# Optical bistability in self-electro-optic effect devices with asymmetric quantum wells

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It is shown theoretically that optical bistability is possible in a self-electro-optic effect device (SEED) with single asymmetric quantum wells because of the blue shift of the optical absorption edge with applied field possible in such structures (in contrast to the normal red shift in symmetric wells). The concept is a simplification of the scheme of J. Khurgin [Appl. Phys. Lett. **53**, 779 (1988)] (which uses unequal, opposed pairs of asymmetric wells) and shares the potential advantages of lower loss in the transmitting state and less stringent requirements on the exciton absorption peaks.

There has been considerable recent interest in optical switching devices using semiconductor quantum wells. One class of such devices is the self-electro-optic effect device (SEED).[1,2] The SEED relies on the large electroabsorption,[2] the quantum-confined Stark effect (QCSE), seen in quantum wells, which enables us to modulate a light beam by varying the voltage across a diode containing quantum wells, and on the combination of this modulation mechanism with photodetection to make an optically controlled optical device. Many such devices have been proposed. Among the simplest of these are optically bistable devices in which the same diode serves as modulator and photodetector.[3,4] In such a system, when the absorption of the diode is such that it decreases with increasing (reverse bias) voltage (or, equivalently, increases with reducing voltage), bistability can result with a simple circuit consisting only of a series resistor and a fixed bias supply. Increasing incident light gives increasing photocurrent, leading to a larger voltage drop across the series resistor and hence to a larger absorption in the diode and, consequently, an even larger photocurrent; this positive feedback can give switching and bistability.

In existing bistable SEEDs employing either resistors[3,4] or other more sophisticated loads,[5,6] the decrease of absorption with increasing voltage results from excitonic peaks. A typical operating condition is to choose the wavelength to coincide with the exciton peak at zero field. Then with increasing field the excitonic peak moves to longer wavelengths, resulting in a reduced absorption at the operating wavelength. The remaining absorption, which results from interband transitions, is still substantial, but the contrast in absorption coefficients is good enough to make useful devices.

Recently, Khurgin[7] proposed an ingenious bistability scheme, called a "scissors SEED" (SC SEED), that does not rely on this aspect of the excitonic peaks for its operation (although, as in all quantum well electroabsorption, the strong exciton resonances are important in giving strong absorption, and the suppression of exciton field ionization inherent in the QCSE is crucial in maintaining the strong and abrupt absorption edge in the presence of the electric field); this method uses pairs of asymmetric quantum wells. In this letter, another scheme is proposed, which could be called an asymmetric well SEED (AW SEED), that achieves the same result. It can be viewed as a simplification of Khurgin's scheme, requiring only single asymmetric wells, and relies on essentially the same property of asymmetric well electroabsorption.

Asymmetric quantum wells could be made in a variety of ways. Two simple extreme cases are a well in which the alloy concentration (e.g., the Al fraction in GaAlAs) is varied linearly through the well (asymmetric graded well) or by making two closely coupled wells of unequal thickness (we will treat this structure as one "composite" well, an asymmetric coupled well). The QCSE electroabsorption in graded[8] and coupled wells (both symmetric[9] and asymmetric[10]) has been studied. Without field, the wave function of the lowest energy level is displaced towards the lower gap region of the well in the graded case and into the thicker well layer in the asymmetric coupled case. The amount of the shift is, however, different for electrons and holes; heavy holes are particularly easily perturbed because of their large mass and resulting small confinement energies, and will usually shift more. Hence, at zero field there is a net average separation of electrons and holes (and, consequently, a net polarization of the pair), and the situation is rather analogous to the effect of prebiasing an otherwise symmetric well with a static field. If we apply a field so as to reduce the separation of electron and hole, the resulting QCSE in the asymmetric well will start out as a blue shift of the lowest electron–hole transition, rather than the red shift that always results with symmetric wells. Of course, with sufficient field in the asymmetric case a red shift will again generally result.

A key point of both Khurgin's[7] and the present proposal is that the blue shift with field allows a decreasing absorption with increasing field regardless of the exciton peaks. One need only operate in the region near the band gap at zero applied field, where the absorption decreases (and possibly essentially disappears altogether) with field because of this blue shift. Another important point is that the remaining absorption in the high transmitting state can consequently be very low. There is some trade-off in that the peak absorption coefficient without field is lower than it would otherwise be because the overlap of electron and hole is reduced by their intrinsic separation. We may, however, hope that the difference between the absorption coefficients with and without field is still large, because it is this parameter that sets the contrast ratio of the device for a given total thickness of absorbing material. Hence we might obtain a device with good contrast ratio and low loss in the highly transmitting state. The precise nature of the exciton absorption peaks is also less crucial than in symmetric well bistability, although it must be emphasized that suppression of exciton field ionization is still crucial to avoid broadening of the absorption edge with field, which would degrade the device performance.

Figure 1 shows example band structures for the AW SEED for the graded and coupled asymmetric wells, and also the required sense of the asymmetry relative to the bias field direction to obtain the bistability. It is common to operate SEEDs with the quantum wells in the intrinsic (*i*) region of a *p-i-n* diode operated primarily under reverse bias[3,4] (or at least using the diode's built-in field[11]); the required polarity of the diode structure is also shown in Fig. 1. The assumption is implicit in Fig. 1 that the hole is heavier than the electron, and the hole barrier is not too low, as is usually the case for heavy holes in direct-gap, type-I, III-V materials systems (e.g., GaAs/AlGaAs and InGaAs/InP). This is not a necessary restriction; the most general statement of the required sense of the asymmetry relative to the field direction is that the asymmetry is such that the polarization of the electron and hole resulting from the asymmetry alone is opposite to that which would be induced by the field alone. Only one quantum well is sketched in each case; as with other quantum well modulator or SEED structures, many wells may be used as desired.

The electrical circuits for AW SEED optical bistability could be implemented in the same ways as have been exploited for conventional symmetric rectangular wells. For example, we would utilize a series resistor and reverse bias supply (resistor-biased SEED),[3,4] or we could substitute another photodiode for the resistor making a diode-biased SEED.[4,5] We could also connect two such asymmetric quantum well diodes in series with a reverse bias supply to make a "symmetric," asymmetric well SEED (SAW SEED), by analogy with the symmetric SEED.[6] The principal difference in operation compared to previous symmetric well SEEDs would be in the choice of operating wavelength or photon energy; the photon energy would be chosen to be below the band-edge absorption peak in its most blue shifted state. In operation, we would typically choose the circuit design so that the device switched between a low voltage, where the absorption is high, and a voltage corresponding to the maximum blue shift, where the absorption is lowest.

As an illustration of the principle, Fig. 2 shows an approximate plot of relative photocurrent versus voltage for an asymmetric coupled well diode for fixed incident light power. In the reverse bias region, this is essentially the same as relative absorption, provided that the quantum efficiency of the diode is good. This plot is based on an extrapolation of Khurgin's calculation (as shown in Figs. 1 and 2 of Ref. 7) in which an attempt is made to remove the effect of the second asymmetric well (actually the "positively polarized QWI" in Khurgin's notation[7]). Hence Fig. 2 is indicative of the kind of behavior that might be expected for asymmetric pairs consisting of 32 and 15 Å GaAs wells separated by a 15 Å AlGaAs barrier (and also separated by much thicker barriers from any adjacent asymmetric pairs), embedded in a 1 $\mu$m intrinsic region and operated at an appropriate wavelength (estimated by Khurgin[7] to be 771 nm); an inhomogeneous broadening of ~ 10 meV was included by Khurgin.[7] Such calculations can only be regarded as indicative of the actual behavior because excitons cannot readily be included in such calculations (the exciton wave functions would have to be evaluated numerically for each field and have never been evaluated even at zero field for such structures to my knowledge). Also indicated is the form of the characteristic as the diode is taken into forward bias; the drop-off in cur-

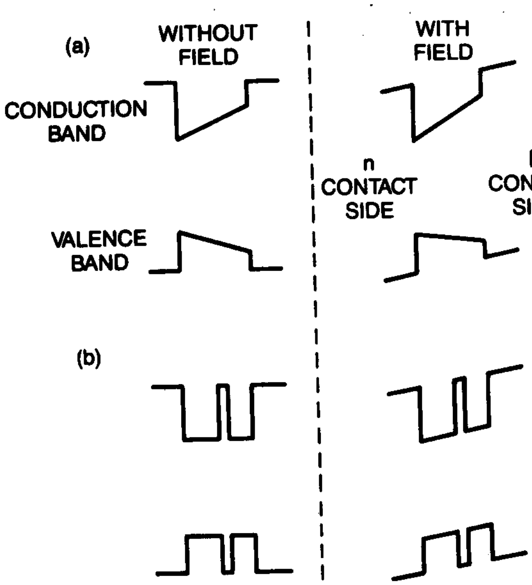

FIG. 1. Sketch of asymmetric quantum well potential structures both with and without field, showing the relative sense of bias field and asymmetry as required for bistability and the polarity of contacts on a *p-i-n* diode required to achieve this under reverse bias or with the built-in field: (a) graded gap asymmetric well; (b) coupled asymmetric well.

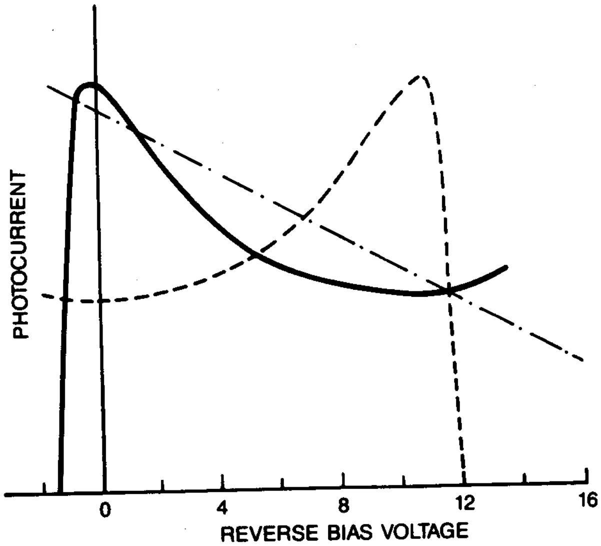

FIG. 2. Representative photocurrent vs reverse bias voltage curve (solid line) for an asymmetric well diode. Dot-dashed line: load line with a resistive load. Dashed line: load line with another similar diode as the load.

rent in forward bias results from reduced quantum efficiency, not reduced absorption, and is a general property of photodiodes. Figure 2 also shows "load lines" corresponding to a resistive load with a 24 V power supply (dot-dashed) and to SAW SEED operation (dashed line) (i.e., using another similar diode as the "load") with a 10.5 V power supply. In both cases, bistability is clearly possible, as evidenced by the triple intersections of the lines.

The existence of the region of decreasing (photo) current with increasing voltage could also of course be used to make a negative resistance optoelectronic oscillator, as has been demonstrated with symmetric well SEEDs.[4] There will also be a spectral region at somewhat higher photon energies where the absorption will increase with increasing reverse bias voltage as the exciton peak moves back up to this photon energy. This region could be used for self-linearized modulation or optical level shifting.[4]

In conclusion, it is shown theoretically that self-electro-optic effect devices could show optical bistability and other functions based on the blue shift of the optical absorption edge that can occur in appropriately biased, asymmetric quantum wells with applied electric fields perpendicular to the quantum wells. This asymmetric well SEED is a simplification of the "scissors SEED" scheme proposed by Khurgin[7] in that it does not require pairs of opposed unequal asymmetric wells, and shares with it the potential advantages of lower loss in the transmitting state of the device and less stringent requirements on the exciton absorption peak form for good optical bistability. A full consideration of the actual advantages of such a scheme must await practical demonstrations and comparisons because of the difficulty of realistically simulating excitonic effects and broadening. It does, however, represent another interesting option with qualitatively different attributes for the quantum-mechanical engineering of optical devices.

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