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A New Current Instability in N-type Germanium

Abstract: This paper reports the observation of a new oscillatory phenomenon in n-type Ge at 77°K. The effect is a coherent oscillatory component of the current through a bar of n-type Ge with ohmic n^+ contacts initiated when the average electric field in the sample exceeds some threshold value which is in the region where the electron drift velocity is nearly saturated. The frequencies of the oscillations vary from a few hundred MHz to 2.8 GHz. The effect depends on sample orientation, temperature, and carrier concentration. Some possible mechanisms for this effect are discussed. At somewhat higher fields a second, not necessarily related instability, is also observed.

In the course of studying the high-field electrical conductivity of n-type Ge¹ at 77°K, we have observed a new instability. It is seen as a coherent, not necessarily sinusoidal, oscillatory component of the sample current when the voltage across the sample is essentially constant.

Figure 1a shows a current-voltage characteristic at 77°K for an n-type Ge sample with $n \approx 10^{15} \text{ cm}^{-3}$. The rectangular sample is 0.022 cm long, 0.025 cm by 0.025 cm in cross section, and has ohmic n^+ contacts on both end faces. The current is along a $\langle 100 \rangle$ direction. The curve is measured by sampling the current and voltage at a fixed time after the application of voltage pulses from 10 to 200 nsec long. The apparatus is shown in Fig. 2. The anomalous region of the I - V characteristic, whose structure is caused by the variation of the phase of the current oscillations at the sampling time as the applied voltage is raised, begins at a definite threshold voltage V_T . Plots of current *vs.* time for various values of the applied voltage are shown in Fig. 1b. The frequencies at the various voltages indicated in the figure are in the gigahertz range. If the average value of the current (averaged over one cycle of the oscillations) is plotted against applied voltage, the resulting curve joins smoothly, within the accuracy of our measurements, onto the I - V curve below V_T .

The frequencies so far observed vary from a few hundred MHz to as high as 2.8 GHz. The depth of modulation of the signal across the current-measuring resistor R_1 is typically a few percent and can be influenced by the stray reactances in the circuit. Although no effort has been made to optimize the power output, we have observed 1.25 mW

output at 0.85 GHz for a power input of 70 W during the pulses. The frequency of the oscillations for a given applied voltage is not sensitive to the value of the current measuring resistor for values in the range 1 Ω to 20 Ω .

The effect has been observed in Ge with carrier concentrations in the range $4 \times 10^{14} \text{ cm}^{-3}$ to $3.3 \times 10^{15} \text{ cm}^{-3}$, but is not observed in material with $n = 2.7 \times 10^{14} \text{ cm}^{-3}$. The five crystals in which the effect has so far been observed were doped with a shallow donor impurity (usually Sb) and were grown in two different laboratories at various times over the past eight years. The n^+ contacts were made by several methods, including diffusion and epitaxial solution regrowth with both As and Sb as the donor species, and no evidence of hole injection was observed. The effect has been observed with the current parallel to $\langle 100 \rangle$ and $\langle 110 \rangle$ crystal axes, but never with the current parallel to the $\langle 111 \rangle$ axis.

Many samples show two or more distinct modes of oscillation for different values of the applied voltage, as is shown in Fig. 1b. The frequency is typically found to vary slowly as the applied voltage is increased from V_T to some higher value (in Fig. 1b, a value above 122 V.). Above that value, the frequency is found to be higher by a factor of about 2. Study of over a hundred samples ranging in length from 0.12 mm to over 1 mm indicates that while there is appreciable scatter in the frequencies observed for a given sample length, there is considerable evidence that the lowest frequency for a given length is inversely proportional to the length. The average minimum product of frequency and length is about $2.5 \times 10^7 \text{ cm/sec}$.

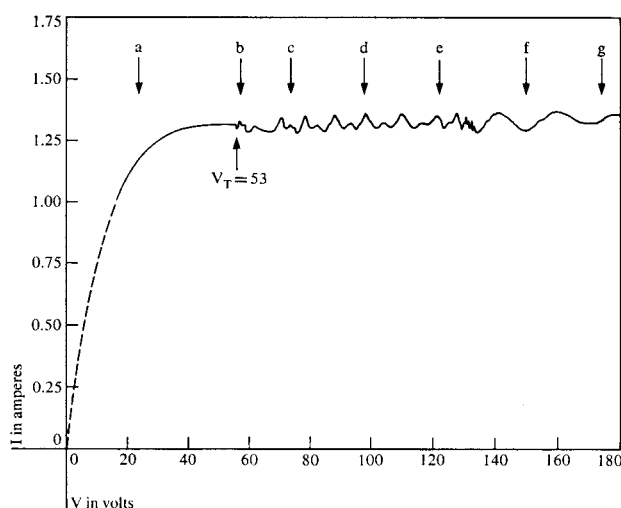


Figure 1a Current-voltage (I - V) characteristic of a 0.22-mm-long rectangular bar of Sb-doped germanium with diffused n^+ contacts (Sample G468). Points a, b . . . g correspond to voltages at which data was taken for Curves a, b . . . g in Fig. 1b.

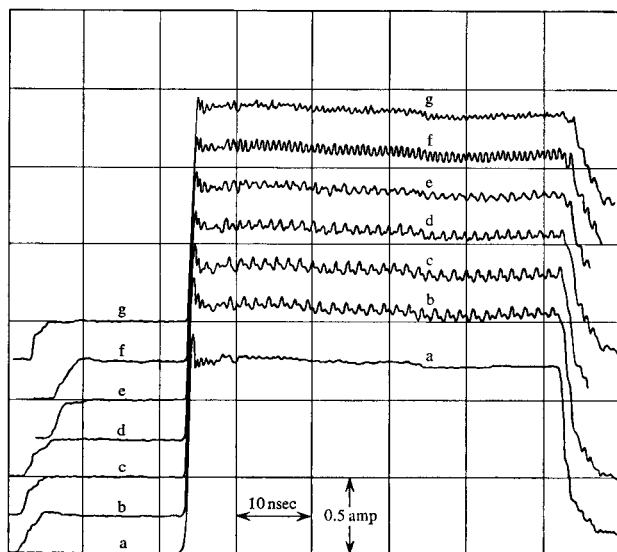
Several experiments have been performed in order to characterize this effect more microscopically and to determine if it can be understood in terms of any known mechanism such as electron transfer to higher minima,^{2,3} which is responsible for the Gunn effect in GaAs⁴. If a negative resistance due to this type of transfer were involved, then the higher valleys involved would presumably be the $\langle 100 \rangle$ minima⁵ located about 0.21 eV above the occupied $\langle 111 \rangle$ minima. For a [100] sample, transfer to the [100] and $\bar{1}00$ minima should be more important than to the [010], $0\bar{1}0$, [001] and $00\bar{1}$ minima, since for the first two the applied field is along a maximum mass axis of the mass ellipsoid, while for the latter four, it is parallel to a minimum mass direction. Experimentally, it is found that for a sample with current along [100], compressive uniaxial stress of up to 1.3×10^4 kg/cm² applied parallel to the current has less than a 2-percent effect on the threshold voltage. The effect of the uniaxial stress in this experiment is to lower the two high-mass $\langle 100 \rangle$ minima with respect to the occupied minima by about 50 percent while raising the four light-mass $\langle 010 \rangle$ minima by only about 10 percent⁶, assuming that the $\langle 100 \rangle$ minima in Ge have the same deformation potential constant Ξ_u as in silicon. If transfer to the $\langle 100 \rangle$ valleys were important in this new effect one would expect that so large a stress applied parallel to the current in a [100] sample would have caused an appreciable reduction in threshold voltage. Although hydrostatic pressure experiments would be more definitive here, such transfer seems to be ruled out as a mechanism for this effect.

If the current is along [110], uniaxial compression along [110] raises the threshold voltage significantly while compression along $[1\bar{1}0]$ reduces the threshold. These results are opposite to those expected if a transverse instability of the type proposed by Erlbach⁷ were involved.

Results of an experiment which capacitively probes⁸ the voltage distribution in the sample, as shown schematically in Fig. 2, indicate that the oscillating component of the voltage has the same phase throughout the sample, and that the maximum amplitude of this voltage occurs between the center of the sample and the anode, as can be seen in Fig. 3. Preliminary results indicate that the steady state electric field in the sample is nonuniform, being substantially higher near the anode. Regardless of the polarity of the applied voltage, the high-field region, as well as the maximum of the oscillating voltage, are found near the anode. No evidence of any travelling domains has been found.

The threshold voltage increases with temperature by a factor of about 4 between 27°K and 120°K, the latter being the highest temperature at which the effect has been observed. Application of a magnetic field of 4 kG, either parallel or perpendicular to the current, increases the threshold voltage by about 20 percent and decreases the amplitude of the oscillations, but does not substantially affect the frequency.

Figure 1b Time dependence of current in Sample G468 for several values of applied voltage. Values of voltage and frequency for Curves a, b . . . g are as follows (a) $V = 24V$; (b) $V = 54V, f = 0.59$ GHz; (c) $V = 74V, f = 0.65$ GHz; (d) $V = 98V, f = 0.70$ GHz; (e) $V = 122V, f = 0.77$ GHz; (f) $V = 150V, f = 1.35$ GHz; (g) $V = 175V, f = 1.40$ GHz.



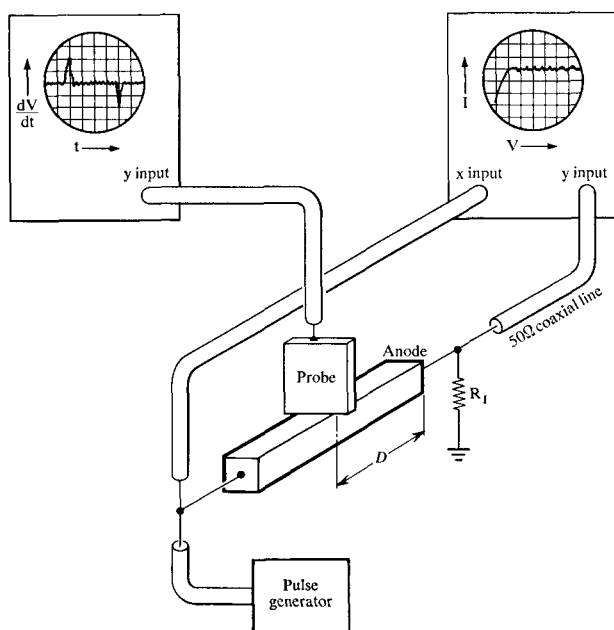


Figure 2 Diagram of apparatus. The sample is at 77°K. One end of the sample is connected to the center conductor of a 50 Ω transmission line; the other, to a small resistor R_1 . The current is measured by feeding the voltage across R_1 into a sampling scope via 50 Ω coaxial cable. The pulse generator can supply pulses of either polarity. The probe position indicated is for negative pulses. The probe couples to the sample capacitively. Probe thickness is 0.0007 inch.

We do not believe that the effect involves appreciable concentrations of minority carriers, because the *average* current during a pulse is essentially independent of time, although the pulse length is considerably longer than the hole transit time.

The fact that the effect can be produced in samples with contacts made in several ways seems to rule out a pathological contact effect. However, the impurity gradient present at a normal $n^+ - n$ contact may play an important role. Since the effect occurs in the saturated current density region, sample inhomogeneities may also be important.

At fields of a few thousand volts/cm, the effects of electrostrictive strains must also be considered if the electromechanical coupling constants are as large as indicated by the measurements of Gundjian.⁹ The importance of electrostriction or current-striction effects of this type is hard to assess because of the inconsistency between the symmetry of the experimental results⁹ and that of the current striction effect¹⁰ allowed by the band structure of Ge.

The frequency of free electron plasma oscillations is several orders of magnitude larger than the frequencies observed, while transit times of acoustic waves are much too long for the frequencies observed.

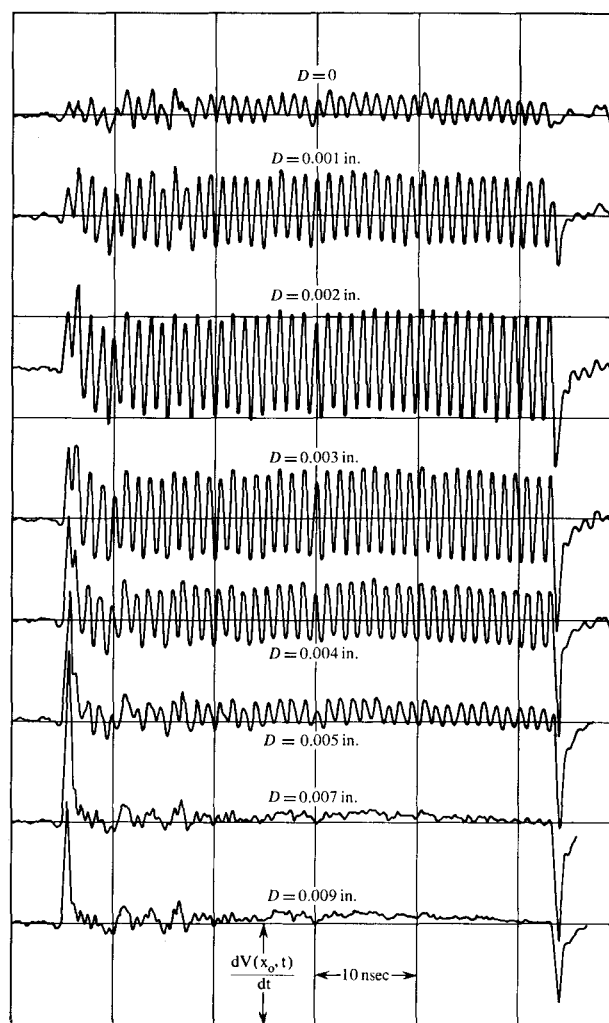


Figure 3 Time dependence of the time derivative of the voltage at several positions along a sample having a length of 0.009 inch (Sample G540). The applied voltage was held constant for all the curves shown. The probe arrangement is as shown in Fig. 2. Probe position is given in thousandths of an inch, where D is the distance from the anode to the probe. The phase of the signal is independent of position, while the amplitude changes rapidly with position, the maximum amplitude occurring at a position nearer to the anode than to the cathode.

The results of the strain experiments and the orientation dependence of the effect indicate that it can be most readily observed when the drift velocity is most nearly saturated. Because of the small differential mobility, small fluctuations in the local conductivity produce much larger local variations in the electric field. Dumke¹¹ has suggested that such fluctuations may be unstable because of the increase of the diffusion coefficient with electron temperature and, therefore, with electric field.

At somewhat higher fields, especially in the longer samples (≥ 1 mm), a second instability is observed. The average field at threshold for this second instability is 3000 ± 1000 V/cm. This effect manifests itself as a partially coherent periodic increase of the sample current with a period of approximately 10^{-8} second. Many of the conditions under which this effect is observed are similar to those for the coherent effect seen at lower fields. Results of double pulse experiments¹² and experiments which probe the voltage distribution in the sample as a function of time⁸ indicate that this second effect is due to periodic generation of excess electron-hole pairs by high energy electrons in localized regions of the sample.

Acknowledgments

It is a pleasure to thank J. B. Gunn, W. P. Dumke, J. C. Marinace, M. Okrasinski and P. J. Price for many helpful suggestions and discussions; S. P. Keller for his encouragement during the course of this work; and J. A. Bradley and F. R. Feigel for technical assistance.

References

1. E. J. Ryder and W. Shockley, *Phys. Rev.* **81**, 139 (1951); and E. J. Ryder, *Phys. Rev.* **90**, 766 (1953). For a list of more recent references, see E. G. S. Paige in *Progress in Semiconductors*, Vol. 8, Chapter 6.
2. B. K. Ridley and T. B. Watkins, *Proc. Phys. Soc. (London)* **78**, 293 (1961).
3. C. Hilsum, *Proc. Inst. Radio Engrs.* **50**, 185 (1962).
4. J. B. Gunn, *Solid State Comm.* **1**, 88 (1963); and *IBM Journal* **8**, 141 (1964).
5. M. I. Nathan, W. Paul, and H. Brooks, *Phys. Rev.* **124**, 391 (1961).
6. R. W. Keyes, *Solid State Physics*, Vol. 11 (Seitz and Turnbull, editors, Academic Press, New York, 1960, p. 149 ff.) and J. J. Hall, private communication.
7. E. Erlbach, *Phys. Rev.* **132**, 1976 (1963).
8. J. B. Gunn, *Plasma Effects in Solids*, Paris, 1964, p. 199 (Dunod, Paris, 1965).
9. A. A. Gundjian, *Solid State Comm.* **3**, 279 (1965).
10. P. Kornreich and H. Callen, *Bull. Am. Phys. Soc.* **12**, 138 (1967).
11. W. P. Dumke, private communication.
12. J. C. McGroddy and M. I. Nathan, *Proc. of Int. Conf. on Semiconductor Physics*, Kyoto, 1966 (published as *J. Phys. Soc. Japan* **21**, Supplement 437, 1966).

Received April 14, 1967