Nonlinear Dielectric Effects in Simple Fluids

NON-LINEAR DIELECTRIC EXPERIMENTS

Roma, Dielectric Tutorial
30 August 2009

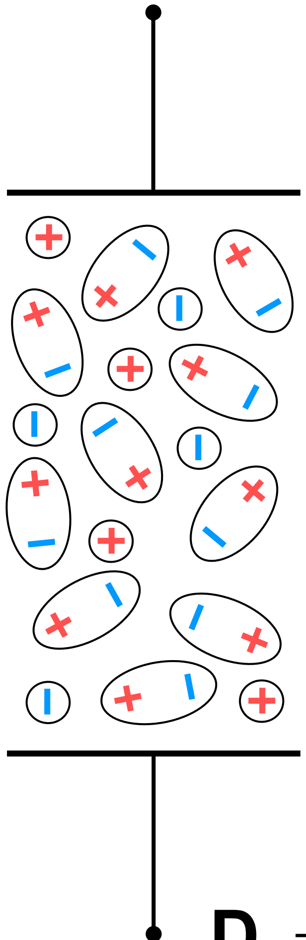
High-Field Dielectric Response:

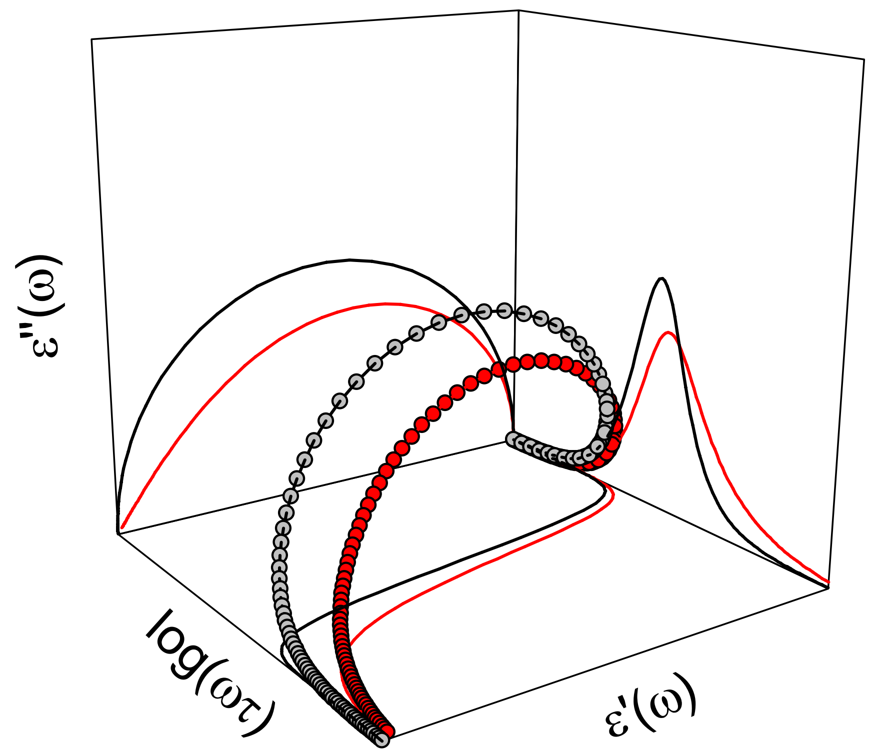
- Coulombic stress
- Langevin effect
- Energy absorption
- Time-resolved technique

Ranko Richert

Arizona State University

dielectric relaxation techniques





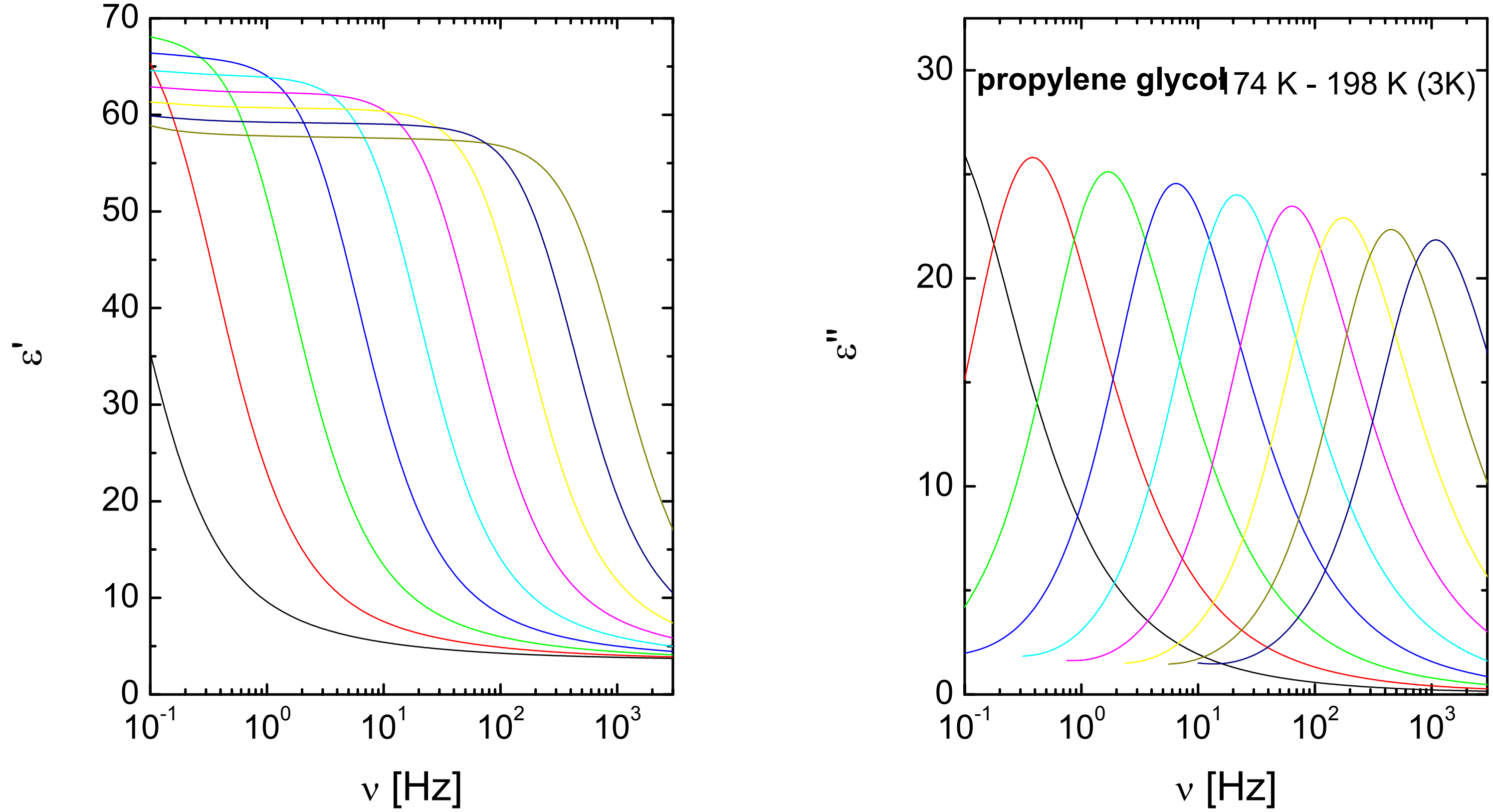
$$\mathbf{D} = \boldsymbol{\varepsilon}\ \boldsymbol{\varepsilon}_0\ \mathbf{E}$$

dielectric displacement $\mathbf{D} \equiv \dfrac{\mathbf{Q}}{\mathbf{A}} \propto \dfrac{\mathbf{V}}{\mathbf{d}} \equiv \mathbf{E}$ *electric field*

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau} \quad \{\text{Debye}\}$$

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{\left[1 + (i\omega\tau)^\alpha\right]^\gamma} \quad \left\{\begin{matrix}\text{Havriliak} \\ \text{- Negami}\end{matrix}\right\}$$

typical case near the glass transition



non-linear susceptibility

$$\frac{\mathbf{P}}{\varepsilon_0} = \underbrace{\chi^{electret}}_{\substack{=0 \\ \text{causality}}} + \chi\mathbf{E} + \underbrace{\chi^{(1)}E\mathbf{E}}_{\substack{=0 \\ \text{symmetry}}} + \chi^{(2)}E^2\mathbf{E} + \underbrace{\chi^{(3)}E^3\mathbf{E}}_{\substack{=0 \\ \text{symmetry}}} + \chi^{(4)}E^4\mathbf{E} + \ldots$$

$$\text{causality}: \ \mathbf{P}(0) = 0$$

$$\text{symmetry}: \ \mathbf{P}(\mathbf{E}) = -\mathbf{P}(-\mathbf{E})$$

$$\frac{\mathbf{P}}{\varepsilon_0\mathbf{E}} = \chi + \chi^{(2)}E^2 + \chi^{(4)}E^4 + \ldots$$

$$\varepsilon_s\left(E^2\right) = \varepsilon_s(0) \times \left[1 - \lambda E^2\right]$$

$$\lambda = -\Delta \ln(\varepsilon_s) / E^2$$

Piekara factor :

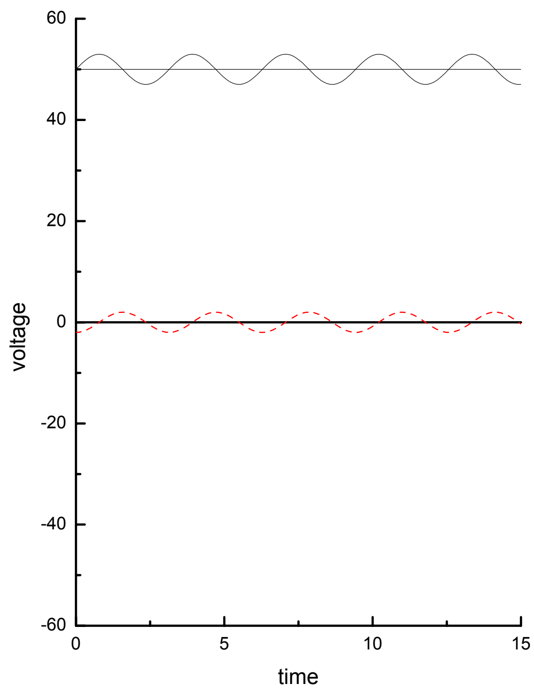
$$\Delta\varepsilon_s / E^2 = -\lambda\varepsilon_s$$

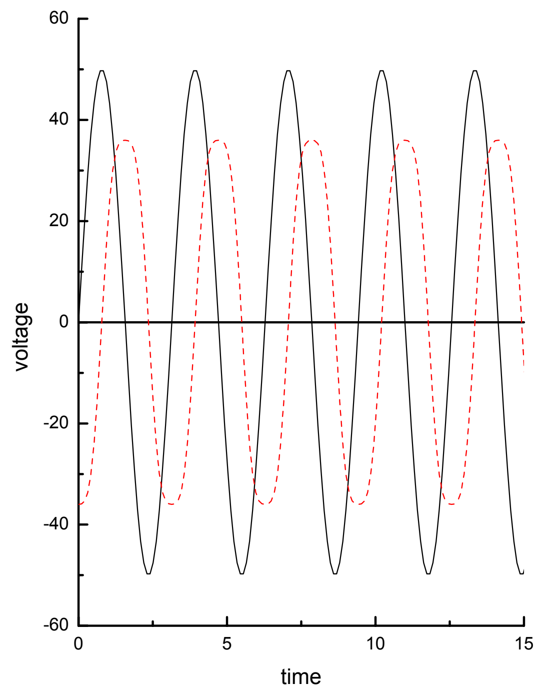
$$\text{superposition principle}: \ P(t) = \int_{-\infty}^{t} dP(\theta) = \chi\varepsilon_0 \int_{-\infty}^{t} E(\theta)\varphi(t-\theta)\,d\theta$$

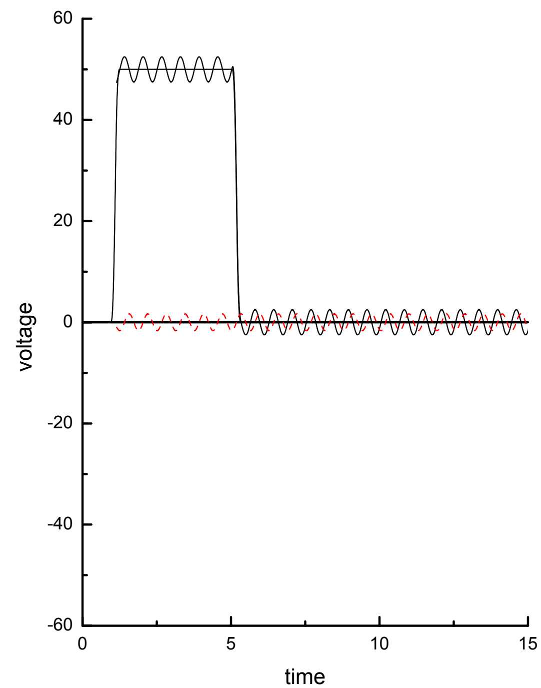
M. S. Green, R. Kubo (1950's) : linear transport coefficients $L_{F_e=0}$ are related to auto - correlation function of the equilibrium fluctuations in the conjugate flux J

$$J = L_{F_e=0}F_e \qquad\qquad L_{F_e=0} = \frac{V}{kT}\int_0^{\infty} \langle J(0)J(t)\rangle_{F_e=0}\, dt$$

variety of high field techniques







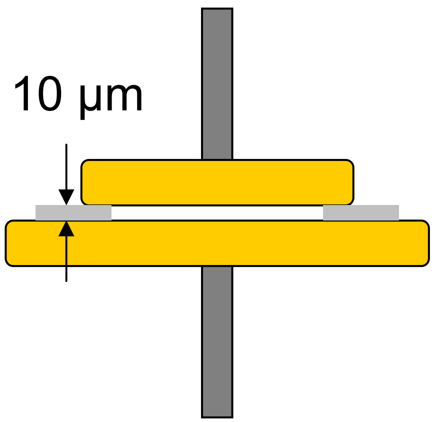
high DC field
low AC field
mainly 1ω

high AC field
no bias
1ω + 3ω

low AC field
on high pulse
NDE(t)

Coulombic stress

Coulombic stress exercise



$$\mathbf{F}_{SI} = \frac{qq'}{4\pi\varepsilon_0 r^3}\mathbf{r} \qquad \mathbf{F}_{cgs} = \frac{qq'}{r^3}\mathbf{r}$$

$$C = \frac{Q}{V} \qquad Q = CV \qquad C = \frac{\varepsilon_0 \varepsilon A}{d}$$

$$Energy = \tfrac{1}{2}QV$$

top electrode 16 mm Ø
bottom electrode 30 mm Ø
ring outer: 20 mm Ø
ring inner: 14 mm Ø

calculate force resulting from voltage $V(t)$

$V(t) = V_0 \sin(\omega t)$

calculate effect on measured ε

assume Teflon spacer with

Young's modulus $E = 1\,\mathrm{GPa}$

$$\text{mechanical modulus} \equiv \frac{[stress]}{[strain]} = \frac{L_0}{\Delta L}\frac{F}{A}$$

Coulombic stress solutions

$$work\ \ Fd\ = energy\ \tfrac{1}{2}QV$$

$$F\partial d = \tfrac{1}{2}\partial(QV) = \underbrace{\tfrac{1}{2}Q\partial V}_{=0} + \tfrac{1}{2}V\partial Q =$$

$$\tfrac{1}{2}V\partial(CV) = \underbrace{\tfrac{1}{2}VC\partial V}_{=0} + \tfrac{1}{2}V^2\partial C = \tfrac{1}{2}V^2\varepsilon_0 A\partial d^{-1}$$

$$F = \tfrac{1}{2}V^2\varepsilon_0 A\frac{\partial d^{-1}}{\partial d} = \frac{\varepsilon_0 A}{2d^2}V^2 = \frac{\varepsilon_0 A}{2d^2}(V_{dc}+V_{ac})^2$$

$$F = \frac{\varepsilon_0 A}{2d^2}[V_{dc} - V_0\sin(\omega t)]^2$$

$$= \frac{\varepsilon_0 A}{2d^2}\left(V_{dc}^2 - 2V_{dc}V_0\sin(\omega t) + \frac{V_0^2}{2}[1-\cos(2\omega t)]\right)$$

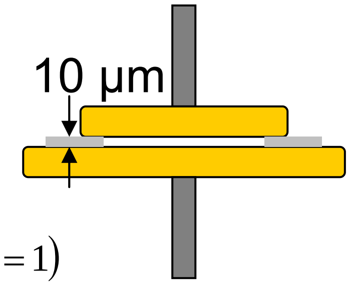
$$\text{Young's modulus } E = \frac{[stress]}{[strain]} = \frac{L_0}{\Delta L}\frac{F}{A}$$

$$\mathbf{F}_{SI} = \frac{qq'}{4\pi\varepsilon_0 r^3}\mathbf{r}$$

$$C = \frac{Q}{V}$$

$$C = \frac{\varepsilon_0 A}{d} \qquad (\varepsilon = 1)$$

$$E = \tfrac{1}{2}QV$$



$$F(t) = \frac{\varepsilon_s\varepsilon_0 A}{2}E^2(t) = \frac{\varepsilon_s\varepsilon_0 A}{4}E_0^2\times[1-\cos(2\omega t)]$$

$$\Delta\ln\varepsilon = -\frac{\Delta d}{d} = +\frac{F_0}{aY} = \frac{\varepsilon_s\varepsilon_0 A}{4aY}E_0^2$$

$$a = 4.7\times10^{-5}\ \mathrm{m}^2\ \text{(Teflon ring, d = 14-16 mm)}$$

$$Y = 1\,\mathrm{GPa}\ \text{(Teflon)}$$

$$F_0 = 31\,\mathrm{N}$$

$$F_0/a = 0.67\ \mathrm{MPa}$$

$$\Delta\ln\varepsilon = -\frac{\Delta d}{d} \le 6.7\times10^{-4}$$

dielectric saturation

expected non-linearity: dielectric saturation, Langevin effect

$$\langle \cos\theta \rangle = \frac{\int_0^{\pi} \cos\theta \, e^{\mu E \cos\theta / kT} \, d\theta}{\int_0^{\pi} e^{\mu E \cos\theta / kT} \, d\theta} \qquad \Rightarrow$$

$$\langle \cos\theta \rangle = \mathrm{cotanh}\left(\frac{\mu E}{kT}\right) - \left(\frac{\mu E}{kT}\right)^{-1}$$

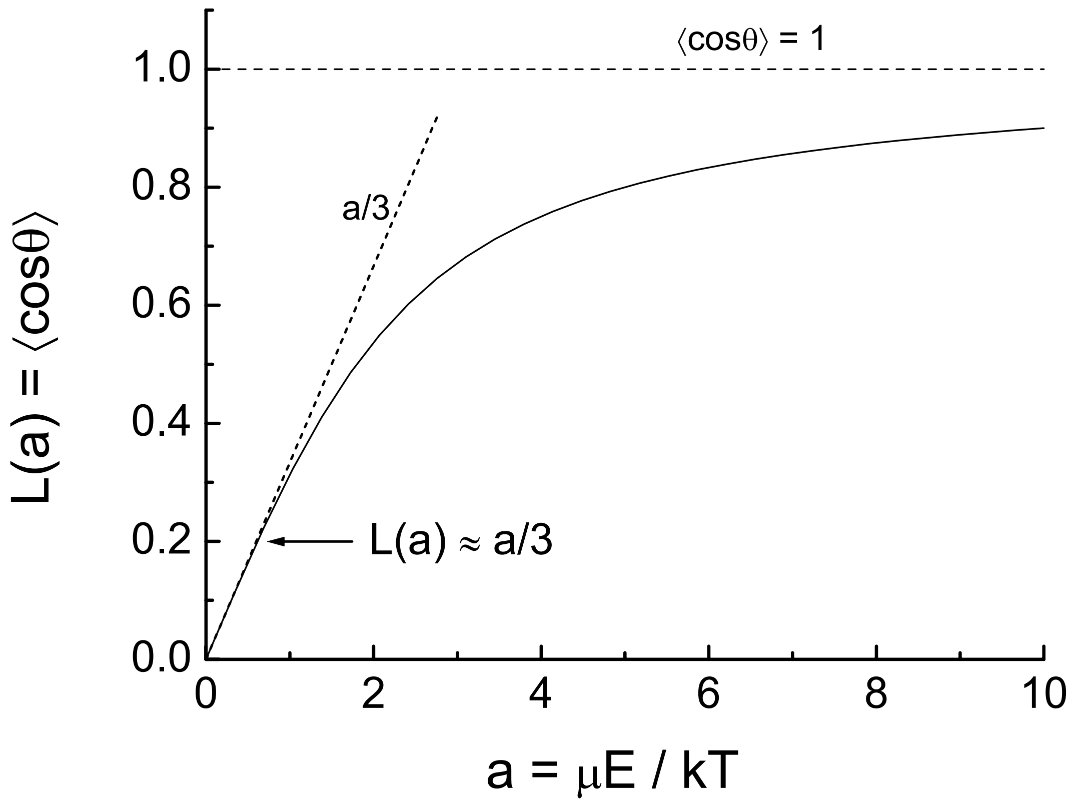
$$\langle \cos\theta \rangle = L\left(\frac{\mu E}{kT}\right) \qquad \begin{pmatrix}\text{Langevin} \\ \text{function}\end{pmatrix}$$

$$\text{with } a = \frac{\mu E}{kT}$$

$$\langle \cos\theta \rangle = L(a) = \mathrm{cotanh}(a) - \frac{1}{a}$$

$$\text{if } \mu E << kT \quad \text{or} \quad a << 1$$

$$\langle \cos\theta \rangle \approx \frac{a}{3} = \frac{\mu E}{3kT}$$

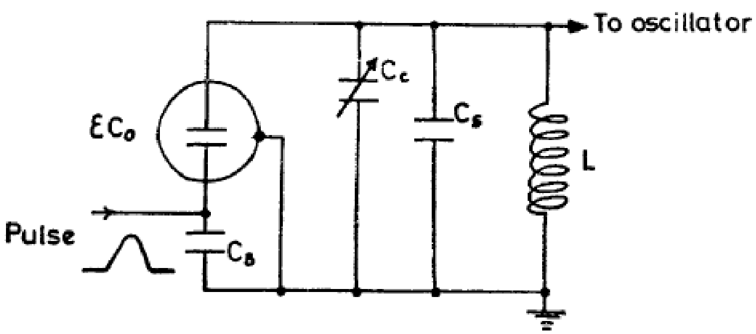


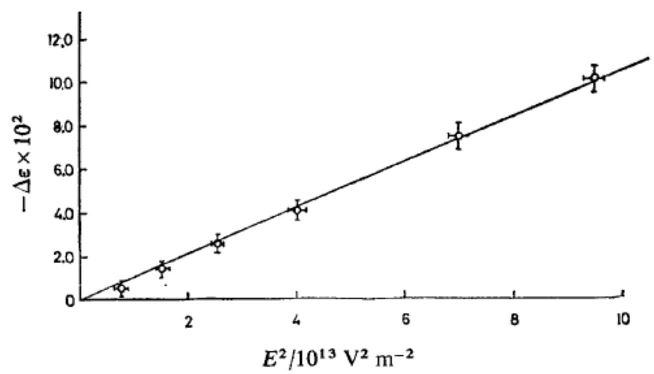
saturation in water at 293 K

Piekara $\Delta\varepsilon_s / E^2 = -\lambda\varepsilon_s$

vanVleck $\dfrac{\Delta\varepsilon_s}{E^2} = \dfrac{\varepsilon_s(E^2) - \varepsilon_s(0)}{E^2} = -\dfrac{N\mu^4}{45\varepsilon_0 V(kT)^3} \times \dfrac{\varepsilon_s^4(\varepsilon_\infty + 2)^4}{(2\varepsilon_s + \varepsilon_\infty)^2(2\varepsilon_s^2 + \varepsilon_\infty^2)}$

J. H. van Vleck, J. Chem. Phys. 5 (1937) 556
A. Piekara, Acta Phys. Polon. 18 (1959) 361





H. A. Kolodziej, G. Parry Jones, M. Davies, J. Chem. Soc. Faraday Trans. 2 71 (1975) 269

time resolved NDE experimens

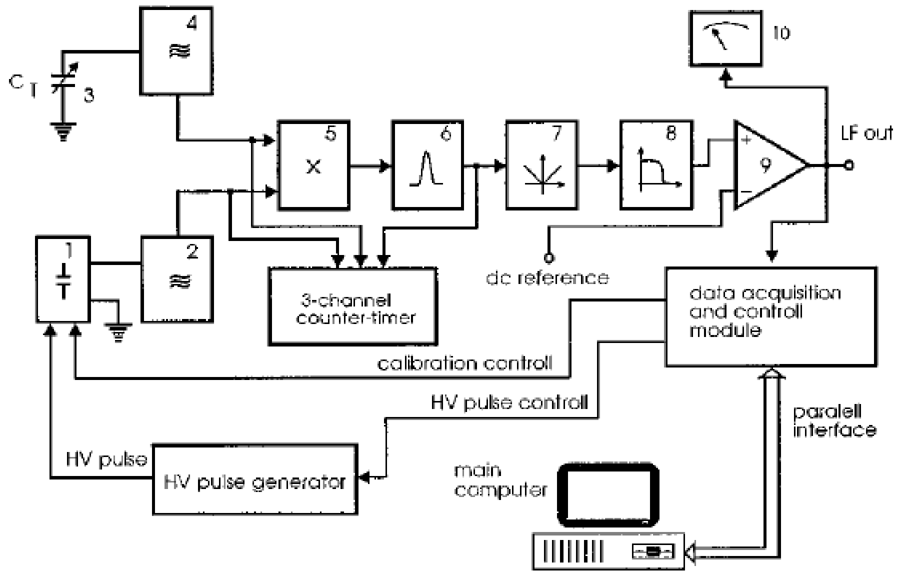
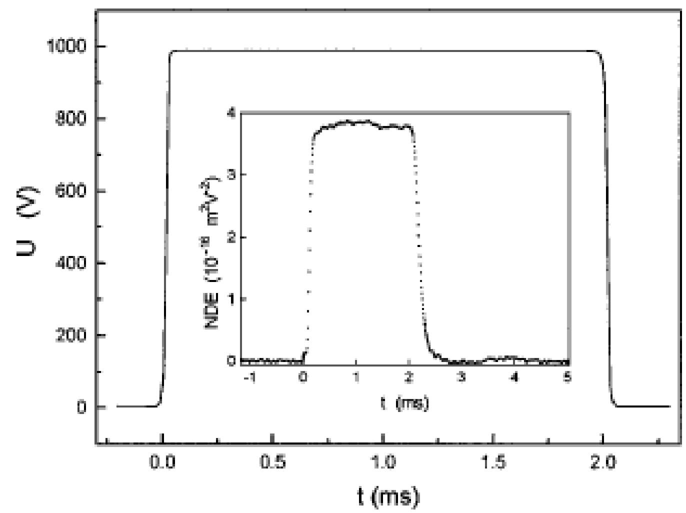
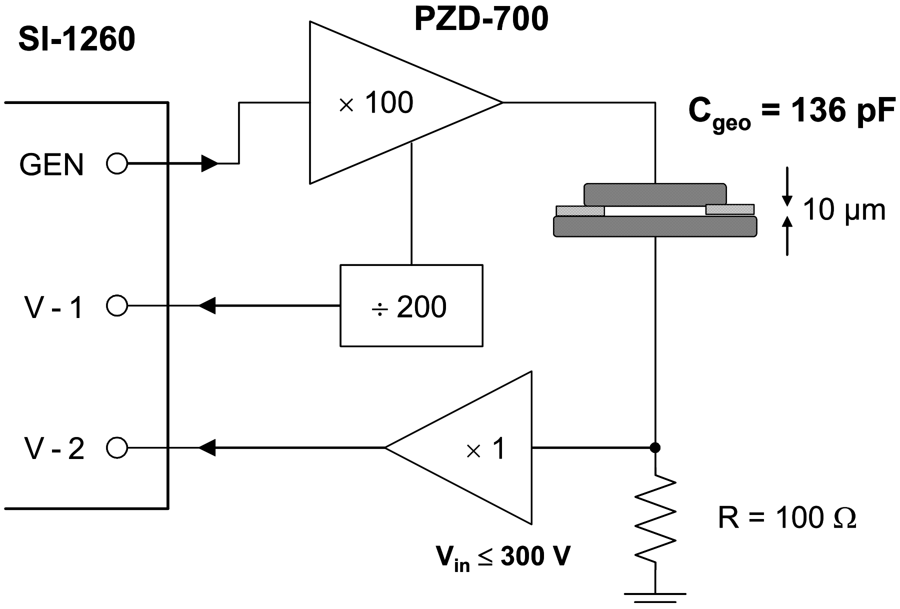


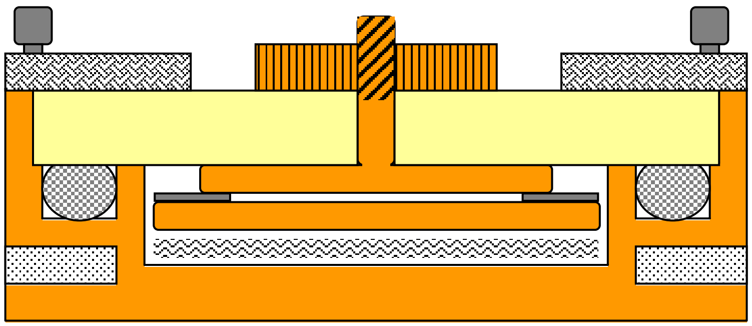
FIG. 1. The NDE measurement setup: 1—Measurement capacitor; 2—measurement generator ($G1$, freq. $f1+\Delta f$); 3,4—reference generator (G_2, freq. $f2$) with tuning capacitor; 5—mixer (freq. Δf); 6—bandpass filter; 7—rectifier; 8—low-pass filter; 9—amplifier; 10—indicator of the tuning of G_2 to $f_2=f_1+\Delta f$. The elements 2 and 4–10 are contained in one measurement unit.

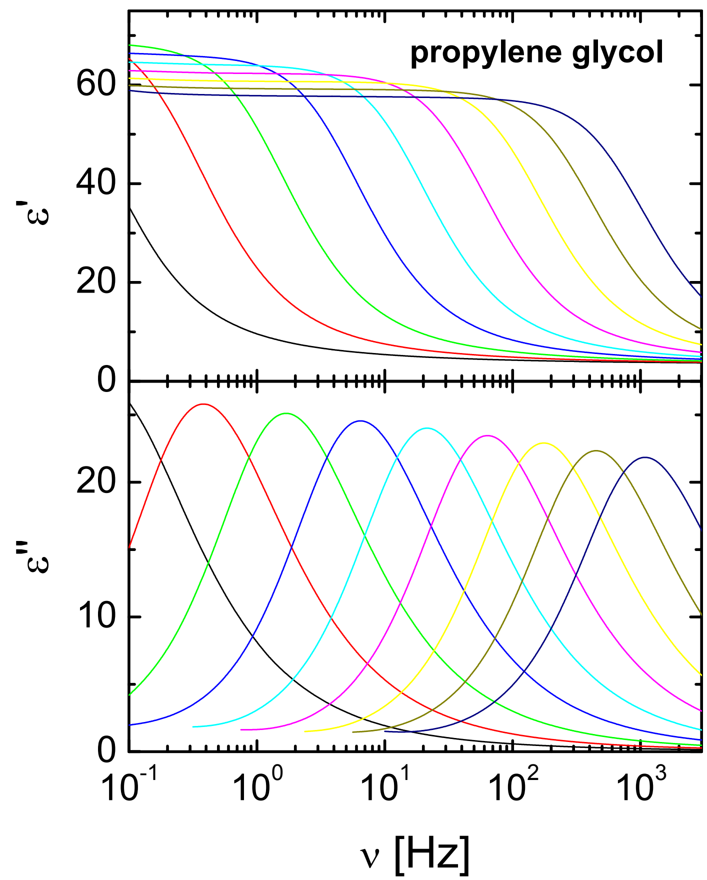


M. Gorny, J. Ziolo, S. J. Rzoska, Rev. Sci. Instrum. 67 (1996) 4290

high field impedance







S. Weinstein, R. Richert, Phys. Rev. B 75 (2007) 064302

S. Weinstein, R. Richert, J. Phys.: Condens. Matter 19 (2007) 205128

analyzer input protection

ANALOG DEVICES

Ultralow, Input-Bias Current
Operational Amplifier

AD549

AD 549 L

$R_{in} = 10^{15}\ \Omega$

$C_{in} = 0.8$ pF

$I_{bias} = 40$ fA

In the corresponding version of this scheme for a follower, shown in Figure 38, R_P and the capacitance at the positive input terminal produce a pole in the signal frequency response at a f = ½πRC. Again, the Johnson noise, R_P, adds to the amplifier's input voltage noise.

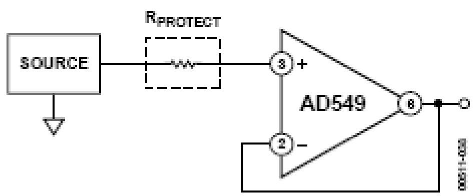
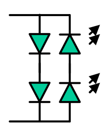
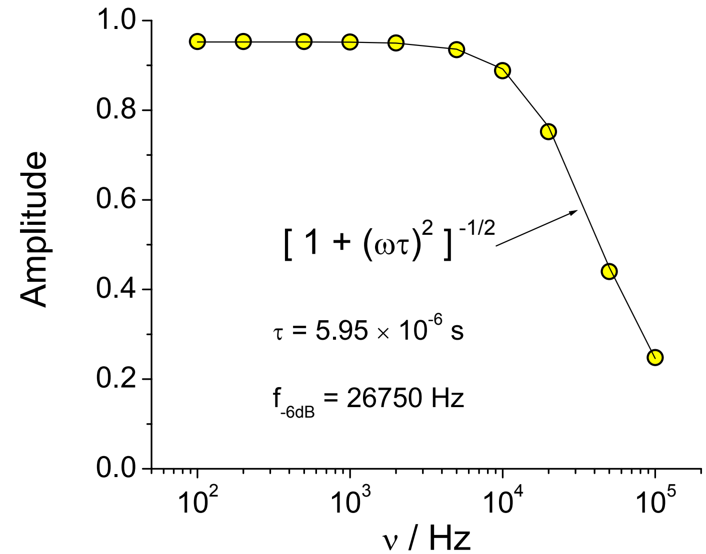


Figure 38. Follower with Input Current Limit

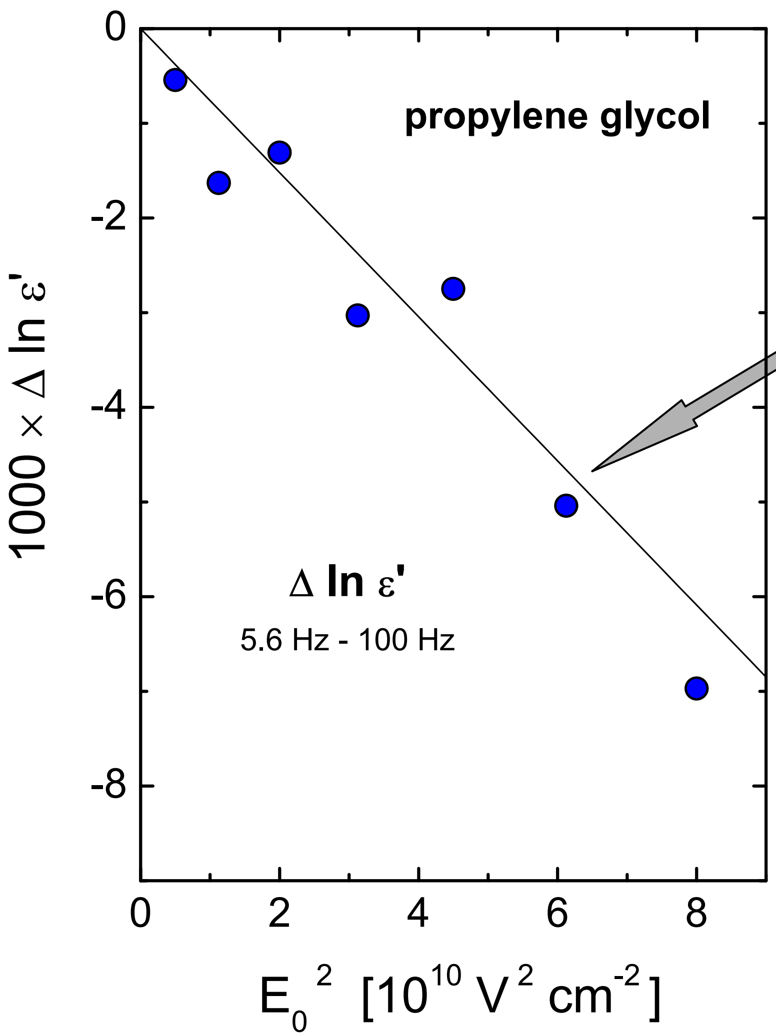




$R_{PROTECT} = 3$ MΩ:
protects against 300 V (no time limit)

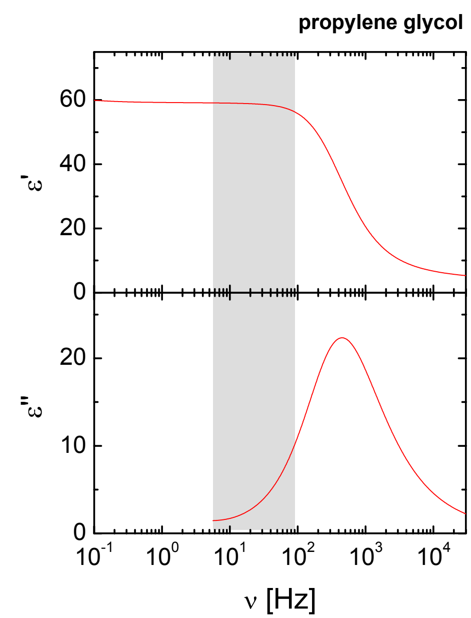
S. Weinstein, R. Richert, Phys. Rev. B 75 (2007) 064302
S. Weinstein, R. Richert, J. Phys.: Condens. Matter 19 (2007) 205128

field effect results for propylene glycol
[71 - 282 kV/cm steady state harmonic measurement]



$$\frac{\Delta\varepsilon_s}{E^2} = -\frac{N\mu^4}{45\varepsilon_0 V (kT)^3} \times \frac{\varepsilon_s^4(\varepsilon_\infty + 2)^4}{(2\varepsilon_s + \varepsilon_\infty)^2 (2\varepsilon_s^2 + \varepsilon_\infty^2)}$$

(van Vleck)



S. Weinstein, R. Richert, Phys. Rev. B 75 (2007) 064302
S. Weinstein, R. Richert, J. Phys.: Condens. Matter 19 (2007) 205128

energy absorbtion

(less) expected non-linearity: sample heating via dielectric loss

$$\frac{q_{eq}}{\upsilon} = \pi \varepsilon_0 E_0^2 \varepsilon''(\omega)$$

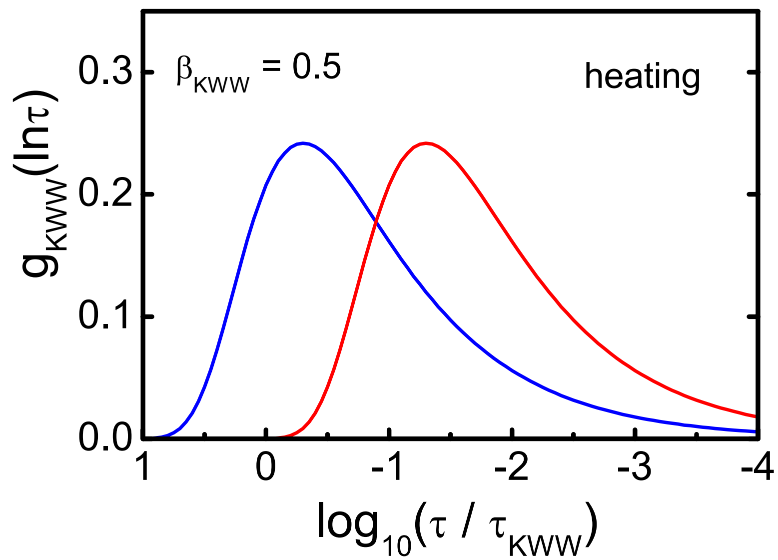
$$\varepsilon'' \approx 10$$

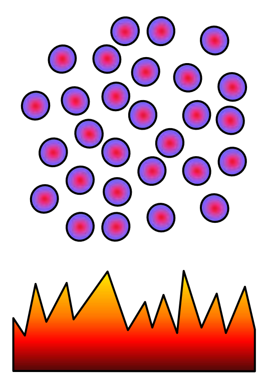
$$E_0 = 28.2\,\mathrm{MVm^{-1}}$$

$$\frac{q_{eq}}{\upsilon} = 0.22\,\mathrm{J\,cm^{-3}}$$

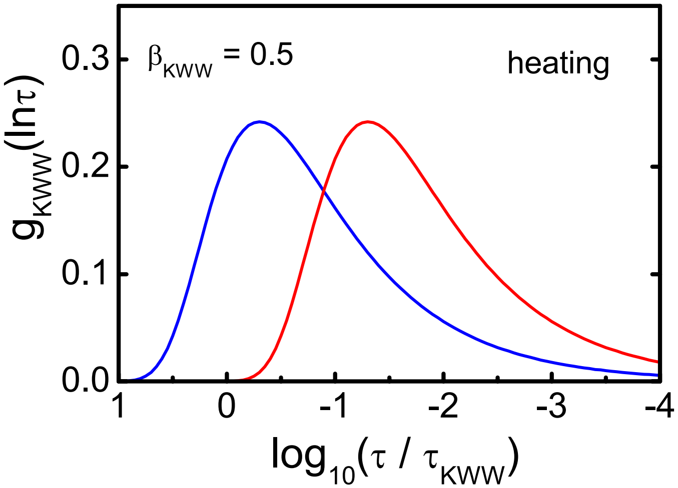
$$\frac{c_p}{\upsilon} \approx 2\,\mathrm{J\,K^{-1}\,cm^{-3}}$$

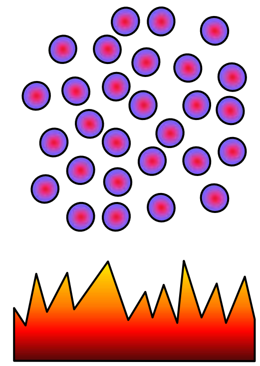
$$\Delta T = \frac{q_{eq}}{c_p} \approx 0.1\,\mathrm{K}$$

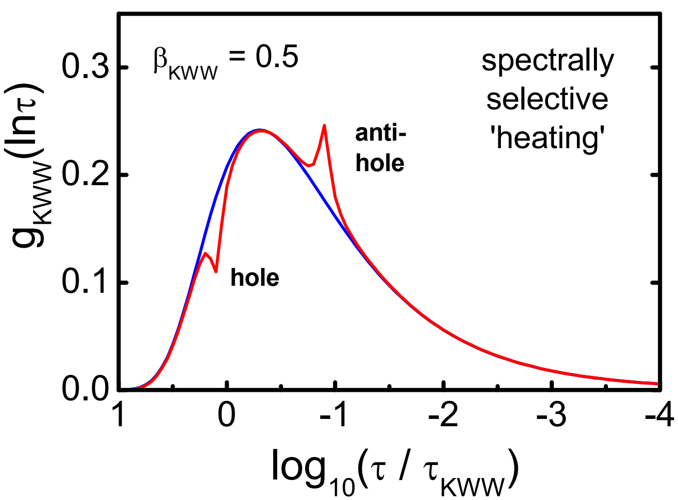


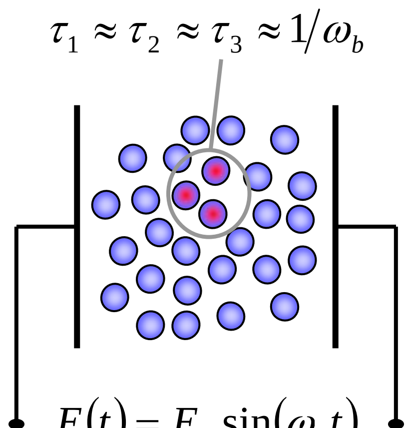


spectrally selective dielectric experiments







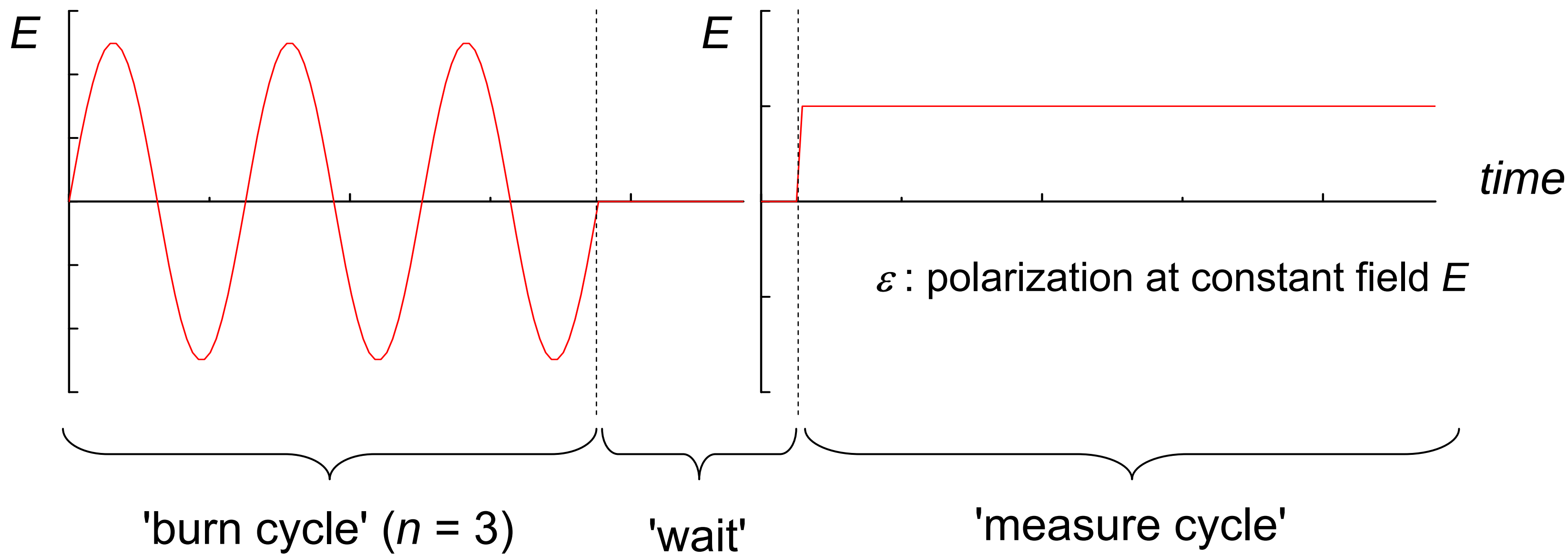


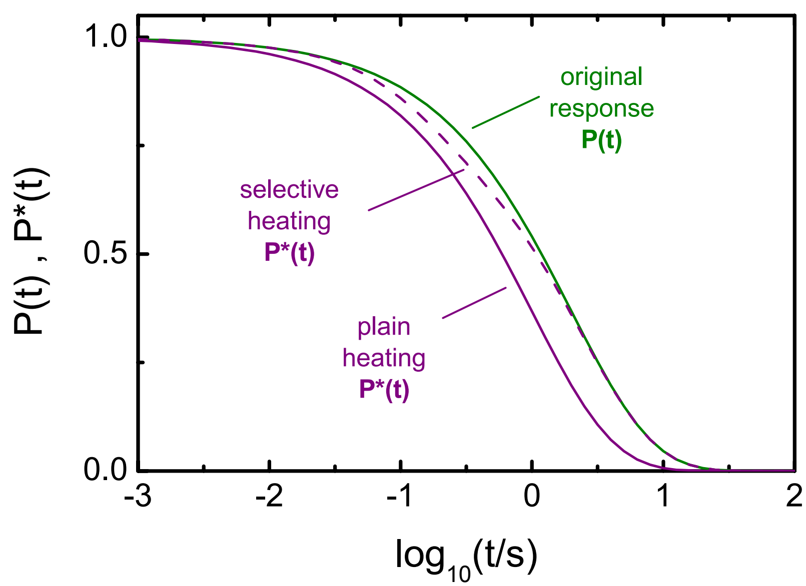
$$E(t) = E_b \sin(\omega_b t)$$

$$\Delta Q = \pi\varepsilon_0\, \varepsilon''(\omega_b)\, E_b^2$$

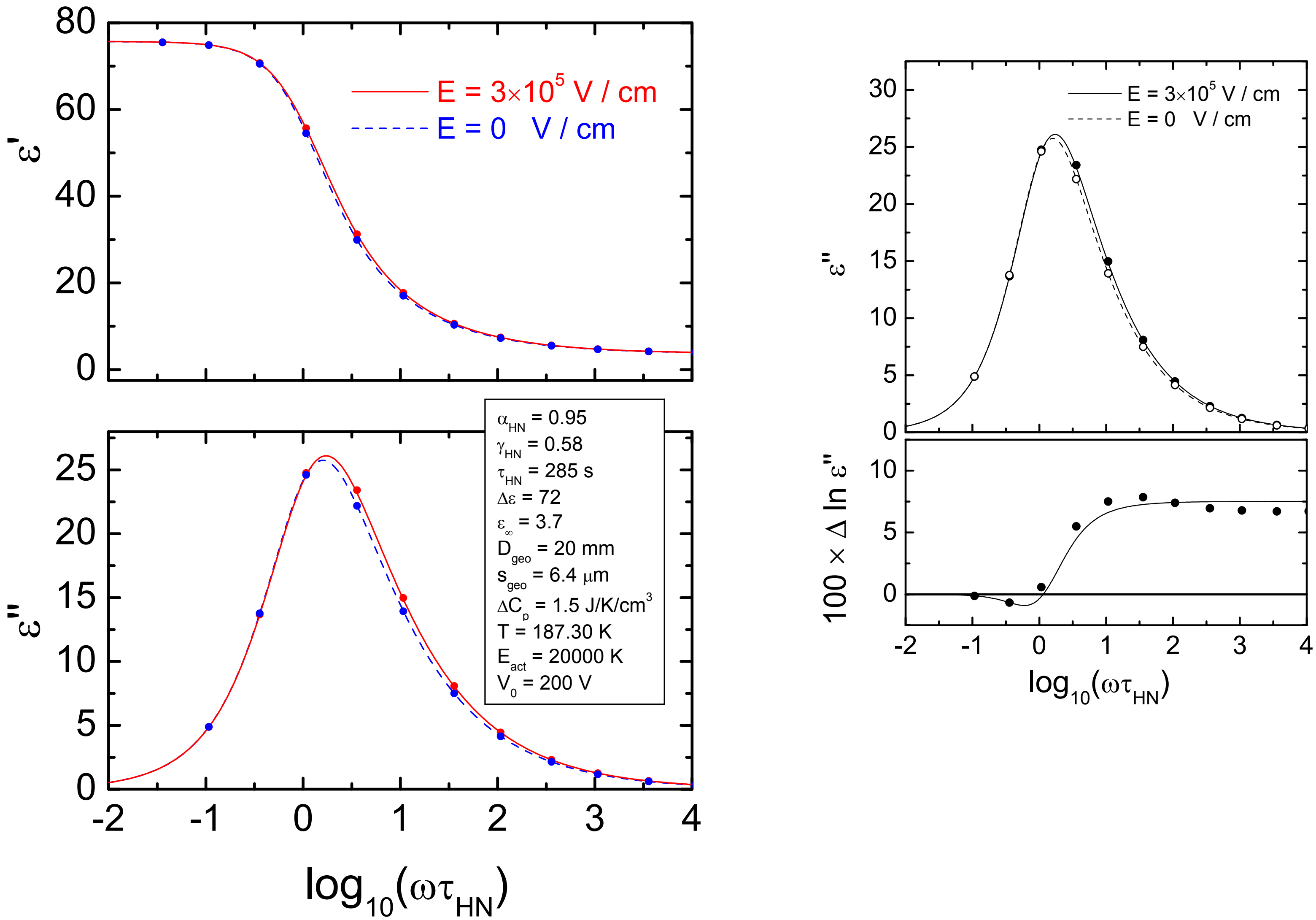
B. Schiener, R. Böhmer, A. Loidl, R. V. Chamberlin, Science 274 (1996) 752
B. Schiener, R. V. Chamberlin, G. Diezemann, R. Böhmer, J. Chem. Phys. 107 (1997) 7746
R. V. Chamberlin, B. Schiener, R. Böhmer, Mat. Res. Soc. Symp. Proc. 455 (1997) 117

dielectric hole-burning technique: what do we look for?





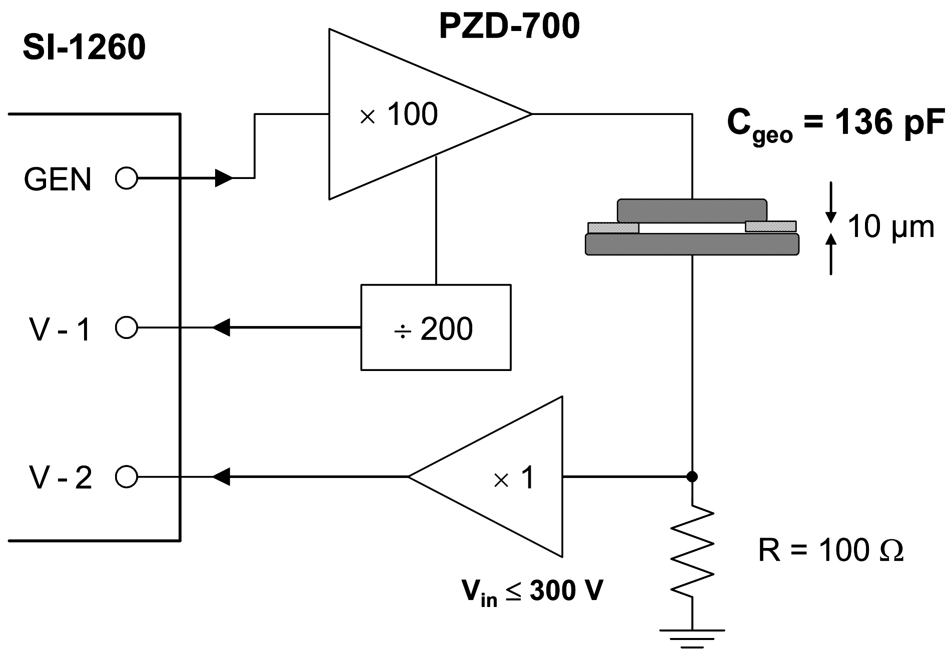
model prediction for 300 kV/cm steady state harmonic field

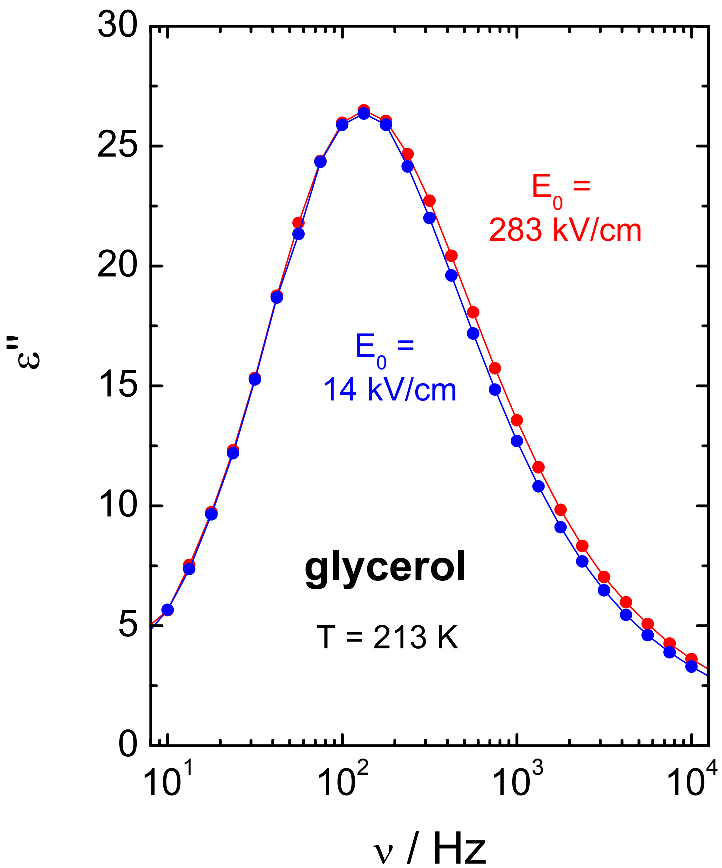


R. Richert, S. Weinstein, Phys. Rev. Lett. 97 (2006) 095703

high field impedance

high field impedance technique





fields up to 450 kV/cm

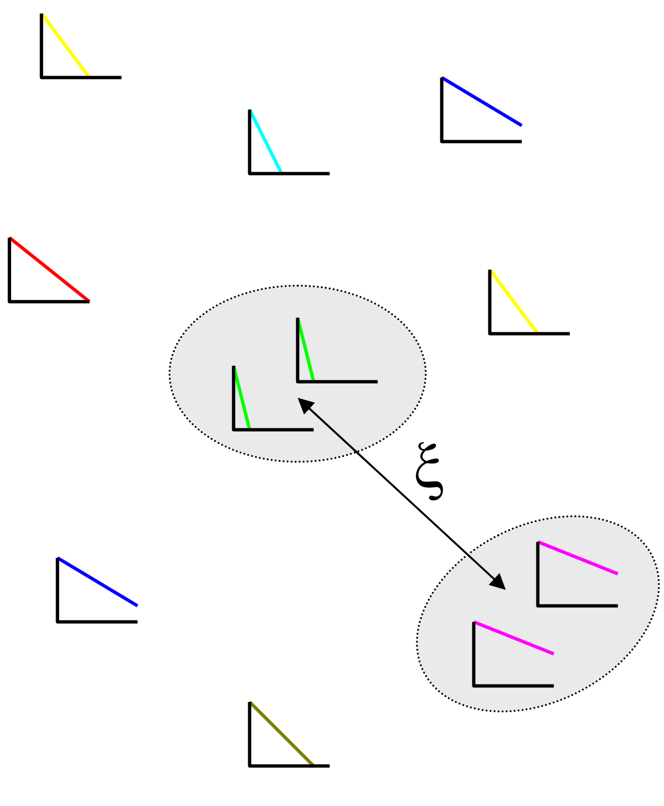
μE **up to 0.082** ***kT***

0.1 Hz to 50 kHz range

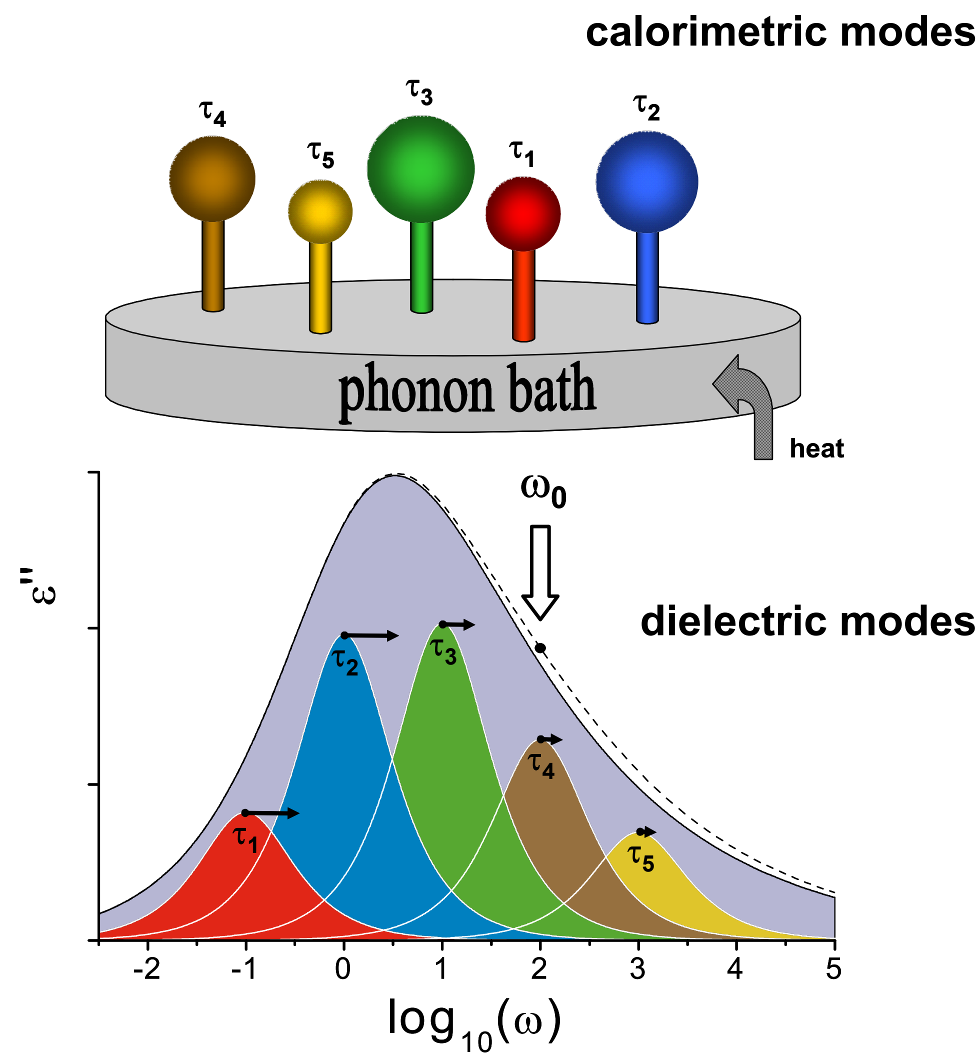
R. Richert, S. Weinstein, Phys. Rev. Lett. 97 (2006) 095703

heterogeneous dynamics and configurational temperatures

dynamically correlated domains



$$\tau_T = \tau_D$$



W. Huang, R. Richert, J. Phys. Chem. B 112 (2008) 9909

model for high-field steady-state harmonic measurement

harmonic field $E_0 \sin(\omega_b t)$ applied:

steady state energy Q/n per period:

$$\frac{Q}{n} = \pi \varepsilon_0 E_0^2 \varepsilon''(\omega) V$$

power p averaged over period:

$$p = \frac{Q\omega}{2\pi} = \frac{\varepsilon_0 E_0^2 \varepsilon''(\omega) V \omega}{2}$$

excess configurational temperature:

$$\frac{dT_{cfg}}{dt} = \frac{p}{c_p} - \frac{T_{cfg} - T}{\tau_T} = 0 \quad \Rightarrow \quad T_{cfg} = T + \frac{\tau_T p}{c_p}$$

for a single domain with $\tau = \tau_{\mathrm{T}} = \tau_{\mathrm{D}}$:

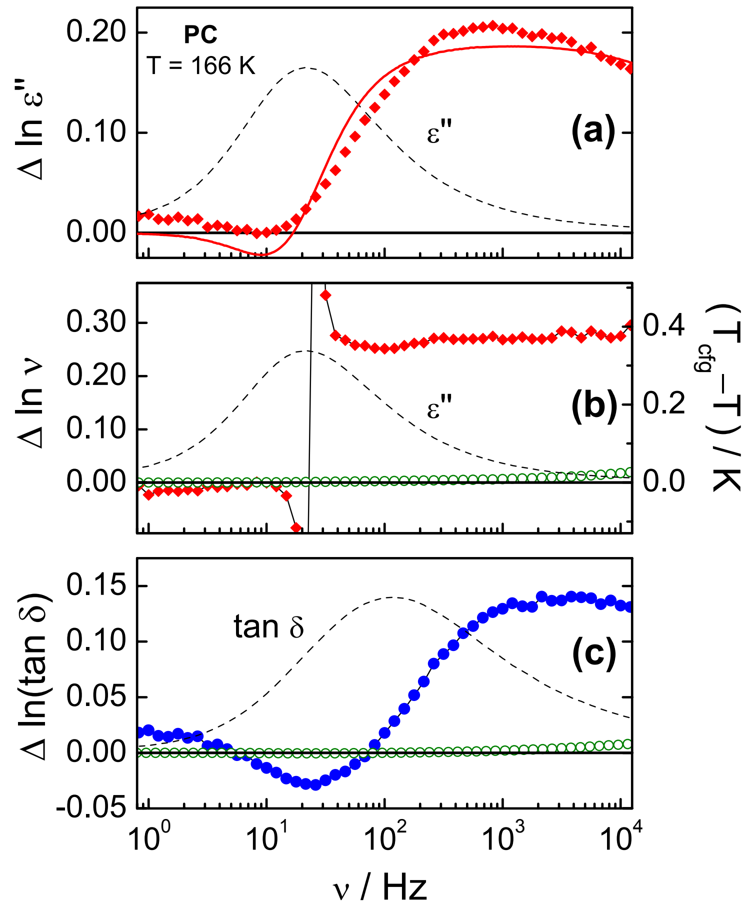
$$T_{cfg} = T + \frac{\varepsilon_0 E_0^2 \Delta\varepsilon}{2\Delta c_p} \frac{\omega^2 \tau^2}{1 + \omega^2 \tau^2}$$

analogous to 'box'-model:

B. Schiener, R. Böhmer, A. Loidl, R. V. Chamberlin, Science 274 (1996) 752

propylene carbonate

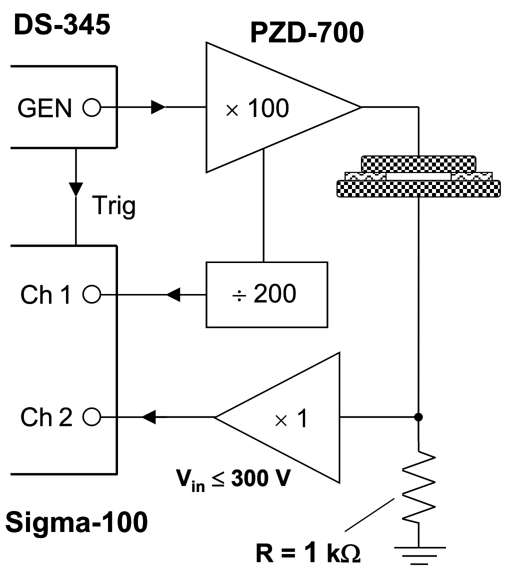
(E_0 = 177 kV/cm)

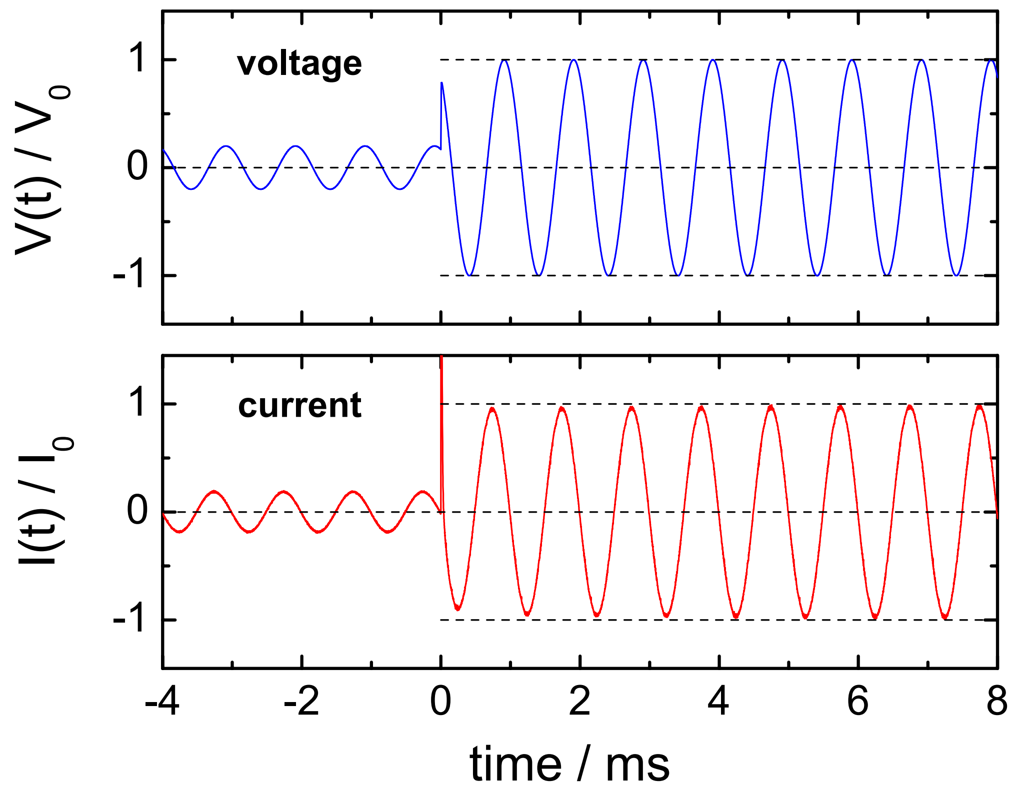


R. Richert, S. Weinstein, Phys. Rev. Lett. 97 (2006) 095703

W. Huang, R. Richert, J. Chem. Phys. 130 (2009) 194509

adding time-resolution capabilities to high-field technique





$$\underline{S(t) = V(t) \text{ or } I(t)}$$

$$R = \frac{\omega}{\pi}\int_0^{2\pi/\omega} \sin(\omega t) S(t)\,dt = A\cos(\varphi)$$

$$I = \frac{\omega}{\pi}\int_0^{2\pi/\omega} \cos(\omega t) S(t)\,dt = A\sin(\varphi)$$

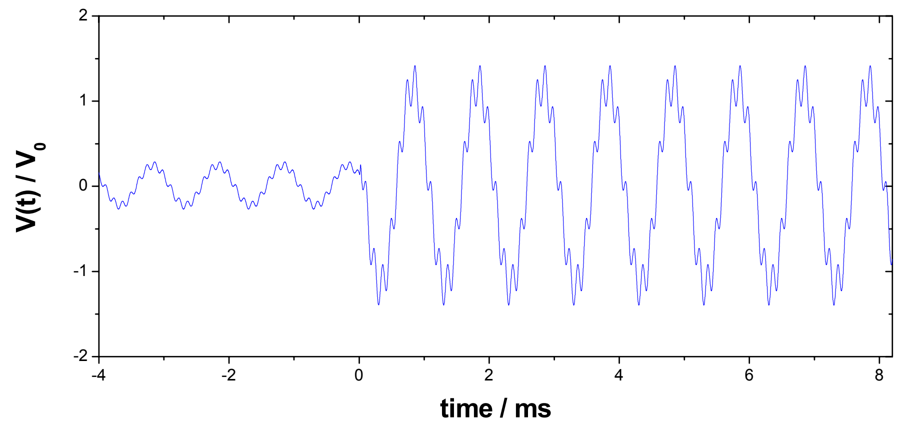
$$A = \sqrt{R^2 + I^2} \quad \varphi = \arctan\left(\frac{I}{R}\right)$$

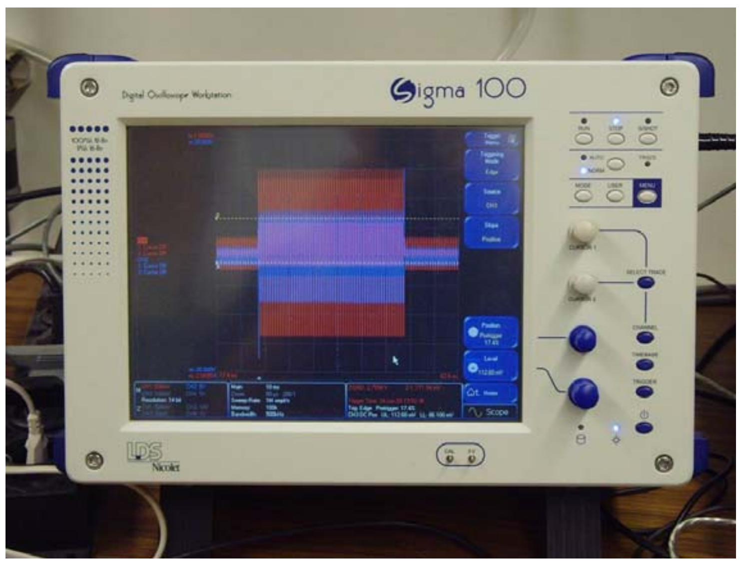
$$\tan\delta = \tan\left(\frac{\pi}{2} - \Delta\varphi\right)$$

L.-M. Wang, R. Richert, Phys. Rev. Lett. 99 (2007) 185701
W. Huang, R. Richert, J. Phys.Chem. B 112 (2008) 9909

single/multiple frequency technique

Stanford Research DS-345 Generator





Nicolet Sigma 100 Digital Oscilloscope

4 channels

1 Ms depth

12 bit @ 100 Ms/s
14 bit @ 1 Ms/s

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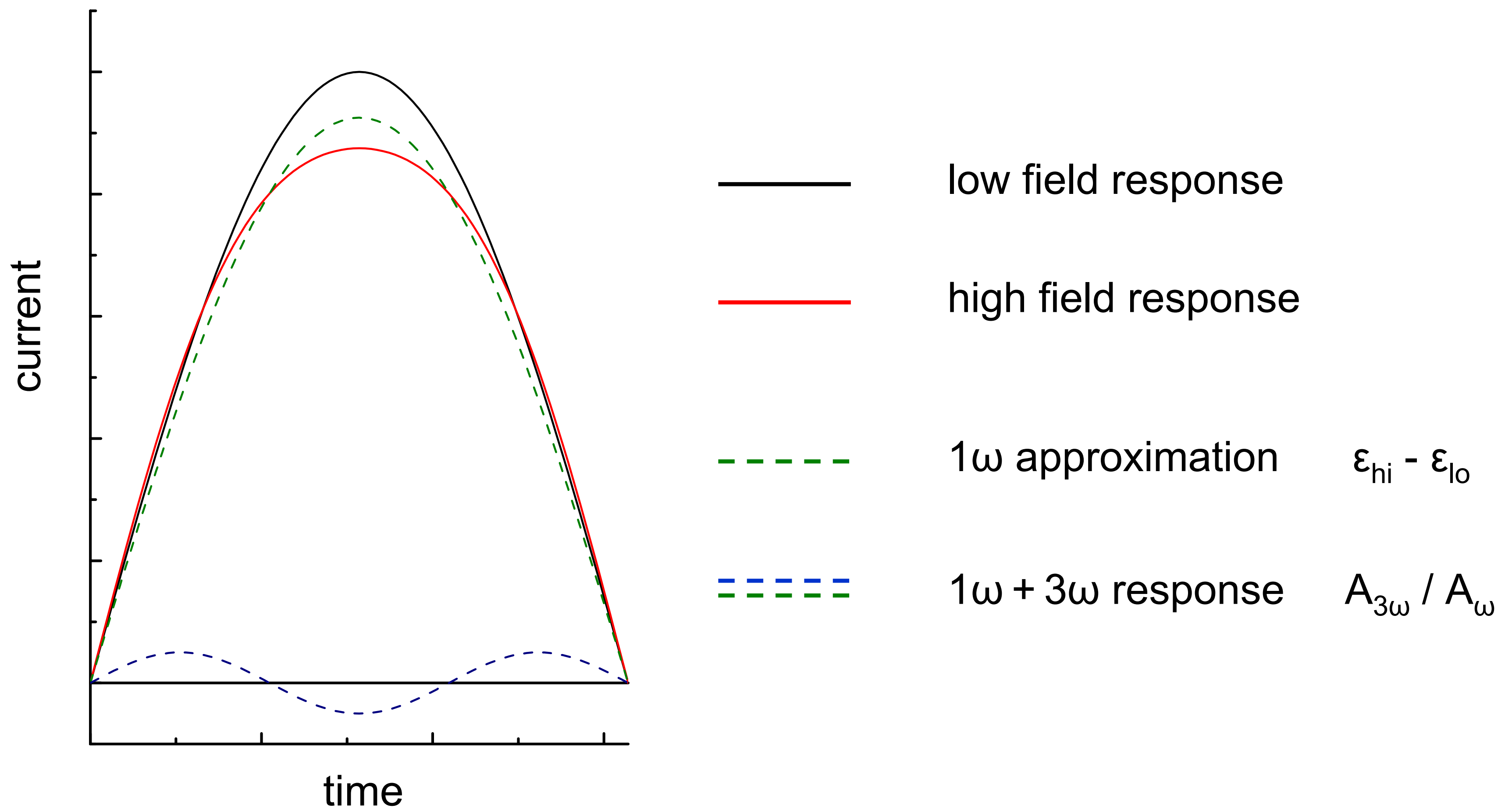
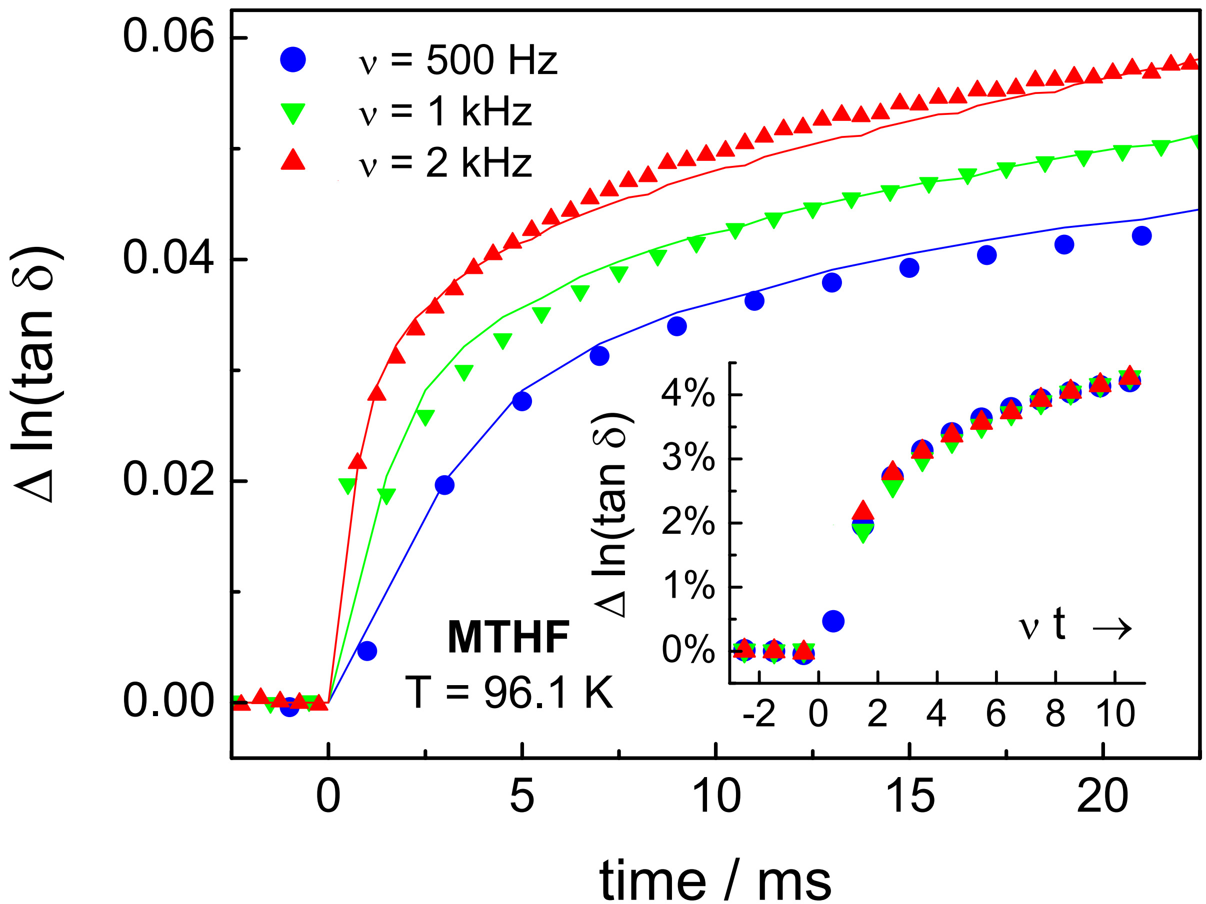
1ω versus 3ω data analysis



rise of configurational temperature for different frequencies



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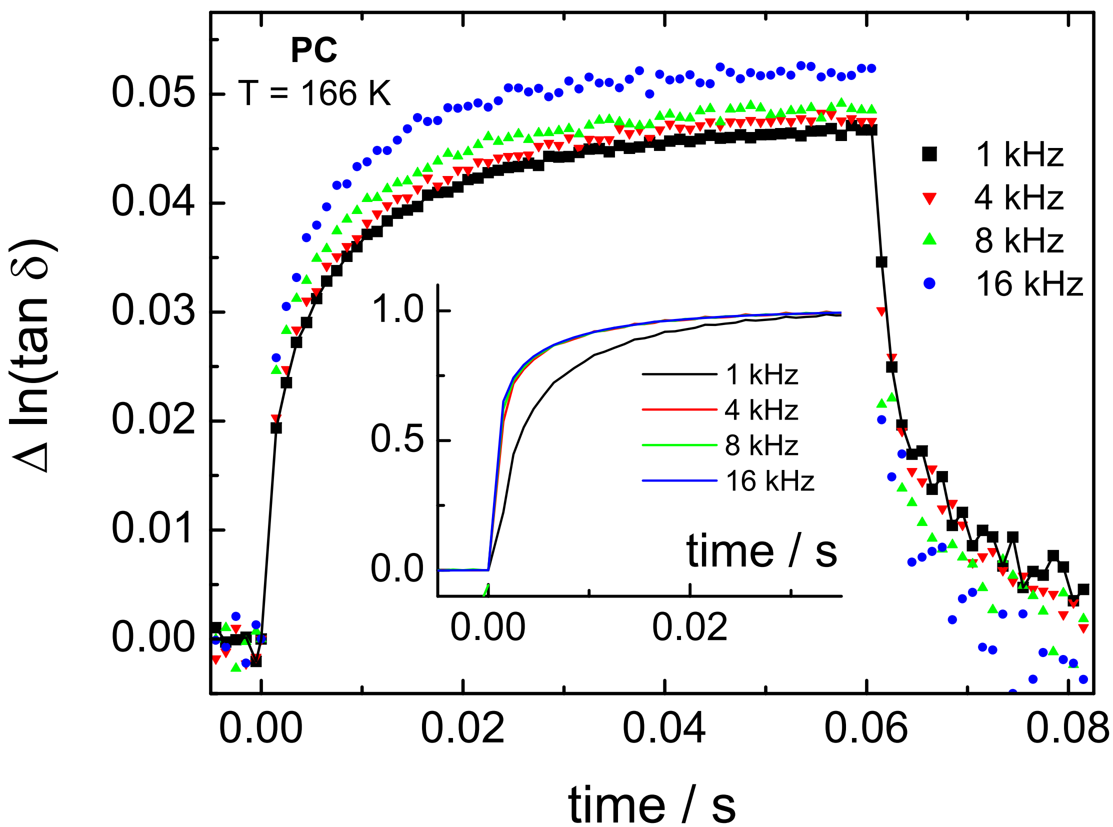
rise of configurational temperature for pumping with 1 kHz and probing at higher frequencies



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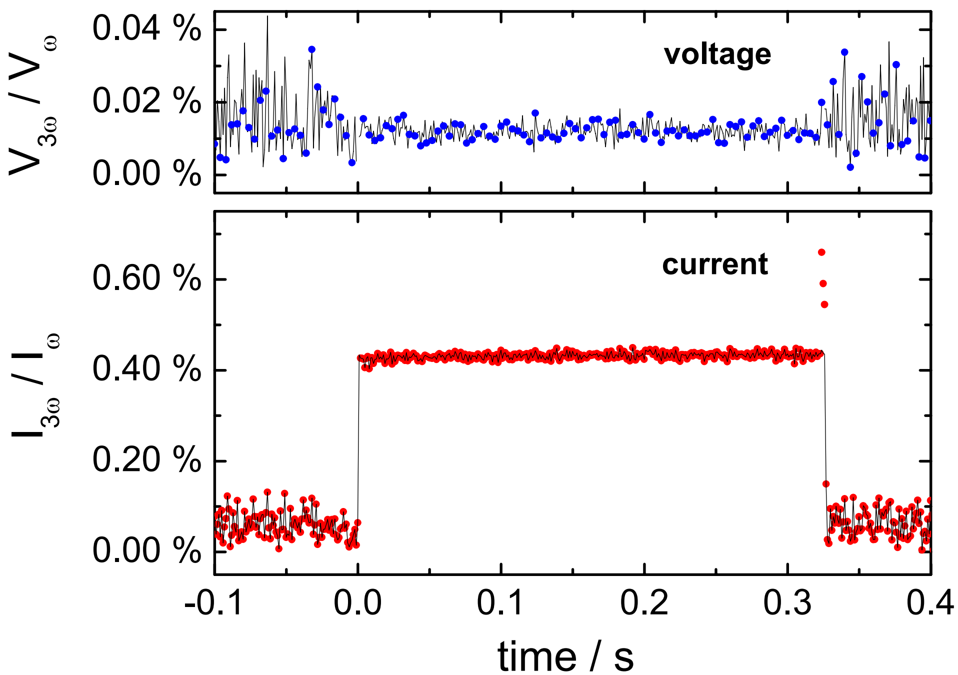
3ω signal during field change



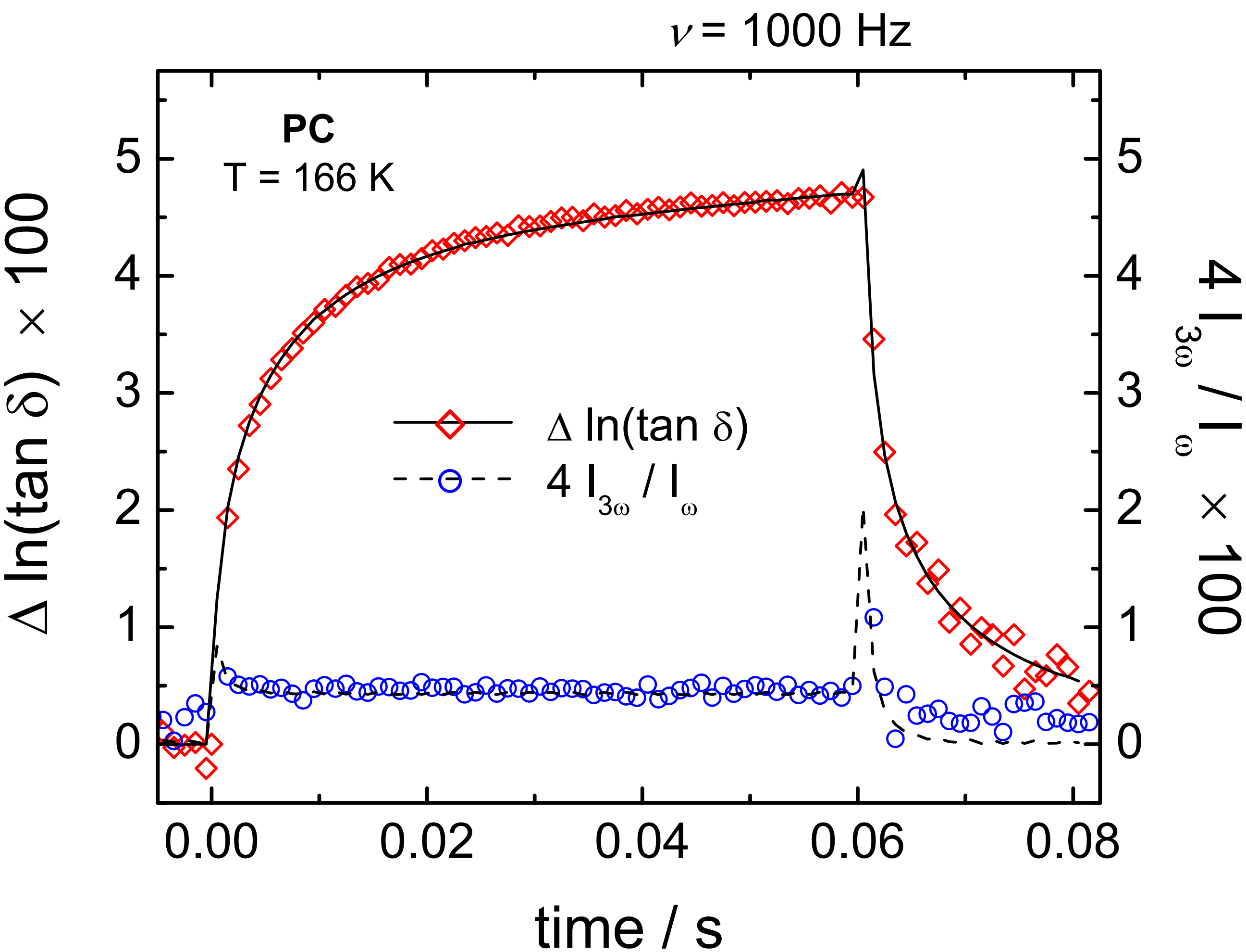
$$D_0 = \varepsilon\varepsilon_0 E_0 + \lambda\varepsilon\varepsilon_0 E_0^3$$
$$= \varepsilon\varepsilon_0 E_0 \times \left(1 + \lambda E_0^2\right)$$
$$\lambda = \Delta \ln \varepsilon \big/ E_0^2$$

$$E = E_0 \sin(\omega t)$$
$$D_\omega(t) = \varepsilon\varepsilon_0 E_0 \sin(\omega t) + \lambda\varepsilon\varepsilon_0 E_0^3 \tfrac{3}{4} \sin(\omega t)$$
$$\Rightarrow \qquad A_\omega \approx \varepsilon\varepsilon_0 E_0$$
$$D_{3\omega}(t) = -\lambda\varepsilon\varepsilon_0 E_0^3 \tfrac{1}{4} \sin(3\omega t)$$
$$\Rightarrow \qquad A_{3\omega} = \tfrac{1}{4} \varepsilon\varepsilon_0 E_0 \Delta \ln \varepsilon$$

$$\left.\begin{aligned} R &= \frac{\omega}{\pi} \int_0^{2\pi/\omega} \sin(3\omega t) V(t)\, dt \\ I &= \frac{\omega}{\pi} \int_0^{2\pi/\omega} \cos(3\omega t) V(t)\, dt \end{aligned}\right\} A = \sqrt{R^2 + I^2}$$

$$\frac{A_{3\omega}}{A_\omega} = \frac{\Delta \ln \varepsilon}{4}$$

agreement between experiment and model



$$R = \frac{\omega}{\pi}\int_0^{2\pi/\omega}\sin(n\omega t)S(t)dt$$

$$I = \frac{\omega}{\pi}\int_0^{2\pi/\omega}\cos(n\omega t)S(t)dt$$

$$A = \sqrt{R^2 + I^2}$$

$$\varphi = \arctan\left(\frac{I}{R}\right)$$

$$\tan\delta = \tan\left(\frac{\pi}{2} - \Delta\varphi\right)$$

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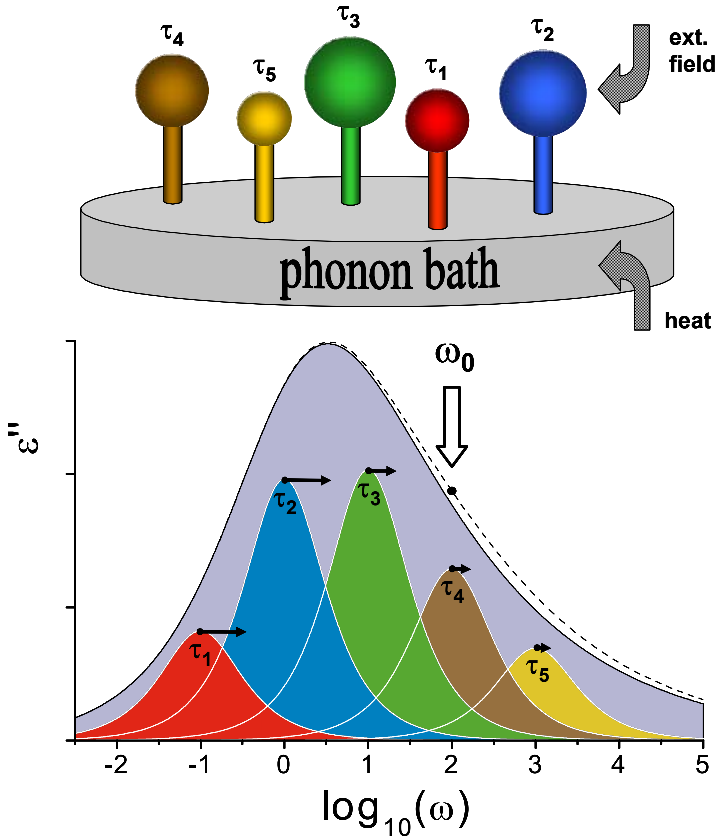
non-steady state version of 'box'-model



separately for each domain *i*

$$\Delta\varepsilon_i = \Delta\varepsilon g(\tau)d\tau \Rightarrow \sum_i \Delta\varepsilon_i = \Delta\varepsilon$$

$$\Delta C_{p,i} = \Delta C_p g(\tau)d\tau \Rightarrow \sum_i \Delta C_{p,i} = \Delta C_p$$

initial conditions :

$D_i(0) = 0$ and $T_i(0) = T$

$$\frac{dD_i(t)}{dt} = j_i(t) = \frac{\varepsilon_0 E(t)\Delta\varepsilon_i}{\tau_i(t)} - \frac{D_i(t)}{\tau_i(t)}$$

$$\frac{dT_i(t)}{dt} = \frac{j_i^2(t)\tau_i(t)V}{\varepsilon_0\Delta\varepsilon_i\Delta C_{p,i}} - \frac{T_i(t)-T}{\tau_i(t)}$$

$$\tau_i(t) = \tau_i(0)\left[1 - \frac{T_i(t)-T}{T}\left(\frac{E_A}{k_B T}\right)\right]$$

$$\frac{dT}{dt} = \sum_i \frac{T_i(t)-T}{\tau_i(t)}\frac{\Delta C_{p,i}}{C_{p.\infty}} \text{ for adiabatic case}$$

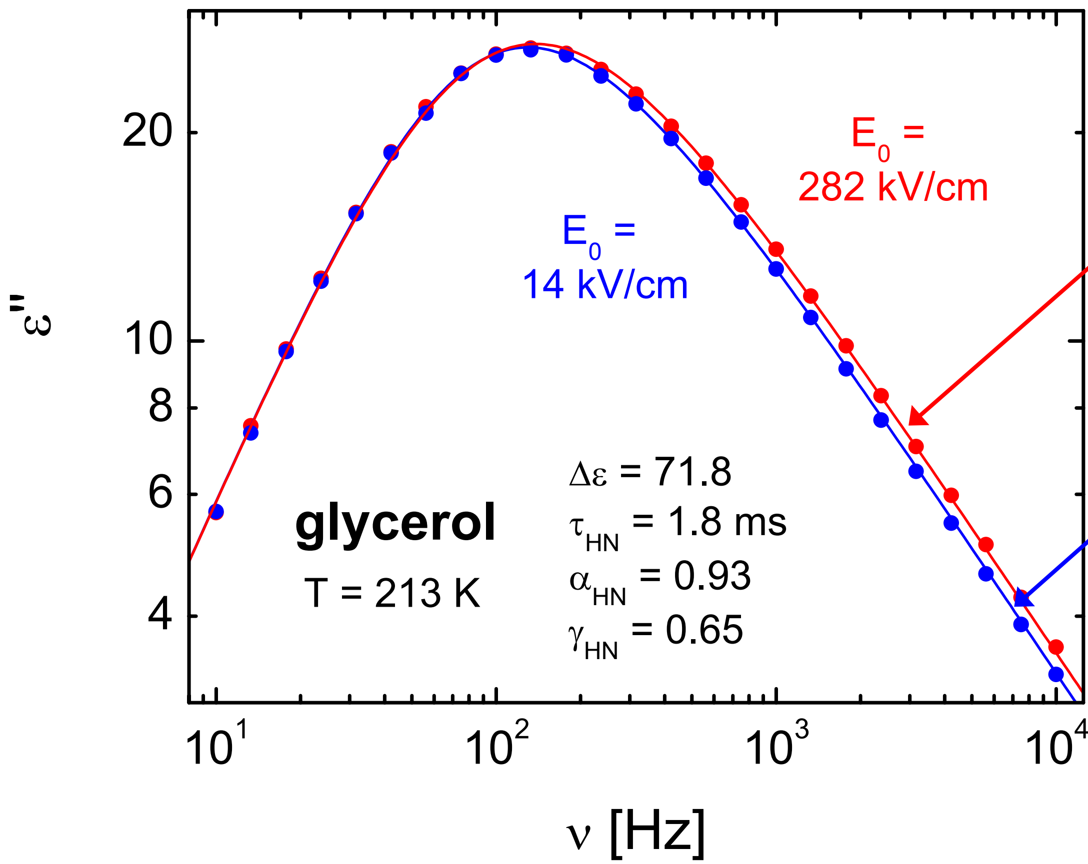
$$V(t) = E(t)d$$

$$I(t) = Aj_\infty + A\sum j_i(t) = A\left(\varepsilon_0\varepsilon_\infty\frac{dE(t)}{dt} + \sum j_i(t)\right)$$

W. Huang, R. Richert, J. Chem. Phys. 130 (2009) 194509

what do we learn ?

high voltage impedance results for glycerol



current model:

$$\ln \tau^* = \ln \tau - \frac{T_A}{T^2} \times \frac{\varepsilon_0 E_0^2 \Delta\varepsilon}{2\Delta c_p} \times \frac{\omega^2\tau^2}{1+\omega^2\tau^2}$$

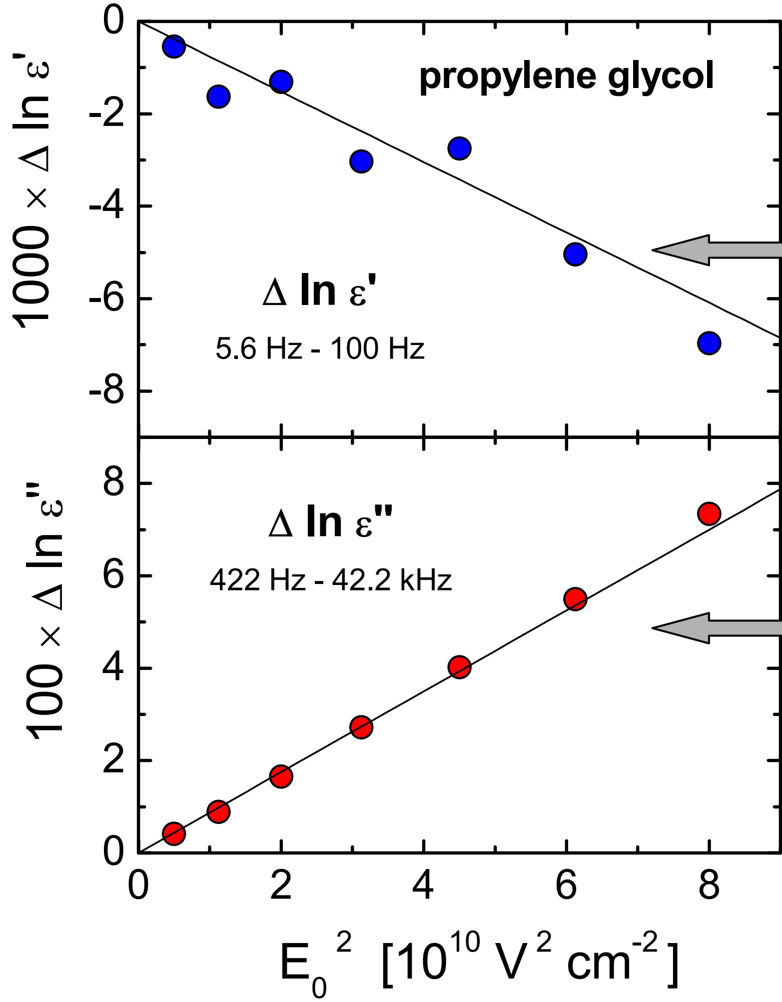
$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \Delta\varepsilon \int_0^\infty g(\tau) \frac{1}{1+i\omega\tau^*} d\tau$$

Havriliak - Negami fit:

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{\left[1+(i\omega\tau)^\alpha\right]^\gamma}$$

R. Richert, S. Weinstein, Phys. Rev. Lett. 97 (2006) 095703

summary of relevant non-linear effects (~E²)



Coulombic stress :

$$Fd = \tfrac{1}{2} QV, Q = CV, C = \varepsilon\varepsilon_0 A/d$$

$$F(t) = \frac{\varepsilon_s \varepsilon_0 A}{2} E^2(t) = \underbrace{\frac{\varepsilon_s \varepsilon_0 A}{4} E_0^2}_{\approx 31\,\mathrm{N}} - \frac{\varepsilon_s \varepsilon_0 A}{4} E_0^2 \cos(2\omega t)$$

dielectric saturation :

$$\frac{\Delta\varepsilon_s}{E^2} = -\frac{N\mu^4}{45\varepsilon_0 V (kT)^3} \times \frac{\varepsilon_s^4 (\varepsilon_\infty + 2)^4}{(2\varepsilon_s + \varepsilon_\infty)^2 (2\varepsilon_s^2 + \varepsilon_\infty^2)}$$

(van Vleck)

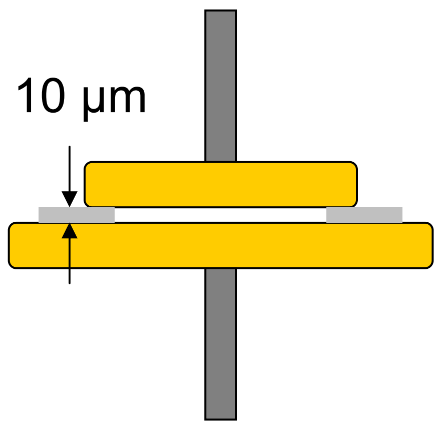
energy absorption :

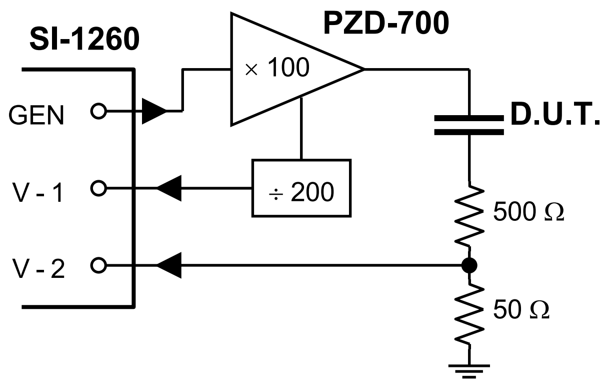
$$T_e(\tau) = \frac{\varepsilon_0 E_0^2 \Delta\varepsilon}{2\Delta c_p} \times \frac{\omega_0^2 \tau^2}{1 + \omega_0^2 \tau^2} = T_\mathrm{e}^0 \times \frac{\omega_0^2 \tau^2}{1 + \omega_0^2 \tau^2}$$

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \Delta\varepsilon \int_0^\infty g(\tau) \frac{1}{1 + i\omega\tau^*} d\tau$$

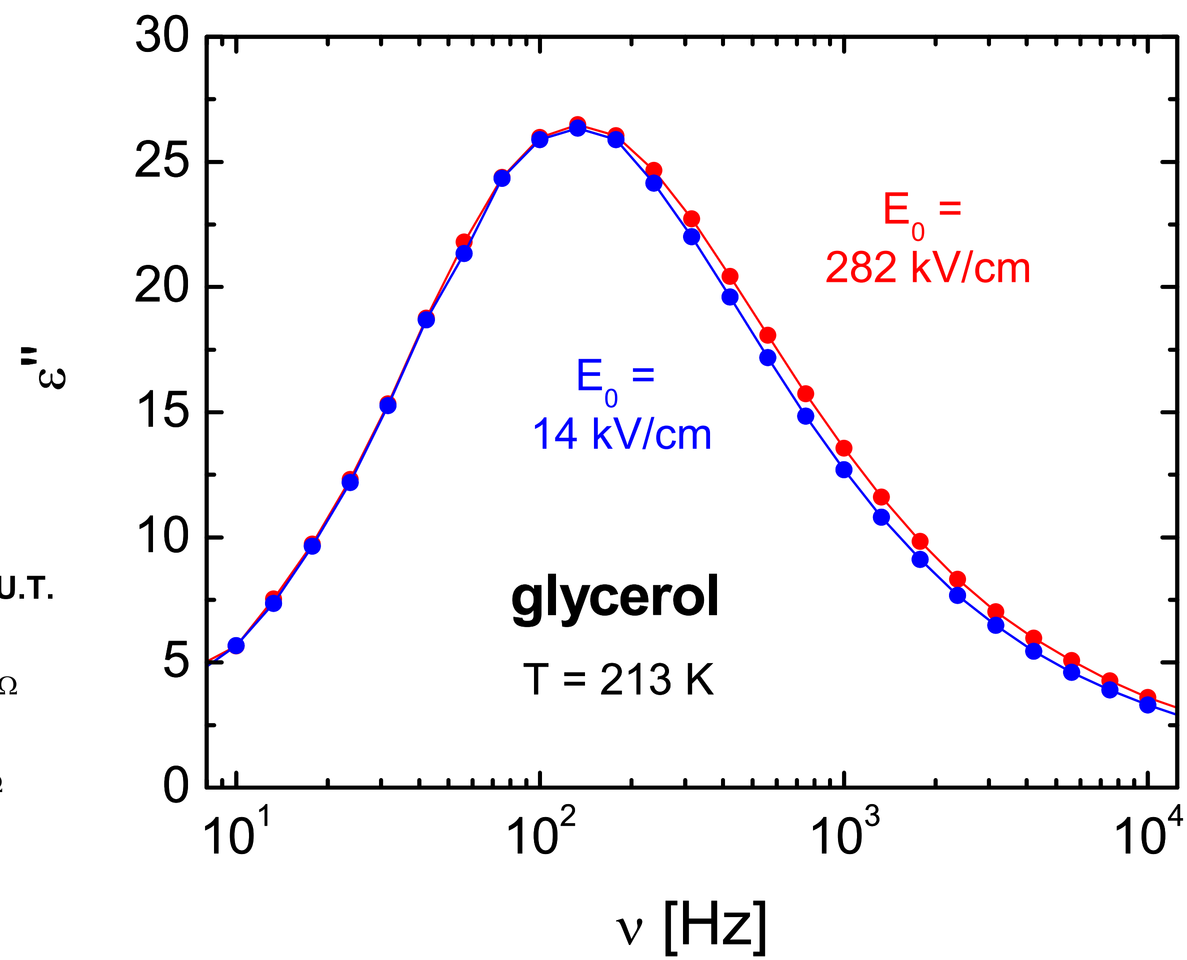
S. Weinstein, R. Richert, Phys. Rev. B 75 (2007) 064302

continuous harmonic (impedance) measurement
(glycerol)



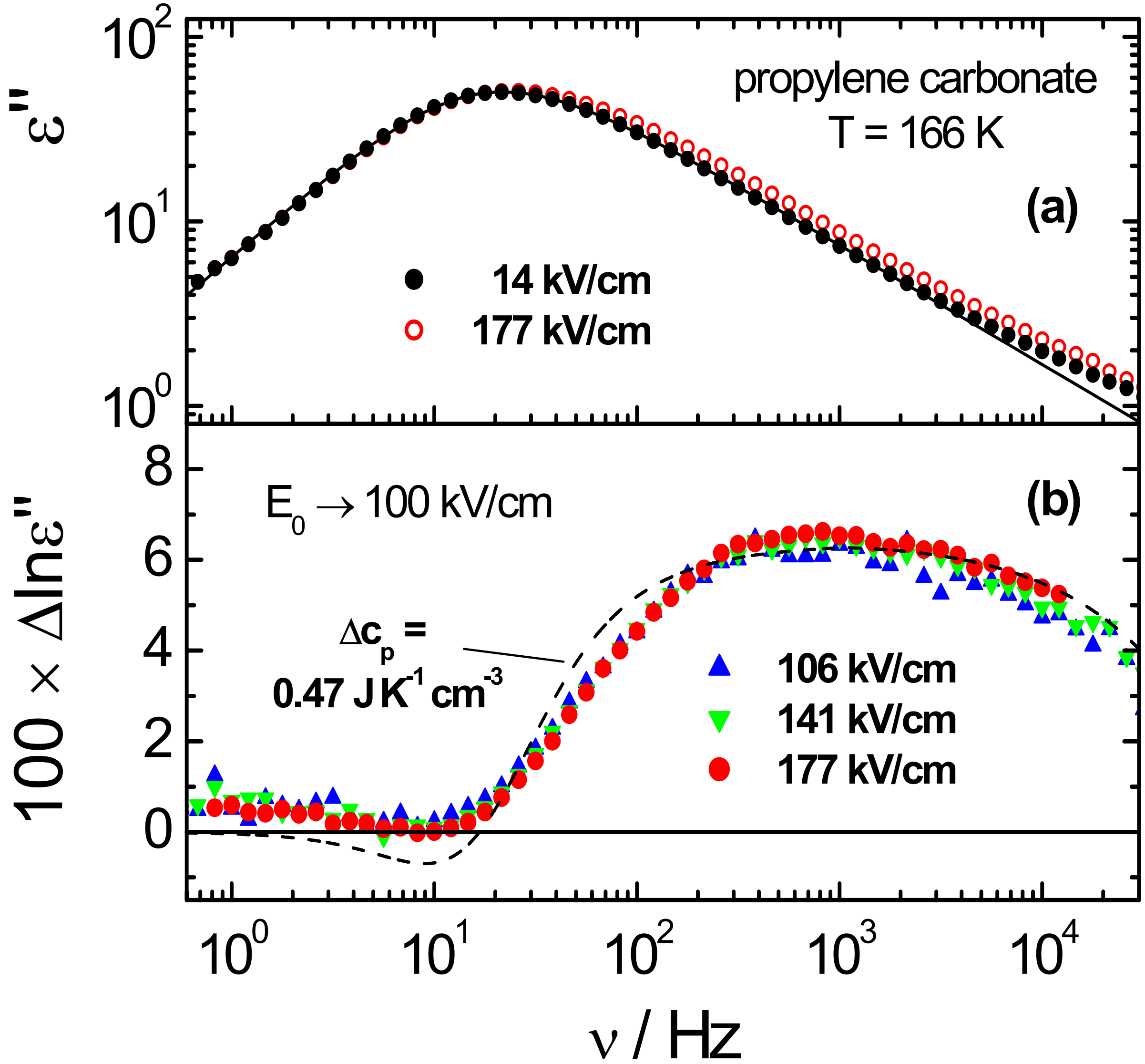


$$\left.\begin{array}{r} \mu_{GLY} = 2.56\,\mathrm{D} \\ E = 28.2\,\mathrm{MVm^{-1}} \\ T = 213\,\mathrm{K} \end{array}\right\} \frac{\mu E}{kT} = 0.082$$



R. Richert, S. Weinstein, Phys. Rev. Lett. 97 (2006) 095703

the case of propylene carbonate



loss increases

by up to <u>20 %</u>

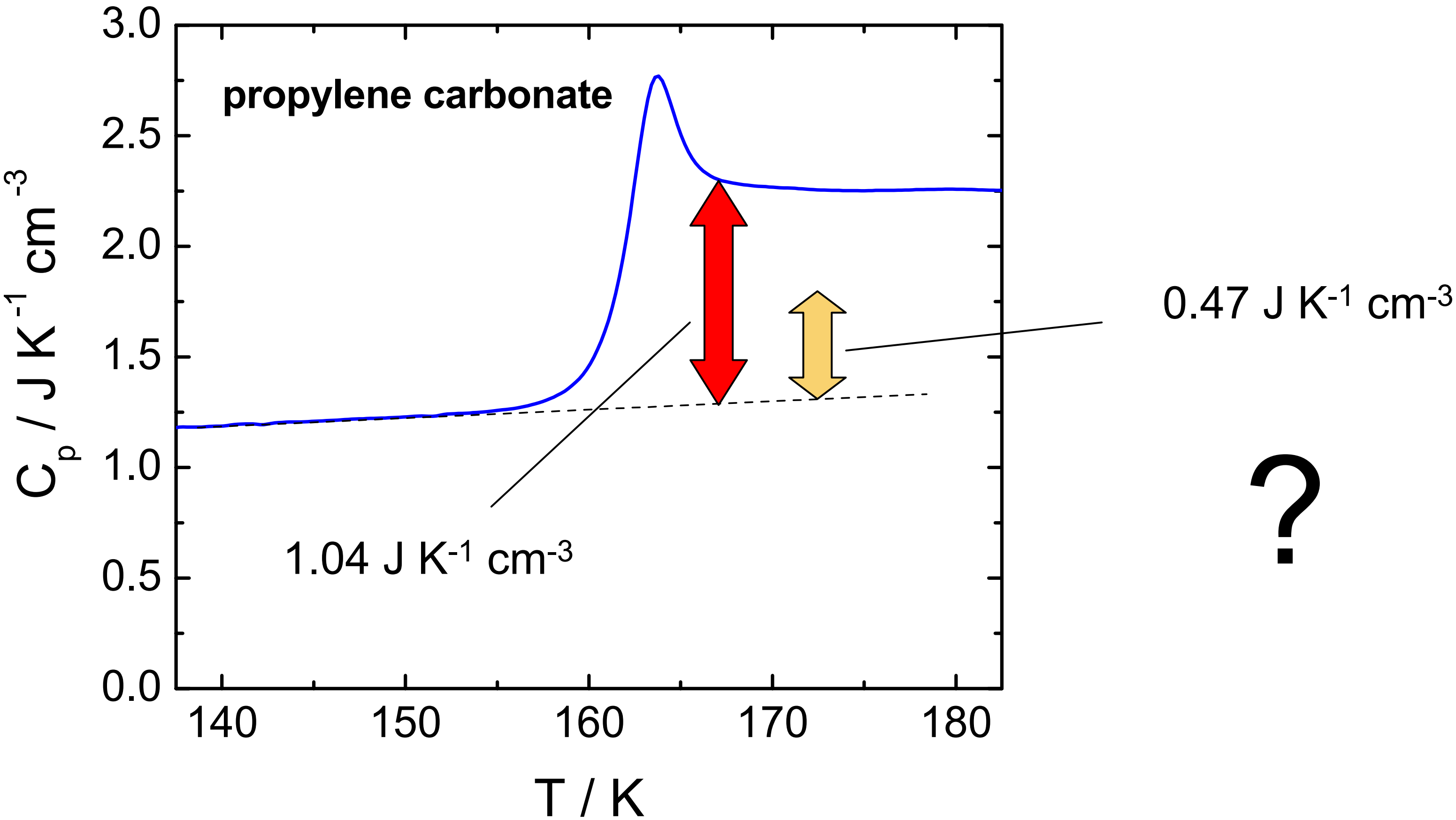
at electric field

of 177 kV/cm

ΔT_{cfg} = 0.185 K

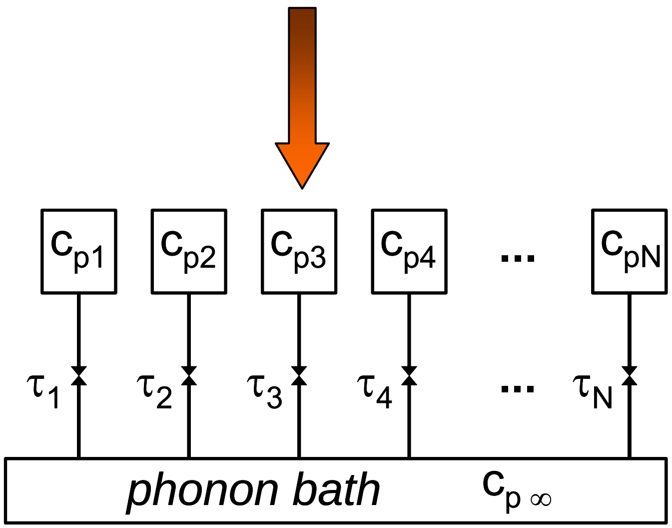
L.-M. Wang, R. Richert, Phys. Rev. Lett. 99 (2007) 185701

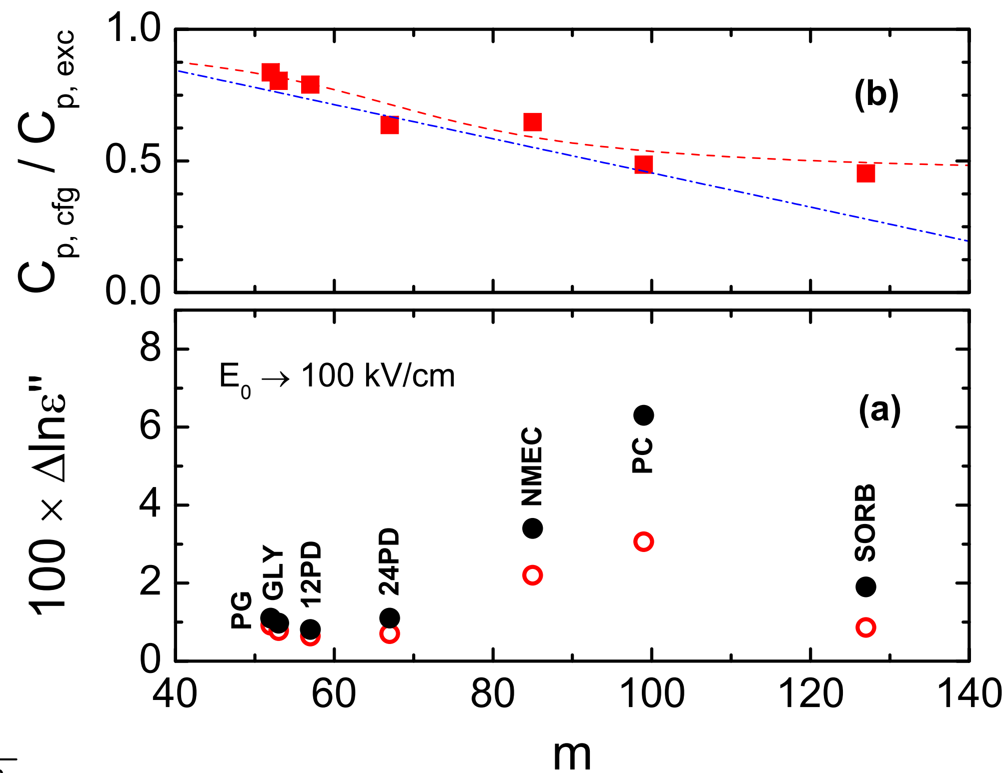
differential scanning calorimetry of propylene carbonate



L.-M. Wang, R. Richert, Phys. Rev. Lett. 99 (2007) 185701

measuring the configurational heat capacity





current model:

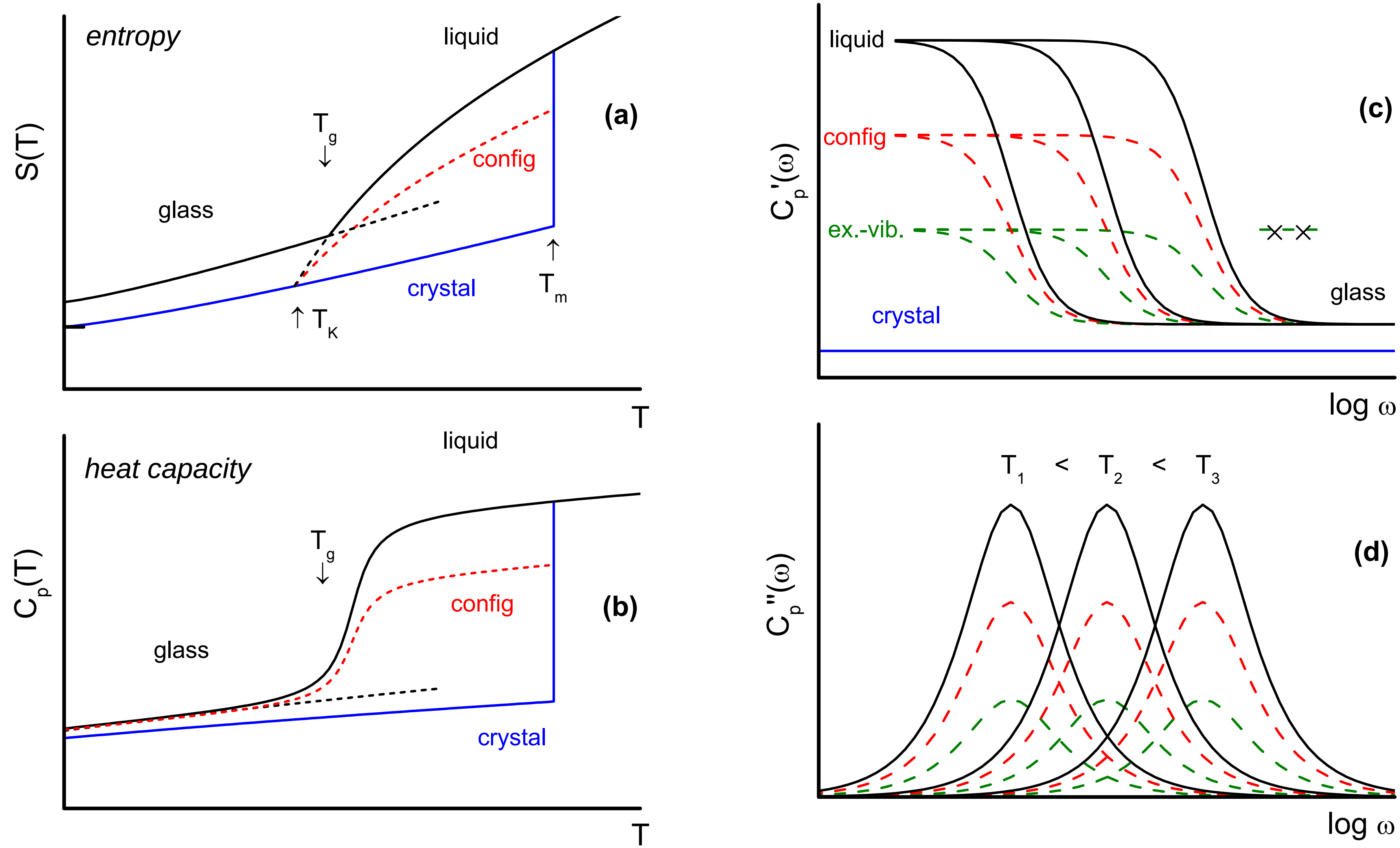
$$\ln \tau_D^* = \ln \tau_D - \frac{T_A}{T^2} \times \frac{\varepsilon_0 E_0^2 \Delta\varepsilon}{2\Delta c_p} \times \frac{\omega^2 \tau_D \tau_T}{1+\omega^2 \tau_D^2}$$

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \Delta\varepsilon \int_0^\infty g(\tau_D) \frac{1}{1+i\omega\tau_D^*} d\tau_D$$

configurational heat capacity

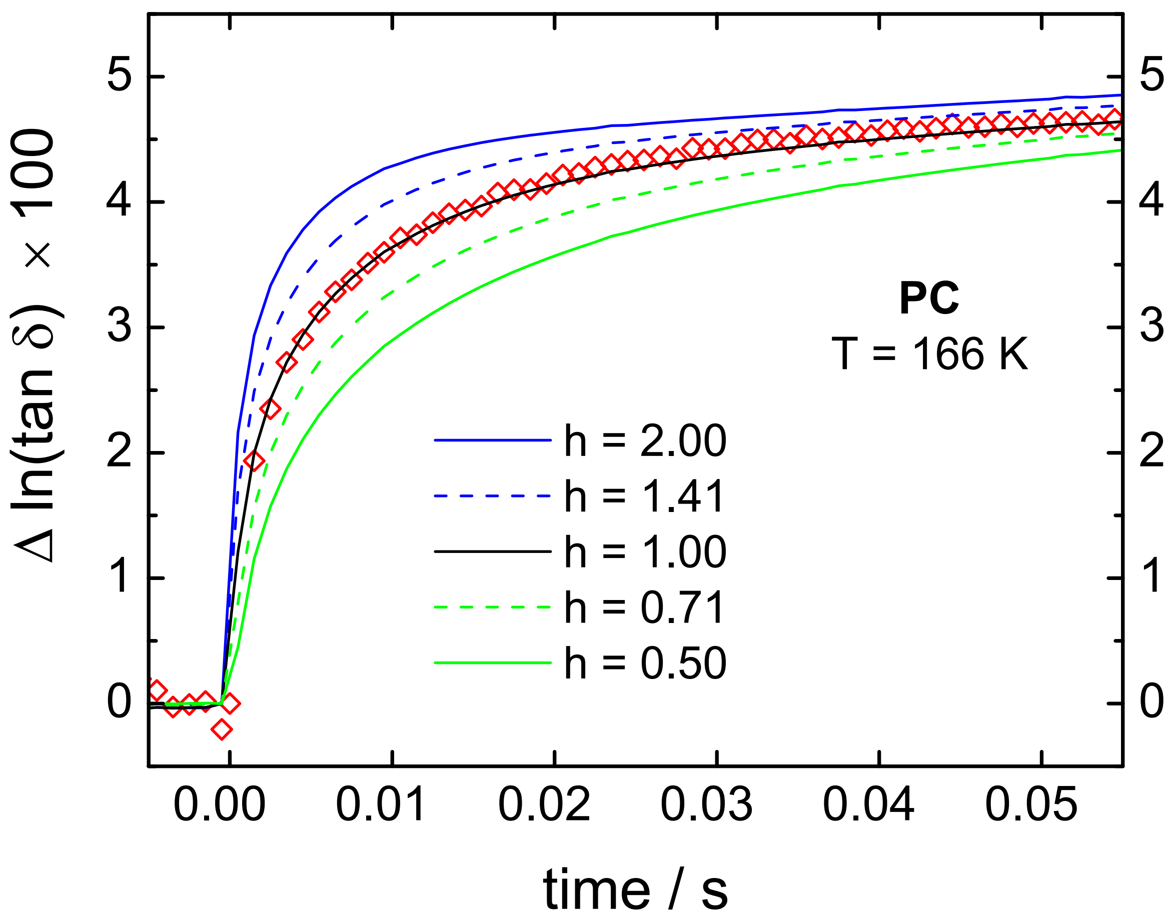
L.-M. Wang, R. Richert, Phys. Rev. Lett. 99 (2007) 185701

configurational versus excess-vibrational heat capacity



testing the claim: $\tau_T = \tau_D$ versus $\tau_T = \tau_D/h$

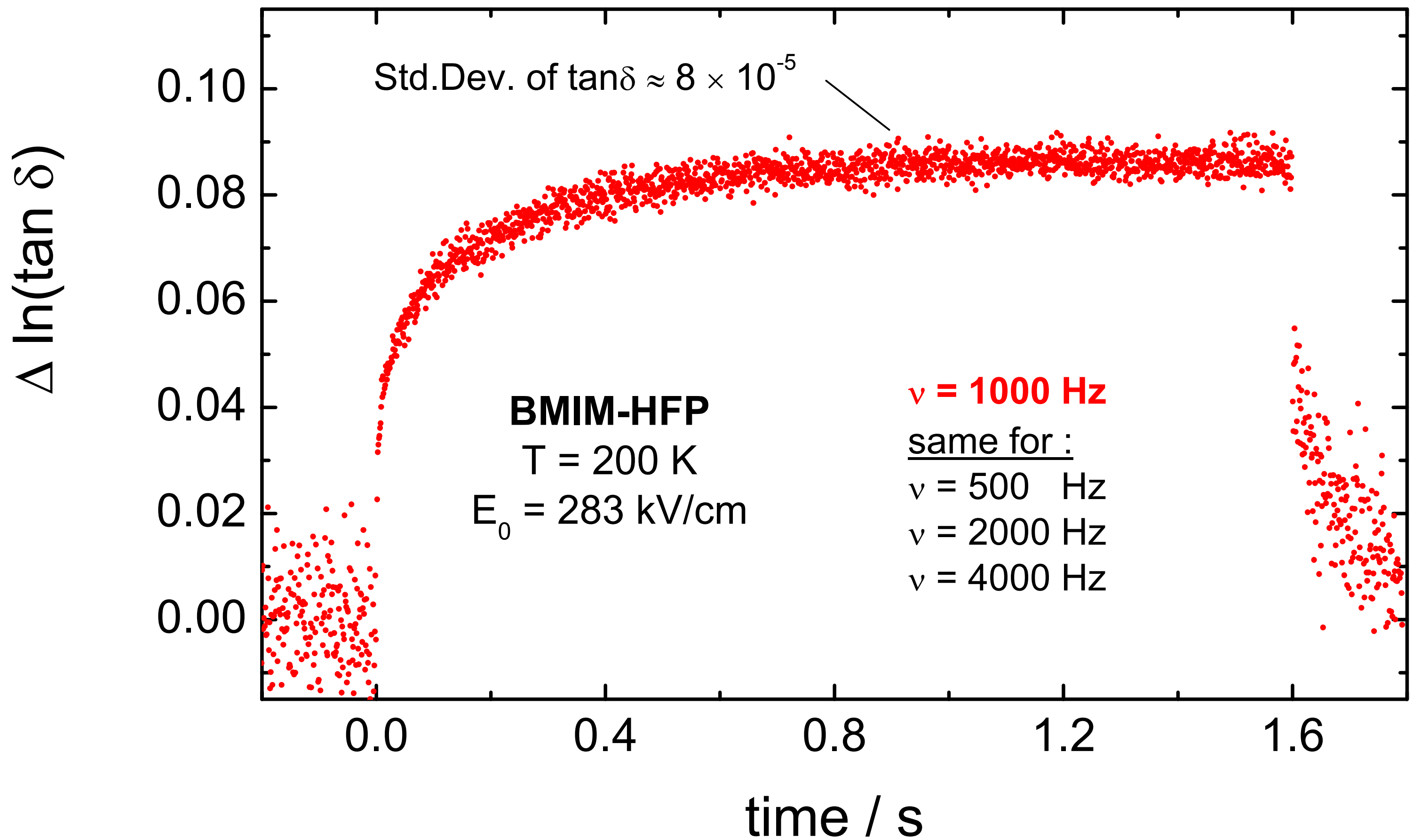
$$\ln\tau_D{}^* = \ln\tau_D - \frac{E_A}{k_B T^2}\times\frac{\varepsilon_0 E_0^2 \Delta\varepsilon}{2\rho\Delta c_p}\times\frac{\omega^2\tau_D\tau_T}{1+\omega^2\tau_D^2}\left[1-e^{-\frac{t}{\tau_T}}\right] = \ln\tau_D - \frac{E_A}{k_B T^2}\times\frac{\varepsilon_0 E_0^2 \Delta\varepsilon}{2\rho\Delta c_p/h}\times\frac{\omega^2\tau_D\,\tau_D/h}{1+\omega^2\tau_D^2}\left[1-e^{-\frac{t}{\tau_D/h}}\right]$$



L.-M. Wang, R. Richert, Phys. Rev. Lett. (submitted)

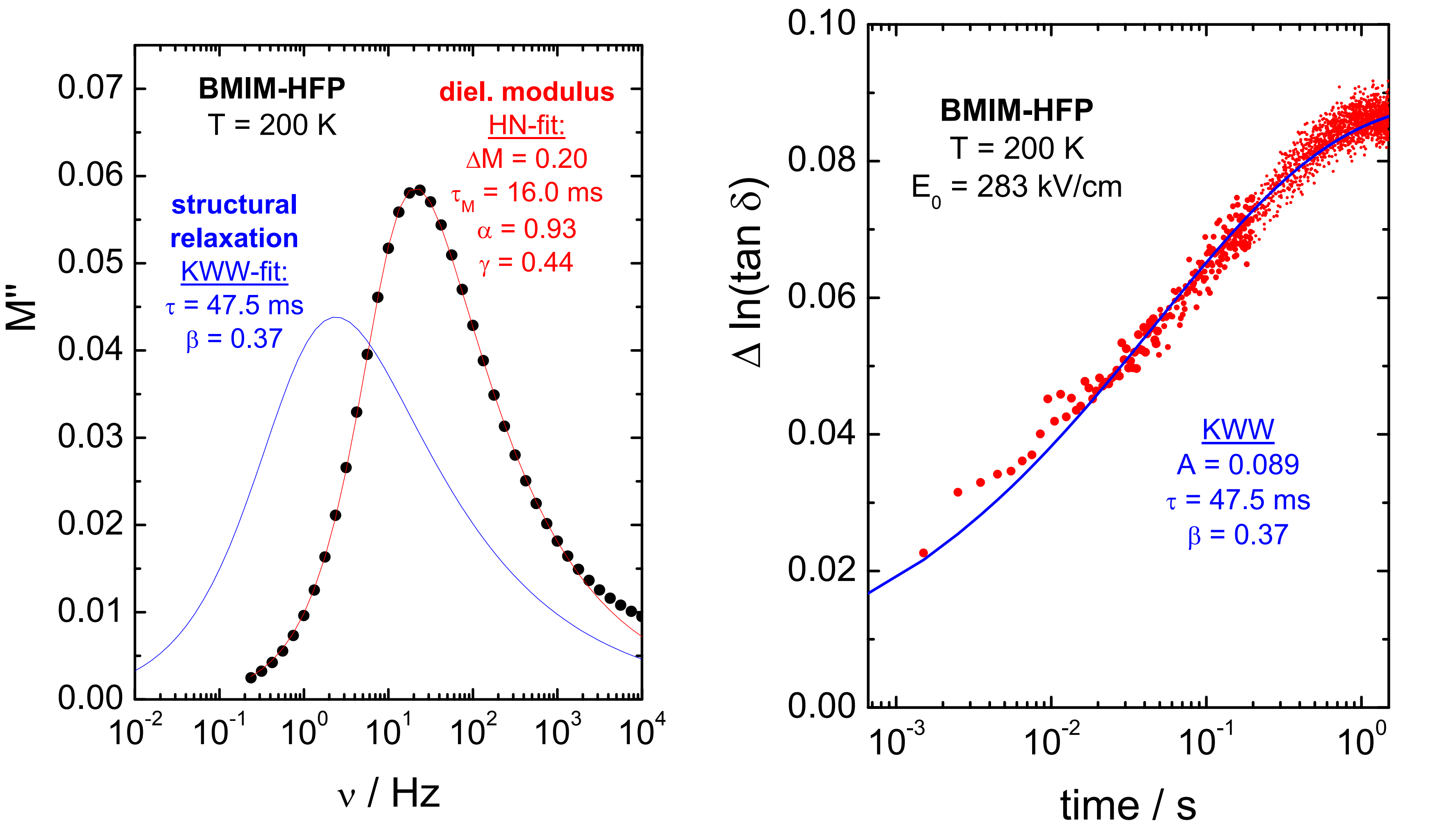
why not look at a RTIL

1-butyl-3-methyl-imidazolium $^{+}$ hexafluorophosphate $^{-}$



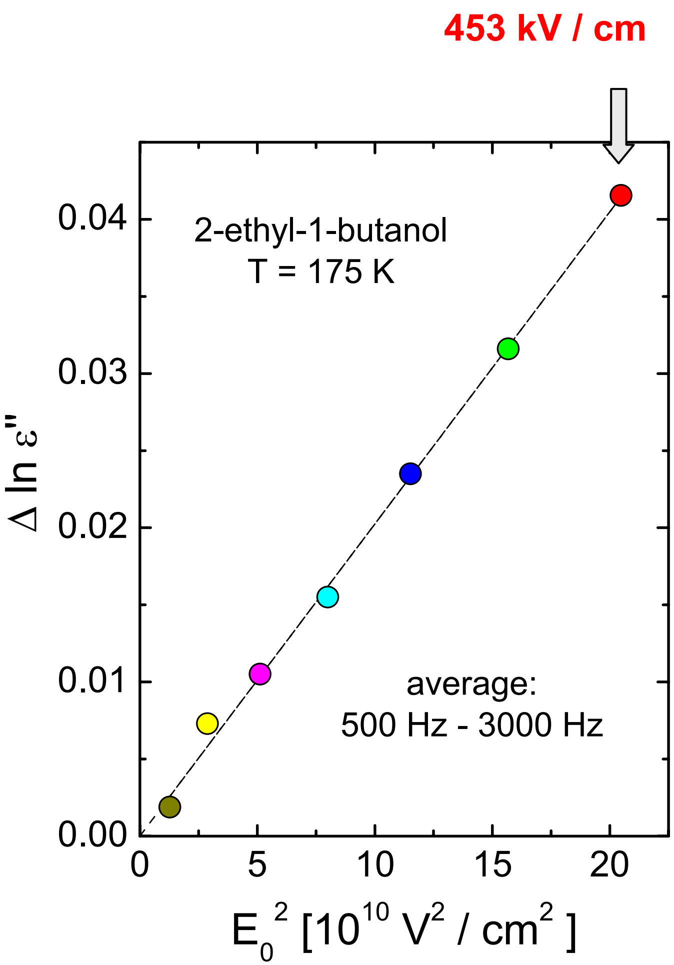
W. Huang, R. Richert, Phys. Chem. Chem. Phys. (submitted)

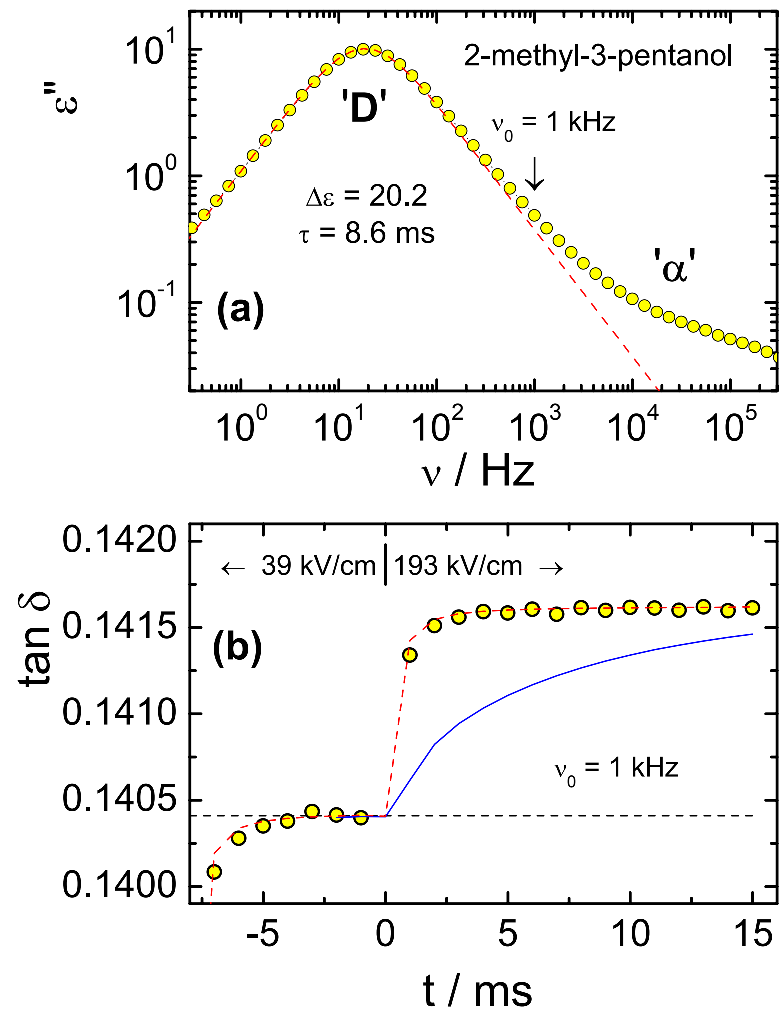
explanation: mild decoupling of τ_M from τ_α



W. Huang, R. Richert, Phys. Chem. Chem. Phys. (submitted)

configurational temperature lifetime of Debye peak





W. Huang, R. Richert, J. Phys.Chem. B 112 (2008) 9909