Influence of intervalley redistribution of the electrons and of the crystal temperature on the excitation of helical instability in an electron-hole plasma of germanium in strong magnetic fields

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The influence of uniaxial deformation that causes intervalley redistribution and of the crystal temperature on the magnetic field at which the helical instability is eliminated is investigated experimentally and theoretically. The elimination of the instability in strong magnetic fields ($\omega_c\tau>1$) is due both to the onset of an ambipolar drift of helical perturbations and to the limited dimensions of the sample in the direction of the current. Depending on the crystal temperature, which determines the ratio of the electron and hole mobilities, uniaxial compression and tension strains of the crystal in the direction of the applied field can lead to both an increase and a decrease of the ambipolar mobility in strong magnetic fields. The magnetic field at which the instability is eliminated decreases or increases accordingly. The experiments were performed at crystal temperatures 77 and 140 K (at these temperatures the electron and hole are in an inverse ratio) and in magnetic fields up to 30 kOe. The results of the calculations agree with the experimental data. Thus, this study demonstrates for the first time that the drift mechanism which occurs even in a quasineutral plasma, can be used to eliminate helical instability in strong magnetic fields.

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1. The effect of helical instability in an electron-hole plasma (oscillistor) was experimentally discovered by Ivanov and Ryvkin[1] in experiments on germanium samples placed in sufficiently electron (E) and magnetic (H) fields parallel to each other. The results of Ivanov and Ryvkin's experiments were explained by Glicksman[2] within the framework of the Kadomtsev-Nedospasov theory[3] of helical instability. It is known[4] that this instability arises if the value of the drift flux of the carriers (Γ_d) in a constant magnetic field and in the electric field of the wave exceeds the combined diffusion (Γ_D) flux and the flux of the ambipolar drift of the perturbations (Γ_a) in a constant electric field. The absolute-instability condition corresponding to excitation of the oscillistor is of the form[4]

$$|\Gamma_d|>(\Gamma_D^2+\Gamma_a^2)^{1/2}. \tag{1}$$

In the case of intervalley redistribution of the electrons, when the anisotropy of the mobility manifests itself strongly, the ambipolar drift of the helical perturbations occurs even in a quasineutral plasma[5] ($n=p$, the electron and hole densities are equal). A quasineutral helical perturbation can exist in this case only in the presence of ambipolar drift (the electron and hole fluxes of the perturbations are equal). In the isotropic case, this drift arises only at $n\neq p$ if the magnetic field is weak[4] ($\alpha_i=\mu_{i=e,h}H/c\ll 1$, where $\mu_{e,h}$ are the mobilities of the electrons and holes). Strong intervalley redistribution of the electrons is produced in Ge when the crystals are deformed along $\langle 111\rangle$ axes. We recall that the equal-energy surfaces of Ge near the bottom of the conduction band are described by four ellipsoids of revolution that are elongated along the $\langle 111\rangle$ axes. When the crystal is compressed, the electrons become repopulated into a valley elongated in the direction of the strain, and in the case of tension they leave the valleys.[6] In the former case the averaged transverse mobility exceeds the longitudinal mobility ($\bar{\mu}_{e\perp}>\bar{\mu}_{e\parallel}$), since the electrons are repopulated into a valley with a larger transverse mobility, while in the latter case we have $\bar{\mu}_{e\parallel}>\bar{\mu}_{e\perp}$. It is assumed in these arguments that the direction of the strain is the same as that of the constant fields.

In the subsequent analysis we shall use the two-valley model.[5] Within the framework of this model it is assumed that the electron gas consists of two ensembles, in which the electrons have different mobilities along and across the electric field. In the first ensemble $\mu_\parallel$ and $\mu_\perp$ are the mobilities corresponding to the long and short axes of the individual ellipsoids of revolution. This ensemble is the equivalent of a valley elongated along the strain axis ($\langle 111\rangle$). In the second ensemble, the corresponding mobilities are $\mu_{\parallel\,\mathrm{eff}}$ and $\mu_{\perp\,\mathrm{eff}}$. It is easy to show that in this ensemble, which is the equivalent of the remaining three valleys, we have

$$\mu_{\parallel\mathrm{eff}}={}^8/_9\mu_\perp+{}^1/_9\mu_\parallel,\quad \mu_{\perp\mathrm{eff}}={}^4/_9\mu_\parallel+{}^5/_9\mu_\perp. \tag{2}$$

The anisotropy of the hole mobility is realized at much larger crystal deformations, and will henceforth be disregarded.

We have shown earlier[5] (theoretically and experimentally) that in weak magnetic fields ($\alpha_i\ll 1$) the oscillistor excitation threshold, which is determined by the value of EH, always increases in a quasineutral plasma both when the Ge crystals are stretched or compressed along an $\langle 111\rangle$ axis. This is easily understood, since the criterion (1) of absolute instability of helical waves does not depend on the direction of the ambipolar drift. We note that in this case the ambipolar drift of the heli-

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cal perturbations is directed towards the hole drift and the electron drift, respectively, when the crystal is compressed or stretched.[5]

Let us examine this question in greater detail. The calculation of the ambipolar mobility for an anisotropic plasma can be easily carried out with the aid of the motion and continuity equations for the electrons and holes. The corresponding expression is

$$\mu_a=\bar{\mu}_{e\parallel}\bar{\mu}_{h\parallel}\left[n\left(1+\frac{k_\perp^2\bar{\mu}_{e\perp}}{k_\parallel^2\bar{\mu}_{e\parallel}}\right)-p\left(1+\frac{k_\perp^2\bar{\mu}_{h\perp}}{k_\parallel^2\bar{\mu}_{h\parallel}}\right)\right]\cdot \times\left[n\bar{\mu}_{e\parallel}\left(1+\frac{k_\perp^2\bar{\mu}_{e\perp}}{k_\parallel^2\bar{\mu}_{e\parallel}}\right)+p\bar{\mu}_{h\parallel}\left(1+\frac{k_\perp^2\bar{\mu}_{h\perp}}{k_\parallel^2\bar{\mu}_{h\parallel}}\right)\right]^{-1}, \quad (3)$$

where $\bar{\mu}_{e\parallel}$, $\bar{\mu}_{h\parallel}$ and $\bar{\mu}_{e\perp}$, $\bar{\mu}_{h\perp}$ are the averaged mobilities of the electrons and the holes along and across the electric field, respectively, while $k_\parallel$ and $k_\perp$ are the wave vectors characterizing the inhomogeneity of the quasineutral perturbations $(n'-p')$. It follows from (3) that if the holes are isotropic ($\bar{\mu}_{h\perp}/\bar{\mu}_{h\parallel}=1$) and $n=p$, then the ambipolar drift is directed towards the hole drift at $\bar{\mu}_{e\perp}/\bar{\mu}_{e\parallel}>1$ (compression of the crystal) and of the electrons at $\bar{\mu}_{e\perp}/\bar{\mu}_{e\parallel}<1$ (tension). In the case of equal degrees of anisotropy of the electrons and holes ($\bar{\mu}_{e\perp}/\bar{\mu}_{e\parallel}=\bar{\mu}_{h\perp}/\bar{\mu}_{h\parallel}$) and $n=p$ we have $\mu_a=0$.

In strong magnetic fields ($\alpha_i\gg1$) the mobilities of both the electrons and holes are anisotropic, naturally, also in the absence of deformation. If $\mu_h>\mu_e$, then particle loss is in the direction of the hole drift, since $\bar{\mu}_{e\perp}/\bar{\mu}_{e\parallel}=1/\alpha_e^2>\bar{\mu}_{h\perp}/\bar{\mu}_{h\parallel}=1/\alpha_h^2$, and in the electron-drift direction at $\mu_h<\mu_e$.

Inasmuch as in strong magnetic fields ($\alpha_i\gg1$) the drift flux that causes the instability is $\Gamma_a\sim E/H$, the onset of ambipolar escape causes the threshold electric field, at which the oscillistor is excited, to increase with increasing magnetic field (this effect can be attributed also to the limited length of the sample[17]). In weak fields ($\alpha_i\ll1$) at the oscillistor excitation threshold we have $E\sim1/H$ [4] and the $E(H)$ dependence should thus have a minimum (insert of Fig. 1). At a given value of the electric field intensity, the excitation of the oscillistor will take place in a definite magnetic-field interval ($H_1<H<H_2$—the shaded region in the insert of Fig. 1). The value of the first threshold field (H_1) lies in the region of weak fields, and that of the second (H_2) in the region of the strong fields. The oscillistor is excited at $H>H_1$ and is suppressed at $H>H_2$. At the point where the function $E(H)$ has an extremum (Fig. 1) we have $\alpha_i(H_e)\approx1$. In short samples, the value of the field H_2 is smaller than in long ones,[7] inasmuch as the role of the longitudinal diffusion becomes stronger in this case. With increasing ambipolar mobility, the field H_2 should decrease, since the threshold $E(H)$ dependence becomes steeper on the strong-field side. At liquid-nitrogen temperature ($T=77$ K) we have $\mu_h>\mu_e$ in Ge[8] and the directions of the ambipolar drift due to the anisotropy of the electron mobility in a strong magnetic field and by the compression strain field will coincide ($n=p$). When the crystal is stretched, the corresponding directions are opposite and the ambipolar drift velocity decreases. Therefore, at a given electric field

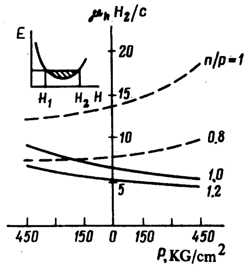

FIG. 1. Theoretical plots of the threshold magnetic field H_2 against the strain (to the right—compression, to the left—tension). The solid curves correspond to a crystal temperature $T=77$ K ($\bar{\mu}_e/\mu_h\approx0.8$, $\mu_h\approx4\cdot10^4$ cm²/V-sec and the dashed lines to $T=140$ K ($\bar{\mu}_e/\mu_h\approx1.4$, $\mu_h\approx10^4$ cm²/V-sec), $E=50$ V/cm.

the value of H_2 should decrease in compression and increase in tension. This effect should manifest itself most clearly in n-type crystals ($n\gtrsim p$). At a crystal temperature $T>100$ K we have $\mu_h<\mu_e$ in Ge[8] and the situation changes. In this case the field H_2 should increase under compression and decrease under tension. The effect is most noticeable in p-type crystals ($p\gtrsim n$).

The present study was devoted to a theoretical and experimental investigation of the dependence of the second threshold field H_2 ($\alpha(H_2)\gg1$) on the uniaxial deformation of Ge crystals in the ⟨111⟩ direction at different lattice temperatures $T=77$ and 140 K. The experiments were performed under conditions of strong plasma injection ($n\approx p$). We note immediately that when the Ge crystals are deformed in the ⟨100⟩ direction and no intervalley redistribution takes place, the field H_2 should be independent of pressure. This fact was confirmed by us experimentally (Fig. 2, curve 1).

2. The theoretical analysis was carried out for the case of a surface helical wave[4] within the framework of the two-valley model. The constant electric and magnetic fields were directed along the strain axis ⟨111⟩. The calculations were performed for a cylindrical sample with a small surface-recombination rate. We considered a potential, $E'=-\nabla\varphi'$ and quasineutral, $n'_{\rm I}+n'_{\rm II}=p'$, perturbation of the type $A'=A_1(r)\exp(i\omega t-im\varphi-ikz)$, where $|m|=1$ (helical waves). The prime pertains to the perturbed quantities and the Roman number labels the valley.

The dispersion equation for an arbitrary magnetic field, obtained in analogy with[4], is of the form

$$y_1y_2I_1'I_2'+m^2\tilde{H}^2I_1I_2a_4-i\frac{m}{2}\tilde{H}(1-a_4)(y_1I_1'I_2+y_2I_1I_2') +i\frac{m}{2}\tilde{H}\frac{n(1+a_4)}{a_2a_3(1+n)(y_1^2-y_2^2)}(y_1I_1'I_2-y_2I_1I_2')\left[2a_2b_2-b_1 -\tilde{k}^2\left(a_1a_3+\frac{a_2}{n}\right)\right]=0, \quad (4)$$

where $I_{1,2}\equiv I(y_{1,2})$ are modified Bessel functions of first order:

$$b_1=i\tilde{\omega}(a_2+a_3)+i\tilde{k}\tilde{E}(a_1a_3/n-a_2)+\tilde{k}^2(a_1a_3/n+a_2),$$
$$b_2=i\tilde{\omega}-i\tilde{k}\tilde{E}+\tilde{k}^2;$$

$y_{1,2}$ are the solutions of the equation

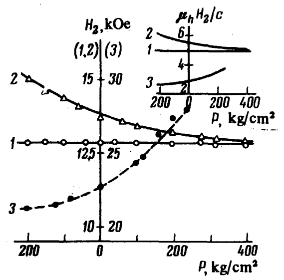

FIG. 2. Experimental plots of the threshold magnetic field H_2 against the strain: curves 1, 2—n-Ge ($\rho = 60$ Ω-cm), $T = 77$ K, $E = 60$ V/cm, 3—p-Ge ($\rho \approx 50$ Ω-cm), $T = 140$ K, $E = 50$ V/cm (right-hand scale).

$$y^4 a_2 a_3^2 (1+1/n) - y^2 a_3 [b_1 + \tilde{k}^2 (a_1 a_3 + a_2/n)] + \tilde{k}^2 [b_1 + b_2 (a_1 a_3 - a_2)] = 0;$$

$$a_1 = \tilde{\mu}_\parallel \tilde{n}_{\rm I} + \tilde{\mu}_{\parallel\,\rm eff} \tilde{n}_{\rm II}, \qquad a_2 = \frac{\tilde{\mu}_\perp \tilde{n}_{\rm I}}{1+(\tilde{\mu}_\perp \tilde{H})^2} + \frac{\tilde{\mu}_{\perp\,\rm eff} \tilde{n}_{\rm II}}{1+(\tilde{\mu}_{\perp\,\rm eff} \tilde{H})^2},$$

$$a_3 = (1+\tilde{H}^2)^{-1}, \qquad a_4 = \frac{1}{a_2}\left[\frac{\tilde{\mu}_\perp^2 \tilde{n}_{\rm I}}{1+(\tilde{\mu}_\perp \tilde{H})^2} + \frac{\tilde{\mu}_{\perp\,\rm eff}^2 \tilde{n}_{\rm II}}{1+(\tilde{\mu}_{\perp\,\rm eff} \tilde{H})^2}\right];$$

$$\tilde{H} = \frac{\mu_h H}{c}, \quad \tilde{E} = \frac{R\mu_h}{D_h} E, \quad \tilde{\omega} = \frac{R^2}{D_h}\omega, \quad \tilde{k} = kR,$$

$$n = \frac{n_0}{p_0}, \quad \tilde{n}_{\rm I,II} = \frac{n_{\rm I\,II}}{p_0}, \quad \tilde{\mu}_{\parallel,\perp} = \frac{\mu_{\parallel,\perp}}{\mu_h},$$

R is the radius of the sample; n_0 and p_0 are the equilibrium concentrations of the electrons and holes.

Using the method of Landau and Lifshitz,[9] we can obtain with the aid of (3) a criterion of the absolute instability of the helical waves:

$$\frac{\tilde{E}^2}{\tilde{H}^2}\left[\frac{c_1(n+c_1)(n+c_2)}{n^2(1+c_1)^2}\right]^2 > \frac{1}{4}\tilde{\mu}_a^2 \tilde{E}^2 + \frac{8}{\tilde{H}^2}\left(1+\frac{1}{n}\right)^2 \frac{c_1(c_1+c_2)}{(1+c_1)^2}. \qquad (5)$$

The expressions for the oscillation frequency and the wave vector are

$$\tilde{\omega}_{\rm thr} = \tilde{k}\tilde{\mu}_a \tilde{E}, \quad \tilde{k}_{\rm thr} = \frac{8}{\tilde{H}^2}\frac{c_1}{c_1+c_2}, \qquad (6)$$

where

$$\tilde{\mu}_a = \frac{\mu_a}{\mu_h} = \frac{nc_1 - c_2}{n(1+c_1)}, \quad c_1 = \frac{\tilde{n}_{\rm I}}{\tilde{\mu}_\perp} + \frac{\tilde{n}_{\rm II}}{\tilde{\mu}_{\perp\,\rm eff}}, \quad c_2 = \tilde{n}_{\rm I}\tilde{\mu}_\parallel + \tilde{n}_{\rm II}\tilde{\mu}_{\parallel\,\rm eff}.$$

In the derivation of (5) and (6) it was assumed that $\alpha_i^2 \gg 1$. The effects connected with the limited length of the sample were not taken into account ($L/R \gg 1$). The ratio of the electron densities in the valleys is connected with the pressure P in the following manner[10]:

$$\frac{n_{\rm I}}{n_{\rm II}} = \frac{1}{3}\exp\left(\frac{4}{9}\frac{\Sigma_u P}{c_{44} kT}\right), \qquad (7)$$

where $\Sigma_u = 18$ eV (the deformation-potential constant) and $c_{44} = 0.67 \times 10^{12}$ dyn/cm^2 (the elastic constants). It is easily seen that the ambipolar mobility differs from zero in the intrinsic plasma ($n_0 = p_0$) even in the absence of deformation ($P = 0$, $n_{\rm I}/n_{\rm II} = \frac{1}{3}$). In this case $\mu_a = \mu_h - \bar{\mu}_e$ ($\bar{\mu}_e = \frac{2}{3}\mu_\perp + \frac{1}{3}\mu_\parallel$). Using the expressions for μ_a and (7), we can show that μ_a increases (decreases) in the case of compression (tension) of the crystal if $\mu_h > \mu_e$. These relations are most strongly pronounced in n-type crystals. At $\mu_h < \bar{\mu}_e$ the corresponding relations are reversed and manifest themselves most strongly in p-type samples.

As seen from condition (5), at a given electric field there exists a threshold value of the magnetic field H_2, above which the criterion (5) is not satisfied, corresponding to elimination of the helical instability. As already mentioned, this effect is due to the onset of ambipolar drift of the helical perturbations in the strong magnetic field. If $\mu_h > \bar{\mu}_e$, then the value of the field H_2 should decrease when the crystal is compressed ($n \approx p$) and increase under tension, this being due to the increase (decrease) of the ambipolar mobility. At $\mu_h < \bar{\mu}_e$ the corresponding relations are reversed. Figure 1 shows the calculated dependences of the field H_2 on the strain for different values of n/p. These calculations agree well with the foregoing qualitative analysis.

3. The experiments were performed on single crystal of n- and p-germanium respectively with $\rho_{300\,\rm K} = 60$ Ω-cm and $\rho_{300\,\rm K} = 50$ Ω-cm. Samples with dimensions $1 \times 1 \times 20$ and $1 \times 1 \times 7$ mm were cut from plates oriented in the directions ⟨111⟩ and ⟨100⟩. The technology of the production and treatment of the samples is described in[4]. The block diagram of the setup is similar to that shown in[11]. The experiments were performed with strong injection through the end-face contacts. The termination of the generation was determined by the vanishing of the alternating signal on symmetrical lateral probes. The experimental curves were plotted at temperatures 77 and 140 K in order, first, to obtain plasma magnetization in a magnetic field up to 30 kOe, by using the increase of the mobilities, and, second, to ensure a sufficient redistribution of the carriers at small deformations.

Figure 2 shows characteristic experimental plots of the threshold magnetic field H_2 against the strain (compression on the right and tension on the left). It is seen that the qualitative course of the threshold plot agrees well with the theoretical ones. Unfortunately, the electromagnets used in the experiments did not produce sufficiently strong magnetic fields in the large gap between the pole pieces, so that the plot 3 of Fig. 2 was obtained in a small gap with short samples. As discussed above, in short samples the field H_2 is smaller than in long ones,[7] a fact confirmed by experiment (compare curves 2 and 3 in the insert of Fig. 2).

The results show that elimination of the oscillistor effect in strong magnetic fields is due not only to a realignment of the spatial structure of the wave in the short sample,[7] but also to the ambipolar drift, which is produced even in a quasineutral plasma. In long samples this elimination mechanism predominates. This effect can arise also in a gas plasma.

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Inelastic scattering of electrons by dislocations in aluminum

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The temperature dependence of the electrical resistance ρ_d due to the presence of dislocations is measured in aluminum samples of various purities. In pure samples the dependence is a step-like function. The introduction of $\approx 0.1\%$ of impurities suppresses the growth of ρ_d. This effect of the additional resistance, on the temperature dependence which corresponds to an increase in the impurity concentration in the dislocation cores, may be due to a change in the scattering of the electrons by quasi-local defect modes.

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A pronounced increase, over a comparatively narrow temperature range, of the additional electrical resistance $\rho_d(T)$ due to dislocations introduced in a crystal, has been observed in a series of metals: Cu, Ag, Au, Mo, Zn.[1–3] The increase in $\rho_d(T)$ turned out to be dependent on the length of the dislocation sections free of pinning points. The quantity $r_{max}=[\rho_d(T_{max})-\rho_d(0)]/\rho_d(0)$ decreased with increase in the density of intersection point of the dislocation lines. The $r(T)$ dependence was studied in detail in samples of Cu and Mo having different dislocation structures; no effect of the presence of impurities on r_{max} was observed. However, for both these metals, the concentration of contaminant atoms along the linear defects was unknown. The distance between the impurity atoms located on the dislocation lines could be significantly greater than the mean distance between the dislocation interactions, and this, as a result, determined the growth of r. The fact that one has managed to create in pure samples a structure with a high number of dislocations indicates the stability of the structure, independent of the dislocation pinning by the impurity atoms.

It is therefore desirable to carry out similar measurements of $\rho_d(T)$ in a metal in which the stable arrangement of the dislocations (after plastic deformation) depends very strongly on the presence of impurity atoms. Aluminum satisfies such requirements completely, since there is a high probability in it at room temperature of displacement of the dislocations under the action of internal stresses.

The plastic deformation of pure polycrystalline aluminum generates the formation of a cellular dislocation structure with very thin walls of the cells.[4] In aluminum containing ~0.1% impurities, a cellular structure is also developed, but with a significantly greater mean density of dislocations after approximately the same deformation. The difference in the mean density of dislocations is brought about by the fact that, in migrating, the dislocations are fixed at many points by foreign atoms, the high concentration of which in this case determines the length of the free dislocation segment L. The effect of a decrease in L_c on the temperature dependence of $\rho_d(T)$ was investigated in samples of Al of various purity.

EXPERIMENT

The measurements of the electric resistance were carried out by the potentiometric method. The sample preparation is similar to that described in Ref. 2.

The samples were plates of polycrystals or single crystals of aluminum with cross sections of (3–4) × (0.2–0.5) mm, length 80–90 mm. The distance between the potential leads was 40 mm. The quantity ρ_d was determined as

$$\rho_d(T)=\left[\frac{R(T)}{R^{\cdot}(273\,\mathrm{K})}-\frac{R_{st}(T)}{R_{st}(273\,\mathrm{K})}\right]\rho(273\,K), \qquad (1)$$

R and R_{st} are the resistance of the sample and the standard, ρ(273 K) is the resistivity of Al. We used ρ(273 K) $=2.5\times10^{-6}$ ohm-cm and ρ(372 K) $=2.64\times10^{-6}$ ohm-cm for the pure and "dirty" Al, respectively.

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