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The Low-Temperature Characteristics of GaSb/AlSb/InAs/GaSb/AlSb/InAs Broken-Gap Interband Tunneling Structure

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The low-temperature characteristics of GaSb/AlSb/InAs/GaSb/AlSb/InAs broken-gap interband tunneling (BGIT) structures are investigated . Some small peaks and kinks are observed at the low-temperature, which are not seen at the room temperature. The heavy-hole states are expected to contribute to the additional phenomena at low temperature. An improved three-band *k.p* model considering the coupling among the conduction-, light-hole and heavy-hole band is utilized to study the low temperature characteristics of the BGIT structures.

1. Introduction

Recently, the resonant interband tunneling (RIT) structures based on InAs, GaSb and AlSb type II material systems have attracted much attention due to the unique band lineups. They offer the tremendous flexibility for hetero- structure device design, resulting in the extensive research in physics[1), 2)] and their applications in high speed devices[3), 4)]. Through the concepts of resonant tunneling and bandgap blocking effects, they exhibit high peak current density and high peak-to-valley current ratios (PVRs) at low and room temperatures.

GaSb/AlSb/InAs/GaSb/AlSb/InAs BGIT structures, as shown in Fig.1, which possessed higher PVRs and peak current density compared with GaSb/AlSb/GaSb/AlSb/InAs double barrier interband tunneling (DBIT) structures[4)], were proposed[5)]. The room temperature characteristics of BGIT structures were investigated previously with a simple three-band $k \bullet p$ model (conduction band, light-hole band and split-off hole band involved)[6)]. This simple model is successful in the discussion of the variations of the main peak current density with InAs well thickness and the observation of multiple negative differential resistance (NDR) behaviors at room temperature. That is due to the electrons in InAs couple easily with light holes in GaSb to contribute to the main peak current. The effects of heavy holes are neglected in the discussion of the main peak.

The low-temperature (77K) characteristics were also demonstrated and found very distinct from the room temperature ones. Some small peaks and kinks in addition to main peaks were observed at the low temperature, which weren't depicted at room one. However, the simple three-band model mentioned above could not be able to interpret these additional low temperature characteristics due to its simplified treatment of the valence-band structure. The coupling between electrons and heavy-hole states is weaker so that the energy spreading at room temperature may lead to the validity of the neglect of the heavy-hole states effects in the discussion of main peak. However, we expect that the heavy-hole states would contribute to the additional low temperature characteristics.

In $k \bullet p$ method, to consider the effect of the heavy-hole states, the transport around Γ-point, i.e. the nonzero in-plane wave vector ($k_{//} \neq 0$), must be involved to include the interactions of electrons and heavy holes, light- and heavy- holes.

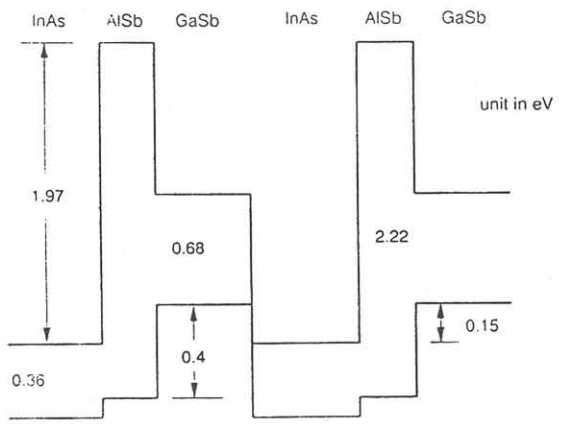


Fig.1 The band diagram of GaSb/AlSb/InAs/GaSb/AlSb/InAs BGIT structure.

An improved three-band $k \bullet p$ model is used to study the low temperature characteristics of the BGIT structures. This model offers easier derivations of the E-k relations and the boundary conditions. The scattering matrix method[7)] is utilized to calculate the transmission coefficients to avoid the numerical instability.

2. Model descriptions

In modeling three-band Hamiltonian, we choose the x axis along the heterostructure growth direction and the y axis along the in-plane $k_{//}$ wave vector ($k_z = 0$), within the cylindrical approximation[8)]. This choice leads to the decoupling of 6×6 matrix Hamiltonian into two equivalent 3×3 matrices; one block corresponding to the set of the three states, and the other block corresponding to the opposite spin set. The Hamiltonian in this shorter basis retains the full coupling of electrons, light holes and heavy holes and can be written as

$$\begin{bmatrix} E-E_c+V & -\frac{\Pi}{6}\hbar(k_x+ik_y) & \frac{\Pi}{2}\hbar(k_x-ik_y) \\ -\frac{\Pi^*}{2}\hbar(k_x-ik_y) & (E-E_v+V)+P & Q \\ -\frac{\Pi^*}{2}\hbar(k_x+ik_y) & R & (E-E_v+V)+S \end{bmatrix}$$

where

$$\Pi = \frac{1}{m_0}\langle S|p_i|i\rangle, \quad i = X, Y, Z$$

reflects the coupling between the conduction band and valence band, and

$$P = \frac{\hbar^2}{2m_0}(\gamma_1 - \gamma_2)(k_x^2 + k_y^2)$$

$$Q = -\frac{\hbar^2}{2m_0}(\sqrt{3}\,(k_y^2 - k_x^2) + i2\sqrt{3}\,\gamma_3 k_x k_y)$$

$$R = -\frac{\hbar^2}{2m_0}(\sqrt{3}\,(k_y^2 - k_x^2) - i2\sqrt{3}\,\gamma_3 k_x k_y)$$

$$S = \frac{\hbar^2}{2m_0}(\gamma_1 + \gamma_2)(k_x^2 + k_y^2)$$

and $\gamma_1, \gamma_2, \gamma_3$ are the Luttinger valence-band parameters[9]. The E-k relations of bulk materials are determined with the three-band Hamiltonian. The boundary conditions are derived and must satisfy the continuous probability current density.

To calculate the current, we consider only the coherent transport, neglecting any scattering mechanisms. The band bending due to charge accumulation is also not taken into account and the potential profile is assumed to be a linear interpolation between higher and lower reservoir potentials. The tunneling current density is given by[2]

$$J = \frac{1}{4\pi^3\hbar}\int T(E, k_{//})[f(E) - f(E + eV)]dE_{\perp}d^2k_{//}$$

where V is the bias voltage applied to the active region, and $T(E, k_{//})$ is the transmission coefficient, f is the Fermi distri- bution function.

3. Results And Discussion

The structure parameters of BGIT structures studied here are with 65 A thick GaSb well and 30 A thick barriers while InAs well thickness is variable. Applying the improved three-band model, the transmission in BGIT structure with a 120 A thick InAs well at different values of k_y are shown in Fig.2. It is found when incorporating an InAs layer, comparing with DBIT structure, LH1 moves down below the InAs conduction band edge and the conduction state (C1) is dominant in the carrier transport at $k_y = 0$. For $k_y = 0.005\frac{2\pi}{a}$, a heavy-hole transmitted component (HH1) appears around 120 meV and another heavy-hole transmitted component (HH2) around 50 meV is observed, resulting in the splitting of C1 transmission peak. With increasing k_y, the opposite curvature between InAs conduction band and GaSb valence band leads to the shift of C1 transmission to higher energy, contrast to the heavy-hole transmission. The calculated tun- neling current density versus voltage for this structure at 77 K is shown in Fig.3(a), the experimental results at low- and room temperatures are also shown in Figs.3(b),(c), respectively, for comparison. The solid curve represents the $k_{//}$ dependent case, and the dashed one for $k_{//}$ independent. In the experiment, in addition to a distinct peak at higher voltage, there are also some small peaks at low and medium voltages. In the calculated result, there is only one peak at higher voltage for the $k_{//}$ independent case. It is evident that for the $k_{//}$ independent case, the peak due to C1 trans- mission is the only resonance and forms the main peak. However, for the $k_{//}$ dependent case, the main peak shifts to higher voltage and some small peaks appear at lower voltage. The shift of the main peak is due to the transmission peak moves to higher energy with increasing $k_{//}$. The small peaks at lower voltage is owing to

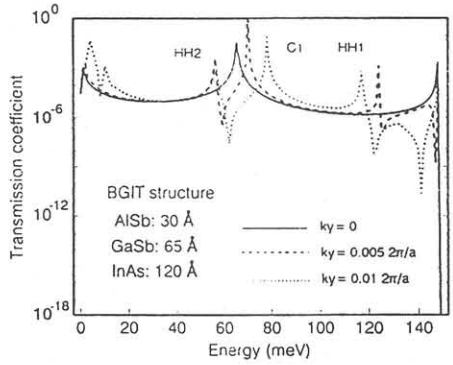
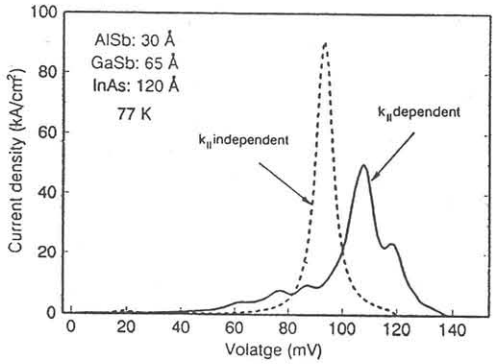
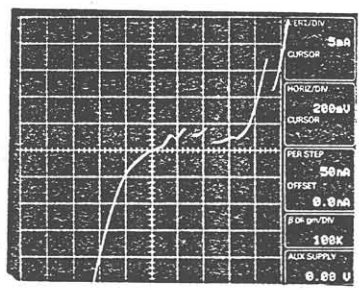


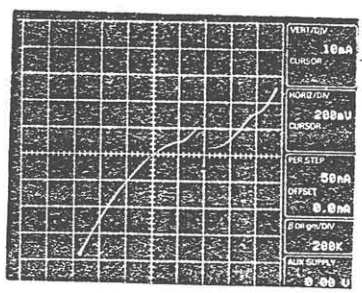
Fig.2 The transmission coefficient of BGIT structure with a 120 A thick InAs well at diffenent k_y.



(a)



(b)



(c)

Fig.3 (a) The plot of the calculated current density versus voltage for BGIT structure with a 240 A thick InAs well. The experimental results at low and room temperature characteristics are illustrated in (b), (c), respectively.

the splitting of C1 and HH2. The HH2 transmission experiences the different coupling stre- ngth at the different voltages and then could form these small peaks.

In the low temperature experiment for BGIT structure with a 240 A thick InAs well, there are two distinct peaks at low and medium voltages and a kink at higher voltage, as shown in Fig.4(a). The room temperature characteristics are also shown in Fig.4(b) for comparison. Figure 4(c) shows the calculated tunneling current density versus voltage for $k_{//}$ independent and $k_{//}$ dependent cases. In the $k_{//}$ independent case, only two distinct peaks are observed explicitly. In contrast, the $k_{//}$ dependent case shows a kink at higher voltage in addition to two distinct peaks. The broadening of the second peak is also observed in contrast to the $k_{//}$ independent case. As compared with the experiment, the result for the $k_{//}$ dependent case is in more agreement than the $k_{//}$ independent one. That indicates the importance of the effects of the heavy-hole states. When $k_{//}=0$, three transmission peaks corresponding to three conduction states (C1, C2 and C3) can be seen. For the $k_{//}$ independent case, C1 and C2 contribute to the first and second current peak, respectively. However, for the $k_{//}$ dependent case, C1 trans- mission also contributes to the first peak at low voltage. For nonzero $k_{//}$, there is substantial coupling between C2 and the heavy-hole states, resulting in the splitting of C2 transmission and the shift of transmission peak to higher energy with increasing $k_{//}$. These effects contribute to the broadening of the second peak and the lowering of peak current at the medium voltage range. Finally, C3 and HH1 couple for nonzero $k_{//}$ and contribute to the kink at high voltage.

4. Comclusions

The low temperature characteristics in GaSb/AlSb/InAs/-GaSb/AlSb/InAs BGIT structures are investigated. It was found that the low temperature characteristics are distinct from the room temperature ones. The heavy-hole states should be included to interpret the additional low temperature characteristics. To this end, an improved three-band model considering the coupling effects among the conduction band, light-hole band and heavy-hole band has been developed. The dependence of the transmission on the $k_{//}$ component is taken into account. It is found that the $k_{//}$ dependence is to aid coupling with the heavy-hole states which shows significant effects on the low temperature characteristics of BGIT structure.

5. Acknowledgement

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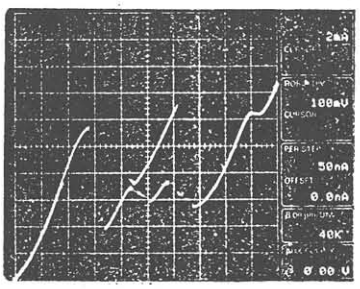
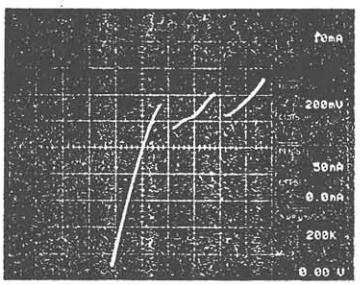


(a)



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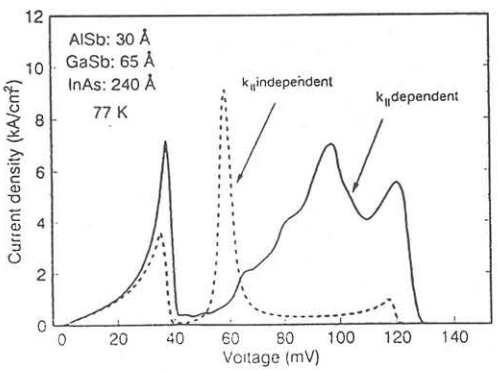

(c)

Fig.4 (a) Low- and (b) room-temperature characteristics for BGIT structure with a 240 A thick InAs well. (c) The calculated tunneling current density for this structure.