Possibility of obtaining low temperatures with the aid of ultrasound

Yu. V. Gulyaev and A. G. Kozorezov

Institute of Radio Engineering and Electronics, USSR Academy of Sciences
(Submitted April 4, 1975)
ZhETF Pis. Red. **21**, No. 10, 572–574 (May 20, 1975)

It is shown that passage of an ultrasonic wave through the boundary between two semiconductors can cool this boundary.

PACS numbers: 72.50., 73.40.L

It is known that when electric current flows through a contact between two conductors, cooling of the contact can take place (the Peltier effect). In this article we show that passage of an ultrasonic (acoustic) wave through the boundary between two conducting solids can also lead to cooling of this boundary, although there is no flow of electric current through the boundary.

For the sake of argument, we consider the boundary between two degenerate n-type piezoelectric semiconductors (such as InSb, GaAs, etc.) 1 and 2 (see the figure), perpendicular to which there propagates a wave of frequency f, wave vector $q \parallel Ox$, and intensity S. We consider the case $ql \ll 1$ (l is the electron mean free path) and neglect completely the heating of the electron gas in the field of the sound wave. The symmetrical part of the electron distribution function can then be regarded as a Fermi distribution with local lattice temperature T and chemical potential $\xi(x,t) = \xi_0 + \xi_1(x,t)$, where ξ_0 is the equilibrium value of the Fermi level and ξ_1 is an alternating increment to this level, due to the formation of electron bunches in the field of the sound wave (see[1]). Inasmuch as at low temperature the kinetic coefficients can be greatly influenced by the mutual dragging of the electrons and thermal phonons (see, e.g.,[2]), the system of fundamental equations of our problem consists of the standard system (the elasticity, Poisson, and current-continuity equations as well as the kinetic equation for the electrons, see, e.g.,[3]) plus the kinetic equation for the thermal phonons that interact with the electrons dragged by the external sound. We solve this system by iterating with respect to the amplitudes of the acoustic wave, and obtain expressions for the acoustoelectric current and for the energy fluxes carried by the sound-dragged electrons themselves, Q_e, and by the thermal phonons dragged via the electrons, Q_{ph}. We shall consider the case of an open-circuited sample, when the acoustoelectric current through the boundary is equal to zero. In the expression for the total energy flux $Q = Q_e + Q_{ph}$ accurate to terms of order $(kT/\xi_0) \ll 1$ and $(v_s/v_F) \ll 1$ (v_s is the speed of sound and v_F is the Fermi velocity) takes the form

$$Q = -\kappa \nabla T - \frac{1}{3}\frac{v_F}{v_s} l_F \Gamma S\left(1 - \frac{m v_s^2}{3kT}\right), \qquad (1)$$

Here Γ is the sound absorption coefficient, κ is the total thermal conductivity of the crystal (lattice κ_L + electronic κ_l) with allowance for the effective mutual dragging of the electrons and thermal phonons. l_F is the mean free path of the Fermi electrons without allowance (!) for the dragging effect, m is the effective mass of the electrons, and

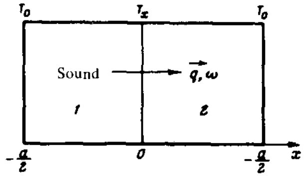
$$l = \frac{3}{8p_F^3}\int_0^{2p_F} dq\, q^2 [L(q)/L_e(q)] \lesssim 1.$$

(p_F is the Fermi momentum, while $L(q)$ and $L_e(q)$ are respectively the total phonon mean free path and the free path of the phonons scattered by the electrons). It is easy to see that down to very low temperatures (on the order of 0.001 °K) the second term in the round bracket in (1), which is connected with dragging of thermal phonons, can be neglected, as we shall do from now on.

It is next necessary to solve for each of the contacting semiconductors the equation of continuity of the energy flux, with allowance for the absorption of part of the sound wave in the volume and its conversion into heat. It is necessary here to specify the concrete dependence of the thermal conductivity κ on the temperature, and the corresponding boundary conditions. Using the boundary conditions as shown in the figure, and a power-law-temperature dependence of the thermal conductivity, $\kappa(T) \sim T^n$, we obtain for the temperature of the boundary between the semiconductors

$$T_x = T_0\left\{1 + \frac{\Gamma_1\left(\frac{a}{2} + \frac{l_{F1}}{3}\frac{v_{F1}}{v_{s1}}\right) + \Gamma_2\left(\frac{a}{2} - \frac{l_{F2}}{3}\frac{v_{F2}}{v_{s2}}\right)}{\frac{T_0}{na}\left[\kappa_1(T_0) + \kappa_2(T_0)\right]} S\right\}^{1/n}, \qquad (2)$$

where a is the length of the semiconductors in the direction of sound propagation, and the subscripts 1 and 2 pertain respectively to the first and second materials.



It is easy to see that if the condition

$$\Gamma_2 \frac{l_{F2}}{3}\frac{v_{F2}}{v_{s2}} > \Gamma_2\frac{a}{2} + \Gamma_1\left(\frac{a}{2} + \frac{l_{F1}}{3}\frac{v_{F1}}{v_{s1}}\right),$$

is satisfied, then the second term in the curly bracket of (2) is negative and the boundary begins to cool down. We assume by way of estimates that material 1 has a small sound absorption ($\Gamma_1 \to 0$) and material 2 is doped n-InSb with $n_0 \approx 10^{18}$ cm^{-3} $\mu = 10^6$ cm^2/V-sec, and a = 1 cm at $T_0 = 0.1$ °K. Then, assuming that the scattering of the thermal phonons takes place predominantly on the electrons ($\kappa \approx \kappa_L \approx 10^{-6}$ W/cm-deg), and choosing a sound frequency $f = 30$ MHz, we find that the second term in the curly bracket of (2) becomes of the order of -0.1 at a sound intensity $s \approx 1$ W/cm^2.

We note finally that formula (2) and the estimates made are valid under the condition $(\xi_1/kT) \ll 1$. Therefore, if the temperature drops to such an extent that this condition is not satisfied, it is necessary, to find the temperature of the boundary, to solve the nonlinear problems when $\xi_1 \approx kT$.

The authors are most grateful to M.I. Kaganov, I.M. Lifshitz, and É.L. Nagaev for a discussion of the work and for many valuable remarks.

[1]Yu.V. Gulyaev, Fiz. Tverd. Tela 8, 3366 (1966) [Sov. Phys.-Solid State 8, 2687 (1967)].
[2]A.I. Ansel'm, Vvedenie v teoriyu poluprovodnikov (Introduction to the Theory of Semiconductors), Fizmatgiz (1962).
[3]Yu.V. Gulyaev and É.M. Épshtein, Fiz. Tverd. Tela 9, 864 (1967) [Sov. Phys.-Solid State 9, 674 (1967)].