Disorder and its effect on the electron tunneling and hopping transport in semiconductor superlattices

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Abstract

In this work we study theoretically vertical electron transport in semiconductor superlattices subject to an electric field. A disorder is introduced into the layer parameters. Both, disordered superlattices with a strong electron scattering and those with a weak scattering, are considered at low temperatures. The interwell hopping transport is simulated for the former structures, and the tunneling approach is adopted for the latter superlattices. In both models the current-voltage characteristics are calculated for various types and degrees of the disorder. The superlattice transport properties can be controlled by the disorder.

Key words: superlattices; disorder; transport

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1. Introduction

Since the work by Esaki and Tsu [1], many efforts in superlattice growth were made to obtain a perfect periodic structure. On the contrary, in [2] the random superlattices were proposed. Semiconductor multiple quantum well structures with an intentional disorder in the well width values were grown and investigated in [3,4]. Such superlattices exhibit a number of interesting optical and electrical properties. This type of the disorder strongly influences the electron transport along the growth direction (vertical transport) [5]. The transport theory in perfect superlattices is well-developed [6]; however, it cannot be applied for the disordered structures due to absence of the translational symmetry. In the current work we study theoretically vertical transport in the disordered superlattices using both, tunneling and hopping approaches.

The applicability of tunneling or hopping approach to the vertical transport through the structure depends on the probabilities of the carrier tunneling and scattering processes. The resonant tunneling time can be expressed via the superlattice parameters. The carrier scattering by optical and acoustical phonons and the Coulomb scattering processes are usually most important. Their rates can be estimated in a straightforward way using ordinary bulk formulae [7]. If the tunneling time is less than the carrier free time, then tunneling approach is applicable. Vice versa, if a scattering process is quicker than the tunneling through the superlattice, the interwell hopping should be adopted.

2. Tunneling transport

We consider semiconductor superlattices with monopolar (e.g. n-type) conductivity at low temperatures. Tunneling approach was applied to the structures with parameters satisfying the condition $\tau_{res} \ll \tau_{scatt}$. To avoid intensive optical phonon scattering, a limited bias interval $eV < eV_{\max} \approx \hbar\omega_{\mathrm{LO}}$ is considered. The effective mass method is used. We approximate the superlattice potential by a consequence of rectangular quantum barriers and wells, and the electric field potential by a step function, that is, the actual potential within the layer is changed to its mean value. The

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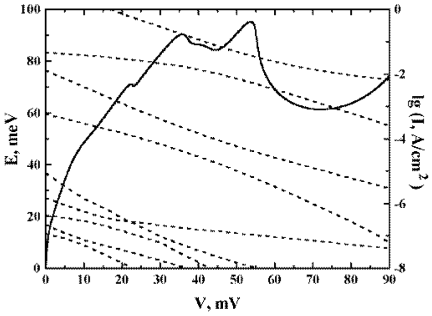

Fig. 1. Current-voltage characteristic (solid curve) and transmission maxima energies vs. voltage (dashed curves) for a disordered superlattice with well width fluctuations.

transmission coefficient is calculated using the transfer matrix method [8]. The I–V curves of the superlattices are derived using the calculated transmission spectra [9].

The calculated transmission spectrum shows peaks that correspond to the electron energy levels within the structure. They give the major contribution to the current due to resonant tunneling through these levels. In electric field the peaks shift to lower energies with different rates (the Stark effect for size-quantized levels in the wells). In a periodic structure only the levels belonging to different superlattice subbands can cross in the field. On the contrary, level (anti)crossings are possible within the same subband for superlattices with a relatively strong disorder, as one can see from Fig. 1. Every (anti)crossing leads to a current increase at the curresponding voltage due to the resonant tunneling via two electron states instead of one. The current-voltage characteristics exhibit also several current drops, clearly shown in Fig. 1, that take place when the levels move below the conduction band bottom in the cathode, so that the transport through such state is no longer possible.

3. Hopping transport

For the transport calculations in the structures with high scattering probability, we utilize interwell hopping approach. The charge carriers are supposed to residue at the quasi-localized states within the quantum wells. The current flowing from the kth quantum well to a neighboring one can be expressed through the 2D electron concentrations n_k and n_{k+1} in these wells:

$$I = e \sum_{q_k, q_{k+1}} [n_k f_k(E_{k,q_k}) \omega_{k,q_k;k+1,q_{k+1}} - n_{k+1} f_{k+1}(E_{k+1,q_{k+1}}) \omega_{k+1,q_{k+1};k,q_k}]. \qquad (1)$$

Here q_k is the number of energy level and $f_k(E)$ is the distribution function in the kth well. The hopping probability between two adjacent wells can be written as the ratio of the probability of transition between the two states under consideration, depending only on their energy difference $(E_{k,q_k} - E_{k+1,q_{k+1}})$, and the tunneling time through the barrier for the electrons with energy E_{k,q_k}. Supposing that the energy levels move together with the corresponding quantum well bottoms, we express the energies of electron states through their zero-field positions calculated by the tunneling method described above and the well bottom potentials. Then Eq. (1) is resolved regarding the well potentials for the given electron concentrations and current density through the superlattice. The new electron concentrations in the wells are then obtained from the Poisson equation, and this cycle is repeated until the procedure converges. The voltage is given by the difference between the potentials of anode and cathode, and for relatively high current several solutions can exist, corresponding to different positions of high-field domains in the sample. Due to the transition to a new branch of the solutions, after the Ohmic intervals of I–V curves regions of constant current occur. The exact form of the curve depends on the particular realization of the disorder in the superlattices parameters.

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