CONDUCTIVITY OF HgTe CRYSTAL UNDER CONDITIONS OF ELECTRON AND PHONON HEATINGS

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The conductivity of HgTe at low lattice temperature is studied. It is shown that longwave acoustic phonons in HgTe are heated strongly and it is necessary to take into account their heating. The dependence of electron concentration on electric field in calculated. The results are compared with experimental data.

In the papers [1,2] the conductivity of HgTe at liquid helium temperature has been studied experimentally and a nonlinearity of current-voltage characteristic has been observed. It is shown that under conditions of the experiments [1,2] the heating of electrons does not influence its mobility μ_n. However, the nonlinearity is related to increase of the concentrations of electrons and holes in the electric field.

Theoretically the nonlinearity in the HgTe was studied in the papers [2-5]. It was shown that under conditions of experiments [1,2] heating both of electrons and holes ($T_e \approx T_h > T$, T is the lattice temperature) [3] and longwave (LW) optic phonons also ($T_0 \approx T_e$) [4] takes place. In the papers [2-5] it was assumed that LW acoustic phonons (which interact with electrons and holes) were in heat equilibrium with the lattice. In the present paper it is shown that in HgTe at low lattice temperature (in particular, under conditions of experiments [1,2]) LW acoustic phonons are heated strongly, and it is necessary to take into account their heating.

The basic equations of the problem are equation of neutrality and energy balance equation. We assume that the acceptor concentration is sufficiently small and all the donors in HgTe are ionized [2]. In this case equation of neutrality has the form $p+N_d=n$, where N_d, n and p are the concentrations of donors, electrons and holes, respectively. Let us assume that the equivalent electrochemical potential of electrons $\eta=\xi/T_e>1$, i.e. the electron gas is strongly degenerated and the hole gas is nondegenerated. In this case:

$$n=\frac{(2m_n\xi)^{\frac{3}{2}}}{3\pi^2\hbar^3}\left(1+\frac{\pi^2}{8\eta^2}\right)\quad,\quad p=\frac{\left(2m_pT_e\right)^{\frac{3}{2}}}{4\pi^{\frac{3}{2}}\hbar^3}e^{-\eta}\qquad(1)$$

The energy balance equation has the form $\sigma E^2=W_a+W_0$, where σ is the conductivity, E is the electric field strength, W_a and W_0 are the energy losses of electron-hole gas due to scattering at acoustic and optic phonons, respectively. The energy loss W_0 was calculated in the paper [4], and W_a is calculated in the present paper.

We assume that for the LW acoustic phonons the distribution function has the form of the Planck distribution with the temperature T_f [6]. Calculations show that the energy of electron-hole system is transferred to acoustic phonons mainly by holes and

$$W_a=\frac{8\sqrt{2}m_p^{\frac{5}{2}}}{\pi^{\frac{3}{2}}\hbar^4\rho}\left(\frac{1}{2}a^2-ab+\frac{5}{4}b^2\right)pT_e^{\frac{1}{2}}\left(T_e-T_f\right).\qquad(2)$$

where a and b are the constants of the deformation potential [4], ρ is the mass density of the crystal.

LW acoustic phonons transfer the energy obtained from electrons and holes to the thermostat. Under conditions of experiments [1,2] main mechanism of energy scattering of LW acoustic phonons is scattering by the crystal boundaries. In this case scattering energy is

$$W_{s,f}=\frac{16\sqrt{2}m_p^{\frac{5}{2}}}{\pi^2\hbar^4\rho}\left(\frac{1}{2}a^2-ab+\frac{5}{4}b^2\right)pT_e^{\frac{1}{2}}\left(T_e-T_f\right).\qquad(3)$$

where ρ_f is the mass density of liquid He, s_f is the sound velocity in He, L is the size of the sample. At equilibrium conditions $W_a= W_{s,f}$. In this case from (2) and (3) we obtain:

$$\frac{T_e-T_f}{T_f-T}=\frac{2}{\sqrt{\pi}}\frac{\hbar\rho_f s_f T_e}{m_pL\rho}\left(\frac{1}{2}a^2-ab+\frac{5}{4}b^2\right)^{-1}.\qquad(4)$$

For the HgTe placed into liquid He it follows from (4) that $T_e-T_f<<T_f-T$, i.e. $T_f\approx T_e$. So, in HgTe at low lattice temperature the LW acoustic phonons are in the state of heat equilibrium with heated electrons and holes, and one cannot consider them to be a part of the thermostat. "Narrow throat" for the scattering of the electron energy by acoustic phonons is the channel by which the energy is transferred from the acoustic phonons to liquid He.

For HgTe the conductivity is $\sigma=en\mu_n+ep\mu_p\approx en\mu_n$. In order to determine conductivity $\sigma(E)$ or concentration of electrons $n(E)$ as a function of electric field E (mobility of electrons μ_n is considered as a parameter taken from the experiment) one must determine at first $\xi(E)$ and $T_e(E)$. The concentration of donors is determined from the value of electron concentration $n(0)$ in the absence of the electric field. From the equations of neutrality and energy balance we obtain the following set of equations:

$$\frac{(2m_pT)^{\frac{3}{2}}}{4\pi^{\frac{3}{2}}\hbar^3}\theta^{\frac{3}{2}}e^{-\eta}+N_a=\frac{(2m_nT)^{\frac{3}{2}}}{3\pi^2\hbar^3}\theta^{\frac{3}{2}}\eta^{\frac{3}{2}}\left(1+\frac{\pi^2}{8\eta^2}\right),$$

$$e\mu_nE^2\frac{(2m_nT)^{\frac{3}{2}}}{3\pi^2\hbar^3}\theta^{\frac{3}{2}}\eta^{\frac{3}{2}}\left(1+\frac{\pi^2}{8\eta^2}\right)=\frac{16\sqrt{2}}{\pi^2\hbar^3}\frac{\rho_l s_l m_p^{\frac{3}{2}}T^{\frac{5}{2}}}{L\rho}\theta^{\frac{3}{2}}(\theta-1)+ \quad (5)$$

$$+\frac{2^{\frac{3}{2}}\hbar^{\frac{1}{2}}m_p^{\frac{3}{2}}}{3\pi^3\rho a_0^2}\omega_l^{\frac{3}{2}}(\omega_l-\omega_t)(s_l^{-2}+2s_t^{-2})\left(e^{\frac{-\hbar\omega_l}{T\theta}}-e^{\frac{-\hbar\omega_l}{T}}\right),$$

where $\theta=T_e/T$, a_0 is the lattice constant, ω_l and ω_t are the frequencies of optic phonons, s_l and s_t are the velocities of longitudinal and transverse sound in the crystal respectively. The numerical solution of equation set (5) gives the dependences on θ and η versus the field E. The calculations are provided using the following values of parameters [4]: $m_n=0.03m_0$, $m_p=0.5m_0$, $\hbar\omega_l=0.017$ eV, $\hbar\omega_t=0.015$ eV, $s_l=2.8\cdot10^5$ cm/s, $s_t=1.6\cdot10^5$ cm/s, $s_l=1.8\cdot10^5$ cm/s, $a_0=6.5\cdot10^{-8}$cm, $\rho=8.1$gm/cm^3, $\rho_l=0.114$gm/cm^2, $a=2.7$eV, $b=-1.3$ eV. The values of $T=4.2$ K, $n(0)=2\cdot10^{15}$ cm^{-3}, $\mu_n=10^5$ cm^2/V·s, $L=0.01$ cm are taken from the experiments [1,2].

The results of calculations for the $\theta(E)$ and $\eta(E)$ show that the electron-hole system is heated significantly at the values of field $E \geq 0.1$ V/cm. Inclusion of energy loss cannel due to the scattering by optic phonons occurs at $E \geq 1$ V/cm ($\theta \geq 3$). The theoretical dependences $\theta(E)$ on $\eta(E)$ and are shown in Fig.1. In Fig.2 the dependence on electron concentration $n(E)$ obtained from the (1) and (5) is shown as a function of field E. Experimental results of works [1,2] are also shown here. The comparison of theoretical dependence with experimental results shows that the theory satisfactorily describes the experiment. However, there is some difference at the weak electric fields. This difference may be related to possible role of acceptors in the experiments [1,2].

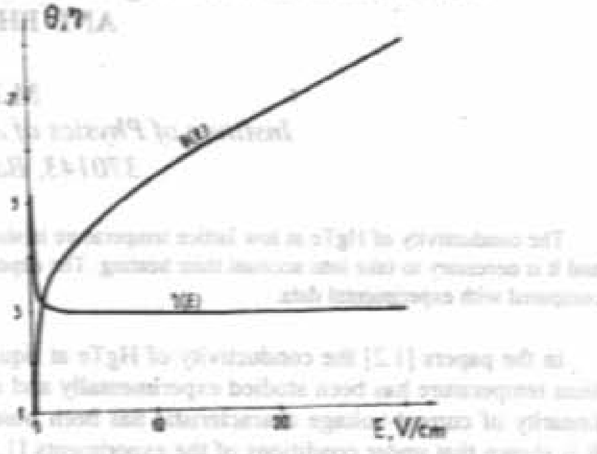

Fig.1. The dependence of nondimensional electron temperature θ and equivalent electrochemical potential η on the electric field E.

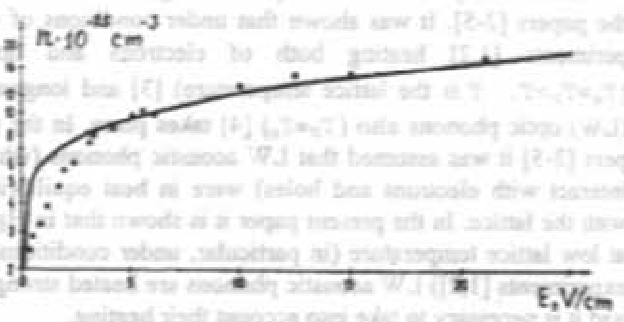

Fig.2. The dependence of electron concentration n on the electric field E. The line is theory date, points are experiments ones.

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ELEKTRON VƏ FONONLARIN QIZDIĞI ŞƏRAİTDƏ HgTe KRİSTALININ ELEKTRİK KEÇİRİCİLİYİ

Nəzəri olaraq qəfəsin aşağı temperaturlarında HgTe kristalının elektrik keçiriciliyi öyrənilmişdir. Uzundalğalı akustik fononların elektron temperaturuna qədər qızması və bu qızmanın elektrik keçiriciliyinin hesablanmasında nəzərə alınmasının zəruriliyi göstərilmişdir. Elektronların konsentrasiyasının elektrik sahəsinin intensivliyindən asılılığı hesablanmışdır. Təcrübi nəticələrlə müqayisə aparılmışdır.

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ЭЛЕКТРОПРОВОДНОСТЬ КРИСТАЛЛА HgTe В УСЛОВИЯХ РАЗОГРЕВА ЭЛЕКТРОНОВ И ФОНОНОВ

Теоретически изучена электропроводность HgTe при низких температурах решетки. Показано, что длинноволновые акустические фононы разогреваются до температуры электронов и учет их разогрева необходим. Рассчитана зависимость концентрации электронов от напряженности электрического поля. Проведено сравнение с экспериментальными данными.

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