

Nonlinear absorption of high-frequency energy by tungsten at large electromagnetic-wave amplitudes

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A nonlinear absorption of high-frequency energy by tungsten, which attains a value of $\approx 10\%$ with increasing amplitude of the high-frequency field, was observed. It is shown that this effect has anisotropy and a frequency dependence that is different from that of known nonlinear effects.

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As recent studies have shown (see, for example, the review article),¹ when pure and perfect single crystals are irradiated with radio waves, various nonlinear effects can be observed that appear as second-harmonic generation, a constant radio-emf, “current” states, and self-excited oscillations.

In this paper we report another type of nonlinear effect in metals, which was

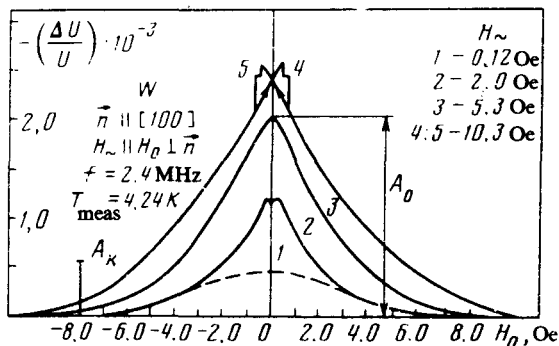


FIG. 1

observed in tungsten as the wave striking its surface increased in zero external magnetic field ($H_0 = 0$). The non-monotonic behavior of the dependence of the surface impedance of gallium, bismuth, and potassium in weak magnetic fields and the complicated nature of its variation with the high-frequency power level were first pointed out in Refs. 2-4; however, these qualitative studies were performed at amplitudes $H_- < 2$ Oe of the variable magnetic field.

The experiments discussed below were performed using single-crystal tungsten samples at a frequency of 0.35-8.0 MHz in the temperature range 1.5-4.2 K at H_- up to 15 Oe. The active losses in the high-frequency loop were recorded with an amplitude bridge. The earth's magnetic field was compensated for within $\pm 2\%$ accuracy.

The Q of the loop and the sensitivity of the recording scheme were calibrated by a resistor connected in parallel to the loop, which included a rectangular inductance coil with the test samples whose dimensions were ≈ 8 mm in diameter and 0.5 to 1.6 mm thick.

The samples, which were cut from a tungsten single-crystal ingot with $R_{300K}/R_{4.2K} \approx 3 \times 10^4$, were defined by using the method described in Ref. 5.

An example of a trace of the experimental curves is shown in Fig. 1 (the arrows indicate the forward and reverse variation of the external field H_0 and \vec{n} is the normal to the sample surface). The H_- values in Fig. 1 were determined with allowance for the shape of the inductance coil, using the formula: $H_- = 0.8 n_c U_c / \omega L_c$, where L_c is the inductance of the coil with a sample, n_c is the number of turns per cm, U_c is the voltage across the loop, and ω is the frequency.

As seen in the figure, the relative variation of the voltage across the loop $\Delta U_c / U_c = A_0$ (for $H_0 = 0$) sharply increases with increasing amplitude of the high-frequency field. At $H_- \approx 2.0$ Oe we can see a small dip, which disappears subsequently, and at $H_- \approx 10$ Oe a hysteresis occurs and the tungsten resistance increases abruptly.

As the studies showed, the line amplitude A_0 , which was almost independent of the direction of H_0 relative to the crystallographic axes of the tungsten, decreased for $H_0 \perp \vec{n}$. By decreasing the temperature of the sample from 4.2 to 1.5 K, we obtained a 30% increase in A_0 . At $H_0 \parallel \vec{n}$ the dependence of A_0 on the external magnetic

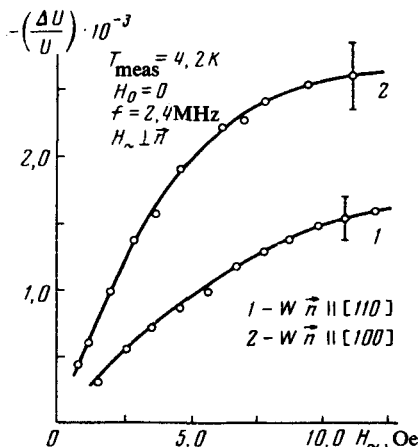


FIG. 2

field completely disappeared.

One of the main factors contributing to the line amplitude A_0 was the quality of the sample surface and the orientation of the crystal plane with respect to the incident electromagnetic wave. The latter situation is graphically illustrated by the results in Fig. 2. This result was verified on several samples prepared by using the same techniques, and the ratio $A_0(100)/A_0(110)$ was ≥ 2 in all the experiments.

The frequency dependence of the line amplitude A_0 is shown in Fig. 3. The non-linear effects in metals are usually described by means of surface impedance.¹ The small value $|\Delta Z| \ll 1$ is considered to be the criterion for applicability of this description. By using this fact as the basis as well as the expression for the surface impedance under anomalous skin-effect conditions

$$Z = R - iX = - \frac{4\pi \omega \delta_h i}{c^2}$$

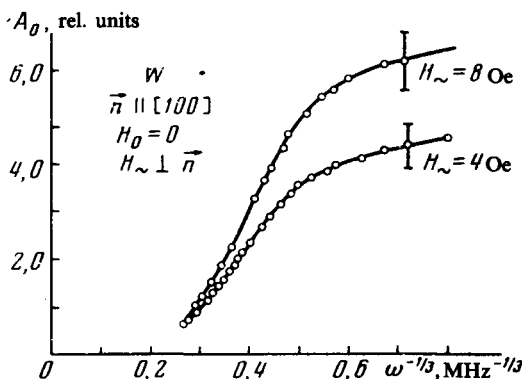


FIG. 3

and the relative variation $\Delta U_c/U_c$ of the voltage of a resonant loop with $Q \gg 1$, which is the result of a variation of the real part of the sample impedance,⁶

$$\frac{\Delta U_c}{U_c} = \frac{\Delta U_{out}}{U_c \xi} = - Q n_c^2 S \frac{\operatorname{Re}(\Delta Z_{sample})}{\omega L_c}$$

we can estimate the value of $\Delta R/R$. Here δ_n is the penetration depth of the field into the metal under anomalous skin-effect conditions, c is the velocity of light, Q is the Q value of the loop, S is the sample area irradiated by an electromagnetic wave, ξ is the transfer coefficient of the bridge, and ΔU_{out} is the voltage variation at the bridge output.

From these equations and from the results in Figs. 1 and 2 and the values $Q = 17.1$, $L_c = 18.7 \mu\text{H}$, $n_c = 170$, $S = 1 \text{ cm}^2$, and $\xi = 0.3$, which were directly determined experimentally, it follows that $\Delta R(100)/R$ is equal to $\approx 10\%$ for $H = 8 \text{ Oe}$.

The experimental data discussed above cannot explain, by using the currently available nonlinearity mechanisms, the increase of the tungsten resistance with the level of the high-frequency field.

This effect cannot be associated with heating of the electron system, since under these conditions it is negligibly small, nor can it be associated with an increase of the sample resistance with increasing magnetic field, since the tungsten conductivity increases in the linear regime in the interval of magnetic fields H_0 from 0 to $\approx 20 \text{ Oe}$ (see line 1 in Fig. 1); this effect also cannot be associated with the process of rf electromagnetic-wave detection by metals, which was examined in Ref. 1. According to Ref. 1, the nonlinear effects attributable to this mechanism must increase with increasing frequency of the electromagnetic field, since the minimum H_- value at which such nonlinearity is noticeable decreases with the frequency as $\sim \omega^{-1/3}$, inconsistent with the results in Fig. 3.

Only the hysteresis and abrupt decrease of tungsten resistance observed at $H_- \gtrsim 10 \text{ Oe}$ (see Fig. 1) can be explained in terms of the existing theoretical concepts of the rectification effect.

The difference in the line amplitudes A_0 for the (100) and (110) planes (see Fig. 2), which is considerably greater than the increase of this line with a decrease in temperature, is most likely caused by a difference in the degree of specularity of these surfaces and, consequently, by a different contribution of the electrons that collide with the metal boundary.

Taking into account the strong dependence of the observed effect on the electron reflection from the metal surface, we think that this effect can be used for studying the mechanisms for scattering of conduction electrons at the metal-vacuum interface.

To perform such studies, however, we need a rigorous theoretical description of the nonlinear effects that takes into account the contribution of surface electrons.

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