Our investigations show that the radiative decay of the auto-ionization states of the atom can occur with an appreciable probability. The observation and investigation of such emission spectra uncovers new possibilities of identifying the mechanism whereby the internal shells of the atoms are excited, and greatly broadens the arsenal of the atomic spectroscopy in the study of the structure of matter.

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NONLINEAR EFFECTS IN n-InSb at 77°K IN THE SHORT-WAVE PART OF THE MILLIMETER BAND

A. M. Belyantsev, V. N. Genkin, A. M. Leonov, and B. A. Trifonov
Radiophysics Research Institute
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Experimental studies of nonlinear effects in the millimeter and submillimeter bands is of great interest for the diagnostics of nonlinear properties of semiconductors, properties connected with the interaband motion of the carriers. In particular, by investigating the power-law dependence of the current density on the electric field intensity, $j(E) = \sum_{n=1}^{\infty}\sigma_n E^n$, we can obtain information on the nonlinearity mechanisms that act in the semiconductor and on the carrier distribution function.

We report here the results of an experimental study of the nonlinear responses in pure single-crystal n-InSb ($n = 7.1\times10^{13}$ cm^{-3}, $\rho = 0.12$ Ω-cm) at liquid-nitrogen temperature and at the combination frequencies $f = f_2 - mf_1$ (m are integers from 1 to 4). The block diagram of the setup is the same as in [1]. The frequencies f_1 and f_2 varied in a wide range (f_1 from 75 to 225 Hz, f_2 from 75 to 400 Hz) and were chosen such that the combination frequency f was equal to 3 GHz1). The signal at frequency f was picked off a load matched to the investigated sample, with dimension 0.25×0.24×0.05 mm. The construction of the mixing unit precluded the possibility of effective multiplication of the frequency f ; the response at the combination frequency $f = f_2 - mf_1$ was therefore treated as due to the (m+1)st and the higher terms in the expansion of j in E. In addition to the signal power P_f at the combination frequency, we measured the powers P_{f_1} and P_{f_2} at the input of the mixing unit, the dc resistance R(I) of the sample, and the current I through the sample. The powers absorbed in the semiconductor at frequencies f_1 and f_2 were monitored against the changes of the dc resistance of the sample2) ($\Delta R_1(P_{f_1}, I)$, $\Delta R_2(P_{f_2}, I)$).

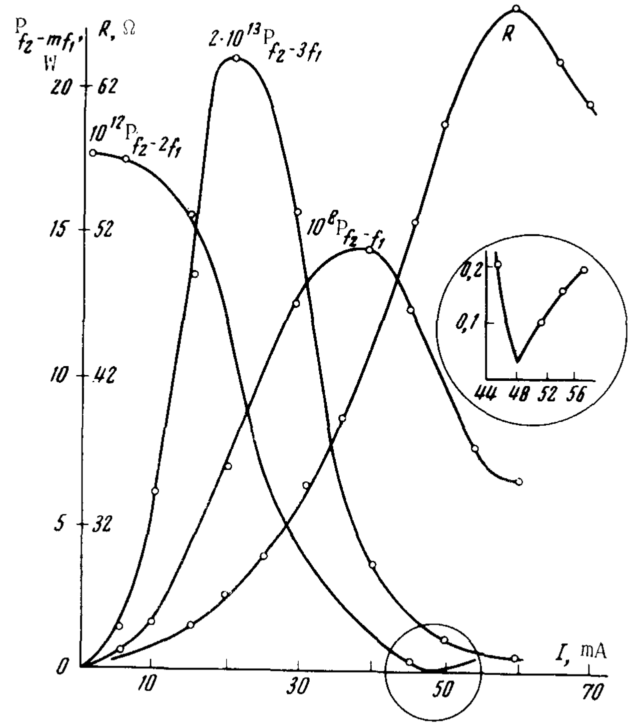

Fig. 1

We note first that in the case of even m, the nonlinear response at the combination frequencies $f = f_2 - mf_1$ was observed with and without a constant bias. In the case of odd m, it was observed only at a constant bias. A typical plot of the signal power at the combination frequency $P_{f_2-mf_1}$ (m = 1, 2, 3) against the current I is shown in Fig. 1. The measurements were performed at fixed powers P_{f_1} and P_{f_2}, the power level was set to obtain an equal increment ΔR_i at a current I_1 = 5 mA ($\Delta R_1(P_{f_1}, I_1) = \Delta R_2(P_{f_2}, I_1) = 10^{-2}R_0$, where R_0 is the resistance at "zero" current and $P_{f_1} = P_{f_2} = 0$). Figure 2 shows the measured values of $P_{f_2-mf_1}$ (m = 2, 3, 4) at $I = I_1$

and at a fixed power $P_{f_2}(\Delta R_2, (P_{f_2}, I_1) = 10^{-2}R_0$ for different values of $P_{f_1}(\Delta R_1(P_{f_1}, I_1))$. We note that so long as $\Delta R_i \ll R_0$, the change in the resistance was well approximated by the expression $\Delta R_i(P_{f_i}, I) = kP_{f_i}[\partial R(I^2R)/\partial(I^2R)]|_{I=\text{const}}$, where k is a coefficient that depends only on the frequency f_i.[3]. It is seen from the plots of Fig. 1 that in the initial section $P_{f_2-f_1}$ and $P_{f_2-3f_1}$ are proportional to I^2, while $P_{f_2-2f_1}$ hardly changes with increasing I. At small P_{f_1} ($\Delta R_1/R_0 \ll 1$), $P_{f_2-mf_1}$ is proportional tp $P^m_{f_1}$ (or ΔR^m_1, see Fig. 2). The ratio $P_{f_2-mf_1}/P_{f_2}$ does not depend on P_{f_2} if $\Delta R_2(P_{f_2}, I) \ll R_0$. Thus, at small currents and powers ($\Delta R_i \ll R_0$) the response at the combination frequency $f = f_2 - mf_1$ is determined mainly by the (m + 1)st term of the expansion of j in E at even m, and by the (m + 2)nd term at odd m. If $I \gg I_1$ and $\Delta R_1 \sim R_0$, the proportionalities noted above are violated. This may be due either to an increase in the losses[4] or to an increase in the contribution made by the nonlinearities of higher order to the response to the combination frequency. The presence of a "minimum" in the function $P_{f_2-2f_1}$ (see Fig. 1) is indicated by the fact that the contributions of the nonlinearities of the fifth and third orders in the current are commensurate and in counterphase at the combination frequency $f_2 - 2f_1$. The minimum is observed at low powers P_{f_i} ($\Delta R_i \ll R_0$), but in a relatively strong constant field. The direct current I_2 at which the response was minimal amounted to 48 mA ($j_2 = 400$ A/cm^2). This value of the current remained practically unchanged when f_1 and f_2 varied in a wide range (at $f_2 - 2f_1 = \text{const}$). Figure 1 shows also the dependence of R on I. The sharp decrease of R corresponds to breakdown (to the growth of the carrier densities), which occurs in n-InSb at 77°K in a constant field $E_2 = 160$ V/cm. The corresponding pre-breakdown value is $\Delta R/R_0 = (R(I) - R_0)/R_0 = 2$. In a high-frequency field ($f_1 = 75$ GHz) a breakdown is likewise observed, and the pre-breakdown $\Delta R_1/R_0$ (measured with a weak dc current) is 3.5, i.e., almost double the value in a dc field.

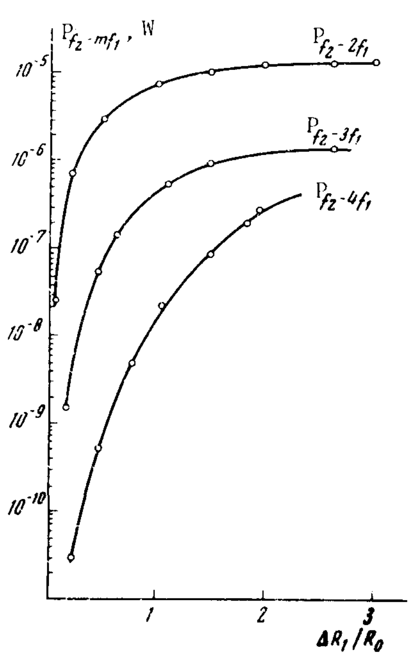

Fig. 2

The plots of $P_{f_2-mf_1}$ against I (Fig. 1) and $P_{f_2-mf_1}$ against P_{f_1} (more accurately, against ΔR_1, Fig. 2) can be explained both within the framework of the model of [1], which is based on the non-quadratic character of the dispersion, and with the aid of the model of [2], based on the dependence of the effective collision frequency ν on the field. However, the experimentally observed nonlinear response $P_{f_2-mf_1}$ is somewhat larger (albeit of the same order) than the maximum possible in the model based on deviation from a quadratic dispersion. Moreover, calculation yields for the current density at which $P_{f_2-2f_1}$ vanishes a value almost twice as large as j_2. It seems that at the combination frequencies $f = f_2 - mf_1 \ll \nu/2\pi$, with which we deal with in the experiment, the nonlinear response in n-InSb at 77°K is determined mainly by the field dependence of the effective collision frequency. In this case the minimum of $P_{f_2-2f_1}$ at a certain constant field was predicted in [3], where it was attributed to strong anisotropy of the distribution function, which causes, in particular, the nonlinear response to be determined by the dependence of ν on the average carrier velocity. In n-InSb at 77°K, in the presence of a strong electric field, the distribution function becomes anisotropic in momentum space, owing to the inelastic scattering of the carriers by the optical phonons. Although an exact calculation of this model has not been made, rough estimates yield a response $P_{f_2-mf_1}$ close to the experimental one. In this model one can explain also the difference between $\Delta R(I)$ and $\Delta R_1(P_{f_1}, I_2)$ in the case of breakdown, if it is assumed that the breakdown is determined only by the power absorbed in the sample. To this end, it suffices to consider that $\Delta R(I)$ is determined by the self-action while $\Delta R_1(P_{f_1}, I_1)$ is determined by the action.

We note in conclusion that pure n-InSb at 77°K is a promising material for millimeter and submillimeter band mixers. The two most interesting characteristics of a mixer, namely the conversion coefficient $\eta_{f_2-mf_1} = P_{f_2-mf_1}/\tilde{P}_{f_2}$ (P_{f_2} is the power at frequency f_2 absorbed in the sample[5] and the time delay, were investigated experimentally. The maximum conversion coefficients for even m=2 and 4 is obtained at zero dc field, $\eta^{max}_{f_2-2f_1} \simeq 10^{-2}$ and $\eta^{max}_{f_2-4f_1} \simeq 10^{-3}$; for odd m we have $\eta^{max}_{f_2-f_1} \sim 5\ 10^{-2}$ at I = 35 mA and $\Delta R/R_0 = 1.3$, and $\eta^{max}_{f_2-3f_1} \simeq 10^{-2}$ at I = 15 mA and $\Delta R_1/R_0 = 2.2$. Decreasing the combination frequency f from 3 to 150 GHz led to practically no change in the conversion coefficient, and consequently the time delay in the frequency mixing in n-InSb at 77°K (see also [4]) does not exceed 10^{-10} sec.

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[1] In the investigation of the inertia of the nonlinearity mechanisms that cause the frequency mixing, the frequency f ranged from 3 GHz to 150 MHz.

[2] $\Delta R_2(P_{f_2}, I)$ was measured only at 75 GHz $\le f_2 \le$ 300 GHz, whereas $\Delta R_1(P_{f_2}, I)$ was measured in the entire range of f_1.

[3] If the resistance is determined only by the absorbed power, then k is the absorption coefficient of the high-frequency power.

[4] There was practically no heating of the semiconductor lattice. This is evidenced by the similarity of the plots of R(I) and $P_{f_2 - f_1}(I)$ at $\Delta R_1 \ll \Delta R_0$ in the continuous regime and in the regime when microsecond pulses were applied with a large off-duty cycle.

[5] To estimate P_{f_2} for the purpose of determining η, we used the dependence of R on I (Fig. 1) and assumed that the sample resistance is mainly a function of the absorbed power.

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SOME RESULTS OF INVESTIGATIONS OF NONLINEAR PHENOMENA IN THE F-LAYER OF THE IONOSPHERE

G. G. Getmantsev, G. P. Komrakov, Yu. S. Korobkov, L. F. Mironenko, N. O. Mityakov, V. P. Rapoport, V. Yu. Trakhtengerts, V. L. Frolov, and V. A. Cherepovitskii
Radiophysics Research Institute

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Results of experiments on the nonlinear action of powerful radio waves on the F-layer of the ionosphere are reported and discussed.

Ginzburg and Gurevich back in 1959 [1], and later Farley [2], pointed out that a strongly-ionized plasma, particularly the F-layer of the ionosphere, can be the site of nonlinear effects connected with heating the plasma with sufficiently powerful electromagnetic radiation. Experiments on the nonlinear action of powerful short-wave radiation on the F-layer were performed in Boulder and in Arecibo (Puerto Rico) in 1970 [3 - 5].

We present here some experimental data on nonlinear effects in the F-layer, obtained in the city of Gor'kii in 1973.

A circularly polarized pump wave was radiated vertically upward at 5.75 MHz by an antenna with gain $G \simeq 150$. The transmitter had an average power $P \simeq 60$ kW and could operate in either a cw or a pulsed mode with $P_p \simeq 300$ kW, pulse duration $\tau \simeq 8$ msec, and repetition frequency 25 Hz.

An auxiliary ionospheric station, located at the same site, was used for the diagnostics of the F-layer state.

The experiments were performed in March - June 1973, in morning and evening hours, when the critical frequency of the F layer was close to 5.75 MHz, and the radio-wave absorption in the D region of the ionosphere was low. When the pump wave was turned on, an appreciable decrease (by a factor 3 — 10) was observed in the intensities of thepump wave as well as of the sounding waves in the 5.5 — 5.9 MHz band, and with an approximate characteristic signal-intensity fall-off time 40 sec. When the pump wave was turned off, the intensities of the sounding waves reflected from the ionosphere returned to their initial values after approximately the same characteristic time (see the figure). This phenomenon is apparently analogous to the effect observed in Boulder [3 - 5]. When the sounding-wave frequency was set 0.2 MHz lower than f = 5.75 MHz, the anomalous attenuation of the sounding wave was noticeably reduced (figure). The decrease in the pump-wave and sounding-wave intensities was observed only evenings, only with