O. G. Vendik. *Ferroelectric films (soft-mode dynamics, microwave applications).* The development of solid-state physics has historically followed a pattern in which a transition is made at a certain stage from study of bulk specimens to study of films. The properties of ferroelectric films at $T > T_c$ in microwave fields are of considerable interest both for the physics of ferroelectrics and for technical applications in microwave devices. The research on ferroelectrics done by I. V. Kurchatov and B. M. Vul, the originators of the ferroelectrics trend in solid-state physics, advanced in direct relation to their practical applications in electronics. The work of G. A. Smolenskiĭ's school made a major contribution to practical applications as well as to the physics of ferroelectricity.

Figure 1 shows curves of the dielectric constants of bulk and film $SrTiO_3$ and of $(Ba,Sr)TiO_3$ solid-solution specimens plotted against temperature at various constant displacement fields.[1-3] These experimental data show that the ferroelectric phase transition is less sharply defined in the film than in the bulk specimen. The difference between the dielectric properties of the thin layer and those of the bulk specimen is usually known as the size effect. In addition to the obvious role of spatial dispersion in the size effect, carriers present in the ferroelectric may also be a factor.

The presence of carriers in the ferroelectric film is manifested through the diffusion current. The influence of the diffusion current in combination with the nonlocal coupling between the ferroelectric polarization and the electric field has been taken into account on the basis of the following model, which holds for $T > T_c$:[4]

1. The ferroelectric polarization is nonlocally coupled with the field that excites it. Correcting for nonlocal coupling on the basis of V. L. Ginzburg's correlation-energy ideas leads to second-order differential equations for the polarization vector.

2. The coupling of the diffusion current to the field and induction is also described by a second-order differential equation.

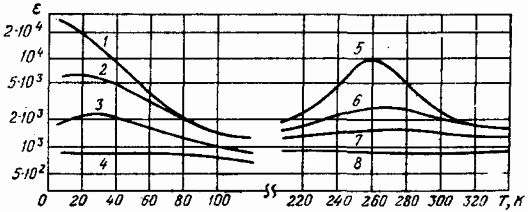

FIG. 1. Dielectric permittivity of bulk specimens and films of ferroelectrics vs. temperature and displacement-field strength. 1, 2—$SrTiO_3$ single crystal; 3, 4—$SrTiO_3$ ceramic film on BeO base; 5, 6—bulk specimen of ceramic $(Ba_{0.6}Sr_{0.4})TiO_3$; 7, 8—film specimens of the same ceramic on a BeO base. 1, 3, 5, 7—$E_{disp} = 0$; E_{disp} [kV] = 2 (2), 20 (4, 6) and 50 (8).

3. All equations are linearized with respect to the applied field and to the response in the form of polarization and the diffusion current, and the variable quantities vary harmonically in time.

4. The boundary conditions are zero polarization vector at the surface of the ferroelectric crystal[5] and the following relation for the normal induction-vector component:

$$D_n + \varkappa \frac{\partial D_n}{\partial x_n} = 0.$$

Possibilities exist for experimental determination of the parameter $\varkappa$ and for study of the effects of the surface-treatment technology applied to the ferroelectric film on the value of this parameter.

If the electric field is normal to the film surface, the relations obtained can be used to calculate the shift of the effective Curie temperature as a function of film thickness and the dependence of $\varepsilon_{\rm eff}$ on the frequency at which the measurement is made.[6] A series of measurements made on single-crystal $SrTiO_3$ films made it possible to determine the characteristic parameters of the size effect for this material.[7] When the electric field is tangent to the surface of the film, the carriers in the film do not participate in the high-frequency processes, since div$D = 0$ with a plane transverse with propagating in the film.

The difference between the dynamics of the ferroelectric mode in the film and the bulk specimen is expressed in the T_c shift, and changes in the dielectric constant and the damping. These phenomena are manifested in the form of size effects with characteristic lengths: l_f, the correlation radius of the ferroelectric mode, and $lg = \sqrt{\alpha g/\omega}$, the depth of carrier diffusion at a given alternating-field frequency.

The results of measurements of film dielectric parameters at radio and microwave frequencies can be extrapolated within the framework of these models to frequencies corresponding to the ferroelectric-mode frequency ω_f. Experimental studies of films at frequencies near ω_f, i.e., at millimeter- and submillimeter-band frequencies, would be of great value. Experimental plots of ε against temperature that were obtained for films produced by the same technology on a solid base by measuring in a field tangent or normal to the film surface indicate that the phase transition is spread out to a much greater degree in the tangential-field case.[6] Experimental data therefore suggest that the spreading of the phase transition in the ferroelectric film is anisotropic.

The use of thin ferroelectric films applied directly to a dielectric base with high thermal conductivity provided a sound basis for study of nonlinear effects in ferroelectrics placed in strong microwave-frequency electric fields. Continuous-duty measurements have been made in this way. It was found that the dependence of tanδ on the microwave field amplitude is sharply weakened as the thickness of the film is reduced.[8]

The most interesting effect that arises in a ferroelectric under the action of a strong microwave field is nonequilibrium overheating of thermal acoustic phonons. Experimental investigation of this effect consisted of measuring the noise radiation of a film ferroelectric specimen placed in a strong microwave field. Figure 2 represents $T_{\rm eff}$ as a function of the frequency and voltage of the pump applied to the active film element. The thinner film shows a much lower noise-radiation temperature.[6,9]

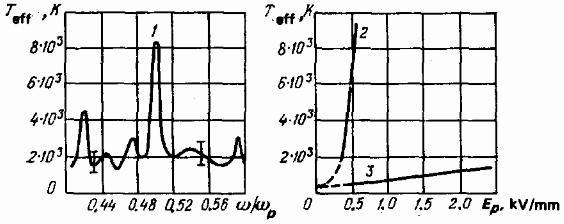

FIG. 2. Effective noise temperature of planar film capacitor placed in microwave pump field. $SrTiO_3$ film at $T = 77$ K, $f_p = 2.5$ GHz. 1—$E_p = 0.5$ kV/mm; film thicknesses: 1, 2—5.0 μm; 3—1.5 μm.

Thus, the size effect—the change in nonlinearity threshold on a change in film thickness—is characteristic of the nonlinear effects in a ferroelectric film in a strong microwave field. The critical dimension in this case is the wavelength of the hypersound in the film at the frequency of the microwave field. Understanding of this effect has made it possible to build a low-noise parametric amplifier based on a ferroelectric-film active element.[6,9,10]

The dielectric nonlinearity of ferroelectric films is the basis for their use in microwave devices in which phase or amplitude control of the wave is obtained by varying the constant displacement field applied to the ferroelectric. Microwave control devices based on ferroelectric films have advantages in their high response speeds, their ability to work at high microwave signal levels, and high radiation stability.[6] Special note should be taken of integrated-circuit microwave devices that use dielectric bases with ferroelectric films applied to them. An example is the FAR module, which uses a coplanar waveguide with a ferroelectric film as an adjustable phase shifter.[11] Improvement of the industrial technology of ferroelectric films on dielectric bases will provide a physical-technological basis for the manufacture of inexpensive microwave-band ICs.

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