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1992 J. Phys.: Condens. Matter 4 L659

(http://iopscience.iop.org/0953-8984/4/49/003)

J. Phys.: Condens. Matter 4 (1992) L659–L662. Printed in the UK

LETTER TO THE EDITOR

Low-temperature saturation of the peak drift velocity in superlattice miniband transport

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Abstract. The peak drift velocity v_p in the Esaki–Tsu miniband conduction of a superlattice is investigated theoretically as a function of the lattice temperature. In contrast to the existing Boltzmann-type theories, the balance-equation calculation predicts a noticeable saturation of v_p at low lattice temperatures, in agreement with the recent experimental observation by Sibille *et al.*

Growing interest in superlattice miniband transport has lately been focused on the detailed velocity–field behaviour of the Esaki–Tsu conduction. Recent experiments by Sibille *et al* [1] disclosed a substantial saturation of the peak current in the vertical conduction of a superlattice. This trend of saturation is remarkably distinct from the temperature dependence of the peak drift velocity v_p predicted by the conventional Boltzmann-type theories [2–4]:

$$v_p \sim \frac{I_1(\Delta/2T)}{I_0(\Delta/2T)} \tag{1}$$

where Δ is the miniband width, T is the (lattice) temperature, and $I_0(x)$ and $I_1(x)$ stand for the modified Bessel functions. The recent improved three-dimensional Boltzmann-equation calculation by Sibille *et al* still gives no explanation for this trend [1].

In order to investigate the temperature dependence of the peak drift velocity in the superlattice vertical transport, we have carried out detailed calculations by means of the balance-equation theory [5] to obtain the velocity–field curves over the lattice temperature range from 10–400 K for several GaAs-based superlattices with miniband widths of $\Delta = 50, 100$ and 300 K, and carrier sheet density $N_s = 0.2$ and 4×10^{15} m^{-2}. The force- and energy-balance equations used are those given in [5]. There the elastic scatterings (due to compositional and structural disorders, including interface roughness) are modelled by the scattering from impurities randomly distributed in the background without loss of any major feature of the miniband conduction, which is influenced by the total strength of the elastic scatterings and is insensitive to the details of the scattering potential.

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0953-8984/92/490659+04$07.50

On the other hand, inelastic phonon scatterings play a decisive role in dissipating energy from the electron system and are strongly temperature dependent. These effects have been carefully included in the balance equations. In the present calculation, we have taken acoustic phonons (through the deformation potential and piezoelectric couplings with electrons) and polar optic phonons (through the Fröhlich coupling with electrons) into account, using three-dimensional phonon modes of GaAs. As far as the electron transport is concerned, the neglect of the phonon confinement effect induces no serious error [6]. All the material parameters used in the calculation are typical and are the same as those used in [5]. The balance-equation predictions for different values of N_s are qualitatively similar. As an example we show the calculated results for $N_s = 4 \times 10^{15}$ m^{-2} in figure 1, together with the experimental data of Sibille *et al* [1] and the predictions of the conventional Boltzmann theories, equation (1). To concentrate on the temperature dependence we plot in figure 1 the peak drift velocity v_p normalized by its value at lattice temperature $T = 150$ K, $v_p(150\text{ K})$. This normalized quantity is insensitive to the only adjustable parameter in the theory, the zero-temperature linear mobility μ_0, which has been chosen so that the peak drift velocity is reached at a field of around $E \sim 6$ kV cm^{-1} at $T = 150$ K for all the systems.

The existing Boltzmann-type theories (equation (1)) yield a much faster temperature-dependent v_p than experiment, not indicating even a slight trace of saturation. The present balance-equation calculations, on the other hand, do show a significant trend of low-temperature saturation of the drift velocity, in qualitative agreement with the experimental results. Notwithstanding the sophisticated and realistic treatment entailed in the balance-equation theory, the physical reason for this v_p behaviour is qualitatively simple. The electron heating in the non-linear miniband conduction is obviously responsible for the low-temperature saturation of v_p. In the inset of figure 1 we show the balance-equation-theory-predicted values of the electron temperature T_e at the peak drift velocity, as a function of the lattice temperature T. As can be seen from the figure, the electron temperature T_e approaches a sufficiently large finite value with decreasing T. This results in the v_p saturation at low lattice temperatures.

Therefore, this saturation trend could also be obtained in the Boltzmann-type theories, if electron heating is properly taken into account. The phenomenological one-dimensional Boltzmann equation with two scattering times (inelastic scattering time τ_ϵ and elastic scattering time τ_{el}) yields [2,3]

$$v_p \sim \frac{I_1(\Delta/2T)}{I_0(\Delta/2T)}\left(\frac{\tau}{\tau_\epsilon}\right)^{1/2} \tag{2}$$

in which

$$\frac{1}{\tau} = \frac{1}{\tau_\epsilon} + \frac{1}{\tau_{el}}. \tag{3}$$

One can reasonably assume that, at low temperatures, τ_ϵ increases while τ_{el} tends to a constant, giving a v_p reduced by a factor of $(\tau/\tau_\epsilon)^{1/2}$ from that predicted by (1). Whether a more sophisticated Boltzmann-equation calculation will also predict this

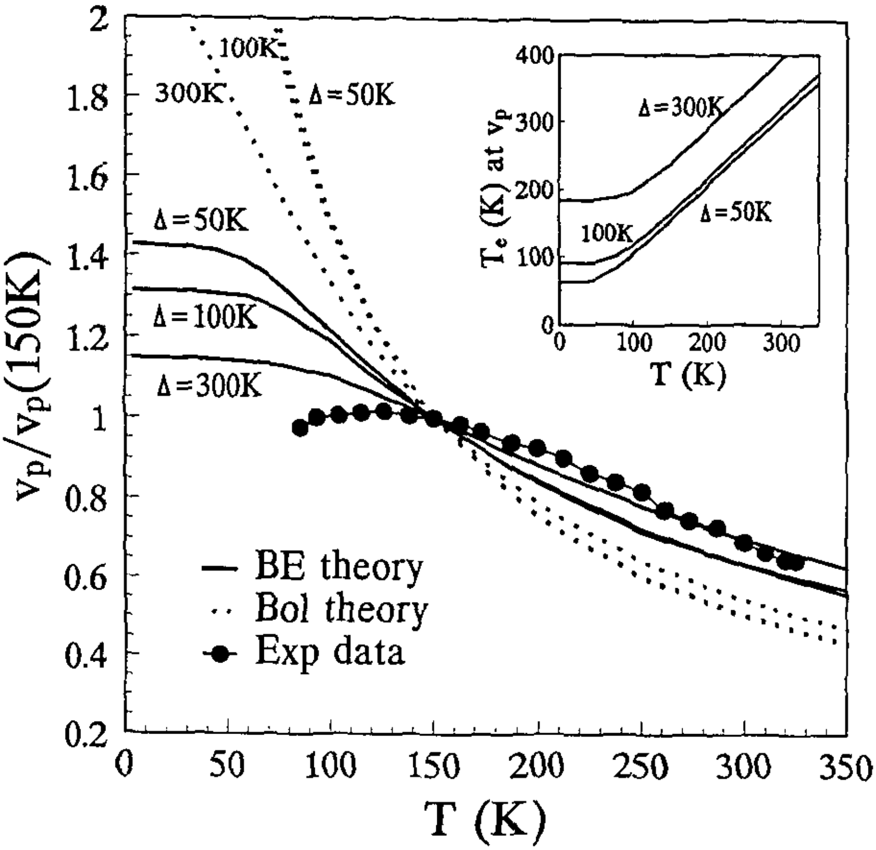

Figure 1. Peak drift velocity v_p, normalized by its value at $T = 150$ K, $v_p(150 \text{ K})$, plotted as a function of lattice temperature T for several GaAs-based quantum-well superlattices with miniband widths of $\Delta = 50, 100$, and 300 K. The dashed lines are the predictions of the Boltzmann-type theories, equation (1). The full lines are calculated from the balance-equation theory, under the condition that the carrier sheet density $N_s = 4 \times 10^{15}$ m^{-2} and the elastic scattering strengths are such that the peak drift velocity is reached at a field of around $E \sim 6$ kV cm^{-1} at $T = 150$ K. The experimental data are from Sibille *et al* [1].

kind of v_p saturation (I believe it will) remains to be seen.

The author wishes to thank the National Natural Science Foundation of China for supporting this work.

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