Invited Paper

Electric field dependence of optical absorption in quantum well structures: physics and applications

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Abstract

Electroabsorption near the optical absorption edge of quantum well materials is interesting both for physics and applications. We briefly summarize the physical mechanisms involved (e.g. the quantum-confined Stark effect) and the applications to optical modulators and switching devices.

Quantum wells have recently become increasingly interesting for their optical properties, especially those associated with the remarkable excitonic absorption resonances near the optical absorption edge. One particular area of interest is in the changes in optical properties that can be induced by static electric fields; this is interesting both for the physical mechanisms involved, some of which are unique to quantum wells, and also the possibility of practical applications. The activity in both physics and applications of these other quantum well optical effects has been documented in a number of recent review articles[1-4] and in some extensive journal articles, and we will not attempt to duplicate these here. Instead, we will present only a brief summary of some key topics and refer the reader to other longer articles for more detailed information.

Because the layered structure of quantum wells quantum-confines the carriers, the optical absorption spectrum breaks up into a series of steps. In addition, however, sharp peaks (the exciton absorption resonances) appear at the edges of the steps. These peaks are much stronger than those observed in the corresponding bulk materials, and can consequently be observed at room temperature. This strength is a direct consequence of the confinement (see e.g. Ref. 5 for a discussion). These peaks also show a number of interesting nonlinear optical effects associated with absorption saturation.[4,5] As for changes in optical properties associated with electric fields, there are obviously two distinct directions in which the electric field can be applied, i.e., parallel to the layers and perpendicular to the layers. For fields parallel to the layers, the resulting changes in the optical absorption near to the band gap energy are qualitatively similar to those seen in bulk direct-gap semiconductors at low temperature; the exciton peaks broaden and disappear with field because the exciton is rapidly field-ionized, leading to a life-time broadening of the resonance.[6] The fact that this phenomenon can be clearly observed in quantum wells at room temperature has made it feasible to perform very high speed tests of the speed of this electroabsorption, with response < 500 fs observed,[7] the fastest electroabsorption ever reported to our knowledge. For perpendicular field, the behavior is quite different; the peaks are not strongly broadened with field, and the lowest peaks shift to lower energy by substantial amounts. This effect can be understood through a mechanism called the quantum-confined Stark effect (QCSE).[6,8] In this case, the field ionization is suppressed by the walls of the quantum well, and very large Stark shifts of the exciton are possible without large broadening. In the limit where the excitonic effects are neglected, the resulting shifts reduce to the sum of the shifts of the single particle electron and hole shifts resulting from the skewing of the quantum well by the applied field. It is, however, important to remember that it is the persistence of the exciton resonance that gives the QCSE much of its practical interest and that enables us to resolve the shift at all.

As the peaks shift, they lose some strength because the overlap of electron and hole is reduced as they are pulled apart by the field. Both the shifts[6,8] and the overlap[9] are in good agreement with theory. The strength lost by the allowed transitions is picked up by the appearance of forbidden transitions,[9] which leads to the sum rules for the quantum well electroabsorption.[9] The forbidden transitions are also important in linking the QCSE to bulk electroabsorption;[10] in the simplifying approximation in which the excitonic effects are neglected (an approximation that we can refer to as the quantum-confined Franz-Keldysh approximation), it can be shown that the QCSE is the quantum-confined limit of the Franz-Keldysh electroabsorption of bulk semiconductors.

The most obvious device application of the QCSE is to optical modulators. The changes in absorption are sufficiently large that useful modulators can be made that are only microns thick. These are usually grown in a p-i-n diode structure with the quantum wells in the intrinsic (i) region so that the field can be applied by reverse biasing this diode.[11] The light can either be propagated perpendicular to the layers or in a waveguide structure parallel to the layers, and modulation can be observed with a variety of materials systems in the near infrared spectral region (see Refs. 2, 3 and 9 for summaries of modulator work). These modulators are fast (e.g. 100 ps) with speed currently limited by simple resistive/capacitive considerations, and require drive voltages between 1 and 20V, depending on the thickness of the intrinsic region. There are many opportunities for integration of modulators with laser diodes, epitaxial mirrors and other structures. The small active volume and moderate fields ($\sim 5 \times 10^4$ to 10^5 V/cm) required in QCSE modulators makes them very attractive from an energy stand point, and they appear to be one of the lowest energy ways of getting optical information out of a system, given an appropriate external light source such as a laser diode. Although the laser diode may consume considerably more power, one diode may be used to illuminate many modulators.

Another class of device that can be built using the QCSE is the self electro-optic effect device (SEED).[12-15] The SEED incorporates both a QCSE modulator and photodetector, so that a light beam shining on the photodetector may change the voltage across the modulator, hence making an optically controlled device with an optical output. The simplest such devices use the quantum well p-i-n diode itself as the only photodetector, giving for example optical bistability with a load resistor in the circuit.[12] Many other configurations are possible, including oscillators,[13] linearized modulators,[13] and spatial light modulators.[14] The opportunities become particularly varied when other photodectors such as photodiodes[13-15] or phototransistors[14] are introduced into the system. The SEED approach becomes energetically very attractive when the resulting device can be very intimately integrated so that no stray capacitance results from this "hybrid" approach. The first such integrated devices have now been demonstrated.[15]

In conclusion, the electroabsorption in quantum wells offers physical mechanisms that are unique to such quantum-confined systems and that are applicable to novel and unusual opto-electronic devices that operate under practical and attractive conditions.

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