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Negative differential conductance in GaAs/AlAs superlattices

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Voltage-controlled superlattice negative differential conductance (NDC) is observed in microwave impedance measurements of n-type GaAs/AlAs superlattices biased perpendicular to the layers. The electron transit time deduced from the peak NDC frequency is in good agreement with the velocity-field relation obtained from dc current-voltage measurements. The data also yield the criteria for the existence of dc or high-frequency NDC. Finally, a fine structure in the conductance-voltage data at low temperatures is interpreted in terms of inhibited perpendicular transport and high-field domain formation beyond the critical field.

Since the pioneering theoretical work of Esaki and Tsu,[1] negative differential conductance (NDC) perpendicular to the layers of semiconductor superlattices (SL), has been practically demonstrated in a few cases almost exclusively at low temperatures: in early[2] and recent[3,4] experiments on multiple quantum wells (MQW), NDC resulted from expanding high-field domains and sequential tunneling through the barriers. Other contributions involve electron tunneling through enlarged barriers sandwiched between two superlattices.[5] It is clear, however, that such mechanisms are intimately related to the inhomogeneous character of the medium, eventually under biasing if not at equilibrium.

We show in this Rapid Communication that perpendicular NDC can indeed be observed at room temperature in properly designed small-period true superlattices, which therefore behave as homogeneous tailorable anisotropic bulk materials, for which macroscopic velocity-field relations (v-F) are suitable concepts at 300 K. On the other hand, such an effective-medium description appears to fail at low temperatures, where evidence of SL heterogeneity is observed.

The samples have been grown by molecular beam epitaxy on n^+-type GaAs:Si substrates and are composed of a lightly Si-doped (10^{16} cm^3) GaAs/AlAs SL sandwiched between Si-doped (2×10^{18} cm^{-3}) GaAs contact and buffer layers. Abrupt heterojunctions between SL and GaAs were avoided by incorporating between them pseudoalloys of gradual composition and doping level. Further processing involved mesa etching of variable-area devices in a proportion from 1 to 3 (40×110 μm^2 for the smallest size) and Au-Ge-Ni evaporated Ohmic contact alloying at 450 °C. Three structures have been grown, differing only by the total SL thickness (1500, 3000, and 6000 Å). In all three the SL parameters were kept fixed, namely 13 GaAs monolayers for the well (37 Å) and 7 AlAs monolayers for the barriers (20 Å), and are from now on referred to as $(GaAs)_{13}/(AlAs)_7$ SL.[6] The growth parameters were calibrated using reflection high-energy electron diffraction (RHEED) oscillations, together with x-ray simple and double diffraction.

We have recently indirectly inferred[6] from current-voltage (I-V) measurements on p^- undoped SL the existence of negative differential velocity (NDV) in a $(GaAs)_{13}/(AlAs)_7$ SL. NDC was nevertheless not achieved because of the strongly nonuniform electric field. It has indeed been theoretically and experimentally demonstrated that dc NDC required that a minimum device length times carrier concentration ($n\times l$ product) criterion was met, in order to minimize injection effects and field nonuniformity.[7,8] Below this threshold, ac NDC may be observed at frequencies very close to the inverse transit time of carriers. Finally, if the nl product is very low, all NDC is inhibited.

We have tested these predictions on a series of n-doped $(GaAs)_{13}/(AlAs)_7$ SL ($n\sim10^{16}$ e/cm^3) of variable thicknesses in a proportion ranging from 1 to 4 ($l=1500$, 3000, and 6000 Å). In Fig. 1 are shown typical I-V data for the three samples at 300 K. A strong sublinearity is found under high voltages, although no NDC is observed. We have computed theoretical I-V curves for the three samples, by solving Poisson and drift-diffusion equations.[9] Electronic transport through the SL is described with the help of an (unknown) v-F relation. All other parameters are known, i.e., layer thicknesses, compositions, and doping levels for the whole structure. The sensitivity of high-voltage data to the very shape of the v-F relation is exemplified in Fig. 2, where several phenomenological re-

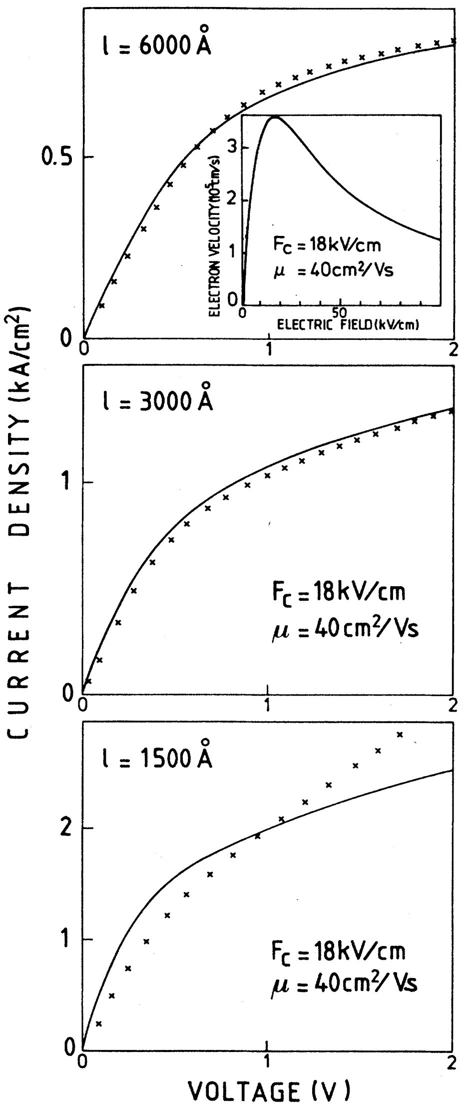

FIG. 1. I-V data at 300 K for the three samples (crosses), and best-fit simulations (full curves) using the same v-F relation (inset) of the form $v=\mu F/(1/F^2/F_c^2)$.

lations have been used of the form

$$v=\mu F/(1+F^n/F_0^n)\,. \qquad (1)$$

Here μ is the low-field mobility. Trivially, NDV is obtained only if $n>1$. Both parameters have to be adjusted by a fitting procedure. However, there is little uncertainty on μ, which is related to the low-field Ohmic conduction, and the value $\mu=40$ cm^2/Vs has been found satisfactory (Fig. 1).

For $n=1$, the velocity saturates to a limit $v_l=\mu F_0$. The complete inadequacy of such a law is obvious in Fig. 2 for $F_0=20$ kV/cm, and the discrepancy still worsens if one attempts to change F_0. On the other hand, an excellent agreement is obtained with $n=2$, resulting in NDV beyond a critical field $F_c=F_0=18$ kV/cm and a peak velocity $v_p=\mu F_c/2=3.6\times10^5$ cm/s. Such experiments thus yield almost directly the SL v-F relation. It is remarkable that the best-fit law is very close to that deduced on undoped $(GaAs)_{13}/(AlAs)_7$ SL structures ($n=2$, $\mu=40$ cm^2/Vs, $F_c=16.5$ kV/cm, $v_p=3.3\times10^5$ cm/s) studied previously.[6] This demonstrates both the excellent reproducibility of the growth together with the well-defined correspondence between SL parameters and v-F relation, and the insensitivity of the v-F relation to the electron concentration in the range 10^{15}–10^{16} e/cm^3. This in turn justifies the validity of such a relation.

The fit is, however, rather poor for the thinnest SL (1500 Å), but this is probably due to an incorrect modeling of transport through the access layers sandwiching the SL.

The relevance of a local equilibrium description of the transport may nevertheless be questioned in such thin samples where nonstationary effects might be expected. Such effects have been demonstrated in GaAs because of the large electron velocities.[10,11] For instance, the threshold field for NDV in 1-μm-thick GaAs n^+-n^--n^+ structures is roughly doubled compared to its stationary value[12] for transit times of order 5 ps. For comparison the

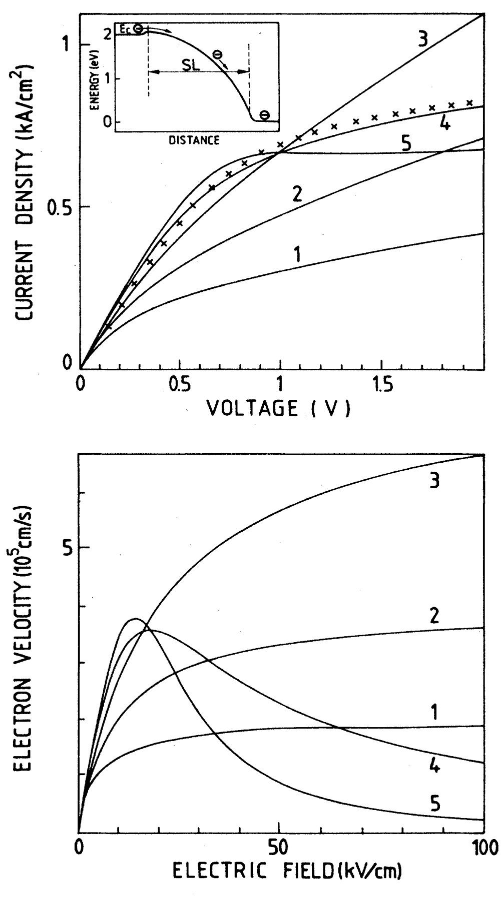

FIG. 2. Experimental (crosses), and simulated I-V data for the thickest sample ($l=6000$ Å) using an analytical relation of the form: $v=\mu F/(1+F^n/F_0^n)$ with $\mu=40$ cm^2/Vs; curves 1, 2, 3: $n=1$, $F_0=5$, 10, 20 kV/cm; curve 4: $n=2$, $F_0=18$ kV/cm; curve 5: $n=3$, $F_0=18$ kV/cm. Inset: Band diagram under 2-V bias, showing the strong field inhomogeneity.

transit time in the present SL devices is at least 100 ps (see below), so that a local description of transport is actually correct.

As shown in Figs. 1 and 2, NDC is not observed at 300 K in all three samples. This indicates that the minimum nl product is not attained. Simulations with the v-F law of Fig. 1 predict NDC with doping levels of $\sim 3\times 10^{16}$ e/cm^3 and above. The criterion for dc NDC therefore appears to be $nl \sim 10^{12}$ e/cm^2 for a $(GaAs)_{13}/(AlAs)_7$ SL, actually very close to GaAs.[8]

The following microwave measurements were performed with the devices mounted at the end of a 50-Ω coplanar waveguide line, using short wire bonding. The device reflexion coefficient was determined with an HP 8409 network analyzer in the range 0.5–18 GHz, from which were extracted real and imaginary parts of the impedance. Standard deembedding techniques allowed us to eliminate the influence of parasitic elements of the mounting system.

From raw data we deduced the sample conductance (R^{-1}) and capacitance (C) through a small signal equivalent RLC circuit analysis including the wire inductance L (Fig. 3).

As expected from the introductory discussion, NDC is indeed observed in a finite-frequency range intimately associated with the transit time of electrons throughout the SL, and only beyond the onset of sublinearity in the I-V curves (Fig. 3). From the peak NDC frequency f_m, we can deduce an average velocity $v_m = l f_m$, i.e., 2.1×10^5 cm/s and 1.8×10^5 cm/s for $l = 6000$ and $l = 3000$ Å SL thicknesses, respectively, corresponding to 42 and 50 kV/cm. The agreement with the v-F relation of Fig. 1 is quite reasonable and confirms the magnitude of the velocities deduced from the I-V data. The scaling relation between f_m and 1 is actually by itself an excellent proof that NDC is indeed a transit-time effect.

We also observe that the magnitude of the NDC is maximum for the thickest sample, and that it decreases with decreasing thickness; in fact, NDC is even absent in the thinnest sample, and only a minimum (positive) conductance out of a broad peak is apparent. It is due to the enhanced role of diffusion near the cathode compared to drift near the anode. Therefore, there is a distribution of transit times. Correlatively, the device impedance "resonates" in a large range of frequencies. This behavior is also in excellent agreement with the introductory discussion, and we can infer the second criterion for microwave NDC, i.e., $n\times l \sim 2\times 10^{11}$ e/cm^2.

We nevertheless stress that this criterion, as well as the first, should not be too strictly considered, as it has been determined for a single doping level and a limited range of thicknesses. In particular, increasing the doping level too much will result in filling of the miniband (degenerate doping), with a resulting modification of the v-F law.

Finally, low-temperature dc I-V measurements have been performed on these samples. There is little difference with 300-K data, except for the appearance of a fine structure in the device conductance (Fig. 4). The oscillatory behavior beyond 1 V is clearly reminiscent of the experiments of Esaki and Chang[2] interpreted in terms of expanding high-field domains on successive SL periods. The "driving force" for successive NDC events is indeed

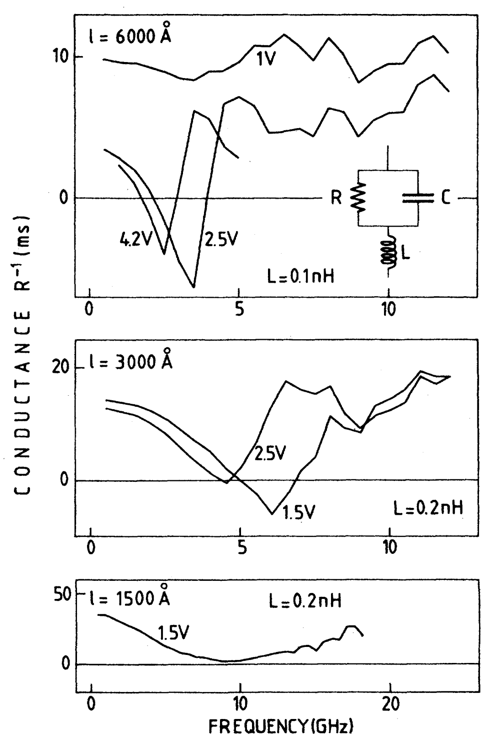

FIG. 3. Conductance R^{-1} of the three samples as a function of the frequency, at various voltages. The data have been analyzed using a simple RLC equivalent circuit (inset).

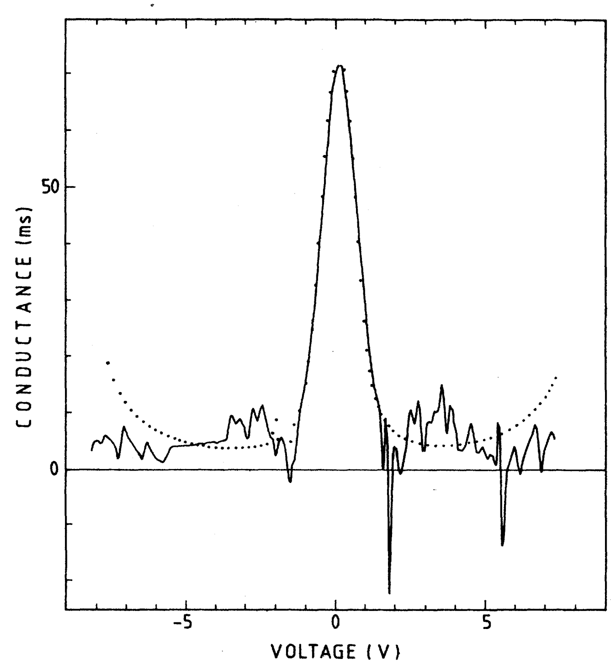

FIG. 4. Conductance-voltage data for the thickest sample ($l = 6000$ Å) at 300 K (dots) and 80 K (full curve). The conductance rise beyond 4 V at 300 K is due to sample heating.

electron-field-induced localization when the voltage drop per period Fd times the electron charge exceeds the miniband width Δ: $eFd > \Delta$.

In the present case, we have $\Delta \sim 12$ meV (from the envelope function calculations, Ref. 13, with a 1-eV Γ-Γ barrier), so that the minimum field is ~ 21 kV/cm. The observation of these features is interesting since it probably rules out Γ-X transfer as the source of NDC. If beyond F_c, a majority of electrons had indeed transferred to a side valley, electric-field-induced localization in the first Γ miniband would be inoperative, and high-field domain formation inhibited. Furthermore, the first NDC peak in the conductance-voltage curves is at 1.5 V, which is very close to the minimum voltage for microwave NDC at 300 K (1.6 V). It is thus clear that both phenomena are intimately connected. We thus propose an interpretation of NDV in terms of electric-field-induced electron localization in the SL.[14] There is also an excellent agreement between the expected critical field for this mechanism (21 kV/cm) and the experimental value for F_c (18 kV/cm). As a further argument, Wannier-Stark ladder formation which is a crucial characteristic of the underlying physics, has recently been directly observed in GaAs/$Ga_{1-x}Al_xAs$ SL by optical techniques.[15]

On the other hand, minibands of X character are only about 50–100 meV higher in energy than the first Γ miniband.[16] We interpret the absence of Γ-X transfer by the small value of the miniband width which inhibits electrons heating. In other words the presence of a higher-lying minigap prevents Γ electrons to gain enough energy from the field to transfer resonantly to the X valley, and localization occurs within the Γ miniband.

The samples studied here are probably intermediate between perfect superlattices with pure miniband conduction, and multiple quantum well with hopping conduction from well to well. The figure of merit allowing to distinguish between these two cases is the ratio of total-energy broadening (SL disorder plus phonons) to miniband width. An upper bound for this broadening is about half the linewidth of intersubband absorption spectra (since two minibands participate in the absorption), i.e., ~ 3 meV from recent work (Ref. 17), so that the broadening is only a fraction of the miniband width. Therefore, we consider justified to call the present samples true SL.

Finally, we may question why a fine structure in the conductance is observed at 80 K, but not at 300 K. This problem relates to transport processes beyond F_c, i.e., when the electron wave functions are mostly localized in one SL period and transport occurs by scattering between Wannier-Stark levels. Domain formation is favored when such transitions are strongly inhibited at high fields, i.e., if the electron velocity is a steeply decreasing function of F beyond F_c. The magnitude of the NDV at 300 K is not quite sufficient for domain formation at this temperature. On the other hand, it increases when the temperature decreases, as shown by temperature-dependent I-V measurements in the range 300–430 K.

In conclusion, we have achieved microwave NDC in a $(GaAs)_{13}/(AlAs)_7$ SL which can be understood through the concept of macroscopic perpendicular v-F relation and NDV. A fine structure in the SL conductance is also observed at 80 K and is shown to result from enhanced NDV when the temperature decreases. This is the first unambiguous demonstration that a uniform SL can behave as a homogeneous anisotropic tailorable bulk material with NDV at room temperatures and above and show a heterogeneous character of the SL at low temperature.

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