MECHANISM OF THE GUNN EFFECT FROM A PRESSURE EXPERIMENT

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An experiment is reported here which we believe provides direct evidence that an electron transfer mechanism of the Ridley-Watkins[1] type is responsible for the current instability discovered and investigated by Gunn[2-4] in *n*-type GaAs. This instability is characterized by a sharp threshold voltage at which current oscillations or noise commences, and is not a contact effect.[3,5] The average electric fields at threshold for GaAs at room temperature fall in the range from about 1250 V/cm for the longest samples to 3700 V/cm for the shortest. Some of the mechanisms which might produce this effect have been summarized by Gunn.[3] They include drifting carrier interactions with acoustical- or optical-mode lattice waves or with plasma waves, trapping of hot electrons at impurities, and energy-dependent scattering of hot electrons, as well as the Ridley-Watkins electron-transfer process. In the Ridley-Watkins mechanism the applied electric field heats the carriers in a high-mobility sub-band so that they transfer at sufficiently high electron temperature to a higher energy low-mobility sub-band. A differential negative resistance results from sufficient transfer.

In GaAs the relevant conduction sub-bands are the low-mass, high-mobility minimum at the center of the Brillouin zone, and a set of six degenerate minima about 0.36 eV higher in energy and located on the ⟨100⟩ axes of the Brillouin zone.[6,7] Hilsum[8] has made a calculation of this negative resistance effect in GaAs. Gunn[3] originally rejected this mechanism on the grounds that the electron temperature was not sufficiently high in GaAs at threshold. Hilsum's calculations show, however, that the large ratio of density of states between the upper and the lower sub-bands leads to a considerable reduction in critical electron temperature, a point that has been recently emphasized by Kroemer.[9]

Our experiment consisted in looking for a change of threshold voltage in a sample of GaAs subjected to hydrostatic pressure. Since the energy separation between the ⟨000⟩ minimum and the ⟨000⟩ minima decreases with pressure at a rate of about 9×10^{-3} eV/kbar,[6,7,10] the electron-transfer mechanism should require a lower electron temperature and hence a lower threshold voltage as pressure is increased. Provided that substantial changes in ⟨000⟩ carrier concentration and concomitant changes in mobility can be avoided, we believe that none of the other possible mechanisms should be appreciably affected by the decrease in the energy separation of the sub-bands. (The pressure-induced changes in phonon frequency, ⟨000⟩ effective mass, and sample length could only slightly influence an instability threshold arising from one of the other mechanisms.)

Many samples of high-resistivity *n*-type GaAs exhibit an exponential increase in resistivity with pressure below 15 kbar. This behavior indicates a loss of electrons to bound states as the ⟨000⟩ minimum moves up in energy[7,11,12] and might be expected to affect the mobility by changing the amount of impurity scattering. For this reason we used GaAs, which does not show this carrier "freeze-out" with pressure. The material was Bell Laboratories grown, sulfur-doped, and float-zoned. It had a carrier concentration of 2×10^{16} cm^{-3} and a room-temperature mobility of 4500 cm^2/V sec. The sample had a cross section of area 3.2×10^{-4} cm^2 and an effective length between tin contracts of about 0.1 cm.

The sample was supported by its leads in a Teflon cell contained in the chamber of a piston-cylinder apparatus to which unshielded electrical connections could be made.[13] The working fluid was an *n*-pentane and amyl-alcohol mixture. The apparatus was at room temperature. At each pressure the dc low-field resistance of the sample was measured and then the current-voltage characteristic was examined using 100-nsec pulses at a repetition rate of 50 pulses per second. For the pulse measurements, external series and shunt resistors were connected as shown in the inset of Fig. 2. The two channels of a sampling oscilloscope were used to measure the voltage across the sample and the current through the 10-ohm series resistor, and the sampling time was adjusted to be close to the end of the pulse where wave-form distortions due to the unavoidable

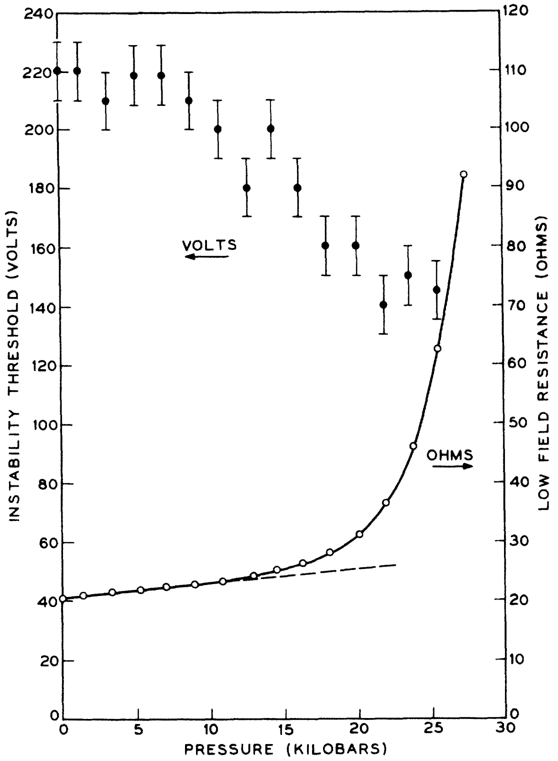

FIG. 1. Instability threshold voltage and low-field resistance of GaAs sample versus hydrostatic pressure.

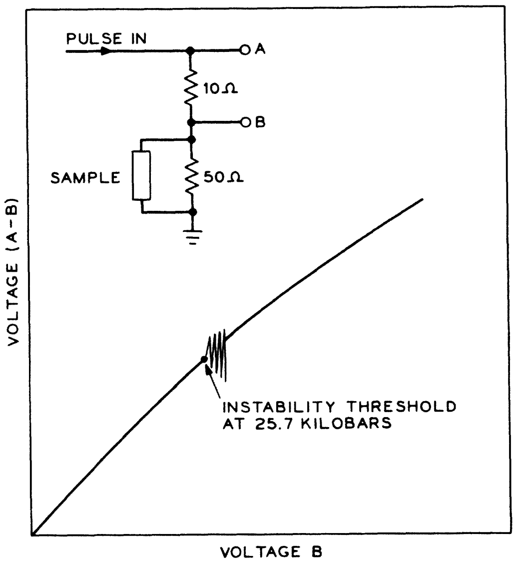

FIG. 2. Current-voltage characteristic at highest pressure at which instability was observed. Inset shows connections to sample for pulse measurement. Voltage (A-B) was obtained from a difference amplifier.

impedance mismatches were small. As the pulse voltage was raised (or lowered), the threshold of the instability was clearly indicated by the appearance (or disappearance) of noisy fluctuations in both the current and voltage channels. We estimate that the residual "ringing" in the circuit limited the precision of the threshold voltage measurement to about ±10 V. Some measurements were checked upon lowering the pressure, and no irreversible effects were observed.

The experimental data are shown in Fig. 1. There is a definite decrease in the voltage threshold with increasing pressure, and a large part of this decrease occurs below 15 kbar where the low-field resistance indicates negligible depopulation of the ⟨000⟩ minimum. (The slow, linear increase of resistance with pressure up to 15 kbar is believed to be chiefly due to the increase in effective mass of the ⟨000⟩ carriers as the forbidden energy gap increases, and is in agreement with earlier measurements of Howard and Paul and of Sagar shown in Fig. 4 of reference 6.) Above 15 kbar the carrier population is divided between the ⟨000⟩ minimum and the ⟨100⟩ minima. At 26 kbar, the highest pressure at which the instability could be observed, less than half of the carriers are in the ⟨000⟩ minimum. At this pressure the instability could only be observed over a narrow range of voltage. The sample appeared to be stable at high voltages as well as at low voltages. The current-voltage characteristic is shown in Fig. 2 as obtained from an X-Y recorder connected to the two channels of the sampling oscilloscope. At pressures above 26 kbar the current-voltage curves showed sample resistance increasing with increasing voltage. A decrease in slope at voltages comparable to the instability voltage at 26 kbar was discernible at 30 kbar but not at 40 kbar.

We have not attempted to fit the data of Fig. 1 with the presently available theory of the electron-transfer mechanism[1,8] because the theory is formulated in terms of the electric field, and the relationship between threshold voltage and sample length obtained by Gunn[3] suggests to us that the electric field at threshold is not uniform. However, we believe that the data of Fig. 1 are compelling evidence favoring the electron-transfer mechanism for this current instability in n-type GaAs.

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[1] B. K. Ridley and T. B. Watkins, Proc. Phys. Soc. (London) 78, 293 (1961); and B. K. Ridley, Proc. Phys. Soc. (London) 82, 954 (1963).

[2] J. B. Gunn, Solid State Commun. 1, 88 (1963).

[3] J. B. Gunn, IBM J. Res. Develop. 8, 141 (1964).

[4] J. B. Gunn, Proceedings of the Symposium on Plasma Effects in Solids, Paris, 1964 (to be published).

[5] A. G. Chynoweth, unpublished data.

[6] H. Ehrenreich, Phys. Rev. 120, 1951 (1960).

[7] A. R. Hutson, A. Jayaraman, J. H. McFee, and A. S. Coriell, to be published.

[8] C. Hilsum, Proc. I.R.E. 50, 185 (1962).

[9] H. Kroemer, Proc. IEEE 52, 1736 (1964).

[10] W. Paul, J. Appl. Phys. 32, 2082 (1961).

[11] A. R. Hutson, A. Jayaraman, and J. H. McFee, Bull. Am. Phys. Soc. 9, 646 (1964).

[12] R. J. Sladek, Bull. Am. Phys. Soc. 9, 258 (1964); and Proceedings of the International Conference on the Physics of Semiconductors, Paris, 1964 (Academic Press, Inc., New York, 1964), p. 545.

[13] A. Jayaraman, to be published.

RADIATION DAMAGE IN PLATINUM

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The assignment of the annihilation of specific defects to various stages of recovery in irradiated materials is subject to some doubt and controversy.[1] This is especially true of stages III and IV of the recovery spectrum, which for platinum occur at 90 to 190°C and 250 to 450°C, respectively.[2] We would like to offer direct evidence that in neutron-irradiated platinum, irradiated below stage III,[3] clusters of interstitials and clusters of vacancies are present.

The experiment was conducted in the following manner: Chemically pure platinum of 99.999% purity was irradiated at 75°C in a reactor to a total irradiation of 10^{18} nvt. Examination of this platinum wire was then undertaken in a field-ion microscope[4] with the specimen coupled to a bath at 78°K. Compared to similar specimens, which were not irradiated, the irradiated materials exhibited a few features which we think can only be associated with the presence of interstitial and vacancy clusters. These are as follows:

A. Bright spots appear characteristically in the pattern and alternate with regions of relative perfection at the tip, Fig. 1, and throughout the volume. The size of these bright spots —a few atom diameters—as well as the enhanced local intensity associated with them indicate a local disturbance of the normal arrangement of the material.

FIG. 1. Neutron-irradiated platinum, 10^{18} *nvt*, showing clusters of interstitials.

B. These bright spots can disappear with the evaporation of atoms when the specimen is held in an electric field slightly below the field necessary for evaporation of atoms not associated with enhanced intensity. This is done by field-evaporating the specimen and slowly lowering the voltage until the field ion pattern becomes stable, and then simply waiting for the removal of a bright spot. From this we conclude that the bright spot is associated with some strain in the lattice, which