Self-oscillations in an exciton-electron system with impact ionization of excitons

B. M. Ashkinadze and A. V. Subashiev
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, Leningrad

(Submitted 10 August 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **46**, No. 7, 284–286 (10 October 1987)

Self-oscillations have been observed in the density of nonequilibrium electrons during the impact ionization of excitons by electrons heated in a microwave field.

The absorption of microwave radiation by a nonequilibrium electron-hole plasma has been studied in pure Si and Ge crystals at low temperatures. The samples were positioned in an 8-mm-range waveguide and subjected to a microwave power level ~100 mW. Nonequilibrium electron-hole pairs were produced by the light beam from a cw He-Ne laser. Most of the electron-hole pairs were bound into excitons. Their recombination radiation was detected by a spectrometer. The temperature of the crystal was determined from the linewidth of the exciton luminescence. The sample was in He vapor, so the temperature was regulated over the range 5–15 K. The free current carriers, not bound in excitons, caused an absorption of the microwave radiation propagating through the waveguide. The magnitude of this absorption was proportional to the nonequilibrium microwave conductivity of the sample.

Figure 1 shows oscilloscope traces of the microwave pulses which have propagated through the waveguide. At an optical pumping intensity below the critical level, the traces are similar in shape to that in Fig. 1a: There is a slight ($<5\%$) absorption of the microwave radiation. At $I_0 \sim 1$ W/cm^2 oscillations appear abruptly in the transmitted microwave signal (Fig. 1b), with a shape which varies as the pump is increased (Fig. 1c).

It follows from Fig. 1 that the microwave conductivity of the sample oscillates in regular fashion, at a frequency which varies over the range $f = 0.5$–5 MHz, increasing with increasing microwave power level, light intensity, and sample temperature. We

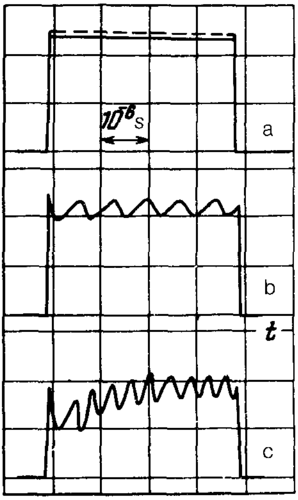

FIG. 1. Oscilloscope traces of the transmitted microwave pulse at various light intensities I (silicon crystal, $t = 10$ K). a—$I < I_0$ (the dashed line shows the pulse in the case $I = 0$); b—$I \sim 1.05 I_0$; c—$I \sim 1.15 I_0$.

should stress that the oscillations appear when the light intensity and the microwave power reach certain critical values, and they exist over certain intervals of these quantities.

In the Si crystals the oscillations could be observed over the temperature interval 8–15 K; in the Ge crystals they appeared at substantially lower microwave power levels and were observed over the interval 4 K $\lesssim T < 8$ K. Similar oscillations were observed during the steady-state application of a microwave field and during excitation of the sample with a pulsed GaAs laser, which provided a higher rate of generation of electron-hole pairs. Figure 2 shows a corresponding oscilloscope trace[1)] of the oscillations at $T \cong 8$ K.

The self-oscillations observed in the plasma density were caused by an ionizational instability of excitons in the microwave field. The reason for this instability is an increase in the electron temperature (the electrons are heated by the microwave field at frequencies near $\omega\tau_r$, where τ_r is the momentum relaxation time) with increasing electron density. Under these conditions an increase in the electron density leads to an acceleration and then an avalanche growth of the impact ionization of excitons.[2] The electron recombination process restores the system to its original state, and then the process repeats itself. Correspondingly, the characteristic frequency of the oscillations is determined in order of magnitude by the electron lifetime with respect to recombination.

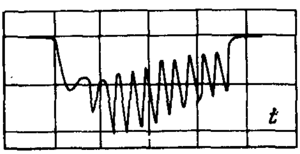

FIG. 2. Oscilloscope trace of the microwave absorption pulse during pulsed illumination (GaAs laser with a pulse length of 4×10^{-6} s).

The time evolution of the electron density n and of the exciton density N in the microwave field is determined by the equations

$$\frac{dn}{dt} = G - \gamma n^2 - \frac{n}{\tau_e} + \gamma N_{cv} e^{-\phi/T} N + \beta n N, \quad (1)$$

$$\frac{dN}{dt} = \gamma n^2 - \frac{N}{\tau_x} - \gamma N_{cv} e^{-\phi/T} N - \beta n N. \quad (2)$$

Here G is the rate of photoexcitation of carriers; γ is the coupling coefficient; τ_e and τ_x are the electron and exciton lifetimes; N_{cv} is the reduced state density; ϕ is the ionization energy of the excitons; and β is the coefficient of the impact ionization of excitons, which depends on the electron temperature T_e. Specifically, it is given by $\beta \cong \pi a_B^2 v_e \exp - (\phi/T_e)$; where a_B is the first Bohr radius, and v_e is the electron thermal velocity.

To determine the electron temperature, we need to take into account that at low temperatures and at significant electron densities ($n > 10^{12}$ cm^{-3}) the electron-electron and electron-hole collisions cause the electron momentum relaxation time τ_r to decrease substantially.[3] From the energy balance equation[4] we find an expression for the temperature of the electrons which are heated by the microwave field under conditions with $\omega\tau_r > 1$:

$$T_e = T + \frac{e^2 E^2 T}{4 m^2 s^2 \omega^2}\left(1 + \frac{n T^2}{n_0 T_e^2}\right), \quad (3)$$

where E and ω are the field strength and frequency of the microwave field, s is the sound velocity, and $n_0 = AT^3$. For silicon crystals at $T = 10$ K, with $\omega = 2.3 \times 10^{11}$ s^{-1} and $E = 65$ V/cm ($n_0 \cong 4 \times 10^9$ T^3 cm^{-3}), the electron temperature increases from $T_e = 25$ K (at $n < 10^{12}$ cm^{-3}) to $T_e = 35$ K (at $n = 4 \times 10^{13}$ cm^{-3}).

To analyze system (1)–(3), we transform to equations with the dimensionless variables $x = \gamma\tau_x n$, $y = \gamma\tau_x(n + N)$, $\tau = t/\tau_x$. We find

$$\frac{dx}{d\tau} = g - (1 + R(x))x^2 - (r + \rho)x + \rho y + R(x)xy,$$

$$\frac{dy}{d\tau} = g - y - (r - 1)x. \quad (4)$$

Here $r = \tau_x/\tau_e$, $g = G\gamma\tau_x^2$, $R = \beta/\gamma$, $\rho = \gamma\tau_x N_{cv} \exp(-\phi/T)$.

System of equations (4) is similar to the system describing the dynamics of a chemical reactor,[5] and it has an analogous phase-space structure. In particular, a limiting cycle may arise near certain stationary solutions of system (4). A linear analysis shows that the stationary state (x_0, y_0) is an unstable focus in the case in which we have $r > 1$ and, simultaneously, the following inequalities:

$$\sqrt{(R(x_0)x_0+\rho)(r-1)} > \frac{1}{2}\left[R'x_0(y_0-x_0)-\frac{g}{x_0}-\rho\frac{y_0}{x_0}-x_0(1+R)+1\right] > 1. \quad (5)$$

The conditions for the onset of the oscillations are satisfied at the following parameter values, which are close to the experimental values: $G = 10^{21}$ cm$^{-3}\cdot$s^{-1}, $r = 2$, $\tau_x = 3\times 10^{-6}$ s, $\phi = 165$ K, $\gamma = 10^{-3}$ T^{-2} cm^3/s, and $E = 65$ V/cm. The electron density at the stationary point is $n \cong 4\times 10^{13}$ cm^{-3}, and the electron temperature is 35 K.

It follows from (5) that the self-oscillations arise in intervals of the lattice temperature and of the hot-electron temperature in which dissociation and ionization occur rapidly enough that the condition $(R(x_0)x_0+\rho)(r-1) > 1$ holds. On the other hand, the self-oscillations can occur only in a certain interval of fields and of the pump G, in which the quantity $R'x_0(y_0-x_0)$ lies in the interval corresponding to the satisfaction of inequalities (5). If $R(x)$ does not grow with x (i.e., if the electron temperature does not increase as the electron density increases), self-oscillations cannot occur. The frequency of the self-oscillations near the threshold for their occurrence is $f \cong (1/2\pi\tau_x)\sqrt{[R(x_0)x_0+\rho](r-1)}$. For the parameter values specified above we find $R(x_0)x_0 \sim 11$, $\rho \sim 1$, and thus $f \cong 2\times 10^5$ Hz. The frequency increases with increasing lattice temperature, with increasing microwave field strength, or with increasing light intensity. The oscillation frequency found here and its predicted behavior agree with the experimental data.

Further evidence for the validity of the proposed model is the fact that oscillations do not occur when electrons are heated under cyclotron resonance conditions (or, equivalently, when electrons are heated in a static field, with $\omega\tau_r < 1$). In this case the electron temperature falls off with increasing density, and inequalities (5) do not hold.

The ionizational instability of excitons during microwave heating has a close physical analog in the temperature-electric instability of Ref. 6, where the nonlinear process, which causes low-frequency ($\sim$1-Hz) oscillations in current-carrying samples, is the thermal ionization of impurity centers due to a heating of the sample.

We wish to thank V. V. Bel'kov for assistance in the experiments.

[1)]The pulsed application of the microwave field or of the light makes it possible to avoid a heating of the sample which would cause a thermal breakdown of excitons.

[1]B. M. Ashkinadze, V. V. Bel'kov, and A. V. Subashiev, Fiz. Tverd. Tela (Leningrad) **29**, 1193 (1987) [Sov. Phys. Solid State **29**, 679 (1987)].
[2]P. D. Altukhov and B. M. Ashkinadze, Fiz. Tverd. Tela (Leningrad) **17**, 1572 (1975) [Sov. Phys. Solid State **17**, 1029 (1975)].
[3]H. Kawamura and H. Saji, J. Phys. Soc. Jpn. **19**, 288 (1964).
[4]K. Seeger, Semiconductor Physics, Springer-Verlag, New York, 1974.
[5]N. V. Butenin, Yu. I. Neĭmark, and N. A. Fufaev, Vvedenie v teoriyu nelineĭnykh kolebaniĭ (Introduction to the Theory of Nonlinear Oscillations), Nauka, Moscow, 1976.
[6]V. S. Vinetskiĭ, Fiz. Tverd. Tela (Leningrad) **11**, 1402 (1969) [Sov. Phys. Solid State **5**, 1140 (1969)].

Translated by Dave Parsons