# Observation of Esaki-Tsu Negative Differential Velocity in GaAs/AlAs Superlattices

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The perpendicular peak velocity and critical field have been measured in a series of GaAs/AlAs superlattices as a function of the miniband width and miniband position relative to the AlAs $X$ confined levels. The data cannot be explained by the electric-field localization mechanism [R. Tsu and G. Döhler, Phys. Rev. B **12**, 680 (1975)] in the range of superlattice parameters investigated, but are qualitatively understood in terms of electron acceleration within the miniband [L. Esaki and R. Tsu, IBM J. Res. Develop. **14**, 61 (1970)].

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Esaki and Tsu[1] proposed years ago to tailor nonlinear electronic transport properties of semiconductors by using superlattice (SL) structures in order to obtain high-frequency oscillators. The idea was that electrons accelerated in a miniband perpendicularly to the layers might exhibit negative differential velocity (NDV) due to the negative effective mass (NEM) they would experience. A related but distinct question is the eventuality of Bloch oscillations for electrons ballistically accelerated beyond the minizone boundary. Another negative-differential-conductance (NDC) mechanism in SL structures was proposed,[2] relying on a transition between Bloch miniband transport and hopping transport between Wannier-Stark quantized levels (WSL).[3]

However, all perpendicular NDC data to our knowledge[4-6] have been interpreted by *microscopic* high-field domain formation, which implies that the SL can no longer be described as a homogeneous entity.

Conversely, the relevance of the WSL mechanism has been argued in a few photoconduction experiments on illuminated SL junctions.[7-9]

In our recent work,[10,11] we have, on the other hand, proved that GaAs/AlAs SL's exhibited reproducible NDV *as a bulk superlattice effect* for fixed SL parameters, but the microscopic mechanism was only speculated. We show in this Letter from systematic measurements on a series of samples that NEM is clearly responsible for NDV over a large range of SL parameters, under the condition of wide minibands. We further argue that WSL may dominate transport properties in SL's with narrow minibands.

The samples have been grown by molecular-beam epitaxy on GaAs substrates, and characterized by simple and double x-ray diffractometry. They consisted of an undoped or lightly Si-doped GaAs/AlAs SL ($\sim 1.5\ \mu$m) embedded between $n^+$ ($2\times10^{18}\ e^-/\text{cm}^3$) contact layers; the latter included intermediate layers of graded average composition in the form of short-period superlattice quasialloys, intended to provide efficient electron injection by the cathode. Electrically contacted mesa devices of area $>350\ \mu\text{m}^2$ were obtained by conventional processing techniques. Throughout the paper we label by $(n/m)$ a SL with $n$ GaAs and $m$ AlAs monolayers (2.83 Å) for the well and the barrier.

Standard current-voltage ($I$-$V$) measurement techniques were applied to these devices using either dc or pulsed (200 ns) voltages. Microwave conductance measurements were also performed in the range 0.05–16 GHz with a WILTRON 360 network analyzer. Finally, investigations under hydrostatic pressure up to 6 kbar were made at 300 K in a cell containing pentane with a calibrated pressure gauge.

Typical $I$-$V$ curves at 300 K are shown in Fig. 1. They are not very different at 77 K. The low-bias rectification is just a consequence of the $p^-$ character ($\sim 10^{15}$ acceptors/cm$^3$) of the SL.[10] We have previously demonstrated that the high-bias sublinearity is characteristic of NDV,[10,11] NDC being absent because of the

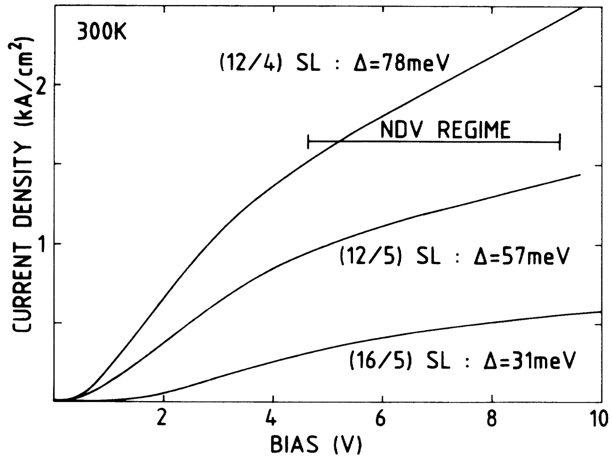

FIG. 1. $I$-$V$ characteristics of undoped SL structures. $\Delta$ is the width of the $\Gamma$ miniband.

electric-field nonuniformity (on a macroscopic scale). On the other hand, doped $n$-type samples exhibit static NDC, on the condition that a minimum (doping level)×(SL length) product was attained.[11,12] These features bear close similarities with the ordinary Gunn effect,[13] although the microscopic origin of NDV is different.

When biased in the sublinear regime, our samples systematically exhibit Hakki microwave conductance resonances (Fig. 2) at frequencies close to the inverse electron transit time or harmonics.[13] This effect stems from the time delay between a voltage excitation and the arrival of electrons at the anode. The very existence of these resonances together with the marked decrease of the frequencies with increasing voltage is actually a double proof of NDV.

Since frequency limitations prevent the determination of velocity-field ($V$-$F$) relations by such techniques, we have chosen to extract these relations from $I$-$V$ data, as successfully achieved previously.[10,11] Whenever they could both be applied, the two methods yielded comparable results; for instance, we deduce a peak velocity $V_p > 1.3\times10^6$ cm/s from the data of Fig. 2, while we find $\sim1.8\times10^6$ cm/s from static $I$-$V$ data. Because of the field nonuniformity, a numerical solver of drift-diffusion and Poisson equations coupled self-consistently, which takes into account the detailed device structure, has in fact to be used in order to extract velocities.[14] The unknowns are the residual acceptor content $N_a$ and the $V$-$F$ relation of the SL, and these are determined by a fitting procedure. We chose a phenomenological $V$-$F$ law of the form

$$V(F)=\mu F/(1+|F/F_0|^{\beta}),$$

where $\mu$ is the mobility. NDV is obtained beyond a critical field $F_c$, only if $\beta>1$. Although we cannot determine a unique set of the fitting parameters, a good agreement over the whole $I$-$V$ curve is impossible outside a narrow zone of the $V$-$F$ graph. We estimate the error on $V_p$ and $F_c$ to be about 30% at most, since each parameter influences the $I$-$V$ in a specific manner.

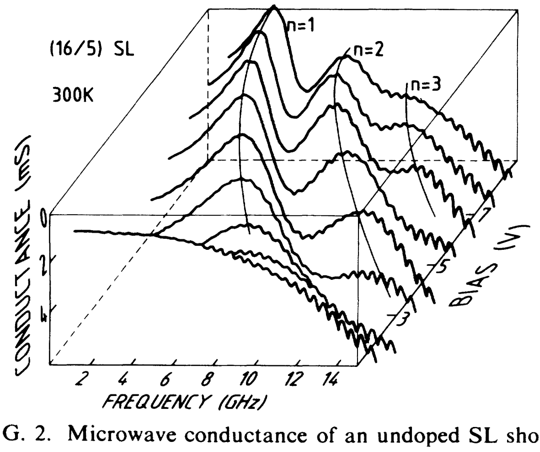

FIG. 2. Microwave conductance of an undoped SL showing up to three Hakki resonances. The bias is varied from 1 to 9 V in steps of 1 V.

This effective-medium approach is correct here because the present samples are true SL structures with miniband conduction, as opposed to multiple quantum wells where microscopic high-field domains may appear.[4,5] Furthermore, overshoot effects can be neglected in our thick (1.5 $\mu$m), low-velocity ($<5\times10^6$ cm/s) structures.

A series of samples has been studied, for SL parameters ranging from 10 to 20 GaAs monolayers and 3 to 7 AlAs monolayers. For the present transport measurements, we only consider the relevant SL quantum states (Fig. 3, inset), i.e., the lowest $X_{1z}$ confined level and the lowest $\Gamma_1$ miniband. The width $\Delta$ of the latter is computed in the envelope-function approximation and takes account of nonparabolicity through a $\mathbf{k}\cdot\mathbf{p}$ calculation of the effective masses. The $L$ valley is neglected as it is much higher in energy.

Having the GaAs Gunn effect in mind, one preliminary question to answer is the eventual participation of the indirect $X$ valley to NDV. We thus performed hydrostatic-pressure experiments on a (13/7) SL ($n=10^{16}\ e^-/\text{cm}^3$) for which the $\Gamma$-$X$ distance between the bottom of the $\Gamma$ miniband and the $X_{1z}$ level is only

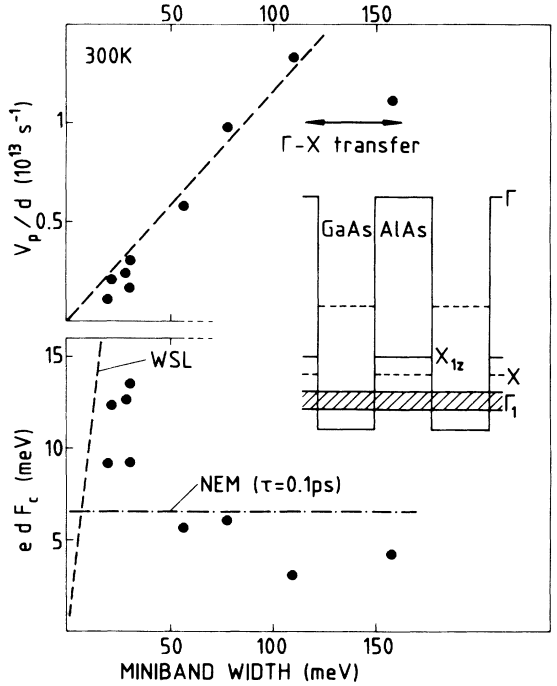

FIG. 3. Top: Dependence on $\Delta$ of the peak velocity divided by the SL period. The dashed line is only a guide to the eye. Bottom: Dependence on $\Delta$ of the voltage drop per period at the critical field, including predicted dependences for the two mechanisms WSL and NEM. Inset: Conduction-band diagram of the relevant energy levels.

60 meV (Fig. 4). We thus expect $F_c \sim 0$ at the pressure of 5 kbar where the $\Gamma$-$X$ direct-indirect crossover occurs, if NDV is due to $\Gamma$-$X$ transfer. The experimental data are, however, inconsistent with this prediction. On the other hand, the experimental dependence of $\mu$ on pressure has a straightforward explanation in terms of pressure depopulation of the $\Gamma$ miniband *at thermal equilibrium,* and of negligible $X$-valley perpendicular conduction: $\mu = \mu_\Gamma f_\Gamma$, where $\mu_\Gamma$ is the true $\Gamma$ miniband mobility and $f_\Gamma$ the fraction of $\Gamma$ electrons. The agreement between data and the calculated dependence of $f_\Gamma$ is good for a transverse $X$ mass of 0.4 (Fig. 4). We also independently obtain a good agreement for the temperature dependence of $\mu$ with the same parameters. Finally, we have investigated samples of varied $\Gamma$-$X$ distances (182 meV down to $-14$ meV, i.e., indirect SL), $\Delta$ being approximately constant (27–31 meV). Except for the indirect sample (no NDV present), both $F_c$ and $V_p$ were independent of the $\Gamma$-$X$ distance within a factor 2. All these results unambiguously prove that NDV is not due to $\Gamma$-$X$ transfer and is a phenomenon specific of the $\Gamma$ miniband.

In order to differentiate between the NEM and WSL mechanisms, we have plotted $edF_c$ and $V_p/d$ in Fig. 3 as a function of $\Delta$, where $d$ is the SL period. Esaki and Tsu's NEM theory[1] indeed predicts $V_p/d = \Delta/4\hbar$, and also $edF_c = \hbar/\tau$ which is thus a fixed quantity for a given scattering time $\tau$. Tsu and Dohler's WSL theory,[2] on the other hand, predicts $edF_c \sim \Delta$ and a superlinear dependence of $V_p/d$ on $\Delta$.

It is obvious from Fig. 3 that the experimental values of $edF_c$ rapidly and strongly deviate from the line predicted by the WSL mechanism. These values instead do not sensibly depend on $\Delta$, especially beyond 30 meV, which results in over an order-of-magnitude discrepancy for, e.g., $\Delta = 100$ meV. Furthermore $V_p/d$ appears to vary linearly with $\Delta$, at least up to $\Delta \sim 100$ meV. These two features strongly argue against the WSL mechanism and in favor of the NEM one. Unfortunately, the agreement with the Esaki-Tsu theory is not quantitative since the slope of the $V_p/d$ vs $\Delta$ plot should be a factor of 3 higher. In view of the theory's extraordinary simplicity, however, a full agreement would have actually been quite surprising. For instance, sophisticated Monte Carlo computations in GaAs/GaAlAs SL's also yield velocities smaller than calculated from the Esaki-Tsu formula by a factor of 3 to 6.[15]

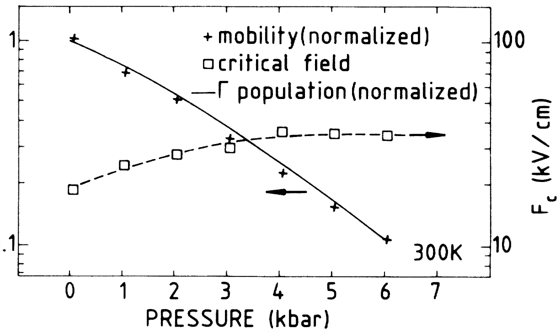

FIG. 4. Hydrostatic-pressure dependence of the mobility and of the calculated $\Gamma$ miniband population, both normalized to their value at ambient pressure. The variation of the critical field is also shown.

The above experiments thus clearly establish the origin of NDV as semiclassical transport in a nonparabolic band with NEM. This does not mean that WSL's do not exist, since they have been convincingly observed by optical techniques.[16] We argue that in wide-miniband SL structures, and for the low critical fields due to NEM, the energy spacing between successive WSL's is just too small to be significant. Conversely, we expect them to prevail in narrow-miniband structures for which localization is achieved under very small fields.

For clarity in the reader's mind, we also stress that Bloch oscillations are not indispensable to NDV *per se.* Instead it is likely that the fraction of electrons accelerated up to the minizone boundary and experiencing Bragg reflection[17] is rather small, due to strong scattering. NDV only requires that the center of the distribution function in $k$ space approaches the inflection point of the miniband dispersion relation under field. Of course, the width of this distribution is such that both phenomena are in fact intimately connected, and cannot be experimentally distinguished at present.

Finally we note that $V_p$ appears to saturate beyond $\Delta \sim 100$ meV in these GaAs/AlAs SL's (Fig. 3). We may interpret this effect as the onset of $\Gamma$-$X$ Gunn transfer, for very wide minibands whose top exceeds the $X_{1z}$ level. In other words, we probably observe a transition between two NDV regimes, one being due to NEM and the other to $\Gamma$-$X$ Gunn transfer. Practically, $\Gamma$-$X$ mixing may in fact render this distinction somewhat arbitrary.

In conclusion, we have obtained the first evidence of miniband negative differential perpendicular velocity in superlattices, and strong arguments in favor of the nonparabolicity mechanism for NDV over a large range of SL parameters. Wannier-Stark quantization does not appear necessary to interpret the experimental data, except for narrow minibands.

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