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Autor: Saermark, K. / Falsig Pedersen, N.

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Transmission of Helicon-Waves through n-type Ge

by **K. Saermark** and **N. Falsig Pedersen**
Fysisk Laboratorium I, The Technical University of Denmark, 2800 Lyngby, Denmark

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Abstract. A comparison of calculated and observed transmission curves for low-field helicon transmission through a n-type Ge-sample at liquid helium temperatures is given.

On the occasion of the 60th birthday of Professor G. Busch we express our heartfelt congratulations and our best wishes for his continued influence on the development of Solid State Physics.

1. Introduction

In a previous publication [1] we reported on preliminary observations of low-field helicon propagation in n-type Ge in the crystallographic directions (1, 1, 1) and (1, 0, 0). The experiments were carried out at a frequency of 43.9 GHz and for a number of temperatures in the range 4–25 °K. The results were interpreted in terms of the dispersion relation given by Wallace, who in a series of papers [2] has given a thorough discussion of helicon propagation in n-type Ge and Si assuming, however, an infinite relaxation time $\tau = \infty$, and neglecting quantum effects. The general form of the dispersion relation is given by

$$\left(\frac{c^2 q^2}{\varepsilon_L} - \omega^2\right) \frac{1}{\omega_p^2} = f\left(\frac{\omega_0}{\omega}\right). \tag{1}$$

Here ε_L, c, q, ω_P and ω have the same meaning as in [1] and [2] and $\omega_0 = eH/mc$, m being the free electron mass, while $f(\omega_0/\omega)$ is a function which depends parametrically on $\alpha_L = m/m_L$ and $\alpha_T = m/m_T$ where m_L and m_T are the longitudinal and transverse masses, respectively. The form of the function f is different for the two different crystallographic directions. By means of (1) and the condition for geometrical resonances: $q = p\,\pi/d$ (p = integer), where d is the length of the sample, it was possible to determine $(\omega_P/\omega)^2$, i.e. essentially the charge carrier density n, as a function of $1/T$. It was concluded that for temperatures above ~ 15 °K and magnetic fields above ~ 8 kG the experimental observations were in good agreement with the dispersion relation (1). However, for temperatures below ~ 15 °K and fields of a few kG it was not possible to determine n versus $1/T$ in a satisfactory way. As the assumption $\tau = \infty$ – implying real q – is unsatisfactory we have tried to correlate the experimental observation of the transmission through the sample with computer calculations of the transmission coefficient taking due regard of the finite value of τ. Very recently Wallace [3] has performed similar calculations of the reflection coefficient for a sample of PbTe. No experimental results were given, however.

2. Numerical Calculations

For finite values of τ, assumed isotropic, a dispersion relation can of course be found. However, the expressions are too complicated to be useful in analytical calculations. The transmission coefficient P was therefore calculated numerically using standard theory (see, e.g., [4], Equation 4.3.9). The dielectric constant

$$\varepsilon\begin{Bmatrix} l \\ r \end{Bmatrix} = \varepsilon_L\,\varepsilon_0 + \frac{1}{i\,\omega}\,\sigma\begin{Bmatrix} l \\ r \end{Bmatrix}$$

and hence the wave-vector $q = q_1 - iq_2$ which enters the expression for P, may be found from a knowledge of

$$\sigma\begin{Bmatrix} l \\ r \end{Bmatrix} = \sigma_{xx} \mp i\,\sigma_{xy}\ .$$

The latter quantities may in turn, be derived from, e.g., [5], Equation 3.3 using the transverse property $\bar{B} \cdot \bar{E} = 0$. In calculating q_1 and q_2 account was taken of the cut-off wave-vector λ introduced by the finite sample diameter. In the limit $\tau \to \infty$ the expression for q reduces to the appropriate simple expression given in (1). ε_L was taken as 16 and the appropriate values of α_L and α_T for Ge were used.

The essential parameters entering the expression for P and q are $(\omega_P/\omega)^2$ and τ. A few of the results obtained by systematically varying these parameters are shown on the accompanying figures and will be mentioned in the discussion of the experimental results. One observation might be made here, however. It turns out that for small carrier concentration, say $(\omega_P/\omega)^2 < 0.01$, with a relatively high transmission in zero magnetic field, the slope of P vs. B for $B = 0$ depends in a rather sensitive way on the value of τ, which may thus be determined with a reasonable accuracy.

3. Experimental

The sample reported on here was n-type Ge, with Sb as donor, and with a room temperature resistivity of 2 ohm cm. The sample was cylindrical in shape with the cylinder axis along a (1, 0, 0) direction. The length and diameter of the sample was 1.56 mm and 3.5 mm, respectively. The end faces were chemically etched. To prevent microwave leakage the sample was glued by means of silver paste in a cylindrical sample holder which again was mounted in a circular wave guide.

The measurements were made with circularly polarized microwaves of a frequency of 43.9 GHz (OKI 45 V 10 Klystron). The microwave system was similar in principle to the one described by e.g., Furdyna [6]. The circular polarization of the microwaves was made in the following way: taper (DMB DBC 030) – circular phase shifter (DMB DBC 930) – sample – circular phase shifter – taper. This set up was mounted in an evacuated brass-can with rectangular wave guides – of low heat conductivity – leading from the tapers to the top of the cryostat. He exchange gas could be introduced into the brass-can. It should be noted that the circular phase shifters (center frequency 44 GHz) gave rise to instrumental faults. In an arrangement of the type: rectangular wave guide – taper – circular phase shifter – circular phase shifter – taper – rectangular wave guide the transmission should be independent on the relative orientation of two circular phase shifters with respect to each other. However, a room-temperature examination revealed that this was not the case. Two narrow dips in the transmission occurred separated by an angle of 180°. The width of the dips were 10–15° at most. The peak of a dip was of the order 10 dB. This of course complicates the interpretation of the experimental results.

The temperature could be varied in the range 4–25 °K by means of a suitably mounted heater coil. An electronic servocircuit was used to control the constancy of the temperature which was measured by a calibrated carbon thermometer. In a number of cases the temperature regulator was used to sweep the temperature for constant magnetic field thus making possible a direct observation of the temperature dependence of the transmission through the sample. In still other cases a temperature modulation was superposed on the temperature sweep. Although this greatly improved the signal particularly with respect to the location of the maxima and minima the results were quantitatively less reliable due to a later discovered fault in the modulation arrangement and will not be delt with here. It is planned to improve on the temperature modulation and to repeat the measurements.

A superconducting solenoid was used in the experiments.

4. Discussion

Comparison of calculated and observed transmission curves shows a good over-all agreement. As an example Figure 1 shows a photographic reproduction of an observed transmission curve ($T = 11.9$ °K) together with a calculated curve ($(\omega_P/\omega^2 = 0.01$; $\tau = 10^{-11}$ sec) normalized with respect to amplitude to coincide with the peak of the geometrical resonance $p = 2$ of the CRA-mode (i.e. $(\omega_0/\omega) > 0$). Except for the minima A and B the agreement is rather good. We interprete the minima A and B to be caused by the instrumental fault of the circular phase shifters as discussed in section 3. At the minimum A we have a relatively high calculated transmission and calculations show that the phase $k_1 d$ varies slowly with the magnetic field. Accordingly we get a broad minimum. At the minimum B calculations show that the phase varies rapidly with the magnetic field and one gets a narrow and barely visible minimum. This interpretation of the minima A and B are consistent with numerous other observed transmission curves. In view of this one might easily imagine the two curves shown on Figure 1 to coincide for ideal circular phase shifters. The minimum seen on the calculated *and* on the observed curve is due to cyclotron resonance

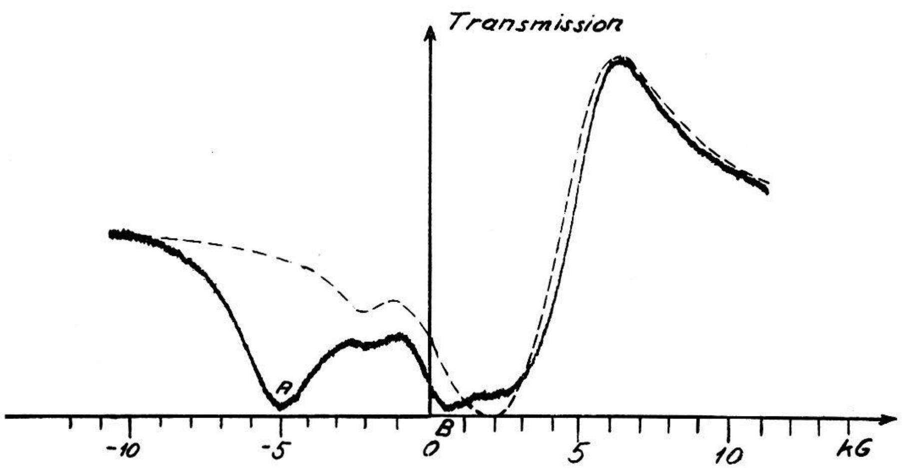

Figure 1

Experimental and calculated ($(\omega_P/\omega)^2 = 0.01$; $\tau = 10^{-11}$ sec) transmission curves.

damping. This minimum has been observed for temperatures in the range 8–12 °K at a fixed magnetic field $H = 2$ kG.

The length of the sample was chosen such that only two CRA and one CRI geometrical resonance should be observable. By comparison with theoretical curves of the type on Figure 2 it was possible to find a set of values of the parameters $(\omega_P/\omega)^2$

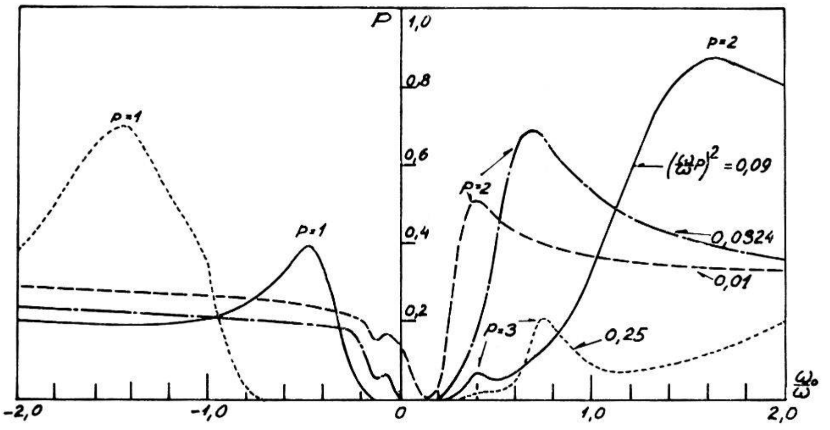

Figure 2

Calculated transmission curves for the (1, 0, 0) direction.
$d = 1.56$ mm; diam. $= 3.5$ mm; $f = 43.90$ GHz; $\tau = 10^{-11}$ sec.

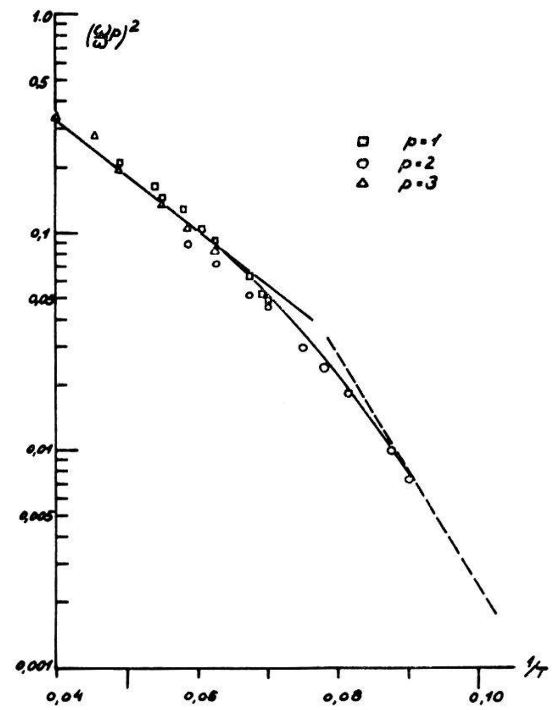

Figure 3

Experimental results for $(\omega_P/\omega)^2$ vs. $1/T$.

and τ giving a good fit, cf. Figure 1, to the experimental curves. The values of $(\omega_P/\omega)^2$ have been plotted vs. $1/T$ on Figure 3. The slope of the curve at the higher temperatures is identical to the one found in [1], while the slope of the curve at the lower temperatures is in excellent agreement with the one found by Koenig [7] for the same type of donor but by other methods. τ varies with a factor of 2 from 10^{-11} at

10 °K to $5 \cdot 10^{-12}$ at 25 °K. Finally Figure 4 shows some details of the development of the cyclotron resonance damping for increasing temperatures.

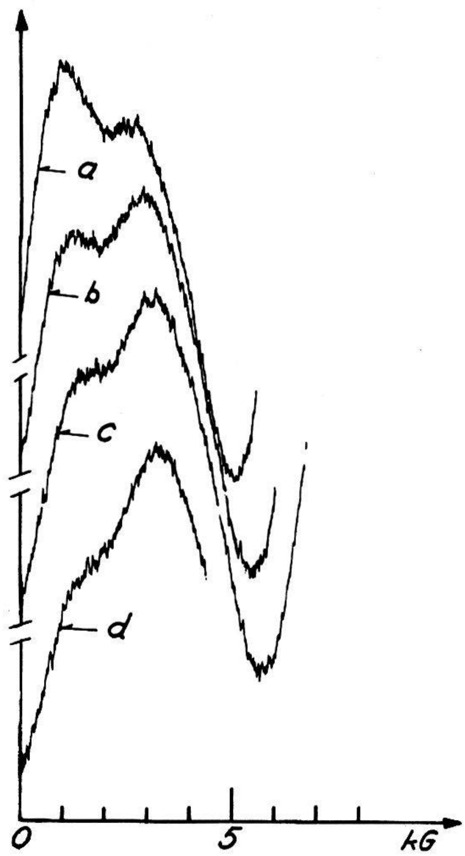

Figure 4

Experimental transmission curves for the CRI mode.
a) $T = 11.9$ °K; b) $T = 12.1$ °K; c) $T = 12.2$ °K; d) $T = 12.4$ °K.

In summary we conclude that it has been possible to find values of the set of parameters $(\omega_P/\omega)^2$ and τ securing a good agreement between the calculated and observed transmission curves. The well defined position of the cyclotron resonance damping may offer a mean of determining the cyclotron frequency ω_C for materials for which ordinary cyclotron resonance experiments are difficult to perform.

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