Relaxation oscillations in Zero Resistance State

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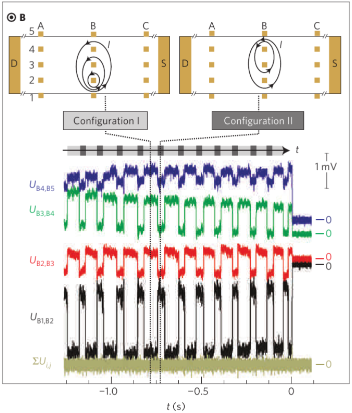
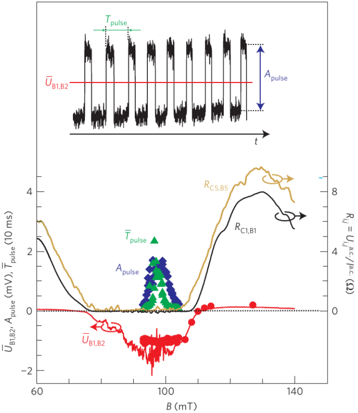
"Slow gate"–induced periodic reversal of electric field in ZRS domains and its relation to experiments presented in previous talk

Experiments frequently show almost periodic switching

Period T ~ 20 ms (new experiments on different samples: T ~ 2 ms)

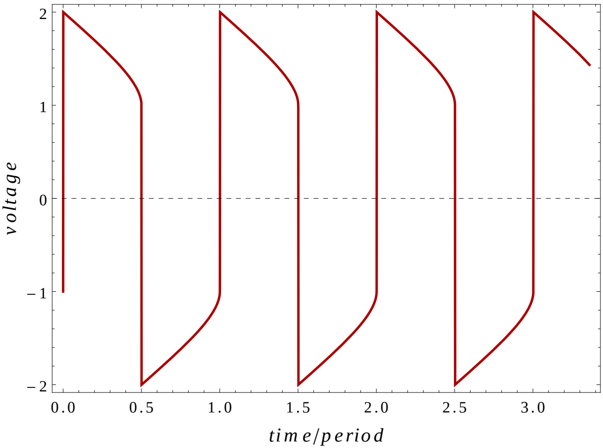




S. I. Dorozhkin[1,2], L. Pfeiffer[3], K. West[3], K. von Klitzing[1] and J. H. Smet[1]★ , Nature Physics (2011)

Why: System is close to the regime of relaxation oscillations (?)

Periodic switching due to strong coupling to slow normal system with $\sigma > 0$



Acknowledgements

- Previous related work:

Transport in ZRS domains with Maxim Khodas, Alexander Mirlin, and Dmitry Polyakov'2013

Photovoltaic effects with Sergei Dorozhkin and Alexander Mirlin'2009-11

Domain dynamics in e-on-He system with Alexei Chepelianskii'2014 (unpublished)

- Discussions:

Jurgen Smet, Vladimir Umansky, Michel Dyakonov, Sergey Vitkalov, Alexei Bykov, Denis Konstantinov, Michael Zudov, Sergey Ganichev, . . .

- Organizers for unique opportunity to share and discuss these ideas with you

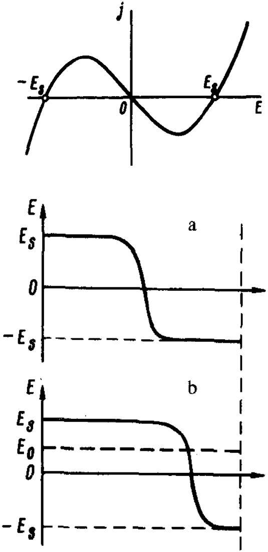
Uniform state with $j \cdot E < 0 \Rightarrow$ Domains $\Rightarrow j \cdot E = 0$

Photoinduced electrical domains in ruby

M. I. D'yakonov
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR

(Submitted 22 December 1983)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 4, 158–160 (25 February 1984)

An explanation is proposed for the appearance of electrical domains in ruby crystals under the action of intense laser irradiation.



- Uniform $j = 0$ & $E = 0$ state - unstable
- Two domains with $|E| = E_c$ are formed:

$$\sigma(E_c) = 0, \;\; \sigma_d(E_c) > 0$$

$\Longrightarrow$ For any $V = \int dx E(x)$, the current $j = 0$

$\Longrightarrow$ zero conductance $j/V = 0$ in the domain state

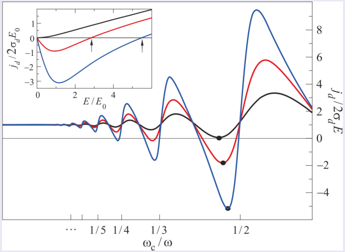
Maxwell equations:

Negative absolute conductivity of homogeneous state, $\mathbf{j} \cdot \mathbf{E} < 0$

$\Rightarrow$ Electrical instability: Uniform state is unstable

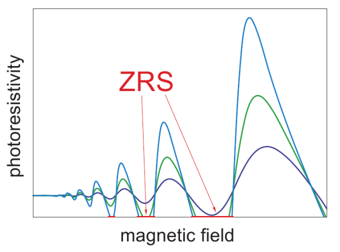
$\Rightarrow$ Domain state $\equiv$ Resulting inhomogeneous state

$\sigma < 0$



$\longleftrightarrow$

ZRS ?=? Static domains

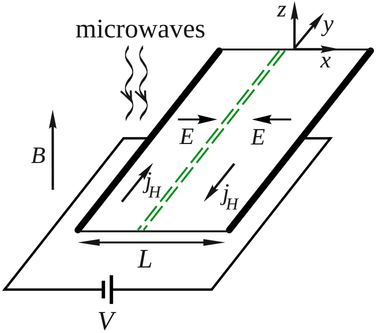


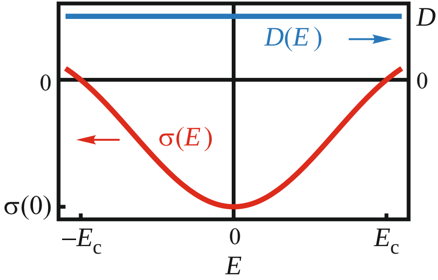
1D model of the domain state in 2D system

$$\boxed{\sigma(E)\,E + D\hat{C}E = j}$$

ID, Khodas, Mirlin, Polyakov'2013

- Static continuity equation $\partial_x j = 0, \qquad j = \sigma(E)\,E(x) - D\,\partial_x \rho(x)$
- Poisson $-\partial_x \rho = \hat{C}E = \partial_x \int \frac{\epsilon\, dx'}{2\pi^2} \frac{E(x')}{x - x'}$ — non-local





- Solve $\sigma(E)\,E + D\hat{C}E = 0, \quad E(x+2L) = E(x)$
- Plots: $\dfrac{E(x)}{E_c}$ and $\dfrac{\pi^2\delta\rho(x)}{\epsilon E_c}$ for $L = 100\lambda$

Nonequilibrium screening length $\lambda = \dfrac{\epsilon D}{2\pi|\sigma(0)|}$

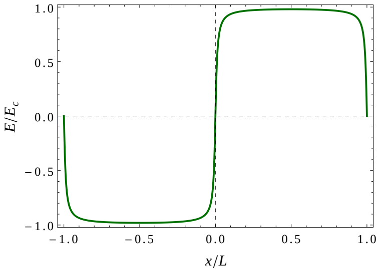
- The only spatial scale, width of domain wall
- Diverges at $\sigma(0) \to 0 \;\Rightarrow\;$ critical parameter
- Equilibrium: Einstein relation $\sigma_{\text{dark}} = e^2\nu D$

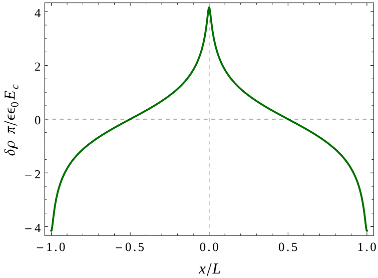
$$\lambda = \frac{\sigma_{\text{dark}}}{|\sigma(0)|}\lambda_{TF} \to \lambda_{TF} = \frac{\epsilon\hbar^2}{2e^2 m} \text{ in equilibrium}$$

Estimate $\delta\rho$ for typical $E_c = 10$ V/m

$$|\delta\rho_{\text{max}}|/e = \frac{\epsilon E_c}{\pi^2 e}\ln\frac{L}{\lambda} \simeq 10^6\ \text{cm}^{-2}\ \ln\frac{L}{\lambda}$$

$$\frac{L}{\lambda} = 1000, \quad n_e = 3\cdot 10^{11}\text{cm}^{-2} \;\Rightarrow\; \frac{|\delta\rho_{\text{max}}|}{e n_e} \sim 2\cdot 10^{-5}$$





Domains in 2D system with metallic gate, $L \gg d \sim \lambda$

- Plots: $\frac{E(x)}{E_c}$ and $\frac{\pi^2 \delta\rho(x)}{\epsilon E_c}$ for $L = 100\lambda$

$\sigma(E) = \sigma(0)(1 - E^2/E_c^2), \quad \lambda/2d = \{0.98, 0.5, 0.1\}$

- Same $\sigma(E)\,E + D\hat{C}E = 0$ BUT

Inside large domains $\hat{C} \simeq C_0 = \frac{\epsilon}{4\pi d}, \quad d \ll L$

Effective $\sigma^*(E) = \sigma(E) + DC_0$ may turn positive!

$E_c^* = E_c\sqrt{1 - \lambda/2d} \to E_c \cdot \{0.14, 0.7, 0.95\}$

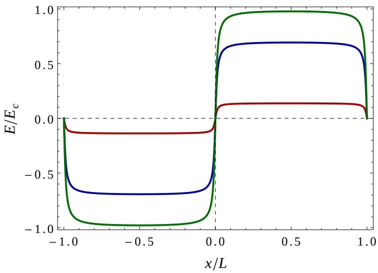
$\lambda/2d > 1:$ uniform state is stable (for $L \gg d$)

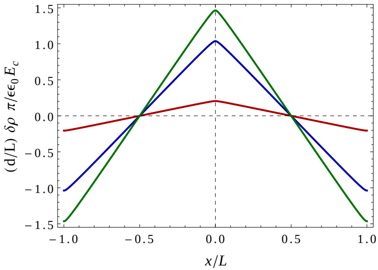
- Estimate $\delta\rho$ for $E_c^* = 10$ V/m

$|\delta\rho_{max}|$: $\ln\frac{L}{\lambda} \to \frac{L}{d}$ and $E_c \to E_c^*$

for $\frac{L}{d} = 1000$ and $E_c \sim E_c^*$, $\delta\rho_{max}$ is $\sim 10^2$ larger

Perfect screening requires $\sim 10^{-3} n_e$ image-charge density





Dynamics in 2D system coupled to slow gate

What happens if (i) $\lambda > 2d$ (no static domains) and (ii) charge carriers in the gate are slow?

Answer: System enters new dynamic regime; no stable static solution exist.

Dynamics: $\dot{\rho} + \partial_x j = 0,\ j = \sigma E + D\hat{C}E,\ -\partial_x \rho = \hat{C}E \ \Rightarrow \boxed{\hat{C}\dot{E} = \partial_x^2(\sigma E + D\hat{C}E)}$

Capacitance operator: non-local coupling of electric field $E_s(x)$ and $E_g(x)$ in two layers

Slow gate: small conductivity $\boxed{\sigma_g = \rho_g \mu_g > 0}$, diffusion coefficient $\boxed{D_g = T\mu_g/e}$

- Single-mode approximation: $E_{s,g}(x) \to \varepsilon_{s,g} \sin kx, \quad k = \pi/L \ll d^{-1}$
- Neglect higher harmonics: $E_s(1 - E_s^2/E_c^2) \to \varepsilon_s(1 - \varepsilon_s^2) \sin kx$
- Capacitance operator: $\hat{C}_k = \frac{\epsilon k/2\pi}{1-\alpha^2}\begin{pmatrix} 1 & -\alpha \\ -\alpha & 1 \end{pmatrix}$, $\boxed{\alpha = e^{-kd}, \quad 1 - \alpha \simeq kd \ll 1}$

$$\boxed{\begin{aligned} (\partial_t + m_{sD})(\varepsilon_s - \alpha\varepsilon_g) &= -(1-\alpha^2) m_{s\sigma}(\varepsilon_s - \varepsilon_s^3) \\ (\partial_t + m_{gD})(\varepsilon_g - \alpha\varepsilon_s) &= -(1-\alpha^2) m_{g\sigma}\varepsilon_g \end{aligned}} \quad \boxed{\begin{aligned} &m_{gD} = k^2 D_g,\ m_{g\sigma} = 2\pi k\sigma_g/\epsilon, \\ &m_{sD} = k^2 D,\ m_{s\sigma} = 2\pi k\sigma(0)/\epsilon < 0 \end{aligned}}$$

Hopf instability $\rightarrow$ Relaxation oscillations

- Eliminate ε_g, rescale t and ε_s $\Rightarrow$ Liénard equation

$$\boxed{\ddot{\varepsilon} + \Lambda(\varepsilon^2 - 1)\dot{\varepsilon} + \Theta\varepsilon + \varepsilon^3 = 0}$$

similar to van der Pol equation, $\ddot{x} + \Lambda(x^2 - 1)\dot{x} + x = 0$

- $\Lambda, \Theta > 0$: unique asymptotically stable limit cycle

$\Lambda > 0 \;\leftrightarrow\; |m_{s\sigma}| > m_{g\sigma} + m_{sD} + m_{gD}$ (slow gate)

$\Theta > 0 \;\leftrightarrow\; \lambda > 2d + \lambda_g$ (unstable static domains)

- $\Lambda = \sqrt{\dfrac{|m_{s\sigma}| - m_{g\sigma} - m_{sD} - m_{gD}}{m_{g\sigma}(2kd + k\lambda_g)/3}} \gg 1$

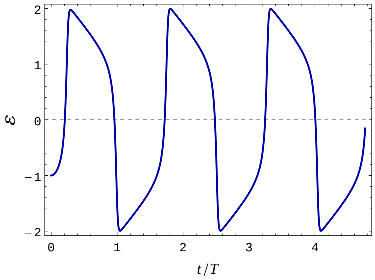
$\Rightarrow$ Relaxation oscillations (slow build-up, sudden discharge)

Introduce rescaled CV: $j = -\varepsilon + \varepsilon^3/3 \Rightarrow$

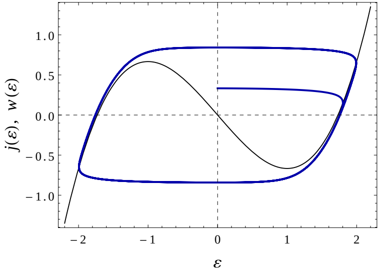
$$\boxed{\Lambda^{-1}\dot{\varepsilon} = w - j(\varepsilon), \qquad \Lambda\dot{w} = -\Theta\varepsilon - \varepsilon^3}$$

Slow motion along CV: $w - j \sim \dot{w} \sim \mathcal{O}(\Lambda^{-1})$

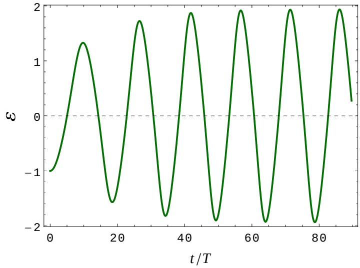
$\Rightarrow$ Period $T = \frac{\Lambda}{\Theta} \ln\left[\frac{1}{4}\left(\frac{4+\Theta}{1+\Theta}\right)^{1+\Theta}\right] \sim \Lambda,\ \Theta \lesssim 1$

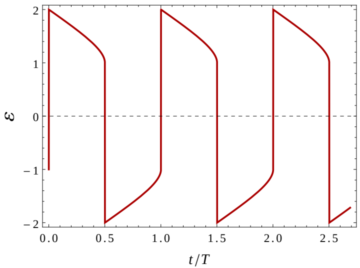


$\Lambda = 8, \quad \Theta = 1$



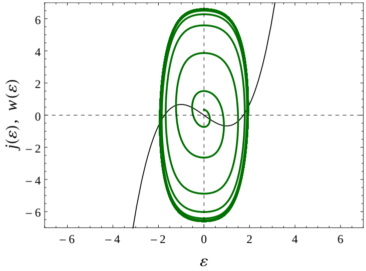
Oscillations for small and large nonlinearity parameter Λ

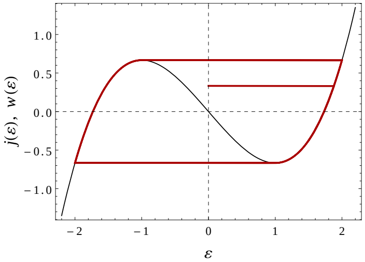




$\Lambda = 0.5, \quad \Theta = 1$

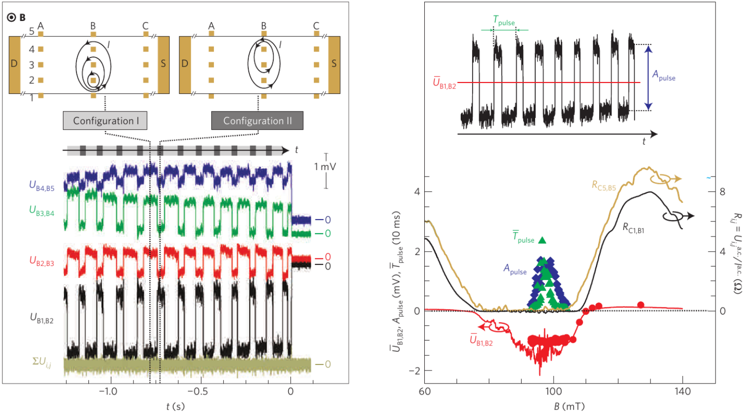
$\Lambda = 1000, \quad \Theta = 1$





Experiments frequently show almost periodic switching

Period T ~ 20 ms (new experiments on different samples: T ~ 2 ms)



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Parameters of slow gate for experimental observation

Experiment: $T_{osc} (\sim L/m_{g\sigma}\lambda) = 2$ ms

$d \sim 0.1\mu$m: spacer thickness

$L \sim 0.1$mm: separation of voltage probes

Restrictive condition:

$\Theta > 0 \quad \leftrightarrow \quad \lambda > 2d + \lambda_g$

Take $\lambda = 5d$, $\lambda_g = d$: $5 > 3$ ✓

Requires $\frac{\sigma_{dark}}{|\sigma(0)|} \equiv \frac{\lambda}{\lambda_{TF}} \sim 100$

$\Lambda = 2015, \qquad \Theta = 2$

Gate parameters:

$$n_g = \frac{\epsilon T}{2\pi e^2 \lambda_g} \simeq 1.15 \cdot 10^8 \text{ cm}^{-2}$$

$\frac{n_g}{n_e} = 4 \cdot 10^{-4}$: sufficient for screening

$$\frac{\sigma_g}{|\sigma(0)|} = \frac{m_{g\sigma}}{|m_{s\sigma}|} \sim 10^{-4} \quad \text{but} \quad \frac{\mu_g}{\mu^*} = \frac{1}{5}$$

$$\mu^* = \frac{\mu \lambda_{TF}}{(\omega_c \tau_{tr})^2 \lambda} \sim 7 \text{ cm}^2/\text{V sec}$$

$m_{sD} = 1\ \mu s^{-1}$

$m_{s\sigma} = -67\ \mu s^{-1}$

$m_{g\sigma} = 0.006\ \mu s^{-1}$

$m_{gD} = 2 \cdot 10^{-5}\ \mu s^{-1}$

$L = \pi/k = 0.1$ mm

$R_c = 1\ \mu$m

$\lambda = 0.5\ \mu$m

$\lambda_g = d = 0.1\ \mu$m

$\lambda_{TF} = 5$ nm

$\omega/2\pi = 50$ GHz

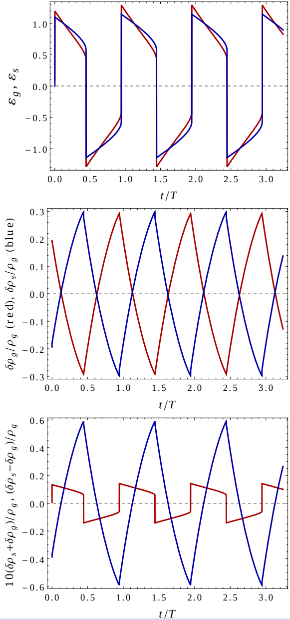
$\mu = 10^7$ cm^2/V sec

$\tau_{tr} = 0.4$ ns, $T = 1$ K

$n_e = 3 \cdot 10^{11}$ cm^{-2}

$n_g = 1.15 \cdot 10^8$ cm^{-2}

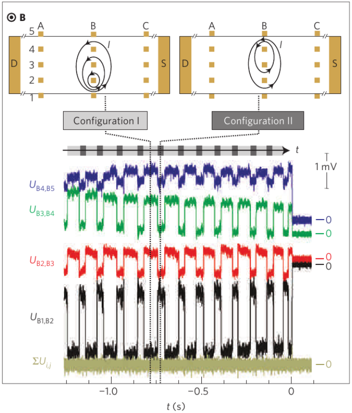
$E_c = 0.1$ V/cm

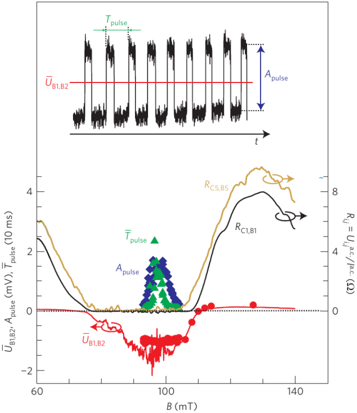


Why oscillations are not strictly periodic in experiments?

- Deep in ZRS: reversal dynamics is driven by slow gate AND noise; $\lambda \lesssim 2d$
- Near transition to ZRS: reversal dynamics is not observed while $\lambda > 2d$

Non-uniform E_{mw}? Long-range disorder?





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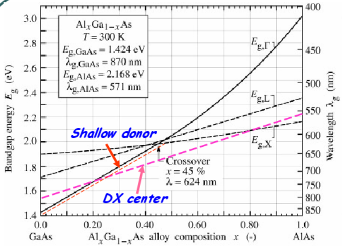
Slow gate: Is it there?

DX centers



The "standard" 2DEG structure:

In the dark:

Pros: Frozen charge (in the dark) allows gating

Cons: Low doping efficiency (in the dark) → high RI scattering

After Illumination in the dark:

Pros: Almost double density after illumination → high mobility.

Cons: Parallel conduction/gate instability. ✓

Stolen slide from presentation by Valdimir Umansky'2010

Slow gate: Definitely there

PHYSICAL REVIEW B **85**, 155307 (2012)

Quantum oscillations of dissipative resistance in crossed electric and magnetic fields

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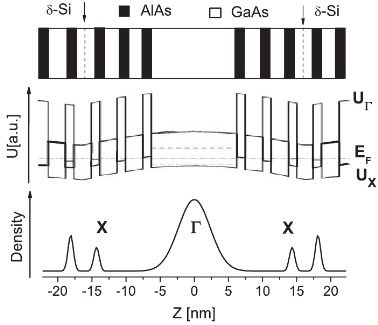
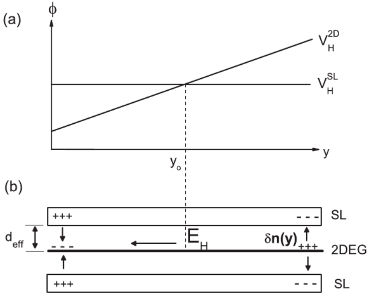
(Received 8 January 2012; published 6 April 2012)





Summary

- Almost periodic reversal of the domain field in experiments can be driven by strong capacitive coupling to nearby conducting layer with very slow dynamics of carriers.

- In experiments, such "slow gate" governs slow evolution of the system along CV-branches with positive differential conductivity; fast reversal of the field orientation in domains is random and is driven by the non-equilibrium noise.

- The regime of relaxation oscillations is accessible in current experiments. Its observation would open new interesting research directions and provide valuable information about ZRS domains which is currently still very limited.