# Strong excitonic nonlinearity in a P-I-N photodiode incorporating narrow asymmetric coupled quantum wells

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Strong excitonic nonlinearity in the photoconductive response of a P-I-N photodiode incorporating narrow asymmetric coupled quantum wells has been observed at 78 K. When the P-I-N photodiode is overbiased, the heavy-hole energy levels in the two coupled quantum wells are moved toward the resonance by increasing the laser intensity. Also, both the light-hole and the heavy-hole excitonic transitions undergo intensity-dependent shifts. Both these effects indicate intrinsic change of bias due to redistribution of photogenerated carriers and, therefore, the existence of an intrinsic feedback mechanism. The magnitude of the blue shift of the heavy-hole excitonic transitions significantly increases when the laser intensity is changed from 9.2 to ~270 mW/cm$^2$.

A self-electro-optic effect device[1] (SEED) consists of multiple quantum wells (MQW's) incorporated into the intrinsic region of a P-I-N photodiode connected in series with a load resistor. The SEED's exhibit optical bistability and have been used as an array of optical logic gates[2] because they have a positive feedback provided by the quantum-confined Stark effect[3] and an external load resistor. In the conventional SEED, the red Stark shift of the excitonic transition[3] is used to provide this positive feedback. Its major disadvantage, however, is significant residual absorption. In an attempt to overcome this, the so-called blue-shifting SEED schemes were proposed[4] and subsequently realized[5] based on a strain-generated piezoelectric effect. Recently, we observed an anomalously large linear blue shift[6] in narrow GaAs/Al$_{0.4}$Ga$_{0.6}$As asymmetric coupled quantum wells (ACQW's) near the anticrossing between strongly coupled heavy-hole (HH) (rather than electron as in Refs. 7–9) energy levels in two coupled QW's.

It would be advantageous if intrinsic feedback inside the MQW P-I-N photodiode were achieved instead of having to use an external resistor; this would result in substantial simplification of the integration and fabrication of the devices. Most recently, a new type of optical bistability in the conventional SEED's (i.e., with red Stark shift) was demonstrated based on the intrinsic feedback mechanism.[10] Since the blue shift observed by us[6] in principle holds a great promise for blue-shift SEED's, it would be important from the viewpoint of application to attain an intrinsic feedback similar to that in Ref. 10. In this Letter we report the observation of such a feedback in our structure. Furthermore, in contrast to Ref. 10, we observed the increase in the magnitude of the excitonic blue shift with increasing laser intensity, which suggests an improved charcteristic of blue-shift SEED's. We emphasize that the nonlinearity discussed here is strictly due to the feedback through the photocurrent and is not related to other types of nonlinearity in ACQW's.[11]

The ACQW sample [Fig. 1(a)] used in this experiment was grown by molecular-beam epitaxy on a Si-doped (100) $n^+$ GaAs substrate. It has 25 ACQW individual pairs, each of them consisting of two GaAs QW's with thicknesses of 1.8 and 3.2 nm, which are coupled by a 1.5-nm Al$_{0.4}$Ga$_{0.6}$As barrier. A 10-nm barrier is used to isolate the pairs of coupled QW's from each other. The ACQW structure is sandwiched between undoped Al$_{0.45}$Ga$_{0.55}$As layers, each 300 nm thick. The entire undoped epitaxial layers were embedded in the intrinsic region of a P-I-N photodiode. Arrays of small mesa photodiodes, 250 $\mu$m in diameter, were fabricated; $p$-type ohmic contacts rings on the top surface (inner diameter ~100 $\mu$m, ring thickness ~50 $\mu$m) and an $n$-type ohmic contact on the back surface were formed by evaporation. The sample was then attached to the end of a cold finger in a cryostat and maintained at 78 K. An argon-pumped cw dye laser with Pyridine 2 was used as a tunable source. Photocurrent spectra were measured with a lock-in amplifier and later corrected for the gain curve of the dye.

In order to explore nonlinear effects, the reverse bias was fixed at −3 V, and the photocurrent spectra were measured for the range of laser intensities between 157 and 850 mW/cm$^2$ [Fig. 2(a)]. According to Fig. 2(a), at low laser intensities, the excitonic transition peaks were barely distinguishable. The reason

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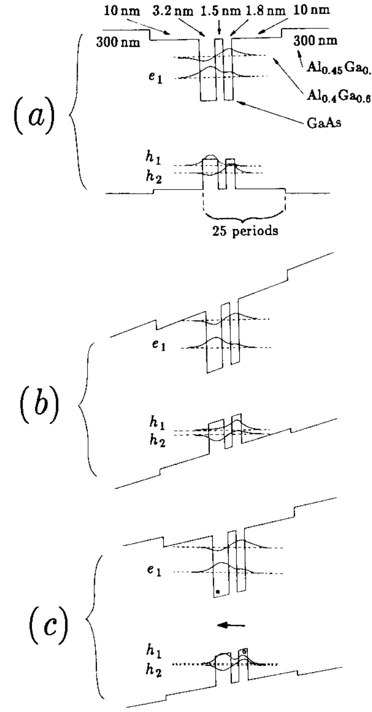

Fig. 1. Band structures of multiple ACQW's and two intrinsic feedback layers (the thick barriers) embedded in the intrinsic region of a P-I-N mesa diode (see the text for a detailed description of this structure). The three configurations are (a) flat band, (b) overbiased in reference to the HH energy levels ($h_1$ and $h_2$) in two coupled QW's, and (c) shining a high-intensity laser beam, which results in the accumulation of photogenerated electrons (filled circle) and holes (open circle) near two thick barriers (300 nm) and therefore brings $h_1$ and $h_2$ toward resonance. The arrow shows the direction of the electric field resulting from this intrinsic feedback mechanism.

for this is that when the device is overbiased, electrons and holes are at the opposite ends of the ACQW's [see Fig. 1(b)], so the exciton oscillator strength and its binding energy are small, and hence the exciton is easily ionized. Also, the inhomogeneous linewidth[12] is large because when the electron or hole is localized close to one of the QW walls, its energy becomes sensitive to the QW width variations. As a result, the excitonic transition peaks appear washed out. When the laser intensity was increased, however, a dramatic change occurred in the photocurrent spectrum: two distinct peaks appeared. These two peaks have been identified by us as HH and light-hole (LH) excitonic transitions [$h_{1,2}e_1$ and $l_1e_1$, where $e_1$ and $h_{1,2}$ are the lowest energy levels of the electron and the HH, respectively (see Fig. 1), and $l_1$ is the lowest energy level of the LH]. As the laser intensity was further increased, the HH peak first narrowed, approaching a resonance (anticrossing) between HH energy levels [$h_1$ and $h_2$ in Fig. 1(c)], then the peak broadened again. The apparent positions of the transitions $h_{1,2}e_1$ and $l_1e_1$ in the spectrum, meanwhile, diverged [Fig. 2(b)], with the lower-energy peak moving toward the lower energies and the higher-energy peak moving toward the higher ones. This diverging trend has indicated the existence of a feedback resistance somewhere in the circuit. The increase in the laser intensity reduced the electric field inside the device and canceled the blue shift of the transitions $h_{1,2}e_1$. As a result, the peak of the transitions $h_{1,2}e_1$ has moved toward the lower energies. In our experiment, a downward shift of $h_{1,2}e_1$ of ~4.9 meV was observed when the laser intensity was increased from 173 to 850 mW/cm$^2$. The situation for the transition $l_1e_1$ is different. Owing to the proximity of the effective masses of the LH and the electron, $l_1e_1$ shows only the red shift, regardless of how the structure is biased. Therefore the intensity-induced reduction of the bias can move the peak of $l_1e_1$ only toward the higher energies, as seen in Fig. 2(a). In our experiment an upward shift of $l_1e_1$ of ~1.7 meV was observed when the laser intensity was increased from 173 to 482 mW/cm$^2$.

Since there was no external resistor in the circuit and the resistance of the contacts was low (according to current–voltage measurements of the device), the key to the nature of the feedback must lie within the structure of the device itself. On examination of our structure (Fig. 1), we conclude that the two 300-nm-thick undoped $Al_{0.45}Ga_{0.55}As$ layers near the top and the bottom of the ACQW's act as barriers for photogenerated carriers. These photogenerated carriers thus accumulate at the opposite ends of the ACQW structure and screen the external reverse bias field [see Fig. 1(c)]. This feedback mechanism was first observed in Ref. 10. Thus one can ascribe the effect observed in Ref. 10 and in our experiment to the intrinsic feedback through a photocurrent, which results in a (highly nonlinear) effective intrinsic resistance. This conclusion is further supported by the fact that the rest of the structure in both these experiments is significantly different: in comparison with the wide symmetric structure used in Ref. 10, our structure

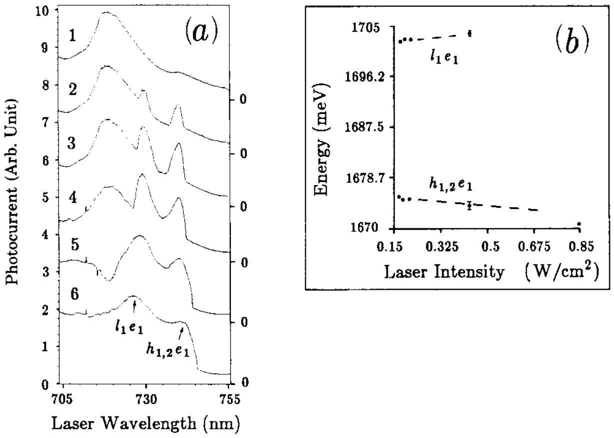

Fig. 2. (a) Typical measured photocurrent spectra shown at a constant reverse bias ($V_b \sim -3$ V) for different laser intensities: 157, 173, 188, 213, 428, and 850 mW/cm$^2$ for curves 1–6, respectively. (b) For a fixed reverse bias ($V_b \sim -3$ V), the energies of the HH and LH excitonic transitions ($h_{1,2}e_1$ and $l_1e_1$) are plotted versus laser intensity for the experimental data (dots) and theoretical simulations (dashed curves).

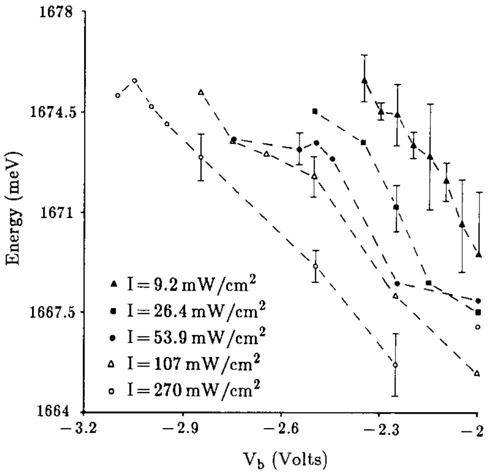

Fig. 3. Energy at the apparent peak of the HH excitonic transitions ($h_{1,2}e_1$) versus the reverse bias for different laser intensities.

consists of narrow ACQW's, which are supposed to show more complicated behavior owing to tunneling of photogenerated carriers. Since the process of the carriers being swept from the ACQW's by the electric field is itself a tunneling process, the sweeping time and hence the quantum efficiency of the device are functions of the electric field. Therefore the quantum efficiency can change significantly, especially close to the anticrossing between the hole energy levels in the two coupled QW's, when the tunneling between the QW's is facilitated. Consequently the sharp enhancement of the photocurrent peaks can be the result of two factors: increase in the absorption coefficient and/or the quantum efficiency. The latter effect is purely electronic rather than electro-optic in nature. A full understanding of these two competing processes can only be obtained after measurements of absorption and photoluminescence excitation spectra are performed. In an attempt to explain the results of our experiments, owing to the accumulation of photogenerated carriers near two thick barriers discussed above, we presumed that a linear intrinsic resistance was present in the circuit. Our preliminary simulations [the dashed curves in Fig. 2(b)] confirm the existence of this intrinsic resistance, which is determined as ~100 kΩ for $h_{1,2}e_1$ and ~320 kΩ for $l_1e_1$.

The existence of an intrinsic resistance has been further confirmed by the results of the measurement of the apparent position of $h_{1,2}e_1$ versus reverse bias at the different laser intensities (Fig. 3). As reported by us previously,[6] the sharpening in $h_{1,2}e_1$ was observed at −2.3 V at a relatively low laser intensity of 9.2 mW/cm$^2$. This indicates that at this reverse bias, the HH energy levels ($h_1$ and $h_2$) in two coupled QW's are brought near a resonance (i.e., an anticrossing). Our photocurrent spectra show that the external reverse bias near which the anticrossing occurs increases as laser intensity is increased. This again indicates the existence of an intrinsic resistance in the device. As the laser intensity is increased, the magnitude of the blue shift of $h_{1,2}e_1$ increases as well. The maximum blue shift observed in our experiment was ~10 meV at a laser intensity of ~270 mW/cm$^2$ (see the data shown as open circles in Fig. 3). This increase of the blue shift (compared with 6.1 meV at the lower laser intensity of 9.2 mW/cm$^2$; see the data shown as the filled triangles in Fig. 3) constitutes considerable enhancement of the Stark shift, to our knowledge never observed before. At a relatively high laser intensity, intrinsic optical bistability was observed by us. Our hope is that by optimizing the ACQW's structure a high on/off contrast ratio and a low threshold laser intensity in intrinsic optical bistable devices can be achieved.

In conclusion, the large excitonic nonlinear effect in the narrow multiple ACQW structure has been observed for the first time to our knowledge using photocurrent measurement. The effect has been attributed by us to the intrinsic feedback mechanism due to the accumulation of photogenerated carriers near the thick barriers in the P-I-N photodiode incorporating the ACQW's. The blue shift of the HH excitonic transitions ($h_{1,2}e_1$) can be strongly enhanced by increasing the laser intensity.

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