Kh. S. Bagdasarov, V. B. Braginskiĭ, V. I. Panov, and V. S. Il'chenko. *Anomalously low dissipation of electromagnetic waves in perfect single-crystal dielectrics.* Measurements of the dissipation of electromagnetic waves in crystalline dielectrics yield important information on the mechanisms of dielectric relaxation. The value of this information stems from the fact that there is as yet no complete theory which permits predicting the value of $\tan\delta$ of a crystal with known composition and structure. The published experimental data on $\tan\delta$ of crystals are often contradictory. For leucosapphire α-Al_2O_3 (the best of the known uhf dielectrics), different authors present estimates of $\tan\delta$ ranging from $1.5\cdot10^{-3}$ to $1.5\cdot10^{-5}$ at $T=300$ K.[1-3] On the other hand, a detailed analysis of phonon relaxation, performed by V. L. Gurevich,[4,5] shows that the dielectric losses in leucosapphire—a centrosymmetric hexagonal ionic crystal—must amount at $T=300$ K to $\tan\delta\approx10^{-6}$ at a frequency of $f=10^{10}$ Hz and decrease with the temperature as T^5. This conflict between the experimental and theoretical estimates is apparently attributable to imperfection of the experimental techniques and the characteristics of the samples used.

An improvement of the technology for growing single crystals stimulated the authors to undertake detailed measurements of $\tan\delta$ of leucosapphire over a wide range of temperatures. The first measurements, performed in 1977,[6] showed that for sapphire single-crystals obtained by the method of progressive freezing one has $\tan\delta<2\cdot10^{-8}$ at $T=2$ K and $f=3\cdot10^9$ Hz. A refinement of these measurements, performed in superconducting resonators (SCR), made it possible to decrease the upper limit on the losses to $\tan\delta<1.5\cdot10^{-9}$.[7,8] This estimate, much lower than the values known for other dielectrics, was confirmed in 1983 by Strayer *et al.*[9]

The SCR technique used in Refs. 6–9 is limited to a narrow temperature range. For this reason, the idea of using ring-shaped dielectric resonators with total internal reflection to measure small losses, proposed by V. F. Vzyatyshev in 1963,[10] was used in subsequent measurements. The Q factor of such resonators is determined by the value of $\tan\delta$ of the resonator material as well as by additional losses associated with the possible contamination of the surface and dissipation of electromagnetic energy:

$$Q^{-1}\approx \operatorname{tg}\delta+(\Delta V/V)\,(\operatorname{tg}\delta)_{\rm sur}+Q^{-1}_{\rm dis};$$

where ΔV is the volume of surface contamination, V is the volume of the resonator, $(\tan\phi)_{\rm sur}$ is the tangent of the loss angle for the material on the surface, and $Q_{\rm dis}$ is determined by the total dissipation of energy associated with the finiteness of the dimensions and irregularity of the resonator (smooth inhomogeneities and protuberances) and the block structure of the crystal. The calculations[11] show that the quality of modern sapphire single-crystals permits realizing a measurement sensitivity of $\tan\delta\lesssim10^{-10}$ even with moderate requirements on the technology of preparation of the resonators. New experimental estimates of losses in α-Al_2O_3 at a frequency of $f\approx10^{10}$ Hz were obtained by this method[12]: $\tan\delta\lesssim4\cdot10^{-6}$ at $T=300$ K, $\tan\delta\lesssim1.6\cdot10^{-8}$ at $T=78$ K, and $\tan\delta\lesssim1.6\cdot10^{-9}$ at $T=10$ K. Detailed development of the ring-shaped dielectric resonator method has enabled the specification of the conditions for obtaining high sensitivity of measurements of $\tan\delta$.

It has been established, for example, that in order to reduce radiation losses to the level $Q_{\rm dis}{}^{-1}\approx10^{-9}$ it is sufficient to specify the geometrical shape and the smoothness of the surface with an accuracy of $\Delta d/d\lesssim5\cdot10^{-3}$ ($\Delta d/d$ is the relative size of the geometric irregularities). The reduction of surface-contamination effects to the same level requires long (many hours) treatment of the resonator in heated corrosive media and careful oil-free evacuation of the cryostat.

The authors performed detailed measurements of the temperature dependence of the Q factor of ring-shaped leucosapphire resonators in the range 3.5–300 K at a frequency of $f\approx1\cdot10^{10}$ Hz (see Fig. 1). In the range 60–250 K, the behavior of Q^{-1} follows with high accuracy the dependence $\tan\delta\sim T^{5\pm0.3}$, predicted by V. L. Gurevich for hexagonal crystals.[4,5] This result, in our opinion, can be viewed as a confirmation of the determining role of fundamental loss

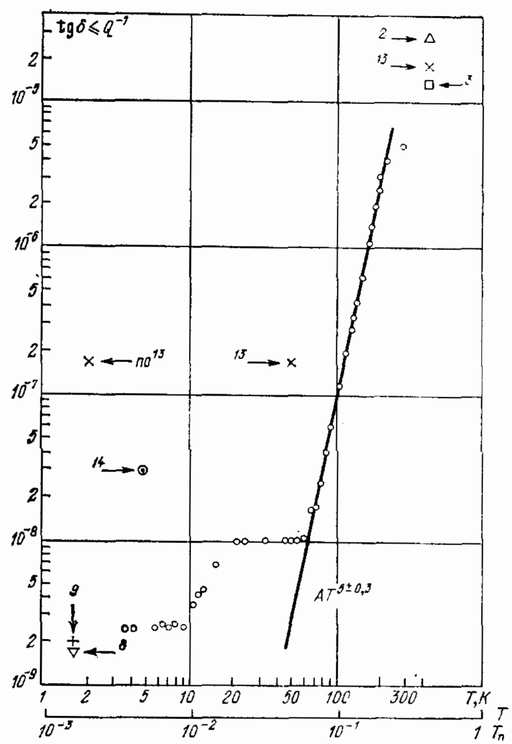

FIG. 1.

mechanisms in this temperature range. As the temperature is decreased, two plateaus clearly appear ($Q^{-1} \simeq 2.5 \cdot 10^{-9}$ for 3.5 K $\lesssim T \lesssim$ 10 K and $Q^{-1} \approx 1 \cdot 10^{-8}$ for 25 K $\lesssim T \lesssim$ 60 K). The deviation from the law $\tan\delta \sim T^5$ for $T < 60$ K is apparently attributable to defects and impurities in the single-crystals used.

It may be expected that as the perfection of the single crystals is further improved it will be possible to eliminate the nonfundamental loss mechanisms for $T < 60$ K and to achieve $Q \approx 10^{12}$ at the temperature of liquid helium. Such losses would make it possible to perform a number of interesting physical experiments.

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