diode. By connecting the diode to a proper load, and by tuning the light wavelength to coincide with the heavy-hole (hh) exciton, a positive feedback mechanism is achieved, leading to switching and bistable behavior. When plotted as a function of the input intensity, the transmitted light intensity through this device exhibits a clear hysteresis. This behavior was observed with GaAs/AlGaAs MQW *p-i-n* diodes, and a variety of switching and other logic operations was demonstrated.[5] Recently, small scale integration of 6×6 arrays was demonstrated showing very uniform switching characteristics.[6]

In a recent letter we reported the observation of the QCSE with relatively little field-induced broadening in high-quality InGaAs/InP MQW grown by organometallic vapor phase epitaxy (OMVPE).[7] The absorption edge of this material system at room temperature is in the 1.55-μm range, making it very attractive for light wave communication. Indeed, high-speed optical modulators operating at 1.6–1.67 μm were made and demonstrated.[8,9] It is important to note that the InGaAs(P)/InP MQW's are grown on an InP substrate which is optically transparent above 1 μm. It is therefore not necessasry to remove the substrate, as is the case with the GaAs devices, thus potentially simplifying the fabrication and especially the integration of large arrays.

In this letter we report the first observation of the self-electro-optic effect in the InGaAs/InP material system. We show clear bistable behavior over a wide spectral range, approximately 40 nm, around 1.6 μm, with 10–30 V bias. We also report a novel new device, a modulation convertor from one wavelength to another, composed of an InGaAs MQW diode electrically connected to a GaAs MQW diode.

The sample structure is shown at the inset of Fig. 1. It is a *p-i-n* diode grown on a p^+ InP substrate, with 100 periods of alternate InGaAs wells and InP barriers, each 100 Å thick, in its intrinsic region. It is grown in a horizontal OMVPE system at atmospheric pressure. The samples are processed to form rectangular mesas of 200×200 μm. The absorption coefficient at the exciton peak is 4000 cm^{-1}, which is about half the absorption of GaAs/AlGaAs MQW's. This implies that thicker structures are required in the InGaAs system, and therefore a larger bias voltage. We used a cw NaCl color center laser, tunable between 1.4 and 1.8 μm, as the illumination source.

Figure 1 shows the photocurrent generated by a weak ($\approx$300 nW) laser beam, which is tuned to the hh exciton resonance, as a function of the applied reverse bias voltage. This is therefore a responsivity curve of the diode. We can see that as the reverse bias is increased from 0 to 8 V the photocurrent rises, until the intrinsic region is depleted. A further increase of the voltage causes a decrease of the photocurrent due to the reduced absorption as the hh exciton resonance is red shifted. At higher voltages the photocurrent reaches a minimum value and then rises again. This increase

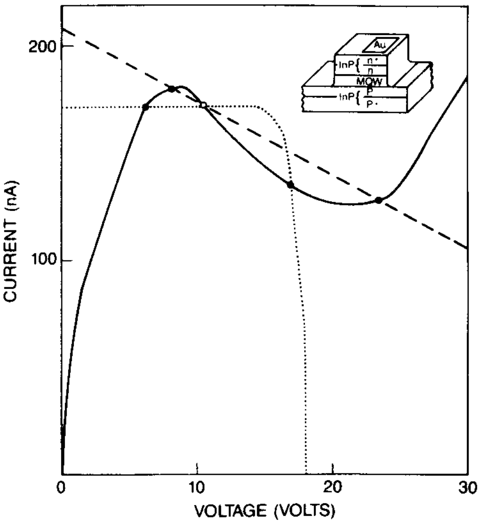

FIG. 1. Responsivity (*I-V*) curve of the diode while illuminated with a weak (300 nW) laser beam at 1.61 μm (the hh exciton peak). The dashed line is a resistive load and the dotted line is a silicon photodiode load. The black dots are stable operating points, while the open circle is an unstable point. The InGaAs/InP sample structure is shown at the inset.

is probably due to an avalanche process which occurs close to the reverse bias breakdown.

It is clear from Fig. 1 that there exists a family of load lines with three intercepts with this responsivity curve. Only two of these intercepts (marked by black dots) are stable working points, while the central one (marked by an open circle) is unstable, giving rise to switching and bistability. The dashed line represents a resistive load and the dotted lined a current source load. The current source is chosen to be a reverse biased Si photodiode, and the current is generated by shinning white light on it. Varying the incident white light we could change the photogenerated current. It is seen that the resistive load requires a high bias voltage (> 60 V), while the current source load requires much lower voltage (> 10 V). We were able to observe bistability with resistive load, but the performance of the devices was by far better with a current source load, as observed for GaAs MQW's.[5] All the results reported here were obtained with a current source load.

Figure 2 shows the output light intensity as a function of the input intensity for different bias voltages, as the diode is illuminated at the hh exciton peak (1608 nm). At 10 V bias voltage we observe the onset of bistability. As the voltage is increased to 20 V we note a significant increase both in the height and width of the bistable loop. Above 30 V the bistable loop remains unchanged. The height of the bistable loop represents the change of transmission as the voltage on the diode is switched from high to low values. We observed a maximum of 30% change in the transmitted intensity as the device is switched off. This maximum occurred at 20 V bias, and remained such at higher voltage. This behavior is consistent with the measured electroabsorption shown in Ref. 7, Fig. 2(a). As can be seen there, the absorption at the hh exciton peak changes strongly up to 20 V, and then remains unchanged. The saturation of the width of the bistable loop can be understood from the responsivity curve (Fig. 1). As the bias voltage exceeds 30 V there is a current level above which the current load line has only one intercept with the diode responsivity curve, and the circuit becomes stable.

Figure 3 shows the bistable loop for various wavelengths, at a constant voltage (20 V). It can be seen that bistability is observed over a wide spectral range, and therefore there is no critical tuning requirement. In fact, there is no significant change in the bistable loop as the wavelength is tuned between 1605 and 1620 nm and clear bistability is observed over a range of 40 nm. This is the spectral range over which the absorption at low voltage is larger than the absorption at high voltage. This range is given by the two intercepts between the solid and dashed lines at Fig. 1 of Ref. 7. This wide spectral range, which is due to the broad excitonic absorption of this material, might be important for practical applications.

The minimum power at which bistability could be observed is 10 nW, and is limited by the leakage current through the diode. This leakage current was a few nanoamps, and might be smaller if the devices are scaled down in size. As the light power was increased to about 10 μW, we observed a degradation of the contrast ratio of the bistable loop. A further increase of the intensity made this degradation even more pronounced. The diode responsivity curve was also changed, such that more voltage was needed to deplete the intrinsic region. These might indicate that a space charge of photocarriers, probably holes, is being built up in the diode intrinsic region, and causes inhomogeneous broadening as well as saturation of the excitonic absorption. Further investigations to understand this saturation process are in progress.

The switching dynamics was also measured. We observed a critical slowing down when the input intensity was just above the critical switching intensity, and a significant shortening of the switching time as the device was overdriven. We also observed that at that limit, of strong overdriving, the switching time was inversely proportional to the light intensity, indicating that the speed is limited by the

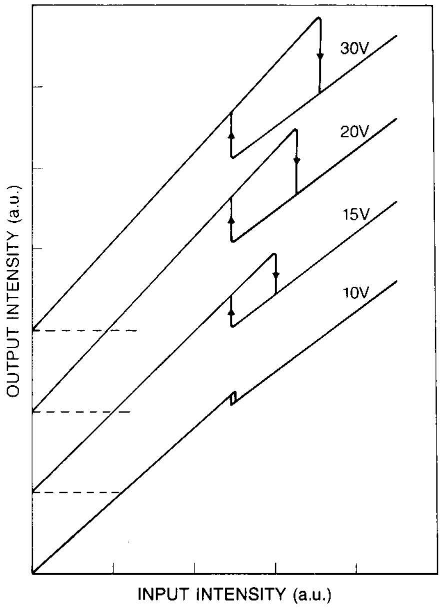

FIG. 2. Output intensity vs the input intensity for several voltages and for $\lambda = 1.61\ \mu$m.

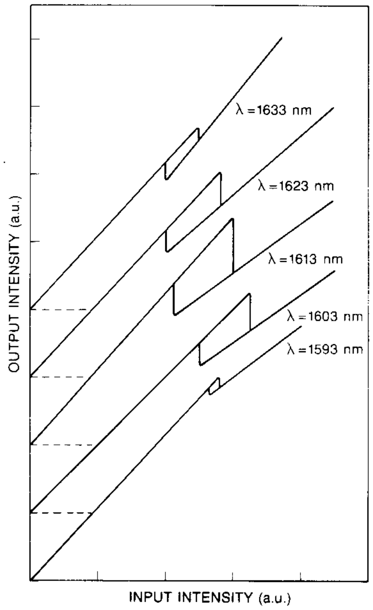

FIG. 3. Output intensity vs the input intensity for several wavelengths and for a bias of 20 V.

device charging time. With incident power of 1 μW and overdriving by 50%, we measured a switching time of ≈0.1 ms.

Finally, we connected the InGaAs MQW diode in series with a GaAs MQW diode, as shown in the inset of Fig. 4. A similar configuration, with two GaAs MQW diodes connected in series, was recently proposed and demonstrated.[10] It was shown that this symmetric SEED can function as an *S-R* latch analogous to an electronic flip-flop. Here, however, we demonstrate another function: a bidirectional modulation convertor from one wavelength to another. We illuminate each diode with laser light tuned to its hh exciton absorption peak. The InGaAs MQW diode is illuminated with a tunable NaCl color center laser operating at 1610 nm, and the GaAs MQW diode, with a tunable LDS 821 dye laser operating at 850 nm. The light intensity of the color center laser was ramped up and down with an electro-optic light modulator, while the dye laser intensity was held constant. Figure 4 shows the output intensity through the GaAs diode (at 850 nm) as a function of the incident intensity on the InGaAs diode (at 1610 nm). It is seen that the output intensity at 850 nm is modulated by the input intensity at 1610 nm.

This behavior can be readily understood if we consider first the GaAs MQW diode as a simple photodiode, similar to the Si one, and use the solid (for the InGaAs diode) and dotted (for the GaAs diode) lines of Fig. 1. Ramping the intensity of the color center laser then corresponds to a vertical magnification of the solid line of Fig. 1. As this incident intensity on the InGaAs diode is increased above the critical value, where there is only one intersection of the two lines, the voltage on this diode drops and falls on the GaAs diode. This causes a Stark shift of the GaAs hh exciton peak and the transmission at 850 nm rises. As the intensity at 1610 nm is ramped down, to the other critical value, the voltage is switched back to the InGaAs diode. The voltage on the GaAs diode drops, the hh exciton absorption at 850 nm is recovered, and the transmission at that wavelength decreases. As all this happens, the output intensity through the InGaAs diode is also switched, but in the opposite direction. A similar behavior is expected as the dye laser intensity is ramped, and the color center laser intensity is held constant.

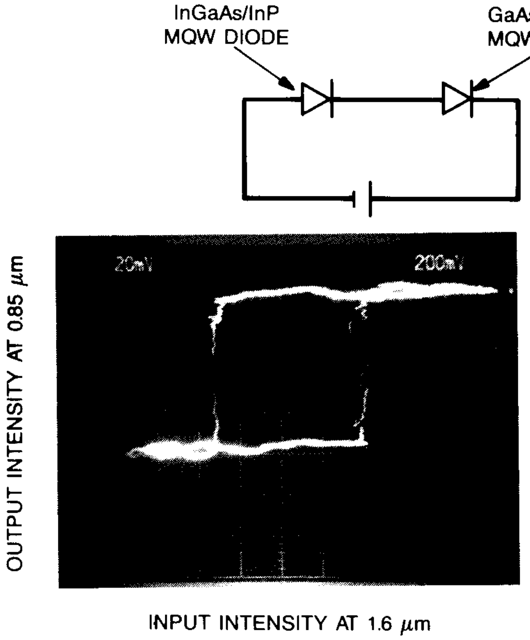

FIG. 4. Output intensity at 0.85 μm vs the input intensity at 1.61 μm. The inset shows the modulation convertor structure. The GaAs/AlGaAs diode is illuminated with the 0.85-μm laser beam, and the InGaAs/InP diode, with the 1.6-μm beam.

This simple configuration functions as a modulation convertor from one wavelength to another. A train of pulses at one wavelength modulates the light intensity at another wavelength to generate a similar train of pulses. It is important to note that this effect is spectrally symmetric, i.e., it can work in both directions, from long to short wavelength and vice versa. In view of recent advances in III-V heterostructure growth, an integrated version of such a modulator convertor can be realized. The response time of such a device is limited by the charging time, which depends on its capacitance and the incident intensity. A 10 μm×10 μm diode operating at 20 V bias and 1 mW incident intensity could switch in the GHz range, providing the intensity-dependent effects would be eliminated. An experimental realization of this integrated device is in progress.

In conclusion, this demonstration of the self-electro-optic effect in the InGaAs/InP material system, at a spectral range which is compatible with light wave communication, seems to open new possibilities for further implementation of this effect. The transparent substrate (at that spectral range) on which these quantum wells are grown allows easy optical access to the active region, without having to etch away the substrate. If large scale integration of optical switches is desired, this might be an important advantage. However, the performance of the device at large intensities needs to be improved. We have also introduced a simple way to perform logic operations with light beams at different wavelengths. The modulation convertor can be viewed as a logic device with two different wavelength outputs which can be driven by each of these wavelengths. This property could be important for both optical communication and optical computing.

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