Optical polarization effects in semiconductor/vacuum nanostructures

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Strong polarization effects in optical absorption and luminescence should occur in semiconductor/vacuum nanostructures, e.g., in quantum wires at the surface of a semiconductor with a planar quantum well.

Semiconductor nanostructures (superlattices and quantum wells) in which neighboring layers differ markedly in permittivity are extremely interesting for possible applications in optoelectronics. Such nanostructures have been the subject of extremely detailed theoretical work. For example, Keldysh[1] has shown that the Coulomb attraction between electrons and holes in such structures is intensified by an interaction with image charges. There is accordingly a significant strengthening of exciton effects. In addition, the circumstance that the spatial distribution of the electric field in such structures depends on the angle which the layers make with the electric field vector means that there should be some clearly expressed optical polarization effects.[2,3]

These effects have been extremely weak in the semiconductor/semiconductor nanostructures which have been studied experimentally to date (e.g., GaAs/AlGaAs quantum wells and superlattices), because the permittivities of the neighboring layers in these structures have been nearly the same. To the best of our knowledge, effects of this sort have been seen experimentally only in naturally grown superlattices based on intercalated compounds of lead diiodide.[4]

Electron nanolithography now makes it possible to fabricate so-called quantum wires and quantum dots (vacuum/semiconductor nanostructures) on the surfaces of heterostructures. In this letter we wish to show that such structures should have some obvious and anisotropic polarization properties. These effects stem from the nonuniform distribution of the electric field in vacuum/semiconductor structures when the electric field has components normal to the interfaces. We show that this circumstance should give rise to 1) a clear dependence of the absorption coefficient of quantum wires on the polarization of the light, 2) a linear polarization of the luminescence of excitons trapped in quantum wires, and 3) an anisotropy in such exciton effects as the steady-state or optical Stark effect.

In the nanostructures which we discuss in this letter, wires of height h and width

w are fabricated on the surface of a semiconductor with a quantum well. These wires are nearly rectangular in cross section and are separated by a distance $l \gg h, w$ (see the inset in Fig. 1). They are surrounded on three sides by vacuum. The dimensions w and h are usually on the order of 10–100 nm. The thickness of the quantum well, d, is usually smaller (on the order of 5 nm); the vertical position of the well in the quantum wire, z, can vary.

Because of the large difference between the dielectric constants of a semiconductor ($\varepsilon \approx 10$) and vacuum, the electric field distribution in such structures depends strongly on the relative orientation of the wire and the electric field. For example, a field which is uniform far from the structure and which is parallel to the quantum wires remains uniform inside the structure. If the field is instead perpendicular to the wires, it becomes extremely nonuniform in the structure (Fig. 1).

The amplitude of the absorption or luminescence is proportional to the product of the dipole matrix element of the interband optical transition and the local electric field of the corresponding electromagnetic mode. The quantum confinement of free carriers and excitons within a wire effectively turns these carriers and excitons into "sensors" of the local electric fields. Since the local fields are quite different for light polarized along and across a wire, the absorption and the luminescence—the probabilities for which are proportional to the square of the corresponding amplitude—become dependent on the polarization.

To calculate the polarization properties of the absorption and luminescence, we must therefore first find the electric field distribution in the nanostructure. Here we make use of the fact that the length scales of the system are short in comparison with the wavelength of the light ($w,h \ll \lambda$), so in finding the natural modes of the electromagnetic field in a nanostructure we can essentially limit the discussion to the electrostatic approximation. In the case of a quantum wire the problem reduces to the 2D Poisson equation and can easily be solved by numerical methods. Figure 1 shows a representative electric field distribution for the case in which E is perpendicular to a wire with $h=2w$ and $\varepsilon=12$.

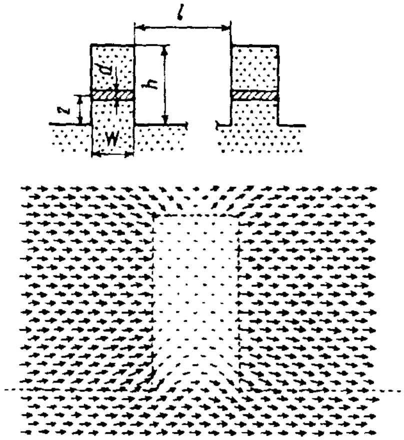

FIG. 1. Distribution of the electric field $E_\perp$ near a quantum wire with $h=2w$. The inset at the top is a schematic cross section of the structure (the quantum well is the hatched area).

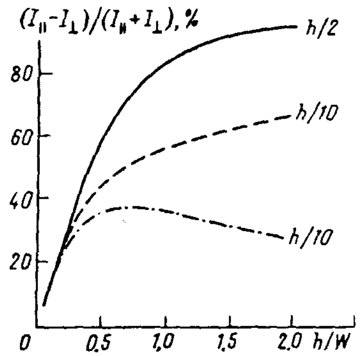

FIG. 2. Degree of linear polarization, σ, versus the wire width w for three positions of the quantum well in the wire. *1*—$z=h/2$; *2*—$h/10$; *3*—$-h/10$.

If, for simplicity, we ignore the spatial structure of the envelope of the wave function of the carriers or excitons trapped in the quantum wire (this procedure can be implemented easily by taking an appropriate average), then we can use the following simple formula to calculate the degree of polarization of the absorption or luminescence:

$$\sigma=\frac{I_{\parallel}-I_{\perp}}{I_{\parallel}+I_{\perp}}=\frac{E_{\parallel}^{2}-E_{6}^{2}\perp}{E_{\parallel}^{2}+E_{\perp}^{2}}. \tag{1}$$

Here $E_{\parallel}$ and $E_{\perp}$ are the electric fields (in the carrier trapping region) of electromagnetic modes whose polarizations are different and whose amplitudes are identical (identical far from the trapping region). The averaging over the electron–hole wave function should evidently lead to some decrease in σ, since $E_{\perp}$ varies to a lesser extent along the edges of the carrier trapping region, as can be seen in Fig. 1.

Figure 2 shows results calculated on σ for various positions (z) of the quantum well in the wire and for various ratios of the height and width of the wire. We see that the degree of polarization reaches a maximum when the well is in the middle of the wire ($z\approx h/2$). The polarization should increase with increasing h/w. We believe that this simple effect can explain the onset of a substantial number of the polarization effects seen in some recent experiments[5,6] with semiconductor/vacuum quantum wires. We wish to stress that this effect is not related to a diffraction-grating effect.[7] It occurs both for individual quantum wires and for randomly distributed wires, if the distance between wires satisfies $l \gg w,h$.

A corresponding orientational dependence should arise for all optical effects (both linear and nonlinear) involving carriers trapped in semiconductor/vacuum quantum wells, e.g., for the static and optical exciton Stark effects.

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