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Nonlinear Conduction in Periodically δ-Doped Semiconductors

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We have studied the current-voltage characteristic of MBE-grown semiconductor layers in which the donor impurities are arranged in sharply-defined layers. Marked non-linearities are found to occur as carriers are heated and transferred into the space between the layers.

Donor impurities in a conventionally doped semiconductor are distributed at random. Using epitaxial growth techniques dopant atoms can be introduced in atomically sharp sheets. When these are repeated periodically in a distance "a" the result is a multi δ-layer, a semiconductor material which may be expected to have an unusual electrical conductivity. The layer spacing "a" is to be considered greater than the random average separation in the plane "b". It is expected that electrons leaving their parent δ-sheet and entering the undoped spaces between the layers will have a greatly increased mobility. The principle is well known and practiced in the modulation-doping technique. For this case the carriers are separated permanently from the ionic scatterers by the heterostructure barrier. In the multi δ-layer there is a delicate, dynamic balance between the free and δ-layer-bound carriers which depends on the carrier heating.

In this paper we explore the nonlinearity of the current-voltage relation in the multi δ-layer sketched the upper part of Fig.1. We compare it with the result for lateral transport in the homogeneously doped material of the figure. There is a distinct difference in the two systems. The electrons of the δ-doping layer are quantized in 2-dimensional subbands. When excited thermally or electrically from these levels they enter the spaces between the layers. There they act as free, 3-dimensional carriers. The real-space transfer of

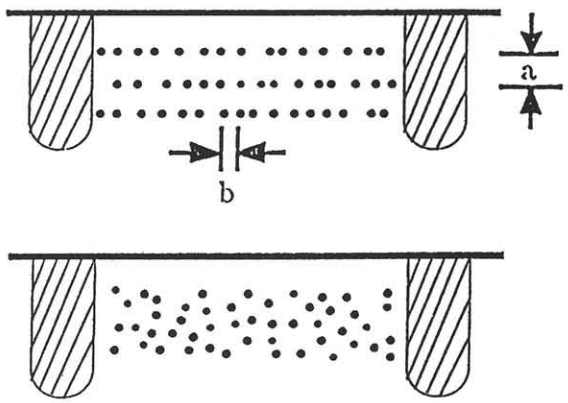

Fig.1 Doping atom configurations for the multi δ-layer (typically n=10) and homogeneous doping case. Current transport between the alloyed Au-Ge contacts takes place laterally.

charge from the δ-layer to the undoped region increases the overall conductivity. A nonlinear rise in the current with increasing electric field can be expected. The problem is analogous to one-dimensional impact ionization. Electrons are ionized out of the δ-layer potential wells and provide a finite conductivity perpendicular to the sheets. In lateral transport, the high density of dopants in the plane assures impurity band or metallic conduction, even without carrier heating. The additional conductivity results from a mobility increase of the hot carriers, between the doping layers.

The first evidence that such a transfer of carriers occurs with rising temperature came from cyclotron resonance experiment /1/. A very sharp, high-mobility carrier cyclotron resonance line was observed for electrons thermally excited away from their parent dopant atoms. In that case, the magnetic field of a few T plays the role of a confining bottle. In weak field the Hall resistance of a multi-layer doping system was shown to be sensitively dependent on the temperature. The effect was explained in terms of a 2-fluid model, with the highly mobile fluid component as the fraction of between-layer electrons.

We demonstrate in Fig.2 that the same effect can also be obtained at fixed temperature when the current, and with it the electric field, is raised in the sample. The figure shows that the Hall resistance strongly changes with the rising measuring current. A thermometer on the sample holder shows the sample temperature to rise only by a small amount above 4.2 K, in any case far less than necessary to explain the change as a temperature effect. The observation is typical of the layer-doped material. It shows that even at small magnetic field, where the confinement effect is insignificant, the electron density between the layers increases with applied voltage.

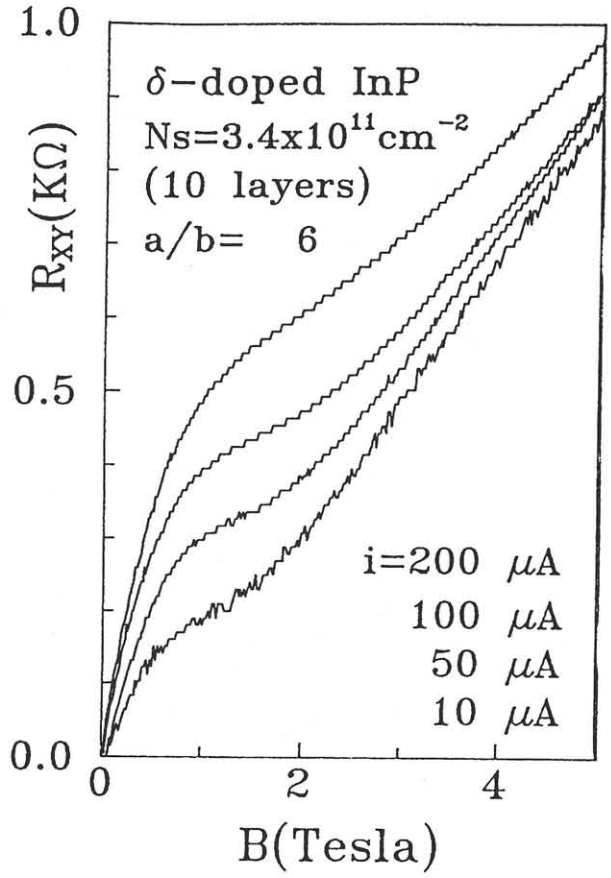

Fig.2 Hall Resistance R_{xy} for a epitaxial InP layer doped with 10 successive sheets with 3.4×10^{11} cm^{-2}. Layer spacing is 100 nm. The nominal temperature is T=4.2 K. Note the increasing slope near B=0 with rising current.

In order to investigate the influence of real space transfer on the conductivity (B=0) we have prepared a series of MBE-grown GaAs materials. Sample (1) is a 10-layer structure with separation a=100 nm and layer density 5×10^{11} cm^{-2}. The average in plane separation b=14 nm. Sample (2) has an identical average volume density of 5×10^{16} cm^{-3}. It is grown by the same MBE technique using a=b=27 nm. For the aspect ratio $^{a}/b=1$ we expect the material to act like homogeneously doped GaAs. The layer sample (3) is designed to equal the conductivity of (1) in the ohmic region. This requires a homogeneous doping of approximately 2×10^{17} cm^{-3}.

We show in Fig.3 the resulting differential conductivity dj/dE in units of S/cm. In the ohmic region,

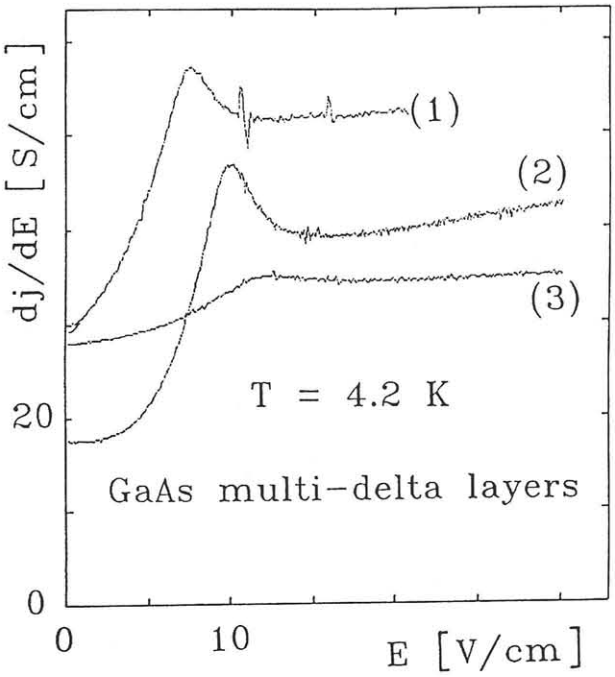

Fig.3 Differential conductivity vs. electric field for three materials with different doping configurations. Each has 10 sheets with different separations a and average in-plane impurity spacing b.
(1) multi δ-layer: a=100 nm, b=14 nm equivalent $n_D=5x10^{16}$ cm^{-3}
(2) homogeneous: a=b=27 nm equivalent $n_D=5x10^{16}$ cm^{-3}
(3) homogeneous: a=b=17 nm

for low E(V/cm), samples (2) and (3) have a constant conductivity. Sample (1) has a strongly rising dj/dE. This is the expected effect of the high mobility electrons. The other interesting observation is that (2) has a much lower ohmic conductivity. The same number of dopant atoms in the form of 10 sheets as in (1) has nearly twice the conductivity. To have the same ohmic conductivity as (1) requires nearly 4 times the homogeneous doping density.

As we increase the field heating, each of the three curves has its own distinct variation of dj/dE with E. Even a small fraction of highly mobile electrons modifies the low field dependence of (1) relative to (2). With rising field both follow a qualitatively similar variation reaching a peak near 10 V/cm. The peak is the result of balancing the decreased impurity scattering with increasing interaction with lattice phonons as the carriers are heated. The fact that the curves (1) and (2) are quite similar, suggests that in the planar-doped system the 3-dimensional, free electrons make the dominant contribution to the current. The dependence of dj/dE on E for sample (3) shows that the non-linearity depends on the doping level. With increased doping the variation with E is much weaker.

We may conclude at this point that it is possible by carefully and deliberately positioning the impurity atoms in an otherwise homogeneous semiconductor material to tailor both the value of the conductivity and the non-ohmic dependence on electric field. The absolute conductivity resulting from a given density of dopants was shown to be higher for the multi δ-layer arrangement. This material also displayed a strongly nonlinear dependence at low value of the electric field.

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