Janta model for the ferroelectric hysteresis loop

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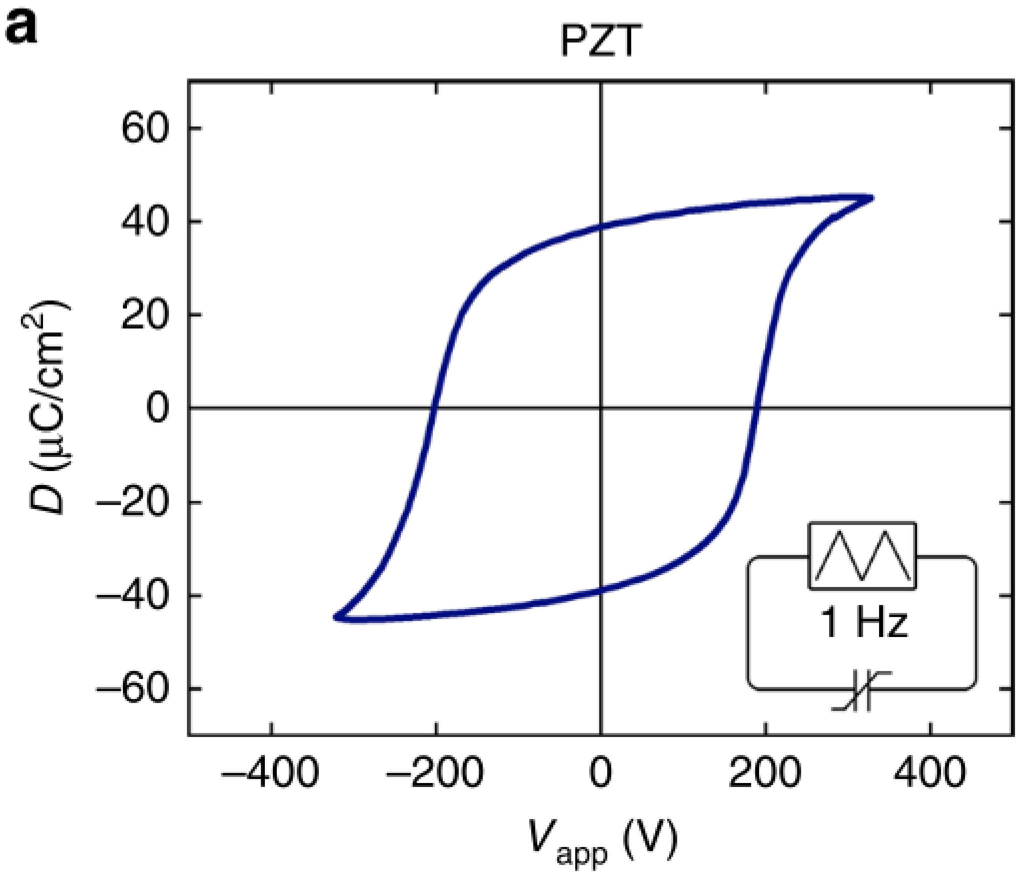
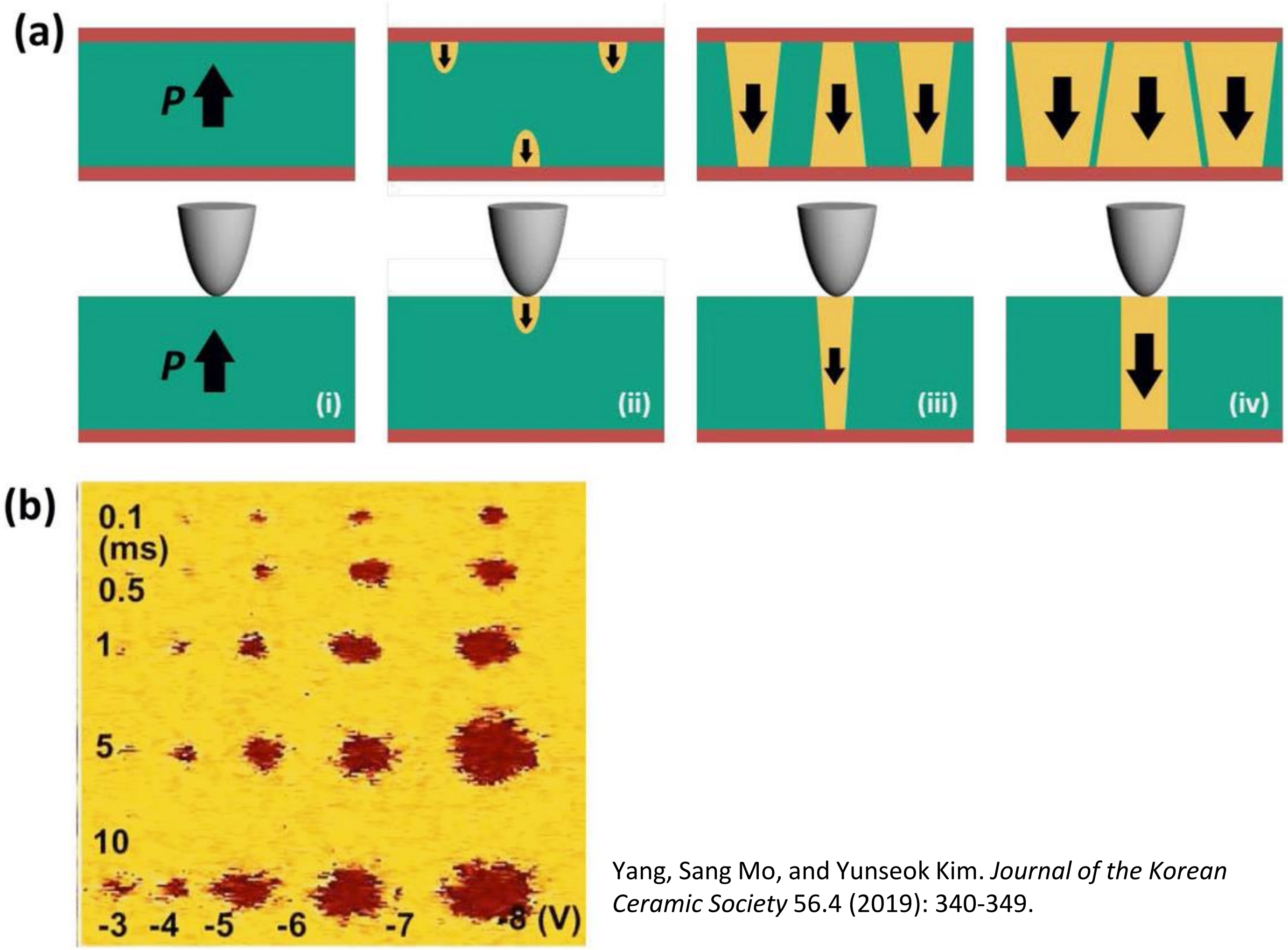
Jiri Janta (1971) The influence of the shape of domains on the ferroelectric hysteresis loop, Ferroelectrics, 2:1, 299-302,

Polarization reversal





Yang, Sang Mo, and Yunseok Kim. *Journal of the Korean Ceramic Society* 56.4 (2019): 340-349.

Fig. 1
(a) Domain switching behavior for (upper) metal-ferroelectric-metal and (lower) AFM tip-ferroelectric-metal structures. (b) PFM phase image of dot-patterned domains formed by negative voltage pulses to the bottom electrode in 90-nm-thick P(VDF-TrFE) thin films.

Janta model

Strongly simplifying models based on the sideways expansion of 180" domains

Assumptions:

Cylindrical domains:
Surface density of nuclei N_1
Initial radius of domains r_0

Strip domains:
Surface density of nuclei N_2
Initial domain half-width d_0

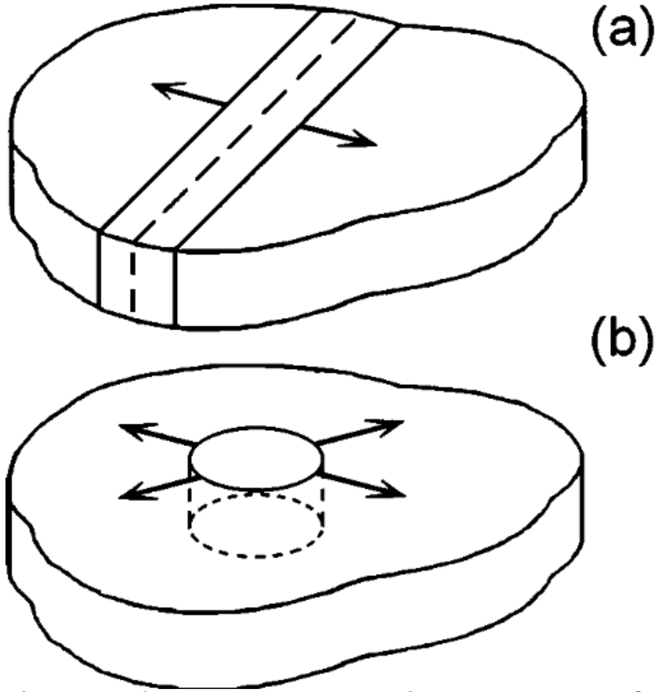


FIG. 2. Scheme demonstrating the variants of domain growth dimensionality: (a) the growth of the lamella domains in finite media, (b) the growth of cylinder domains in finite media

The velocity of the sideways motion of the domain walls is $v = v_{\infty} \exp(-\alpha/E)$ Eq. 1

Eq. 1 $v = v_\infty \exp(-\alpha/E)$ is determined by the Mertz law

α The activation field

v_∞ The extrapolated wall velocity for $E = \infty$

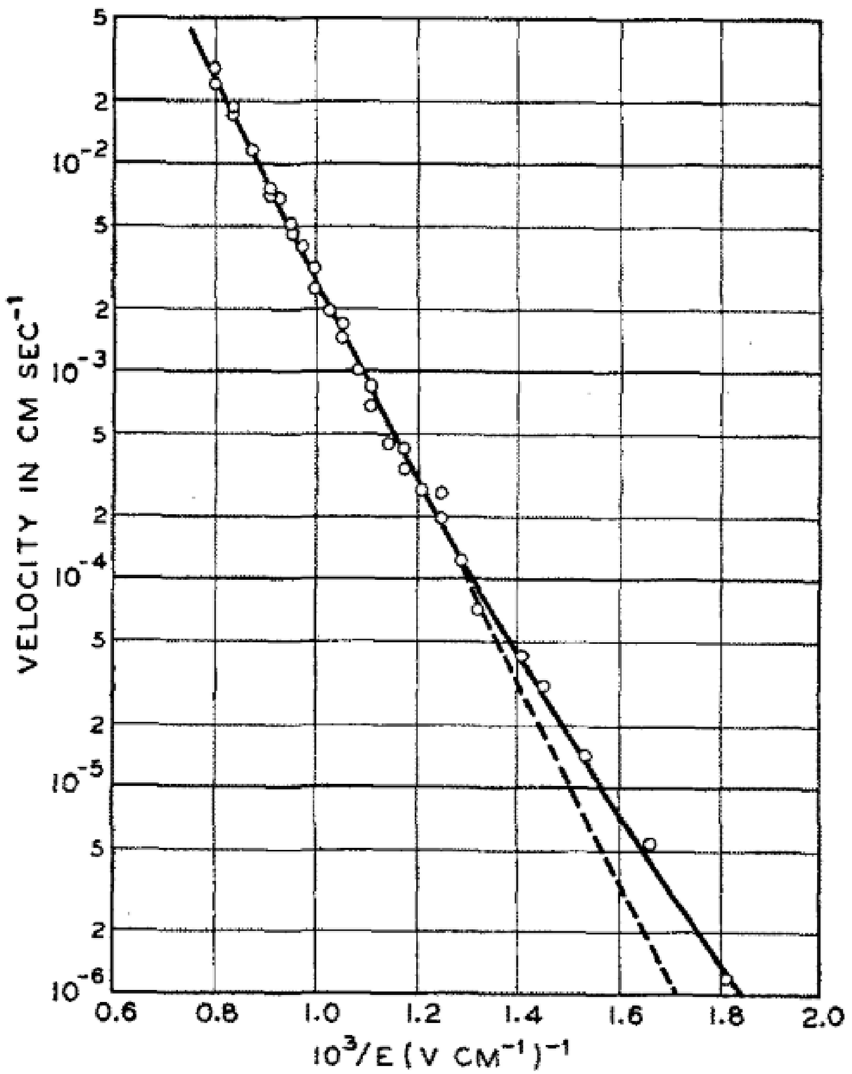


FIG. 2. Logarithm of the sidewise 180° domain-wall velocity vs the reciprocal of the applied electric field for a sample 4.0×10^{-3} cm thick. The dotted line is an extrapolation of the straight line drawn through the data for $v>10^{-4}$ cm sec^{-1}.

Journal of Applied Physics 31, 662 (1960);
https://doi.org/10.1063/1.1735663

Janta model

Cylindrical domains:
Surface density of nuclei N_1
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Strip domains:
Surface density of nuclei N_2
Initial domain half-width d_0

$$v = v_\infty \exp(-\alpha/E)$$

Applied field: $E = E_0 \sin(wt)$
Increased domain area:

Cylindrical domain: $\pi\left(r_0 + \int v dt\right)^2 = \pi\left(r_0 + v_\infty \int \exp\left(-\frac{\alpha}{E_0 \sin(wt)}\right) dt\right)^2 = \pi\left(r_0 + \frac{v_\infty}{w} I\left(wt, \frac{E_0}{\alpha}\right)\right)^2$

Strip domain: $2\left[d_0 + \frac{v_\infty}{w} I\left(wt, \frac{E_0}{\alpha}\right)\right]$

$$I(\omega t, E_0/\alpha) = \int_0^{\omega t} \exp\left(-\frac{\alpha}{E_0 \sin x}\right) dx,$$

The areas of reversed polarization per unit area:

$$a_{1\mathrm{ex}}(\omega t) = \pi N_1 \left[r_0 + \frac{v_\infty}{\omega} I(\omega t, E_0/\alpha)\right]^2, \quad (2')$$

$$a_{2\mathrm{ex}}(\omega t) = 2N_2 \left[d_0 + \frac{v_\infty}{\omega} I(\omega t, E_0/\alpha)\right], \quad (2'')$$

Janta model

The areas of reversed polarization per unit area:

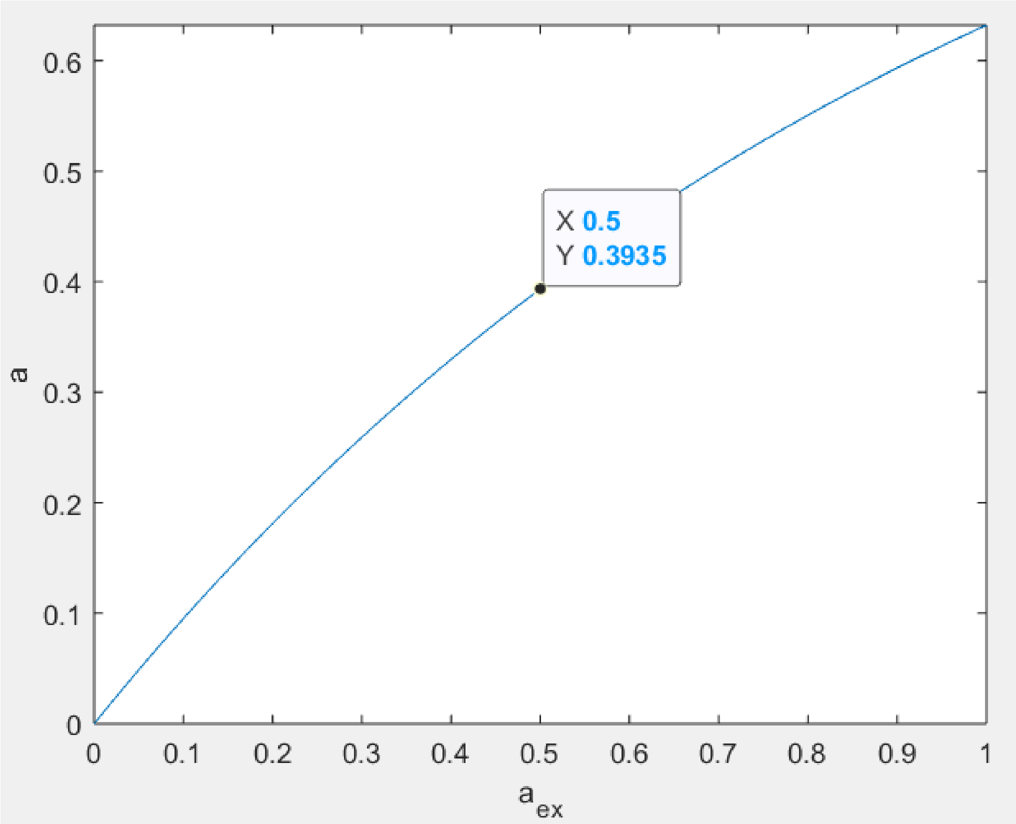
$$a_{1ex}(\omega t) = \pi N_1 \left[r_0 + \frac{v_\infty}{\omega} I(\omega t, E_0/\alpha) \right]^2, \qquad (2')$$

$$a_{2ex}(\omega t) = 2N_2 \left[d_0 + \frac{v_\infty}{\omega} I(\omega t, E_0/\alpha) \right], \qquad (2'')$$

The mutual overlap of growing domains is described by the equation[7]:

$$\boxed{a(\omega t) = 1 - \exp(-a_{ex}(\omega t)), \qquad (3)}$$

(assumption of random distribution of grain centers throughout the volume)



$$a_1(\omega t) = 1 - \exp\left(-\pi N_1 \left[r_0 + \frac{v_\infty}{\omega} I\left(\omega t, \frac{E_0}{\alpha} \right) \right]^2 \right)$$

7. M. Avrami, *J. Chem. Phys.* **8**, 212 (1940).

Janta model

Cylindrical domains:

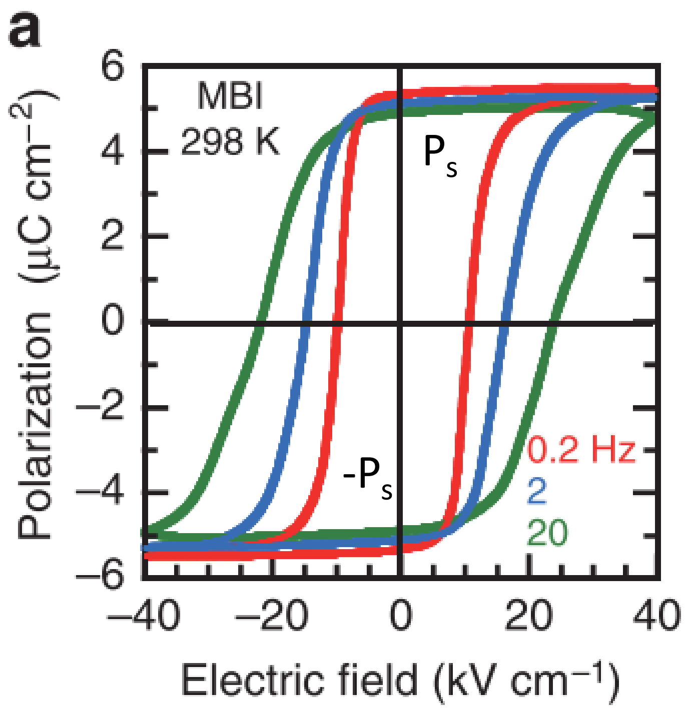
$$a_1(\omega t) = 1 - \exp\left(-\pi N_1\left[r_0 + \frac{v_\infty}{\omega} I\left(\omega t, \frac{E_0}{\alpha}\right)\right]^2\right)$$

$$\frac{P(\omega t)}{P_s} = 2a(\omega t) - 1.$$

$$\frac{P_1(\omega t)}{P_s} = 1 - 2\exp\left\{-\pi N_1[r_0 + \frac{v_\infty}{\omega} I(\omega t, E_0/\alpha)]^2\right\} \qquad (5')$$

where r_0 is given by the symmetry condition $P(\pi) = -P(0)$

$$\exp\{-\pi N_1\left[r_0 + \frac{v_\infty}{\omega} I(\pi, E_0/\alpha)\right]^2\} + \exp(-\pi N_1 r_0^2) = 1$$



$$\delta = \sqrt{N_1} * v_\infty / w$$

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Janta model

Strip domains:

$$\frac{P_2(\omega t)}{P_s} = 1 + \left\{1 + \tanh\left[N_2 \frac{v_\infty}{\omega} I(\pi, E_0/\alpha)\right]\right\} \times \exp\left[-2N_2 \frac{v_\infty}{\omega} I(\omega t, E_0/\alpha)\right]. \qquad (5'')$$

$$\delta = \sqrt{N_1} * v_\infty / w$$

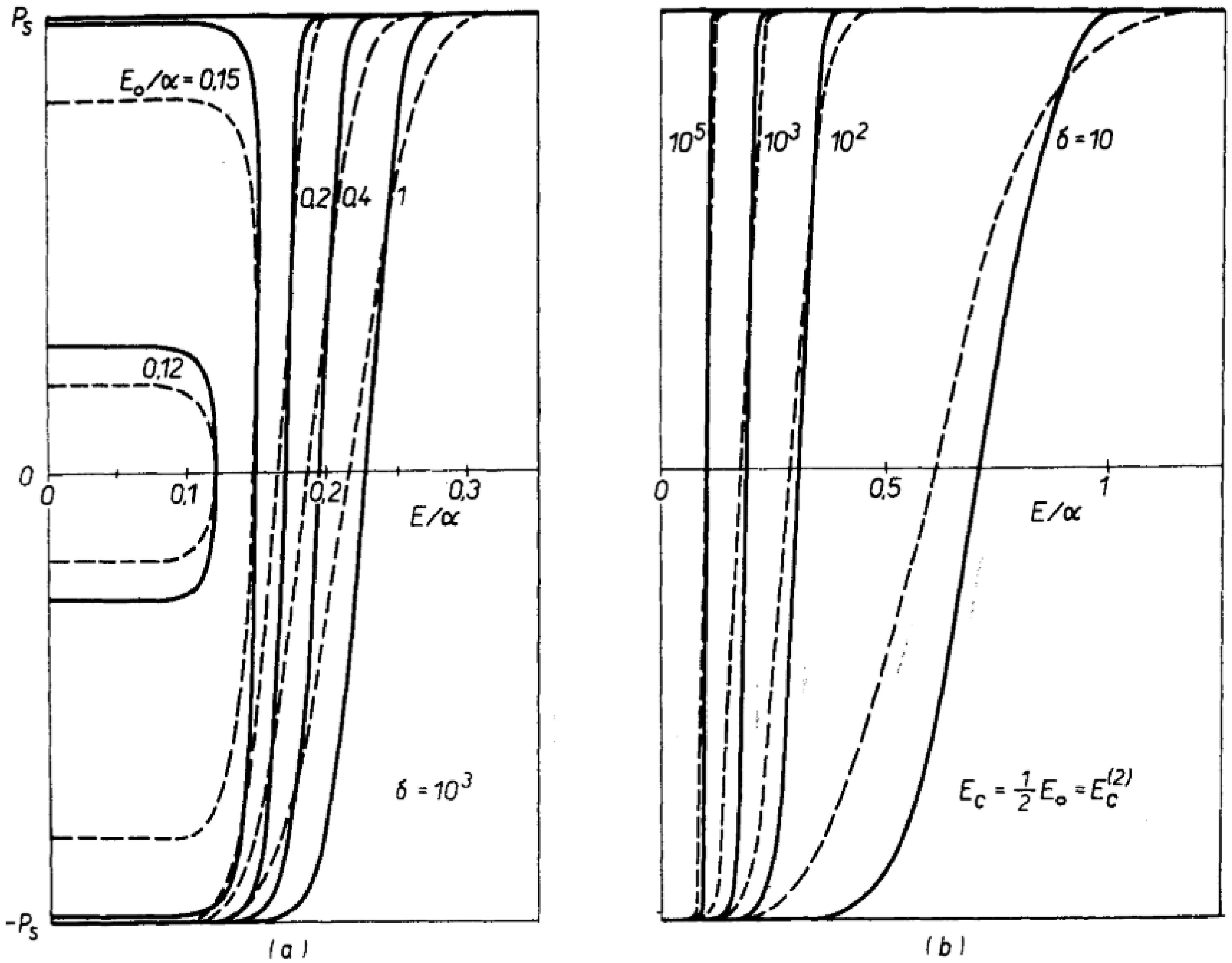

FIGURE 1. Halves of hysteresis loops computed using the models of cylindrical domains (full line, $\delta = (v_\infty/\omega)\sqrt{N_1}$) and strip domains (dashed line, $\delta = v_\infty N_2/\omega$): (a) for various amplitudes of the electric field, (b) for various values of the parameter δ inversely proportional to the frequency.

Application of Janta model

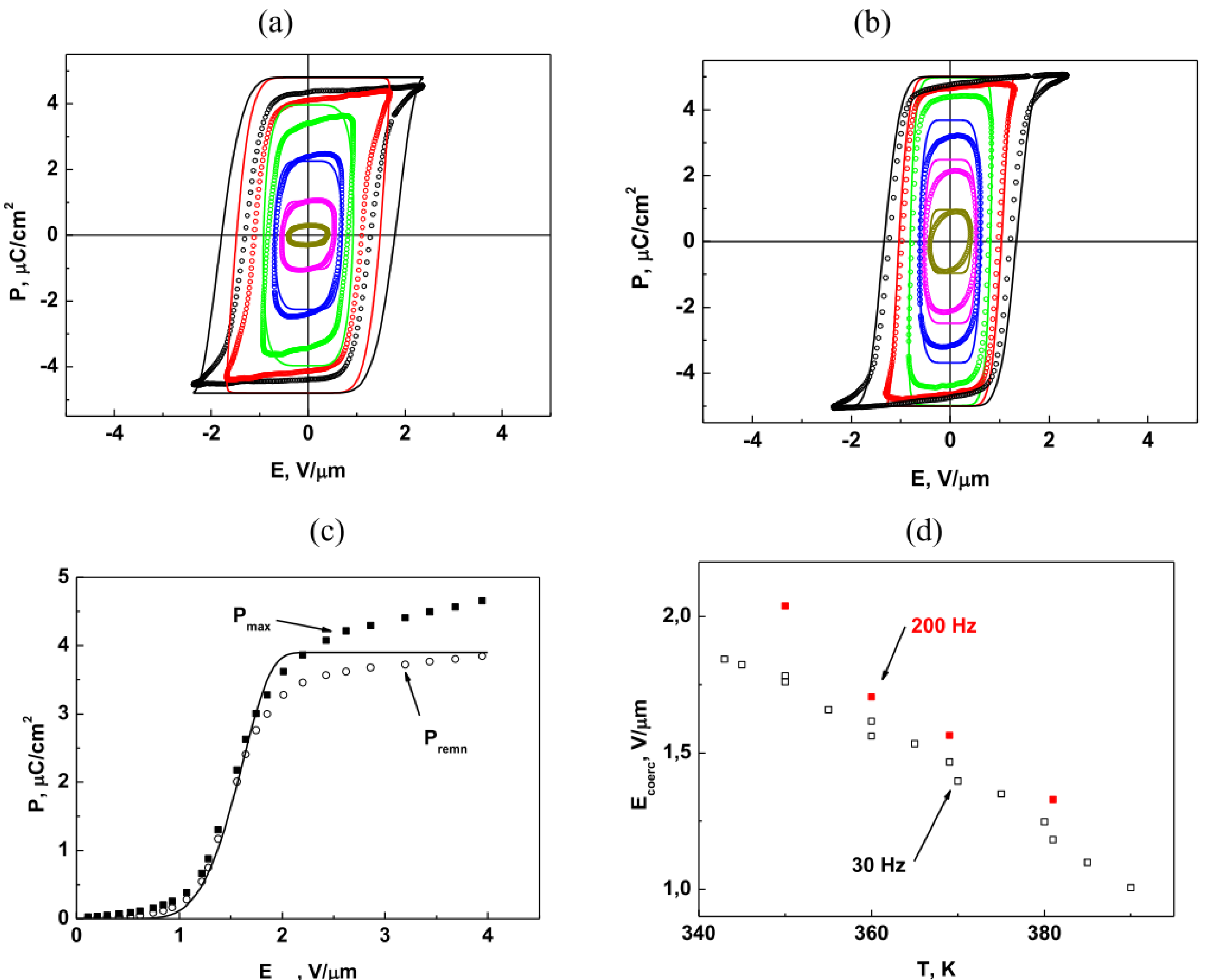

Figure 4. Dielectric hysteresis loops in an MBI single crystal for f = 50 Hz and different values of the amplitude Emax of the applied field for T = 350 K (a) and T = 381 K (b). The lines show the simulations. Dependence of the maximum polarization Pmax and remnant polarization Prem on the amplitude of the applied field for f = 50 Hz, T = 334 K (c). Temperature dependence of coercive field Ec for f = 30 Hz and 200 Hz, Emax = 2.4 V/μ (d).

F B Svinarev et al 2018 J. Phys.: Conf. Ser. 1038 012117

In summary

Janta model is just a particular case of Kolmogorov-Avrami-Ishibashi (KAI) model. The KAI model assumes either a constant nucleation rate during switching (category I) or only latent nuclei and no new nucleation during switching (category II), leading to different effective dimensionalities (n).

KAI model: $$P(t) = 2P_S\{1 - \exp[-(t/t_0)^n]\},$$

Janta model: $$\frac{P_1(\omega t)}{P_s} = 1 - 2\exp\left\{-\pi N_1\left[r_0 + \frac{v_\infty}{\omega} I(\omega t, E_0/\alpha)\right]^2\right\}$$

THANK YOU!