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ON THE ~~MICROWAVE MODE~~ PROPAGATION OF ELECTROMAGNETIC WAVES IN A MAGNETOACTIVE PLASMA AT BELOW THE PLASMA FREQUENCY

V.I. Aksenov

1. Introduction

The ~~Microwave mode~~ propagation of electromagnetic waves in a magnetoactive plasma at below the plasma frequency is both an intriguing and a poorly investigated problem.

This seems to warrant a laboratory experiment for its study.

Reference [1] suggests a similar mode called the "whistler" mode ~~— a similar mode —~~ as a means for the diagnosis of a dense plasma and describes a relevant experiment carried out on the ZETA slow thermonuclear machine at Harwell, England. The specific features of such a machine inevitably complicate experimentation.

After a discussion of some theoretical points, this author suggests what he considers a simpler experimental arrangement for the observation of microwave mode propagation in a magnetoactive plasma at below the plasma frequency.

2. Some Points of Theory

A homogeneous plasma in a magnetic field is a bi-refractive medium, and its complex refractive index, $n-j\chi$, for two characteristic waves (ordinary and extraordinary) propagating in it at frequency ω, will be given by the equation [2]:

~~[illegible]~~

$$(n-j\chi)^2_{1,2} = 1 - \frac{2v(1-v-js)}{2(1-js)(1-v-js) - u\cdot\sin^2\alpha \pm \sqrt{u^2\cdot\sin^4\alpha + 4(1-v-js)^2\cdot u\cdot\cos^2\alpha}} \quad (1)$$

where $v=\frac{\omega_0^2}{\omega^2}$; $u=\frac{\omega_H^2}{\omega^2}$; $s=\frac{\nu}{\omega}$; (2)

$\omega_0=\sqrt{\frac{4\pi e^2 N}{m}}$ is the plasma frequency;

$\omega_H=\frac{eH}{mc}$ is the electron gyro frequency;

N is the electron density;

α is the angle between the wave normal and the magnetic field H.

In equation (1), in which the influence of ions is neglected ~~the ion plasma~~, the subscript '1' and the "-" sign at the root refer to an extraordinary wave, while the subscript '2' and the "+" sign are related to an ordinary wave. In a general case, equation (1) is too complicated for an investigation. Therefore, we make some simplifying assumptions. For one thing, the collision frequency, ν, is assumed small compared with ω, and the quantity S in equation (1) negligable compared with unity. Secondly, we use what is known as the quazi-longitudinal approximation[2]. On the basis of this approximation which is valid for

$$\frac{u\cdot\sin^4\alpha}{4\cdot\cos^2\alpha} \ll (1-v)^2 \tag{3}$$

when s = 0, equation (1) may be replaced by a simpler expression for ~~$A_{1,2}$~~ $n^2_{1,2}$

$$n^2_{1,2} = 1 - \frac{v}{A_{1,2}} \tag{4}$$

where

$$A_{1,2} = 1 - \frac{u\cdot\sin^2\alpha}{2(1-v)} + \sqrt{u}\cdot\cos\alpha \tag{5}$$

It should be noted that inequality (3) is valid for relatively large α (50 to 60°), provided $v \gg 1$ and $v \gtrsim u$.

From $n^2 > 0$ and equation (4), it follows that characteristic mode propagation may occur either when $A_{1,2} > v$ or when $A_{1,2} < 0$. It may be shown that $A_{1,2} > v$ does not satisfy the conditions of the quazi-longitudinal approximation and is therefore ruled out.

At $A_{1,2} < 0$ and for an extraordinary wave (subscript 1) we have

$$1 < \sqrt{u}\cdot\cos\alpha\left[1 + \frac{\sqrt{u}\cdot\sin^2\alpha}{2(1-v)\cdot\cos\alpha}\right] \tag{6}$$

In view of (3), the conditions in (6) may be approximated as follows

$$\left.\begin{array}{ll} & 1 < \sqrt{u}\cdot\cos\alpha \\ \text{or} & 1 < \frac{\omega_H}{\omega}\cdot\cos\alpha \end{array}\right\} \qquad (7)$$

Condition (7) determines the upper frequency limit for the propagation of the characteristic wave under review. As can be seen from equations (4) and (5), the refractive index, n, of these waves is greater than unity.

3. Experimental Arrangement

Two conflicting factors would have to be taken into account in an experiment for the observation of microwave mode propagation in a magnetoactive plasma at below the plasma frequency. On the one hand, it would be desirable that the working wavelength, λ, be as short as possible in order to avoid the necessity of obtaining large bodies of plasma. On the other hand, as can be seen from $v \gg 1$ and (7), the shorter wavelength, λ, would necessitate a higher electron density, N, and a stronger magnetic field, H (see Tables 1 and 2).

Table 1

Plasma Frequency vs. Electron Density

N 1/cu.cm	10^{12}	10^{13}	10^{14}
$f_o = \omega_o/2\pi$, c/s	8.96×10^{9}	2.84×10^{10}	8.96×10^{10}
$\lambda_o = c/f_o$, cm	3.35	1.06	0.335

Table 2

Electron Gyro Frequency vs. Field Strength

H, oersteds	1,000	2,000	3,000
$f_H = \omega_H/2\pi$,c/s	2.799×10^{9}	5.59×10^{9}	8.38×10^{9}
$\lambda_H = c/f_H$,cm	10.7	5.35	3.58

Tables 1 and 2 seem to suggest the choice of a working wavelength of 3 cm or somewhat greater, as in that case it woild be possible to keep N to below 10^{13} 1/cu.cm and H, to below 3,000 oersteds. This order of magnitude of N is quite attainable under laboratory conditions. By way of illustration, in an electrical discharge through mercury vapour, the plasma has $N=10^{13}$ 1/cu.cm for a current density of about 1 A/sq.cm.

Fig. 1 shows one of the possible experimental arrangements. The source of plasma is an electrical discharge. In order that the metal electrodes may not interfere with the passage of electromagnetic waves, they may be arranged in the form of a grid of parallel wires spaced at less than the wavelength. Then, with the electric wave vector, $\vec{E}$, normal to the wires, the wave will pass through the grid without any appreciable attenuation.

4. Conclusion

The suggested experiment would make it possible to prove (or disprove) the theoretical considerations set forth at the beginning and also to obtain experimental data on some other problems. These would be:

(a) the mechanism of the penetration of electromagnetic waves in a magnetoactive plasma for $\omega < \omega_0$ and the conditions under (7), and the determination of the maximum angle, α, at which the waves enter the plasma;

(b) attenuation of the microwave mode under review in the plasma.

Besides, with H measured by any other method, equation (4) could be easily solved for the electron density, provided ω_H and α are known.

I wish to thank V. Kislov and E. Bogdanov for helpful discussions of the experimental arrangement.

Captions to Figures

Fig. 1 - Experimental arrangement:

1 - transmitting horn

2 - receiving horn

3 - electrodes

Electrode arrangement is shown at the bottom of the drawing.

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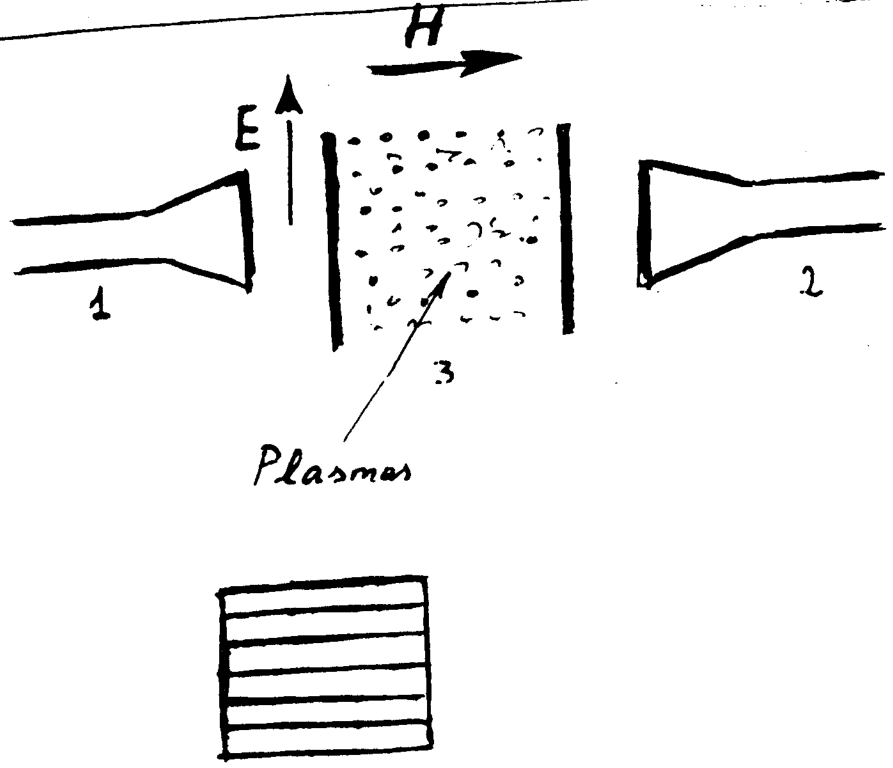

Fig 1

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A STUDY OF THE SURFACE STATES OF GERMANIUM

A. V. Rzhanov

Studies of surface recombination and trapping on so-called "real" surface of germanium in different ambients have been made in Semiconductor Lab. Lebedew's Physical Institute, Academy of Sciences USSR.

The experimental data was obtained by well known field effect tecnic coupled with steady photoconductivity measurements from which we be able to obtain surface recombination velosity and a trapped charge as functions of a surface potential. (1)

It was found from these measurements that the main uncommon feature of the fenomena for samples of different cristal orientation and different etching is a sharp dependence of the surface recombination velosity and trapping on the quantity of adsorped molecules of water.

With desorption of water during the pumping of the vacuum sistem with the sample inside and particularly as a result of heating of the sample in vacuum, the consentration of the surface recombination centers sharply goes up. The primary periods of this process shown on figure 1 are of a particular interest. Here the lowest curve represents the dependence of the surface recombination velosity on the surface potential taken on the freshly etched sample in room air ambient. Other curves here represent the result of drying of air using liquid nitrogen trap in vacuum sistem and following pumping to a vacuum of 10^{-2}, 10^{-4}, 10^{-6} mm Hg (?). One can see here, that the caracter of the dependence of the surface recombination velosity on the surface potential changes itself: where ambient is moist one finds a component of the surface recombination velosity which depends linearly on surface potential end for vacuum -- a component which has a bell like shape, when it is plotted against surface potential.

In some experiments, while the samples were put into water bensole or ethel ether, the linear component of the surface recombination velosity could be seen directly. The existence of such a component of the surface recombination velosity prooves the presence of a special mechanism for surface recombination, which, probably, is a direct band-to-band recombination on the surface.

The investigation of the dependence of the surface recombination velosity on the sorface potential in vacuum at different temperatures permitted us to make some conclusions on the caracter of temperature dependence of the cross section ratio of the recombination center for the hole and electron. This dependence found by the position of the maximum at the recombination curves is shown on Figure 2 in semilog (sic) scale against the reciprecal temperature. (2) Of most interest here is the sharp, approcsimatly (sic) exponential decreese of the cross section ratio with the decrese of temperature in the low temperature region. The theory cannot explain the sharp temperature dependence of the cross sections, which results in an inversion of the cross-section ratio.

Some experimentators try to determend the energy positions of surface levels from trapping experiments data and measurements of the surface recombinations. (3) Their results may be ambiguous because they could be concidered from the different points of view. We tried to use direct way to obtain some information on the energy positions of surface levels on the basis of the spectral dependence of impurity photoconductivity in infrared.

To divide the volume and surface effects we used previosly obtained data (5) on the large increase of surface level concentrations due to heating of the germanium samples in vacuum. The vacuum heating was made at relatively low temperatures, without creating any volume deffects.

On Figure 3 are shown the spectral photoconductivity curves for a thin germanium sample taken at about 100°K. Curve 1) corresponds to the unheated sample. Curves 2), 3), 4) correspond to the same sample after preheating at 400°, 500° and 600° K. After heating at 400° and 500°K some visible peaks appear at the energy of quantum equals 0.4 ev. At 0.26 ev there are sharp decreases ("sholders") on the photoconductivity curves not shown on this figure.

These peak and "sholder" correspond to the energy positions of the surface levels at about 0.04 ev below center of gap and 0.1 above center of gap on the surface of germanium. Many experimentators expected the existence of these levels. Their concentrations raise sharply after exposing the germanium surface to ozone (curve 5), but the concentration of them goes down after heating at 600° K (curve 4). Both of these results are in a good correspondence with ours and some other worker's surface recombination and trapping data. Other discrete levels, located closer to the ends of the gap, are expected from trapping data. But the spectral dependence of the photoconductivity does not indicate the existance of such levels. The gradual increase of the photoconductivity towards higher energy of quantum implies the presence of levels continuously distributed in energy through the gap. Theire concentrations also change as a result of the heating of the sample in vacuum. This existance of a continuous spectrum of surface levels permit us to explain some experiments results of the surface recombination investigation, which were not previously understood.

Inflection points on the trapped charge versus surface potential curves would be observed clearly if discrete levels prevealed in the surface spectrum. But this inflection points of discrete levels are not resolved even in the low temperatures experiments. (6) The existence of descrete and continiously distributed levels on the surface explanes this discrepancy. Our experiments with heating in vacuum showed that with the changing of the concentration of surface levels after heating there is only qualitative correspondence between changing of the slopes of the trapping curves and maximum values of the surface recombination velosity. (5) Not only direct proportionality but also simple quantitative correspondence between these two things is absend in all region of the surface potential. This descreaponse also can be easily explained, if the parts of the surface recombination velosity resulting from the descrete and continiously distributed levels are of comparable magnitude. According to the photoconductivity data the concentrations of the continiously distributed levels are large when their energy positions are away from the middle of the gap. Then their influence on the trapping curves measured near the middle of the gap can be very small.

In such a situation one can expect only qualitatively correlation between the slopes of the trapping curves and maximum values of the surface recombination velosity, as it was found experimentally.

Finally it is nessery to point out that in surface recombination investigations some results were obtained, which would not be explained from the common theoretical point of view. I mean the above mentioned complicated temperature dependence of the maximum of recombination curve; deferences in the recombination curves shape obtained on the surfaces of different crystal orientation; and very specific influence of polar molecule adsorption on the surface recombination velosity. (7)

We have managed to explain, at least qualitatively these results by some development of the recombination theory.(8) We have taken into account the life time of the carriers captured on the excited levels of the recombination center. In this case the espresions for the resiprocal effective cross section are as follows:

$$\frac{1}{\alpha_n} = \frac{1}{C_n} + \frac{n_1^*}{r_n}$$

$$\frac{1}{\alpha_p} = \frac{1}{C_p} + \frac{p_1^{**}}{r_p}$$

here C_n, C_p - are the probabilities of capturing of an electron and a hole on the excited levels of the recombination center;

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The general equation for the surface recombination velosity can be written as follows:

cosh

$$s = \frac{N_t \cdot (C_p \cdot C_n)^{1/2} \cdot \frac{n_0 + p_0}{2n_i}}{\mathrm{Ch}\,\frac{q(\varphi_s - \zeta)}{kT} + \mathrm{Ch}\left(\frac{E_t - q\zeta}{kT}\right) + M \cdot \left[\mathrm{Ch}\,\frac{q(\varphi_s - \eta)}{kT}\right] + \mathrm{Ch}\left(\frac{E_t - q\eta}{kT}\right)\Big]}$$

Here parameters $\frac{q\zeta}{kT}$, $\frac{q\eta}{kT}$ and M are connected with capture and transition probabilities in such a way:

$$\frac{q\zeta}{kT} = \frac{1}{2} \ln\left(\frac{C_p}{C_n}\right) \; ; \; \frac{q\eta}{kT} = \frac{1}{2} \ln\left(\frac{\gamma_p}{\gamma_n} \cdot \frac{n_1^*}{p_1^{**}}\right) \text{ and } M = \left(\frac{C_p \cdot C_n}{\gamma_p \cdot \gamma_n} \cdot n_1^* \cdot p_1^{**}\right)^{1/2}$$

$\frac{q\varphi_s}{kT}$ is surface potential; E_t - the main recombination level of the centers and N_t - the concentration of the centers.

The theoretical recombination curves shown on the fig. 4 ~~as a function~~ ~~of the~~ with the given values of the parameters $\frac{q\zeta}{kT}$, $\frac{q\eta}{kT}$ and E_t and for different choises of the parameter M from zero to infinity.

It is seen, that in the new theory the position of the maximum of the curve and its width at the half high(?) are connected in a more complicated way with the energy position of the level on the cross section ratio. But the new theory permits us to explain all known experimental facts, connected with surface recombination on germanium.

/NOTE: Figures to which the author refers were not with the handwritten text. They may have been slides shown at the presentation./

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