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Interband magnetotunneling in RTS with type II heterojunctions

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In resonant tunneling structures (RTS) with type II heterojunctions such as InAs/-AlSb/GaSb RTS with a GaSb quantum well and GaSb/AlSb/InAs RTS with an InAs quantum well, the interband tunneling of electrons through the quasibound states in the valence band quantum well or holes from GaSb through the quasibound states in the conduction band quantum well occurs. These interband RTS showed sufficiently high values of peak-to-valley current ratio at room temperature [1], [2] and attracted a considerable attention of researchers. In papers [3], [4] the interband magnetotunneling in RTS made from InAs, AlSb, GaSb was investigated. In strong magnetic field normal to the interfaces, the interband tunneling current oscillations were observed conditioned by the interband tunneling through different Landau levels [3]. The magnetic field parallel to interfaces results in a considerable shift in peak voltage [4]. The interband magnetotunneling in InAs/AlSb/GaSb RTS in the magnetic field parallel to interfaces was considered theoretically in Ref. [5]. The aim of this paper is to investigate theoretically the interband magnetotunneling in structures with type II heterojunctions in magnetic field normal to interfaces. The transmission coefficients corresponding to the tunneling processes from the states of each Landau level with conservation and changing of the Landau-level index were calculated using the eight-band Kane model. We show that in the InAs/AlGaSb/GaSb RTS (see Fig. 1) the interband tunneling probability for transitions with changing the Landau-level index may be comparable with the interband tunneling probability with conservation of the Landau-level index, that can result in the additional peaks on the current-voltage (I–V) characteristics of these RTS.

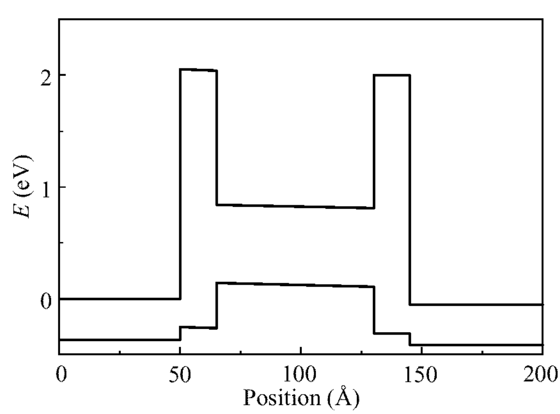

Fig 1. Conduction and valence band diagram of InAs/AlSb/GaSb RTS.

We use the **kp** band model, which takes into account the coupling of the conduction band with three valence subbands exactly and neglects the higher bands to investigate the interband tunneling processes in RTS such as InAs/AlGaSb/GaSb RTS, whose conduction and valence band diagram is shown in Fig. 1. In this way we consider only the interband tunneling processes through the light hole states in the quantum well. These processes are dominant for the values of external bias, when the interband resonant tunneling processes through the light hole states can occur [6], [7]. We consider only the coherent tunneling neglecting the phonon-assisted processes, which can be essential in structures with thick barriers [8]. If the axis z is normal to interfaces, than an 8×8 Hamiltonian can be written in the following form

$$\hat{H} = \begin{pmatrix} \hat{H}_{+-} & \hat{H}_{--} \\ \hat{H}_{++} & \hat{H}_{-+} \end{pmatrix}, \tag{1}$$

where

$$\hat{H}_{\pm\mp} = \begin{pmatrix} E_C(z) & \sqrt{2}iP\hat{k}_z/\sqrt{3} & -iP\hat{k}_z/\sqrt{3} & P\hat{k}_\pm \\ -\sqrt{2}iP\hat{k}_z/\sqrt{3} & E_V(z) & 0 & 0 \\ iP\hat{k}_z/\sqrt{3} & 0 & E_V(z)-\Delta(z) & 0 \\ P\hat{k}_\mp & 0 & 0 & E_V(z) \end{pmatrix}, \tag{2}$$

and

$$\hat{H}_{\pm\pm} = \begin{pmatrix} 0 & P\hat{k}_\pm/\sqrt{3} & \sqrt{2}P\hat{k}_\pm/\sqrt{3} & 0 \\ P\hat{k}_\pm/\sqrt{3} & 0 & 0 & 0 \\ \sqrt{2}P\hat{k}_\pm/\sqrt{3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{3}$$

Here $\hat{k}_\pm = \mp i(\hat{k}_x \pm i\hat{\bar{k}}_y)/\sqrt{2}$, $\hat{k}_x = -i\partial/\partial x$, $\hat{\bar{k}}_y = -i\partial/\partial y + |e|Bx/(\hbar c)$, $\hat{k}_z = -i\partial/\partial z$, $E_C(z)$, $E_V(z)$ are the conduction and valence band edges, $\Delta(z)$ is the split-off energy, $P = -\hbar^2 < s|\partial/\partial z|p_z > /m_0$, where s, p_z are the basis states of the conduction and valence bands, m_0 is the free electron mass. We have supposed, that the magnetic field B is parallel to axis z, so that $B_z = B$, $B_x = 0$, $B_y = 0$; and the components of vector potential are: $A_y = Bx$, $A_x = A_z = 0$. We use the same basis functions as in Ref. [9] and neglected g-factor of the free electron. Then the envelope functions obey the equations

$$\sum \hat{H}_{ij}\psi_j = E\psi_i, \qquad i = 1, 2, \ldots, 8. \tag{4}$$

In (4) ψ_i is an envelope function, E is the energy. At the heterointerfaces should be continuous the following functions

$$\psi_1, \qquad \sqrt{2}\psi_2 - \psi_3, \qquad \psi_5, \qquad \sqrt{2}\psi_6 - \psi_7 \tag{5}$$

to conserve the probability current density component normal to interfaces.

The equation system (4) in a bulk material have two solutions for a given value of energy E and Landau-level index n with wave vector components $k_z^\pm$ and opposite average values of spin. For the first solution $\psi_1 \neq 0$, $\psi_5 = 0$, for the second solution $\psi_5 \neq 0$, $\psi_1 = 0$ [10]. In the conduction band these two solutions correspond to the states with spin $s \approx \pm 1/2$, respectively. In the heterostructure due to the spin-orbit interaction, the mixing at the heterointerfaces of the states with opposite spin orientations

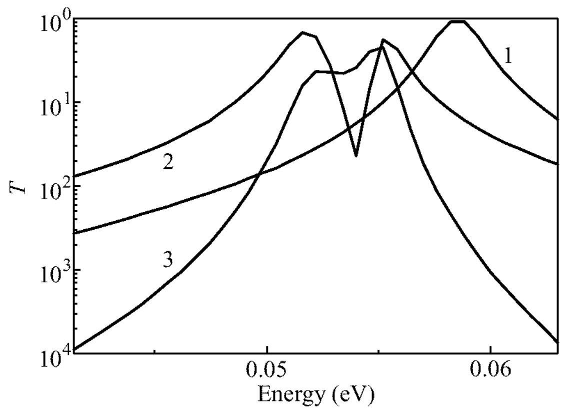

Fig 2. Transmission coefficients versus energy.

of Landau levels n and $n + 1$ occurs. So that electron from the state corresponding to Landau-level index n with spin parallel to magnetic field can tunnel not only into the similar state to the right side of RTS, but also into the state corresponding to Landau-level index $n + 1$ with spin opposite to magnetic field. Only the states with Landau-level index $n = 0$ and spin opposite to the magnetic field are not mixed with the other states.

To investigate the interband resonant tunneling in the presence of magnetic field, we use the transfer matrix method. The transfer matrices were calculated to obtain the transmission coefficients for the transitions from the states with different spin orientations, corresponding to each value of Landau-level index. The results of calculations for the InAs/AlGaSb/GaSb RTS under bias 0.05 V are presented in Fig. 2. The investigated structure contains two InAs contact layers doped by donors, two 25 Å AlGaAs barriers and 50 Å GaSb quantum well. The value of magnetic field is equal to 15 T. We have used the same parameters as in Ref. [9].

Curve 1 in Fig. 2 corresponds to the transitions from the electron states to the left of the double barrier structure with spin opposite to the direction of magnetic field corresponding to the value of $n = 0$ into the similar states to the right of it. Curve 2 represents the transmission coefficient versus energy for the transitions from the states in the conduction band of the left InAs layer corresponding to the Landau-level index $n = 0$ and spin parallel to the magnetic field into the similar states to the right of tunneling structure. Curve 3 represents the transmission coefficient versus energy for the transitions from the states in the conduction band of the left InAs layer corresponding to the Landau-level index $n = 0$ and spin parallel to the magnetic field into the states to the right of the double barrier structure with Landau-level index $n = 1$ and opposite direction of spin. All these resonant tunneling processes occur through the light hole quasibound states in the quantum well. Due to strong mixing of the quasibound states in the valence band quantum well corresponding to the values of $n = 0$ and $n = 1$, resonant tunneling in the case of curves 2 and 3 occurs through two states in the quantum well with different spin orientations, which correspond to the same subband of size quantization. For this reason the dependencies $T(E)$ have two peaks. This effect can result in the existence of the additional peaks on the I–V characteristics of the InAs/AlGaSb/GaSb RTS.

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