PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON THE PHYSICS OF SEMICONDUCTORS, KYOTO, 1966
JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 21, SUPPLEMENT, 1966

XVIII-3. Instability of Electron-Hole Plasma in Semiconductor, Caused by Non-Linearity of Voltage-Current Characteristics

M. I. IGLISIN, E. G. PEL, L. Ya. PERVOVA and V. I. FISTUL
Institute of Rare Metals, Moscow, USSR

It is shown that oscillations in conductivity may appear in the crystal in which electron and hole components of conductivity are non-linear, for example, as a result of dependence of recombination cross-section on electric field. Instability of this kind has resonance character. Conditions which are necessary for appearance of oscillation are formulated, and formulas for oscillation frequency and critical field are obtained. Agreement between experimentally measured oscillation-period for gold-doped germanium crystal with hole conductivity and its calculated value is satisfactory.

§ 1. Theory

If electrons and holes take part simultaneously in conduction, so that

$$\sigma(E)=\sigma_n(E)+\sigma_p(E)\ , \tag{1}$$

then electrical instability may appear in semiconductor when σ_n and σ_p depend on external field intensity E. Indeed, if such crystal is included in direct current circuit in such a way that voltage on the sample is defined by its conductivity (current generator condition), then any fluctuation of one of the conductivity components, for example σ_n, will change the value of σ and therefore the value of electric field intensity in the sample, E. As a result, the second conductivity component σ_p will change too. Thus, σ_n and σ_p will be connected with each other through field intensity in the sample, and electric oscillations may occur in this system. Dependence of electron and hole components of conductivity on field intensity may be characterized by non-linearity factors

$$\beta_n=\frac{1}{\sigma_n}\frac{d\sigma_n}{d(E^2)}\ , \qquad \beta_p=\frac{1}{\sigma_p}\frac{d\sigma_p}{d(E^2)}\ . \tag{2}$$

Supposing that time dependence of σ_n and σ_p, resulted from field change in the sample, has relaxation character, then complex conductivity for electron and hole components may be defined as follows:[1)]

$$G_{n,p}(\omega)=\sigma_{n,p}\left(1+\frac{2\beta_{n,p}E^2}{1+j\omega\tau_{n,p}}\right)\ , \tag{3}$$

where $\tau_{n,p}$=relaxation time of electron and hole component of conductivity. Using eqs. (1) and (3) total conductivity $G(\omega)$ may be written as follows:

$$G(\omega)=G_n(\omega)+G_p(\omega)=g+jy\ , \tag{4}$$

where

$$g=\sigma_n\left[1+\frac{2\beta_nE^2}{1+(\omega\tau_n)^2}\right]+\sigma_p\left[1+\frac{2\beta_pE^2}{1+(\omega\tau_p)^2}\right]\ , \tag{5}$$

$$y=2\omega E^2\left[\frac{\sigma_n\beta_n\tau_n}{1+(\omega\tau_n)^2}+\frac{\sigma_p\beta_p\tau_p}{1+(\omega\tau_p)^2}\right]\ . \tag{6}$$

Self-oscillation in discussed system may appear, if the real part of total conductivity g turns into zero. This takes place at the critical field in the sample, which is equal to;

$$E_{cr}^2=-\frac{1}{2}\frac{(\sigma_n+\sigma_p)(\tau_n+\tau_p)}{\sigma_n\beta_n\tau_p+\sigma_p\beta_p\tau_n}\ . \tag{7}$$

Oscillation frequency is defined by $y=0$ and is equal to:

$$\omega^2=-(\tau_n\tau_p)^{-1}\frac{\sigma_n\beta_n\tau_n+\sigma_p\beta_p\tau_p}{\sigma_n\beta_n\tau_p+\sigma_p\beta_p\tau_n}\ . \tag{8}$$

There exist oscillations if E_{cr} and ω are positive. It is possible if inequalities are carried out simultaneously:

$$\sigma_n\beta_n\tau_p+\sigma_p\beta_p\tau_n<0$$
$$\sigma_n\beta_n\tau_n+\sigma_p\beta_p\tau_p>0\ . \tag{9}$$

Conditions for occurrence of instability may be inferred from these inequalities, namely:

1. Factors β_n and β_p have different signs.
2. $\tau_n\neq\tau_p$.

Among many other possibilities discussed situation may be realized in a semiconductor, having multiply charged recombination and shallow compensating impurities, for example, germanium with gold and antimony, copper and antimony etc..

When a minority carrier injection takes place in such semiconductor, electron and hole components of conductivity may be connected with each other through field E, because the probability of capture of electron and hole by charged centers depends upon electric field E.

In sufficiently strong fields voltage-current characteristic for hole component conductivity will be superlinear ($\beta_p>0$).

In the case of electron conductivity situation is somewhat more complicated than for holes. It is known that probability of electron capture by a negative impurity increases with field *i.e.* $\beta_n<0$. As a result of the absence of theory it is difficult to determine the sign of β_n beforehand in case of capture by a neutral center. Both cases may take place in semiconductor with hole-type conductivity depending on concrete conditions (capture cross-sections $S_n{}^0$ and $S_n{}^-$, ratio, degree of compensation, etc). Later it will be shown that $\beta_n<0$ in the investigated case of hole conductivity.

If $\beta_n<0$, then condition $\tau_n\neq\tau_p$ will be

$$\tau_p>\tau_n\,, \tag{10}$$

where τ_p and τ_n are life-times of holes and electrons for discussed model, which are caused by their capture by impurity centers.

From ratios of eqs. (5) and (7), taking into account that $\beta_n<0$, it follows that total differential conductivity of the sample with direct current ($\omega=0$) and field $E=E_{cr}$ is defined as follows:

$$G(0)=(\sigma_n+\sigma_p)\omega^2\tau_n\tau_p\,. \tag{11}$$

By taking into account eqs. (9) and (10) we find that the differential conductivity of electron component $G_n(0)$ is negative when $E=E_{cr}$, namely $G_n(0)\simeq-\sigma_p$. Although the differential resistance of electron component is negative in an instability region, total differential resistance of the crystal remains positive ($G(0)>0$). Thus, the above discussed instability is not bound up with regions of negative differential resistance in the voltage-current characteristic of the sample.

If $\beta_n<0$ and $\beta_p>0$, then conductivity electron component in strong field will have capacitive phase shift and hole component inductive phase shift. Such semiconductor in strong field may be presented formally as parallel circuit whose resonance frequency is defined by eq. (8), and the critical field E_{cr} in eq. (7) corresponds to the field, at which resonance conditions are satisfied.

§ 2. Experiment

Experimental investigation of phenomena discussed above was carried out on germanium single crystals of hole conductivity doped with gold ($N_{\mathrm{Au}}=10^{15}\,\mathrm{cm}^{-3}$) and antimony ($N_{\mathrm{Sb}}=8\times10^{13}\,\mathrm{cm}^{-3}$). Hole mobility at 77°K amounted to $10^4\,\mathrm{cm}^2\,\mathrm{sec}^{-1}\,\mathrm{V}^{-1}$.

As the sample was dumbbell-like (see Fig. 1), strong field region was placed in the sample volume and not near contacts. Current contacts (1, 4) and probe ones (2, 3) were produced by fusing of indium. Contact 5 served as electron emitter in strong field region and was obtained by fusing in tin alloy and antimony.

a) Voltage current characteristics

Voltage-current characteristics were measured at current-generator conditions (R_4 and $R_5\gg R_{1-4}$) at 77°K. Hard current-generator conditions allowed to regulate current J_5 and J_4 independently.

Figure 2 (curve 1) shows J_4-E relationship on the narrow region of the sample 2-3 at $J_5=0$ (emitter is switched off). Marked curve J_4 deviation from Ohm's law occurs at fields $10^2\,\mathrm{V\,cm}^{-1}$.

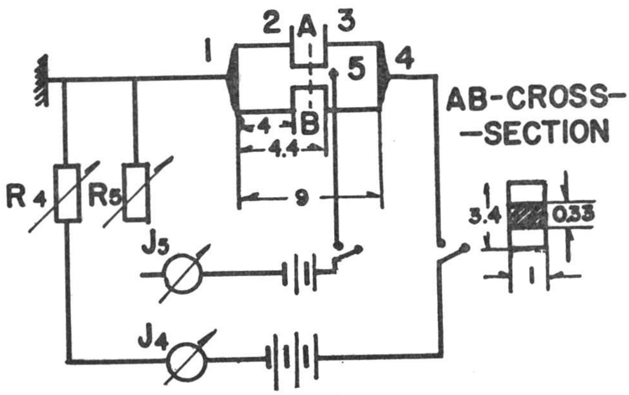

Fig. 1. Measuring circuit. Sizes are in mm.

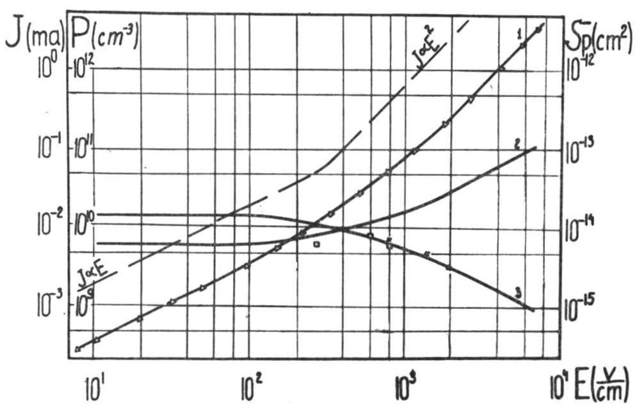

Fig. 2. Current J_4 (curve 1), hole concentration P (curve 2), hole-capture-cross-section S_p^- (curve 3: ×× $N_{Au}=2\times10^{15}$ cm^{-3}, $N_{Sb}=8\times10^{14}$ cm^{-3}; □□ $N_{Au}=10^{15}$ cm^{-3}, $N_{Sb}=4\times10^{14}$ cm^{-3}) vs. field E.

At fields higher than 10^3 V cm^{-1} current J_4 increases proportionally to field intensity square. Supposing that non-linear behaviour results from hole concentration change (mobility is constant*) we may plot the hole concentration p vs. field relationship (curve 2).

Taking into account that mobility remains constant the increase of hole concentration with field growth may be explained by proportional decrease of the hole-capture-cross-section by negatively charged gold atoms, S_p^-. Curve 3 shows relative S_p^- change vs. field E.

Absolute values of S_p^-, obtained by double injection method[2], are plotted on curve 3 too (crosses and square dots).

Matching the obtained values of the cross-section S_p^- with relative curve 3 in Fig. 2 we have $S_p^-=1.5\times10^{-14}$ cm^2 when electric field is weak. Obtained value for capture-cross-section in weak field comes to an agreement with S_p^- values got by other methods (2.3×10^{-14} cm^2 [3]) and 3×10^{-14} cm^2 [4]). S_p^- vs. field relationship may be defined as follows:

$$S_p^-(E)=S_{p_1}^-\left(\frac{E_1}{E}\right)^m,$$

where E_1 is electric field, and $m\simeq1$. In our case $E_1\simeq10^3$ V cm^{-1}.

b) Conductivity oscillations

When emitter circuit is switched off ($J_5=0$, and only holes take part in conductivity), oscillations are absent up to analized fields $E=7\times10^3$ V cm^{-1}. If the emitter current is kept constant at a certain regulated value, and the field in the sample is increased so as to obtain some value of E, we may note appearance of regular component in chaotic noise, which increases its amplitude and coherence with field growth, then begins to disassemble and eventually disappears in noise. The point of the most distinct oscillations (black one) of curve 2 in Fig. 3, showing total current (J_4+J_5)-field relationship when $J_5=0.3$ ma, corresponds to field $E=2\times10^3$ V cm^{-1}. When $2.2\times10^3<E<1.5\times10^3$ V cm^{-1}, oscillations disappear in noise.

Current and voltage oscillograms at pulsed voltage supply are given in the same Fig. 3. Oscillations start with current decrease and voltage increase on the sample. Oscillation period is 2.5×10^{-6} sec.

Analogous oscillations having the same period could be obtained when the sample is illuminated by integral light from the glow lamp. In this case emitter circuit was switched off.

Thus, conductivity oscillations of the sample appear only if:

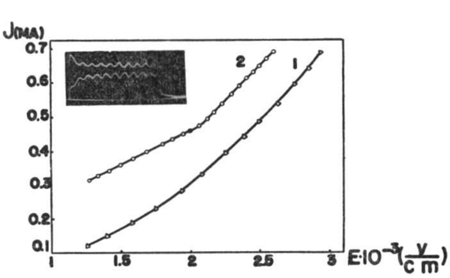

Fig. 3. Current J_4 (curve 1) and total current (J_4+J_5) at $J_5=0.3$ ma (curve 2) vs. field E. Upper curve-current oscillogram. Lower curve-voltage oscillogram.

* Usually it is true for not very strong fields.

1) Both positive and negative current carriers take part in conductivity. It is not important how minority carriers are created (by light or by field).

2) Field reaches some definite value. Let us consider that the field corresponding to the most distinct oscillations is critical ($E_{cr}=2\times10^3$ V cm^{-1}).

If one of these conditions was not fulfilled then oscillations did not appear.

§ 3. Discussion

From eqs. (8) and (11) one may obtain:

$$\frac{\sigma_n\beta_n\tau_n+\sigma_p\beta_p\tau_p}{\sigma_n\beta_n\tau_p+\sigma_p\beta_p\tau_n}=-\frac{G(0)}{\sigma}=-\kappa\,. \tag{12}$$

In this case using eq. (2) it is not difficult to show that expression for E_{cr} (7) is simplified and becomes:

$$E_{cr}=\frac{\sigma}{\sigma_p'}\frac{\kappa\tau_p-\tau_n}{\tau_p-\tau_n}\,. \tag{13}$$

And the period is equal to:

$$T^2=\frac{4\pi^2}{\kappa}\tau_n\tau_p\,. \tag{14}$$

Excluding τ_n from eqs. (13) and (14) we shall obtain:

$$\left(\frac{T}{\tau_p}\right)^2=\frac{4\pi^2}{\kappa}\frac{E_{cr}-\kappa\dfrac{\sigma}{\sigma_p'}}{E_{cr}+\dfrac{\sigma}{\sigma_p'}}\,. \tag{15}$$

For the case shown in Fig. 3 from curve 2 at point $E_{cr}=2\times10^3$ V cm^{-1} we obtain $\sigma=5.7\times10^{-6}\,\Omega^{-1}$ cm^{-1}, $G(0)=4\times10^6\,\Omega^{-1}$ cm^{-1}, $\kappa=0.7$ and from curve 1 for the same field $\sigma_p'=d\sigma_p/dE=3.5\times10^{-9}\,\Omega^{-1}$ V^{-1}. Substituting all values in eq. (15) we obtain $T/\tau_p=3.7$.

Measured values $T=2.5\times10^{-6}$ sec and $\tau_p=1/N_{\mathrm{Sb}}\cdot S_p^-\cdot v_+=4.2\times10^{-7}$ sec (value $S_p^-=3\times10^{15}$ cm^2 is taken from curve 3 of Fig. 2 for $E_{cr}=2\times10^3$ V cm^{-1}), and yield $T/\tau_p=6$.

Thus, the calculated value is in satisfactory agreement with the experimentally measured one of T/τ_p.

Best agreement between measured and calculated values may be obtained if one takes into account hole mobility vs. E relationship (suppose that scattering occurs on lattice oscillations and mobility decreases with field growth).

Expression (14) allows to determine τ_n. It is equal to 2.7×10^{-7} sec and is less than any of two times for weak field irrespective of charge state of recombination center as $S_n^0\sim S_n^-\sim10^{-16}$ cm^2[5]. In other words capture probability increases with field growth in our case at any type of capture, so that ratio $\beta_n<0$ really takes place.

Besides we may show that the voltage-current characteristic of conductivity due to the electron component has a negative differential resistance ($G_n(0)<0$).

Indeed difference between total and hole current densities is

$$\Delta j=eE(\mu_n n+\mu_p p)\,.$$

Suppose that quasi-neutrality condition is realized, *i.e.* $\Delta p\tau_n=n\tau_p$, then the ratio of inserted electron concentrations for two fields E and E_1 will be

$$\frac{n}{n_1}=\frac{\Delta j}{\Delta j_1}\cdot\frac{E_1}{E}\cdot\frac{\left(1+b\dfrac{\tau_{p_1}}{\tau_{n_1}}\right)}{\left(1+b\dfrac{\tau_p}{\tau_n}\right)}\,,$$

where $b=\mu_p/\mu_n$. Taking $E_1=1.5\times10^3$ and $E=E_{cr}=2\times10^3$ V cm^{-1} we shall define Δj corresponding to them from data of curves 2 and 1 in Fig. 3. The values τ_{p_1} and τ_{n_1} may be defined by the same method as τ_p and τ_n. If $b=0.7$ then $n/n_1=0.49$. Decreasing of inserted electrons concentration owing to field growth at constant emitter current is equivalent to appearance of negative differential resistance.

Thus, conditions (different signs for β_n and β_p and $\tau_p>\tau_n$) formulated above as necessary for existence of such kind of instability are satisfied and it is shown that conductivity electron component has negative differential resistance.

From the analysis instability of electron-hole plasma in p-type germanium is really caused by non-linearity of voltage-current characteristics and has resonance character in our case.

Acknowledgements

The authors are grateful to A. Ya. Shulman, S. V. Konstantinov, V. E. Perel and D. G. Andrianov for their valuable comments and suggestions.

References

1) T. M. Lifshits, A. Ya. Oleinikov and A. Shulman: Phys. Status solidi **14** (1966) 511.
2) K. L. Achley and A. G. Milnes: J. appl. Phys. **35** (1964) 369.
3) T. P. Vogel, I. R. Hansen and M. Carbuny: J. Opt. Soc. Amer **51** (1961) 70.
4) L. Pervova: Radiotekhnika i Elektronika **6** (1961) 1745.
5) E. V. Karpova, V. G. Alekseeva and S. G. Kalashnikov: Fiz. tverdogo Tela **4** (1962) 634.