LOW FIELD ELECTROABSORPTION AND SELF-BIASED SELF-ELECTROOPTIC EFFECT DEVICE USING SLIGHTLY ASYMMETRIC COUPLED QUANTUM WELLS

K. W. Goossen, J. E. Cunningham, D. A. B. Miller, W. Y. Jan, A. L. Lentine*, A. M. Fox, and N. K. Ailawadi

AT&T Bell Laboratories,
Holmdel, NJ 07733,
USA

*AT&T Bell Laboratories,
Naperville, IL 60566,
USA

Quantum wells and related layered semiconductor structures show strong electroabsorption that can be applied to make optical switches and modulators [1]. Many different structures are possible, each with different electroabsorption characteristics. In addition to conventional rectangular wells, structures investigated include coupled wells, both symmetric [2] and asymmetric [3], graded wells [4], low-barrier wells [5], and superlattices [6]. The optimum structure depends to some extent on the application. Here we describe a novel, slightly asymmetric coupled well structure designed to operate at very low fields. The resulting operating fields are so low that we can make a self-biased symmetric self-electrooptic effect device(S-SEED); this is an opto-electronic switching device without a power supply [7], and this is the first demonstration of such a device suitable for use in two-dimensional arrays.

For S-SEED operation, we want to use the lowest possible electric field so that we can minimize the switching energies [8]. The optical switching energy is directly proportional to the field change required in switching; this is because all of the charge involved in charging and discharging the internal capacitance, C, of the device is photogenerated by absorption of the incoming light. The charge required per unit area (and hence the required absorbed optical energy per unit area) is proportional to the field in the device. In addition, it is obviously important to minimize the operating voltage swing, V, to reduce the electrical energy, since this energy is about $(1/2)\,CV^2$ for electrically driven modulators.

One problem with trying to design a modulator that is very sensitive to field is that, in the usual p-i-n structure, even in moderate forward bias we never get to zero field (flat-band) in the structure. In operation of the S-SEED, and in operating a modulator without incurring a large forward current, the device will only typically be forward biased to about 1V. This leaves about 5000 V/cm field across the quantum wells for a 1 μm thick intrinsic region and a 1.5 eV bandgap energy (as in GaAs). If we design a symmetric structure such as a superlattice or coupled quantum well to be very sensitive at low field, we may not be able to take advantage of this because in operation we cannot reduce the field sufficiently.

The solution we attempt here is to make a slightly asymmetric structure. In this case we can use the asymmetry effectively to prebias the structure to try to compensate for the unavoidable minimum field. At zero or very low fields, the lowest electron state is predominantly in the thicker well (see Fig. 1). Beyond some field, this electron becomes predominantly in the thinner well. The basic operation is then otherwise similar to that of a coupled well [2]. The overlap of electron and hole in the lowest states is strongly reduced with field because the electron and hole are pulled into opposite wells; this is sometimes referred to as an effective "blue shift" because the oscillator strength lost from the lowest transition is largely transferred to higher energy transitions. We can also view the slightly asymmetric coupled well in terms of resonant coupling. Below a certain critical field, the lowest electron state is substantially in the left well. At a finite field, the left well and right well states resonantly couple. Beyond this field, the lowest electron state is substantially in the right well. Such behavior, including excitonic effects, has recently been explained in detail [9]. Asymmetrizing the structure serves to move this critical field away from zero to the desired finite value. These two descriptions are equivalent.

In Fig. 2, we show experimental results for a structure with 63 angstrom and 58 angstrom wells separated by a 14 angstrom barrier, with each such period separated by a 35 angstrom barrier. An intrinsic ("i") region approximately 1 μm thick containing these coupled wells is contained in a p-i-n structure as usual. The spectra clearly show the effective blue shift or loss of overlap of the lowest transition. The structure is clearly useful for voltages between 1V forward bias and 1-4 V reverse bias. Note in particular that there is a substantial change in absorption between +1 V and -1 V. This is quite exceptional compared to conventional quantum wells. This design therefore has given us a modulator that is indeed very effective at low fields. (In contrast to the conventional quantum well, however, there is little further improvement in contrast with further increase in voltage past 4 V.)

By connecting two such p-i-n diodes in series, as shown in Fig. 3, we can make a S-SEED without an electrical power supply. This device behaves like any other S-SEED, showing optical bistability in the ratio of the two light beam powers shining on the diodes. (The bistability arises from the decrease in photocurrent with increasing reverse bias, a negative differential conductivity.) In the present case, there is, however, no need for a voltage supply. The stable states correspond to one diode in forward bias (about +1 V) and the other in reverse bias (about -1 V). Because the device shows considerable change in absorption between +1 and -1 V, there is no need for any other supply voltage. The optical input/output characteristic is also shown in Fig. 3 for a wavelength of about 835 nm.

The ability to make two-dimensional arrays of self-biased devices should enable us (i) to avoid the space taken by power supply rails, (ii) to avoid having to define the position and size of the array until after fabrication, potentially increasing the yield of usable arrays, (iii) to eliminate any electrical crosstalk between devices, and (iv) to avoid one failed device from shorting the rest of the array.

In principle, this structure should also have an enhanced exciton near flat band. When the electron and hole are substantially in the same well, the exciton should be relatively strongly bound because they are close. This should lead to a smaller exciton, with correspondingly strong absorption. As the electron is pulled into the opposite well by the field, the exciton should get weaker and larger, further reducing the absorption. It is not clear in practice, however, whether we are yet getting any significant benefit from this in the actual device.

In conclusion, we have demonstrated that slightly asymmetric coupled quantum wells allow us to make modulators that can operate at very low fields and voltages while still allowing us to handle the finite field always present in the diode structure. This should allow low-energy optical modulators and switches, and has enabled us to demonstrate a self-biased S-SEED suitable for parallel arrays without an electrical power supply.

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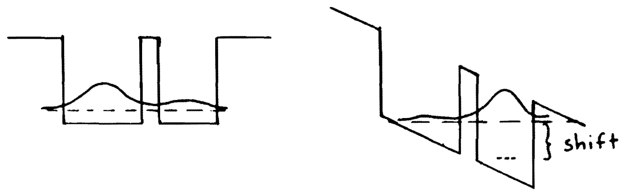

Fig. 1. Electron in a slightly asymmetric coupled quantum well without and with field.

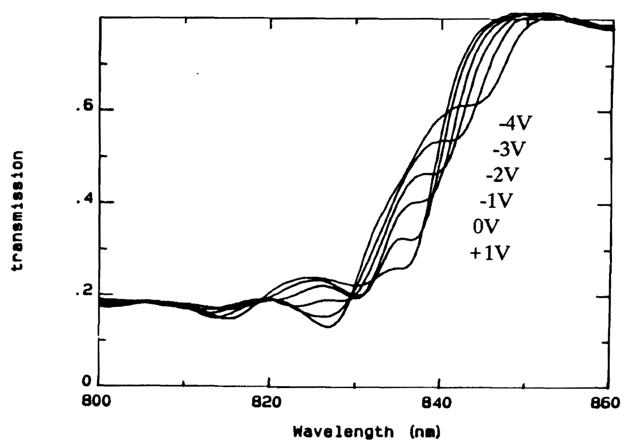

Fig. 2. Electroabsorption in the slightly asymmetric coupled quantum well sample.

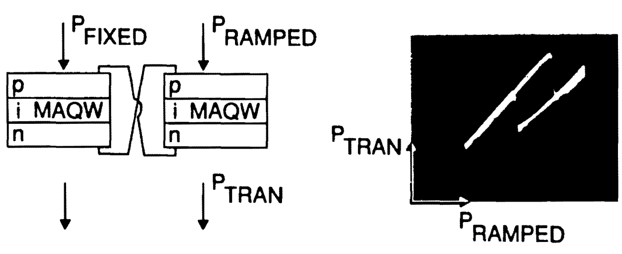

Fig. 3. Schematic and optical input/output characteristic for the self-biased SEED.