

Establishment of temperature in dielectric glasses below 1 K

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The process of establishing the temperature in a system of two-level centers + phonons is discussed. It is shown that the time for establishing the temperature is very large (at $T \simeq 0.2$ K it is about 10 ms).

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The problem of how two-level centers, responsible for the linear heat capacity of dielectric glasses below 1 K, interact with phonons has recently been widely discussed.

This interaction is characterized by the width Γ of the upper level relative to the transition into the lower level with emission of a phonon. According to the tunneling model,^{1,2} for centers with fixed splitting ϵ there is a wide spectrum of values of Γ ; in this case, the maximum value $\Gamma_0 = \alpha \epsilon \operatorname{cth}(\epsilon/2T)$, where the small parameter $\alpha \cong (\Xi^2 / M_0 s^2) \rho a_0^3$ is expressed in terms of the constant of the deformation potential Ξ , mass and volume of the unit cell M_0 and a_0^3 , the velocity of sound s , and the phonon density of states ρ at $\omega = \epsilon$, while the minimum Γ remains undetermined.

Attempts to obtain information on the distribution of centers over Γ are based on measuring the so-called “fast heat capacity,” i.e., actually the dynamics of cooling of specimens over short times.^{3–8} The interpretation of experiments implicitly assumes that phonons injected into the glass, instantaneously thermalize and transfer their

temperature to the centers and, in addition, centers with $\Gamma^{-1} \lesssim t$, equilibrate with phonons over a time t . Meanwhile, it is well known that the process of establishing the phonon temperature T in insulators at low temperatures is very slow.⁹ The thermalization time t_T due to anharmonic processes (decay and coalescence) can be estimated from the spontaneous decay time $\tau_a^{-1} \cong \gamma \omega_D \cdot (\omega/\omega_D)^5$ for thermal phonons $\omega \cong T$: Here ω_D is the Debye temperature and the adiabatic parameter $\gamma \cong \omega_D/M_0 s^2 \cong 10^{-2}$. Assuming that $\omega_D = 400$ K and $T = 0.2$ K, we obtain $t_T \cong 10^4$ s. Thus the anharmonic processes are excluded even in the longest experiments,⁸ where $t < 10^4$ s.

In connection with what was said above, it is interesting to understand how equilibrium is established and to determine the times at which we can begin to talk about the temperature of the glass.¹⁾ First, it is clear that if the temperature is established over the time of the experiment, then this occurs via centers and the temperature established in this manner describes both phonons and centers.

The fastest processes of interaction of centers and phonons are resonant absorption of a phonon by an unexcited center and emission of a phonon by an excited center. The lifetime of a phonon relative to resonant absorption is $\tau_r^{-1} = c\omega h(\omega/2T)$, where $c \cong (\Xi^2/M_0 s^2)ga_0^3$, and g is the density of states for centers. A typical value is $c \cong 10^{-3}$, so that for a thermal phonon $\omega \cong T = 0.2$ K, we have $\tau_r \cong 0.1 \mu\text{s}$. In order to estimate Γ_0 , we shall write $\alpha \cong \gamma^{-1}(\epsilon/\omega_D)^2$, which for a thermal center with $\epsilon \cong T = 0.2$ K gives $\alpha \cong 10^{-4}$ and $\Gamma_0^{-1} \cong 1 \mu\text{s}$. For sufficiently low temperatures $\Gamma_0^{-1} \gg \tau_r$, i.e., trapping of phonons occurs: A phonon is rapidly absorbed and its energy ω exists for a long time in the form of an excited center with $\epsilon = \omega$.

Over the time $\tau_r + \Gamma_0^{-1}$ energy is exchanged between phonons and centers, but the processes indicated do not change the spectral composition of the phonons and the distribution of centers with respect to ϵ ; for this reason, they cannot thermalize the centers + phonons system. The temperature is established much more slowly due to higher-order processes in α and c , for example, due to de-excitation of a center ϵ with emission of two phonons (both with frequency $\omega \cong \epsilon/2$). The maximum width relative to such a process is easy to estimate; it is $\Gamma'_0 \cong \alpha^2 \epsilon$. If resonant absorption of a phonon ω occurs, followed by de-excitation of the absorbing center with the emission of two phonons ω_1 and ω_2 , then this is equivalent to the decay of a phonon $\omega \rightarrow \omega_1 + \omega_2$ over a time $\tau_r + \Gamma_0^{-1}$, and, in addition, the de-excitation, as a second-order process, is the bottleneck. Phonons combine when two phonons ω_1 and ω_2 are absorbed by a single center, which then emits a single phonon $\omega = \omega_1 + \omega_2$. The effective anharmonicity that arises is described by the rate of spontaneous decay $\Gamma'_0 \cong \gamma^{-2} \omega_D \cdot (\omega/\omega_D)^5$, which is a factor $\gamma^{-3} \cong 10^6$ more rapid than the real τ_a^{-1} .

Amplification of the effective anharmonicity compared to the seed value can be explained as follows. The seed anharmonicity in an insulator arises due to polarization of atomic shells, whose excitation energies are of the order of the atomic energy; the effect of anharmonicity can be understood as arising due to the polarization of two-level centers, whose excitation energy is much lower.

The other possible mechanism for energy exchange is inelastic scattering of a phonon with excitation or de-excitation of a center. The lifetime of a thermal phonon relative to such a process (with a transfer of energy of the order of T to the center) is

also easy to estimate; it is $\tau_s^{-1} \cong c\alpha T$. Under the conditions of capture, when $c \gg \alpha$, we have $\tau_s^{-1} \gg \Gamma'_0$. However, under these conditions τ_s cannot be viewed as the time for establishing equilibrium. The probability for a phonon to scatter inelastically over the lifetime τ_r is $\tau_r/\tau_s \cong \alpha$. For this reason, inelastic scattering will occur only after α^{-1} acts of reabsorption of the phonon, i.e., after a time $\alpha^{-1}\Gamma_0^{-1} \cong \Gamma_0'^{-1}$. In other words, the effective time of inelastic scattering of a phonon is the same as the time for two-phonon de-excitation.

Thus all second-order processes involved in the interaction of centers and phonons lead to thermalization of phonons over a time $t_T \cong \gamma^2 \omega_D^{-1} (\omega_D/T)^5$, which at $T = 0.2$ K gives $t_T = 10$ ms. This thermalization occurs with the participation of centers with $\Gamma \cong \Gamma_0$, but over this time the established temperature T will be imparted to all centers with $\Gamma^{-1} \ll t_T$; the remaining centers with $\Gamma^{-1} \gg t_T$ will be thermalized already after the phonon temperature is established.

The discussion above indicates that the concept of a rapid heat capacity as a function of temperature $C(T, t)$ is meaningful only for $t \gg t_T$, so that by measuring $C(T, t)$ it is possible to study only centers with $\Gamma^{-1} \gg t_T$. This is precisely the situation in experiments^{5,8} performed over times $t \gtrsim 0.1$ s. The estimates of the time t_T made above raise doubts about the interpretation of experiments^{3,4,6,7} performed at shorter times $t \cong 1 \div 100$ μ s and, possibly, explain their contradictory results.

In connection with the aforementioned effective anharmonicity, we note the following. A number of experiments¹⁰⁻¹³ indicate that near the surface of perfect crystals there exists some unknown mechanism of inelastic phonon scattering. On the other hand, near the surface there always exists an imperfect layer of the crystal which contains a large number of dislocations, i.e., a substantially amorphous layer, possibly containing an appreciable number of two-level centers. If this is the case, then inelastic scattering of phonons at the surface can be explained by the effective anharmonicity arising due to the two-level centers. Two-level centers near the surface were used to explain the Kapitsa jump.¹⁴

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¹¹The Planckian distribution of phonons injected from films, after being distributed over the glass, is multiplied by some factor less than 1; we recall that such a distribution is not an equilibrium distribution: the temperature characterizing it is only a "color temperature."

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