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Effects of crossed electric and magnetic fields on the interband optical absorption spectra of variably spaced semiconductor superlattices

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ABSTRACT

The interband optical absorption spectra of a GaAs–$Ga_{1-x}Al_xAs$ variably spaced semiconductor superlattice under crossed in-plane magnetic and growth-direction applied electric fields are theoretically investigated. The electronic structure, transition strengths and interband absorption coefficients are analyzed within the weak and strong magnetic-field regimes. A dramatic quenching of the absorption coefficient is observed, in the weak magnetic-field regime, as the applied electric field is increased, in good agreement with previous experimental measurements performed in a similar system under growth-direction applied electric fields. A decrease of the resonant tunneling in the superlattice is also theoretically obtained in the strong magnetic-field regime. Moreover, in this case, we found an interband absorption coefficient weakly dependent on the applied electric field. Present theoretical results suggest that an in-plane magnetic field may be used to tune the optical properties of variably spaced semiconductor superlattices, with possible future applications in solar cells and magneto-optical devices.

1. Introduction

Over the last decades, a considerable amount of theoretical and experimental studies has been carried out on the electronic and optical properties of multiple quantum well (MQW) heterostructures. The central motivation of such studies has been the possible applications of these systems in optoelectronic devices. Growth techniques, such as molecular-beam epitaxy and metal-organic chemical vapour deposition, have made possible the fabrication of highly pure structures with abrupt interfaces, allowing for the tailoring of the electronic structure to suit almost any need. An interesting example is the variably spaced semiconductor superlattice (VSSL), which is designed to obtain a resonant tunneling between adjacent quantum-well states at a specific value of the growth-direction applied electric field. Such heterostructure was originally proposed by Summers and Brennan [1] to provide high-energy injection of electrons into a bulk semiconductor substrate at the operating bias and was thoroughly investigated from both theoretical [2–5] and experimental [6–8] points of view. Of special interest is the application of resonant heterostructures in photovoltaic power generation. In that respect, Barnham and Duggan [9] proposed the use of a VSSL within a p-i-n structure to minimize the electron–hole recombination. More recently, Courel et al. [10,11] theoretically investigated the conversion efficiency of p-i-n GaAs/$Ga_{1-x}In_xN_yAs_{1-y}$ solar cells based on resonant tunneling and an improvement of 4% was achieved with respect to standard MQW solar cells. Similar studies in p-i-n GaAs/$Ga_{1-x}In_xN_yAs_{1-y}$ MQW solar cells were theoretically [12,13] and experimentally [14] performed.

The combined effect of applied electric and magnetic fields has proven to be a powerful tool in the study of several phenomena related with vertical transport in semiconductor heterostructures. Investigations of the influence of in-plane magnetic fields on the negative differential conductivity of double-barrier resonant heterostructures [15] and miniband transport in semiconductor superlattices under magnetic fields [16,17] were carried out at the end of the past century. Nowadays similar studies are of great importance in fields such as laser physics [18,19] and spintronics [20], to mention some few examples. In most of these studies of magnetic-field effects on the electrical and optical properties of resonant heterostructures, one observed a dramatic change in the photoluminescence (PL) spectrum as a function of the applied magnetic field. Similar results for the intraband absorption coefficient of VSSLs under crossed electric and magnetic fields were recently reported [21]. Motivated by the possibility of tuning the optical and electrical properties of resonant heterostructures by applying external magnetic fields, here we study the interband absorption of a GaAs–$Ga_{1-x}Al_xAs$ VSSL under crossed growth-direction applied electric and in-plane magnetic fields. The work is organized as follows. The solutions of the Schrödinger equation for electron and hole states in the VSSL, as well as the calculation of the interband absorption coefficient, are outlined in Section 2.

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Numerical results and discussions are presented in Section 3 whereas conclusions are given in Section 4.

2. Theoretical framework

We study a GaAs–$Ga_{1-x}Al_xAs$ VSSL, grown along the y direction, under crossed electric and magnetic fields. The magnetic field is applied parallel to the heterostructure layers whereas the electric field is along the $-y$ direction. A VSSL is designed as a resonant heterostructure in which a field-induced quasiminiband appears in the conduction band for electric-field values in the vicinity of a critical electric field F_c [5]. Here we take the VSSL to be composed of N GaAs QWs and $N-1$ $Ga_{1-x}Al_xAs$ barriers of thickness a_n and b_n, respectively, where n denotes the position of each element (well or barrier) in the heterostructure. The whole system is sandwiched between two semi-infinite $Ga_{1-x}Al_xAs$ barriers. One may impose a resonance condition between the ground-state energies associated with adjacent wells in the heterostructure so that such states are brought into alignment by an $F = F_c$ applied bias. The a_n thickness of the n-th GaAs QW may be computed by taking into account the resonance condition according to the procedure described in Reyes-Gómez et al. [22]. The VSSL may then be generated by starting from three parameters a_1, d, and F_c, with $d = a_n + b_n$ fixed. This choice of d allows one to tune the width of the resonant quasiminibands appearing at F_c, a fact which may be of importance in photovoltaic applications. As an example, we show in Fig. 1 a pictorial view of the V_{sl}^e electron-confining potential corresponding to various GaAs–$Ga_{0.7}Al_{0.3}As$ VSSLs in the absence of applied external fields. Moreover, we display in Fig. 2 the electric-field dependence of the conduction-electron energies associated with the GaAs–$Ga_{0.7}Al_{0.3}As$ VSSLs of Fig. 1 in the absence of magnetic fields. Numerical results were obtained by using the transfer-matrix formalism, which results from the continuity conditions of the electron wave function and the probability current at the interfaces. We have chosen $a_1 = 90$ Å, $d = a_n + b_n = 100$ Å, and $F_c = 20$ kV/cm for calculation purposes. The rest of parameters (effective masses and barrier heights) were taken as in Ref. [22]. Resonant quasiminibands, induced by the $F \approx F_c$ applied electric field, are also highlighted.

One should note that the procedure to generate the VSSL may be used for any value of the Al concentration within the range $0 < x < 0.45$. Such restriction is imposed in order to guarantee a direct-gap (type I) heterostructure [23].

2.1. Conduction-electron and hole states in the VSSL

Within the effective-mass and parabolic-band approximations, the Hamiltonian for electron or hole states in the VSSL is given by

$$\hat{H}_\lambda = \frac{1}{2m_\lambda^*}\left(\hat{\vec{\mathbf{p}}} + e\vec{\mathbf{A}}\right)^2 + \eta\, eF(y - y_c) + V_{sl}^\lambda(y), \tag{1}$$

where m_λ^* and V_{sl}^λ are the effective mass and VSSL confining potential for conduction electrons $(\lambda = e)$ or holes $(\lambda = \upsilon)$, respectively, $\eta = -1$ for electrons and $\eta = 1$ for holes, y_c corresponds to the position over the y-axis where the electrostatic potential energy vanishes, $\vec{\mathbf{A}} = B(-y, 0, 0)$ is the vector potential associated

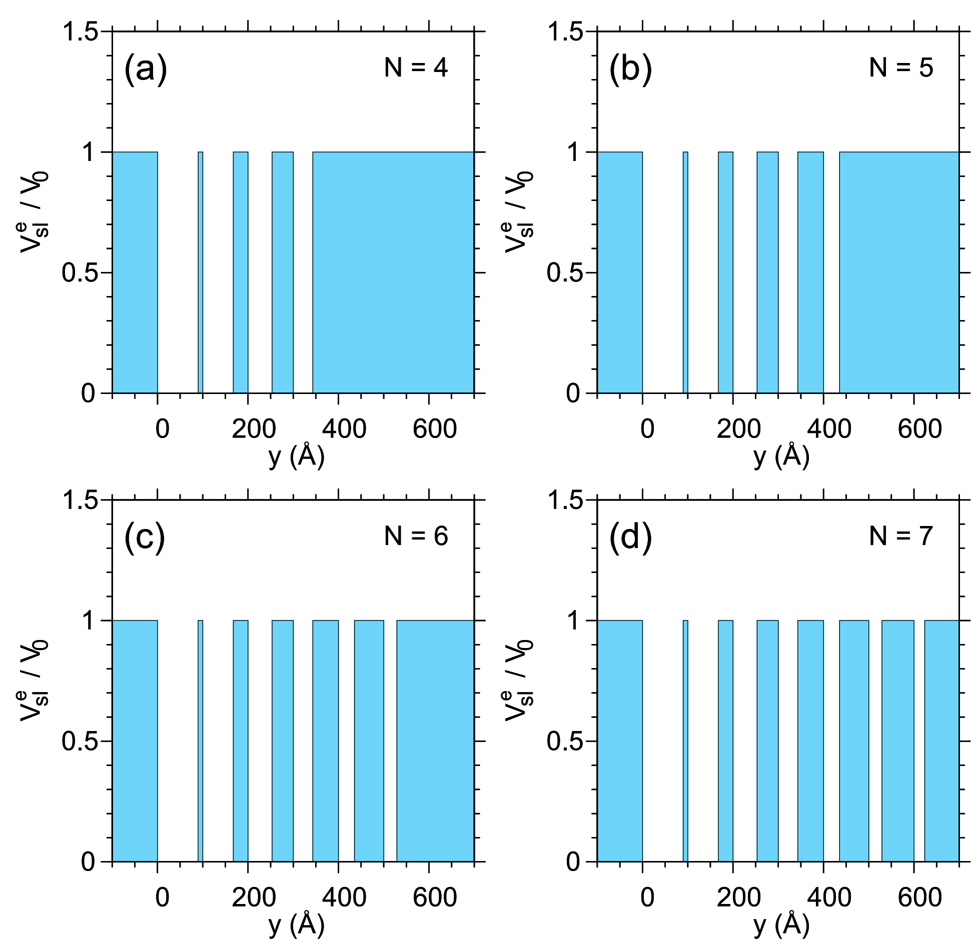

Fig. 1. Pictorial view of the V_{sl}^e confining potential corresponding to GaAs–$Ga_{0.7}Al_{0.3}$ As variably spaced semiconductor superlattices with N wells in the absence of applied external fields. Results were obtained according to the numerical procedure described in Ref. [22], with $a_1 = 90$ Å, $d = a_n + b_n = 100$ Å, and F_c=20 kV/cm.