PHYSICAL REVIEW B VOLUME 43, NUMBER 14 15 MAY 1991-I

Electrical transport in narrow-miniband semiconductor superlattices

H. T. Grahn, K. von Klitzing, and K. Ploog
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, D-7000 Stuttgart 80, Federal Republic of Germany

G. H. Döhler
Institut für Technische Physik, Universität Erlangen-Nürnberg, Erwin-Rommel-Strasse 1, D-8520 Erlangen, Federal Republic of Germany

(Received 29 October 1990)

Miniband transport in GaAs/AlAs superlattices with narrow band widths is investigated by electrical time-of-flight experiments as a function of temperature. Negative differential velocity is observed in all cases. The low-field drift mobility is inversely proportional to the temperature above 40 K, indicating miniband transport in the nondegenerate case with a temperature-independent scattering time. Below 40 K, the temperature dependence shows the signature of hopping transport. The occurrence of these two transport regimes can be taken as evidence for the existence of a mobility gap in these superlattices.

Semiconductor superlattices exhibit a very anisotropic band structure due to the formation of minibands parallel to the growth direction. The bandwidth can be tuned over a wide range by changing the width of the barriers and wells of the superlattice. The effect of a periodic modulation of the potential in one spatial direction on the band structure of a crystal has been discussed by Keldysh.[1] The transport characteristics of semiconductor superlattices was later investigated theoretically by Esaki and Tsu[2] in a one-dimensional model. The existence of minibands with a nonparabolic band structure in such systems results in a negative differential velocity (NDV) at electric-field values that can easily be achieved experimentally. A treatment of miniband transport with Boltzmann's equation for an arbitrary carrier concentration using a fully degenerate Fermi-Dirac distribution at zero temperature[3] yielded the same field dependence as derived by Esaki and Tsu.[2] The additional result was a peak current density that exhibits a dependence on the position of the Fermi level in the miniband. A number of subsequent theoretical papers calculated the drift velocity or current density for miniband transport using Boltzmann's equation at finite temperatures.[4-6] The main results were a low-field drift mobility that is inversely proportional to the temperature in the nondegenerate limit, not taking into account any temperature dependence of the scattering time, and the existence of NDV. For scattering on acoustic vibrations a temperature dependence proportional to T^{-2} was obtained[7] in agreement with the mobility of charged carriers in semiconducting layer structures.[8] Miniband and intersubband transport by hopping also seemed at first to result in a T^{-1} dependence of the mobility.[9,10] However, a closer look at the calculations by Calecki, Palmier, and Chomette[11] reveals that hopping transport leads to an increase of the mobility with increasing temperature instead of the T^{-1} dependence.

More recently, miniband transport in semiconductor superlattices has been investigated experimentally to determine the origin of NDV (Ref. 12) and to study thermal saturation[13] and field-induced localization[14] of miniband transport. Theoretical calculations on the mobility[15] and the existence of a mobility gap in superlattice minibands[16] have raised some interesting questions about the nature of miniband transport for narrow minibands (in the range of a few meV).

In this paper we report on measurements of the field and temperature dependence of the drift velocity in narrow-miniband superlattices with a width of the lowest miniband of about 1 meV. Negative differential velocity is clearly observed at all temperatures (14–130 K). The field dependence of the drift velocity can be reproduced by a solution of Boltzmann's equation which takes into account the occupation of the lowest miniband at finite temperatures. In contrast to the general belief we observe miniband transport at higher temperatures (above 40 K) in these samples. At low temperatures we attribute the temperature dependence of the drift mobility to hopping transport. The presence of these two transport regimes is taken as evidence for the existence of a mobility gap in narrow-miniband superlattices.

The samples are GaAs/AlAs superlattices grown by molecular-beam epitaxy on n^+-type GaAs substrates. The superlattice constitutes the intrinsic region of a p-i-n diode with $Al_{0.5}Ga_{0.5}As$ as the material for the doped window layers. Sample I has a well width d_W of 12.3 nm and a barrier width d_B of 2.1 nm, while for sample II $d_W = 11.8$ nm and $d_B = 1.6$ nm, both determined by double-crystal x-ray diffraction. The number of periods N is 50 in both samples resulting in a total thickness $L = Nd$ of the intrinsic region for sample I of 0.72 μm and for sample II of 0.67 μm. The p-i-n diodes are processed into mesas of 0.03 mm^2 area and supplied with Ohmic Cr/Au and Au-Ge/Ni contacts at the top and substrate side, respectively.

Electrical time-of-flight experiments are used to investigate the vertical transport in these superlattices. A thin sheet of carriers is excited near the p contact of the p-i-n structure; due to the application of an electric field in reverse bias the electrons will drift across the intrinsic region and be collected at the n contact. Both of these processes lead to a time-dependent photocurrent. Hole transport occurs on a much longer time scale[17] than electron transport and will be neglected. The experiments are performed with a Toshiba laser diode with a pulse width of 80 ps at a repetition rate of 170 Hz. The wavelength of the laser diode is fixed at 670 nm corresponding to a penetration depth[18] of 317 nm. The photocurrent is detected with a Tektronix transient recorder (7912AD). The samples are mounted in a optical cryostat to vary the sample temperature between 10 and 300 K. A voltage source is used to apply the external electric field $F_{\rm appl}$. Together with the built-in field $F_{\rm BI}$ of the p-i-n diode, the intrinsic layer experiences an effective electric field $F_{\rm eff}$. The relation between the applied voltage and magnitude of the effective electric field is $F_{\rm eff}=(V_{\rm appl}-V_{\rm BI})/(Nd)$. A detailed description of the experiment is given in Ref. 19.

In the experiment the maximum of the photocurrent transient I_p is recorded as a function of the applied voltage. At the same time we measure the integrated photocurrent which is equal to the photogenerated charge Q_0. This allows us to obtain the drift velocity as a function of the applied voltage $V_{\rm appl}$:

$$v_d(V_{\rm appl})=\frac{L}{Q_0}I_p(V_{\rm appl}) . \tag{1}$$

In Figs. 1 and 2 we show the drift velocity as a function of the applied voltage $V_{\rm appl}$ for both samples at different temperatures. The built-in voltage is approximately 1.54 V. The effective electric field is of the order of 1 kV cm^{-1} in the linear regime of the drift velocity near $F_{\rm eff}=0$. This is the regime of miniband transport in these samples. From a simple Kronig-Penney model ($m_{\rm GaAs}=0.067m_0$, $m_{\rm AlAs}=0.15m_0$, and a conduction-band offset of 1 eV) we estimate a miniband width Δ of 0.5 meV for sample I and 1.5 meV for sample II. This implies that the miniband regime occurs at electric fields of about 1 kV cm^{-1} corresponding to an effective voltage drop over the superlattice region of approximately 100 mV (compare Figs. 1 and 2).

Both samples clearly exhibit negative differential velocity over the whole temperature range (14–130 K) in contrast to the work by Sibille *et al.*[12] who were not able to directly observe NDV due to electric-field inhomogeneities. While in sample I the drift velocity is symmetric around $F_{\rm eff}=0$, we note that in sample II a long tail of the drift velocity extends into the forward bias region for temperatures above 40 K. This tail gives rise to the rather large values of v_d near $F_{\rm eff}=0$ in sample II (see Fig. 2). The origin of this tail is not well understood.

The slope of v_d in the linear field regime is equal to the low-field drift mobility μ_d. In both samples the drift mobility increases with decreasing temperature above 40 K. This is shown in Fig. 3 where we plot the low-field drift mobility as a function of the inverse temperature. While the absolute values of the drift mobility are somewhat uncertain due to the incomplete knowledge of the drift length L (we take $L=Nd$),

$$\mu_d=\frac{L^2}{Q_0}\frac{dI_p}{dV_{\rm appl}} , \tag{2}$$

the temperature dependence of μ_d can be measured rather accurately. Above 40 K a linear dependence of μ_d on T^{-1} with a *positive* slope is observed as illustrated by the solid line in Fig. 3. Below 40 K the mobility depends linearly on T^{-1} with a constant offset and a *negative*

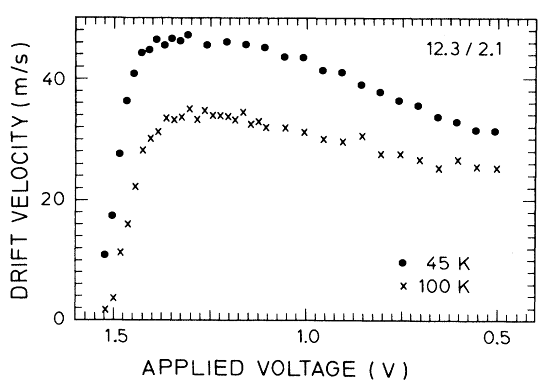

FIG. 1. Drift velocity vs applied voltage for sample I [(12.3 nm GaAs)/(2.1 nm AlAs)] at two temperatures. The data at 45 K were shifted upward by 10 ms^{-1} to avoid a crossing of the two curves. The built-in voltages are 1.52 V for both samples.

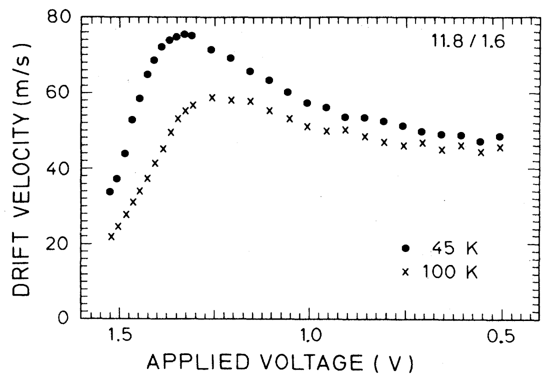

FIG. 2. Drift velocity vs applied voltage for sample II [(11.8 nm GaAs)/(1.6 nm AlAs)] at two temperatures. The data at 45 K were shifted upward by 20 ms^{-1} to avoid a crossing of the two curves. The built-in voltages are 1.54 V at 45 K and 1.62 V at 100 K.

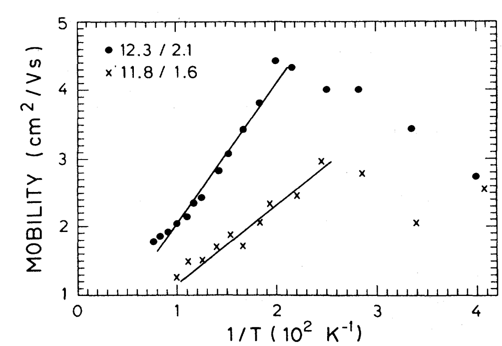

FIG. 3. Low-field drift mobility as defined by Eq. (2) vs inverse temperature for both samples. The solid lines mark the regime where the mobility is proportional to T^{-1}.

slope. The latter temperature dependence can be approximated by $\exp(-E_a/k_BT)$, where E_a is an activation energy with a value of approximately 1 meV and k_B is Boltzmann's constant.

In the first model of NDV in superlattices proposed by Esaki and Tsu[2] the drift velocity did not contain an explicit temperature dependence. Nevertheless, the qualitative field dependence of NDV for miniband transport is rather well described by the Esaki-Tsu formula using an oversimplified approach which does not distinguish between momentum and energy relaxation:[2]

$$v_d(F)=A_1\frac{F/A_2}{1+(F/A_2)^2}\,, \tag{3}$$

where $A_1=d\Delta/(2\hbar)$ and $A_2=\hbar/(e\tau d)$ with τ being a scattering time. The parameter A_1 is the largest possible drift velocity which can only be achieved in the idealized case of field-independent energy relaxation. The electric field F is the effective electric field discussed above. The only parameter in Eq. (3) that can be temperature dependent is the scattering time τ. The drift mobility in the limit of $F\rightarrow 0$ is given by $\mu_0=e\tau\Delta d^2/(2\hbar^2)$. If we take this model and compare it with the experiment, we find a scattering time of the order of 1 fs which does not seem to be physical. This is not surprising, since the model by Esaki and Tsu is oversimplified and does not take into account the finite occupation of higher miniband states at finite temperature. Lebwohl and Tsu[3] took into account a finite occupation of the miniband in the degenerate limit at zero temperature. Except for a multiplicative factor which varies between 1 and 0.5 depending on the position of the Fermi level in the miniband, the drift velocity is again given by Eq. (3). Shik[4] calculated the low-field drift mobility in the linear field regime for arbitrary occupation at finite temperatures. In the nondegenerate limit which is achieved in our samples (the photogenerated carrier density is of the order of 10^{14} cm^{-3}), the drift mobility reads

$$\mu_d=\mu_0\frac{\Delta}{2k_BT}\frac{\gamma_1}{2}\,, \tag{4}$$

where μ_0 is the Esaki-Tsu drift mobility. γ_1 is a number of order unity. This result differs significantly from the drift mobility in bulk semiconductors with a constant effective mass. In this case the mobility is independent of temperature for Maxwell-Boltzmann statistics.[20] Using the same parameters as above we obtain at 80 K a scattering time of about 30 fs from Eq. (4) which seems to be much more reasonable. A more complete solution of Boltzmann's equation in the nondegenerate limit leads to[5]

$$v_d(F)=A_1\frac{I_1(\Delta/2k_BT)}{I_0(\Delta/2k_BT)}\frac{F/A_2}{1+(F/A_2)^2}\,, \tag{5}$$

where A_1 and A_2 are taken from Eq. (3) and I_n are the modified Bessel functions of order n. Equation (5) differs from Eq. (3) by the occupation factor I_1/I_0. The drift mobility at low electric fields is then given by

$$\mu_d=\mu_0\frac{I_1(\Delta/2k_BT)}{I_0(\Delta/2k_BT)}\,, \tag{6}$$

which in the limit of $\Delta\ll 2k_BT$ reduces to Eq. (4) with $\gamma_1=1$. For large values of the miniband width with respect to the temperature the occupation factor in Eq. (6) becomes temperature independent and the drift mobility is equal to the Esaki-Tsu value μ_0. The same limit applies to Eq. (5). Our experimental results of the temperature dependence of the drift mobility as shown in Fig. 3 agree above 40 K very well with the temperature dependence given by Eq. (6) in the limit of $\Delta\ll 2k_BT$ which is valid in this temperature range. The absolute values of the drift mobility are still an order of magnitude smaller than one would expect with the scattering time of a few hundred femtoseconds in bulk GaAs.[21] However, the temperature dependence is clearly reproduced. This implies that the scattering time that governs the transport is only weakly temperature dependent or independent of temperature. Note that the slope of the mobility-vs-temperature curve is reduced for the sample with the wider miniband in agreement with Eq. (6).

In Fig. 4 the drift velocity is shown for both samples at 45 K including a fit to Eq. (5) in the limit of small miniband widths. The fit for sample II [Fig. 4(b)] is excellent over the whole temperature range, while the drift velocity for sample I [Fig. 4(a)] is not as well reproduced by Eq. (5). However, in both cases the parameters obtained from the fits are very reasonable. The resulting scattering time τ is 135 fs in sample I and 157 fs in sample II. Both values are considerably smaller than the period for Bloch

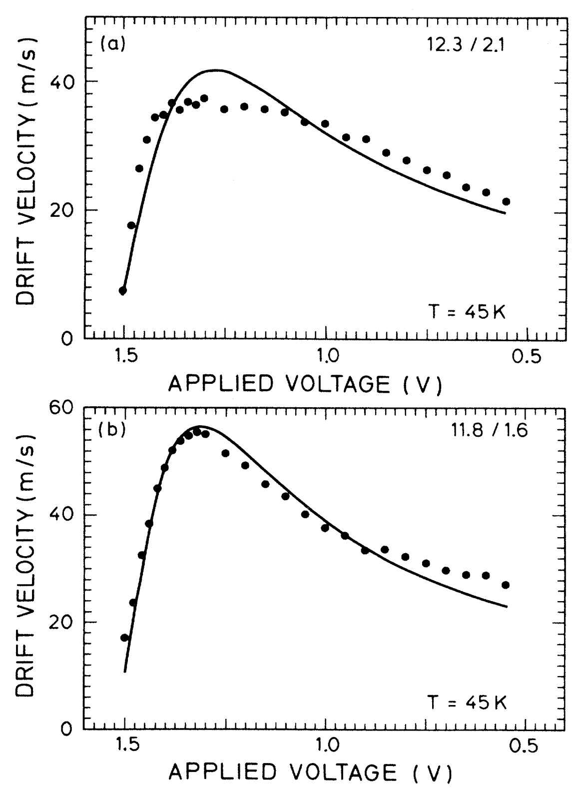

FIG. 4. Experimental data (solid circles) and theoretical simulation (solid lines) according to Eq. (5) of the drift velocity in (a) sample I and (b) sample II at 45 K.

oscillations $\tau_B = h/(eFd)$ at 1 kV cm^{-1} which has a value of 2.7 ps. The prefactor A_1 together with the occupation factor leads to a miniband width of about 0.4 meV in reasonable agreement with the estimated bandwidth in these samples.

We have also tried to fit the data with a model proposed by Kazarinov and Suris[9] for intersubband tunneling. It can be rewritten for miniband transport so that the drift velocity has the following field and temperature dependence:

$$v_d(F) = B_1 \frac{1-\exp(-eFd/k_BT)}{1+(F/A_2)^2} \tag{7}$$

with $B_1 = 2d\tau\Delta^2/\hbar^2$. The temperature-dependent term appears because of the finite probability for a carrier to diffuse in the opposite direction of the field drift. The low-field drift mobility has the same temperature dependence as in Eq. (4), but the magnitude is a factor of 16 larger, resulting again in a much smaller scattering time. We are able to achieve quite good fits with Eq. (7), but only if we assume an unphysical value for the superlattice period d in the exponential function in Eq. (7). A similar temperature dependence was proposed for hopping conduction.[10,22] But as we do not have a complete analytical expression for the hopping probability, we are not able to use the hopping model to fit our data. Calecki, Palmier, and Chomette[11] calculated the hopping conduction in multiple-quantum-well structures and found that the mobility actually increases with temperature. This temperature dependence is observed below 40 K in our samples. The existence of a crossover between miniband transport and hopping conduction could be taken as evidence for the presence of a mobility gap in narrow-miniband semiconductor superlattices as was proposed by Fertig and Das Sarma.[16] Our miniband widths fall exactly into the range where the mobility gap should be observable. The activation energy that is obtained from the temperature dependence of the mobility below 40 K should be a measure of the mobility gap. This activation energy is about 1 meV which is in the same range as discussed by Fertig and Das Sarma.[16]

In summary, we have measured the drift velocity in GaAs/AlAs superlattices with narrow minibands as a function of electric field and temperature. The field dependence exhibits negative differential velocity as proposed by Esaki and Tsu. A transport model as applied by Suris and Shchamkhalova which includes the occupation at finite temperatures results in a good reproduction of the experimental data with reasonable parameters. Two transport regimes are observed. At temperatures above 40 K we find miniband transport with a temperature-independent scattering time (e.g., neutral impurity scattering). Below 40 K we attribute the temperature dependence of the drift mobility to hopping conduction. The presence of a crossover between band transport and hopping conduction is taken as a signature for the existence of a mobility gap in these narrow-miniband superlattices. Finally, we note that heating of electrons at large electric fields can be neglected in our samples since the miniband width is much smaller than the thermal energy of the electrons.

We would like to thank H. Schneider for helpful discussions. This work was supported in part by the Bundesminister für Forschung und Technologie.

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