and to G. T. Nikitina and D. V. Pronkin for help with the experiments and with the data reduction.

[1] S. T. Sekula, R. W. Boom, and C. I. Bergeron, Appl. Phys. Lett. 2, 102 (1963).
[2] C. I. Bergeron, ibid. 3, 63 (1963).
[3] Yu. F. Bychkov, V. G. Vereshchagin, V. R. Karasik, G. B. Kurganov, and V. A. Mal'tsev, Zh. Eksp. Teor. Fiz. 56, 505 (1969) [Sov. Phys.-JETP 29 (1969)].
[4] P. R. Aron and H. C. Hitchcock, J. Appl. Phys. 33, 2242 (1962).
[5] Yu. F. Bychkov, V. G. Vereshchagin, M. T. Zuev, G. B. Kurganov, and V. A. Mal'tsev, ZhETF Pis. Red. 9, 451 (1969) [JETP Lett. 9, 271 (1969)].
[6] B. A. Matt and J. A. Roberts, Acta Metall. 8, 575 (1960).
[7] G. W. Cullen, G. D. Cody, and I. P. McEvoy, Phys. Rev. 132, 577 (1963).

SPACE-CHARGE-LIMITED TUNNEL CURRENT IN Al-Al_2O_3-Al JUNCTIONS

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In [1 - 4] they reported observation of negative-resistance sections on the current-voltage characteristics of Me-D-Me tunnel junctions, including Al-Al_2O_3-Al junctions. The appearance of a negative-resistance section is attributed in [1] to the process of a pn junction in the dielectric film.

We observed negative-resistance regions in the tunnel characteristics of Al-Al_2O_3-Al junctions at bias voltages of both polarities. The conductivity curve $g(U) = di/dU(U)$ has an almost symmetrical w-shaped form with a deep trough at $U = 0$ (Fig. 1). The bias voltages U_1, U_2, U'_1, and U'_2, corresponding to the extrema on the current-voltage characteristic, equal 0.052, 0212, -0.155, and -0.213 V, respectively. Positive bias corresponds to positive voltage applied to the upper electrode of the tunnel junction. The plot of $g(U)$ for the

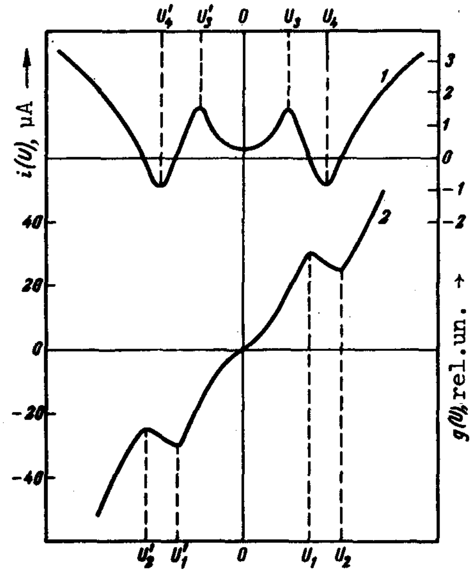

Fig. 1. Plots of tunnel current i(U) (1) and tunnel conductivity g(U) (2) of Al-Al_2O_3-Al tunnel junction.

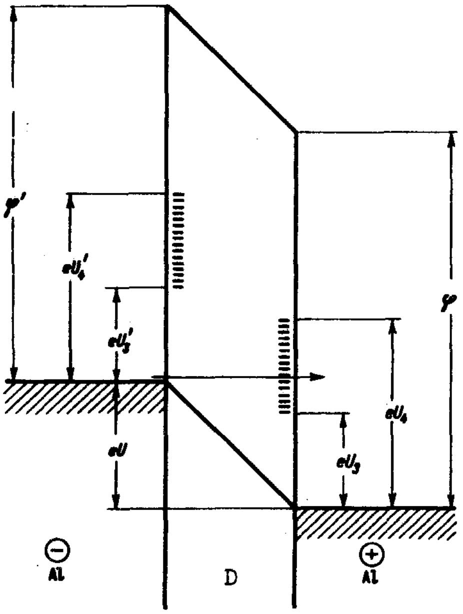

Fig. 2. Energy diagram of Al-Al$_2$O$_3$-Al tunnel junction with surface traps in the potential barrier. A positive bias voltage is applied to the junction, $U_3 < U < U_4$.

considered Al-Al$_2$O$_3$-Al junctions is analogous to the w-curves observed by us earlier for Me-D-Bi$_{1-x}$ Sb$_x$ junctions [5]. By analogy, we believe that the negative-resistance sections observed in this investigation can be attributed to the presence of surface traps in the Al$_2$O$_3$ layer near the dielectric-electrode interface. Figure 2 shows the energy diagram for the Al-Al$_2$O$_3$-Al junction. At bias voltages $U_3 < U < U_4$ or $U'_4 < U < U'_3$, some of the tunneling electrons, when captured by the traps, produce a negative surface space charge in the dielectric. The presence of this charge leads to a change of the configuration of the electric field in the potential barrier, and strongly limits the tunnel current flowing through the junction. Current-voltage characteristics of the junctions, with clearly pronounced negative-resistance sections, were observed by us at nitrogen and helium temperatures. No such characteristics were observed at room temperature. This circumstance can be attributed to the exponential temperature dependence of the lifetime of the trap in the ionized state, and accordingly to the strong temperature dependence of the space-charge density accumulating on the traps when tunnel current flows. According to an approximate estimate, the density of the surface traps on each side of the barrier, in the energy intervals $\Delta E = e(U_4 - U_3)$ and $\Delta E' = e(U'_3 - U'_4)$, amounts to

$$\delta(E) > 10^{17}\ \mathrm{cm}^{-3}\mathrm{eV}^{-1}.$$

The origin of the surface states (traps) has not been established. It is assumed, however, that these states can result from an interaction of the surface layer of the thin aluminum film, which is produced to form the potential barrier by the through-oxidation method [5], with the adsorbed molecules or the residual gases, and also with the water vapor in the working liquid in the diffusion-pump fluid (VM-1 oil).

At low temperatures, the current-voltage characteristics of the Al-Al$_2$O$_3$-Al junctions revealed also irregularities in the form of very narrow and sharp dips Δi of the tunnel current at bias voltages of both polarities. The relative depth of the dip in the absence of a magnetic field is $\Delta i/i \approx -0.06$. With increasing magnetic field intensity, $|\Delta i/i|$ decreases and vanishes in fields $H \geq 8$ kOe. The bias voltage U_d corresponding to the dip Δi is practically independent of the magnetic field. The obtained data can be explained by assuming that the tunneling electrons are inelastically scattered by quasiparticles with energy $\varepsilon_q = eU_d = 1.3$ meV, reckoned from the Fermi level. We have not established the nature of these quasiparticles. At helium temperature we observed on the $d^2i/dU^2(U)$ curves distinct maxima due to the interaction of the tunneling electrons with the phonons. The energies of the phonons in the condensed aluminum film, obtained from tunnel measurements, are $h\omega = 8.0$, 13.3, 19.6, and 30.8 meV. These results are in satisfactory agreement with the data given in [6].

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[1] T. W. Hickmott, J. Appl. Phys. 33, 2669 (1962); 35, 2118 (1964); 36, 1885 (1965).
[2] V. I. Stafeev et al. Fiz. Tekh. Poluprov. 2, 767 (1968) [Sov. Phys.-Semicond. 2,642(1968)]
[3] G. A. Filaretov et al., ibid. 1, 1492 (1967 [1, 1242 (1968)].
[4] S. Pakswer and K. Pratinidi, J. Appl. Phys. 34, 711 (1963).
[5] A. A. Galkin and O. M. Ignat'ev, Ukr. fiz. zh. (in press).
[6] J. Lambe and R. C. Jaklewic, Phys. Rev. 165, 828 (1968).

TWO-LEVEL GAS LASER WITH COHERENT OPTICAL PUMPING

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1. In [1] we proposed a method of coherent optical pumping, making it possible to obtain exceedingly narrow amplification lines (up to $10^4 - 10^5$ Hz) within the Doppler line of a beam of atoms or molecules. This is of interest for the development of a quantum frequency standard in the optical band (see the review [2]). In the present paper we propose to obtain narrow amplification lines by coherent optical pumping using a two-level scheme in a low-pressure gas, and a two-level gas laser based on coherenet pumping by its own radiation.

2. Coherent optical pumping of low-pressure gas in accordance with a two-level scheme consists of combining pulsed inversion of molecules as they pass through a coherent light field ("π-pulse") and "tubular" geometery of the pumping light beam, thus ensuring spatial isolation of the inverted molecules without using a directional flux (beam) of molecules. Let the field of the pump beam have the form $E = \mathcal{E}_0(r_\perp)\cos(\omega t - \vec{k}\cdot\vec{r})$, where $\mathcal{E}_0(r_\perp)$ describes an annular distribution of the amplitude in the transverse directions. If the molecule mean free path greatly exceeds the beam diameter, then the molecules whose velocity $\vec{v}$ satisfies the resonance condition

$$|\omega_{12} - \nu + kv| < \frac{\pi}{\tau} \qquad (1)$$

interact effectively with the field (ω_{12} is the frequency of the center of the Doppler line