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Résumé. — La formule pour dépendance de la fréquence de mode ferroélectrique suivant la température et le champ de polarisation est reçue conformément avec l'expérience connue. On a considéré la contribution des mécanismes de perte liés à l'électrostriction et aux champs statiques dus aux défauts. On a reçu une simple formule pour plusieurs paramètres électriques des couches ferroélectriques. L'application pratique des ferroélectriques aux microondes est présentée par les expériences avec un amplificateur paramétrique à la fréquence de 10^9 Hz de la puissance pompage moins de 100 mW.

Abstract. — The formula for dependence of the soft mode frequency on the temperature and biasing field has been obtained in a good agreement with known experimental data. The contribution of mechanisms of losses connected with electrostriction and statical fields produced by defects is considered. The simple formula for some electrical parameters of ferroelectric film is derived. Practical applications of ferroelectrics at microwaves are represented by the experiments on parametric amplifier at frequency 10^9 Hz with the pump power less than 100 mW.

1. **Introduction.** — There are good reasons to believe that the applications of ferroelectrics at microwaves open the new way for the use of these materials in electronics. Concurrent with development of ultrasonic transducers, electrooptic modulators and elements of computor memory, the microwave applications of ferroelectrics have to determine efforts of engineers and physicists working at the ferroelectricity.

2. **Dielectric nonlinearity.** — Modern theory of dielectrical properties of ferroelectrics is based on the lattice dynamics [1], [2] and particularly on the soft mode representation. We considered a motion of the soft mode in a crystal of $BaTiO_3$-type starting with the assumption that the potential function of interaction between Ti and O sublattices is averaged by the motion of ions taking part in the thermal oscillations of non-ferroelectric modes of the crystal. The following dependence of the soft mode frequency on temperature and biasing field has been obtained :

$$\frac{\omega_f^2(E, T)}{\omega_{0,0}^2} = \begin{cases} [(\xi^2+\eta^3)^{1/2}+\xi]^{2/3}+[(\xi^2+\eta^3)^{1/2}-\xi]^{2/3}-\eta & \text{for } \xi^2+\eta^3 \geqslant 0 \\ \eta & \text{for } \xi=0, \eta \geqslant 0 \\ -2\eta & \text{for } \xi=0, \eta \leqslant 0 \end{cases} \quad (1)$$

where $\xi = E/E_n$ normalized biasing field

$$\eta = \frac{\theta_F}{T_0}\left(\frac{1}{2} - \frac{T_0}{\theta_F}\cdot\frac{1}{e^{\theta_F/T}-1}\right) \to 1 - \frac{T}{T_0} \quad \text{for} \quad T \gg \theta_F \quad (2)$$

θ_F : characteristic temperature for the sublattice oscillation [3], [4].

Figure 1 presents the function $\omega_f^2(E, T) \sim \varepsilon^{-1}(E, T)$ plotted according to the formulae (1), (2) for $SrTiO_3(a)$ in comparison with experimental data (*b*) [5], [6]. The following parameters are chosen :

$$T_0 = 40\ ^{\circ}\mathrm{K},\ \theta_F = 84\ ^{\circ}\mathrm{K},\ E_n = 2\times10^6\ \mathrm{V/m},\quad \omega_{00} = 6.7\times10^{12}\ \mathrm{s}^{-1},\ \varepsilon_{00} = 2\times10^3.$$

3. **Dielectric losses.** — Theoretical investigations of the part of an anharmonism in formation of dielectric losses showes that the 4-phonon processes take preference over 3-phonon processes [7]. The computations for 4-phonon processes are in good agreement with the experimental data for high-quality crystals of $SrTiO_3$.

We considered the contribution to tan δ of the other three mechanisms of the losses in ferroelectrics [8] : 1. Scattering through the sample boundaries. 2. Scattering at the residual domain formations [9]. 3. Scattering at the static field caused by defects [10].

Apparently, the analysis of the losses nature in the solid solution (Ba, Sr)TiO_3 which has been made by

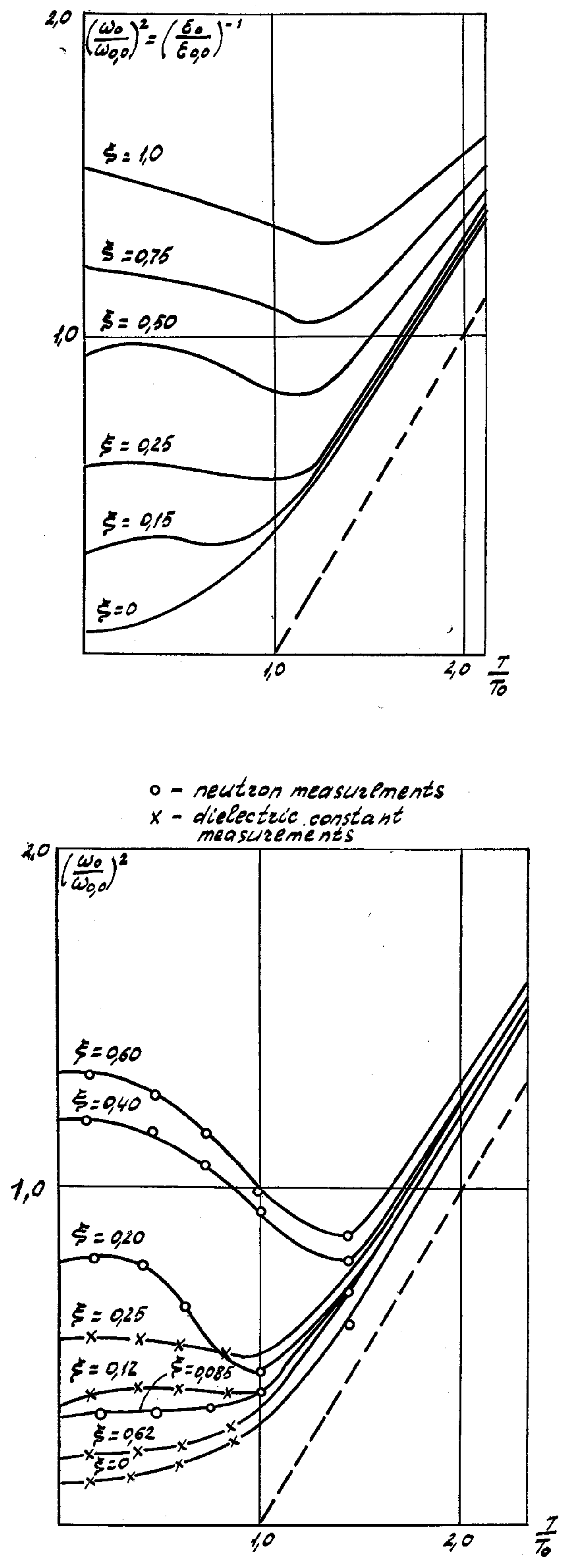

FIG. 1. — For $SrTiO_3$: $T_0 = 40$ °K, $\theta = 84$ °K, $E_n = 2 \times 10^6$ V/m, $\omega_{0,0} = 6{,}7 \times 10^{12}$ s^{-1}, $E_{0,0} = 2 \times 10^3$.

K. Bethe [11], has to be verified by the exclusion of 3-phonon processes and taking into account the processes mentioned above.

Figure 2 shows the dependence of tan δ on frequency for a high-quality crystal of $SrTiO_3$ (*a*) and for a crystal with an appreciable block structure (*b*). The run of (*a*) is in line with the known data [11], [13], the maximum at (*b*) can be explained by the presence of charges at the block boundaries [10].

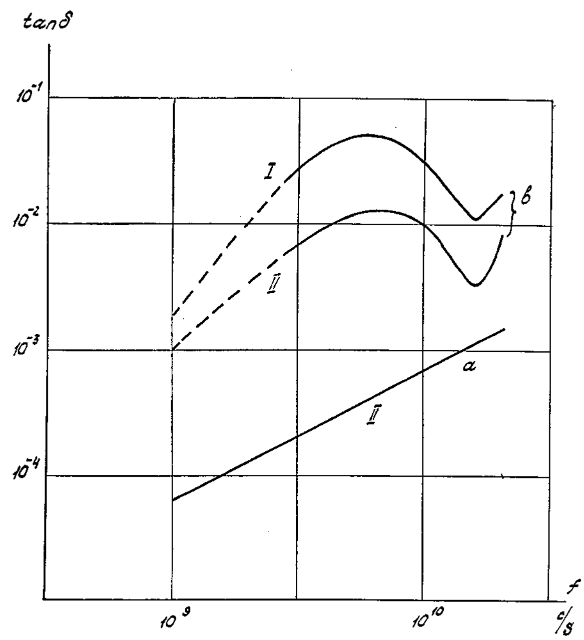

FIG. 2. — I : $T = -190$ °C ; II : $T = -160$ °C.

If a ferroelectric film is to be considered it is important to take into account the transference of energy dissipated from electromagnetic field into substrate by hypersound. This phenomenon can appreciably reduce the temperature of the film element [12].

It is known from experiment that tan δ increases under the intensive microwave field. The thermal phonons phasing arises under the influence of the microwave field which performs a role of pumping in this parametric process [14]. If the microwave field amplitude is rather great mentioned parametric process leads to the nonequilibrium distribution of thermal phonons with frequencies. This might turn out to be important when noise characteristics of the material is investigated.

4. **Ferroelectric films.** — There are many experimental data concerning the dependence of ε on the temperature for different thicknesses at low frequencies [15]. The characteristic feature of these data is dependence of dielectric properties of the film on its thickness. The generally accepted explanation of this phenomenon is based on the assumption about the specific properties of surface layers. But estimations

of the thickness and ε of these layers are very different and numerically can differ by several orders [16].

We obtained the formula for effective dielectric constant of ferroelectrics above the Curie point which is not at variance with the experimental data :

$$\varepsilon_{\text{eff}} = \frac{\varepsilon}{1 + \varepsilon \frac{2\, l_{\text{m}}}{h} + \frac{\varepsilon}{\varepsilon_\infty} \cdot \frac{2\, r}{h}} \tag{3}$$

where h thickness of the film ; l_{m} radius of the Debye screening in the metal of electrodes ; r-correlation radius for a spatial dispersion in ferroelectrics ; ε, ε_∞ are dielectric constants of bulk material at low and optic frequencies respectively. The value of r can be found from the neutron scattering data. If $l_{\text{m}} = 7$ Å, $r = 10$ Å, $\varepsilon = 18 \times 10^3$, $\varepsilon_\infty = 6$, we obtained from (3) the curve $\varepsilon_{\text{eff}}(h)$ which is plotted in figure 3 where the experimental points [15] are presented also.

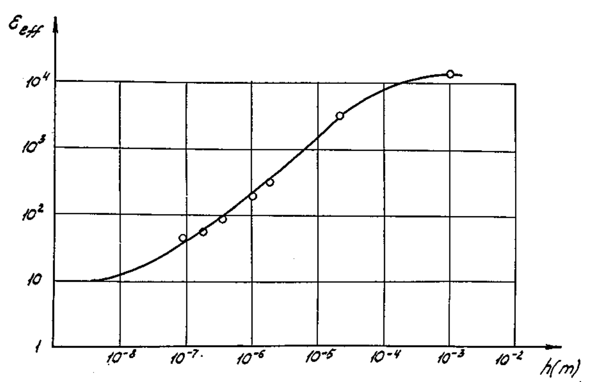

FIG. 3. — $l_{\text{m}} = 7$ Å, $r = 10$ Å, $\varepsilon = 18 \times 10^3$, $\varepsilon_\infty = 6$.

For the microwave applications of the films as well as of bulk materials the nonlinearity of $\varepsilon(E)$ is very important. This characteristic has to be found for the certain constructions of the elements because the field distribution in the element can influence the form of the function $\varepsilon(E)$ to a large extent [17].

Figure 4 presents the results of the experimental investigation of the planar condenser carried out on the base of the film of solid solution (Ba, Sr)TiO_3 with $T_c \sim 0$ °C. The film was obtained by fritting on the dielectric substrate with great thermal conductivity.

5. **Parametric amplifier on the nonlinear dielectrics.** — A parametric amplifier on the nonlinear dielectric has been investigated at 1967-68 [18]. It was a degenerate amplifier at the frequency 10^9 Hz operating at the room temperature. As an active dielectric the ceramics of a solid solution (Ba, Sr)TiO_3 with $T_c = -8$ °C was used. The stable amplification about 20 dB has been obtained, the pumping power being 0,4 W. With increasing pumpung, amplifier

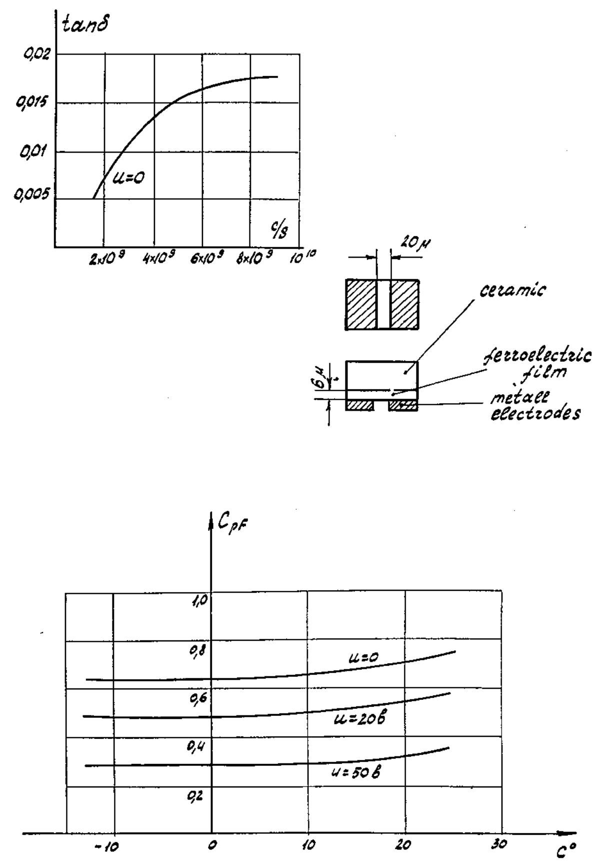

FIG. 4

began to act as a generator. The pumping pulse duration was 4 μs, the increasing of the pulse duration caused the decreasing of the amplification at the end of the pulse which can be explained by the heating of an active area in the nonlinear condensor.

The noise properties of the parametric amplifier on nonlinear dielectric were tested with the double-circuit amplifier using a film active element from $SrTiO_3$ in continual mode of operation at the temperature 80 °K. The signal and pumping frequencie were 10^9 Hz and 4×10^9 Hz respectively. The signal circuit was completely matched with the feeder. Under these conditions the noise temperature of about 100 °K has been obtained. As may be inferred from some preliminary experiments the measurements of the noise temperature of a ferroelectric element being under the high microwave voltage can give interesting information about physical processes in the crystal lattice of the material.

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