Transient phenomena and instability of a surface wave in the presence of a current flow

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Transient phenomena and two types of instabilities have been observed when a surface electromagnetic wave propagates in a periodic structure made from pure aluminum.

Nonlinear phenomena which occur in pure metals when an electric current flows through them have recently begun to be studied. A deviation of the current-voltage characteristic from the linear behavior leads to a magnetoacoustic instability,[1] because of the excitation of acoustic phonons by the carriers that drift at acoustic velocities, and to a galvanomagnetic instability[2,3] which is seen in the turbulent current flow. High-frequency nonlinear phenomena, in which the effect of the wave field on the properties of the medium is evident, generally occur at high signal power levels. In the present letter we report the observation of instabilities and transient phenomena at low signal amplitudes when the strength of the wave fields is considerably smaller than the strength of the field produced by the electric current or the strength of the external magnetic field.

We studied the characteristics of propagation of a surface electromagnetic wave traveling along the surface of a periodic "meander"-type structure at low temperatures and when an electric current flowed through the metal. A periodic structure, a single crystal of pure aluminum (Fig. 1), is used to form an electromagnetic wave. The

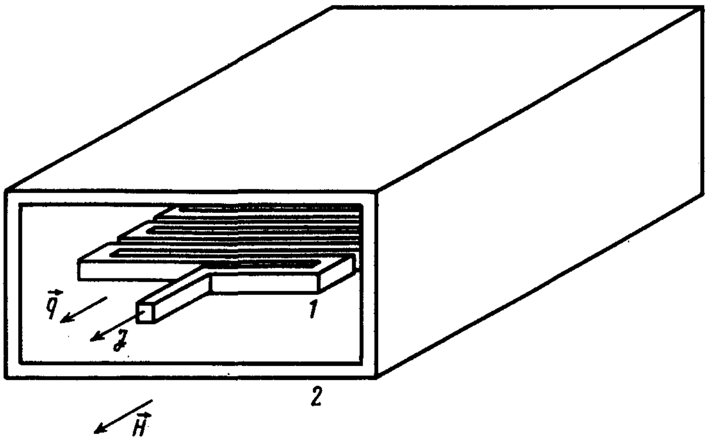

FIG. 1. Periodic system. 1—Meander structure made from aluminum single crystal; 2—brass screen.

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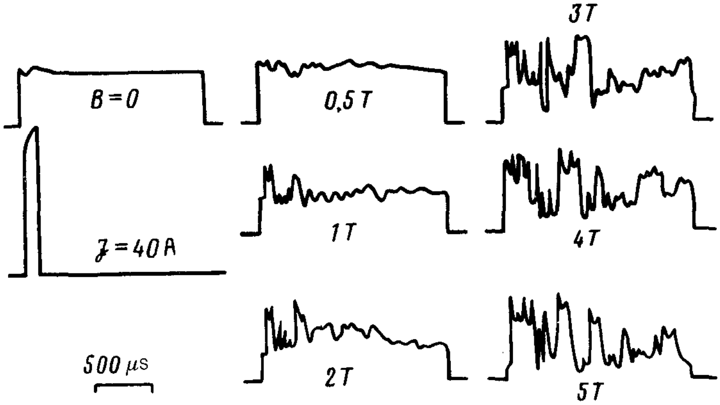

FIG. 2. Transient phenomena accompanying the propagation of a surface electromagnetic wave. The frequency is $f = 1956$ MHz.

meander conductors, cut out along the ⟨100⟩ axes of the crystal, have a rectangular cross section 0.5×1 mm. The meander period is 1.6 mm. A direct or pulsed current was passed through the meander line and the current-induced changes in the rf signal transmitted through the line were recorded. The magnetic field was applied along the direction of propagation of the surface electromagnetic field perpendicular to the meander conductors. The measurements were carried out at a temperature of 4.2 K.

The transient phenomena consist of the distortion of the shape of the rf signal. These phenomena, which occur as a result of the action of a current pulse on the system, decay within 100–9000 μs. An rf pulse of frequency in the range 1–2.3 GHz and power 10^{-5} W was sent to the input of the periodic system. The pulse which was transmitted through the system in the absence of a current had a rectangular shape of the envelope which became slightly distorted when a pulsed current began to flow through the system (Fig. 2). The oscilloscope traces in Fig. 2 were recorded in a single sweep. An imposition of a magnetic field increases the distortion of the signal.

Beginning with an induction of 2T, the shape of the envelope of the given signal begins to change with time at characteristic frequencies ranging from several hertz to several tens of hertz. The propagation of a surface wave therefore has an instability, in addition to the transient phenomena.

We observed two types of instability-related time-dependent variations of the signal. The first signal variation, which occurs when either a pulsed or a direct current is turned on, is attributable to the change in the time-averaged values (or the average values over the repetition period of the pulse) of the parameters of the system. The train of rf pulses several tens or several hundred microseconds long in this case changes in amplitude, without changing its shape. The second type of instability, which involves a temporal variation of the nonstationary phenomena, occurs only as a result of the action of a pulsed current in a strong magnetic field. The envelope of the rf pulse acquires one or several regions in which the rf signal executes oscillatory motion. The length of these regions and the oscillation intensity depend on the fre-

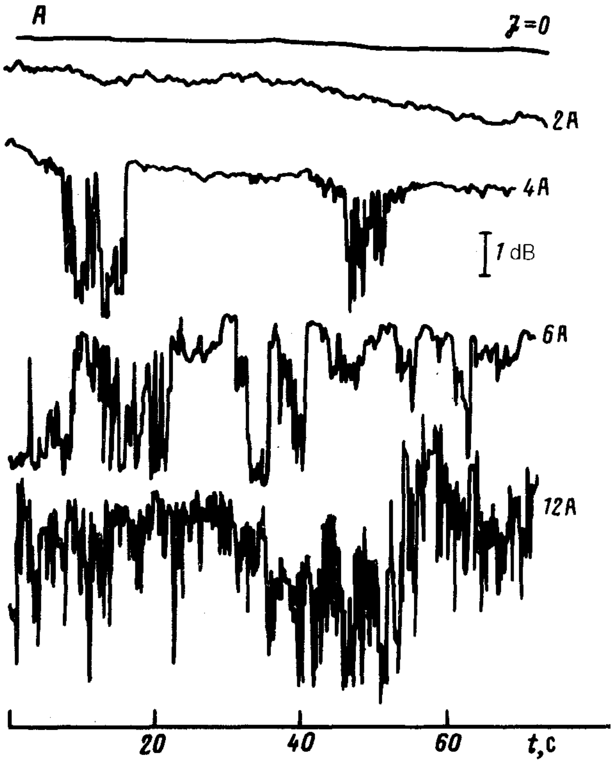

FIG. 3. Trace of the variation in the amplitude of an rf pulse vs time.

quency of the wave, the strength of the current and the strength of the magnetic field. It varies from several microseconds to several hundred microseconds. The oscillating regions are localized inside the region of the time-varying distortions of the rf pulse. These regions appear during the delivery of the current pulse or immediately after it. The frequency dependence of the magnitude and nature of the temporal variations of the signal is apparently related to the parameters of the electromagnetic wave.

Figure 3 is a recording, obtained by a peak-detecting method, of the temporal variations of the amplitude of an rf pulse that was transmitted through the periodic system. The frequency of the signal was $f = 2184$ MHz, the length of the rf pulse was 31 μs, the length of the current pulse was 20 μs, and the repetition frequency was 200 Hz. The measurements were carried out in a 6-T magnetic field at various values of the current. As can be seen in Fig. 3, in the absence of a current pulse there are no temporal variations in the amplitude of the rf pulse. Appreciable instabilities in the amplitude arise when the threshold value of the current is about 9 A. The characteristic frequencies of the instabilities increase with increasing current. These features of the transient phenomena are similar to those observed in Refs. 2 and 3. In contrast with Ref. 3, however, the instabilities observed by us are not suppressed as a result of application of the magnetic field. Furthermore, the time scale of the instabilities may be much smaller than that in Refs. 2 and 3.

These phenomena are not related to the characteristic features of the heat transfer from the sample to the helium or the warming of the entire sample, since the average (over the repetition period of the current pulses) increase in the temperature of the sample is no greater then 0.01 K. An increase in the temperature above 5 K resulted in the disappearance of the instability and in an abrupt decrease in the dependence of the amplitude of the transmitted signal on the current. These circumstances and the effect of the magnetic field on the instability and transient phenomena suggest that we are dealing with electronic phenomena in metals.

In the phenomena we are studying here the Esaki effect and the generation of acoustic phonons are not a factor because of the low drift velocities of electrons. The relative orientation of the current and magnetic-field directions was found to be an important factor, in contradiction of the explanation of these phenomena in terms of the effect of the magnetic field of the current on the magnetostriction and the magnetoresistance of the conductor. The effect of electrodynamic forces in an external magnetic field and of the neighboring conductors on the conductor in which the current flows should be taken into account. These forces are responsible for the change in the geometric dimensions of the system, such as its period, which may affect the characteristics of the wave transmitted through the system. These forces, nonetheless, are not able to explain the time-varying phenomena and the instabilities with time scales of several tens to several hundred microseconds, nor can they explain the disappearance of these phenomena when the temperature is raised slightly.

Measurements of the *I*-*V* characteristic of the sample under study showed that it becomes nonlinear at currents in excess of 2 A. A variable component of the voltage drop across the sample, similar to that observed in Ref. 3, was not detected.

We suggest that the observed phenomena, especially the time-varying phenomena, may be caused by the excitation of thermomagnetic waves and the instability of these waves,[4] which distort the motion of the electrons carrying the rf currents and which have an effect on the propagation of an electromagnetic wave. A flow of current in the conductor gives rise to temperature gradients which decrease and eventually vanish as time elapses. The excitation and interference of thermomagnetic waves occurs in the presence of temperature gradients, which may account for the transient phenomena in the propagation of an electromagnetic wave.

At the currents $J = 4$ A and 6 A the data in Fig. 3 suggest that alternating periods of "turbulent" and "laminar" propagation of waves occur when a certain threshold value of the current is exceeded. The laminar period decreases in length as the current is increased. In hydrodynamics[5] there is an analog of such a turbulence-development scenario which is called intermittence transition.

The forces associated with the current flow and imposition of a magnetic field on the rf eddy currents could also affect the wave parameters.

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