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Suppression of the singularly localized states in dimer quasiperiodic Fibonacci superlattices

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ABSTRACT

Using the transfer-matrix technique, we have numerically investigated the effect of introducing the dimer on the nature of the states across Dimer Fibonacci semiconductor superlattices on the miniband structure of the GaAs/$Al_xGa_{1-x}As$ superlattices. By the introduction of the dimer model, the transmission spectra reveal the appearance of a miniband structure with a concomitant disappearance of the singularly localized states. This behavior is due to the interaction between the states of the dimer wells inside the potential and, therefore, the system is seen by the particle as two overlapped ordered structures.

1. Introduction

Materials with restricted geometry, such as semiconductor quantum-well structures [1], quantum dots and wires [2,3], organic thin films [4] as well as quasiperiodic structures [5], are nowadays subjects of growing interest from both fundamental and practical points of view. Quasiperiodic systems are of great interest in solid state physics because they are structures intermediate between periodic and fully disordered ones [6–8]. Theoretical studies demonstrate that ideal aperiodic SLs should exhibit a highly-fragmented and fractal-like electronic spectrum [7,9–12]. After the pioneering work, other quasiperiodic structures were experimentally realized [13]. In particular, there has been an extensive study on the propagation of electrons or other classical waves in one-dimensional quasiperiodic superlattices or dielectric multilayers by Enrique Macia et al. [14] in which they have presented an analysis of wave transmission through Fibonacci Dielectric Multilayer (FDM) structures.

Most devices work under bias conditions and, consequently, a complete characterization of the electronic states in quasiperiodic SLs subject to an applied electric field is needed. This is to be compared with periodic SLs, where Bloch oscillations have been predicted and detected in $Ga_{1-x}Al_xAs$ [15,16].

In this paper we address the study of the electronic properties of the FHBSL and DHBSL in the stationary case. For definiteness, we consider a quantum well-based SL constituted by two semiconductor materials GaAs and $Al_xGa_{1-x}As$ [17,18], with the same well width a and barrier thickness b in the whole sample, which in turn preserves the periodicity of the lattice along the growth axis; the unit supercell has the period $d = a + b$. For an appropriate understanding of the FHBSL and DFHBSL effect on the nature of the electronic and transport properties, the physical picture may be handled through the investigation of states close to the bottom of the conduction miniband with $k_\perp = 0$. As usual, the nonparabolicity effects can be neglected without loss of generality.

The structure of FHBSL starts from two basic building blocks A and B. Here A and B contain the two barrier heights of the potential. A usual method to construct the Fibonacci sequence is to use an inflation process according to the rule of concatenation: $S_n = S_{n-1} \cdot S_{n-2}$. This sequence comprises S_{n-1} elements A and S_{n-2} elements B. The initial sequence is $S_0 = A = V_1$ and $S_1 = B = V_f$.

2. Model

In this model of the SL, we consider that the height of the barriers takes only two values, namely V_1 for the basic block A and V_f for the basic block B. These two energies are proportional to the two values of the Al fraction in the $Al_xGa_{1-x}As$ barriers. The sixth sequence, for example, of energies is correlated as: ABAABABAABAAB corresponding to a ($V_1V_fV_1V_1V_fV_1V_fV_1V_1V_fV_1V_1V_f$) form of the potential profile.

In the following treatment, we include the electron effective masses corresponding to the different regions of the potential: m_{b1} and m_{b2} corresponding to barrier heights V_1 and V_f, respectively, and m_w to the well.

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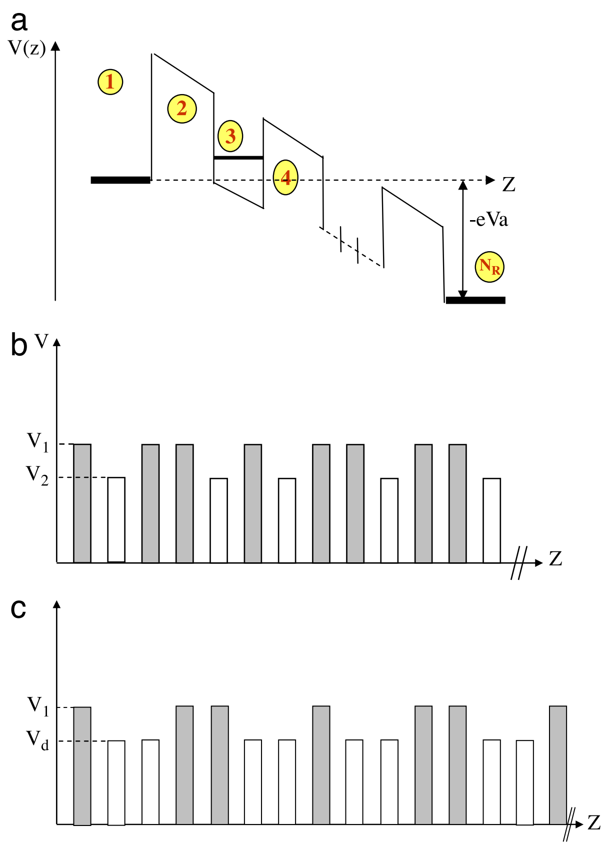

Fig. 1. Potential energy profile for (a) applied bias multibarrier system; (b) Fibonacci Height Barrier superlattice (FHBSL) for $Va = 0$ V and (c) Dimer Fibonacci Height Barrier superlattice (DFHBSL) for $Va = 0$ V.

The one-dimensional time-independent Schrodinger wave equation is given by:

$$\frac{1}{m^*(z)}\frac{\partial^2}{\partial z^2}\psi(z) + \frac{2}{\hbar^2}\left[E - V_{SL}(z)\right]\psi(z) = 0 \tag{1}$$

where z is the growth axis, E the incoming electron energy, $\psi(z)$ the wave function in the growth direction and m^* the effective mass of each monolayer.

The potential energy profile of the applied bias Va is represented in Fig. 1(a):

The SL potential V_{SL} derives directly from the different energies of the conduction band-edge of the two semiconductor materials (GaAs and $Al_xGa_{1-x}As$) at the interfaces.

The solutions of Eq. (1) in each potential region are given by the following equations:

$$\text{Region (1)}: \quad V(z) = 0 \quad \text{and} \quad m^*(z) = m_a \tag{2}$$

$$\psi_1(z) = 1e^{ik_z} + Re^{-ik_z} \tag{3}$$

where $k = \sqrt{\frac{2m_aE}{\hbar^2}}$.

$$\text{Region (2)}: \quad V(z) = V_0 - \frac{eV_a}{L}z \quad \text{and} \quad m^*(z) = m_b. \tag{4}$$

If we define the following transformation rule in the barrier:

$$\rho(z) = \left(\frac{2em_bV_a}{L\hbar^2}\right)^{1/3}\left(\frac{V_0 - E}{eV_a/L} - z\right) = Z(\eta - z). \tag{5}$$

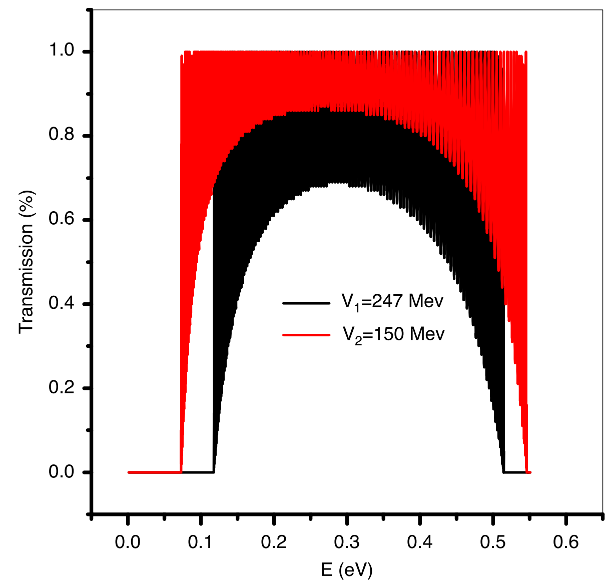

Fig. 2. Transmission coefficient versus the incident electron energy E of the ordered structure with $N = 144$ barriers, $V_1 = 247$ meV, $V_2 = 150$ meV and $a = b = 15$ Å.

The Eq. (1) becomes the Airy equation:

$$\frac{\partial^2}{\partial \rho^2}\psi_2(\rho) - \rho\psi_2(\rho) = 0. \tag{6}$$

The solutions to Airy's equation in (7) are the well-known linearly independent Airy functions $A_i(\rho)$ and $B_i(\rho)$.

$$\psi_2(\rho) = C_2^+A_i(\rho) + C_2^-B_i(\rho). \tag{7}$$

Region (3):

$$V(z) = -\frac{eV_a}{L}(z + b) \quad \text{and} \quad m^*(z) = m_a. \tag{8}$$

If we define the following transformation rule in the well:

$$\rho'(z) = \left(\frac{2em_aV_a}{L\hbar^2}\right)^{1/3}\left(-\frac{\frac{beV_a}{L} - E}{eV_a/L} - z\right) = Z'(\eta' - z), \tag{9}$$

then Eq. (1) becomes,

$$\frac{\partial^2}{\partial \rho'^2}\psi_3(\rho') - \rho'\psi_3(\rho') = 0. \tag{10}$$

The solutions to Airy's equation in (10) are the well-known linearly independent Airy functions $A_i(\rho')$ and $B_i(\rho')$.

$$\psi_3(\rho) = C_3^+A_i(\rho') + C_3^-B_i(\rho'). \tag{11}$$

For reasons of periodicity, the solutions in the regions which follow are the same ones as those in the region (2) and (3), except that the amplitude changes.

$$\text{Region } (N_R): \quad V(z) = 0 \quad \text{and} \quad m^*(z) = m_a \tag{12}$$

$$\psi_{NR}(z) = 0e^{-ik'_z} + \tau e^{ik'_z} \tag{13}$$

where $k' = \sqrt{\frac{2m_a(E+eV_a)}{\hbar^2}}$ and τ represents the transmission amplitude.

The first amplitude in the Eq. (13) is null, because the electron is supposed as coming from the left.

Using the Bastard conditions of continuity [19], one has the relation between the reflected and transmitted amplitude, R and