

STRAINED PIEZOELECTRIC [111] MULTIPLE QUANTUM WELLS: CLAMPED OR FREE?

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We illustrate a procedure whereby the nonlinear optical response can be used to determine the strain distribution in properly engineered InGaAs/GaAs multiple quantum well (MQW) structures with piezoelectric fields along the growth direction. We do this by fabricating two p-i(MQW)-n samples which are designed such that, if the materials are mechanically clamped, the quantum well exciton of one will shift to the blue upon optical excitation, whereas the quantum well exciton of the other will shift to the red. However, if the materials are mechanically free, the quantum well excitons of both samples will shift to the red. We illustrate the technique by determining that InGaAs/GaAs MQWs grown on [111]-oriented GaAs substrates are (as expected) mechanically clamped. That is, that we observe an excitonic blue shift in one sample, and a red shift in the other.

1. Introduction

Strained [111]-oriented zincblende multiple quantum well (MQW) structures are attractive for novel nonlinear optical and electronic device applications because of the presence of large piezoelectric fields in the growth direction. For example, strain-induced piezoelectric fields have been exploited to produce blue-shifting self electro-optic devices (SEEDs) that have a low switching voltage [1], and other strained, [111]-oriented optoelectronic device structures have been proposed [2,3]. In addition, improved performance has been predicted for piezoelectric electronic devices such as HEMTs [4].

However, the full exploitation in devices of strained piezoelectric MQWs will require a thorough understanding of their band structure and carrier dynamics. The band structure, precise nature of the carrier dynamics, and the temporal evolution of the optical nonlinearities will depend critically on

the distribution of strain throughout the MQW structure. The two limiting cases of the strain configuration are known as mechanically clamped and mechanically free. Under clamped conditions, the lattice constant of the unstrained substrate material is imposed on the entire structure. Thus, there is no strain in the barrier regions, and piezoelectric fields exist only in the strained QWs. By contrast, under free conditions, the strain is distributed between the barriers and wells, and the lattice spacing acquires a value that is weighted by the relative widths of the barriers and wells. Attempts have been made to grow mechanically free piezoelectric MQW structures [5]. In fact, early calculations of the nonlinear optical properties of [111]-oriented MQW structures were based on the assumption of a free band structure [6,7], and early measurements of the nonlinear optical properties of piezoelectric InGaAs/GaAs MQWs grown on GaAs substrates were interpreted in terms of this model [8].

However, InGaAs/GaAs MQWs grown on [100]-oriented GaAs substrates are commonly assumed to be mechanically clamped, and it seems reasonable to expect that [111]-oriented samples will be mechanically clamped as well. In fact, more recent measurements [9] of the nonlinear optical properties of piezoelectric MQWs grown on [111]-oriented GaAs substrates were consistent with mechanical clamping, but these measurements were not definitive on this point. Recent photocurrent and photoluminescence measurements [10] on the structures used here are also consistent with mechanical clamping, but the issue is not addressed directly.

In this paper we implement a technique that provides unambiguous evidence that strained, piezoelectric MQWs grown on [111]-oriented GaAs substrates are mechanically clamped. The technique consists of measuring the optical nonlinearities associated with the screening of the piezoelectric fields at low pulse repetition rates in two carefully engineered structures. Specifically, we have designed two InGaAs/GaAs p-i(MQW)-n samples such that, if the samples are clamped, one should exhibit a blue shift of the MQW exciton when optically excited, and the other a red shift. By contrast, if they are mechanically free, each should show a red shift.

2. Sample Structures

Each sample used in this study consists of a strained, [111]-oriented InGaAs/GaAs MQW located in the intrinsic region of a p-i-n diode. The two samples are identical except for the widths of the barriers between the wells. Each sample contains ten 10-nm-wide $\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$ quantum wells separated by GaAs barriers. In one sample (#279) the barriers are 15 nm wide, whereas in the other (#280) the barriers are 30 nm wide. In each sample, the MQW region is clad by undoped GaAs spacer layers to make the total thickness of each intrinsic region 570 nm. Both samples were grown on n+ doped, [111]B-oriented substrates with a 300-nm-thick p+ GaAs cap layer to complete the p-i-n structure. There was a p-i-n potential of ~ 1.4 V between the doped regions in each sample; the samples were not connected to any external potential. The piezoelectric field is in the opposite direction to the p-i-n field.

Assuming that the structures are mechanically clamped, the net potential difference, V_{MQW} across the MQW region of each sample is given by [10]

$$V_{MQW} \equiv \frac{n(L_W + L_B)}{D} V_{pin} + \frac{2dnL_W}{D} E_p, \quad (1)$$

where V_{pin} is the built-in potential of the p-i-n junction, E_p is the piezoelectric field, n is the number of InGaAs wells, L_W is the well width, L_B is the width of barriers between the QWs, d is the width of intrinsic GaAs spacer between MQW region and the doped layers, and D is the overall width of the intrinsic region, which is a constant in both samples, assuming that the thickness of depletion layers is negligible.

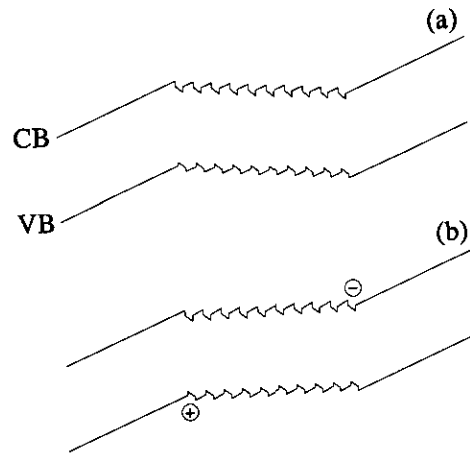


Fig. 1. Band structure of sample #279 (a) before excitation and (b) when sufficient carriers have accumulated at the potential minima to completely flatten the bands across the MQW region.

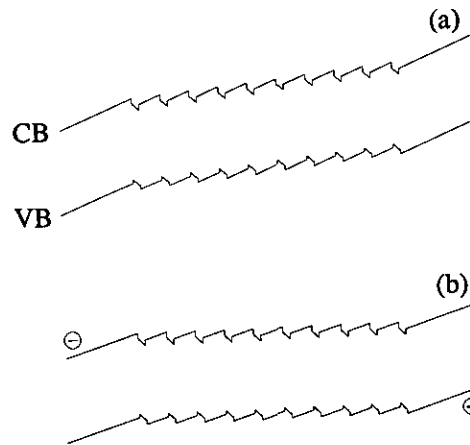


Fig. 2. Band structure of sample #280 (a) before excitation and (b) after excitation. Photogenerated carriers drift to the doped regions and flatten the bands across the entire intrinsic region.

Using a value of 15.5 V/ μm [11,12] for E_p , Eq. (1) allows us to predict that the accumulated decrease in potential over the MQW region due to the piezoelectric field in sample #279 will exceed the accumulated increase due to the p-i-n field. Consequently there will be a local potential minimum for electrons at one end of the MQW region and holes at the other end, as shown in Fig. 1(a). Similarly, if we assume that sample #280 is mechanically clamped, Eq. (1) predicts that the accumulated decrease in potential associated with the

piezoelectric field will be less than the accumulated increase due to the p-i-n field. In this case, as illustrated in Fig. 2(a), there are no local minima for either electrons or holes. However, if the structures are assumed to be mechanically free it is easy to show that the resulting potentials for both samples would be similar to that shown in Fig. 2(a), *i.e.*, there would be no local minima in either.

3. Optical Nonlinearities

The nonlinear optical response of the p-i(MQW)-n is expected to be very different for samples with and without local potential minima: For a sample such as #279, which has local potential minima, the electrons and holes created by the optical excitation will move towards, and then accumulate at, the local minima, as shown in Fig. 1(b). The electric field resulting from the spatial separation of the photogenerated electrons and holes is in the same direction as the p-i-n field, and therefore reduces the total electric field in the quantum wells. A reduction in the electric field causes the quantum well excitonic absorption to shift to the blue via the quantum confined Stark effect. By contrast, for a sample such as #280, which does not have local potential minima, the optically-generated electrons and holes move towards the n- and p-doped regions and therefore screen the p-i-n field, as shown in Fig. 2(b). As a result, the total field in the quantum wells increases and the excitonic optical absorption shifts to the red. If the samples were mechanically free, the band structures of both would qualitatively resemble that shown in Fig. 2(b), and each sample would exhibit an excitonic red shift upon optical excitation.

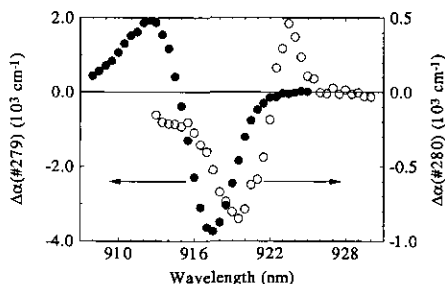


Fig. 3. Absorption coefficient change, $\Delta\alpha$, plotted as a function of wavelength, for samples #279 and #280. A picosecond pump/probe technique was used to make these measurements. There was a delay of 800 ps between the pump and the probe.

The nonlinear optical responses of both samples were determined by differential transmission, in which a weak probe pulse is used to measure the change in transmission induced by a strong pump pulse. Measurements were made for both

samples at 80 K as a function of probe delay, of wavelength, and of pump fluence. The pump and probe pulses were produced by a tunable, cavity-dumped cw modelocked dye laser. The laser produced 3.2 ps pulses (FWHM) at a repetition rate of 25 kHz ($\sim 40 \mu\text{s}$ between pulses). The low laser repetition rate was chosen to ensure that significant recombination of photogenerated carriers, which are long-lived because of the large spatial separation of electrons and holes, occurs between laser pulses.

The results of our nonlinear optical measurements are consistent with the mechanically clamped band structure assumed here. Representative spectra of $\Delta\alpha$, the pump-induced change in the absorption coefficient, for samples #279 and #280 are shown in Fig. 3 for the probe arriving 800 ps after the pump pulse. This probe delay allows ample time for the nonlinearity to evolve, but is well before significant recombination of the photogenerated carriers occurs. Note that the spectrum for sample #279 is that of a blue-shifted exciton, whereas that for sample #280 is that of a red-shifted exciton. Again, we emphasize that a mechanically free structure would have produced a red shift for both structures, contrary to our observations.

4. Conclusions

We have illustrated a nonlinear optical technique that allows us to determine unambiguously that the lattice constant of strained, piezoelectric p-i(MQW)-n structures grown on [111]-oriented GaAs substrates is mechanically clamped to that of GaAs. This was done by designing samples such that, if the materials were clamped, upon optical excitation, the quantum well exciton of one sample would shift to the blue, and that of the other sample would shift to the red. However, if the materials were mechanically free, the exciton would shift to the red in both cases. We made measurements of the nonlinear optical properties of the samples and observed a blue shift in one case and a red shift in the other. This technique can be readily modified to allow the determination and quantification of the strain distributions in piezoelectric MQW structures grown or processed in ways that make their bandstructures less obvious.

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