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

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 superlattices and 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 because of the absence of the translational symmetry. In the current work we study theoretically vertical transport in the disordered superlattices using both, tunneling and interwell hopping approaches.

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2. Tunneling and scattering times

We consider semiconductor superlattices with monopolar (e.g. n-type) conductivity at low temperatures. 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 estimated as

$$\tau_{\rm res} \approx \frac{m\kappa^2 d^4}{2\pi^3\hbar} {\rm e}^{N\kappa b}, \tag{1}$$

where $\kappa \approx \sqrt{2mU}/\hbar$, U is the barrier height, d and b are the well and barrier widths, respectively, and N is the number of barriers. 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.

3. Tunneling transport

We consider superlattices with parameters satisfying the condition $\tau_{res} \ll \tau_{scatt}$. To avoid intensive optical phonon scattering, we consider a limited bias interval $eV < eV_{\max} \approx \hbar\omega_{\rm LO}$. To extend the voltage interval, we choose the superlattice material having the greatest LO-phonon energy, which is GaN. For GaN-based structure with 6 quantum barriers, 3 monolayer wide and 100 meV high each, and 5 wells, 12 monolayer wide each, we find the following characteristic times:

$$\tau_{\rm res} \approx 2{\times}10^{-11}{\rm s},\ \tau_{\rm DA} \approx 1{\times}10^{-10}{\rm s},\ \tau_{\rm Coul} \approx 5{\times}10^{-10}{\rm s}.$$

We use the effective mass approximation. The superlattice potential is approximated by a consequence of rectangular quantum barriers and wells. We approximate the electric field potential by a step function, that is, the actual potential within the layer is changed to its mean value. The 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. Every (anti)crossing leads to a current increase at the corresponding voltage because the resonant tunneling takes place via two electron states. The current-voltage characteristics exhibit also several current drops 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.

4. Hopping transport

For the transport calculations in the structures with high scattering probability, we utilize interwell hopping approach. The current flowing from the kth quantum well to a neighboring one can be expressed through the electron concentrations n_k and n_{k+1} in these wells:

$$I_k = eb_k(n_k\omega_{k,k+1} - n_{k+1}\omega_{k+1,k}), \qquad (2)$$

where b_k is the corresponding barrier width. The hopping probability between two adjacent wells can be written as $\omega_{k,k+1} \approx \Omega(\delta E_k)/\tau_{\rm res}$, where $\delta E_k = E_k - E_{k+1}$ is the difference between the energy levels in the wells under consideration; $0 \le \Omega(\delta E) \le 1$ is an analytical function having maximum at $\delta E = 0$, and for positive δE values $\Omega(\delta E) > \Omega(-\delta E)$.

One can resolve Eq. (2) and find the set of E_k values for a given current density through the superlattice ($I = I_k \quad \forall k$) and given electron concentrations. As the tunneling spectra described above show, we can suppose that the energy levels move together with the corresponding quantum well bottoms. Thus, taking zero-field positions of the levels calculated by the tunneling method, and knowing their energies under the bias, we get the quantum well potentials. The new electron concentrations in the wells are than obtained from the Poisson equation, and the whole cycle is repeated until the procedure converges. The voltage is given by the difference between the potentials of anode and cathode and depends on the current I. Several solutions for given current can exist, which correspond to different positions of high-field domains in the sample. The current-voltage characteristics are calculated for various realizations of the disorder in the superlattices parameters.

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