Screening of external electric field by photoinduced carriers in Bragg multiple quantum wells

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We study screening of external bias in a multiple-quantum-well structure by optically injected excess carriers. By solving self-consistently the Poisson equation and the equations for the electron and hole densities, we analyze how realization of different screening regimes depends on the applied bias, excitation power, temperature, and the parameters of the structure. Our calculations show the feasibility of using the proposed setup as an optically controlled electric switch in photonic circuits. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2001743]

Interband optical transitions and excitonic effects in multiple quantum wells (MQW) have been exploited in a number of existing and proposed semiconductor photonic devices. The functionality of these structures as optical switches, modulators, etc. is achieved through control of exciton frequencies in such structures via the quantum confined Stark effect.[1] Ultrafast applications, however, require an all-optical control, which can be achieved by combining the external electric field with the photogeneration of carriers that screen this field. The effectiveness of screening, and hence, the strength of the electric field across the active element of the structure, is controlled by the intensity of pumping radiation responsible for the photogeneration of carriers. This idea, for instance, was realized in Ref. 2 for an ultrafast all-optical switch with short-period multiple quantum wells as a working structure, as well as in a number of other devices.

In this Letter we study a possibility of using photogenerated carriers for optical control of the spectra of Bragg MQWs. These structures consist of periodically positioned quantum wells with a period satisfying the Bragg resonance condition at the frequency of the exciton radiation.[3,4] The reflection spectra of such structures are characterized by the presence of a strong and wide reflection band and a sharp change of reflectivity in the vicinity of its boundaries, which make them prospective materials for optical switches, modulators, and other optical logical devices.

There are several important distinctions between our approach and previously studied situations, in particular, Ref. 2. First, we consider a spatially uniform excitation of a relatively large area of the sample. Therefore, the diffusion of voltage considered in Ref. 2 as the main relaxation mechanism is not effective here. In our situation, the capture of the carriers by quantum wells should be taken into account, and we have to consider screening by both mobile and confined electrons and holes. Second, we assume that our structure is electrically isolated from the surrounding, so that there is no net current across the boundaries of the structure. Our main objective, in this case, is studying the distribution of the electric field throughout the structure, which is important for simulating optical spectra of the structure under consideration.

In the following, we consider the optical excitation of the carriers above the band gap of the barrier material, i.e., to the continuous spectrum of MQW. Since we assume that the excitation is uniform in the plane of the structure, and that the structure is electrically isolated, there is no in-plane diffusion and drift. Thus, the relaxation processes involved include the intraband relaxation of the carriers, the carrier capture by quantum wells, carrier relaxation inside of the quantum wells, and finally, recombination processes.

According to their characteristic time scales, the evolution of the carrier distribution after excitations can be separated into three stages: (i) Intrasubband scattering leads to the formation of quasiequilibrium carrier distributions of barrier and quantum well electrons and holes. The characteristic times for these processes range from 40 to 300 fs.[5,6] (ii) The distributions of carriers that belong to the three-dimensional spectrum and those confined in quantum wells, although having regular quasiequilibrium form, are not necessarily in equilibrium with each other, i.e., are characterized by different effective chemical potentials and temperatures.[7] They evolve towards a common intraband equilibrium by means of carrier capture by quantum wells with characteristic time scales in the range from 100 fs to 2 ps.[5,8] (iii) The relaxation of these intraband distributions towards global equilibrium is determined by various recombination processes and is characterized by times of the order of hundreds of picoseconds or greater.[9]

In what follows we limit ourselves to considering the regime where the carrier distributions in quantum wells and in a three-dimensional spectrum have come to equilibrium with each other, and therefore, can be characterized by the common temperature and chemical potential, but recombination processes have not yet occurred.

Our description of MQW screening is based on the self-consistent solution of the Poisson equation and the equations for the electron and hole densities. The quasiequilibrium distribution of carriers implies the constant values of the electrochemical potentials throughout the structure,

$$\zeta_e = E_F^e - e\varphi(z) = \mathrm{const}_e, \quad \zeta_h = E_F^h - e\varphi(z) = \mathrm{const}_h, \quad (1)$$

where $\zeta_{e,h}$ are the electrochemical potentials for electrons and holes, $E_F^{e,h}$ are the corresponding Fermi energies, and $e\varphi(z)$ is the potential energy of carriers in the self-consistent potential $\varphi(z)$, which varies only in the direction perpendicular to the quantum wells. The densities of mobile (i.e., those

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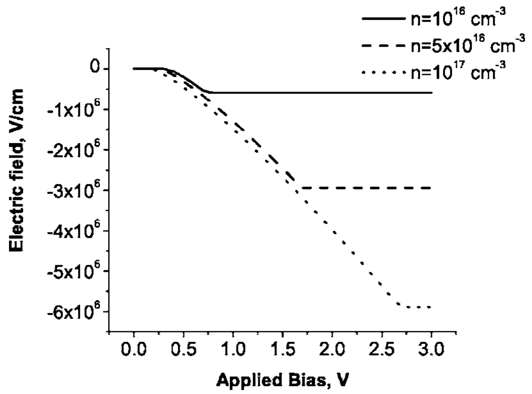

FIG. 1. Electric field at the end of the structure vs applied bias for different carrier concentrations, $N=10$. (Note that the slope of the lines corresponding to the regimes of low bias and saturated screening is very small and is hardly visible in the graph.)

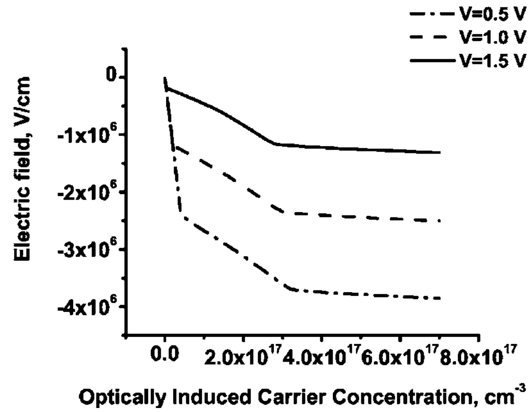

FIG. 2. Electric field at the end of the structure vs optically induced carrier concentration for a different applied bias, $N=10$.

that belong to the three-dimensional spectrum) electrons and holes are given by

$$n_m(z) = 2\left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} F_{1/2}\{[\zeta_e - E_c + e\varphi(z)]/k_B T\}, \qquad (2)$$

$$p_m(z) = 2\left(\frac{m_h k_B T}{2\pi\hbar^2}\right)^{3/2} F_{1/2}\{[E_v - \zeta_h - e\varphi(z)]/k_B T\}. \qquad (3)$$

In these equations, $m_{e,h}$ are electron- and heavy-hole effective masses, k_B is the Boltzmann constant, T is the temperature, $\hbar$ is the Plank constant, whereas $E_{c,v}$ denote the conduction and valence band edges of the barrier material. $F_{1/2}(\eta)$ is the Fermi integral-1/2: $F_{1/2}(\eta) = (2/\sqrt{\pi})\int_0^\infty dx\sqrt{x}/[\exp(x-\eta)+1]$. The concentrations for the carriers bound in the quantum wells are given by

$$n_{qw}(z) = \frac{m_e k_B T}{\pi\hbar^2}\sum_{j=1}^{N} |\psi_0^e(z-z_j)|^2 \times \ln\{1 + \exp[(\zeta_e - E_c + E_0^e + e\varphi(z))/k_B T]\}, \qquad (4)$$

$$p_{qw}(z) = \frac{m_h k_B T}{\pi\hbar^2}\sum_{j=1}^{N} |\psi_0^h(z-z_j)|^2 \times \ln\{1 + \exp[(E_v + E_0^h - \zeta_h - e\varphi(z))/k_B T]\}, \qquad (5)$$

where $\psi_0^{e,h}(z-z_j)$ is the z-dependent part of the wave function for electrons/holes localized in the jth quantum well, whereas $E_0^{e,h}$ is the corresponding confinement energy (we assume that each quantum well has only one subband). When considering densities of the carriers confined in quantum wells, we neglect a quantum mechanical shift of electron and hole levels due to the Stark effect, but take into account that different wells feel different electrostatic potentials, which change the relative positions of the bottoms of conductance bands for different wells. In the density functional formulation we would have to solve the Schrödinger equation for the carriers bound in quantum wells. However, since we are not interested in the details of the charge distribution inside the wells, and since the width of the wells is much smaller than the interwell spacing, we can approximate the density of charges bound to a quantum well as an infinitely thin charged plane, i.e., $|\psi_0^{e,h}(z-z_j)|^2 = \delta(z-z_j)$. The potential $\varphi(z)$ involved in the expressions for the charge densities should be calculated self-consistently by solving the Poisson equation,

$$\frac{d^2\varphi(z)}{dz^2} = -\frac{4\pi e}{\varepsilon}[p_m(z) - n_m(z) + p_{qw}(z) - n_{qw}(z)], \qquad (6)$$

with the boundary conditions $\varphi(0)=-V/2$, $\varphi(D)=-V/2$, where $z=0$ and $z=D$ are the end points of the MQW structure, and V is the applied bias.

Because our structure is electrically insulated, the position of electron and hole Fermi levels is fixed not by the boundary conditions at infinity (as it would have been in typical problems for a charge distribution in semiconductor heterojunctions), but by the carrier densities, which can be related to the intensity of photoexcitation. Therefore, we supplement Eqs. (2)–(6) by the normalization conditions

$$\int_0^D [n_m(z) + n_{qw}(z)]dz = \int_0^D [p_m(z) + p_{qw}(z)]dz = Dn_0, \qquad (7)$$

where n_0 is the average carrier density, which is the same for electrons and holes due to the overall electrical neutrality.

We solved Eqs. (2)–(7) numerically, paying special attention to the dependence of the electric field induced at the ends of MQW structure on the applied potential difference and the average density of carriers induced by photoexcitation, n_0. The screening causes the electric field to change in every part of the structure: The electric field deep inside of MQW decreases and optimally turns to zero, whereas the field near the ends of MQW, where the potential varies significantly, increases. Therefore, the electric field at the end of the structure appears to be very indicative of the carriers distribution. The results are presented in Figs. 1 and 2, respectively. One can immediately notice the existence of several regimes of screening: (1) Low-bias regime, in which all carriers are confined in quantum wells, and screening can be described in terms of screening by a set of charged planes. The screening by confined carriers is somewhat surprising. It results from the changes in the population of wells due to the presence of the potential. (2) Moderate-bias regime sets in, when increased bias causes some of the carriers to leave quantum wells, which results in a significant enhancement of screening. (3) Saturated screening, corresponding to an applied bias, which is so high that the amount of charge present is not sufficient to screen the field. In this case, the structure

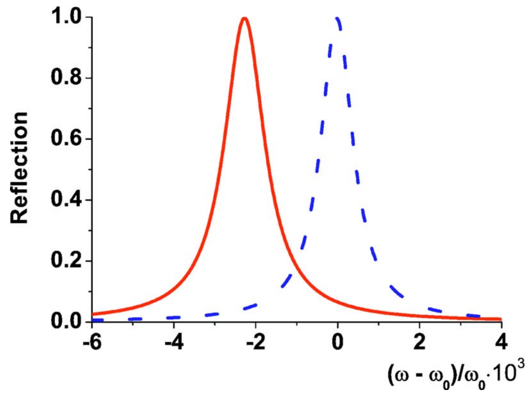

FIG. 3. (Color online) The reflection spectra of the structure before (solid line) and after (dashed line) the injection of the carriers. The structure is assumed to satisfy the Bragg condition at the exciton frequency with no external field, $\omega_0=1.491$ eV. The carrier concentration is $n_0=10^{17}$ cm^{-3}.

can be modeled as a parallel-plate capacitor with surface charge $\sigma=n_0 D$, which allows for a simple analytic fit: $E_{\text{ext}}=-V/D-4\pi e n_0 D/\varepsilon$.

The dependence of the induced electric field on the average density of carriers for fixed bias is shown in Fig. 2. It is seen that for the parameters chosen, the sensitivity of screening to the increase of the pumping strength is significantly reduced for the carrier concentrations above 3×10^{17} cm^{-3}. In this regime, the amount of mobile carriers is sufficient for the efficient screening of the applied bias without any participation of the carriers in quantum wells. For lower carrier concentrations the screening is assisted by the confined carriers, whose mobility in the direction of the field is limited, which results in less efficient screening and stronger dependence on the average carrier concentration.

The results presented in Figs. 1 and 2 were obtained for zero temperature. The analysis for finite temperature was also carried out; however, for the potential differences at hand in all the regimes we have a condition $eV \ll k_B T$, which reduces the role of finite temperature to only smoothing the sharp features of the curves. The other parameters used in the calculations are typical for GaAs/AlGaAs heterostructures: spacing between the quantum wells and between the left/right end of the structure and the first/last quantum well is $a=4.13\times 10^{-5}$ cm, electron and hole effective masses are $m_c=0.0665 m_0$ and $m_h=0.45 m_0$, respectively, $\epsilon_0=12.4$ is the dielectric constant. The separation between the conduction (valence) band edge and the bottom of the quantum well subband in an unbiased structure was taken to be $E_c-E_0^e=0.193$ eV ($E_0^h-E_v=0.162$ eV).

To illustrate the effect of the screening of the field we calculated the reflection spectra of the structure before and after the injection of the carriers (Fig. 3). The screening of the field restores the exciton frequencies shifted due to the quantum confined Stark effect. Thus, the exciton-induced peculiarity in the reflection spectrum returns to its position in the structure without an applied field.

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