$$|22(2)200\rangle=\frac{5\sqrt{14}}{112\pi^{3/2}}\{1-3(\mathbf{ev})(\mathbf{ve}_H)(\mathbf{ee}_H)-3([\mathbf{e}\times\mathbf{v}]\mathbf{e}_H)^2\},$$

$$|22(3)300\rangle=-i\frac{3\sqrt{10}}{32\pi^{3/2}}\{(\mathbf{ev})([\mathbf{e}\times\mathbf{v}]\mathbf{e}_H)-5(\mathbf{ee}_H)(\mathbf{ve}_H)([\mathbf{e}\times\mathbf{v}]\mathbf{e}_H)\},$$

$$|22(4)400\rangle=\frac{15}{32\cdot 70^{1/2}\pi^{3/2}}\{-4+7(\mathbf{ev})^2-30(\mathbf{ve})(\mathbf{ve}_H)(\mathbf{ee}_H)+35(\mathbf{ve}_H)^2(\mathbf{ee}_H)^2+5([\mathbf{e}\times\mathbf{v}]\mathbf{e}_H)^2\}.$$

[1)]The situation is similar to the one discussed in Refs. 7 in connection with spin relaxation of photoexcited electrons and excitons in a magnetic field.

[2)]Here and below we are interested in the asymptotic representation of the function f_{220} and of the other quantities $f_{j_1 j_2 j_3}$ in that energy region where the asymptotic representation of the function f_{000} is valid. The latter takes place when[6] $\Delta\varepsilon \gg T$ and $\Delta\varepsilon \gg \delta\varepsilon$.

[3)]It should be noted that since $D_2(\varepsilon)\sim\varepsilon\delta\varepsilon/\tau_\varepsilon'$, the condition (44) written for the Stokes region coincides with the condition for the existence of the periodic distribution obtained from intuitive considerations in Sec. 1.

[4)]It was shown in Refs. 3–5 that in GaAs the heavy diagonal holes have the lowest energy at a given quasimomentum p, and that the wave function of the ground state of the shallow acceptor in the momentum representation is made up mainly of wave functions of the heavy diagonal holes.

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Change of phonon energy in germanium at pressures up to 3 GPa

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Tunnel spectroscopy is used to measure the phonon energies in germanium at pressures up to ~3 GPa. It is shown that the restructuring of the germanium bands at ~1.8 GPa, wherein the minimum Δ_1 of the conduction band drops below the L_1 minimum, is accompanied by a change in the character of the tunneling with phonon participation. The values of the Grüneisen constants are obtained for the acoustic modes of the phonons with wave vector in the [100] direction; they are found to be −0.8 and 1.2 for the *TA* and *LA* modes, respectively.

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The participation of phonons in electron tunneling through a p-n junction which manifests itself by singularities on the current-voltage characteristics, yields information on the phonon spectra and the band structure of solids.[1]

In germanium at normal pressure, the tunneling is accompanied by a transition of the electrons to the valence band ($\Gamma_{25'}$) in the minimum of the conduction band L_1 (Ref. 2). Therefore, in accordance with the momentum conservation law, the positions of the singularities on the tunnel characteristics correspond to the phonon energies on the boundary of the Brillouin zone in the [111] direction (see Fig. 1).

The change of the phonon frequencies under hydrostatic compression to 1.8 GPa was investigated in Ref. 3 on a Ge tunnel diode (of n-type). In Ref. 4, using n-Ge samples with a Schottky barrier they investigated, in approximately the same pressure range, the shift of the singularities connected only with the optical branches of the spectrum. Finally, Payne[5] investigated the change of the phonon frequencies in a germanium p-n diode under uniaxial compression. These data were used to calculate the Grüneisen constants in Ge in the linear approximation.

Besides the change in the phonon frequencies, the band structure of Ge also changes under pressure. Various experiments have established that the minima of the conduction band L_1, $\Gamma_{2'}$ and Δ_1 under pressure are shifted relative to the valence band at different rates dE/dP, equal respectively to $5\cdot 10^{-11}$, $14\cdot 10^{-11}$ and $-(0-2)\cdot 10^{-11}$ eV/Pa.[6] At a pressure ~1.5–1 GPa, as a result, the minimum Δ_1 of the conduction band with

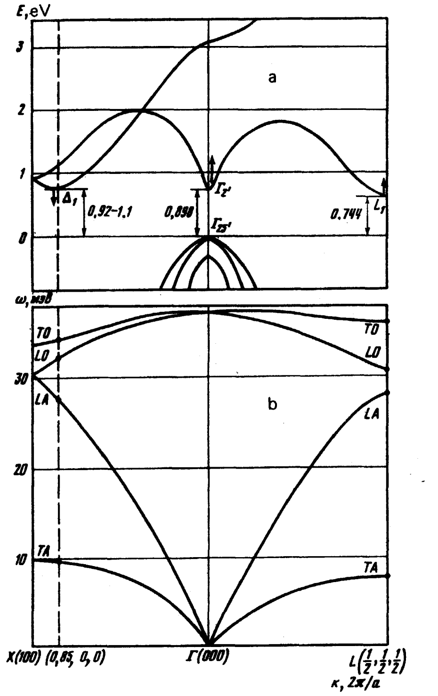

FIG. 1. Engergy-band scheme for germanium. The arrows at the band minima indicate the direction of their motion under pressure. The data on the gap sizes are taken from Ref. 12; b) dispersion-curve scheme for phonons in germanium according to the data of Ref. 9.

$k = 2\pi/a[0.85, 0, 0]$ becomes an absolute minimum. This change of the band structure should lead to the onset, at these pressures, of a new tunneling channel, corresponding to emission of phonons with this wave vector, as a result of which one should expect a qualitative change in the form of the tunnel characteristic. We have attempted to observe this effect.

1. The investigations were made on the tunnel p-n diodes with acceptor (Ga) density of the order of $\sim 5 \times 10^{19}$ cm^{-3}. The donor density, calculated by us by starting from the value of the peak voltage, is $\sim 2.3 \times 10^{19}$ cm^{-3}. This corresponds to degrees of degeneracy ~150 and ~50 MeV, in the p and n regions respectively. The tunnel current was directed along the [111] axis of the crystal.

The pressure-producing procedure was analogous to that described in Ref. 7 (variant b), except that all the parts were made of 45 KhNMFA steel, while the piston was made of the hard alloy VK6. The pressure-transmitting medium was a mixture of transformer oil and pentane (40 and 60%, respectively).

This design permitted reliable operation in the range up to 3 GPa, as confirmed by observation of the BiI–BiII and BiII–BiIII transitions. The pressure at helium temperature was determined from the change of the critical temperature T_c of a tin manometer.

To register the tunnel characteristics $d^2I/dU^2(U)$ we used a system similar to that described in Ref. 8, in which provision was made for automatically maintaining the modulating signal constant. The analog multiplier in the system was based on a K140MA1 microcircuit. The use of differential amplifiers at the input, and of buffer decouplers at the output of the circuit, made it possible to decrease the amplitude of the modulating signal to 30–50 μV, with a good signal/noise ratio. The operating frequency was 500 Hz. The sweep rate in the measurement did not exceed 0.1 mV/min.

2. Figure 2 shows a typical experimental plot of $d^2I/dU^2(U)$ at different pressures. As seen from the figure, the application of the pressure changes the position of the singularities and their relative amplitude. In addition, at a pressure ~1.8–2.0 GPa there appears a new singularity (TA') approximate at displacements ~10 mV, with an amplitude that increases sharply with increasing pressure. On the contrary, the amplitude of the peak corresponding to the TA phonons decreases with increasing pressure, so that the peak vanishes at ~3.1 GPa. The experimental curves obtained after removing the pressure and repeated loading were perfectly reversible and had no hysteresis. It is interesting to note that a similar singularity can be seen also on the experimental curve in Ref. 3 at ~1.7 GPa, but because of the insufficient pressure it was weakly pronounced and, naturally, no importance was attached to it.

The change of the energies of the corresponding phonons with pressure, determined from our experiments with account taken of the corrections for the parasitic series resistance of the sample (~0.1 Ω at a junction resistance ~3 Ω) is shown in Fig. 3, and the numerical values of the parameters are listed in the table. The same table gives the corresponding data obtained by others.

Besides the already mentioned appearance of a new singularity near 10 meV, the data of the table and Fig. 3 indicate the following circumstances.

a) The initial slopes $d\omega/dP$ at $P < 1.8$ GPa, determined by us, agreed with the data obtained by others for all the phonon branches with the exception of LA. for the LA branch, according to the data of Ref. 3,

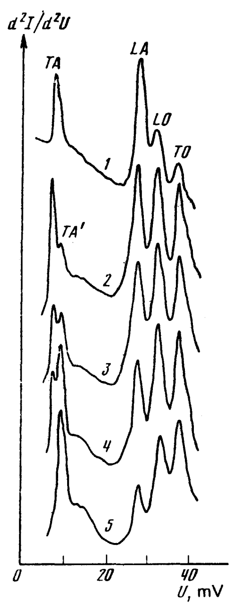

FIG. 2. Experimental plots of $d^2I/dU^2(U)$ at various pressures. 1—P = 0, 2—1.93 GPa, 3—2.29 GPa, 4—2.49 GPa, 5—3.12 GPa. T = 1.5 K.

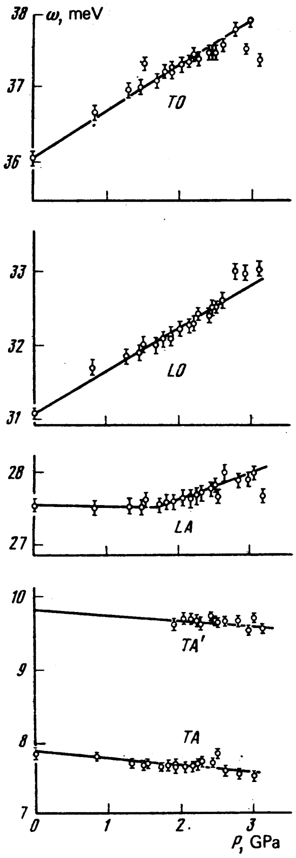

FIG. 3. Pressure dependence of phonon energy ω for various branches.

there is a small positive slope, while in Ref. 5 the sign of the slope varies with the direction of the uniaxial compression, whereas according to our data, $d\omega/dP(LA)\approx 0$.

b) The slope $d\omega/dP$ for the LA branch changes noticeably on going through the point $P\sim 1.8$ GPa, but for the TA branch it remains unchanged.[1)]

c) There are no noticeable changes of the slopes $d\omega/dP$ for the optical branches LO and TO in the entire pressure range.

3. We believe that our results agree with the assumptions made above concerning the change, under pressure, of the character of the tunneling with participation of the phonons in germanium. Namely the singularities on the $d^2I/dU^2(U)$ curves at $P>1.8$ GPa should correspond to the energies of phonons with wave vector $\mathbf{k}=2\pi/a[0.85, 0, 0]$. If we extrapolate to $P=0$ the energies of the LA and TA phonons obtained at $P>1.8$ GPa, then the corresponding quantities agree well with the energies of the acoustic phonons with $\mathbf{k}=2\pi/a[0.85, 0, 0]$, determined in experiments on inelastic scattering of neutrons.[9] In addition, the ratio of the amplitudes of the peaks on our experimental curves, obtained at the highest pressures, is similar to the ratio of the amplitudes of the corresponding peaks on the tunnel characteristics of silicon at $P=0$,[10] as might be expected when account is taken of the similarity between the band structures of the germanium at high pressure and silicon.

Thus, the pressure-induced change of the electronic structure in germanium makes it possible to obtain in-

TABLE I.

Phonon branch	ω, meV: Our data	ω, meV: Data of Ref. 9	10^{-10} $d\omega/dP$ meV/Pa	$\gamma=\frac{d\ln\omega}{d\ln V}$, Data of Refs. 3-5	γ ***, Our data
TA [111]	7.85±0.05	7.86	−1.3±0.2 *	−1.6±0.2 * [3]; −0.4 * [5]	−1.3±0.2 *
TA' [0,85, 0, 0]	9.8±0.1 (extrapolation to $P=0$)	9.92	−0.8±0.4 **	–	−0.8±0.4 **
LA [111]	27.55±0.1	27.54	0±0.2 *	0.42±0.06 * [3]; 0.5 * [5]	0±0.05 *
[0,85, 0, 0]	27.0±0.4 (extrapolation to $P=0$)	26.88	4±1 **	–	1.2±0.1 **
LO [111]	31.05±0.1	30.36	6.2±0.2 *	1.57±0.06 * [3]; 1.84 * [4]; 1.2 * [5]	1.52±0.04 *
[0,85, 0, 0]	–	32.26	–	–	–
TO [111]	36.0±0.1	35.98	5.3±0.2 *	1.21±0.06 * [3]; 1.38 * [4]; 0.9 * [5]	1.08±0.03 *
[0,85, 0, 0]	–	34.20	–	–	–

$^*P\lesssim 1.8$ GPa.
$^{**}pP\gtrsim 1.8$ GPa.
***Compressibility data from Ref. 11.

formation on the influence of the pressure on the phonon energy for one more set of points in the Brillouin zone.

On the other hand, the behavior of the LO and TO peaks does not fit the considered scheme, according to which at $P>1.8$ GPa we should observe new singularities analogous to TA' or, at least, a change of the slope $d\omega/dP$ as in the case of the LA phonons.

It appears that the mechanism whereby the singularities corresponding to optical phonons are produced has a more complicated dependence on the band structure and on the degree of degeneracy of the semiconductor. This, in particular, is evidenced also by the behavior of the peak of the optical phonons $O(000)$ with $\mathbf{k}=2\pi/a[000]$, observed in some studies[3,4] and not observed in others,[5,10] including ours. Its appearance is usually connected with the tunneling of the electrons in the Γ_2' state, and their energy, as indicated above, increases very rapidly with pressure, so that its amplitude should decrease sharply, as takes place in Ref. 3 but was not observed in the experiments of Ref. 4. Thus, the cause of the difference in the character of the participation of the acoustic and optical phonons in the tunneling process in germanium remains unexplained.

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Auxiliary surface polaritons in the region of resonance with oscillations in a transition layer

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It is shown that an auxiliary surface wave is produced in the region of a resonance between a surface polariton and oscillations in a transition layer and is due to spatial dispersion with respect to the parameter kd (k is the wave vector of the surface wave and d is the thickness of the transition layer). The law of dispersion of the surface waves is investigated and their propagation lengths are determined. The additional boundary condition is obtained, corresponding to the case of a dielectric film in the vicinity of the resonance of the surface polariton with the frequency of the longitudinal oscillations in the film.

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I. INTRODUCTION

The presence of the so-called transition layer on the surface of a medium or on an interface between media influences the dispersion law of the surface polaritons (SP). Since the dispersion of the SP is presently determined by various methods (the method of attenuated total reflection, Raman scattering, and others), this circumstance uncovers new possibilities of studying the physical properties of the surfaces in thin films.[1] The influence of the transition layer is particularly strong when the frequency ω_0 of the dipole oscillations in the transition layer[1)] lands in the SP frequency—restructuring region. As shown earlier[2] (see also Ref. 1), in this case a gap Δ is produced in the SP frequency spectrum, with a depth of the order of $(d/\lambda_0)^{1/2}$, $\lambda_0=2\pi c/\omega_0$, d is the thickness of the transition layer. This effect of the splitting of the SP dispersion curve, as well as the square-root dependence of Δ on d, was first observed in Ref. 3 for the IR region of the spectrum in a study of SP propagating along a sapphire surface covered with an LiF film ($\Delta\approx 20$ cm^{-1} at $d\approx 100$ Å). The width of the gap increases substantially in the visible part of the spectrum.[4] In the last reference, the splitting effect was observed for SP propagating along an aluminum surface coated with silver films ($d\approx 20-60$ Å). The splitting Δ at $d=26$ Å turns out, in accord with the theory, to be $\approx$ 0.4 eV.

It appears that the resonance of the oscillations in the transition layer with the SP is a rather common phenomenon. In particular, its possible occurrence must be taken into account also in the analysis of the spectra of reflection of light from surfaces of molecular crystals (e.g., anthracene[5]), and also in the study (see Ref. 6) of Fermi resonance with SP.

In view of the foregoing, further study of the dispersion of SP in presence of resonance with oscillations in the transition layer becomes vital, particularly an analysis of the possible effects brought about by allowance for spatial dispersion. For the nonresonant situation this analysis was carried out in the author's earlier paper[1] (see also Ref. 7, where energy dissipation in the transition layer was taken into account with the aid of a certain model). It was shown,[1] in particular, that in the region of the Coulomb frequency ω_s of the surface polariton on the interface with vacuum (the frequency ω_s satisfies the condition $\varepsilon(\omega_s)=-1$, $\varepsilon(\omega)$ is the dielectric constant of the substrate) the transition layer produces an $\omega_s(\mathbf{k})$ dependence linear in the wave vector k of the SP, and this leads to the appearance of an additional surface electromagnetic wave. In the frequency region $\omega\approx\omega_s$, however, the damping is large, and should hinder in particular the propagation of precisely this additional surface wave.

We note in connection with the foregoing that for SP propagating along dielectric surfaces, a rather strong damping can occur not only at $\omega\approx\omega_s$ but also at $\omega<\omega_s$, i.e., for the entire region of the SP spectrum. However, for SP propagating along metal surfaces the situation is, generally speaking, different. Inasmuch as for waves of frequency $\omega\approx\omega_s\approx\omega_p/\sqrt{2}$($\omega_p$) is the frequency of the volume plasmon) the surface-polariton field penetrates markedly into the metal, the SP is strongly damped in this spectral region. In the frequency region $\omega\ll\omega_p/\sqrt{2}$, however, the surface-wave field penetrates only insignificantly into the metal, the damping of the SP is weak, and its propagation length turns out to be macroscopically large (on the order of several centimeters, see Ref. 8; a review of later experiments is contained in the book of Ginzburg and the author[9]). As will be shown below, the relative smallness of the damping is preserved in many cases, and in the region of the resonance of the oscillations in the transition layers with the SP, provided that the frequency of these os-

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