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Impurity Breakdown and Current Filamentation in MBE Grown GaAs with Parallel Monolayer Doping

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Detailed investigations of impurity breakdown are performed in dependence on partial ordering of the impurities by doping in parallel nominally monoatomar layers. The results are compared to equivalent bulk doping. The S-shaped current–voltage characteristics are discussed with respect to the dimensionality of the electron gas as well as to hysteresis and possible filamentation. Furthermore, the dynamic behaviour is investigated concerning the ionization of the carriers from the impurity band as well as their recombination.

In the present paper we investigate the influence of ordering the dopants in nominally mono-atomar planes (δ-layers) on impurity breakdown at low temperatures for the first time whereas it has been studied extensively in bulk semiconductors as well as in homogeneously doped epitaxial layers by various groups. We examined MBE grown GaAs samples with equidistantly positioned Si δ-doping layers. The material was compensated with a lower concentration of Be either ordered in δ-layers, too, or randomly distributed in the volume.

As long as the Si concentration in the δ-layers remains below $10^{11}cm^{-2}$ the current voltage characteristics are of S-shape and exhibit 3 distinctly pronounced regions. A typical I–V characteristic of a sample with such a doping concentration is depicted in Fig. 1. In contrast the characteristics for $10^{11}cm^{-2}$ Si atoms per layer and $3 \cdot 10^{10}cm^{-2}$ Be, respectively, exhibit a region of strong current increase instead of a branch with negative differential conductivity.

From the lack of frequency dependence of the conductivity and the low Hall mobility $\mu_H = 220cm^2/Vs$ together with $n/r_H = 3.3 \cdot 10^{10}cm^{-2}$ in region I we conclude that almost all electrons are in an impurity band. From the angular dependence of the magnetoresistivity the two-dimensional character of the electron gas was deduced. The same measurements in region III delivered that the electrons are in three

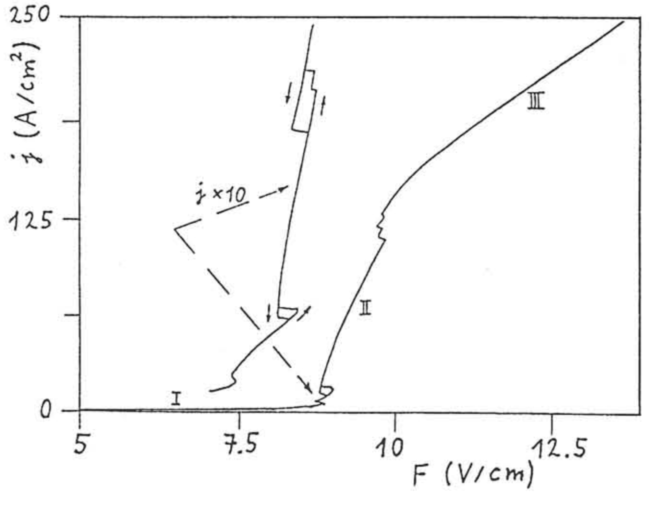

Figure 1: Current vs. field strength for a sample with $7 \cdot 10^{10}cm^{-2}$ Si and $2 \cdot 10^{10}cm^{-2}$ Be atoms per δ-layer (type A sample). The insert shows a magnification of the lower part of region II.

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in region III delivered that the electrons are in three dimensional states (e.g. in the conduction band) with $\mu_H = 14000 cm^2/Vs$ and $n/r_H = 4 \cdot 10^{10} cm^{-2}$.

Region II shows a current increase of three orders of magnitude with a reproducible structure. In this region we also measured periodic circuit limited oscillations beginning just above the threshold for impurity breakdown. For higher currents two or more regions with strongly pronounced hysteresis appear. In bulk material [1, 2] these are conventionally explained by current filamentation. Since we assume that carrier heating results in a sufficient "real space transfer" of the electrons from the doping planes to the 3D interspace, there should be no principal difference to bulk material.

If a magnetic field is applied in the plane of the layers but perpendicular to the current ($B_{\|}^{\perp}$) a shift of the curves to higher electric fields appears which is due to the positive magnetoresistance (Fig. 2).

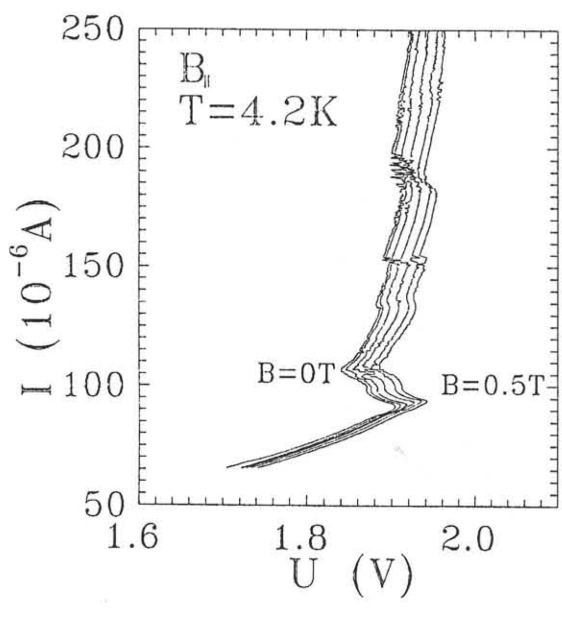

Figure 2: I–V characteristic for a sample with 10 δ-layers with $7 \cdot 10^{10} cm^{-2}$ Si atoms each and a homogeneous p-type doping of $2 \cdot 10^{15} cm^{-3}$ (type B sample) in dependence on a magnetic field applied parallel to the layers and perpendicular to the current.

In the case of a magnetic field applied perpendicular to the layers ($B_{\perp}$) the breakdown field is shifted to higher values in spite of the negative magnetoresistance of the 2D electrons in the impurity band (Fig. 3). This can be explained by the reduced heating of the 3D electrons in region I ('magnetic cooling effect'). Furthermore a striking effect of $B_{\perp}$ not seen for $B_{\|}$ is the smearing out of the structures in the breakdown region. This elucidates the crucial role of the ordered doping.

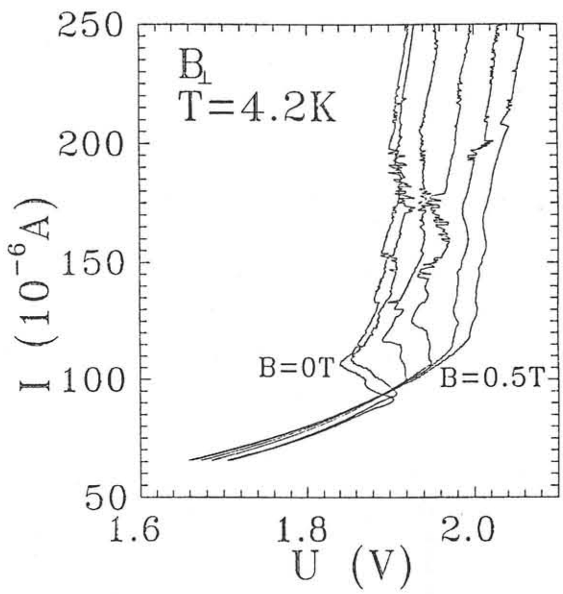

Figure 3: The same as Fig. 2 but with the magnetic field applied perpendicular to the layers.

As well known from bulk semiconductors the inset of impact ionization depends on the compensation of the donors by acceptors. Therefore we investigated the influence of the local distribution of the acceptors by comparing samples with alternating strongly n-type and weakly p-type δ-layers (sample A) on one hand and n-type δ-layers with homogeneous p-type background doping of a concentration equivalent to sample A on the other hand (sample B). The partial ordering of the impurities in planes evidently leads to stronger carrier heating at a given field strength because of a lower impurity scattering rate (Fig. 4). This enhanced mobility in the extended electron states between the planes should be an interesting feature with regard to devices based on avalanche. Furthermore, the behaviour of both samples is compared with a sample doped homogeneously with a slight p-type background.

With regard to the hysteresis of the instable branch connected with current filamentation it is to be noticed that the width of the samples was reduced down to $20\mu m$, yielding qualitatively the same behaviour. This is in contrast to reported widths of $50\mu m$[2] and more[1] in bulk material.

The temperature dependence of the static I-V characteristics is demonstrated in Fig. 5, showing a shift to smaller values of the applied electric field with growing T as expected due to the increasing number of electrons in the conduction band. Above a certain critical temperature the S-shape vanishes completely.

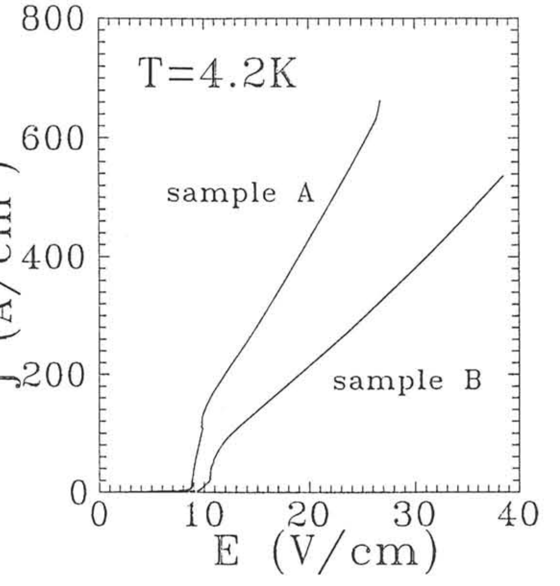

Figure 4: Dependence of I–V characteristics on partial ordering of impurities. Sample A: donors and acceptors in δ-layers, Sample B: donors in δ-layers, acceptors as homogeneous background.

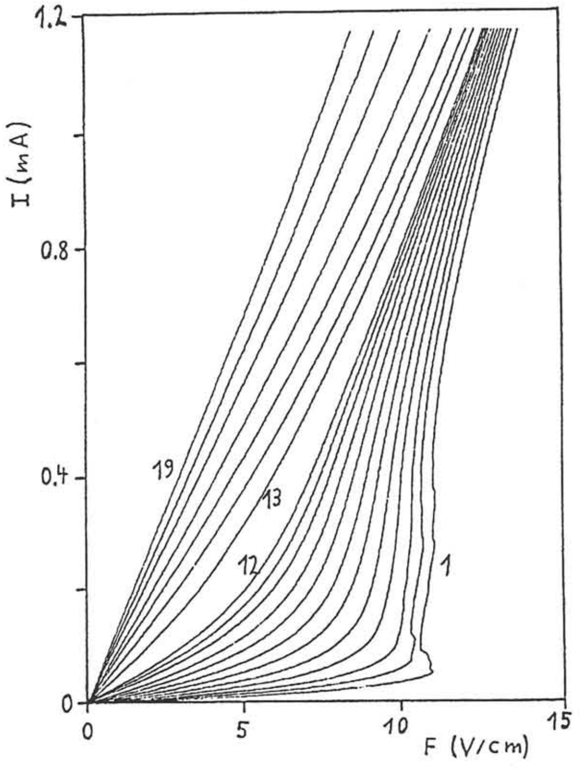

Figure 5: Temperature dependence of the impurity breakdown for sample B.

The dynamic behaviour of the samples was investigated by double pulse technique. As demonstrated in Fig. 6 the current remains small for a certain time after the pulse rise dependent on the applied field. The carrier density is still insufficient for effective impurity ionization (on a scale of $10^{-8}s$). Then the current increases exponentially with a time constant of about 10 ns, of course depending on the applied field again. When nonequilibrium carriers are already generated by an additional voltage prepulse then the first current step vanishes (within the uncertainty of the rise time of the main voltage pulse). For fields above 20 V/cm another process can be remarked, giving rise to an additional increase of the current pulse with a longer time constant. In a similar manner the current was investigated at the decreasing edge of the voltage pulse. The drop can be examined by an additional small pulse switched on after the end of the main voltage pulse demonstrating the exponential decay of the nonequilibrium carriers with a time constant of about 10 nsec.

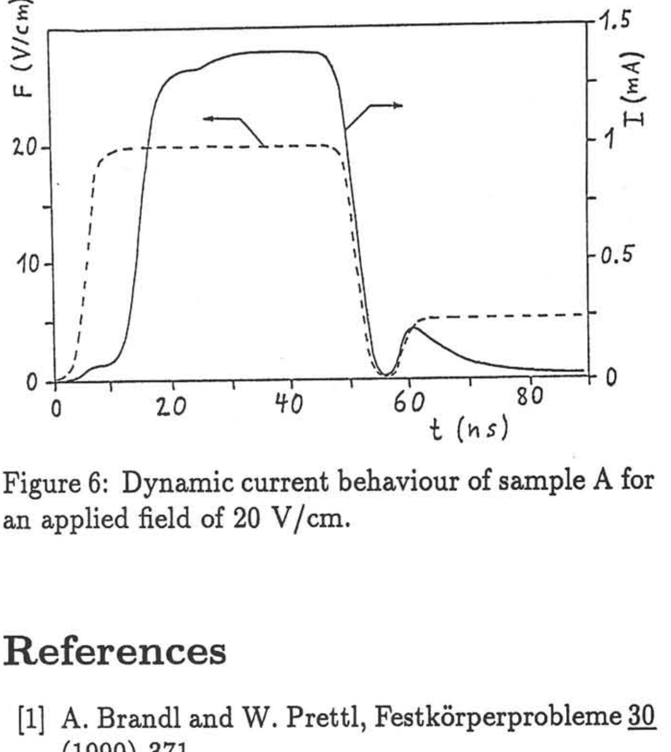

Figure 6: Dynamic current behaviour of sample A for an applied field of 20 V/cm.

References

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