Threshold switching and microwave-induced spontaneous emission in *p*-Ge in a static magnetic field

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Experiments on the impurity breakdown of *p*-Ge in a circularly polarized electric field **E** and a static magnetic field $\mathbf{B}_0 \perp \mathbf{E}$ reveal a switching accompanied by the formation of an anomalously large number of light holes. This switching occurs after a threshold value of E/B_0 is reached. A magnetized hole plasma radiates photons at wavelengths $\lambda \simeq 100\ \mu$m.

The effort to achieve a population inversion of charge carriers[1] has attracted much interest to the excitation of semiconductor crystals by intense, circularly polarized electromagnetic waves.[2,3] In the present letter we report a development in experimental research in this direction. Specifically, in *p*-Ge we have detected a threshold switching and an anomalous buildup of light holes in a microwave electric field **E** crossed with a static magnetic field $\mathbf{B}_0$.

In the measurements, an rf pulse ($\omega/2\pi = 9.45\times10^9$ Hz) 1 μs long passes through a circular polarizer to a disk-shaped *p*-Ge sample. The axis of revolution of the disk runs along the [100] direction. The disk is inside a superconducting solenoid (Fig. 1a). The diameter D and the thickness d of the disk are both considerably smaller than the wavelength in the waveguide. The transmitted microwave power is absorbed by a matched load, while the reflected signal goes to a microwave detector. The direction in which the field **E** is rotated and that of the cyclotron revolution of the holes are either the same (+) or opposite (−), depending on the direction of $\mathbf{B}_0$. In the case of the + polarization, the reflection coefficient is no higher than 3%, while the reflected signal reproduces the shape of the incident rf pulse.

We observe a completely different behavior in the response to the − polarization (Fig. 1b): 1) The increase in the reflected signal is delayed a time τ with respect to the application of the microwave field. 2) The reflection coefficient abruptly reaches a peak value R_I. 3) After a time of about 10^{-8} s, a transition occurs from states 1 to a steady state 2. Peak 1 is not observed in a strong magnetic field ($B_0 > 4$ T).

The length of the delay, τ, is determined by the ratio $E^{\rm out}/B_0$ (Fig. 1b), where $E^{\rm out}$ is the amplitude of the microwave coming from the source. An extrapolation of $\tau^{-1} = f(E^{\rm out}/B_0)$ yields an absolute threshold $(E^{\rm out}/B_0)_t$, below which a jump in the reflection coefficient does not occur no matter how long the wait ($\tau \rightarrow \infty$).

The threshold behavior of the microwave response can be seen particularly clearly in measurements of the reflection coefficient as a function of B_0 at $E^{\rm out}$ = const (the solid line in Fig. 2a).

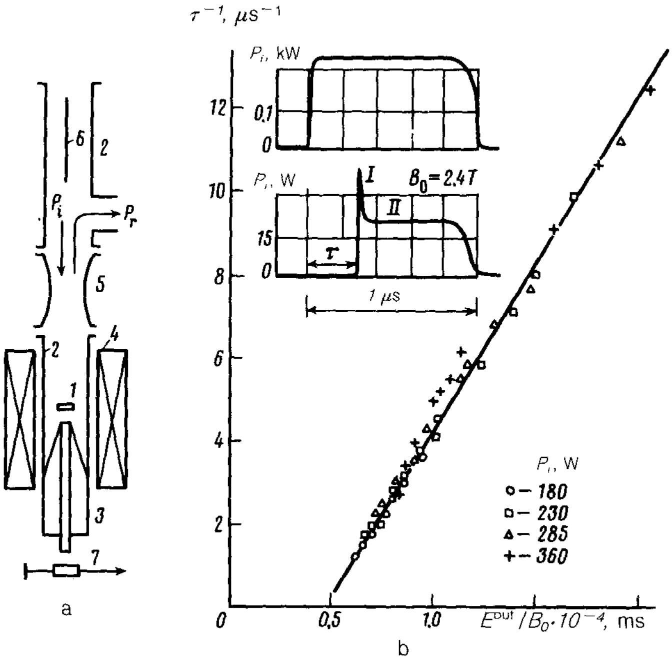

FIG. 1. a: Experimental layout. 1—sample, $D = 5$ mm, $d = 3$ mm ($N_A - N_D = 1.8 \times 10^{14}$ cm^{-3}); 2—circular waveguide; 3—matched load; 4—solenoid; 5—polarizer; 6—absorber; 7—Ge:Sb detector. b: Time evolution of the power of the incident (P_i) and reflected (P_r) microwaves and the functional dependence $\tau^{-1}(E^{\rm out}/B_0)/T_0 = 4.2$ K.

Treating the sample as a rotating electric dipole excited by the incident wave, we can think of the reflected wave as radiation from this dipole. The reflection coefficient can then be written

$$R = \frac{2\pi^3}{9a^2}\left(\frac{V}{AL}\right)^2 \frac{1-(\lambda/\lambda_c)^2}{\lambda^4}\left|\frac{\epsilon_\pm - 1}{\epsilon_\pm + \gamma_L}\right|^2, \qquad (1)$$

where V is the volume of the sample, L is the depolarization factor of the ellipsoid inscribed in the disk, $\gamma_L = (1-L)/L$, $A \simeq 1.5$ is a coefficient which reflects the difference between the volume of the disk and of the inscribed ellipsoid,[4] λ_c is the cutoff wavelength for the H_{11} mode in a waveguide of diameter $2a$, and $\epsilon_\pm = \epsilon'_\pm + i\epsilon''_\pm$ are the effective dielectric constants for the + and − polarizations. In strong magnetic fields $|B_0| \gg B_{CR}$ and $\mu B_0 \gg 1$ (B_{CR} is the magnetic induction at which cyclotron resonance occurs at the given frequency ω, and μ is the mobility), the quantity $\epsilon'_\pm \simeq \epsilon_L \pm pe/(\omega\epsilon_0 B_0)$ is determined by the concentration of free holes, p, and the lattice dielectric constant ϵ_L. In this case we have $\epsilon''_\pm \simeq |\epsilon'_\pm - \epsilon_L| \mu^{-1} B_0^{-1}$. The holes which have migrated from acceptor states to the valence band make negative contribution to the dielectric constant ϵ'_-, causing the system to move closer to a magnetoplasma resonance (MPR): $\epsilon'_- \to -\gamma_L$.

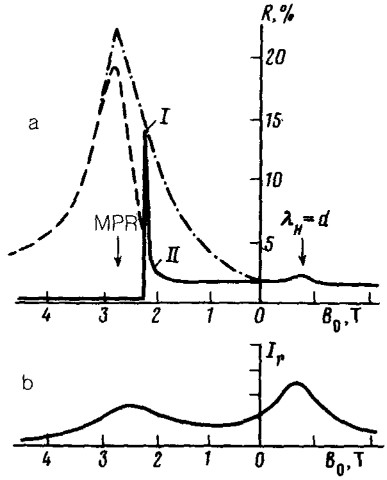

FIG. 2. a: The functional dependence $R(B_0)$ measured $\Delta t = 0.1$ μs after the begining of the microwave pulse (solid line); envelopes of the R_1 and R_2 values measured at various values of Δt (dashed lines). b: Emission intensity $I_r(B_0)$. The time constant of the Ge:Sb detector is 5 μs. $P_i = 720$ W. The arrows show the calculated positions of resonances.

The internal field E^{in}_{-} and the ionization rate both increase, and the state of the crystal with the low hole concentration p is unstable. An abrupt change in p (a threshold effect) is found from the solution of the kinetic equation[5] with a resonance.

Treating the peak R_{I} as a magnetoplasma resonance in a time-varying hole plasma, we can determine the mobility $\mu_{\text{I}} = W\sqrt{R_{\text{I}}}$ and the electric field in the sample, $E^{\text{in}}_{\text{I}} = \mu_{\text{I}} B_{\text{I}} E^{\text{out}} [AL(\epsilon_L + \gamma_L)]^{-1}$, where the value of W is taken from (1) under the resonance condition, and B_{I} is the magnetic induction corresponding to the peak. The value found, $\mu_{\text{I}} = (36 \pm 2)$ $\text{m}^2/(\text{V}\cdot\text{s})$, indicates that, on the average, the holes have enough time between collisions to execute a significant number $(\mu_{\text{I}} B_{\text{I}}/2\pi)$ of revolutions in the magnetic field. At $p_i \geqslant 720$ W, i.e., at $E^{\text{out}} \geqslant 3.7 \times 10^4$ V/m, a ratio $E^{\text{in}}_{\text{I}}/B_{\text{I}} > (2\hbar\omega_0/m_h)^{1/2}$ is reached, where $\hbar\omega_0 = 36$ meV is the energy of an optical phonon, and $m_h \simeq 0.35 m_0$ is the effective mass of the heavy holes. In this situation, however, the heavy holes cannot be responsible for resonant peak R_{I}, since their cyclotron revolution is interrupted by the emission of optical phonons ($\omega_c \tau_0 \leqslant 1.5$, where $\omega_c = eB_{\text{I}}/m_h$, and τ_0 is the hole lifetime in the region $\epsilon > \hbar\omega_0$). The peak R_{I} is thus formed primarily by light holes, and the concentration (p_l) of these holes, determined by the position of peak 1 at $B_0 \leqslant B_{\text{MPR}}$, turns out to be extremely large: $p_l \simeq (N_A - N_D) B_{\text{I}}/B_{\text{MPR}}$.

The reflection coefficient R_2 is determined by a resonance of the steady-state plasma with $p = N_A - N_D$ (dashed line in Fig. 2a). The mobility and internal field in state 2 are lower than those in state 1 to the extent that the condition $E^{\text{in}}_{\text{II}}/B_0 < (2\hbar\omega_0/m_h)^{1/2}$ holds; i.e., the condition for the buildup of light holes is disrupted. The emission of photons plays an important role in the I→II transition. It can be seen from Fig. 2b that it is in the region of the maximum change in the reflection coefficient, $\Delta R = R_{\text{I}} - R_{\text{II}}$, that we find the maximum in the emission intensity (I_r) detected by a Ge:Sb photoresistive detector.

Judging from the emission, the buildup of light holes can also occur in a field of the + polarization, in this case intensified by the size resonance of helicons, $d = \lambda_H$ (Fig. 2b), where $\lambda_H \simeq 2\pi c/\omega\sqrt{\epsilon'_+}$ is the length of the helicon microwave[6] at complete ionization of the acceptors.

The buildup of light holes in a field of circular polarization $\mathbf{E}\perp\mathbf{B}_0$ is consistent with the model of Ref. 3, although the experiment unexpectedly reveals that plasma effects play an extremely important role.

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