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High-field Nonlinear Perpendicular Transport in a GaAs/$Al_{0.3}Ga_{0.7}As$ Short-period Superlattice

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Abstract Electron's perpendicular transport in a GaAs/$Al_{0.3}Ga_{0.7}As$ undoped short-period superlattice n^+-SL-n^+ structure has been investigated through current-voltage (I-V) and differential conductance measurements at 300K and 77K. The results show the sublinear I-V characteristics in the region of high-field at both temperatures. Moreover, the conductance at 77K is larger than that at 300K in the corresponding region. Esaki-Tsu' mechanism may be responsible for these experimental results.

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Twenty-three years ago, Esaki and Tsu[1] proposed semiconductor superlattice structures as a way of obtaining electronic properties in an entirely new domain of physical scale . This family of new materials is clearly attractive for scientific investigations and

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technological applications. Esaki and Tsu predicted the presence of a negative differential conductivity (NDC) for $\omega\tau>1$, where $\omega\equiv eFd/h$, F and d are the applied electric field and the period of the superlattice, respectively, and τ is the scattering time. However, subsequent observations of NDC in carrier transport perpendicular to the superlattice layer have been due to the formation of high-field domains and the sequential tunneling[2-4] at low temperature. Recently, Sibille *et al*[5]. demonstrated experimentally the negative differential drift velocities (NDV) attributed to Esaki-Tus miniband transport model in a series of GaAs/AlAs superlattices. They demonstrated that the high—bias sublinearity is characteristic of NDV. Beltram *et al*[6]. directly observed NDC effect stemming from Esaki-Tsu′ mechanism in GaInAs/AlInAs superlattices. Esaki-Tsu′ model[1] does not consider temperature effect. Later theoretical works[7-8] expanded Esaki-Tsu′ theory and pointed out the temperature dependence of miniband conductance. More recently, Grahn *et al*[9]. demonstrated that the drift velocity depends on temperature indeed in GaAs/AlAs superlattices with very narrow minibands. In this letter we report the experimental results of electron transport in GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice with wide miniband (~70meV) at 300K and 77K. In the region of relatively high bias I-V curves show the high—bias sublinearity. The conductance at 77K is obviously larger than that at 300K in this bias region.

The sample studied in this work was grown by molecular-beam epitaxy on n^+-GaAs : Si substrates. In order of growth the layers are (i) 500nm n^+-GaAs (Si-doping $2\times10^{18}cm^{-3}$), (ii) 100nm GaAs (Si—graded doping from $2\times10^{18}$to $1\times10^{15}cm^{-3}$), (iii) 60 periods undoped $Al_{0.3}Ga_{0.7}As$, (2nm/4nm) superlattice, (iv) 2nm undoped $Al_{0.3}Ga_{0.7}As$, (v) 800nm n^+-$Al_{0.3}Ga_{0.7}As$ (Si-doping $2\times10^{18}cm^{-3}$), (vi) 20nm n^+-GaAs (Si-doping $2\times10^{18}cm^{-3}$) top contact layer. X-ray double-crystal rocking curves and photoluminescence measurements demonstrated high-quality of the sample. Electrically contacted mesa devices of area $400\times400\mu m^2$ were obtained by conventional processing techniques. And then, standard I-V and dI/dV measurement techniques were applied to the devices at 300K and 77K.

Figure 1 shows I-V and dI/dV curves measured at 300K and 77K, respectively. It should be noted that the electrons are injected from the top contact layer. The high-bias sublinearity of I-Vdata and the NDC of dI/dV are found. From Fig. 1 we can see the conductance at 77K is slightly smaller than conductance at 300K at bias less than about 1. 28V, but conductance at 77K is obviously larger than that at 300K at bias high than1. 28V. It is obvious that there are two different transport mechanisms for two bias regions. Following analysics shows that reason of producing this phenomenon is the electric-field nonuniformity (on a macroscopic scale).

For usual MBE grown high-quality samples the residual p-type acceptor (~$10^{15}cm^{-3}$) exists in the undoped epitaxy layers[5]. Thus, the devices consist of actually n^+-p^{-1}-n^+ structures . Due to different doping the built - in potential barrier forms at interfaces . But the built-in potential barrier can be almost totally cancelled by applying a bias. According to the Kronig-Penney model, we calculate the energy band structure of GaAs/$Al_{0.3}Ga_{0.7}As$ (40Å/20Å) superlattice. The calculated only one bound electron miniband dispersion is $\Delta E \approx 69$meV and its bottom lies at $E_{C0} \approx 80$meV (reference at GaAs conduction band bottom). It is reasonable to assume that the acceptor concentration is $N_A = 1.5 \times 10^{15} cm^{-3}$, and all acceptors are ionized in the undoped superlattice region. Through calculating, before electron can transport through the miniband an about 1.28V bias (positive voltage applied to n^+-substrate) should be applied. For bias less than 1.28V electrons transport in thermonic emission across the barrier, while bias high than 1.28V electrons transport through miniband. In our experimental results the voltage at which transport mechanism occurs transition is indeed about 1.28V.

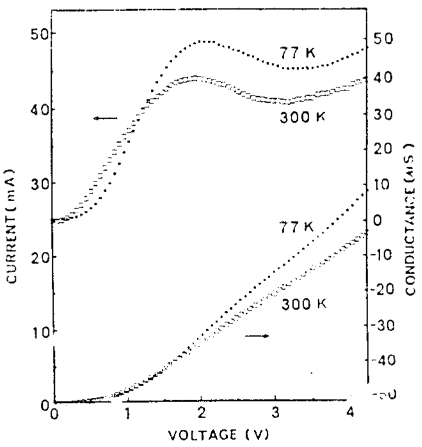

Fig. 1 Measured I-V and dI/dV data of the GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice sample at 300K and 77K

It is very known that a key physical parameter is the critical electric field F_C in Bloch miniband transport. We can estimate the critical electric field by use of a simple formual, $F=(V-V_B)/L$, where $V_B=1.28$V, $L=3.6\times10^{-5}$ cm is the total thickness of the superlattice region. Substituting the voltage at which the dI/dV reaches the peak value, we obtain the critical electric field $F_C \approx 17.8$kV/cm. Tsu and Esaki[10] recently pointed out that the band model of Esaki-Tsu applies for $eFd > h/\tau$ and $eFd < \Delta E/4$. For our sample the physical quantity $eF_Cd = 10.7$meV is less than $\Delta E/4 = 17.25$meV. If the scattering time τ equals 0.1ps, h/τ equals 6.58meV. It is very evident that $eF_Cd > h/\tau$ and $eF_Cd < \Delta E/4$, for which Esaki-Tsu model applies. Now, let us consider another important physical quantity-the drift velocity V_D.

In Esaki—Tsu model the drift velocity-field relation for miniband transport is written by the fellow formula,

$$V_D(F) = A_1 \frac{F/A_2}{1+(F/A_2)^2} \tag{1}$$

where $A_1 = d\Delta E/2h$ and $A_2 = h/e\tau d$. According to the formula (1), the peak drift velocity V_p predicted by Esaki-Tsu theory equals 1.57×10^7cm/s. A more complete drift velocity-field relation including an explicit temperature dependence can be deduced from Boltzmann's equation[7-8],

$$V_D(F) = A_1 \frac{F/A_2}{1+(F/A_2)} \frac{I_1(\Delta E/2K_BT)}{I_0(\Delta E/2K_BT)} \tag{2}$$

where A_1 and A_2 are same as those in Eq. (1) and $I_n(x)$ are the modified Bessel functions of order n. Eq. (2) differs from Eq. (1) by the occupation factor I_1/I_0. The peak velocity $V_p=8.6\times10^6$cm/s is obtained with Eq. (2) at 300K. Ratio of the peak velocity to period width V_p/d equals $1.43\times10^{13}s^{-1}$.

From Fig. 1 we see that the conductance at 77K is larger than that at 300K after the bias higher than about 1.28V. The T^{-1} temperature dependence of the low field miniband conduction in the limit K_BT large compared with the miniband width is predicted[7-8]. According to the Eq. (2) we can calculate the peak velocity $V_p=1.4\times10^7$cm/s at 77K. The theoretical peak velocity V_p at 77K is more than the theoretical V_p at 300K by a factor of 1.63. The experimental peak conductance σ_p at 77K is larger than the σ_p at 399K by a factor of 1.25. The agreement should be satisfying.

Very recently, Waschke *et al.*[11], directly detected the coherent submillimeter wave emission stemming from Block oscillations of charge carriers in an electrically biased GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice at low temperature. It is well known that an essential feature of Bloch oscillation is NDC effect predicted by Esaki and Tsu. We think that it is able to observe emission at room temperature.

In summary, we have measured the *I-V* and d*I*/d*V* in the GaAs/$Al_{0.3}As_{0.7}$ superlattice with relative wide miniband at 77K and 300K. In the region of relatively high-bias sublinearity of *I-V* curves and decrease of conductances are observed at both temperature. Especially, the conductance at 77 K is larger than that at 300 K, consistent with the theoretical predictions. Esaki-Tsu′ mechanism may be responsible for these experimental results.

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