

$\rho$ ,  $R$ , and  $\mu$  at room temperature are shown in Fig. 1. A characteristic feature of the dependences of  $\rho$  and  $\mu$  on  $L$  is the presence of oscillations. The period of the oscillations on the thick end of the sample was  $\Delta L \approx 500$  Å. An estimate of the effective carrier mass in accordance with [1]

$$\Delta L = \pi \hbar / \sqrt{2mE_F},$$

where  $E_F$  is the Fermi energy of the bulky sample, yields a value  $m = 0.01m_0$ , which is in satisfactory agreement with the data of the optical measurements [3]. Oscillations of the mobility appear against the background of a monotonic decrease of  $\mu$  with decreasing thickness. The decrease of the monotonic component of the mobility was observed in Bi films [1] and recently in InSb films [4]. It should be noted that the authors of [4] observed no mobility oscillations, probably because of the large thickness steps used in the measurement of the thickness dependences.

As seen from Fig. 1, a sharp increase of  $\rho$  is observed at  $L \leq 300$  Å, due principally to the decrease of the carrier density. This phenomenon can be interpreted as the lifting of the degeneracy of the electron gas. Favoring this conclusion is the appearance of sections with an exponential temperature dependence of the concentration (Fig. 2, curves 1 and 2), the activation energy increasing with decreasing  $L$ . For films of minimum thickness (240 Å) the activation energy  $\Delta E$  determined from the expression  $n \sim \exp(-\Delta E/2kT)$  is equal to 0.24 eV.

We assume that the above-described singularities of the electric properties of thin InSb films are manifestations of quantum size effects.

In conclusion, the authors thank B. A. Tavger and V. Ya. Demikhovskii for a discussion of the results.

- [1] Yu. F. Ogrin, V. N. Lutskii, and M. I. Elinson, *ZhETF Pis. Red.* 3, 114 (1966) [*JETP Lett.* 3, 71 (1966)].
- [2] Yu. F. Komnik and E. I. Bukhshtab, *Zh. Eksp. Teor. Fiz.* 54, 63 (1968) [*Sov. Phys.-JETP* 27, 34 (1968)].
- [3] O. N. Filatov and I. A. Karpovich, *Fiz. Tverd. Tela* 11, 1639 (1969); 10, 2886 (1968); 11, 805 (1969) [*Sov. Phys.-Solid State* 11, No. 4 (1969), 10, 2284 (1969); 11, 655 (1969)].
- [4] K. Berchtold and D. Huber, *Phys. stat. sol.* 33, 425 (1969).

#### MICROWAVE RADIATION OF TELLURIUM

V. N. Kobyzhev, A. S. Tager, and V. I. Shepshel'ei  
 Submitted 18 July 1969  
*ZhETF Pis. Red.* 10, No. 5, 227 - 230 (5 September 1969)

We investigated the microwave radiation of tellurium single crystals in strong pulsed electric fields. The effect was initially observed in the 7.5 - 10 GHz range at a temperature  $T = 77^\circ\text{K}$  in a crystal measuring  $5 \times 2$  mm with a low hole density ( $p \approx 2 \times 10^{14} \text{ cm}^{-3}$ ) and high mobility ( $\mu_p \approx 800 \text{ cm}^2/\text{V-sec}$ ), to which an electric field of intensity  $E \geq 200 \text{ V/cm}$  was

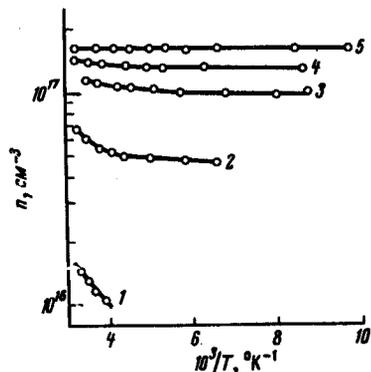


Fig. 2. Temperature dependences of carrier density for films of various thicknesses  $L$  (in Å): 1 - 240, 2 - 300, 3 - 360, 4 - 390, 5 - 410.

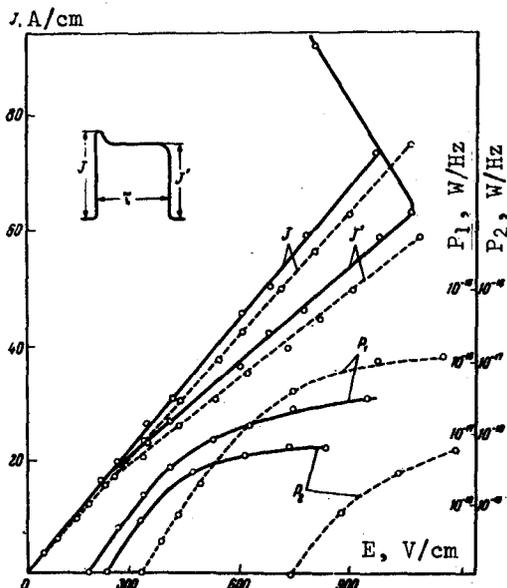


Fig. 1. Current-voltage characteristics of tellurium crystal measuring  $4 \times 4$  mm at  $T = 77^\circ\text{K}$  (curves  $J$  and  $J'$ ) and average spectral density of the microwave radiation in the bands 1 - 1.5 GHz ( $P_1$ ) and 3.5 - 5.5 GHz ( $P_2$ ). Solid and dashed lines -  $\tau$  equal to 2 and 0.4  $\mu\text{sec}$ , respectively.

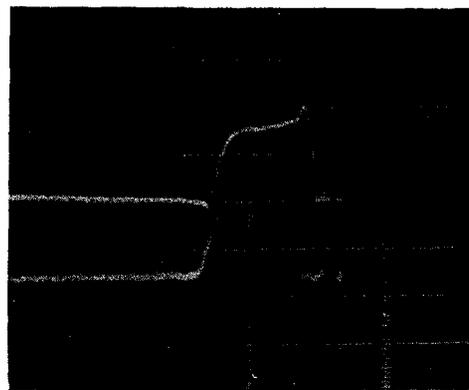


Fig. 2. Oscillogram of current pulse (lower) and of envelope of microwave pulse (upper). Horizontal scale 1  $\mu\text{sec}$ /division, vertical scale 1 A/division.

the side faces were produced either by cleaving or by polishing. Ohmic contacts were produced on the polished end faces of the crystal with bismuth and a neutral flux.

The sample was placed either in a gap of the internal conductor of a coaxial cable with wave resistance 50 ohm, or between the broad walls of a  $10 \times 23$  mm waveguide. The microwave radiation was registered broad-band direct-amplification traveling-wave receivers covering the 1 - 10.5 GHz band with a sensitivity  $10^{-10} - 10^{-11}$  W. The spectral distribution of the radiation intensity was determined by tunable resonant filters, with bandwidth 10 - 15 MHz, connected in the amplifier circuit. Voltage (current) pulses of duration 0.2 - 10  $\mu\text{sec}$  and amplitude up to 500 V were fed to the crystal from a source with internal resistance 15 ohm. The crystal current was determined from the voltage drop on the series connected ohmic resistance  $\sim 1$  ohm. The envelope of the microwave pulse was displayed on an oscilloscope.

Noise-type microwave radiation was observed in the entire indicated frequency region for most investigated samples, both at  $T = 77^\circ\text{K}$  and at higher temperature, including room temperature. The spectral density of the radiation was  $10^{-18} - 10^{-15}$  W/Hz (equivalent noise temperature  $T_{\text{eq}} = 10^5 - 10^8$   $^\circ\text{K}$ ). At a given frequency  $\omega$ , the appearance of radiation is registered when the field in the sample exceeds a certain threshold value  $E_{\text{thr}}(\omega)$ ; with further increase of  $E$  and  $J$ , the radiation intensity increases monotonically (Fig. 1). The measured values of  $E_{\text{thr}}(\omega)$  and  $J_{\text{thr}}(\omega)$  at  $T = 77^\circ\text{K}$  were approximately 80 - 500 V/cm and  $(0.5 - 10) \times 10^2$  A/cm<sup>2</sup>.

At constant durations of the supply pulse  $\tau$  and at a sample temperature  $T$ , the threshold value of  $E_{\text{thr}}$  increases rapidly with frequency, and the average radiation intensity decreases. The spectral density of the radiation varies in this case not monotonically, but passes through

a number of more or less strongly pronounced irregular maxima, separated by 100 - 300 MHz. An external magnetic field of intensity up to 6 kOe, of any orientation, has practically no effect on the value of  $E_{thr}(\omega)$  or on the radiation spectrum.

Other conditions being equal, the radiation threshold, as a rule is lower in samples with larger hole mobility, larger length in the direction of the electric field, and larger electric conductivity. A decrease of the duration of the supply pulse leads to an increase of  $E_{thr}(\omega)$ ; this increase is particularly large when  $\tau < 2$   $\mu\text{sec}$  (Fig. 1). Heating of the sample is also accompanied by an increase of  $E_{thr}(\omega)$  and by a simultaneous decrease of the radiation intensity. At  $T = 300^\circ\text{K}$ , the value of  $E_{thr}$  is approximately 2 - 3 times larger than at  $T = 77^\circ\text{K}$ . The minimum value  $E_{thr} = 80$  V/cm was obtained at  $T = 77^\circ\text{K}$ ,  $\omega/2\pi = 1 - 1.5$  GHz, and  $\tau = 6$   $\mu\text{sec}$  in a sample 4 mm long with  $p = 10^{15}$   $\text{cm}^{-3}$  and  $\mu_p = 8300$   $\text{cm}^2/\text{V-sec}$ , oriented along the z axis.

The start of the microwave pulse usually lags the start of the supply pulse by  $\Delta\tau = 0.1 - 0.3$   $\mu\text{sec}$ , and  $\Delta\tau$  decreases with increasing power and duration of the supply pulse. An "afterglow" of the signal is also observed, in that microwave radiation is registered for 0.1 - 0.2  $\mu\text{sec}$  following the end of the supply pulse (Fig. 2).

The current-voltage characteristics of most investigated crystals in fields  $E < 10^3$  V/cm, at which the microwave radiation was observed, are close to linear. On some relatively long samples ( $l = 4$  cm) in fields  $E \geq 150 - 300$  V/cm close to the threshold values, a smooth deviation from Ohm's law was observed, occurring 0.2 - 0.4  $\mu\text{sec}$  after the start of the supply pulse, and corresponding to a small (20 - 40%) increase of the differential resistance of the sample. A characteristic overshoot, lasting about 0.5  $\mu\text{sec}$  (Fig. 2) was then observed on the initial section of the current pulse.

In the region of strong fields ( $E \geq E_{cr} \approx 10^3$  V/cm), a readily reproducible S-shaped section is registered on the current-voltage characteristics (Fig. 1). This section was observed earlier at shorter pulses ( $\tau = 15 - 36$  nsec) and in stronger fields ( $E = 3$  kV/cm) and was attributed to heating excitation of the light holes [1]. The intensity of the microwave radiation in this section usually decreases sharply. The value of  $E_{cr}$  decreases with increasing average current flowing through the crystal.

We consider the most probable mechanism producing the microwave radiation in tellurium to be the conversion of the microwave acoustic oscillations, excited in the tellurium crystals by the drifting carriers, into electromagnetic oscillations. This assumption agrees with the data on the strongly pronounced piezoelectric properties of tellurium, sufficient to amplify ultrasound [2], and explaining probably the main features of the observed effect - the threshold character of the radiation and its dependence on the frequency, on the pulse duration, on the crystal parameters, and on the temperature. Such characteristic details as the change of the current at the start of the pulse and the delay of the microwave radiation (Fig. 2) can be related to the buildup and decay times of the acoustic instability in the crystal; the increase of the threshold field in short pulses can be attributed to the decrease of the current flow time compared with the time of passage of the acoustic waves through the sample; the drop of the radiation intensity with increasing frequency may be due to the increase of

the acoustic losses, etc. A final assessment of the nature of the microwave radiation in tellurium calls, however, for more detailed experimental investigations.

The authors are grateful to S. S. Shalyt and I. I. Farbshtein for kindly supplying the tellurium crystals.

- [1] G. Nimtz and K. H. Seeger, Appl. Phys. Lett. 14, 19 (1969).
- [2] T. Ishiguro and T. Tanaka, J. Phys. Soc. of Jap. 21, Supplement, p. 489 (1966)

#### GENERATION OF HIGH-FREQUENCY OSCILLATIONS BY THIN SUPERCONDUCTING TIN FILMS

G. E. Churilov, V. M. Dmitriev, and A. P. Beskorsyi  
Physico-technical Institute of Low Temperatures, Ukrainian Academy of Sciences  
Submitted 21 July 1969  
ZhETF Pis. Red. 10, No. 5, 231 - 233 (5 September 1969)

At the present time there is no doubt in anyone's mind that superconductors, particularly with small dimensions, have strong nonlinear properties. Their mechanisms may be different, but their outward manifestations are similar in many respects. This can be traced by analyzing weak-coupling superconductors [1] in thin superconducting films [2 - 5]. Whereas weak-coupling superconductors of the type of Josephson junctions or point contacts certainly generate electromagnetic waves, all that could be obtained so far with bridge structures was a low-frequency noise spectrum [6]. On the other hand, thin superconducting films having no special geometry or structure produced only parametric generation, which required the presence of at least one high-frequency pump signal [2 - 4].

We describe in this paper the results of experiments on observation of the generation of high-frequency oscillations by long thin superconducting films. We investigated films of tin deposited on a glass substrate by the vacuum-sputtering method and having the following dimensions: thickness 250 Å, width 0.15 mm, length 13 mm. The films had current and potential contacts and were connected either as part of a resonant circuit kept in liquid helium

and serving as the input circuit of a tuned amplifier, or else directly to the amplifier input. The amplifier had several frequency bands in the range from 30 to 230 MHz and its gain was  $4.5 \times 10^5$ .

The investigated films had at 4.2°K a resistance of 60 ohms. Direct current flowed through the film during the time of the experiment, and the current-voltage characteristics were recorded in synchronism with the generated high-frequency signal.

As seen from Fig. 1, the generation of high-frequency oscillations occurs when the film is in the resistive state. A singularity then appears on the current-voltage characteristic if the film is connected in the resonant circuit. There is no hysteresis in the region of the singularity when the current is alternately increased and decreased. But the film was connected directly to the amplifier input, the generation of the high-frequency oscillations continued at the same values of the current, and the singularity vanished from the current-voltage characteristic.

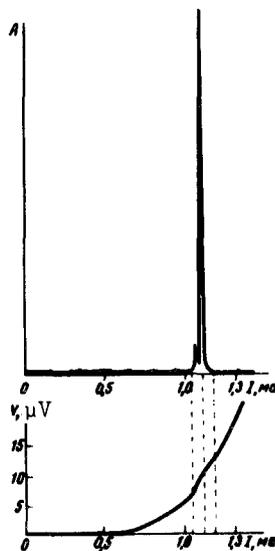


Fig. 1