FAR-INFRARED PHOTOCONDUCTIVITY AS A PROBE FOR NON-EQUILIBRIUM PHASE TRANSITIONS IN n-GaAs

R. OBERMAIER, W. BOHM, W. PRETTL and P. DIRNHOFER
Institut für Angewandte Physik, Universität Regensburg, Regensburg, W. Germany

Received 6 June 1984

A strong enhancement of the cyclotron resonance induced FIR-photoconductivity has been observed in n-GaAs close to the threshold of impact ionization breakdown. The results are discussed in terms of phase transitions far from equilibrium showing that the photoconductivity reflects the Curie–Weiss behaviour of the generalized susceptibility.

In high purity n-GaAs at low temperatures impact ionization breakdown occurs at an electric field of a few volts per cm resulting in a rapid increase of the current at a critical electric field strength [1,2]. The transition from the low conducting state, where almost all electrons are bound to shallow donors, to the high conducting state, where almost all donors are ionized, can be considered as a phase transition in an open system far from thermal equilibrium [3,4]. The steady state concentration of electrons n corresponds to the order parameter; and the kinetic coefficient of impact ionization X is the control parameter comparable to the temperature in equilibrium phase transformations. The single electron excitation probability X^s due to thermal excitation takes the place of an external force conjugate to the order parameter.

In this paper we report on measurements of the cyclotron resonance induced far-infrared photoconductivity in n-GaAs as a function of the electric bias field. Close to the threshold field a pronounced peak of the photosignal is observed. The experiments are discussed by means of a simple generation–recombination model showing that the photoconductivity probes the generalized susceptibility $\chi = dn/dX^s$ of the non-equilibrium phase transition. In the limiting case of vanishing thermal excitation, χ approaches a Curie–Weiss law diverging for a critical value X_c of the control parameter.

The experiments were carried out on high purity epitaxial layers mounted in a metallic light pipe and immersed in liquid helium at the center of a superconducting magnet. Photoconductivity was measured in Faraday configuration with the electric bias field perpendicular to the magnetic field using a CH_3F molecular far-infrared laser of frequency $\tilde{\nu}$ = 20.1 cm^{-1} (λ = 496 μm). Below the threshold a usual load resistor circuit was used whereas in the infinite slope portion of the current voltage characteristics a constant current source was applied.

The photoconductive signal at constant infrared intensity is displayed in fig. 1 as a function of the magnetic field strength for various bias voltages below threshold. On a continuous background cyclotron resonance at B = 1.43 T yields a narrow line whose peak increases superlinearly with the bias voltage. From the measurements the relative conductivity change $\Delta\sigma/\sigma$ was determined as a function of the bias voltage. $\Delta\sigma$ was calculated from the height of the cyclotron resonance line above the background photosignal. The result together with the dark current voltage characteristics measured at the magnetic field strength of the cyclotron resonance is plotted in fig. 2 showing that $\Delta\sigma/\sigma$ strongly peaks close to the critical voltage of impact ionization breakdown.

It was shown that in n-GaAs cyclotron resonance absorption at liquid helium temperature yields a photoconductive signal predominantly due to an increase in free electron concentration and not due to a mobility change [5]. Landau levels depleted by cyclotron transitions are repopulated thermally and in the present

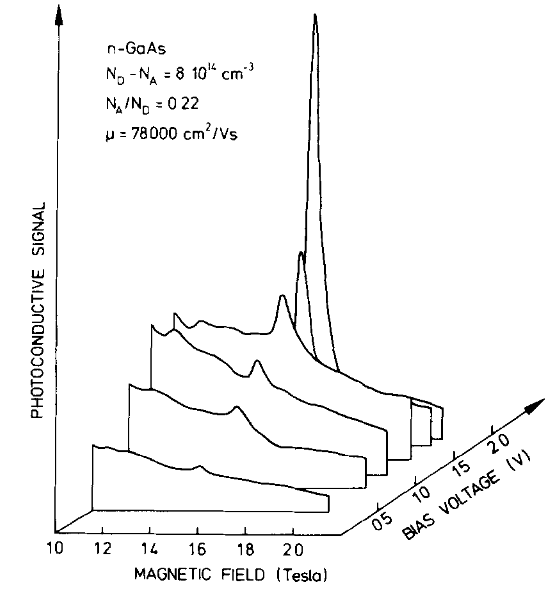

Fig. 1. Photoconductivity due to cyclotron resonance for various bias voltages. The indicated voltages are for the magnetic field strength of resonance.

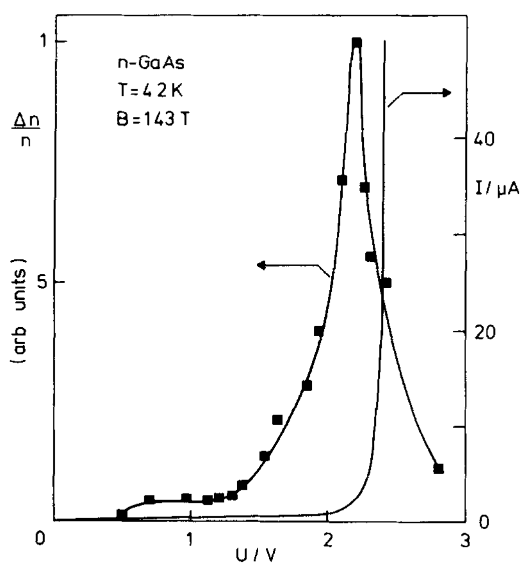

Fig. 2. Relative photoconductivity $\Delta\sigma/\sigma$ of cyclotron resonance as a function of the bias voltage and current voltage characteristics at the resonance magnetic field strength.

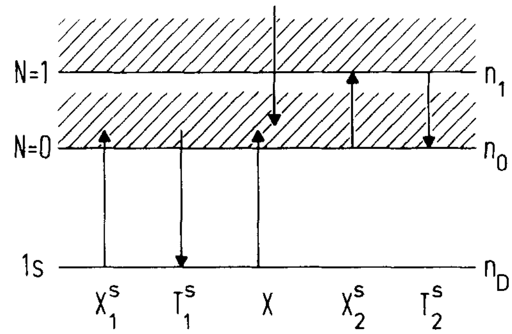

Fig. 3. Schematic diagram of 1s donor ground state and $N = 0$ and $N = 1$ Landau levels with electron transitions denoted by rate coefficients.

case also by impact ionization of neutral donors. Thus $\Delta\sigma/\sigma = \Delta n/n$ where n is the steady state electron concentration. In order to describe the electric field dependence of the cyclotron resonance induced photoconductivity qualitatively we apply a three level model including the 1s donor groundstate and the $N = 0$ and $N = 1$ Landau levels. At low temperatures the generation and recombination processes displayed in the energy level diagram of fig. 3 are of importance. The resulting rate equations are

$$\dot{n}_1 = X_2^s n_0 - T_2^s n_1 , \tag{1}$$

$$\dot{n}_0 = X_1^s n_D + X n n_D + T_2^s n_1 - T_1^s n_0 p_D - X_2^s n_0 , \tag{2}$$

$$\dot{n}_D = T_1^s n_0 p_D - X_1^s n_D - X n n_D , \tag{3}$$

where n_0, n_1, n_D, and p_D are the concentrations of electrons in the $N = 0$ and $N = 1$ Landau level and in the donor ground state and the density of positive donors, respectively. We assume that X_2^s is is solely due to optical transitions ignoring thermal excitation of the $N = 1$ Landau band. Then $X_2^s = \sigma_0 F$ where σ_0 is the cross section of cyclotron resonance absorption and F is the photon flux density. Taking into account the conservation of donor number, $N_D = p_D + n_D$, and local neutrality, $P_A = n_D + n_0 + n_1$ where $P_A = N_D - N_A$ is the effective density of donors, the free electron concentration $n = n_0 + n_1$ in the steady state ($\mathrm{d}/\mathrm{d}t = 0$) follows from

$$f(n, X^s) = (X^s + nX)(P_A - n) - T_1^s n (N_A + n) = 0 , \tag{4}$$

where X^s is an effective single electron excitation probability defined by

$$X^s = X_1^s + (X_1^s + nX)\sigma_0 F/T_2^s \,. \tag{5}$$

The concentration of optically excited carriers Δn at low photon flux may be expressed by

$$\Delta n = (\mathrm{d}n/\mathrm{d}F)\,F = \chi(X_1^s + nX)\sigma_0 F/T_2^s \,, \tag{6}$$

where

$$\chi = (\mathrm{d}n/\mathrm{d}X^s)_{F=0} \tag{7}$$

is the generalized susceptibility of the impact ionization phase transition. Thus, the photoconductivity is proportional to the susceptibility.

For the present model a true phase transition occurs only in the case $X_1^s = 0$ i.e. at zero temperature. For finite X_1^s the phase transition is lost because the order parameter n is different from zero for all X. The situation is similar to the case of e.g. a ferroelectric crystal in an external electric field. At zero temperature eq. (4) has the stable solutions $n = 0$ and $n = (X - X_c)P_A/(X + T_1^s)$ below and above the critical value $X_c = T_1^s \times N_A/P_A$ of the control parameter X, respectively. Introducing this solution into eq. (7) yields a Curie–Weiss behaviour of χ

$$\begin{aligned} \chi &= (X_c - X)^{-1} \,, & X < X_c \,, \\ &= (T_1^s + X_c)\,[(T_1^s + X)(X - X_c)]^{-1} \,, & X > X_c \,. \end{aligned} \tag{8}$$

At finite temperatures, $X_1^s > 0$, we find

$$\chi = \frac{P_A - n}{(X_c - X)P_A + 2n(T_1^s + X) + X_1^s} \,. \tag{9}$$

The divergence of the susceptibility at $X = X_c$ disappears in this case, however χ still peaks close to X_c.

The kinetic coefficients for n-GaAs defined in the rate equations eqs. (1) – (3) are not known with sufficient accuracy. In particular the band-to-donor recombination coefficient T_1^s shows large variations within a moderate range of the magnetic field strength [6, 7], and the detailed dependence of T_1^s on the magnetic field is not yet evaluated. Therefore no effort has been made to fit the theoretical results to the experimental data. Instead we calculated the photoconductivity for various electron excitation parameters expressed in units of T_1^s and compared the result with the experimental observations. For the impact ionization coefficient X as a function of the electric field E the Shockley relation [8] $X = X_0 \exp(E_0/E)$ was used where X_0 and E_0 were assumed to be constant. Numerical results were determined as functions of E/E_0 without specifying E_0. In fig. 4 the relative photoconductivity $\Delta\sigma/\sigma = \Delta n/n$ is plotted for three different parameters $\nu = X_1^s/T_1^s N_A = \bar{n}/P_A$. From eq. (4) follows that $\bar{n}$ is the thermal equilibrium electron concentration at zero electric field, $X = 0$, and at low temperatures, $\bar{n} \ll N_A, P_A$. For small ν, i.e. low single electron excitation rate, $\Delta n/n$ peaks strongly close to the critical field strength $E_c = E_0\,[\ln(T_1^s N_A/X_0 P_A)]^{-1}$ and agrees well with the measured electric field dependence of the relative photoconductivity (fig. 2). With increasing ν the system departs more and more from the phase boundary and the peak rapidly degrades.

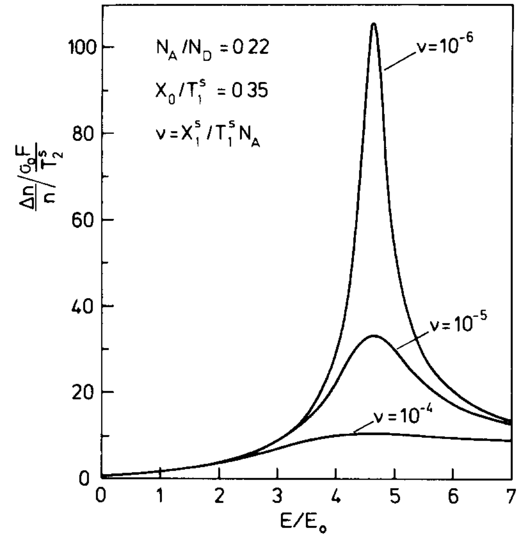

Fig. 4. Calculated relative photoconductivity $\Delta\sigma/\sigma$ in units of $\sigma_0 F/T_2^s$ as a function of the electric bias field for different thermal equilibrium electron concentrations $\bar{n} = \nu P_A$. Data are given in the figure; the critical electric field strength is $E_c = 4.6E_0$.

In conclusion we have shown that FIR photoconductivity is a suitable method to investigate the critical behaviour of impact ionization induced phase transitions in semiconductors. Within the accuracy of our measurements the phase transition in n-GaAs is properly described by a mean field theory based on simple rate equations.

We thank E. Bauser, Max-Planck-Institut für Festkörperforschung, Stuttgart, for provision of the samples and gratefully acknowledge helpful discussion with E. Schöll.

References

[1] D.J. Oliver, Phys. Rev. 127 (1962) 1045.
[2] R.A. Reynolds, Solid State Electron. 11 (1968) 385.
[3] P.T. Landsberg, Eur. J. Phys. 1 (1980) 31.
[4] E. Scholl, Z. Phys. B46 (1982) 23; B48 (1982) 153, B52 (1983) 321.
[5] H.J.A. Bluyssen, I.C. Maan, L.J. van Ruynen, F. Williams and P. Wyder, Solid State Commun. 25 (1978) 895.
[6] C.R. Pidgeon, A. Vass, G.R. Allan, W. Prettl and L. Eaves, Phys. Rev. Lett. 50 (1983) 1309.
[7] W. Prettl, A. Vass, G.R. Allan and C.R. Pidgeon, Int. J. Infrared Millimeter Waves 4 (1983) 561.
[8] W. Shockley, Solid State Electron. 2 (1961) 35.