admits of the processes $p + p \to \pi^+\pi^+$, $p + p \to \ell^+ + \nu + \ell^+ + \nu$, $n + n \to \pi^0 + \pi^0$, etc., and also of the oscillating process $n \rightleftarrows \tilde{n}$ in second order in βG. Using the experimental data on the stability of the nucleons in the nucleus [5] and estimating the permissible value of the period of the oscillations of the free neutron at 10^4 sec, we obtain approximately equal limitations in both cases: $\beta < 10^{-9}(m_\kappa/m_p)^{1/2}$. Taking (4) into account we get $\beta < 10^{-7}$ and $(m_\kappa/m_p) > 10^3$. It should be noted that the diagram of the process $n \rightleftarrows \tilde{n}$ diverges, so that the estimate of the corresponding transition probability depends on the employed cutoff momentum (we chose $\Lambda \sim m_p$). The obtained limitations on β and m_κ are still far from the values that should be ascribed to the maximons [6] if the κ particles are identified with them, namely $m_\kappa \sim 10^{19}\, m_p$ and $\beta \sim 10^{-33}$.

It must be emphasized that, in light of the foregoing, searches for the process of baryon-number nonconservation are of great interest, especially searches for the oscillation process $n \rightleftarrows \tilde{n}$.

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[1] A.D. Sakharov, ZhETF Pis. Red. 6, 772 (1967) [JETP Lett. 6, 236 (1967)].
[2] L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1964).
[3] Ya.B. Zel'dovich and I.D. Novikov, Astron. zh. 43, 758 (1966) [Sov. Astron. AJ 10, 602 (1967)].
[4] Ya. B. Zel'dovich and I.D. Novikov, Relyativistskaya astrofizika (Relativistic Astrophysics), Nauka, 1967.
[5] C.C. Giamati and P. Reines, Phys. Rev. 126, 2178 (1962).
[6] M.A. Markov, Zh. Eksp. Teor. Fiz. 51, 878 (1966) [Sov. Phys. JETP 24, 584 (1967)].

INSTABILITY OF INHOMOGENEOUS DEFORMATION AND OF CARRIER DENSITY IN A SEMICONDUCTOR, INDUCED BY A DEFORMATION POTENTIAL

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In an isotropically-elastic medium, in electron-phonon interaction via a deformation potential, the law of dispersion of the charge-acoustical longitudinal waves is given by [1]

$$(s^2k^2 - \omega^2)\left(Dk^2 + \frac{1}{\tau} + i(kv - \omega)\right) - ADs^2k^4 = 0, \quad A = \frac{b^2 n_0 \mu}{e\gamma s^2 D}. \tag{1}$$

The deformation, the carrier density, and the electrostatic potential are assumed to be proportional to $\exp i[\vec{k}\cdot\vec{r} - \omega t]$, s is the velocity of longitudinal sound in the absence of carriers, D, n_0, μ, τ, and $\vec{v}$ are the diffusion coefficient, the equilibrium concentration, the mobility, the Maxwellian relaxation time, and the drift velocity of the carriers, γ is the density of the medium, and b is the constant of the deformation potential.

It is known [2] that when $v > s$ Eq. (1) has roots $k(\omega)$ corresponding to the growth of a sound wave in space or in time (amplification). However, it turns out that when $A > 1$ the growth exists also when $v < s$ and even in the

absence of an external field (v = 0). For example, when $(A - 1)D\omega^2 s^{-2}\tau \ll 1$ and v = 0, Eq. (1) has the roots

$$k = \pm \sqrt{\frac{1 - i\omega\tau}{D\tau(A-1)}} \quad . \tag{2}$$

Given a real ω, both roots correspond to an exponential growth of the wave in space. For a given real k, the displacement of the medium u and the excess concentration $n' \equiv n - n_0$ vary in accordance with

$$\sin(kx + \alpha)\exp\beta t; \qquad \beta \equiv -i\omega = (A-1)Dk^2 - \frac{1}{\tau} \quad . \tag{3}$$

At sufficiently large k^2, β(k) > 0 and u and n' increase in time without limit (instability). At a certain value of $k = k_0$ we have $\beta(k_0) = 0$ and (3) describes static bunching of the crystal density and the carrier density.

The solution (2), (3) is, of course, not an ordinary wave, for there is no energy transfer, group velocity, and so forth. But it is important in what follows that (2) and (3) are solutions of the equations of motion. The remaining two roots of (1), k(ω), represent an ordinary wave of the acoustic type.

The solution of (1) can be simplified in the limiting case $|As^2k^2\tau\beta^{-1}| \ll 1$. To this end it is necessary to substitute in the first of the expressions of (3)

$$\beta = \pm sk\sqrt{\frac{Dk^2\tau(A-1) - 1}{Dk^2\tau + 1}} \quad . \tag{4}$$

When $k < k_0$, β is imaginary and (4) represents an ordinary sound wave with allowance for the electron-phonon interaction. When $k > k_0$, one of the solutions (4) describes an exponential time growth of n' and u.

In the case of a bipolar semiconductor, in the quasineutrality approximation, the dispersion law for v = 0 and $n_0 = p_0$ is

$$(s^2k^2 - \omega^2)\left(Dk^2 + \frac{2}{\tau_r} - i\omega\right) - As^2k^2\left(Dk^2 + \frac{2}{\tau_r}\right) = 0, \quad A = \frac{(b_n + b_p)^2 n_0}{2\gamma s^2 kT}, \tag{5}$$

where D and τ_r are the coefficient of bipolar diffusion and the recombination time, k is Boltzmann's constant, and the indices n and p pertain to electrons and holes.

Certain roots of Eq. (5) also correspond to instability. They can be simplified in limiting cases. For example, when

$$Dk^2 + \frac{2}{\tau_r} \gg |sk(A-1)^{1/2}| \text{ and } A \neq 1$$

we have

$$\beta = \pm sk(A-1)^{1/2} - \frac{As^2k^2}{2\left(Dk^2 + \frac{2}{\tau_r}\right)} + \ldots, \tag{6}$$

when $\left|\frac{sk}{A-1}\right| \gg Dk^2 + \frac{2}{r_r}$ we have

$$\beta = (A-1)\left(Dk^2 + \frac{2}{r_r}\right). \tag{7}$$

When A > 1 Eq. (7) and one of the expressions in (6) describes exponential time growth of n', p', and u. The instability has no lower threshold in this case.

When $b_n + b_p = 20$ eV, $\gamma = 4$ g/cm^3, $s = 2 \times 10^5$ cm/sec, and kT = 0.025 eV, the value of A reaches approximately unity at $n_0 = 1.25 \times 10^{19}$ cm^{-3}. Consequently, an increase of the donor concentration or of the temperature in a stable crystal can cause A to reach a value unity and the crystal to lose stability. The thermodynamic potential of a monopolar nondegenerate semiconductor, in the case of total ionization of the donor, at a fixed arbitrary deformation, is given by

$$\Phi = \int \left\{ \frac{\gamma s^2}{2} (div\, u)^2 + b_n n \operatorname{div} u + \right.$$

$$\left. + \frac{e\phi n'}{2} + (E + \zeta)n - kT\left[n_0 \ln 2 + n - n \ln \frac{n}{2}\left(\frac{2\pi\hbar^2}{m^* kT}\right)^{3/2}\right] \right\} dv; \tag{8}$$

$$\Delta\phi = -4\pi e n'$$

where E is the dissociation energy and ζ the chemical potential of the carriers. The equilibrium conditions (minimum of Φ, u, and n), together with the Poisson equation, lead after linearization to the equation $\Delta^2\phi + k_0^2\phi = 0$. Its solutions, for example C sin $k_0 r$ or $C(\sin k_0 r)/r$(A > 1) show that there can exist in the crystal static bunching of ϕ, n', and u with arbitrary amplitude C. This is the consequence of the fact that the linear and quadratic terms vanish in the expansion of external Φ in powers of n' or u. The aforementioned indifferent equilibrium states relative to the amplitude C may vanish in the nonlinear theory that retains the higher powers of n' and u in (8). This leads to the following results: a) Φ as a function of the bunching amplitude can have a minimum greatly exceeding the lattice constant k even at k^{-1}. In this case stable bunchings(domains) occur with a definite amplitude even in the region where the macroscopic theory is valid. b) The system may not be in equilibrium at all in the region where the macroscopic theory holds. In this case it is most likely that a phase transition will occur in the crystal. The tendency to this phenomenon is seen from formula (3), which shows that the larger k the larger the growth increment. If the initial arbitrary fluctuation is expanded in a Fourier integral in terms of the functions (3), then harmonics with maximum k will begin to predominate with increasing t, i.e., bunching with a period on the order of the lattice constant takes place.

The possibility that the metal becomes unstable when A exceeds a certain critical value was first noted in [3], and later in [4]. It follows also from formula (14) of [5]. In [4, 5] there were obtained almost identical dispersion laws $\omega(k)$. They differ appreciably from all those given above, with the exception of the result (6), which they approach when $k^{-1} \gg d$ (if we disregard the fact that A in (6) pertains to the bipolar and therefore nondegenerate case). The closeness of these results is due to the fact that quasiacoustic branches are consirered and the quasineutrality approximation is used in both cases. The solutions (3) and (7) pertain to concentration waves, and there is no quasineutrality in (4); these results therefore have no analogs in [4, 5].

[1] A.A. Demidenko, S.I. Pekar, V.N. Piskovoi, and B.E. Tsekvava, Zh. Eksp. Teor. Fiz. 52, 715 (1967) [Sov. Phys.-JETP 25, 470 (1967)].
[2] C. Weinreich, Phys. Rev. 104, 321 (1956).
[3] G. Wentzel, Phys. Rev. 83, 168 (1952).
[4] S.V. Tyablikov and V.V. Tolmachev, Zh. Eksp. Teor. Fiz. 34, 1254 (1958) [Sov. Phys.-JETP 7, 867 (1958)].
[5] A.B. Migdal, ibid. 34, 1438 (1958) [7, 996 (1958)].

ERRATA

In the article by I. Ya. Krasnopolin and M. S. Khaikin, Vol. 12, No. 2, p. 55, the points of Fig. 2 should be identified as follows: o - from measurements of $\partial X/\partial H + \beta\partial R/\partial H$, ● - from measurements of $\partial R/\partial H + \beta\partial X/\partial H$.

In the article by V. I. Shtyrkov, Vol. 12, No. 3, p. 93, formula (2) should read

$$K_\nu = \sigma_{21} N_0 \frac{g_2}{g_1} \left\{ \left(1 + \frac{g_2}{g_1}\right) \frac{B_{21}(\nu)\rho\left[1 - \exp(-A\tau_0)\right]}{A} - 1 \right\}, \qquad (2)$$

In the title of the article by Yu. P. Mukhtorov and V. I. Pustovoit, Vol. 12, No. 3, p. 106, the word "photon" should be replaced by "phonon."