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DYNAMIC NEGATIVE CONDUCTIVITY DUE TO NONLINEARITY OF THE CURRENT VOLTAGE CHARACTERISTIC AND TO THE FINITE ELECTRIC-CONDUCTIVITY RELAXATION TIME

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Owing to the finite relaxation time (τ) of the conductivity in a certain interval of frequencies (ω), when $\omega\tau \sim 1$, a phase difference is produced between the current and the voltage. If the conductor has a nonlinear stationary current-voltage characteristic, then the dynamic dependence of the current on the voltage becomes multiple-valued and forms a loop that can have descending sections. As will be shown below, under certain conditions the phase difference between the current and the voltage may exceed $\pi/2$, and such a conductor, if connected in an oscillating circuit or a resonator, can be used for the amplification and generation of oscillations. The conductor need not necessarily have stationary negative differential conductivity in this case.

This effect can occur, in particular, in semiconductors. To illustrate this possibility, let us consider the simple case of a semiconductor whose stationary current voltage characteristic has a section close to current saturation, and the time of establishment of the conductivity does not depend on the voltage U. We put

$$i = \sigma_0(U)\,U = \frac{i_s v}{1 + v}, \quad \frac{d\sigma}{dt} = \frac{\sigma_0 - \sigma}{\tau}, \tag{1}$$

where i_s is the saturation current, $v = U/U_c$, and U_c is a certain characteristic voltage. Putting $v = v_0 + v_1 \cos \omega t$ and representing i and $\sigma_0(v)$ in the form of Fourier expansions, we can find the ac conductivity G of the specimen. Calculation yields

$$\frac{G}{G_0} \equiv \frac{2 < i v_1 \cos \omega t >}{G_0 v_1^2} = \frac{8F(z^2)}{(1 + z^2)(1 + 4z^2)\sqrt{(1 + v_0)^2 - v_1^2}} \tag{2}$$

where G_0 is the conductivity in a weak field, $z = \omega\tau$, and F is given by

$$F = 2z^4 - z^2\left[\frac{3v_0 - 1}{v_1^2}\left(1 + v_0 - \sqrt{(1 + v_0)^2 - v_1^2}\right) - 2\right] + \frac{1 + v_0 - \sqrt{(1 + v_0)^2 - v_1^2}}{v_1^2}. \tag{3}$$

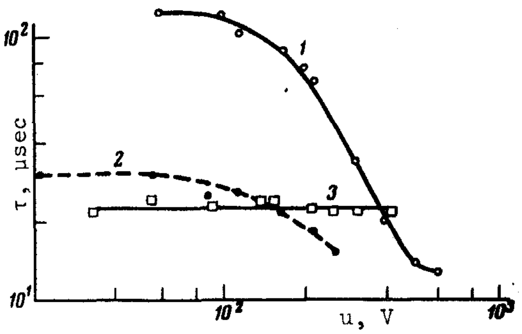

Fig. 1

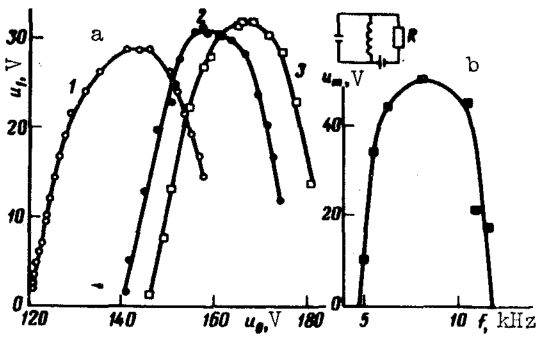

Fig. 2

Fig. 1. Current relaxation time vs. amplitude of rectangular voltage pulse at different bias voltages U_0: 1) $U_0 = 0$, 2) 230 V, 3) 400 V. Specimen 1-01, length 6.9 mm.

Fig. 2. Amplitude U_1 of the specimen voltage oscillations vs. the bias voltage U_0 (a), and maximum oscillation amplitude U_m vs. the frequency (b): 1) f = 5.6 kHz, 2) 9.8 kHz, 3) 10.2 kHz. $\tau \cong 6 \times 10^{-6}$ sec. Specimen 4-21, length 1.5 mm.

It was assumed here that $v_1 < 1 + v_0$. Investigating the expression (3), we can verify that by suitable choice of v_0 and v_1 we can obtain $G < 0$. The limiting frequencies are determined by the roots of the function $F(z^2)$. In particular, if $v_0 \gg 1$, then the conductivity is negative if $3/4 < v_1^2/v_0^2 < 1$ and $1/v_0 < \omega^2\tau^2 < 1/2$. At small amplitudes v_1, we always have $G > 0$, and therefore the regime under which the oscillations are excited is hard.

We have observed current oscillations with such properties in a circuit containing germanium crystals with partially compensated copper. The crystals were at liquid-nitrogen temperature. The necessary electric conductivity was produced by extraneous illumination. The stationary current-voltage characteristics of the specimens had sections close to current saturation [1], but nevertheless the current increased somewhat when the voltage was increased, so that the differential conductivity certainly was positive. The current relaxation for a rectangular voltage pulse and a fixed bias U_0 was exponential. At small values of U_0 the relaxation time τ decreased rapidly with increasing voltage, but at a large bias this dependence became very weak (Fig. 1), so that the conductivity of the specimens satisfied approximately the expression in (1). When an external sinusoidal voltage was applied, at $U_0 \neq 0$, a phase shift appeared between the voltage and the first harmonic of the current; with increasing bias, this shift became larger than $\pi/2$. In the absence of an oscillating circuit, no current instability set in. When the sample was connected in an oscillating circuit, as shown in Fig. 2, oscillations appeared in the circuit. Figure 2a shows the dependence of the amplitude of the voltage oscillations in the specimen on the bias voltage, while Fig. 2b shows the frequency dependence of the maximum oscillation amplitude. Self-oscillations were observed when $\omega\tau$ was changed from 0.2 to 0.45 and v_0 from 6 to 9. These values agree in order of magnitude with the expected ones.

It can be assumed that a negative conductivity of the type considered here will appear also in other systems with strong nonlinearity of the current-voltage characteristic at frequencies on the order of the reciprocal relaxation time of the conductivity, and the oscillation frequency in a resonator containing active elements of this type can apparently be very high.

We note also that inasmuch as the real part of the small-signal impedance of the systems under consideration is positive, they differ from the systems considered, for example, in [2], in which the real part of the conductivity can be negative already at a small signal. To this end, however, it is necessary to have at least two suitably chosen characteristic times, whereas in the case considered by us only one such time is necessary.

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MAGNETIC STRUCTURE OF THE ANTIFERROMAGNETIC GARNET $NaCa_2Co_2V_3O_{12}$

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"Single-sublattice" garnets (i.e., garnets in which the magnetic ions are situated in voids of only one kind, either tetrahedral or octahedral) are of great interest from the point of view of the study of the nature of intra-sublattice exchange interactions. The synthesis and investigation of such compounds with garnet structure and with magnetic 3d-ions in octahedral voids only are described in [1]. Several articles are devoted to the results of neutron-diffraction studies of the magnetic structures of the analogous compounds $Ca_3Mn_2Ge_3O_{12}$ [2], $Ca_3Fe_2Ge_3O_{12}$ [3, 4], and $Ca_3Fe_2Se_3O_{12}$ [5].

We have undertaken a neutron-diffraction study of the garnet $NaCa_2Co_2V_3O_{12}$ for the purpose of determining its atomic and magnetic structures, and also the spin state of the Co^{2+} ion.

The neutron-diffraction pattern of polycrystalline $NaCa_2Co_2V_3O_{12}$ powder was obtained at room and helium temperatures (T_N = 8.1°K according to the data of [1]). The general form of the neutron diffraction patterns is shown in Fig. 1 (the reflections 200 and 222 were obtained with larger statistics). We have assumed that the investigated compound belongs to the space group O_h^{10} - Ja3d with the sodium and calcium ions statistically distributed in the position 24 (c), the cobalt ions in the position 16 (a), the vanadium ions in position 24 (d), and the oxygen in the common position 96 (h).

The coordinates of the oxygen atoms characterize the geometry of the bonds in the structure, and therefore one of our tasks was to determine the oxygen parameters. The calculation was performed with the M-220M computer of our institute, using a least-squares refinement procedure in accordance with the program "Rentgen-69" [8]. The results of the calculation are listed in Table 1, which shows for comparison the parameters of the oxygen atoms in the analogous "single-sublattice" garnet $Ca_3Fe_2Ge_3O_{12}$, obtained by various workers, including ourselves.

The observed magnetic reflections are indexed in the same unit cell, and their indices satisfy the condition $h + k + \ell = 4n + 2$. The magnetic structure corresponding to this extinction law is shown in Fig. 2a. It can be described by two primitive cubic ferromagnetic sublattices ("sub-sublattices" would be more correct) imbedded antiferromagnetically one in the other.

It should be noted that the observed magnetic structure is the third in the series of "single-sublattice" garnets. Two other types of antiferromagnetic ordering are observed in $Ca_3Mn_2Ge_3O_{12}$ [2] (Fig. 2b), $Ca_3Fe_2Ge_3O_{12}$ ([3, 4] and our unpublished data), and in $Ca_3Fe_2Se_3O_{12}$ [5] (Fig. 2c). We can conclude