Observation of anomalously large blue shift of the heavy-hole photocurrent peak and optical bistability in narrow asymmetric coupled quantum wells

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Blue shift of the heavy-hole peak of the photocurrent spectra has been observed, for the first time, in narrow $GaAs/Al_{0.4}Ga_{0.6}As$ asymmetric coupled quantum wells near the heavy-hole resonance. With an external reverse bias of only -2.35 V, a maximum upward shift of the apparent peak position of ~ 6.1 meV has been measured at 78 K. Sharp change of the inhomogeneous linewidth of the heavy-hole peak has also been observed. cw optical bistability has been observed with the external feedback.

The self-electro-optic effect device (SEED)[1,2] utilizes the electric field induced change of the optical absorption coefficient of multiple quantum wells (MQWs) which is the result of quantum-confined Stark effect in quantum wells (QWs)[3] and the change in the oscillator strength of optical transitions. The feedback necessary for switching is provided by a resistor via photocurrent. In the conventional SEED, to assure the positive feedback, the existence of the sharp excitonic transition peak is essential. The drawback of this scheme is a large residual absorption. The blue-shifting SEED proposed in Refs. 4 and 5, in principle, does not rely on sharp excitonic transitions. Its major advantage therefore would be large on/off ratio, which has been realized in a blue-shifting SEED based on a strained InGaAs-GaAs ⟨111⟩ structure.[6] The blue-shifting SEED can also be based on Wannier–Stark localization.[7] In this letter, we report the first experimental results of anomalously large blue shift of the heavy-hole (HH) peak in the photocurrent (PC) spectra and cw optical bistability in narrow $GaAs/Al_{0.4}Ga_{0.6}As$ asymmetric coupled quantum wells (ACQWs) near the HH resonance.

ACQWs have been used to study the resonance of *electron* energy levels in two coupled QWs resulting in only the red-Stark shift of the excitonic transition.[8,9] Based on such mechanism, ACQWs have been used in optical modulators[10] and SEED.[11] However, it was shown in Refs. 4 and 5 that blue-Stark shift can be achieved by a proper design of the ACQWs: when the first two *heavy-hole* states in two asymmetric coupled QWs are approaching the resonance. Typically, it occurs at the electric field less than the resonant electric field by 10–20 kV/cm [i.e., at a bias between those for Figs. 1(a) and 1(b)]. We call this state of the ACQWs preresonance. Thus, the thicker QW of each period is placed closer to the *n*-doped side of the *p-i-n* structure. In order to attain strong HH coupling, we have chosen very narrow QWs with their widths being nearly *three times* narrower than those used so far.

Our sample was grown by molecular beam epitaxy on Si-doped (100) n^+ GaAs substrate. It had 25 ACQW periods, each consisting of two GaAs QWs of thicknesses 18 and 32 Å, coupled by a 15 Å $Al_{0.4}Ga_{0.6}As$ barrier. A 100 Å barrier isolates the pairs of coupled QWs from each other. These layers were sandwiched between n^+ and p^+

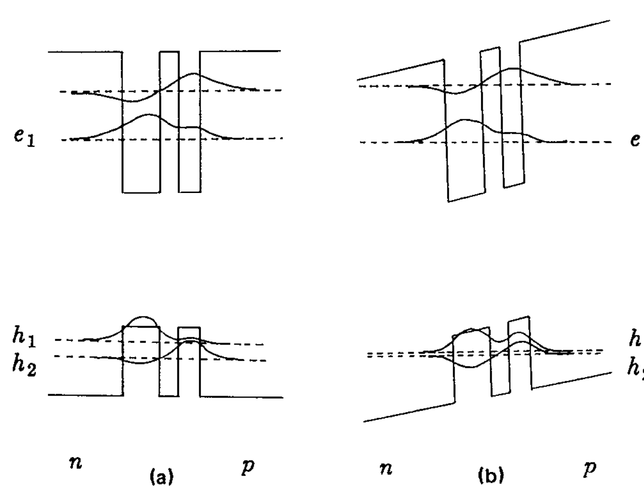

FIG. 1. (a) An unbiased ACQW structure. (b) A reverse-biased ACQW structure in reference to (a) with a wider well closer to the *n*-doped region. The resonance (anticrossing) between the HH energy levels in the two coupled QWs (h_1 and h_2) can be realized.

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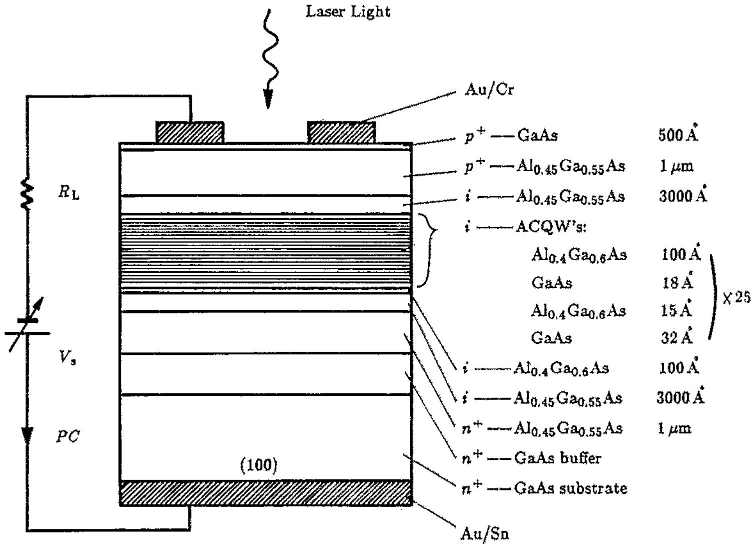

FIG. 2. The structure of a mesa *p-i-n* diode in which the intrinsic region contains ACQWs. The *i*-ACQWs layers correspond to multiple (25) QW pairs of the type shown in Fig. 1.

$Al_{0.45}Ga_{0.55}As$ layers, as shown in Fig. 2. Arrays of small mesas were fabricated. *P*-type ohmic contact rings on the top surface and an *n*-type ohmic contact on the back substrate were formed by evaporation. All the measurements were made at 78 K. The measurements of the PC spectra, taken at a fixed laser intensity of $\sim$9.2 mW/cm^2 and zero external resistance, are shown in Fig. 3(a) for different reverse biases (no clearly resolvable peaks near $\sim$ 7400 Å in PC spectra in the bias region $V_b > -2$ V or $V_b < -2.4$ V). The peak near $\sim$7400 Å was identified as the superposition of the HH excitonic transitions h_1e_1 and h_2e_1 [see Fig. 1(b)] and that near $\sim$7300 Å as the light-hole (LH) excitonic transition l_1e_1. Away from the resonance, the oscillator strength for h_1e_1 is about one order of magnitude larger than that for h_2e_1, and therefore, the peak at 7400 Å is probably dominated by h_1e_1. In Fig. 3(a) the intensity of the HH absorption does not seem to be three times larger than that of LH due to the fact that the LH is superimposed on the top of HH band-edge absorption as well as due to the strong valence band mixing[12] in the narrow QWs. The position of the *apparent* PC peak near 7400 Å is plotted versus the reverse bias in Fig. 3(b). Since the width of the PC peak changes rapidly, the shift of the PC peak may be a combination of the real shift of the excitonic transition and the change in the linewidth, therefore, blue shift mentioned by us refers to the shift of the position of the PC peak rather than to the shift of the transition energy—hence the use of the word apparent. The anomalously large shift of the apparent peak position, up to 6.1 meV can be seen in Fig. 3(b), while Fig. 3(a) shows that there is no observable change in either apparent position or width of the LH peak.[13]

As shown in Fig. 3(a), the sharp decrease in the HH peak linewidth can be observed at a reverse bias of ~ -2.3 V. This reverse bias corresponds to the electric field (including the measured built-in field ~ -15 kV/cm) of ~ -38 kV/cm, while our calculations show that the exact resonance is achieved at ~ -50 kV/cm. So, the change in the linewidth occurs near the preresonance, although all the given numbers are approximate, due to the uncertainty

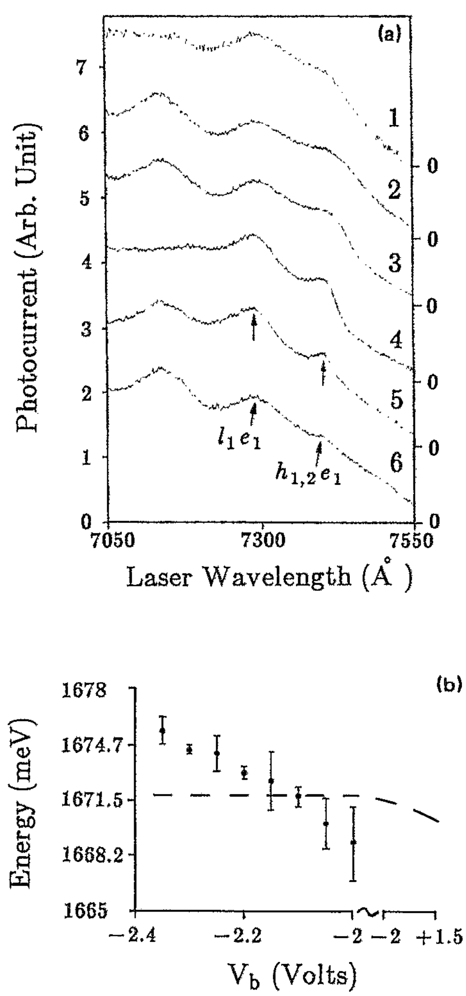

FIG. 3. (a) PC spectra at 78 K are plotted with laser intensity $I \sim 9.2$ mW/cm^2 for different reverse biases: Curve 1, 0 V; Curve 2, -2 V; Curve 3, -2.1 V; Curve 4, -2.2 V; Curve 5, -2.3 V; Curve 6, -2.4 V. Arrows: the predicted apparent positions of the LH and HH excitonic transitions. (b) The apparent position of the HH peak vs the reverse bias for the experimental results (dots) and theoretical calculations (broken lines).

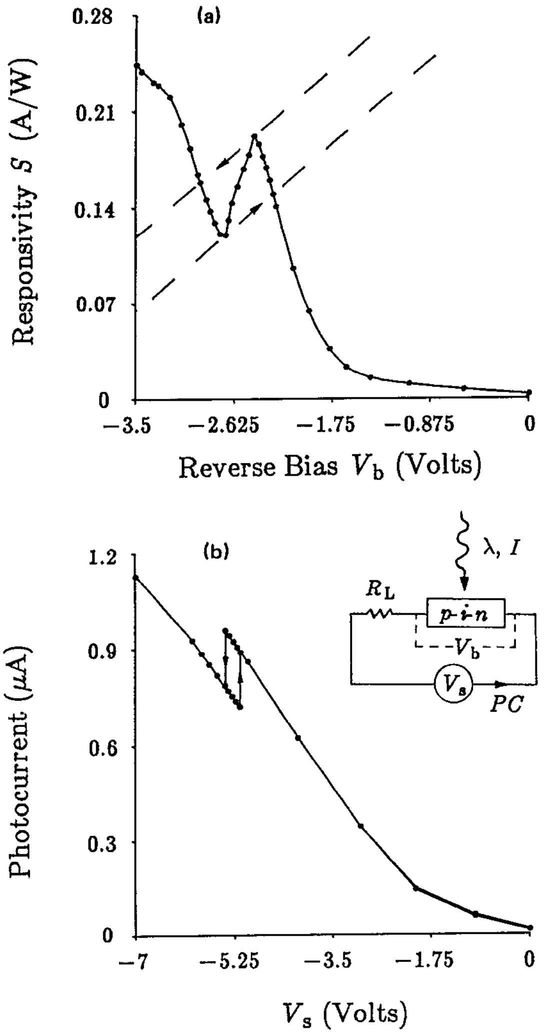

FIG. 4. (a) Measurement (dots) of responsivity of the diode at laser wavelength ~7421 Å (near the apparent HH peak) and laser intensity ~56 mW/cm^2 without feedback resistor. Dashed lines correspond to two load lines [R_L = 3.2 MΩ, V_s = −5.16 V and V_s = −4.40 V, see inset in (b)]. Arrows correspond to switchings in (b). (b) Optical bistability is observed in the PC characteristic vs output of voltage source (V_s). Under the same experimental conditions as (a) but the feedback resistance R_L is now ~3.2 MΩ.

in the determination of the intrinsic region thickness.[14] Thus, two major results: the general trend of the PC peak position as a function of the reverse bias, and the peak's sharpening near preresonance are consistent with our theory. However, the very rapid change in the linewidth and an anomalously large blue shift of the apparent peak over a very small range of biases, and the sudden disappearance and subsequent reappearance of the broad peak near $\lambda \sim$ 7125 Å occurring at −2.2 and −2.3 V respectively, require further study. Our calculations show that the exciton oscillator strength reaches its maximum and the homogeneous exciton linewidth (due to ionization) reaches its minimum near preresonance. The magnitude of this change, however, is not sufficient to explain the observed sharp change in the PC peak linewidth. One possibility is that the observed phenomenon is the result of the oscillator strength transfer between two transitions, not unlike Wannier–Stark localization,[7] but, as mentioned above, the h_1e_1 transition is dominant. The other intriguing possibility, first mentioned in Ref. 6, is the change in inhomogeneous broadening due to fluctuations in the QWs and barrier widths from well to well as well as in the plane of QWs. This effect is extremely important in narrow QWs, where the inhomogeneous broadening is dominant.[15] Indeed, the inhomogeneous broadening of h_1e_1 is expected to be the narrowest when the oscillator strength is the largest, i.e., at the preresonance. Finally, the observed change in linewidth can also be related to the change in the tunneling probability of the photogenerated carriers. This process is related to quantum efficiency of the device and is an electronic effect.

The responsivity of the diode is measured and plotted in Fig. 4(a). We can clearly see the negative differential resistance. (The bias for the negative resistance is a little bit larger than that near the narrowest linewidth in Fig. 3(a) due to the accumulation of the photogenerated carriers near two thick intrinsic AlGaAs barriers similar to Ref. 16.) In order to observe optical bistability, the *p-i-n* diode was connected with a voltage source (V_s) and an external resistor (R_L) [see inset in Fig. 4(b)]. As V_s was increased, cw optical bistability was observed in the PC response [see Fig. 4(b)]. This result is quite consistent with the expectation from Fig. 4(a) with $R_L = 3.2$ MΩ.

In conclusion, an anomalously large blue shift of the HH photocurrent peak, accompanied by sharp changes in the total linewidth of the peak has been observed in narrow ACQWs near the HH preresonance. cw optical bistability has been observed using an external feedback.

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