To explain the loss tangent phenomenologically, eqs. (42) & (43) must be picked up. The value of tan δ_1 which corresponds to the loss tangent in paraelectric phase is 0.018 from Fig. 11. The parameter P_0 is calculated by putting the value of tan δ (0.062) at p=48 kbar in Fig. 11 into tan δ of eq. (42), and its value is $P_0=1.673\times10^{-4}$ C/m^2. Here, $u=4.14\times10^{10}$ m/F, $g=-8.81\times10^8$ m/F·kbar & $\xi=2.48\times10^{13}$ $m^5/F\cdot C^2$ were used for the values of u, g, ξ & ζ in eq. (42) as shown in the case of the dc-electric field dependence of the dielectric constant.

The dc-electric field dependence of tan δ at p=48 kbar is obtained by substituting above values for those of eq. (43), and is shown as a solid line in Fig. 12. The value of the ratio of P_0 to P_s, namely A, is the order of 10^{-2}.

In this case, if the parameter P_0 is entirely independent of pressure, the loss tangent in ferroelectric phase obtained from eq. (42) decreases with pressure, but such a behavior of the loss tangent is inconsistent with Fig. 11. On the contrary, if the parameter P_0 increases with pressure as shown in Fig. 13, the pressure dependence of tan δ in ferroelectric phase is exhibited as adotted

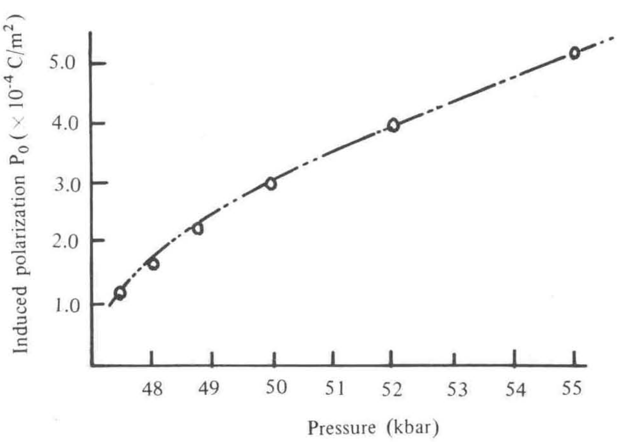

Fig. 13. The pressure dependence of the induced polarization of powder $NaNO_3$.

line in Fig. 11, and this fact is reasonable.

The dc-electric field dependence of tan δ calculated at p=47.5 kbar & 52 kbar is exhibited as a solid line in Fig. 12 by using eq. (43) and the parameter P_0 shown in Fig. 13.

The loss tangent decreases with the dc-electric field, and furthermore, the rate of the decrease of tan δ with the dc-electric field decreases with increasing pressure.

From above facts, it will be concluded that this phenomenological treatment of tan δ is appropriate to explain experimental results.

(2) The case of $BaTiO_3$

The temperature dependence of tan δ with pressure reported by G.A.Samara is shown in Fig. 14 for $BaTiO_3$. Let us apply eq. (45) & eq. (47) to the results of above experiment. As the value of tan δ at the transition temperature is given by eq. (45), the values of parameter P_0 in ferroelectric phase are determined by eq. (45) and Fig. 14. The tan δ_1 corresponds to the loss tangent in paraelectric phase, and its value is 0.01 from Fig. 14.

In this case, the loss tangent in paraelectric phase is almost independent of pressure. It is seen

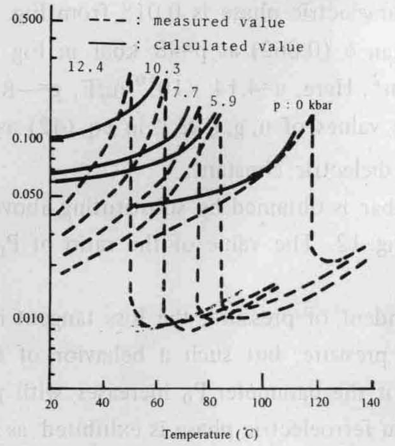

Fig. 14. The temperature dependence of the loss tangent ($\tan\delta$) of single crystal $BaTiO_3$ with pressure parameter.

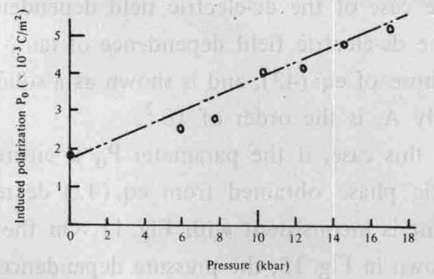

Fig. 15. The pressure dependence of the induced polarization of single crystal $BaTiO_3$.

that the value of $\tan\delta$ at the transition temperature increases with increasing pressure from Fig. 14. The pressure dependence of parameter P_0 obtained by eq. (45) is shown in Fig. 15 and it is found that the value of P_0 increases with pressure. This behavior of parameter P_0 with $BaTiO_3$ is similar to that with $NaNO_3$.

The temperature dependence of $\tan\delta$ calculated by using eq. (46) and the value of P_0 given in Fig. 15 is shown as a solid line in Fig. 14. The value of $\tan\delta$ increases with temperature and rapidly near the transition temperature. Here, $\xi=-0.96\times10^9\,m^5/F{\cdot}C^2$, $\zeta=5.93\times10^{10}\,m^9/F{\cdot}C^4$ & $C_0=4.52\times10^5$ m/F·°C were used for the values of ξ, ζ & C_0 in eqs. (45) & (46) as shown in the previous section.

In this case, the pressure dependence of $\tan\delta$ shown in Fig. 14 is based on that of the characteristic temperature T_0 in eq. (47), that is;

$$T_0 = 104 - 4.92\,p \qquad (p \text{ in kbar } \& \; T_0 \text{ in } ^\circ C)$$

The value of the ratio of P_0 to P_s is also the order of 10^{-2} for $BaTiO_3$.

Thus, the analytical loss tangent derived from free energy is given in forms of both the dc-electric field and temperature dependence including the pressure in the case of the first and the second order transition, and follows experimental results on $\tan\delta$.

And eq. (40) gives the relationship between P_s and $\tan\delta$, and seems to show that the domain motion will contribute to the dielectric loss.

5. Conclusion

Based on this analysis which is obtained by modifying Devonshire's free energy for the bound crystal, when the hydrostatic pressure is applied to the crystal which has the centrosymmetry in paraelectric phase, the ferroelectric phenomena, for example, the pressure dependence of the permittivity & the spontaneous polarization with temperature parameter and the temperature dependence of the permittivity & the spontaneous polarization with pressure parameter etc., are explained very clearly. Especially, the analysis for the pressure characteristics of ferroelectric phase