Glassy Behavior in a Two-Dimensional Electron System in Si

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Outline

• 2D metal-insulator transition (MIT) in electron and hole systems: experimental features and puzzles

• the MIT occurs at low carrier densities, in the regime where both disorder and electron-electron interactions are strong
  (glassy ordering???)

• we employ a combination of transport and resistance noise measurements to probe the glassy behavior in a 2D electron system in Si MOSFETs

  2D metal-insulator transition in Si: melting of the Coulomb glass

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2D metal-insulator transition

- dramatic change of behavior near "separatrix" at $T < 0.3 T_F$
- Large resistivity drop! (origin?)
- "separatrix" ($n_c$)
- $k_f l \sim 1$ at the transition
- for $n_s \sim 10^{11} \text{ cm}^{-2}$:
  - $E_F = \frac{\pi}{2} n_s/2m^* = 0.6 \text{ meV}$
  - $E_{c-e} \sim (e^2/\varepsilon)(\pi n_s)^{1/2} \approx 10 \text{ meV}$
- $r_s = E_{c-e}/E_F \propto n_s^{-1/2} \sim 10$

[Kravchenko et al., PRB 51, 7038 (1995); Si MOSFET devices]

Metal-insulator transition as a quantum critical point:

- $T_0 \sim |\delta_n|^{2\nu}$
  - $\delta_n = n_s/n_c - 1$, $\nu = 1.6$
- origin of the small energy scale $T_0$?

"dynamical scaling":

$$\sigma(n_s, T) = \sigma_c f(T/\delta_n^{2\nu})$$

[Kravchenko et al., PRB 51, 7038 (1995)]
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Scaling of low-field magnetoconductivity:

• at T=0, scaling parameter 
  \[ B_c \propto n^{1/\beta} \]  
  (\( \beta \sim 1 \))

• \( B_c \sim B_{\text{pol}} \)  
  (\( B_{\text{pol}} \) – field for full spin polarization)

• origin of the small field scale \( B_c \) ?

• similar behavior observed in a variety of other 2D electron and hole systems but ‘best” in Si

• experiments other than macroscopic transport: mesoscopic, compressibility, thermopower, magnetization

  nonmonotonic, qualitative changes near the MIT

   BUT:

• no generally accepted microscopic description of the metallic phase and the MIT (or “MIT”?)

• need something else

• noise provides complementary information and a clear evidence for a (glass) transition

• also: what is the nature of the insulator?

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From the insulating side (low $n_s$): an electron glass?

- disorder $\rightarrow$ nonuniform density
- Coulomb repulsion $\rightarrow$ uniform density
- Frustration!
- many metastable states with similar (free) energy

- emergence of (exponentially!) many states

Fluid

\[ \text{config} \]

Glass

\[ \text{configuration space} \]

- glassy behavior deep in the insulator (Coulomb glass)
  (numerical studies: Efros&Shklovskii; Pollak)
- experimental signature of glassiness: dynamics;
  dramatic slowing down, history dependence
  - phase transition?
  - use resistance noise to probe glassy dynamics
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Si MOSFET devices:

- disorder due to (Na⁺) ions randomly distributed throughout the oxide (frozen out below ~100 K), and to surface roughness
- ‘peak mobility’ at 4.2 K – rough measure of disorder

1. high disorder
(from IBM, Yorktown Heights):
- poly-Si gates, self-aligned ion-implanted contacts
- \( d_{ox}=50 \text{ nm}, N_a \sim 2 \times 10^{17} \text{ cm}^{-3} \)
- sample length 1 \( \mu m \), width 90 \( \mu m \), but also Hall bars
- peak mobility 600 \( \text{cm}^2/\text{Vs} \) at 4.2 K

2. low disorder
(from Groningen/Delft):
- peak mobility 25,000 \( \text{cm}^2/\text{Vs} \) at 4.2 K
- Al gates with submicron gaps near contacts
- \( d_{ox}=147 \text{ nm}, N_a \sim 10^{14} \text{ cm}^{-3} \)
- Hall bar sample with the 120x50 \( \mu m^2 \) central part

Low-mobility (high disorder) Si MOSFETs

- the relative fluctuations are of the order of 100% at low \( n_s \) and \( T \)
- noise decreases with increasing \( n_s \) and \( T \)
- non-Gaussian
- the character of the noise changes dramatically as \( n_s \) is varied: at high \( n_s \), the variance no longer varies with time

\(<\sigma> - \text{time-averaged conductivity}\)
High-mobility (low disorder) Si MOSFETs

- the character of the noise changes with \( n_s \); at low \( n_s \), the variance varies with time; at high \( n_s \), the noise always looks the same

\[ \rho \text{ - resistivity} \]
\[ \delta \rho^2 \text{ = variance} \]

Transport in high-mobility (low disorder) Si MOSFETs

- lowest \( n_s \) and \( T \): \( \langle \rho \rangle \propto \exp(\frac{E_d}{k_B T}) \) \[ n_c \approx 9.7 \times 10^{10} \text{ cm}^{-2} \] \[ n_c \approx n_s^* \]
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Transport in low-mobility (high disorder) Si MOSFETs

- metallic $<\sigma(T)>$ at high $n_s$
- $d<\sigma>/dT=0$ at $n_s^*=12.9\times10^{11}$ cm$^2$
- metal-insulator transition:
  $n_c=(5.0\pm0.3)\times10^{11}$ cm$^2$
- glass transition:
  $n_g=(7.5\pm0.3)\times10^{11}$ cm$^2$

- at the lowest $n_c$:
  $<\sigma> \propto \exp(-T_o/T)$, $n_c=(5.0\pm0.3)\times10^{11}$ cm$^2,$ $n_c \cdot n_s^*$
  near $n_c$:
  $<\sigma> = a(n_c) + b(n_c)T_x,$ $x=1.5$
  $<\sigma(n_c,T)> \propto T^{3/2}$

(consistent with V. Dalidovich and V. Dobrosavljević, PRB 66, 081107 (2002), for the metallic glass phase)
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\[ \delta \sigma = \langle (\sigma - \langle \sigma \rangle)^2 \rangle^{1/2} \]

- \( T = 0.130 \, \text{K} \)
- \( T = 0.196 \, \text{K} \)
- \( T = 0.455 \, \text{K} \)
- \( T = 0.805 \, \text{K} \)

- A dramatic change of \( d(\delta \sigma)/dn_s \) at \( n_c \)
- A dramatic increase of noise \( (\delta \sigma/\langle \sigma \rangle) \) at \( n_g \)
- Various glassy phenomena observed below \( n_g \)

Noise power spectra:

\[ S_1 = S(I, f)/I^2 \propto 1/f^\alpha \]

(\( I \)-current)
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- A striking increase of the slow dynamic contribution to the conductivity for $n_s < n_g = 7.5 \times 10^{11} \text{ cm}^{-2}$
- A sudden and dramatic slowing down of the electron dynamics
- Increase of noise with decreasing temperature

- A sharp jump in $\alpha$ at $n_s = n_g$!
- A sudden shift of the spectral weight towards lower $f$ indicates a sudden and dramatic slowing down of the electron dynamics at $n_g$
- Observable only at low enough temperatures
- Similar large values of $\alpha$ observed in some spin glasses
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Resistance noise and power spectra in high-mobility (low disorder) Si MOSFETs

- a dramatic increase of the low-frequency noise, and
- a rapid increase of the exponent $\alpha$
  with decreasing $n_s$

$T=0.24$ K

$S_R \propto 1/f^\alpha$, $1 \leq \alpha \leq 2$

$\Delta R/R > 5\%$

$\eta_s = 8.7/9.27/9.38$
$9.56/11.9/13.0 \times 10^{10}$ cm$^{-2}$

$n_c \approx 10 \times 10^{10}$ cm$^{-2}$
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**Second spectrum – “noise of the noise”**

(Voss & Clarke, Restle & Weissman, Seidler & Solin)

- $S_2(f_2,f)$: power spectrum of the fluctuations of $S_R(f)$ with time (fourth-order noise statistic)

- probes correlations between fluctuators:
  - uncorrelated fluctuators $S_2(f_2,f)$ white;
  - correlated fluctuators $S_2 \propto 1/f^{1-\beta}$ (non-Gaussian)

- similar to spin glasses with long-range (RKKY) correlations
- a dramatic change in $S_2$ near $n_g$: $S_2$ white – uncorrelated at high $n_g$, $S_2$ nonwhite – correlated below $n_g$
- high-mobility samples: $n_c \bullet n_g \sim n_s^*$
- low-mobility samples: $n_c < n_g \approx 1.5n_c < n_s^*$ [consistent with Dobrosavljević et al., PRL 90, 016402 (2003)]
Scaling of the second spectra
[measured at $f = (f_L, 2f_L)$]

- no systematic dependence on $f$ → scale invariance
- consistent with the hierarchical picture of glassy dynamics
- rules out interacting two-state systems (droplets, clusters, defects, …) as possible sources of noise

Slow relaxations and history dependence below $n_g$

Two different cooling protocols:
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What we have learned so far:

- glassy freezing of the 2DES near the metal-insulator transition in all Si inversion layers

- glass transition manifested by:
  1) a sudden and dramatic slowing down of the electron dynamics
  2) an abrupt change to the sort of statistics characteristic of complicated multistate systems (hierarchical picture)

- the width of the metallic glass phase depends on disorder

- evidence for the 2D MIT as the melting of an electron glass

Spin or charge?
Noise measurements in parallel magnetic fields

- a sufficiently strong magnetic field is expected to destroy the spin glass order

\[ S_R \sim 1/f^\alpha \]

\( \alpha = 1.58 \)  
\( \alpha = 1.24 \)  
\( \alpha = 0.96 \)  
\( \alpha = 0.58 \)

\( n_s = 11.9 \times 10^{11} \text{ cm}^2 > n_s(B=0) \)

- at high \( n_s \), in the metallic phase, 1/f noise is suppressed by parallel \( B \)
- \( B_g \) for \( n_s = 11.9 \times 10^{10} \text{ cm}^2 \)
- a sudden and dramatic increase of \( S_R \), a rapid rise of \( \alpha \), and a change of \( (1-\beta) \) at \( B_g(n_s) \) at low \( B \) and \( n_g(B) \) at high \( B \)
- glass transition at \( B_g(n_s) \) and \( n_g(B) \)
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Phase diagram

- critical densities $n_c$ determined from $\sigma(T)$ on the insulating side
- broadening of the MG phase with $B$ (suppression of screening by $B$ effective disorder higher favors glassiness)

- glass transition persists in high parallel $B$, where the 2DES is spin polarized charge, as opposed to spin, responsible for glassy ordering

Metallic glass phase at low $B$

$\sigma(n,s,T,B)=\sigma(n,s,T=0,B)+b(n,s,B)T^{3/2}$ !
(same as in low-mobility samples at $B=0$!)

$\sigma(n,s,T=0,B) \propto n^\mu$, $\mu \sim 1.5$
consistent with QPT

- at $B=0$, $\mu \sim 1.5$ [Fletcher et al., Semicond. Sci. Tech. 16, 386 (2001)]
- first determination of $n_c(B)$ from the metallic side; good agreement with $n_c(B)$ from the insulating side

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**Conclusions**

- glassy ordering of the 2DES in Si as a precursor of the MIT
- Coulomb glass
  
  [Bogdanovich, Popović, PRL 88, 236401 (2002);
  Jaroszyński, Popović, Klapwijk, PRL 89, 276401 (2002);
  Jaroszyński, Popović, Klapwijk, cond-mat/0302527]

Other systems:

- \(1/f^\alpha\) noise in 2D holes in GaAs (much less disorder than in Si) – some similarities but not conclusive
  
  [Leturcq, L’Hote, Tourbot, Mellor, Henini, PRL 90, 076402 (2003)]

- \(1/f^\alpha\) noise in bulk P doped Si:
  a huge increase of noise and the onset of non-Gaussianity at the MIT!!
  
  [Kar, Raychaudhuri, Ghosh, cond-mat/0212165]