S-shaped current-voltage characteristic of n-Si in strong magnetic fields

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An S-shaped current-voltage characteristic of n-Si was observed in classically strong magnetic fields and heating electric fields at low temperatures.

The conductivity of multivalley semiconductors in strong but not quantizing transverse magnetic fields increases with increasing electric field in the region of heating electric fields when the current is directed along a high-symmetry axis, whereas in the absence of a magnetic field the conductivity decreases.[1,2] The physical reason can be understood from the two-valley model shown in Fig. 1. The heating electric field $\bar{F}$ will heat the electrons more strongly in the valley A, since this field is directed along the smaller axis of the effective-mass ellipsoid in this valley. This will expel the electrons into valley B, where the carrier mobility in the field direction is lower, so that the total conductivity in the field direction decreases with increasing $\bar{F}$. The magnetic field produces a Hall field, and at sufficiently large $\bar{H}$ it can become much larger than $\bar{F}$. Therefore at $\mu H/c \gg 1$ this field will heat the electrons in valley B more strongly than in valley A. This will drive the electrons back to the valley A. Inasmuch as the mobility in this valley is larger in the direction of the field $\bar{F}$, the conductivity will increase with increasing Hall field. This increase is determined by the derivative dn_g/dF of the electron density in the valley A with respect to the field. This effect was predicted theoretically in[1] and investigated experimentally at relatively high temperatures in[2].

It is indicated in[1] that if the derivative dn_g/dF becomes large (this can be attained in strong magnetic fields at low temperatures), then the current-voltage characteristic can change from superlinear to S-shaped. The present study is devoted to the current-voltage characteristics under such conditions.

n-Si samples with room-temperature resistivities $\rho_{300°K} = 12$, 25, 62, and 85 Ω cm, of approximate length 1 cm in the ⟨001⟩ direction, and with cross section ~0.06×0.06 cm, were cut in the (110) plane. They were placed in a cryostat in which the sample temperature was maintained in the range 77–4.2 °K accurate to 10^{-2} °K. The electric field from a standard rectangular-pulse generator, in the form of single pulses of 10 μsec duration, was applied in the ⟨001⟩ direction. A transverse magnetic field H of intensity up to 50 kOe was produced by a superconducting solenoid placed in a liquid-helium bath.

The results obtained with samples having different ρ were qualitatively the same. The current-voltage characteristics of one of the samples, measured with the aid of a two-beam long-persistence oscilloscope, are shown in Fig. 2. Curve 1 corresponds to $H=0$. The saturation of the current is due to the presence of an N-shaped characteristic and to the instability of the state with negative differential conductivity.[3] This explains also why we have observed a section with a constant voltage in a rather wide current interval (curves 2) at $H \neq 0$ in the case of the S-shaped characteristics. In a number of samples, small inflections in the direction of the S-shaped section were observed at the start of the vertical section.

Attention should be called to the fact that when the current-voltage characteristics were measured the voltage pulse was picked off not from the entire sample, but from two potential probes located on the lateral face near the central part of the sample. When the voltage was measured on the entire sample, the current-voltage characteristic had no region with constant voltage, but remained superlinear. This was due to the shunting of the Hall field by the contacts of the sample near the

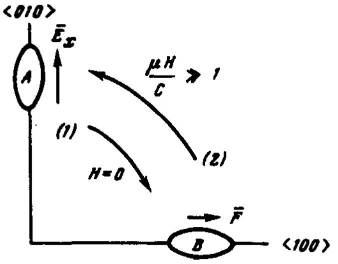

FIG. 1. Intervalley transfer of electrons in heating electric fields in the absence (1) and in the presence of a strong magnetic field (2).

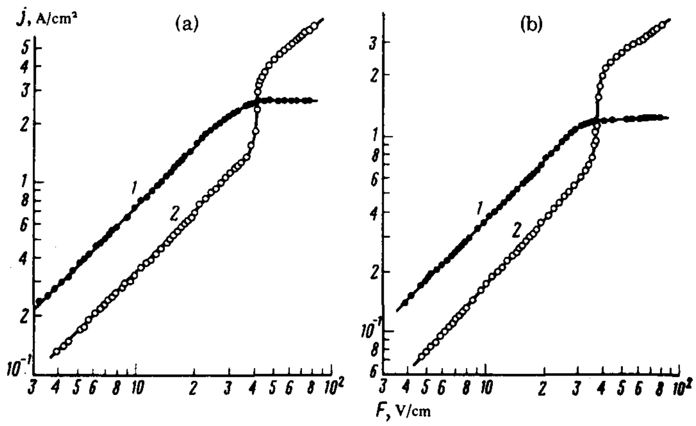

FIG. 2. Current-voltage characteristics of n-Si sample ($\rho_{T=300°K} = 62$ Ω cm) without a magnetic field (curve 1) and with a magnetic field (curves 2) at $T=46.1$°K, $H=15$ kOe (a) and $T=38.5$°K, $H=17$ kOe (b).

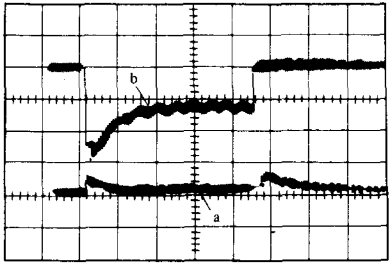

FIG. 3. Oscillogram of voltage pulse (negative, a) and current pulse (positive, b) in the S-shaped region of the current-voltage characteristic of one of the samples.

ends, as the result of which the effect under consideration did not take place in these parts of the sample, thereby distorting the overall current-voltage characteristic.

It is known[4] that current oscillations can be observed in the region of differential conductivity, for both N-shaped and S-shaped characteristics. Indeed, in our experiments oscillations were produced on the current pulse at voltages and currents corresponding to the S-shaped section of the characteristic with negative differential conductivity (NDC). The frequency (on the order of 1 MHz) and amplitude of these oscillations depended on the current flowing through the sample and on the magnetic field. An oscillogram of the voltage (a) and current (b) pulses for one of the points of the vertical section of the current-voltage characteristics is shown in Fig. 3. It should be noted that whereas the oscillations on the section with the negative differential conductivity were not observed for all samples with N-shaped characteristics,[5] and were observed particularly rarely in our experiments, these oscillations appeared practically always in the case of S-shaped characteristics, without need for any special measures, and were stable.

We note also that the observed S-shape of the current-voltage characteristic is pronounced to different degrees for different samples and depends in a complicated manner on the magnetic field and on the temperature. These relations will be investigated in greater detail in the future.

[1]V. V. Mitin, Phys. Stat. Sol. **B49**, 125 (1972).
[2]M. Asche, V. M. Bondar, L. F. Kurtenok, and V. I. Martynchenko, Phys. Stat. Sol. **B60**, 497 (1973).
[3]A. F. Volkov and Sh. M. Kogan, Usp. Fiz. Nauk **96**, 633 (1968) [Sov. Phys.-Usp. **11**, 881 (1969)]
[4]V. L. Bonch-Bruevich, I. P. Zvyagin, and A. G. Mironov, Demennaya élektricheskaya neustoĭchivost' v poluprovodnikakh (Domain Electric Instability in Semiconductors), Nauka, (1972).
[5]M. Asche and O. G. Jarbei, Phys. Stat. Sol. **A8**, 61 (1971).