Glassy behavior in a two-dimensional electron system in Si

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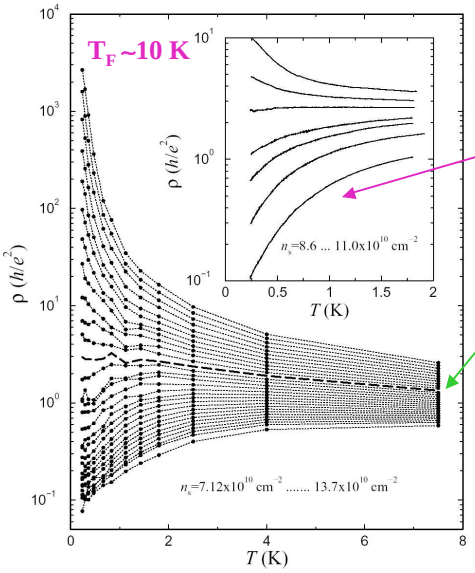
Outline

- **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**

2D metal-insulator transition



- dramatic change of behavior near "separatrix" at $T < 0.3T_F$

Large resistivity drop! (origin?)

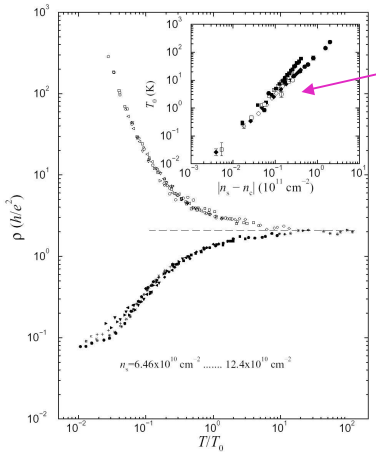
"separatrix" (n_c)

$k_F l \sim 1$ at the transition

- for $n_s \sim 10^{11}$ cm^{-2}:
  $E_F = \pi\hbar^2 n_s/2m^* \approx 0.6$ meV
  $E_{e\text{-}e} \sim (e^2/\varepsilon)(\pi n_s)^{1/2} \approx 10$ meV

→ $r_s \equiv E_{e\text{-}e}/E_F \propto n_s^{-1/2} \sim 10$

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



$T_0 \sim |\delta_n|^{z\nu}$ ($\delta_n = n_s/n_c - 1$, $z\nu \approx 1.6$)

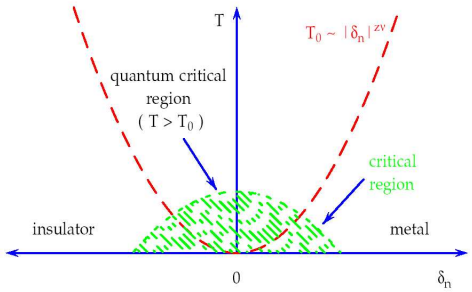
- origin of the small energy scale T_0?

[Kravchenko *et al.*, PRB 51, 7038 (1995)]

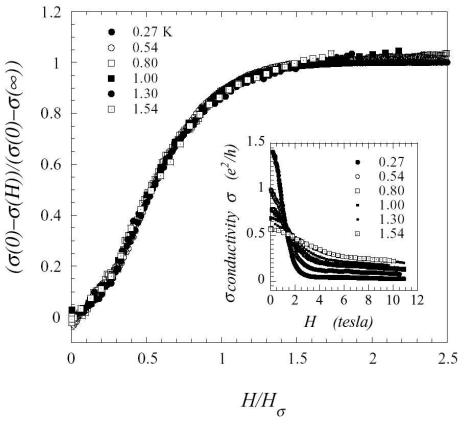
"dynamical scaling":

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

Metal-insulator transition as a quantum critical point:

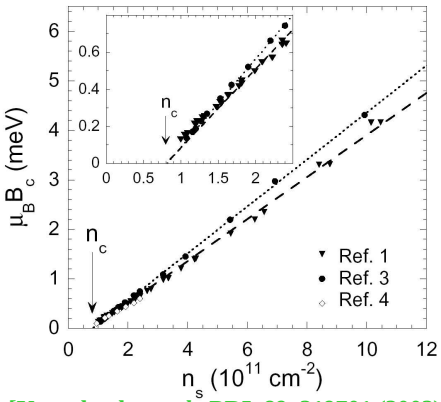


Scaling of low-field magnetoconductivity:



[Vitkalov *et al.*, PRL 87, 086401 (2001)]

- at T=0, scaling parameter $B_c \propto \delta_n^{1/\beta}$ ($\beta \sim 1$)
- $B_c \sim B_{pol}$ (B_{pol} – field for full spin polarization)



[Kravchenko *et al.*, PRL 89, 219701 (2002)]

- origin of the small field scale B_c ?

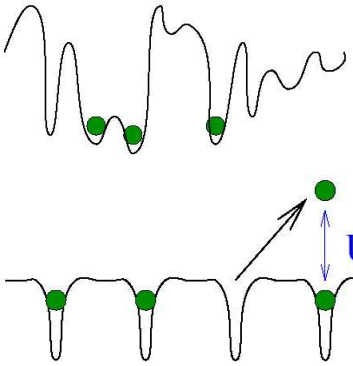
- similar behavior observed in a variety of other 2D electron and hole systems but "best" in Si
- experiments other than macroscopic transport: mesoscopic, compressibility, thermopower, magnetization

→ 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?

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



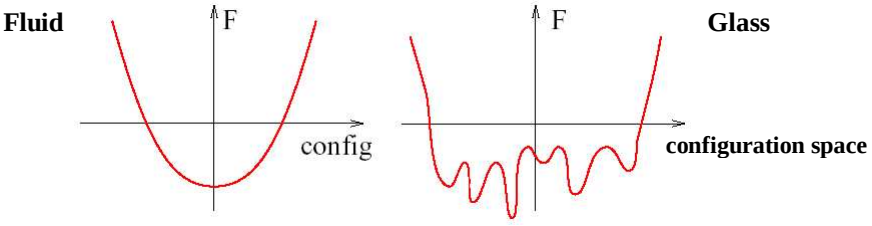
• disorder ⟹ nonuniform density

• Coulomb repulsion
⟹ uniform density

⟹ Frustration!

⟹ many metastable states with similar (free) energy

• emergence of (exponentially!) many states



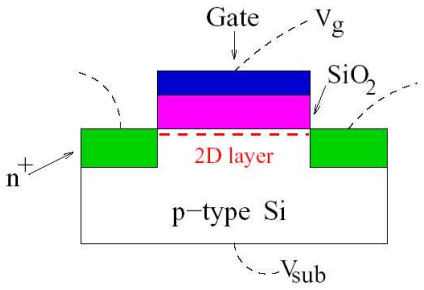
• glassy behavior deep in the insulator (Coulomb glass)
(numerical studies: Efros&Shklovskii; Pollak)

• experimental signature of glassiness: dynamics;
dramatic slowing down, history dependence

• phase transition?

⟹ use resistance noise to probe glassy dynamics

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

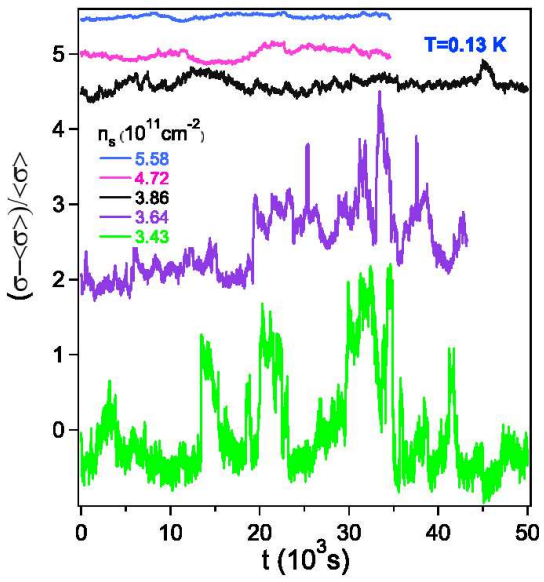
1. high disorder
(from IBM, Yorktown Heights):

- poly-Si gates, self-aligned ion-implanted contacts
- d_{ox}=50 nm, N_a~2×10^{17} cm^{-3}
- sample length 1 μm, width 90 μm, but also Hall bars
- peak mobility 600 cm^2/Vs at 4.2 K

2. low disorder
(from Groningen/Delft):

- peak mobility 25,000 cm^2/Vs at 4.2 K
- Al gates with submicron gaps near contacts
- d_{ox}=147 nm, N_a~10^{14} cm^{-3}
- Hall bar sample with the 120×50 μm^2 central part

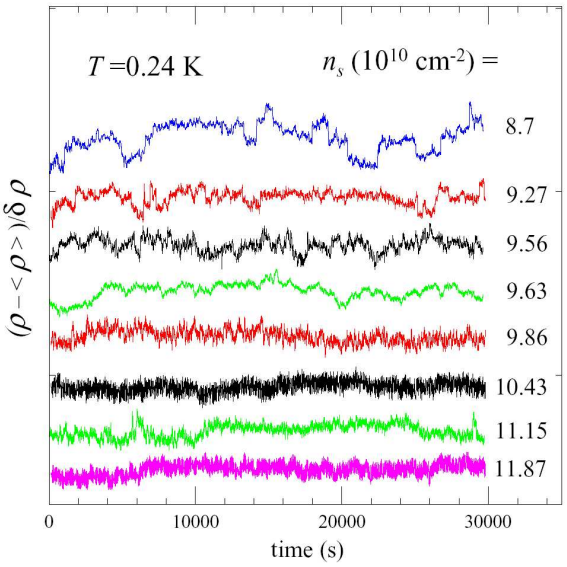
Low-mobility (high disorder) Si MOSFETs



- 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

$\langle\sigma\rangle$ - time-averaged conductivity

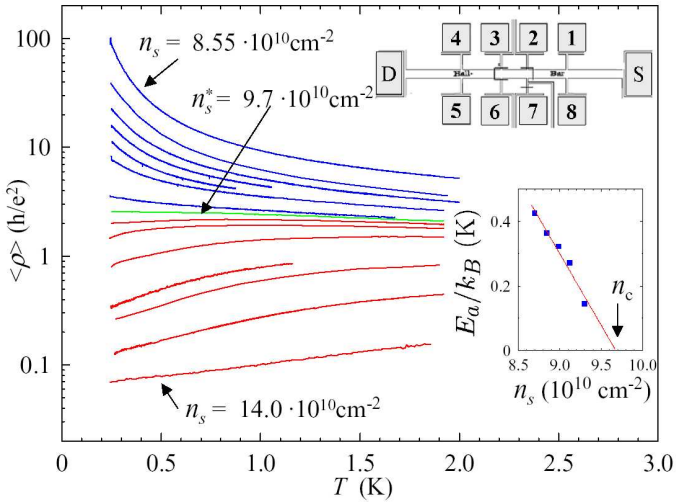
High-mobility (low disorder) Si MOSFETs



- 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

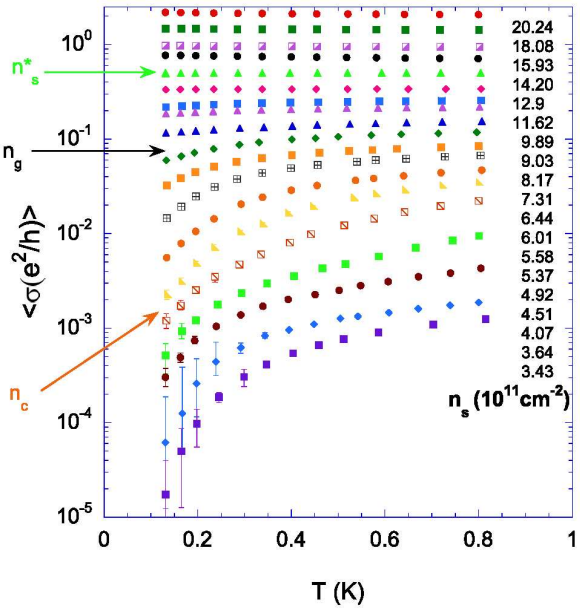
ρ - resistivity
$\delta\rho^2$ = variance

Transport in high-mobility (low disorder) Si MOSFETs



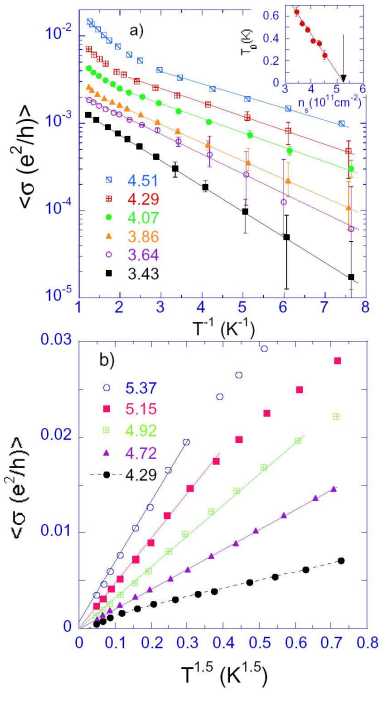
- lowest n_s and T: $<\rho> \propto \exp(E_a/k_BT)$ ⟶ $n_c \approx 9.7\times10^{10}$ cm^{-2}
  $n_c \approx n_s^*$

Transport in low-mobility (high disorder) Si MOSFETs



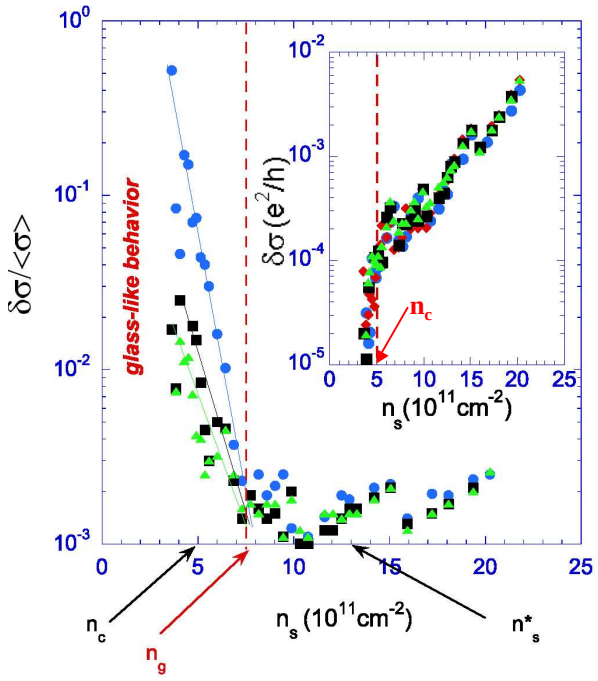
- metallic $<\sigma(T)>$ at high n_s
- $d<\sigma>/dT=0$ at $n_s^*=12.9\times10^{11}$ cm^{-2}
- metal-insulator transition: $n_c=(5.0\pm0.3)\times10^{11}$ cm^{-2}
- glass transition: $n_g=(7.5\pm0.3)\times10^{11}$ cm^{-2}

→ metallic glass



- at the lowest n_s: $<\sigma> \propto \exp(-T_o/T)$, → $n_c=(5.0\pm0.3)\times10^{11}$ cm^{-2}, $n_c \bullet n_s^*$
- near n_c: $<\sigma>=a(n_s) + b(n_s)T^x$, $x\approx1.5$ $<\sigma(n_c,T)> \propto T^{3/2}$

(consistent with V. Dalidovich and V. Dobrosavljević, PRB 66, 081107 (2002), for the metallic glass phase)

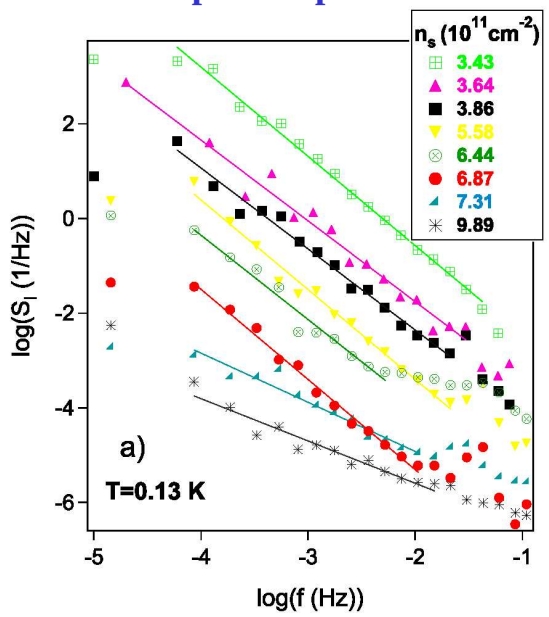


$\delta\sigma = \langle(\sigma - \langle\sigma\rangle)^2\rangle^{1/2}$

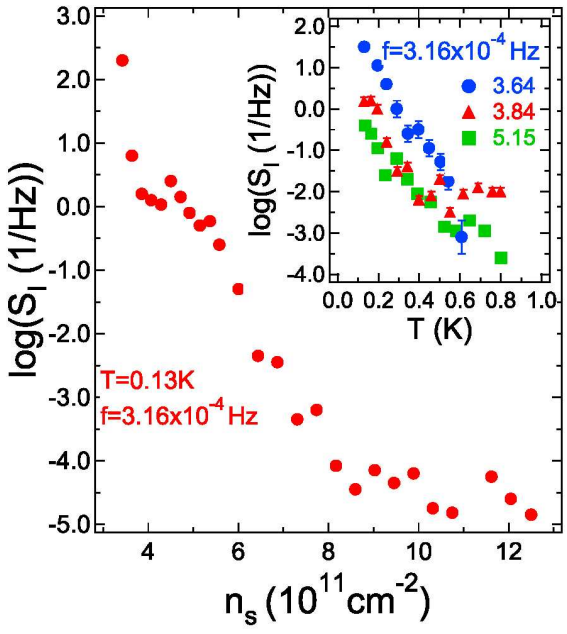
T=0.130 K
T=0.196 K
T=0.455 K
T=0.805 K

- 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

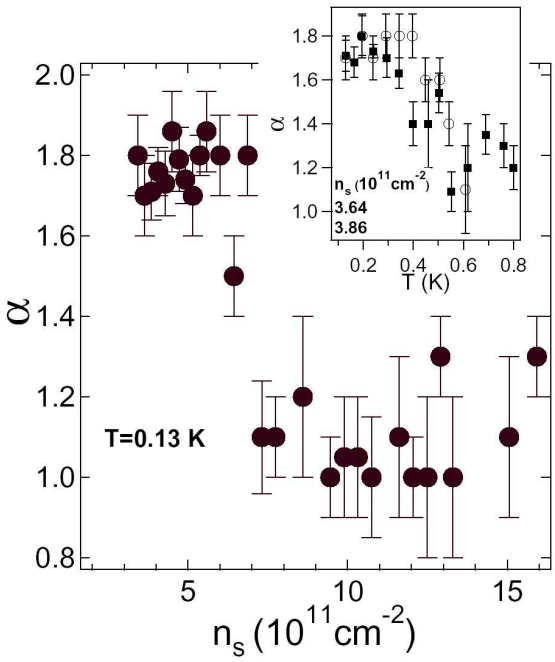
Noise power spectra:



$S_I = S(I,f)/I^2 \propto 1/f^{\alpha}$
(I-current)

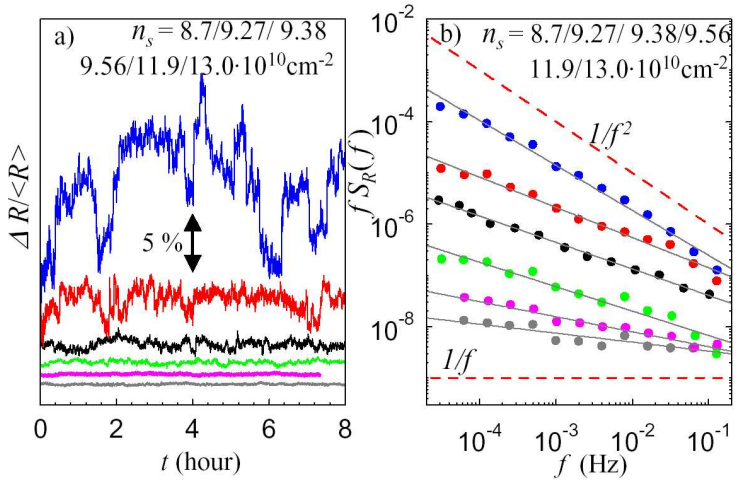


- a striking increase of the slow dynamic contribution to the conductivity for $n_s < n_g \approx 7.5\times10^{11}$ cm^{-2}
- a sudden and dramatic slowing down of the electron dynamics
- increase of noise with decreasing temperature

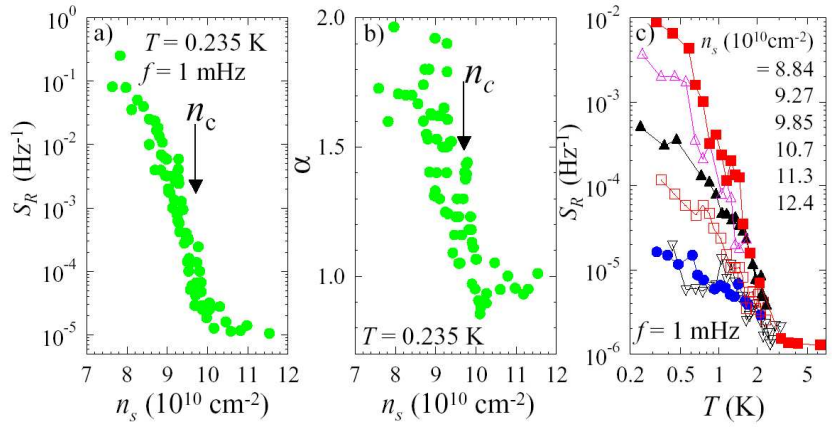


- a sharp jump in α at $n_s \approx n_g$!
- a sudden shift of the spectral weight towards lower *f* indicates a sudden and dramatic slowing down of the electron dynamics at n_g
- observable only at low enough temperatures
- similar large values of α observed in some spin glasses

Resistance noise and power spectra in high-mobility (low disorder) Si MOSFETs



T=0.24 K $\quad S_R \propto 1/f^{\alpha}, \quad 1 \le \alpha \le 2$



- **a dramatic increase of the low-frequency noise, and**
- **a rapid increase of the exponent α with decreasing n_s**

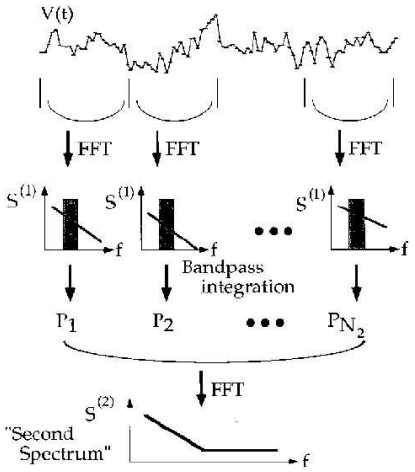
→ **$n_c \cdot n_g \approx 10 \times 10^{10}$ cm^{-2}**

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

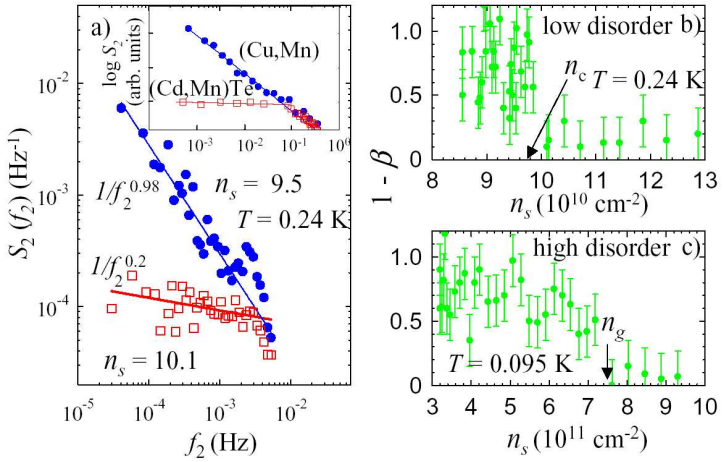
(fourth-order noise statistic)



- probes correlations between fluctuators:

uncorrelated fluctuators → $S_2(f_2,f)$ white;

correlated fluctuators → $S_2 \propto 1/f^{1-\beta}$ (non-Gaussian)

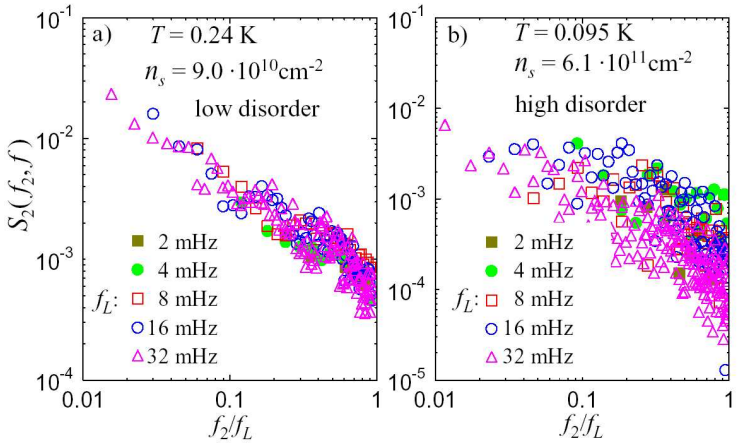


- similar to spin glasses with long-range (RKKY) correlations
- a dramatic change in S_2 near n_g: S_2 white – uncorrelated at high n_s, S_2 nonwhite – correlated below n_g
- high-mobility samples: $n_c \bullet n_g \sim n_s^*$
- low-mobility samples: $n_c < n_g \approx 1.5 n_c < n_s^*$

[consistent with Dobrosavljević et al., PRL 90, 016402 (2003)]

Scaling of the second spectra

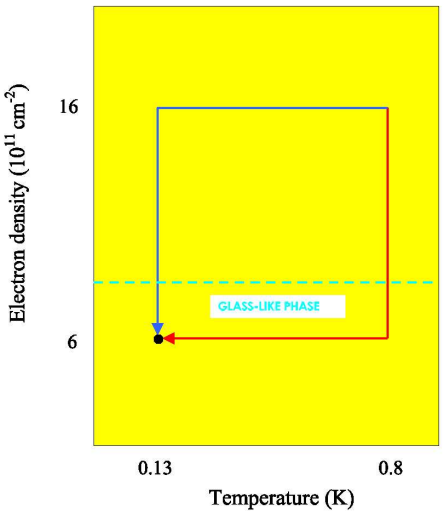
[measured at $f = (f_L, 2f_L)$]

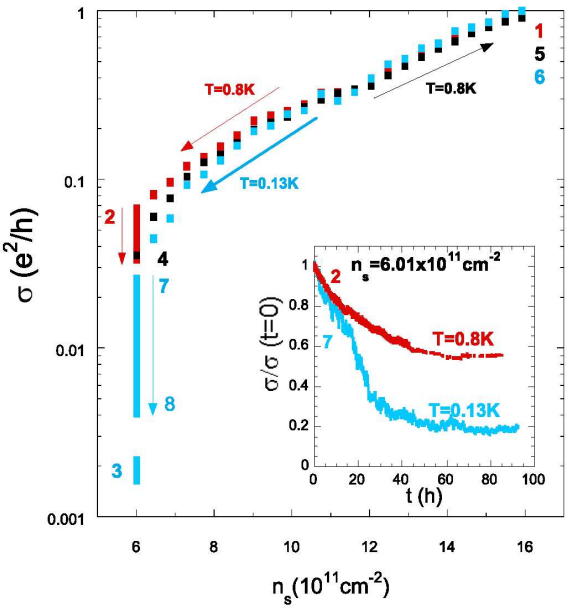


- **no systematic dependence on f → scale invariance**
- **consistent with the hierarchical picture of glassy dynamics**
- **rules out interacting two-state systems (droplets, clusters, defects, …) as possible sources of noise**

Slow relaxations and history dependence below n_g

Two different cooling protocols:





(low-mobility samples)

- the final conductivities (points 3 and 8) obtained for the same n_s and T using two different cooling protocols, differ by a factor of 2!
- nonergodic behavior

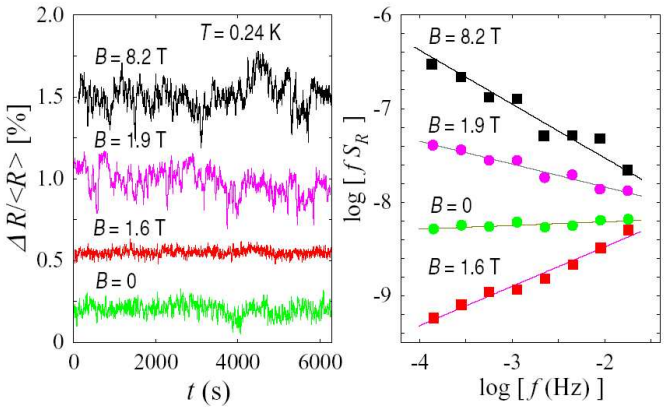
What we have learned so far:

- 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

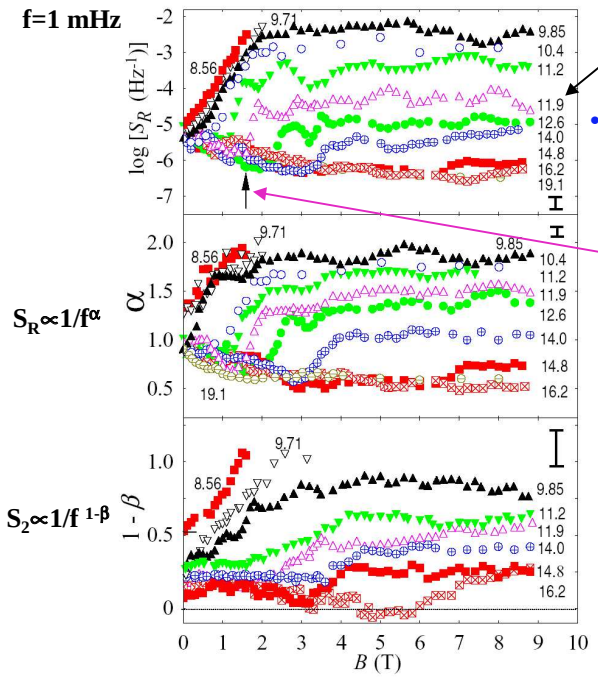
- a sufficiently strong magnetic field is expected to destroy the spin glass order



$S_R \propto 1/f^{\alpha}$

α=1.58
α=1.24
α=0.96
α=0.58

(high-mobility samples) $n_s = 11.9\times10^{11}$ cm^{-2} > $n_c(B=0)$



$n_s(10^{10}$ cm$^{-2})$

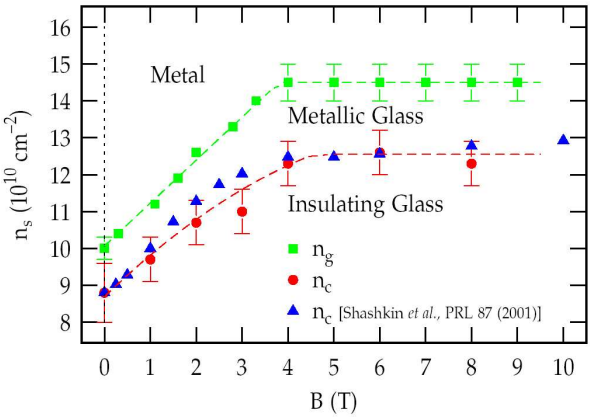
- at high n_s, in the metallic phase, 1/f noise is suppressed by parallel B

B_g for $n_s = 11.9\times10^{10}$ cm^{-2}

- a sudden and dramatic increase of S_R, a rapid rise of α, 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 $n_g(B)$

Phase diagram

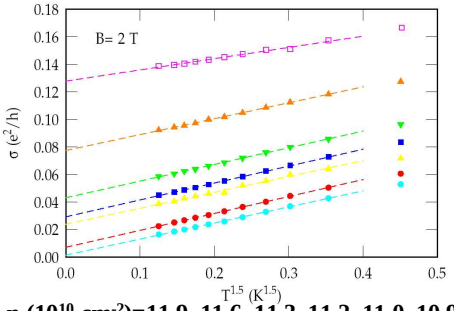


- critical densities n_c determined from $\sigma(T)$ on the insulating side
- broadening of the MG phase with B (suppression of screening by B ⟹ effective disorder higher ⟹ favors glassiness)

- 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



$n_s(10^{10}$ cm$^{-2})$=11.9, 11.6, 11.3, 11.2, 11.0, 10.9, 10.7 from top; n_c(B=2T)=10.67×10^{10} cm^{-2}

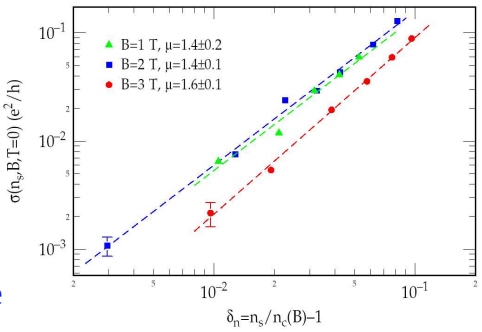
- at B=0, $\mu \sim 1$-1.5 [Fletcher et al., Semicond. Sci. Tech. 16, 386 (2001)]
- first determination of n_c(B) from the metallic side; good agreement with n_c(B) from the insulating side

$\sigma(n_s,T,B)=\sigma(n_s,T=0,B)+b(n_s,B)T^{3/2}$!

(same as in low-mobility samples at B=0!)

$\sigma(n_s,T=0,B) \propto \delta_n^{\mu}$, $\mu \sim 1.5$

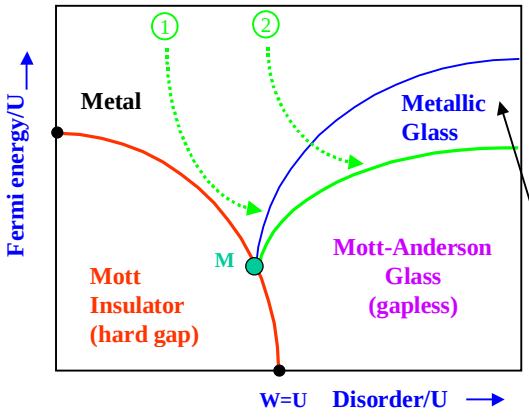
consistent with QPT



Global phase diagram

(stolen from V. Dobrosavljević)

[Pastor and Dobrosavljević, PRL 83, 4642 (1999); Dalidovich and Dobrosavljević, PRB 66, 081107 (2002); Dobrosavljević et al., PRL 90, 016402 (2003); Tanasković et al., cond-mat/0303145]



- (2D) MIT as a Mott-Anderson transition
- glass as a precursor of MIT
- melting of glass even at T=0 (by quantum fluctuations)
- also provides microscopic origin of small energy and field scales near the MIT, and describes the metallic T-dependence
- Metallic glass phase: $\sigma(T) - \sigma(0) \sim T^{3/2}$
- hierarchical, correlated dynamics

Physical trajectory: $E_F \sim n_s$; $U \sim n_s^{1/2}$; $W \sim$ const. ⇒ $(E_F/U) \sim (W/U)^{-1}$

1 High-mobility samples, 2 Low-mobility samples

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]