Observation of room-temperature blue shift and bistability in a strained InGaAs-GaAs ⟨111⟩ self-electro-optic effect device

K. W. Goossen, E. A. Caridi, T. Y. Chang, J. B. Stark, and D. A. B. Miller
AT&T Bell Laboratories, Holmdel, New Jersey 07733

R. A. Morgan
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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We have observed room-temperature exciton blue shift with applied voltage in a ⟨111⟩ $\mathrm{In}_{0.1}\mathrm{Ga}_{0.9}$As-GaAs *p-i-n* multiple quantum well modulator. We have also observed optically induced bistability in a symmetric self-electro-optic effect device circuit composed of these modulators. Very large (2.5:1) ratios of photocurrent were obtained with only 0–3 V applied bias.

Recently the first direct demonstration of misfit strain generated piezoelectric field was made at 77 K in a single InGaAs-GaAs quantum well (QW) *p-i*(QW)*-n* sample grown on ⟨111⟩ GaAs.[1] This field is caused by an electric polarization which occurs when biaxial stress (in this case resulting from the lattice mismatch) is applied in the (111) plane of a III-V semiconductor.[2,3] The measurement was of a blue shift of the QW exciton peak with reverse bias, rather than the usual red shift associated with the quantum-confined Stark effect (QCSE). This was caused by the piezoelectric field being in a direction opposite to the applied bias, so that under bias the total field in the QW was reduced.

A blue-shifting QW diode has important consequences for self-electro-optic effect devices (SEEDs).[4] These devices achieve bistability with applied light intensity because the QW diode has higher absorption at lower biases. When light is incident upon a QW diode which is in series with a battery and some load so that it is reverse biased, the voltage across the diode decreases, causing the absorption to increase, so that there is positive feedback and bistability can occur.[5] Previously this was achieved by tuning the light energy to the exciton peak of the QW at zero bias (Fig. 1). Upon bias the exciton red shifts, and the absorption decreases. However, large residual absorption remains even at very large biases (e.g., 20 V/μm). In a blue-shifting QW diode upon bias the absorption would decrease to subband-gap values under much smaller biases (Fig. 1). Therefore, a blue-shifting SEED should operate at lower voltages, and have much less absorption in its transmitting state. However, note that since a blue-shifting QW diode is prebiased, its excitonic absorption at zero bias is less than a red-shifting (non-prebiased) QW diode. Possible causes for this reduction are reduced overlap of the electron-hole wave functions, greater sensitivity to well-width fluctuations or exciton ionization. Therefore, its change in absorption with bias could be less than a red-shifting QW diode if not designed properly. Clearly, the best design would be one in which the diode is only prebiased enough so that when voltage is applied to bring the QW to flatband, the exciton has shifted an amount slightly greater than its width. From experience, this prebias would be on the order of 5 V/μm.

We present here measurements at room temperature of blue shifting in a multiquantum well (MQW) $\mathrm{In}_{0.1}\mathrm{Ga}_{0.9}$As-GaAs ⟨111⟩ *p-i*(MQW)*-n* sample. The prebias we find is about 8.5 V/μm (note this is the piezoelectric field minus the built-in diode field). Differential transmission measurements will also be shown. Finally, we show optically induced bistability with our sample.

The growth of our sample was by conventional molecular beam epitaxy (MBE) at 580 °C on a ⟨111⟩ *B* undoped GaAs substrate miscut 2° toward [100]. The structure of our sample consists of a 1.2 μm n^+-GaAs layer, followed by an intrinsic region consisting of ten $\mathrm{In}_{0.1}\mathrm{Ga}_{0.9}$As-GaAs (70/150 Å) quantum wells clad on both sides by 3000 Å of undoped GaAs, yielding a total intrinsic thickness of 0.82 μm. Finally a 1.2 μm p^+-GaAs layer was grown to complete the diode.

The large undoped GaAs regions on either side of the QWs were made to ensure a constant field in the QWs. In future devices designed for performance rather than study these will be made much thinner, since as we will show below they blur the QW signal and also cause larger voltages to be needed for the same field. Also, the realtively wide barriers between wells, deemed necessary because of the low offset, will be reduced in future designs.

Gold alloyed contacts were made to the p^+ layer, then 200×300 μm mesas etched down to the substrate. A 200×100 μm region of the mesa was etched to the n^+ layer,

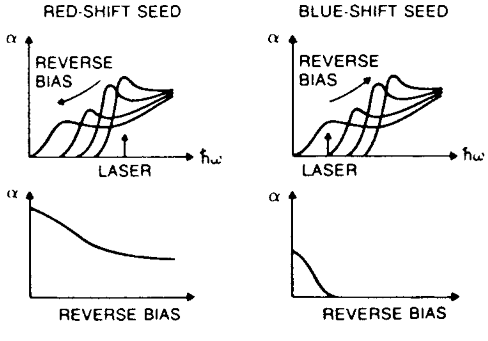

FIG. 1. Schematic of SEEDs employing red-shifting (left) and blue-shifting (right) QW diodes.

and an alloyed AuGe contact was made to it. For the differential transmission measurements the back of the substrate was polished with a 700:1 H_2O_2:NH_4OH solution[6] using standard polishing techniques.

Shown in Fig. 2 are photocurrent measurements of the sample at room temperature at 0, 2, 4, and 6 V applied bias. A single exciton peak associated with the QW is evident which blue shifts under applied bias. Presumably, only one peak is seen due to shifts of the heavy and light hole excitons caused by the strain. Note that the exciton is significantly reduced at zero applied bias due to the prebias as discussed above. An added detriment to the zero-bias signal could be the low band offset possibly resulting in decreased overlap of the exciton. Note that using an increased In mole fraction in the well to produce a larger offset will also increase the piezoelectric field. The larger signal at higher energies is due to bulk absorption in the undoped GaAs. This signal broadens with bias in accordance with the Franz–Keldesh effect, blurring the QW signal. In future devices the large undoped GaAs regions will be replaced with QWs, significantly reducing this problem. The inset of Fig. 2 shows the peak position versus bias. The quadratic behavior is clear, as has previously been observed with QCSE. The solid line is a quadratic fit yielding a prebias (i..e, the field required to bring the QW to the flatband condition) of 7/0.82 V/μm. Note that since only the well is strained, the piezoelectric field exists only in it. This leads to interesting questions regarding the band structure of these types of samples.[7]

Difference transmission measurements are shown in Fig. 3. These curves are of $[T(V) - T(0)]/T(0)$, where $T(0)$ is the transmission at zero applied bias and $V = 1, 2, 3$, and 4 V. The measurement was made through the substrate, causing results below 885 nm to be excessively noisy. The peak near 914 nm is an increase in transmission resulting from the blue shift of the exciton peak, which also causes the dip at slightly shorter wavelengths. The broadening of the bulk GaAs causes the dip near 890 nm. This extends to longer wavelengths so that the maximum transmission increase occurs for 0–3 V. Because of the small number of wells this is only about 2%. This yields a $\Delta\alpha$ of only about 2800 cm^{-1}, small because of the exciton reduction at zero applied bias as discussed above.

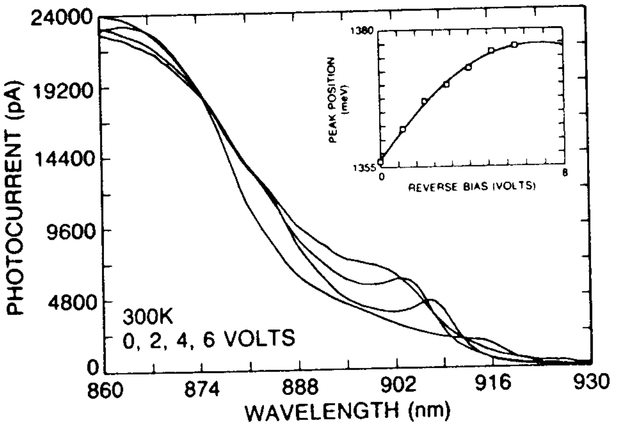

FIG. 2. Room-temperature photocurrent spectra at 0, 2, 4, and 6 V reverse bias. One exciton peak is evident which blue shifts with applied bias. The large absorption at higher energies is due to bulk absorption in the GaAs intrinsic cladding layers, which shows red shifting due to Franz–Keldysh effect. The inset shows the peak position vs voltage, with the quadratic fit (solid line) yielding a prebias field of 7 V/0.82 μm.

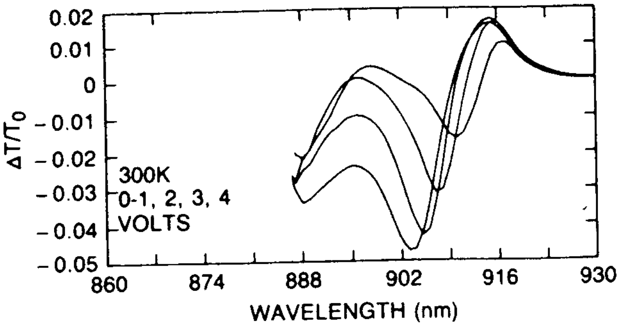

FIG. 3. Difference transmission spectra for 0 to 1, 2, 3, 4 V applied square wave. The transmission increase at low energies is due to the blue shift of the QW absorption edge.

A Ti:sapphire laser was used to illuminate the sample at 912 nm for a current-voltage measurement. (The maximum response obtained with the laser was at 912 nm.) This is shown in Fig. 4(a) for an input intensity of about 1 mW. The

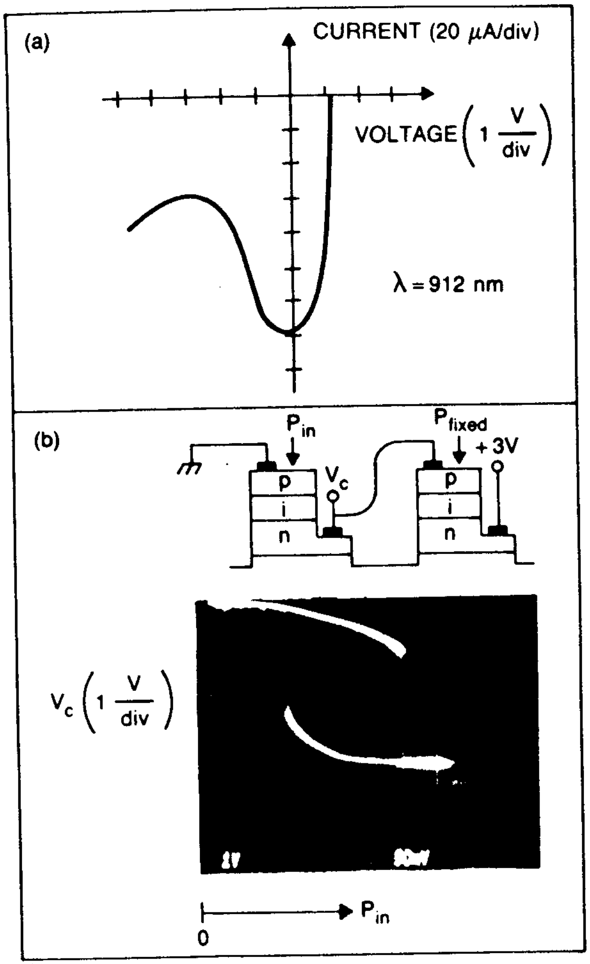

FIG. 4. (a) Current-voltage measurement of illuminated (912 nm) diode and (b) bistability curve of two blue-shifting QW diodes arranged in a symmetric SEED circuit (see inset). Due to the small changes in transmission resulting from having only ten wells, we show the voltage of the center tap vs P_{in} rather than the usual P_{out} vs P_{in}.

sample shows a pronounced negative photoconductivity due to the blue shift of the absorption edge. A photocurrent ratio of about 2.5 was obtained for only 3 V bias. The photocurrent would drop further to near zero, but the red shifting of the undoped bulk GaAs layer causes it to rise for higher voltages.

We then connected two mesas in series with a 3 V battery as shown in the inset of Fig. 4(b). This is a symmetric self-electro-optic effect (S-SEED) circuit, in which the state of the circuit depends on the ratio of the input powers on the two mesas.[8,9] In one state nearly all of the applied voltage is across one mesa and the converse is true for the other state. We fixed the input power on one of our mesas and varied the input power on the other, causing the circuit to change state. One conventionally demonstrates optical bistability by plotting the output power versus the input power. However, the transmission difference between 0 and 3 V is only about 2% as described above. Therefore, to show bistability, we monitored the voltage of the center pin (V_c) as a function of the input power.[9] This is shown inFig. 4(b). Clear bistability was observed. We were able to obtain bistability for wavelengths ranging from 908 to 916 nm.

In the design of these devices the prebias is clearly an important parameter. However, with the GaAs-InGaAs barrier-well system, the piezoelectric field cannot be adjusted without also changing the well depth, since both are an increasing function of the In mole fraction. Our prebias of 8.5 V/μm is somewhat higher than necessary. However, the well depth appears to already be too small judging from the exciton reduction under a fairly moderate prebias. A possible solution is an AlGaAs-$In_xGa_{1-x}As$ QW, since then the well depth could be tailored independently of the strain field. From this work it seems that x should be between 0.05 and 0.1. Another possibility is to use the InAlGaAs-InGaAs system, since then the operating photon energy could be adjusted to 1.06 μm, the Nd-YAG energy.

In summary, we have observed a blue shift of the exciton peak of a QW at room temperature with applied bias caused by the presence of a built-in strain field. Difference transmission measurements were made, and optically induced bistability observed in a symmetric self-electro-optic effect device circuit composed of two of our mesas. Very large (2.5:1) photocurrent ratios were obtained with only 3 V bias. From this work we recommend an AlGaAs-$In_{0.05}Ga_{0.95-0.9}As$ QW system, so that well depth and strain field can be tailored independently.

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