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Response to "Comment on 'Optical bistability in self-electro-optic effect devices with asymmetric quantum wells' and on 'Novel configuration of self-electro-optic effect device based on asymmetric quantum wells'" [Appl. Phys. Lett. 57, 1363 (1990)]

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made much larger than in the other configurations discussed above. This follows since the mechanism is simply the quantum-confined Stark effect, with a built-in bias resulting from the alternating *n*- and *p*-type doping. The effect of an external field is simply to "undo" the Stark shift. However, it is difficult in practice to control thicknesses and doping in molecular beam epitaxial growth to better than several percent. The inability to achieve exact cancellation of donors and acceptors in a *n-i-p-i* leads to an undesirable electric field profile when the *n-i-p-i* is placed between *n*- and *p*-type contact layers for reverse biasing. Detailed solutions to Poisson's equation show that the effects are similar to those produced by a uniform background charge of density $e(d_n N_D - d_p N_A)/l$, where d_n and d_p are the thicknesses of the *n*- and *p*-type layers, N_D and N_A are the donor and acceptor densities, and l is the superlattice period. For example, if $d_n = d_p = 200$ Å, $N_D = 1.1 \times 10^{18}/\text{cm}^3$, $N_A = 10^{18}/\text{cm}^3$, and $l = 1000$ Å (i.e., a net charge imbalance of 10%), the equivalent uniform background density is $2 \times 10^{16}/\text{cm}^3$. With background densities this large, the excitonic transitions in the quantum wells embedded in the *n-i-p-i* become very broad and may split up into a number of lines.[8] Thus the sharp decrease in absorption with increasing bias, required for optical bistability, would not occur in practice.

We conclude that none of the proposed implementations of the asymmetric well device will achieve the desired effects. We suggest, however, that a number of potentially workable alternatives are available for obtaining a blue shift with electric field in quantum well optical transitions. One is to use the piezoelectric effect in strained quantum wells grown along the (111) direction. Another is to use an "effective" blue shift in symmetric coupled quantum wells[9] or in a strongly coupled superlattice.[10] In these systems, the lowest energy transition red shifts with field but its oscillator strength decreases rapidly; the net effect is to transfer oscillator strength to higher energies and thereby dramatically decrease the optical absorption at the energy at which the exciton occurs at zero field.

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Response: In their comment, Leavitt and Little[1] perform detailed analysis of three configurations of asymmetric quantum wells for applications in self-electro-optic effect devices (SEEDs)[2,3] and come to the conclusion that none of them seems to be practical for room-temperature application due to small blue shifts or other reasons.

In reply, I would like to mention that the purpose of the original letter was merely to state that asymmetric quantum wells with blue shift may simplify the design of SEED by getting rid of the requirement for strong excitonic resonance. All calculations for the coupled well were preliminary and were used, as mentioned in the letter, as a simplistic model based on perturbation theory. As a result the maximum blue shift had been overestimated, although by not as much as mentioned in the "Comment." The result in the Ref. 2 was 5.8 meV (not 8 meV). The refined model, using a variational method gives 1.4 meV for the 60:40 band offset ratio. Considering *n-i-p-i* implementation I agree with the comment that there is no experimental evidence of successful reverse biasing of *n-i-p-i* structures.

Therefore, I agree with Leavitt and Little that one may have to consider different structures than those discussed in Ref. 2. It may be stepped quantum wells[3] or strained quantum wells, conceptually similar to the structures discussed in Ref. 2. The SEED device based on the latter has been recently experimentally operated[5,6] at room temperature, proving the validity of ideas expressed in Refs. 2 and 3.

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Response: I agree with Leavitt and Little[1] (hereafter referred to as LL) in their thesis that blue shift bistability is difficult to achieve in practice in asymmetric quantum wells made by grading or coupling in the AlGaAs system. The blue shifts achievable in this system by these methods are indeed small, and in this case the practical utility therefore depends on the size of other phenomena such as excitonic broadening.

The principle of blue shift bistability suggested in the original work of Khurgin[2] and myself[3] does, however, seem to have some utility. LL suggest several other methods of achieving sufficient blue shifts for bistability. All of these have now been demonstrated. One method is to use the "effective" blue shift of symmetric coupled wells or superlattices in which the lowest transition(s) actually red shift with field, but the dominant absorption edge blue shifts because of localization. In the original experimental letter on electroabsorption in symmetric coupled quantum wells,[4] optical bistability was demonstrated (although only briefly noted there because of its obviousness). In current parlance, this would be a blue shift bistability from localization. A similar "effective" blue shift bistability has also been demonstrated from Wannier–Stark localization in a superlattice.[5] The other method suggested by LL, namely, the use of piezoelectric fields in strained [111] quantum wells to asymmetrize the well, was recently demonstrated in InGaAs/GaAs wells on a [111] GaAs substrate,[6] with clear bistability observed.

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