Non Linear Conductivity in Coulomb Glasses

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KITP Program: The Electron Glass

Outline

- Introduction. Experiments on nonlinear conductivity
- Model and numerical techniques
- Effective temperature
- Non linear conductivity. Hot electron model
- Dissipated power in hopping systems
- Switching transition
- Open questions

Mainly Monte Carlo simulations of 2D Coulomb glasses

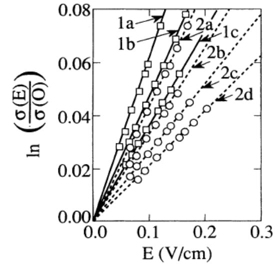
Field effects models are predictions for noninteracting systems (trivially extended to interacting systems)

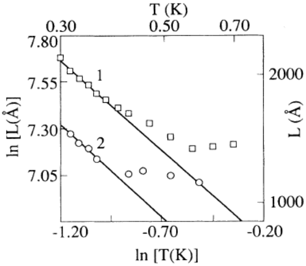
$$\sigma(T,E) = \sigma(T,0)\exp\{eEl_{\rm h}/kT\}$$

where $l_{\rm h}$ is a characteristic hopping length.

- Hill and Pollak and Riess $l_{\rm h} \propto T^{-1/2}$
- Shklovskii $l_{\rm h} \propto T^{-1}$

(Grannan et al, 92)





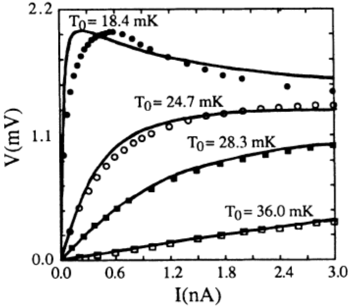
Non linear effects in hopping

Hot electron model

Wang et al (90) interpreted results on NTD Ge in terms of a hot electron model:

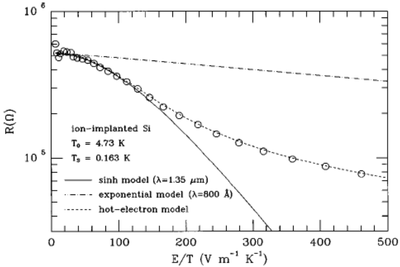
$$\sigma(T,E)=\sigma(T_{\rm eff},0)\propto \exp\{-\,(T_0/T_{\rm eff})^{1/2}\}$$

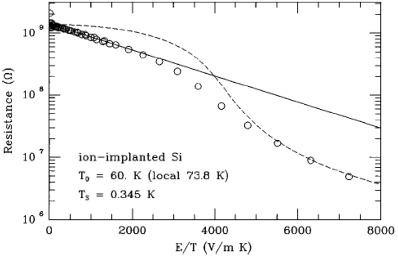
$$P=a(T_{\rm eff}^{\beta}-T^{\beta})$$



Zhang et al (98) studied systematically non linear effects in doped Si and Ge and concluded that

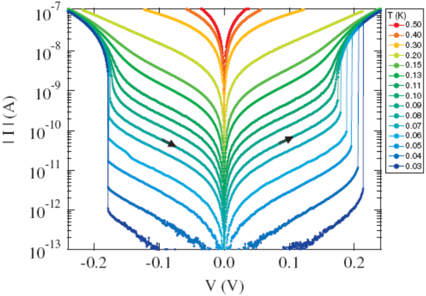
- If $T_0/T < 135$ hot-electron models provide a better fit
- If $T_0/T > 135$ field effect models are better

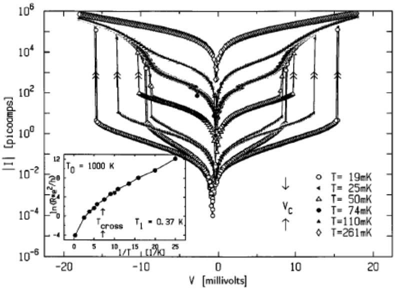




Switching transition
Hot electron model

Altshuler et al (09) interpreted the switching transition observed in InO by Ovadia et al (09) as a bistability of the effective temperature. Ladieu et al (96) had observed a similar effect in a-YSi.





In both experiments the conduction is activated.

- Disorder and long range interactions

$$H = \sum_i \phi_i n_i + \sum_{i>j} \sum_j \frac{(n_i - K)(n_j - K)}{r_{i,j}}$$

  - $n_i = \{0, 1\}$ occupation number (very large U).
  - $\phi_i \in [-W/2, W/2]$ random site energy.
  - K compensation.
- Transfer energies considered in lowest possible order.
  - 0 for energies, density of states, etc.
  - 1 for conduction, relaxation, etc.
  - No exchange terms. Degenerate with respect to spin.

- Site energies are defined as

$$\epsilon_i = \phi_i + \sum_{j \neq i} \frac{(n_j - K)}{r_{i,j}}$$

- The excitation energies are

$$\Delta_{i,j} = \epsilon_j - \epsilon_i - \frac{1}{r_{i,j}}$$

- The stability of the ground state requires

$$\Delta_{i,j} \leq 0 \qquad \Longrightarrow \qquad r_{\min} \propto |E|^{-1}$$

Density of states $N(E) \propto |E|^{d-1}$

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- We apply an electric field

$$H = H_{\text{CG}} - \sum_i x_i E n_i$$

- Periodic boundary conditions
    - Interaction: minimum image distance.
    - Field included in the transition energies. Stationary state.
    - Field not included in the energy.
- One-electron transition rates

$$\Gamma_{i,j} = \tau_0^{-1} e^{-2r_{i,j}/\xi} \min\{1, e^{-\Delta E_{i,j}/kT}\}$$

- Many-electron transition rates

$$\Gamma_{\alpha,\beta} = \tau_0^{-1} \Xi_{\alpha,\beta} e^{-2\sum_{i,j} r_{i,j}/\xi} \min\{1, e^{-\Delta E_{\alpha,\beta}/kT}\}$$

    - Shortest possible transition
    - For two electrons $\Xi_{\alpha,\beta} = \frac{1}{r_{1,3}} + \frac{1}{r_{2,4}} - \frac{1}{r_{1,4}} - \frac{1}{r_{2,3}}$

Numerical algorithms

Monte Carlo simulation

- We choose a pair i, j with probability $e^{-2r_{i,j}/\xi} / \sum_{i,j} e^{-2r_{i,j}/\xi}$ and then accept or reject the transition according to its energy.
- One-electron jumps.
- High temperature regime.
- Joakim is implementing relevant two-electron transitions in a 2D lattice.

Master equation

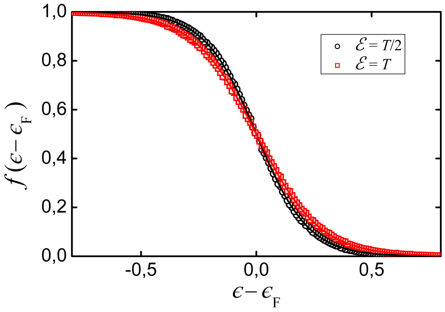
- We first obtain low-energy many-particle configurations and then calculate transition rates between them.
- Many-particle transitions are easily included.
- Very low values of E, T.

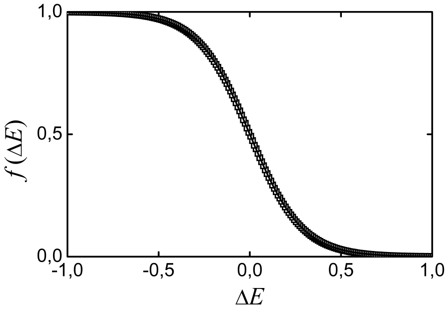
Effective temperature

Distribution function

- Site energies near E_F follow FD statistics with a T_{eff}.
- Long excitations at T_{eff}.
- Short excitations at T.

$$\frac{P(E,r>10)}{P(E,r>10)+P(-E,r>10)}$$





Effective temperature
Fluctuation dissipation theorem

Extension of the fluctuation dissipation theorem:

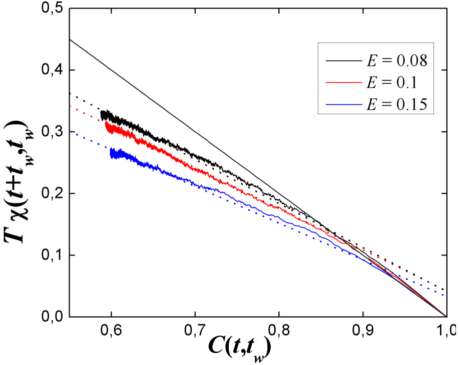
Spin glass (Jorge, Leticia, etc.)

External perturbation
$\delta\phi_i = \lambda(t)\varphi_i$

Response $\delta n(t) = \lambda\chi(t, t_w)$

At equilibrium $T\chi(t) = 1 - C(t)$
where

$$C(t, t_w) = \frac{4}{N}\sum_i \langle \delta n_i(t)\delta n_i(t_w)\rangle$$

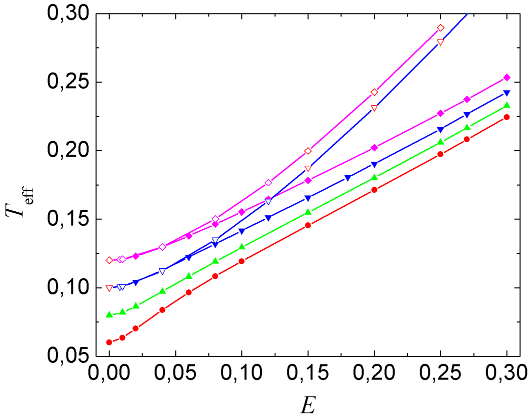


These results are compatible with our procedure.

Effective temperature, obtained from long excitations probabilities, as a function of E and T

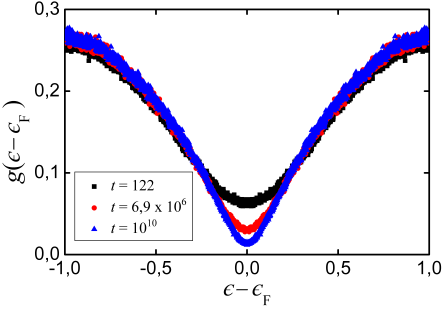
At low T, results not compatible with

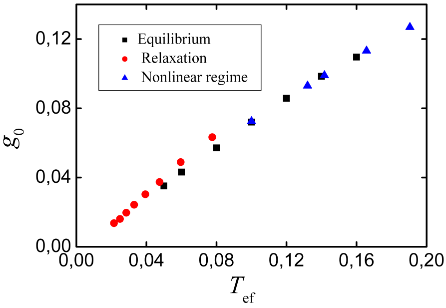
$$T_{\text{eff}}^2 - T^2 = aE^2$$



Effective temperature

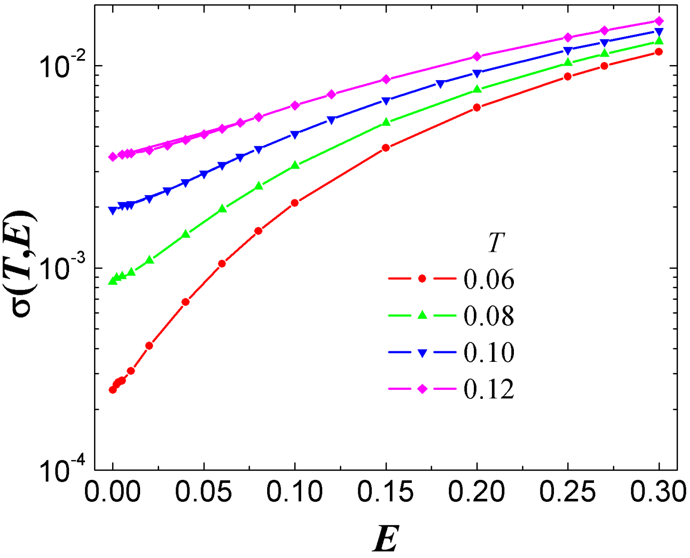
Density of states





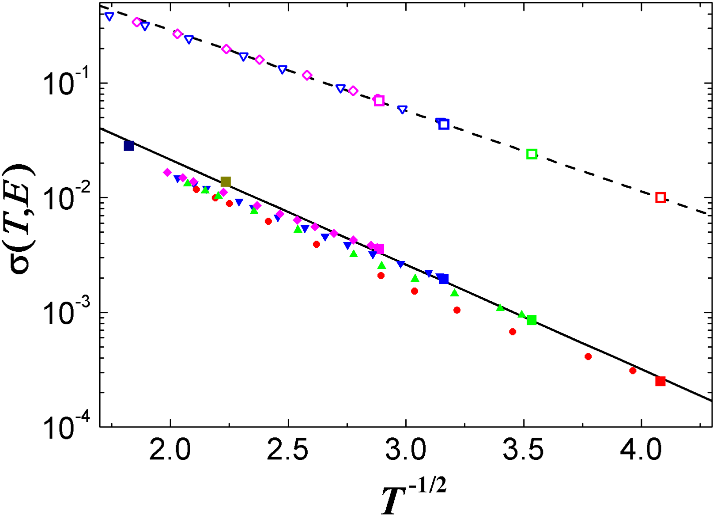
Non linear effects

Conductivity



Non linear effects

Variable range hopping



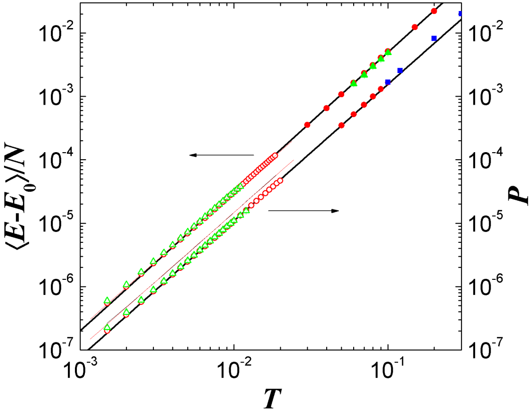
Emitted and absorbed powers

Equilibrium

At equilibrium
$\langle E - E_0 \rangle \propto T^2$

Emitted and absorbed powers also proportional to T^2

Contribution of short dipoles

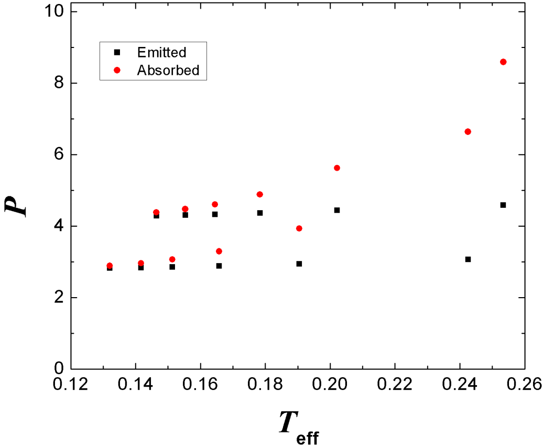


Emitted and absorbed powers

With electric field

Large common T dependent contribution

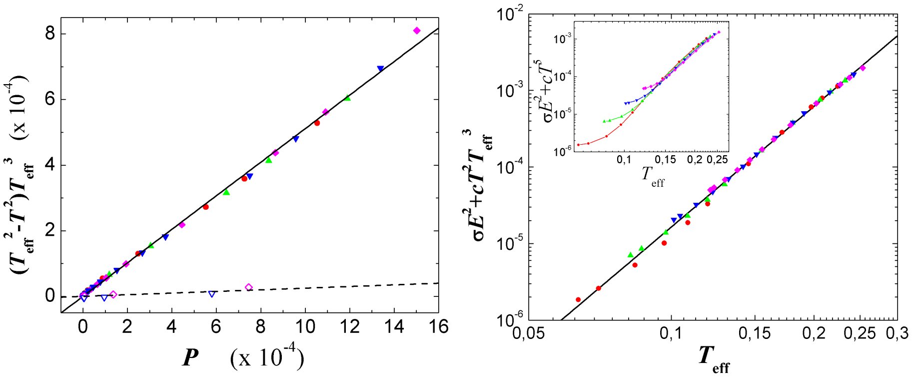
The emitted power depends weakly on T



Matteo obtains the full range with exchange Monte Carlo (equlibrium).

Hot electron model

Dissipated power vs T_{eff}

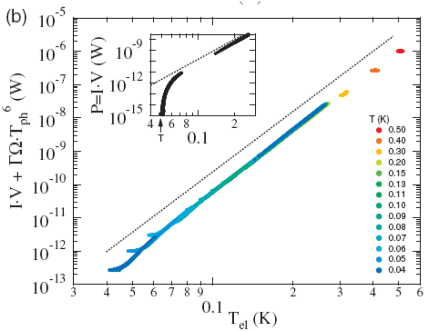


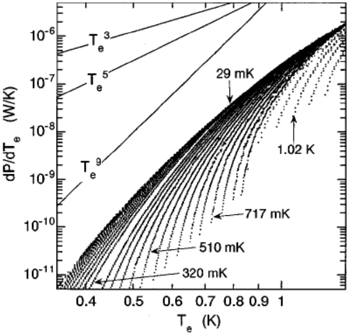
Dissipated power in the hopping regime

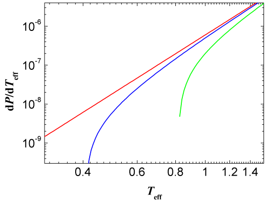
$$P = c \left(T_{\text{eff}}^{\alpha} - T^{\alpha} \right) T_{\text{eff}}^{\beta - \alpha}$$

Hot electron model

Low P correction







Hot electron model

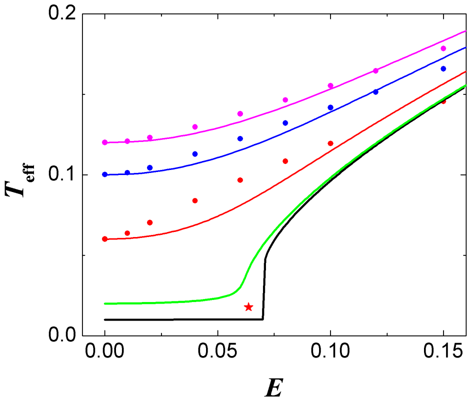
Effective temperature

$$E^2 = ce^{\sqrt{T_0/T_{\text{eff}}}}(T_{\text{eff}}^2 - T^2)T_{\text{eff}}^3$$

$$\frac{dE^2}{dT_{\text{eff}}} = 0$$

$$\frac{d^2E^2}{dT_{\text{eff}}^2} = 0$$

$$\Longrightarrow T_c = \frac{T_0}{144\sqrt{3}} \quad T_{\text{eff}} = \frac{T_0}{144}$$



Open questions

Open questions

- Mechanism of thermalization of the effective temperature (relaxation)
- Explanation of the expression for the dissipated power in hopping systems
- Switching transition versus Glassy behavior.
  Is activated conduction a necessary condition for the switching bistability?
- Role of many-electron transitions in VRH (in both linear and non linear regimes). Many particles per localization volume.