Resonant tunneling through Gaussian superlattices

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We study the tunneling of electrons in semiconductor superlattices (SL) where the width of the barrier is modulated by a Gaussian function. The system is modeled using the effective mass approximation for the electrons and it is solved with the transfer-matrix method. We found, as in the previous models of Gaussian SL, that the probability of transmission is almost equal to unity in the miniband. In comparison with previous designs of SLs, our system shows experimental advantages.

Keywords: Quantum wells, tunnel effect, superlattice.

Estudiamos el tunelamiento de electrones en super-redes semiconductoras donde el ancho de las barreras es modulado por una función gaussiana. Modelamos el sistema usando la aproximación de masa efectiva y los resolvemos usando el método de matriz de transferencia. Como en los diseños anteriores de super-redes gaussianas encontramos que la probabilidad de transmisión es muy próxima a la unidad en toda la minibanda. En comparación con los modelos anteriores de super-redes gaussianas, nuestro sistema presenta ventajas experimentales.

Descriptores: Pozos cuánticos, efecto túnel, super-redes.

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Introduction

The analysis of resonant tunneling through semiconductor superlattices (SLs) has a lot of interest whether from fundamental point of view as for its applications in microelectronic devices. Since the pioneering work of Esaki and Tsu [1], the transport properties of those structures have been subjected to intense experimental and theoretical investigations [2–5]. Due to advances in manufacturing techniques of semiconductor heterostructures, it is possible to tailor the band structure of SLs to the particular needs of every experiment. Recently, Tung and Lee [6] proposed a novel SL where the heights of the barrier and the bottom of the quantum wells are modulated by Gaussian functions. These authors found some plateaus in the transmission characteristic where electrons are almost unscattered. This is quite different from uniform SLs, where the transmission probability have great oscillations in each miniband. The number of monolayers (ML) of the barrier centred in \( z_b \) is the integer closest to

\[
N_b = N_0 \exp \left\{ \frac{1}{2} \left( \frac{z_b - L/2}{\sigma} \right)^2 \right\}. \tag{1}
\]

In the left side of the SL (\( z < 0 \)) the solution of this equation is the superposition of a incident plane wave with amplitude \( I \) and a reflect wave of amplitude \( r \). In the right
side of the SL \((z > L)\) only a transmitted wave is expected, therefore the wave function is assumed to be

\[
F(z) = \begin{cases} 
  I e^{ikz} + I e^{-ikz}, & \text{for } z < 0, \\
  I e^{-ik'z}, & \text{for } z > L;
\end{cases}
\]  

(3)

where \(k, k'\) are the wave vectors in the emitter region and the collector region respectively.

We calculate the tunneling current by the usual approximation \([8]\). The current density is

\[
J(V) = \frac{e m^* k_B T}{2\pi^2 \hbar^3} \int N(E, V) T(E, V) dE,
\]

(4)

where \(V\) is the bias voltage and \(k_B\) is the Boltzmann constant. The transmission probability

\[
T(E, V) = |t/I|^2
\]

is obtained using the continuity conditions to the wave function, continuity of the probability flux and the transfer-matrix method \([7]\). \(N(E, V)\) consider the states of occupation on both sides of the SL in accordance with the Fermi distribution function and is given by

\[
N(E, V) = \ln \left[\frac{1 + e^{\beta(E-\mu)}}{1 + e^{\beta(E+eV-\mu)}}\right],
\]

(5)

where \(\mu\) is the chemical potential.

**Results**

The tunneling probability through such potential profile is illustrated in Fig. 2 for a effective-mass \(m^* = 0.067 m_e\) in the wells and \(m^* = 0.082 m_e\) in the barriers. For certain range of energies below the barrier height the particle can tunnel almost unattenuated (solid line), in contrast with the uniform SL with the same parameters and 6 ML width, shows a transmission probability that oscillates with the energy (dashed line). The shape of plateau in the transmission probability does not depend of the difference in the effective mass between wells and barriers. It is obtained similar results if the effective mass is constant in all SL. These results are for a SL with 70 nm approximately where the electron transport is coherent for these materials \([9]\).

Figure 3 display the current density for the same parameters of Fig. 2 at 77 K. Note that the J-V characteristics shows negative differential conductivities (NDC) for both Gaussian and uniform SLs. The details of NDC depends of the kind of SL. Moreover, as in the previous design \([6, 7]\), the Gaussian SL shows a peak-to-valley ratio much greater that the uniform SL, nevertheless to difference them, in our design, the mole concentration remains constant in barriers and wells. This is a great advantage from the experimental point of view at the time of growing the SL.

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