

Nonlinear effects in the vicinity of doppler-shifted cyclotron resonance of holes in cadmium

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The surface resistance of cadmium plates R and its derivative with respect to the magnetic field dR/dH were investigated in positive and negative circular polarizations in a magnetic field parallel to the hexagonal axis [0001]. The measurements were performed at different amplitudes H_1 of the exciting electromagnetic field. A nonlinear behavior of the surface resistance at positive polarization was observed in the vicinity of the threshold of the hole doppleron. The possible physical nature of the observed phenomenon is discussed.

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It is well known that the surface resistance R of a semi-infinite metal with equal number of electrons and holes has, in the case of specular reflection of the carriers from the boundary, a maximum at the threshold of the doppleron wave.^[1,2] It was shown in^[3] that in compensated metals, when the reflection is diffuse, the surface resistance R as a function of the magnetic field H has a kink at the doppleron threshold. The kink is all the more pronounced the larger the mean free path of the carriers. This singularity of $R(H)$ at the threshold of the hole doppleron in cadmium was observed experimentally in^[3,4] at $H \parallel [0001]$. In these studies, the metallic plate was excited by a radio-frequency field of circular polarization. The measurements were performed with the aid of an autodyne detector at low amplitude H_1 of the exciting field. In the present study, these measurements were continued in RF fields of higher intensity.

The investigation of the surface resistance was carried out with an amplitude bridge at temperatures 1.6–4.2 °K in the frequency interval 0.001–2.0 MHz. The cadmium plates were 0.43 and 0.6 mm thick. The normal to the plate surface coincided with the direction of the hexagonal axis [0001]. The sample was placed in a system of two crossed coils producing a circular polarization of the field.^[3] The voltage on the coils could be smoothly varied in the range 0.05–30 V. This voltage was amplified with a broad band amplifier and fed to a detector. The detected signal, proportional to $R(H)$, was recorded with an automatic x - y plotter, the x -coordinate of which received a signal from the magnetic-field pickup. In addition to $R(H)$, it was possible to measure the derivative $dR/dH=f(H)$. The magnetic field was produced by an electromagnet. The plots were taken at an orientation $H \parallel [0001]$.

In the investigations of the $R(H)$ dependence, the transfer function of the amplifier at the input of the bridge was chosen such that the voltage at the detector input was the same at different amplitudes of the exciting field H_1 . As a result, the plots of $R(H)$ and $dR/dH=f(H)$, carried out at different amplitudes H_1 , coincide if the surface resistance does not depend on the field H_1 .

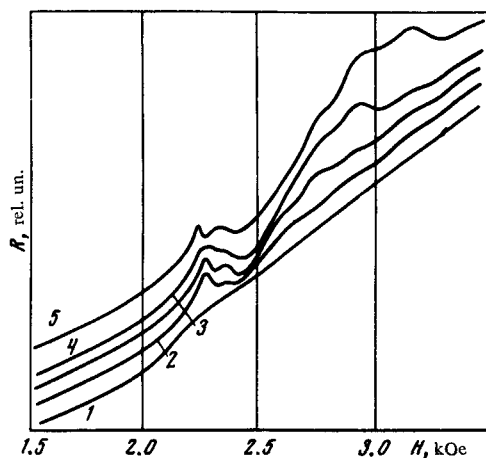


FIG. 1. Plots of $R(H)$ at different field amplitudes H_1 . $T=1.6^\circ\text{K}$, sample thickness $d=0.6\text{ mm}$, $\mathbf{H} \parallel [0001]$, field frequency $f=116\text{ kHz}$: curve 1— $H_1=0.15\text{ Oe}$, curve 2— 2.2 Oe , curve 3— 3.3 Oe , curve 4— 4.4 Oe , curve 5— 6 Oe .

Typical plots of $R(H)$ at different amplitudes H_1 of the exciting field in a positive circular polarization are shown in Fig. 1. The maximum field amplitude H_1 for these plots is approximately $\sim 10\text{ Oe}$. As shown by estimates, this corresponds to a power flux on the order of 10^{-2} W/cm^2 .

At low radial frequency voltages, the plot of $R(H)$ (curve 1) is similar to that observed earlier in^[4]. Near the threshold of the hole doppleron the $R(H)$ curve has a smoothed-out kink, and at stronger fields the resistance increases almost linearly with increasing magnetic field. The behavior of the surface resistance changes significantly with increasing amplitude of the alternating field. First, the kink of the surface resistance at the doppleron threshold gives way to a maximum whose amplitude increases with increasing field H_1 (curve 2). This maximum then doubles, and in stronger fields an additional singularity appears (curve 3). On the curve $R(H)$ in fields above the doppleron threshold, oscillations are observed, caused by excitation of the hole doppleron in the plate. With further increase of the alternating field H_1 , the changes of $R(H)$ at the threshold of the wave become smoothed out somewhat as a result of the splitting of the threshold maximum into several weaker extrema (curve 4). Simultaneously, the singularity in the region of the stronger fields increases and a smoother maximum appears. At a higher field amplitude H_1 , the threshold maximum becomes sharper and shifts towards weaker fields. In turn, the maximum in strong fields increases in amplitude and shifts towards stronger field (curve 5).

The threshold field amplitude H_1 at which the nonlinearity comes into play depends strongly on the temperature and on the angle between the direction of the constant magnetic field \mathbf{H} and the $[0001]$ axis. It has a minimum value at the lowest temperature and at $\mathbf{H} \parallel [0001]$.

The nonlinear behavior of the impedance of cadmium in the plus polarization

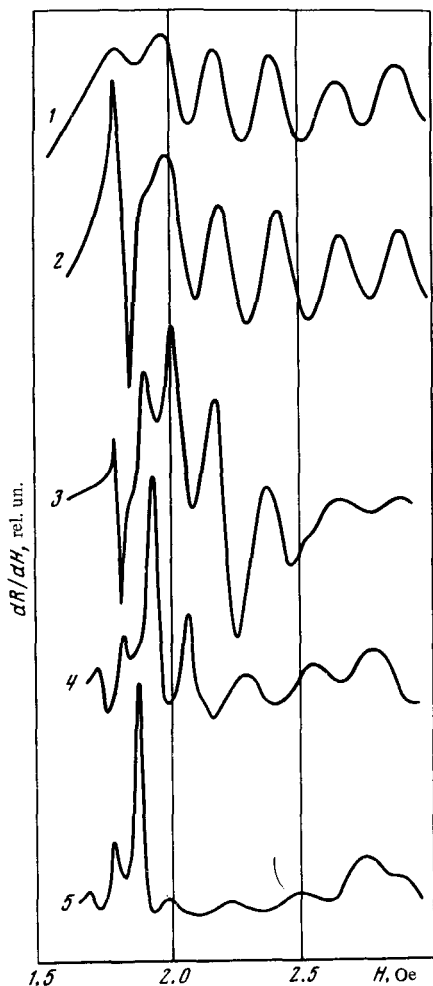


FIG. 2. Derivative $dR/dH=f(H)$ at different values of the field H_1 . $T=1.6^\circ\text{K}$, $d=0.6\text{ mm}$, $f=55\text{ kHz}$, $\mathbf{H} \parallel [0001]$; curve 1— $H_1=0.3\text{ Oe}$, curve 2— 0.8 Oe , curve 3— 4 Oe , curve 4— 7.5 Oe , curve 5— 11 Oe . Curves 1 and 2 were plotted at identical values of the gain $k=k_0$. Curve 3 was plotted with $k=(1/8)k_0$ and curves 4 and 5 with $k=(1/13)k_0$.

is most clearly pronounced on the plots of the derivative $dR/dH=f(H)$. Typical plots of $dR/dH=f(H)$ at different values of H_1 are shown in Fig. 2. The gains for each of the curves are indicated in the figure caption. The last figure shows how the dR/dH plots against H are transformed with increasing field $H_1 < 0.5\text{ Oe}$ in a wide interval of its values, the oscillatory picture remains constant (curve 1). The first maximum on the left on this curve corresponds to a singularity at the threshold of the hole doppleron. Its position with respect to the magnetic field coincides with the data of^[3]. The oscillations on the curve are connected with excitation of a hole doppleron in the plane. At $H_1 > 0.5\text{ Oe}$ there appear in the vicinity of the threshold two sharp extrema—a maximum and a minimum (curve 2), the amplitudes of which increase rapidly with increasing H_1 . In a stronger alternating field, besides these extrema, there appear additional sharp extrema of large amplitude (curves 3 and 4). Gradually, the entire oscillatory picture is strongly deformed. Near the wave threshold, a series

of sharp extrema is observed with a small period. In the region of nonlinearity, a noticeable increase takes place in the amplitudes of the oscillations (curves 3 and 4). At large values of H_1 ($H_1 > 8$ Oe), the amplitude of the oscillations of the hole doppleron decreases with increasing intensity of the alternating field (curve 5).

It should be noted that the position of the extrema of the doppleron oscillations relative to the magnetic field depends on the field intensity H_1 . With increasing H_1 , the extrema shift towards weaker fields. This means that in sufficiently strong alternating fields the dispersion law of the hole doppleron changes.

The observed nonlinear behavior of the surface resistance of cadmium in plus polarization takes place in a wide frequency interval at temperatures $T = 3.9^\circ\text{K}$, when oscillations due to the hole doppleron can be seen. At higher temperatures, the oscillations of the impedance and its linear behavior are not observed. This suggests that the nonlinear effects in cadmium are connected with the doppleron wave.

An investigation of the surface resistance of cadmium in negative polarization has revealed the absence of nonlinear effects at amplitudes H_1 up to several dozen oersteds.

An examination of the curves of Fig. 1 suggests that the observed nonlinear effect may be connected with the onset of specular reflection of the holes from the metal boundary in an electromagnetic field of relatively large amplitude. Estimates show, however, that the appearance of a potential barrier in cadmium in an electromagnetic field, in analogy with the situation in bismuth in the field of a sound wave^[5] is apparently of low probability.

Another possible cause of the nonlinearity may be the mechanism considered by Kopasov and Demikhovskii.^[6] They have shown that in alternating fields of larger amplitude in a vicinity of the Doppler-shifted cyclotron resonance the collisionless wave damping decreases strongly. The surface resistance of the cadmium at the doppleron threshold should increase as a result of the decreased damping. This leads to a considerable increase of the amplitude of the doppleron oscillations in this region of the magnetic field. It is impossible, however, to explain in this manner the change of the spectrum of the hole doppleron in a wide range of the magnetic field. Additional theoretical and experimental research is necessary to explain the physical nature of the nonlinear effect in cadmium.

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