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XII-7. Electrical Instability in Germanium due to Hot Electron Recombination on Repulsive Centers

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The electron life time, τ, and mobility, μ, were measured as functions of the electric field strength, E, for n-type Ge samples doped with copper and antimony. The life time obtained decreased noticeably on raising E. The $j-E$ curves expected from the data on τ and μ had a well-defined negative resistance region. At high enough light intensity the stationary current oscillations were observed in the circuit in the temperature range of $\sim$16°K—100°K. The field distribution along the samples was studied by the modulated light probe method. The electrical domain movement was observed in the instability region. The experimental data on the domain velocities were shown to be in qualitative agreement with the theory.

§ 1. Introduction

If the free electron concentration is controlled by recombination on the repulsive centers the differerential conductivity may become negative when the electrons are heated by the electric field. Then the system may become unstable and the domains—the strong and weak field regions may be formed.[1] The domain movement is observed as the space charge and field strength waves.

This type of electrical instability was studied in germanium doped with gold,[2,5] in CdS[6] and in other crystals. This paper contains some results on the formation and motion of the space charge waves in germanium doped with copper.

§ 2. Results

The samples contained copper in concentration from 10^{15} to 10^{16} cm^{-3} and were partly compensated with antimony. Only $Cu^{=}$ and $Cu^{\equiv}$ ions were present at low temperatures in the dark. The samples were made conductive by illuminating via the germanium filter. The filter was at room temperature.

To study the spatial distribution of the resistivity and of the electrical field we used the modulated light probe method described in previous papers.[7,8] The life time of the non-equilibrium charge carriers (τ) was determined from the current relaxation kinetics after the rectangular voltage pulse was applied to the sample under voltage generator condition. The field dependence of the mobility (μ) was determined from the current vs. voltage curves by short ($T \ll \tau$) voltage pulses. In the field range in question the 80°K mobility changed no more than by a factor of two.

In accordance with our previous results[7] and with what had been expected theoretically the life time decreased noticeably on applying the electric field. The typical results for one of the samples are given in Fig. 1. The τ-values did not practically depend on the light intensity. The shape of the stationary current (j) vs. field strength (E) curve, as is expected from the data on τ and μ, is also shown in Fig. 1. The curve contains a well-defined negative resistance region.

However, the observed steady state $j-E$ curves of the low conductivity samples did not show up any negative resistance. At nitrogen and

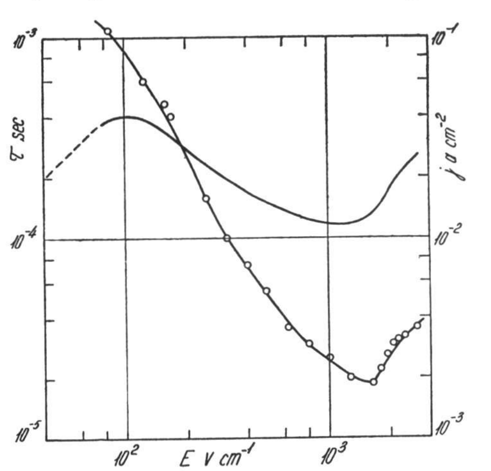

Fig. 1. The electron life time dependence on the field strength (○) and the expected $j-E$ curve. Sample 11-01. 90°K.

lower temperatures the current density was but very weakly field dependent in the expected negative resistance region (current saturation). The probe measurements showed that the field distribution was becoming sharply inhomogeneous in this case and the immobile high field region (the static domain) was being formed in the sample.[7]

The phenomena observed were in qualitative agreement with the Shockley conclusion[9] that the spatially inhomogeneous field distribution due to the boundary conditions may prevent the formation of the *dc* negative impedance. However, in our experiments the static domains were formed not at the electrodes but in the volume of the sample, near some initial small inhomogeneities. The existence of static domains is in qualitative agreement with the results of ref. 10).

At high enough light intensity the stationary current oscillations were observed in the circuit if the field strength exceeded some critical value, E_c. Figure 2 shows the typical dependence of the current density upon the average field strength under the instability conditions as well as the magnitude of current oscillations.

No instability was observed at the temperatures above $\sim$100°K. This is thought to be due to the pronounced weakening of the field dependence of the electron capture probability by the negative Cu-ions, in accordance with theoretical results.[11] On lowering the temperature

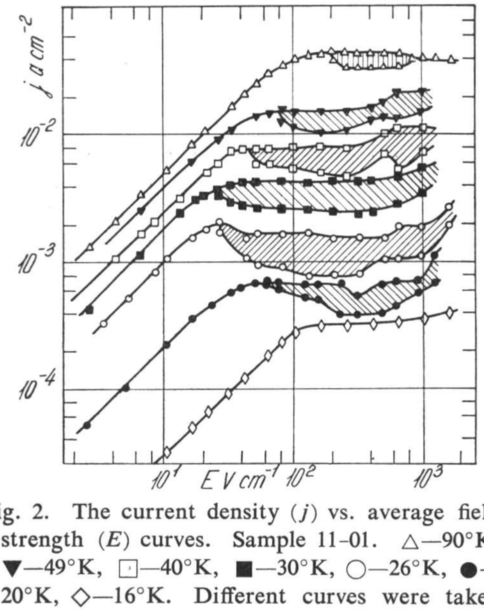

Fig. 2. The current density (j) vs. average field strength (E) curves. Sample 11-01. △—90°K, ▼—49°K, ⊡—40°K, ■—30°K, ○—26°K, ●—20°K, ◇—16°K. Different curves were taken under different light intensities to facilitate their placement in the figure.

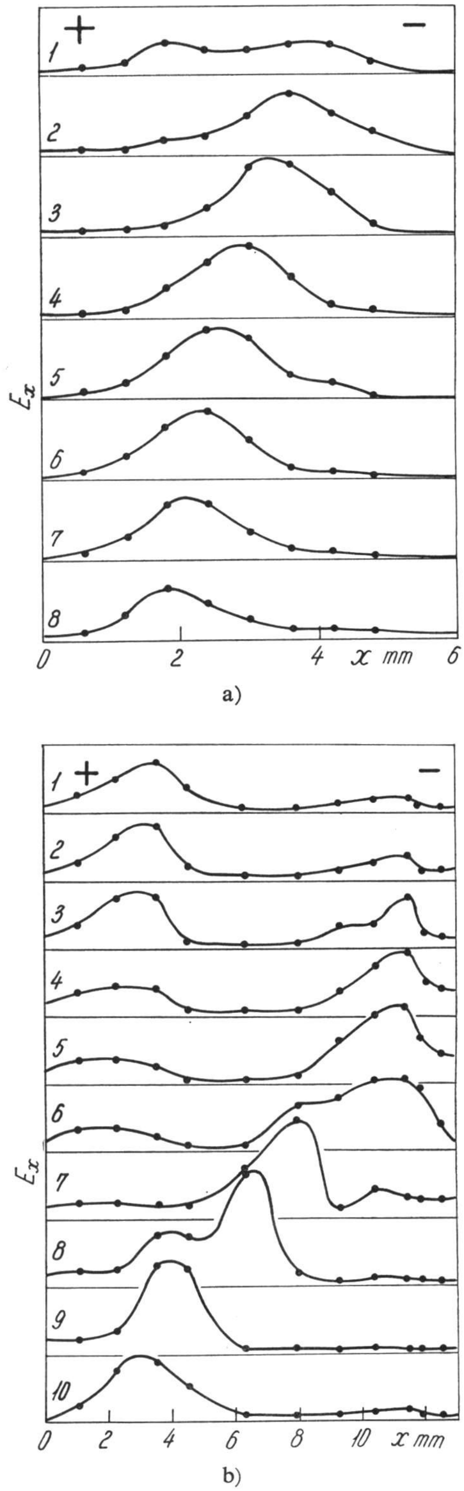

Fig. 3. The field distribution (arbitrary units) under the moving domains condition. 90°K. a) Sample 11-01, $\Delta t = 3\cdot 7\times 10^{-4}$ sec.; b) sample 10-01, $\Delta t = 5\cdot 0\times 10^{-4}$ sec. The curves are repeated periodically in the following.

the E_c-values at first decreased substantially. But further on E_c began to raise and no instability was observed below $\sim 16°K$. This may be understood if account is taken of that antimony is but incompletely ionised at low temperatures. Therefore it takes some part in the recombination process thus lowering the life time field dependence.

The probe measurements showed that in the instability regime the domain, localized initially near some inhomogeneity, began moving towards the anode and the dipole type space charge wave arose in the sample. An example of such a wave is shown in Fig. 3.

The domain velocity increased markedly on raising the light intensity and could be changed by orders of magnitude. It increased as well by raising the sample temperature, but depended but weakly on the voltage applied to the sample. On raising the voltage the velocity always increased.

The initial inhomogeneities could produce a decisive effect upon the domain motion. At small inhomogeneities the domain motion was becoming non uniform (cf. Fig. 3b). When the inhomogeneity was high enough the domains could stop and accumulate at it. The current oscillations were becoming damped in such cases and stopped altogether. However, they could be made undamped again by the nonuniform illumination.

§ 3. Discussion

We tried to compare the observed values of the domain velocity with the theory. It may be shown[12] by treating the non-linear problem of the domain motion in the concentration instability case that the domain velocity, u, is given by different expressions depending upon the relation between the recombination time, τ, and the Maxwellian relaxation time, τ_M (to be more precise, some effective time τ_M^*, see below). When $\tau_M^* \ll \tau$ (this corresponds to our experimental conditions)

$$-u=\frac{\tau_M^*}{\tau_g}\mu E+\frac{D}{\mu E\tau}, \tag{1}$$

where D—the electron diffusion coefficient, τ_M^* and "the generation time" τ_g are defined by the expressions:

$$\tau_M^*\cong\frac{\varepsilon}{4\pi q\mu n}\left(1+\frac{d\ln\mu}{d\ln E}\right)^{-1},\quad \tau_g=(g+C(E)n)^{-1}. \tag{2}$$

Here q is the elementary charge, n—the free electron concentration, g—the generation rate (per one bound electron and per second), $C(E)$—the capture probability in the field E. Equation (1) coincides with the result for the phase velocity of the space charge waves obtained in ref. 13) by linearising the basic equations. In the non-linear case eq. (1) gives the group velocity and is valid in the case of small τ_M^* only (see ref. 12)); all the values entering eq. (1) are to be referred to the center of the domain (the field strength maximum).

The maximum field value (E_m) could be obtained from the field distribution curves (Fig. 3) and the total voltage. The quantity $\tau(E_m)$ could be determined from the $\tau(E)$ measurements. Thus the contribution of the second term in eq. (1) could be determined. It was found that, as a rule, this diffusion term could be responsible only for some part of the observed velocity value; in some cases it contributed no more than a few percents.

Once E_m and the current through the sample were known we could find $n(E_m)$ and then, using the data on $\mu(E)$, determine τ_M^*. It was much more difficult to obtain the reliable values of τ_g and we could estimate its order of magnitude only obtaining g from the data on n and τ for the recombination equilibrium conditions and then using eq. (2). It turned out to be 1—0.1 sec. On the other hand, we ob-

Table I. Domains properties.

Samples	$n_0\times10^{-11}$ cm^{-3}	u cm sec^{-1}	Δ cm (average)	E_m kV cm^{-1}	$\tau_M\times10^{+8}$ sec	$\tau\times10^{+5}$ sec	$\tau_g\times10^{+2}$ sec	$n'_{oc}\times10^{-9}$ cm^{-3}	$n_{oc}\times10^{-11}$ cm^{-3}
10-01	2.7	400	0.3	4.1	35	1.0	1.9	1.5	0.9
11-01	16	75	0.15	1.0	11	2.4	0.8	1.5	1.0
11-01	2.3	21	0.3	0.67	5.4	3.0	1.0		
11-02	1.1	1.3	0.15	2.2	49	17		1.5	1.0

tained τ_g from the measured values of u and eq. (1). The results for the three samples and some chosen light intensity are shown in Table I. The table contains also the domain width, Δ, (at half of the maximum field), the life time τ at the center of the domain and the low field electron concentration. The values of τ_g given in the table are considerably less than those expected from the data on n and τ. The possible reason for this may be that in our experiments the domain width was comparable with the sample length so that the stationary wave of the dipole type (to which eq. (1) refers only) could not be formed.

To interpret the role of illumination one has to consider the variation of different quantities entering eq. (1). The probe measurements show that the domain width decreases and the field E_m increases on increasing the light intensity. However, the product $E_m\tau$ decreases (in the instability range). Therefore the diffusion term in eq. (1) increases (note that the ratio D/μ increases as well when the electron are heated). The drift term in eq. (1) also increases on raising the light intensity mainly due to the increase of E_m and decrease of τ_g. Thus the observed strong influence of the light intensity is in qualitative agreement with eq. (1).

An interesting question is that of the criteria for the domain instability. We measured the low field electron concentration (n_{oc}) above which the stationary current oscillations may arise on raising the field. The 90°K n_{oc} values are given in the Table I. They decrease markedly on lowering the temperature.

On the other hand, we can estimate the concentratian (n'_{oc}) above which the small field fluctuation with the minimum wave-number $k=2\pi/l$ (l—the length of the sample) begins to be amplified at some value of the field. Assuming that it is possible to consider the homogeneous sample, a linearised problem[13,14] is sufficient in this case. Then the critical quantity is the product $n'_{oc}l^2$.

As the functions $\tau(E)$ and $\mu(E)$ were known from experiment we could estimate the value of $n'_{oc}l^2$ using the relation (18) of the ref. 13). The values τ_g needed for such a calculation were obtained experimentally from the measured values of the domain velocity (see above). The values n'_{oc} thus obtained (at 90°K) are also shown in Table I. It is seen that the concentration n'_{oc} (the beginning of instability) and n_{oc} (the formation of the stationary space charge waves) may be considerably different.

§ 4. Conclusion

The capture probability of hot electrons by the negative copper ions in Ge increases strongly on raising the electric field. In a certain range of the temperatures and the field strengths this leads to the negative bulk differential conductivity and to the drastic breaking up of the spatially homogeneous electric field distribution. If the electron concentration is lower than a certain value (dependent probably upon the composition and the dimensions of the sample) the immobile high-field regions (static domains) are formed. At higher concentrations the moving domains and the space-charge waves of the dipole type are formed.

The experimental data on the domain velocities are in qualitative agreement with eq. (1).

Somewhat unclear remains the problem of the form and width of the domains as well as the problem of the instability criteria.

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References

1) B. K. Ridley: Proc. Phys. Soc. (London) **82** (1963) 954.
2) B. K. Ridley and R. G. Pratt: J. Phys. Chem. Solids **26** (1965) 21.*
3) I. A. Kurova and S. G. Kalashnikov: Fiz. tverdogo Tela **5** (1963) 3221.
4) I. A. Kurova, V. S. Vavilov and M. Wrana: Fiz. tverdogo Tela (in print)
5) V. P. Sondayevski, V. I. Stafeyev and E. I. Karakushan: *Proc. Int. Conf. Semiconductor Physics*, Paris (1964) p. 481.*
6) K. W. Boer: Phys. Rev. **6A** (1965) A1949.*
7) M. S. Kagan, S. G. Kalashnikov and N. G. Zhdanova: Phys. Status solidi **11** (1965) 415; Fiz. tverdogo Tela **8** (1966) 774.
8) M. S. Kagan, S. G. Kalashnikov and N. G. Zhdanova: Fiz. tverdogo Tela **8** (1966) 788.
9) W. Shockley: Bell Syst. tech. J. **23** (1954) 799.
10) V. L. Bonch-Bruevich: Fiz. tverdogo Tela **8** (1966) 356.
11) V. L. Bonch-Bruevich and S. G. Kalashnikov: Fiz. tveodogo Tela **7** (1965) 750.
12) S. G. Kalashnikov and V. L. Bonch-Bruevich: Phys. Status solidi **16** (1966).
13) B. K. Ridley: Proc. Phys. Soc. (London) **86** (1965) 637.
14) V. L. Bonch-Bruevich and Sh. M. Kogan: Fiz. tverdogo Tela **7** (1965) 23.

* The previous papers by these authors are given.