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Blue Stark shift in modulation strained InGaAs/InP quantum wells

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We show that by a proper design and modulation of the composition of a ternary InGaAs quantum well one can considerably alter the optical properties of the system. We demonstrate a novel InGaAs/InP strained-layer heterostructure in which a blue Stark shift of the absorption edge of more than 10 meV is achieved. This blue shift, together with a field-enhanced room-temperature excitonic effect, has applications to bistable electro-optic devices.

In recent years much attention has been given to strained-layer superlattices (SLSs) and quantum wells[1-8] (SLQWs) in which multilayer structures are grown lattice mismatched to the substrate with the layer thickness small enough to accommodate the mismatch strain coherently.[9] However, modulation of the strain within a quantum well has not been studied. The $In_xGa_{1-x}As$/InP heterostructure system is particularly suitable for this since for $x > 0.53$ the $In_xGa_{1-x}As$ ternary layer is biaxially compressively strained and for $x < 0.53$ it is tensively strained. A proper design of the modulation can therefore balance the strain forces, overcoming the limitations set by the individual layer critical thicknesses.[9] As long as the growth is commensurate, the lattice constant in the plane of the well is strained to match the lattice constant of the InP substrate. As a result, the unit cell of the strained layer is tetragonally distorted and the lattice constant in the growth direction no longer equals the in-plane lattice constant. The strain sign and absolute magnitude can therefore be engineered by modulating in the quantum well composition, with consequent effects on the electronic bands and the potential structures. A knowledge[5] of energy-band alignments within such mismatched systems is essential to properly take advantage of the flexibility introduced with this new way of using strain modulation. In this letter we report on the design and fabrication of an electro-optic modulator using a modulation strained multiquantum well system (MSQW). The knowledge of the details of the electronic band alignment in this strained material system, together with excellent control of composition, allows us to design and demonstrate a new type of modulator which exhibits blue Stark shift and enhancement of the oscillator strength when it is subjected to moderate transverse electric fields. A modulator with such features is very promising as a component of future optical logic and communication systems.[10,11]

Figure 1 shows the composition profile [Fig. 1(a)] of one MSQW together with the resultant strain profile [Fig. 1(b)] and electronic band configuration [Fig. 1(c)]. (For the details of the band calculations, see Ref. 7.) The device under study contains ten periods of the MSQW in the intrinsic region of a *p-i-n* structure. The device was grown by a hydride source molecular beam epitaxy system (HSMBE).[12] This technique is particularly well suited for growth of structures containing both As and P and allows for excellent control of layer thickness, composition, and lattice match. It was grown on an *n*-type (100) oriented InP substrate, on which a 0.3-μm-thick intrinsic InP buffer layer was deposited prior to the multiple MSQW structure. The ten quantum wells are separated by 500 Å InP barriers and each well contains three layers of $In_xGa_{1-x}As$ of different indium content as described in Fig. 1. The periodic structure was capped with a 0.3-μm-thick intrinsic layer of InP followed by a 0.3-μm-thick *p*-type layer of InP with gradually graded doping from about 5×10^{17} to 1×10^{19} to complete the *p-i-n* device. For the response measurements of the samples, detectors were prepared by conventionally etching a 100 μm mesa and the depositing of metal contacts in a form which allows for light insertion perpendicular to the plane of the layers.

The energy change of the first two discrete levels of electrons and heavy holes in the potential structure of Fig. 1, with an applied electric field, is described in Fig. 2(a). The calculations are performed using the resonant tunneling

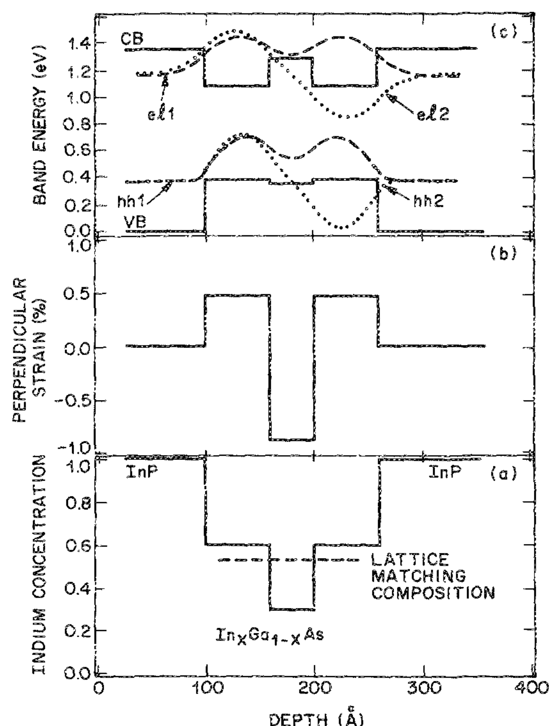

FIG. 1. Depth profile of the MSQW (a) composition, (b) strain perpendicular to the plane and (c) potential structure. The lowest two symmetric (dashed) and antisymmetric (dotted) wave functions for electrons and heavy holes are also depicted.

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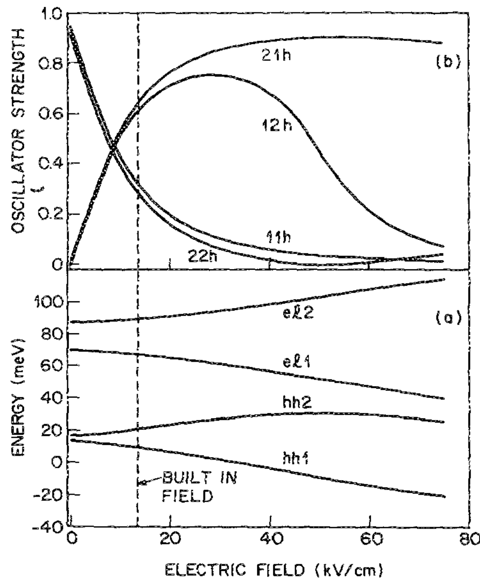

FIG. 2. (a) Electric field dependence of the electron and heavy hole subband energies. (b) Electric field dependence of the squared overlap integral (oscillator strength) between the first two levels of heavy holes and electrons. The first digit refers to the electronic level and the second to the hole. The letter (h) indicates that this is a heavy hole state.

method[13] with inclusion of band nonparabolicity corrections.[7] For simplicity the electric field dependence of the excitonic binding energy is neglected. Qualitatively, one can see how the field removes the degeneracy between the symmetric and antisymmetric states of the coupled quantum wells. The symmetric states (el1, hh1) are moved towards lower energies and the antisymmetric ones (el2, hh2) are blue shifted.

The oscillator strength of the optical band-to-band transition is proportional to the square of the overlap integral beween the carriers' envelope wave functions.[13] The overlap integral squared between each one of the two electronic states and the two heavy hole states, as a function of applied electric field, is shown in Fig. 2(b), which describes quantitatively how the oscillator strength of the various excitonic transitions varies with the applied field. At zero field only transitions between states of the same symmetry (SS) are allowed (el1–hh1 = $11h$ and el2–hh2 = $22h$). Transitions between the symmetric and antisymmetric (SAS) states (el1–hh2 = $12h$ and el2–hh1 = $21h$) are strictly forbidden. The perpendicular electric field reduces the symmetry in the system which in turn reduces the oscillator strength of the normally "allowed" excitonic transitions, and enhances that of the normally "forbidden" ones. It can be seen in Fig. 2(b) that the "forbidden" transitions are a factor of 2 stronger than the "allowed" ones, as a result of the built-in field of ~ 13 kV/cm. Thus from the considerations of Figs. 2(a) and 2(b) one can expect that the dominant excitonic features to be observed in our modulation strained sample result from the forbidden symmetric antisymmetric (SAS) transitions. Those transitions are expected to gain oscillator strength with increasing electric field, in marked contrast to the conventional quantum-confined Stark effect (QCSE).[13] Moreover, the lowest energy SAS transition el1–hh2 is expected to shift towards the blue, as the applied electric field is increased. This is because the antisymmetric hh2 states moves upward in energy much faster than the movement downward of the symmetric el1 electronic state. Blue Stark shifts of higher energy excitonic transitions in coupled quantum well have been observed in the past.[14,15] For the operation of electro-optical bistable devices, however, it is desirable to have blue Stark shift of the absorption edge, together with the enhancement of its oscillator strength. Several ways to achieve these features were recently suggested[10,11,16,17]; however, none of them have been demonstrated. In the following we demonstrate for the first time how this combination of effects is achieved by using the flexibility of modulation straining.

The room-temperature photocurrent excitation (PCE) response of the device under various biases is shown in Fig. 3. Dispersed light from a tungsten lamp was used as a continuously tunable source of excitation for these measurements and a standard lock-in technique was used for the photocurrent detection. The spectra are corrected for the system response. The spectra demonstrate that the expected features of the MSQW device are achieved. The lowest excitonic resonance ($12h$) moves upward more than 10 meV in energy as the applied bias is varied from $+0.5$ V to -6 V (which is equivalent to field changes of ~ 8 kV/cm to ~ 73 kV/cm). The oscillator strength of this transition peaks at a reverse bias of -1.5 V corresponding to an electric field of ~ 28 kV/cm in good agreement with the calculations of Fig. 2. At higher energies the other SAS transition ($21h$) is also clearly observed in the spectra, although its absolute position is somewhat different from our expectations based on calculations assuming nominal dimensions and compositions. As expected this transition undergoes a red Stark shift and its oscillator strength also increases for application of moderate electric fields. At higher fields it broadens, probably due to absorption from continuum states, which are not taken into account in our calculations.

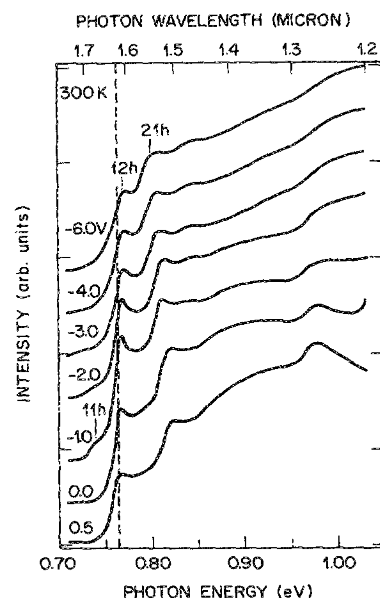

FIG. 3. Photocurrent excitation spectra of the MSQW, under various applied biases.

The el1–hh1 (11h) SS "allowed" transition is observed as a shoulder on the lower energy side of the much stronger 12h SAS transition. It is best seen in the -1.0 V curve, where the electric field is strong enough to separate the two, but not too strong to diminish the oscillator strength of the SS transition altogether.

In summary, the flexibility offered by modulating the strain within a InGaAs/InP quantum well to design its band-gap structure, has been used for the first time. Using this new concept in design, we have fabricated an optical modulator which demonstrates an effective room-temperature blue Stark shift effect. This blue shift together with the enhancement of the oscillator strength can be very useful for bistable electro-optic devices.

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