The frequency dependence of coercivity in ferroelectrics

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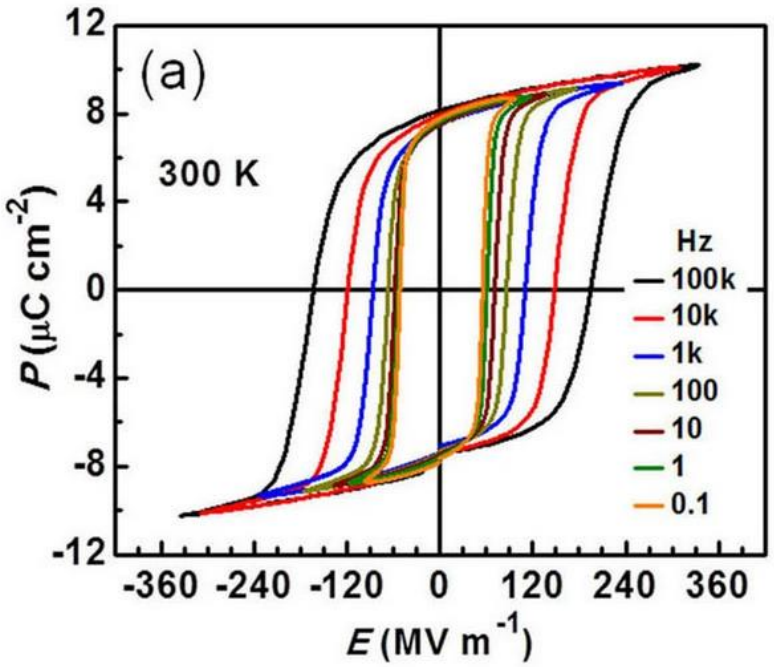
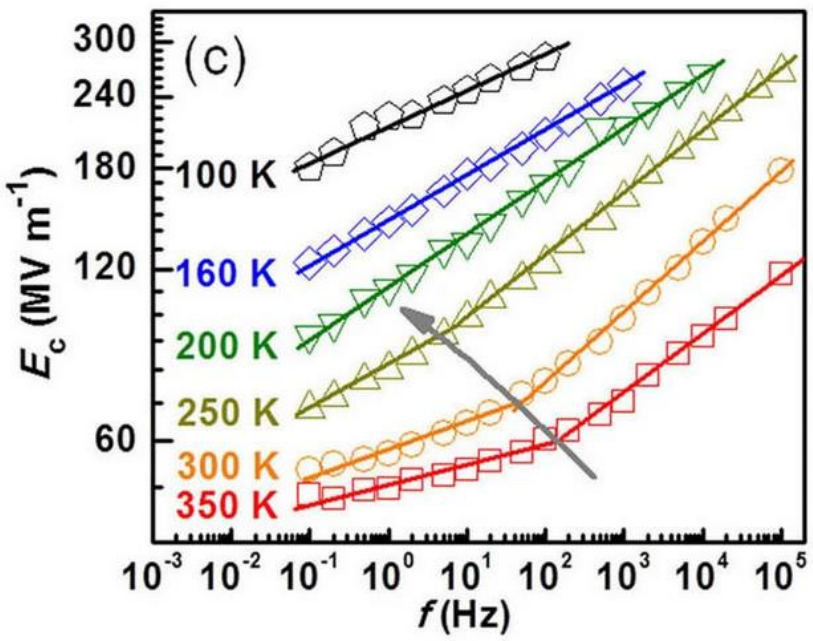
Cu/P(VDF-TrFE)/Cu capacitor-type device and scaling behaviors of coercivity E_c over frequency f.





$E_c = (E_{c+} - E_{c-})/2$

$E_c \sim f^{\beta}$

- two different regimes of switching dynamics
- domain switching in a ferroelectric involves domain wall motion
- Equivalent to the dependence upon pulse width

Hu, W., Juo, D., You, L. *et al. Sci Rep* **4,** 4772 (2015). https://doi.org/10.1038/srep04772

The Ishibashi–Orihara power law $E_c \sim f^{\beta}$

KAI model for polarization switching kinetics $$P(t) = 2P_s\left\{1 - \exp\left[-\left(\frac{t}{t_0}\right)^n\right]\right\}$$ Under constant electric field E

The volume fraction of reversed domains, *q(t)* is given by *(*generalized formula)

$$q(t) = 1 - \exp\left[-\int_0^t C(t, t')n(t')\,\mathrm{d}t'\right], \quad (1)$$

The mutual overlap of growing domains

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

where *C (t,t'*) is the volume of the domain at time *t* which has grown from the nucleus formed at time *t'***,** and *n(t')* is the number of nuclei per unit volume and unit time nucleated at time *t'*

$$C(t, t') = C_d\left[\int_{t'}^{t} v(t'')\,\mathrm{d}t''\right]^d, \quad (2)$$

where ***v(t)*** is the velocity of domain wall, ***d*** is the growth dimension and $\boldsymbol{C_d}$ is a constant

The nucleation and growth process actually occur under an oscillating field.

$$n(t)\,\mathrm{d}t = n_E(E)\,\mathrm{d}E, \quad (3)$$

The Ishibashi–Orihara power law $E_c \sim f^{\beta}$

(1)+(2)+(3) => (4)

$$q(E)=1-\exp\left[-\int_0^E C_d\left(\int_{E'}^E v(E'')\frac{\mathrm{d}t}{\mathrm{d}E}\bigg|_{E=E''}\mathrm{d}E''\right)^d n_E(E')\,\mathrm{d}E'\right], \qquad (4)$$

Let us apply an oscillating field *E=h(ft)* with a frequency *f*, where ***h(x)*** is a periodic function with a period of unity

$$q(E)=1-\exp\left[-f^{-d}\Phi(E)\right] \qquad (5a)$$

with

$$\Phi(E)=\int_0^E C_d\left[\int_{E'}^E v(E'')\{h'(h^{-1}(E''))\}^{-1}\,\mathrm{d}E''\right]^d n_E(E')\,\mathrm{d}E' \qquad (5b)$$

From the experimental data of TGS, $(NH_2CH_2COOH)_3{\cdot}H_2SO_4$.

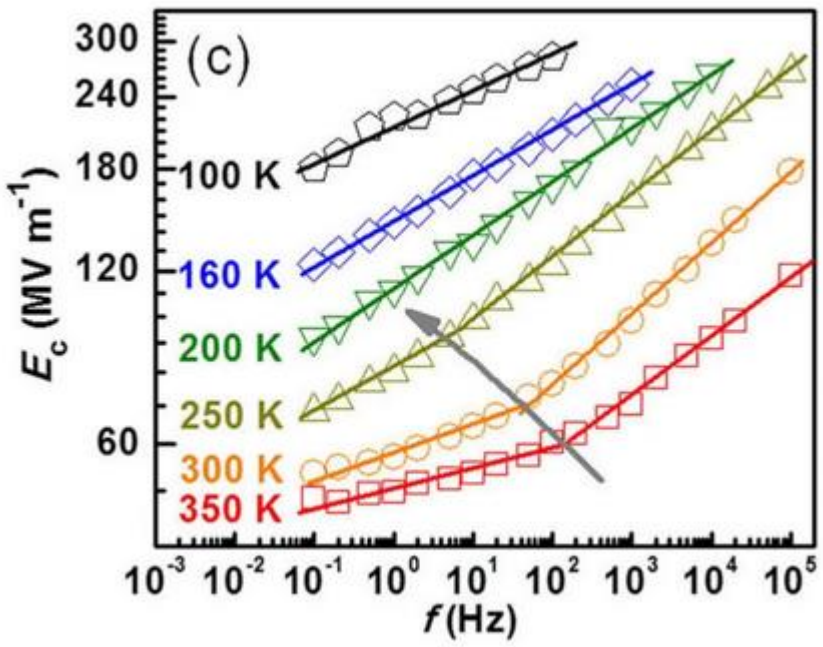
$$\Phi \propto E^{\alpha} \qquad (6)$$

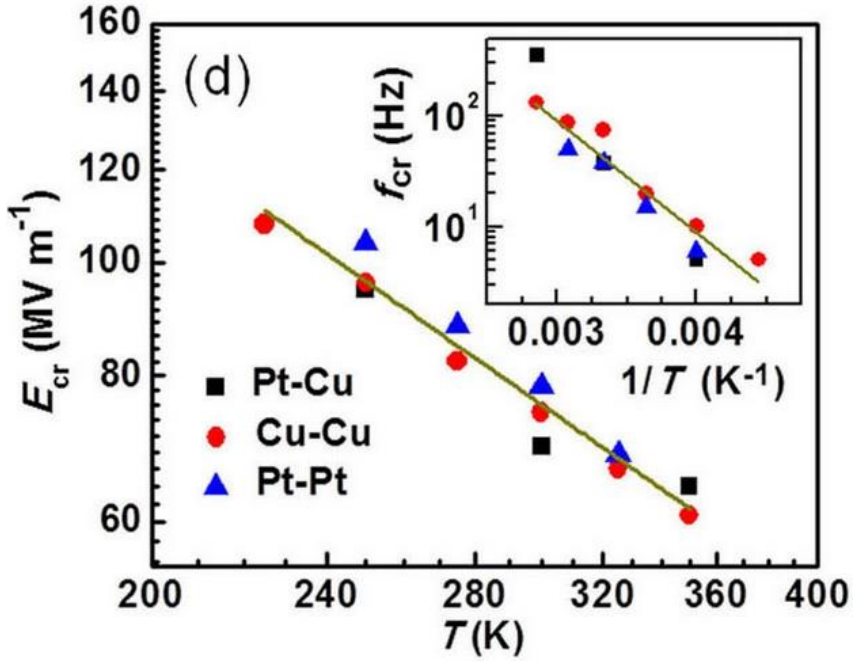
with α being about 5.7 both for the sinusoidal and triangular waves.

If we define the coercive field *Ec* as $q(E_c) = 1 - \exp[-f^{-d}\Phi(E_c)] = \frac{1}{2}$ → $E_c \propto f^{d/\alpha}$

The Ishibashi–Orihara power law $E_c \sim f^{\beta}$

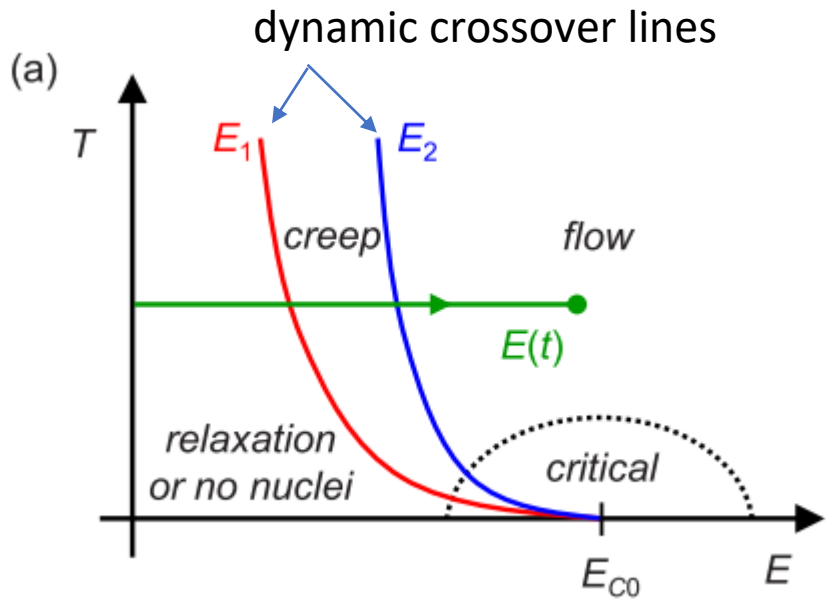
For TGS, *d* is found, from the switching transient for the step field, to be about 1.3 - 1.6. Thus, the exponent of the coercive field is found to be about 0.23.



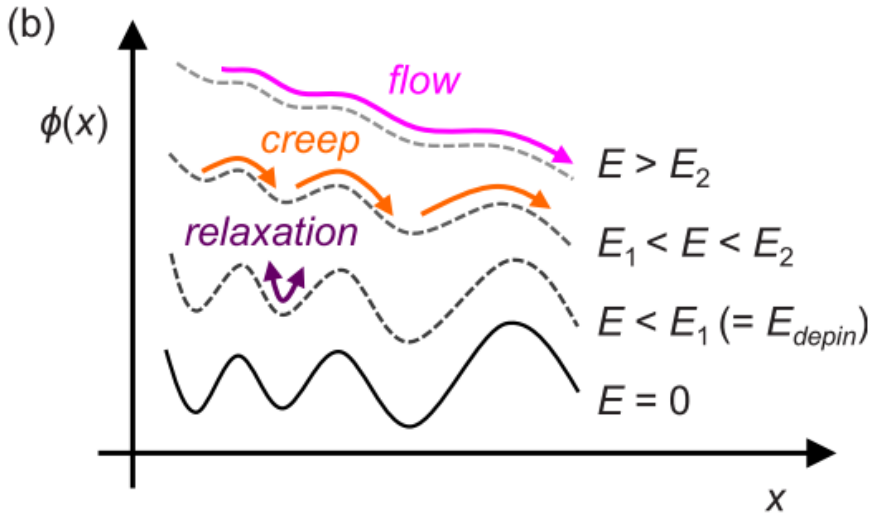


Why is there a cross-over coercive field?

Theoretical work on the ac dynamics of domain walls



The dynamic phase diagram



Three regimes for domain wall motion:

- pinned (v=0)
- creep (v has an exponential relationship)
- flow (v ∝ E)

Dynamic crossover between the relaxation and creep regimes (E_1)

$$\tau \approx \tau_0 \exp(U_{B,max}/k_B T), \quad (1)$$

$$U_{B,max} \approx U(E_{C0}/E)^{\mu}(1 - E/E_{C0})^{\eta}, \quad (2)$$

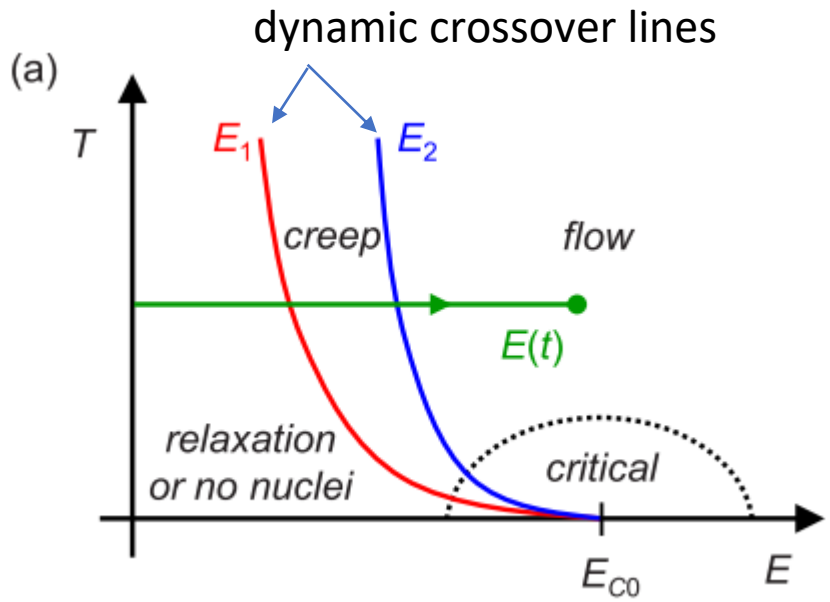
$$\tau f = 1$$

$$E_{depin}/E_{C0} = [(U/k_B T\Lambda)(1 - E_{depin}/E_{C0})^{\eta}]^{1/\mu}, \quad (3)$$

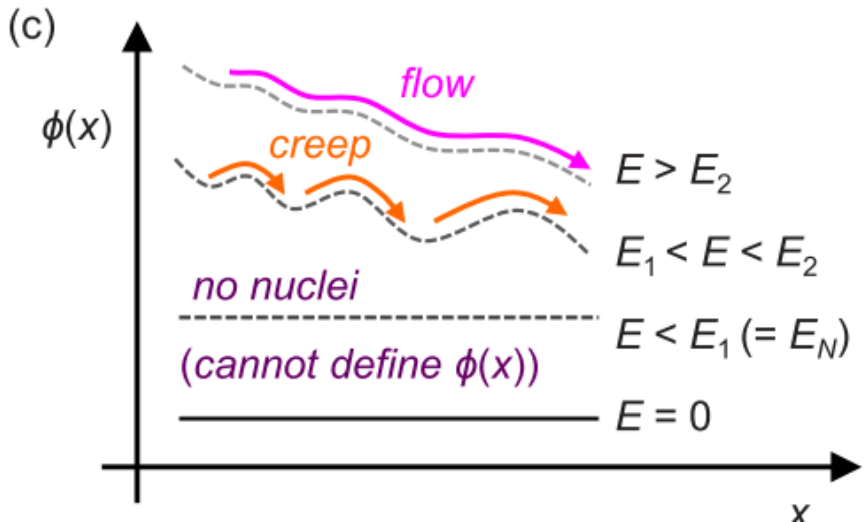
where $\Lambda = \ln(1/f\tau_0)$. the E_{depin} plays the role of E_1

Yang, Sang Mo, et al. *Physical Review B* 82.17 (2010): 174125.

Theoretical work on the ac dynamics of domain walls



The dynamic phase diagram



Three regimes for domain wall motion:

- pinned (v=0)
- creep (v has an exponential relationship)
- flow (v ∝ E)

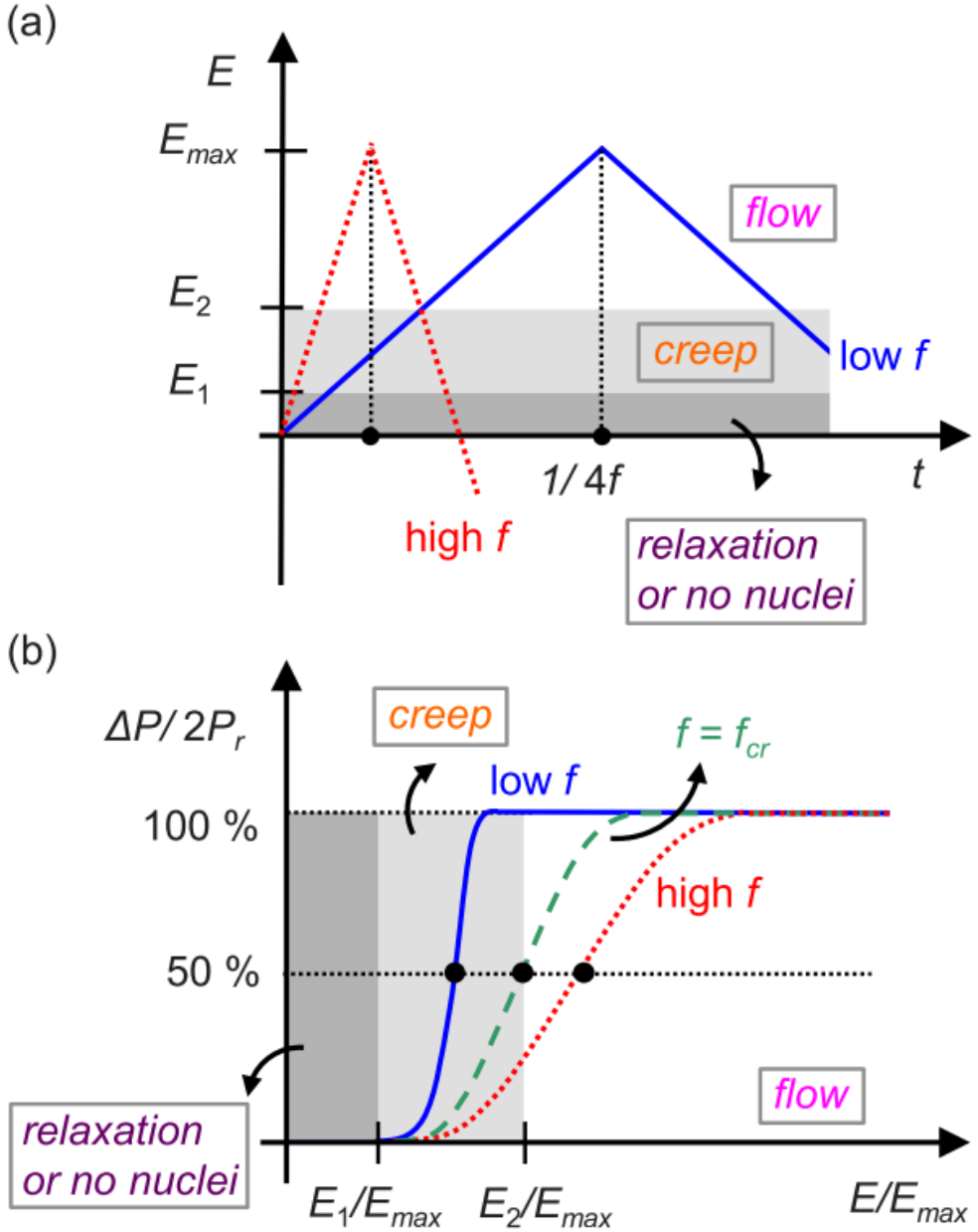
Dynamic crossover between the creep and flow regimes (E_2)

$$v \propto \gamma E,$$

$$v \approx \gamma E \exp[-(U/k_B T)(E_{C0}/E)^{\mu}(1 - E/E_{C0})^{\eta}]. \qquad (4)$$

$$E_2/E_{C0} = [(U/k_B T)(1 - E_2/E_{C0})^{\eta}]^{1/\mu}$$

Theoretical work on the ac dynamics of domain walls



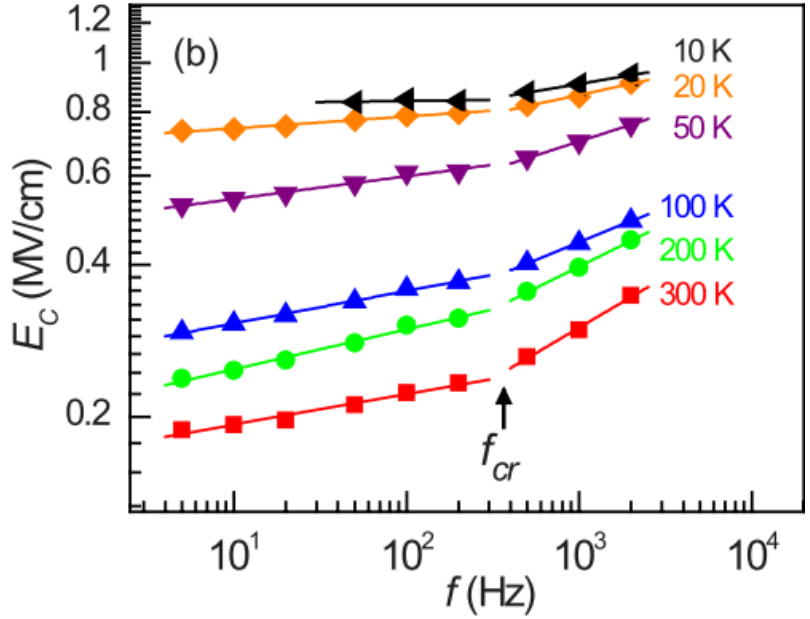
The relative time duration in each regime will vary depending on f

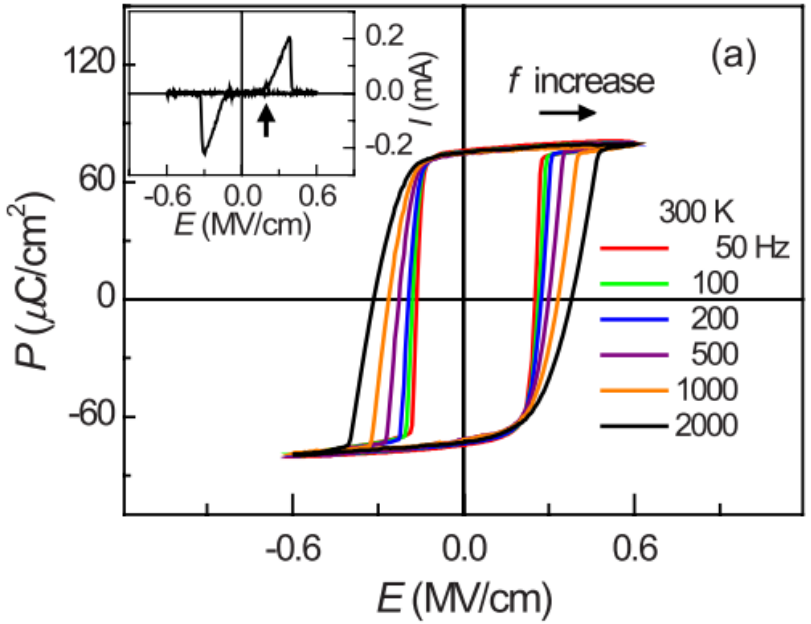
if $f<f_{cr}$, the DW creep motion plays the major role

if $f<f_{cr}$, the viscous flow motion will dominate.

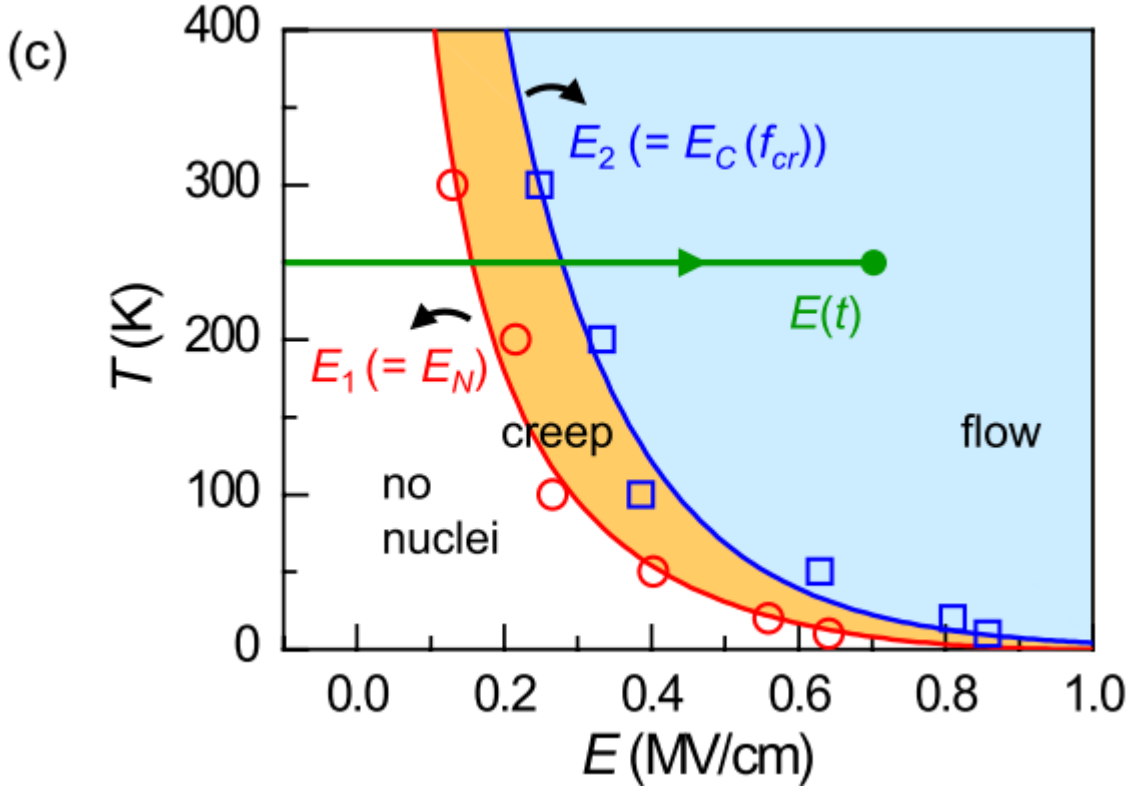
the polarization reversal (ΔP) during the first 1/4f

Theoretical work on the ac dynamics of domain walls





E1 is measured by using the E value where the switching current I started to increase significantly



$$E_2/E_{C0} = [(U/k_BT)(1 - E_2/E_{C0})^{\eta}]^{1/\mu}$$

THANK YOU