Nonequilibrium dynamics in Coulomb glasses near the metal-insulator transition

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Lecture I: Metal-insulator transition and complexity in electronic systems

- Modern technology: synthetic materials, devices
- Designing materials: metals *vs.* insulators
- Metal-insulator transition
- Coulomb glass
- Miscellaneous complex electronic systems
- Metal-insulator transition in two dimensions (2D) - general
- Practical realizations of 2D systems
- Metal-insulator transition (MIT) in 2D – some experiments
- Literature

Lecture II: Studies of the electron dynamics near the 2D MIT: Relaxations of conductivity

Lecture III: Studies of the electron dynamics near the 2D MIT: Fluctuations of conductivity

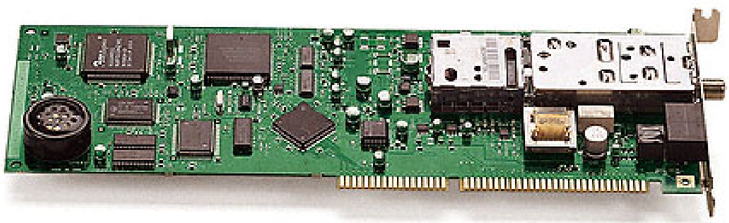
Lecture I: Metal-insulator transition and complexity in electronic systems

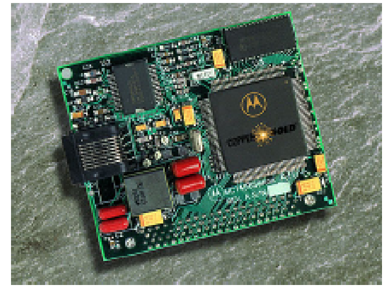
Modern technology: 1947 - present

Invention of the transistor

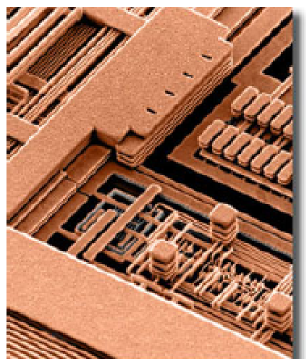
(Bardeen, Brattain, Shockley, Nobel Prize in Physics, 1956)

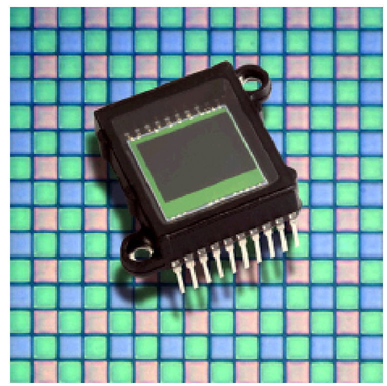
How does all this work: "The art of electronics"





- Ultra small integrated circuits, transistor chips,..





Invention of integrated circuits

(Kilby, Nobel Prize in Physics, 2000)

- Devices that control (switch on–off) electrical currents:

Turn conductors into insulators and vice versa

Why semiconductors?

Designing materials: metals *vs.* insulators

- good metals (Cu, Au, Ag, ...) and (band) insulators (C-diamond, Si, Ge, ...) well understood – see textbooks (band theory)
- many "old" (doped semiconductors – Si:P, ...) and novel materials (high-T_C superconductors, ...) not understood

Turning insulators into metals using doping!

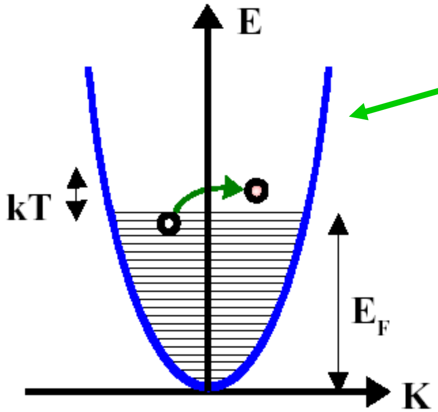
Metals vs. insulators

$\sigma(T=0)\neq 0$ $\sigma(T=0)=0$

(σ – conductivity; metal-insulator transition at T=0 – quantum effects)

- **Metals:** Pauli principle, large Fermi (kinetic) energy

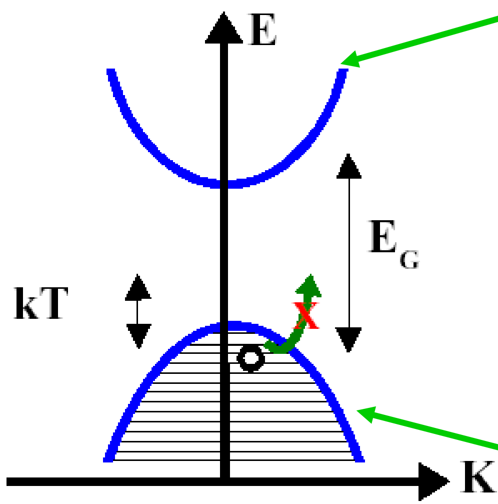
(E_F ~ 10 000 K)



Conduction band (partly filled)

- conductivity σ (T=0) ≠ 0 ($\sigma = 1/\rho$)
- elementary excitations: a few electron-hole pairs (fermions; weakly interacting – "Fermi liquid")
- hard to affect, stable, robust

- **Insulators:** large energy gap (> 5 eV≈ 50 000 K; room T ≈ 300 K)



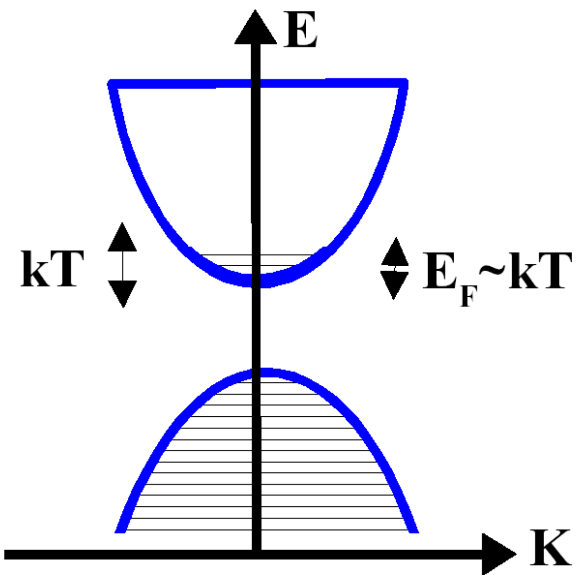
Conduction band (empty)

- σ (T=0) = 0
- elementary excitations: collective modes (phonons, spin waves; typically bosons)
- hard to affect, stable, robust

Valence band (filled)

♦ **Semiconductors:** insulators with E_G < 1-2 eV (~ 10 000 K); some electrons in the conduction band at room T as a result of thermal fluctuations

Doped insulators: small Fermi energy



- intentional adding of specific impurities (dopant)

  → introducing new charge carriers

- easy (!!!) to affect and control

  (ρ depends on doping)

- elementary excitations: ????
  (no simple picture)

So, are doped semiconductors metals [$\sigma(T=0)\neq 0$]?

Doped semiconductors: Si:P – a classic example
(the basis of semiconductor technology!)

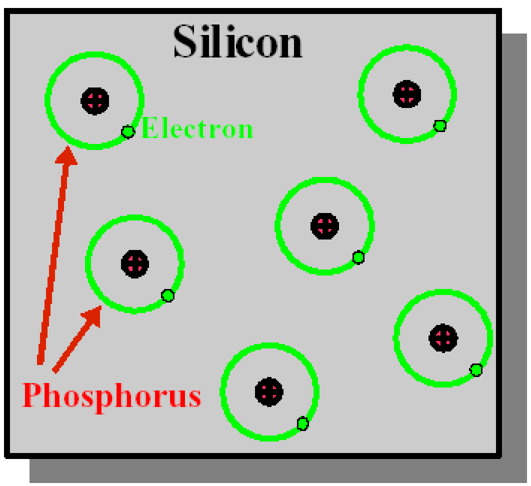
Si – group IV element (four valence electrons)

P – group V element (five valence electrons; substitutional impurity)

• the fifth P electron is only weakly bound to the P atom

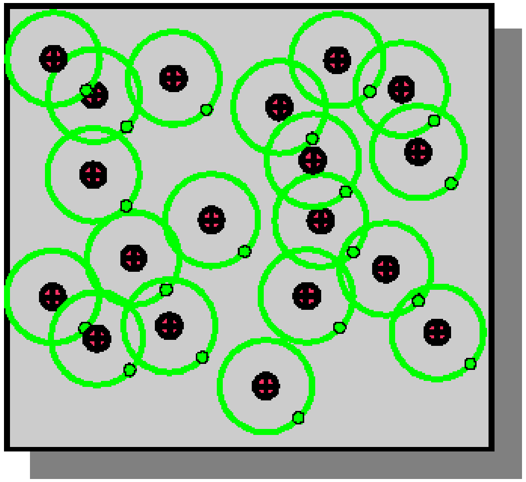
$\sigma(T=0)=0$

Insulator



$\sigma(T=0)\neq 0$

Metal



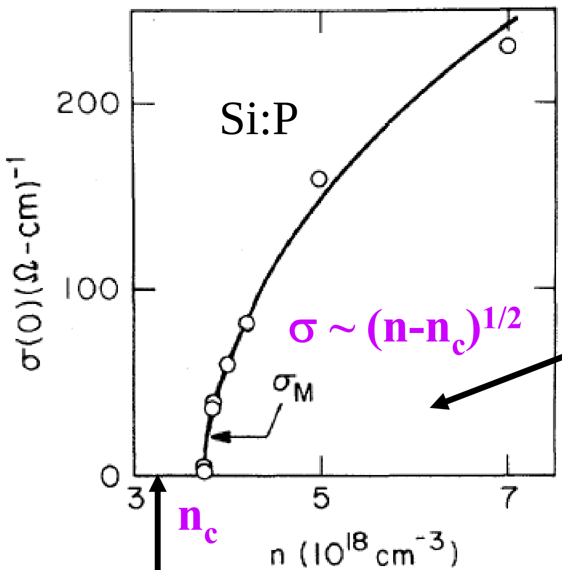
Carriers but no conductivity at T=0!!?

What do the experiments say?

Metal-insulator transition

Low-temperature (< 1 K) conductivity: experiment (Si:P)

(Paalanen, Rosenbaum, Thomas, Bhatt; 1982)



n_c

$\sigma(n<n_c) = 0$:
insulator

- **at low density $n<n_c$, there are carriers, but no conductivity!!**

$\sigma(n>n_c) \neq 0$:
metal

Metal-insulator transition at $n=n_c \neq 0$

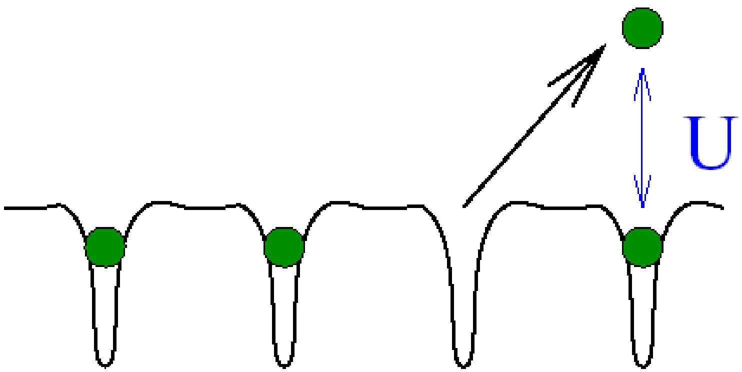
(quantum, *i.e.* T=0 phase transition)

Failure of the single-electron model (*i.e.* band structure calculations)

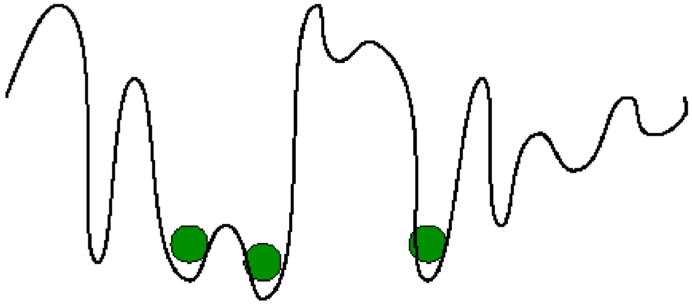
What's missing???

- **high density – kinetic energy (Fermi energy) dominates**
- **low density – potential energy dominates:**

➢ **electron-electron interactions**
(Mott insulator)



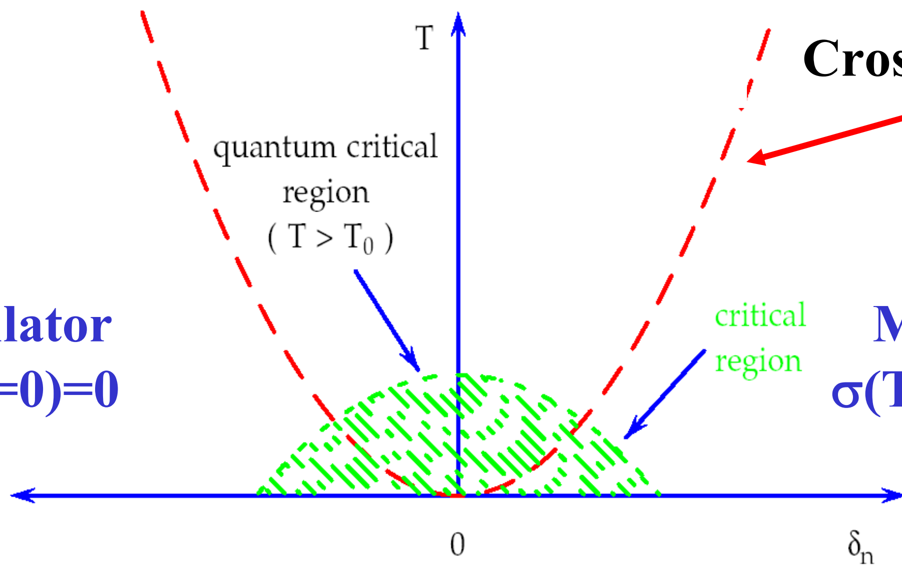
➢ **disorder due to impurities, defects (Anderson insulator)**



Result: formation of localized (bound) states ⟶ no conduction

Metal-insulator transition: a quantum critical point

- Experiments: a continuous transition; sharp phase transition at $T=0$



Crossover temperature

$T_0 \sim |\delta_n|^{z\nu}$

Insulator
$\sigma(T=0)=0$

Metal
$\sigma(T=0)\neq 0$

Control parameter
$\delta_n=(n_s-n_c)/n_c$
(n_s- carrier density)

- "dynamical scaling" in the critical region: $\sigma(n_s,T) \propto T^x f(T/\delta_n^{z\nu})$

- power-law critical behavior: $\sigma(n_s,T=0) \propto \delta_n^{\mu}$

Theoretical problems: no broken symmetry; order parameter? No small parameter; elementary excitations? Standard approaches fail

It gets even more complicated…

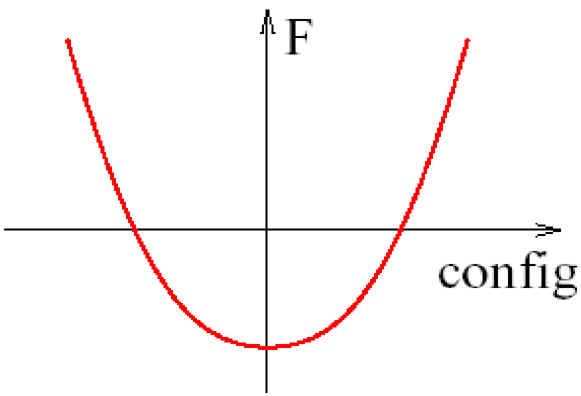
- Coulomb repulsion: keep electrons apart (uniform density)
- Random potential: nonuniform density

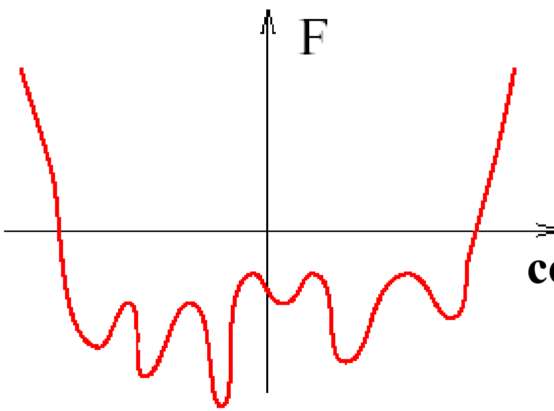
- competition between Coulomb interactions and disorder

→ **Frustration!** (can't make everyone happy)

→ emergence of (exponentially) many metastable states with similar (free) energy

Fluid



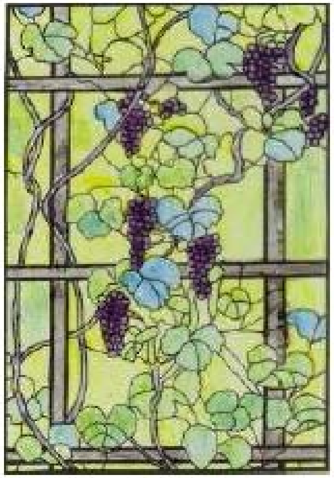


Glass

configuration space

Experimental signature: slow, out-of-equilibrium dynamics

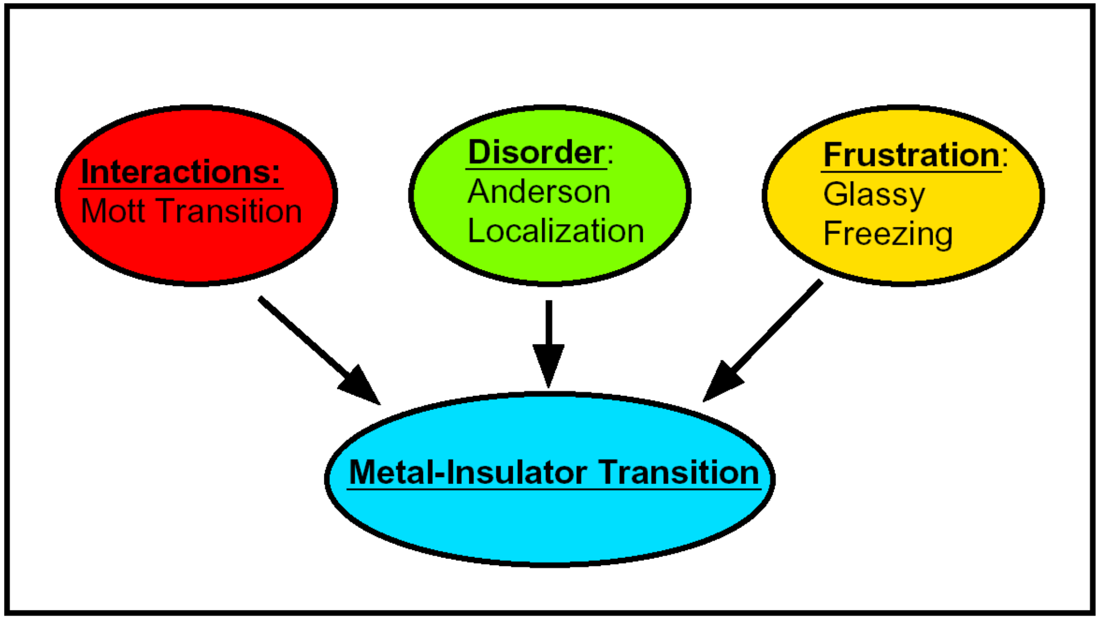
• **Slow nonequilibrium dynamics – similarities to other glasses?**



• **Unifying ideas, concepts?**

Relevance for the MIT?

Three basic mechanisms for electron localization:



Metal-insulator transition and glassiness –
two of the most fundamental problems in condensed matter physics

Coulomb glass

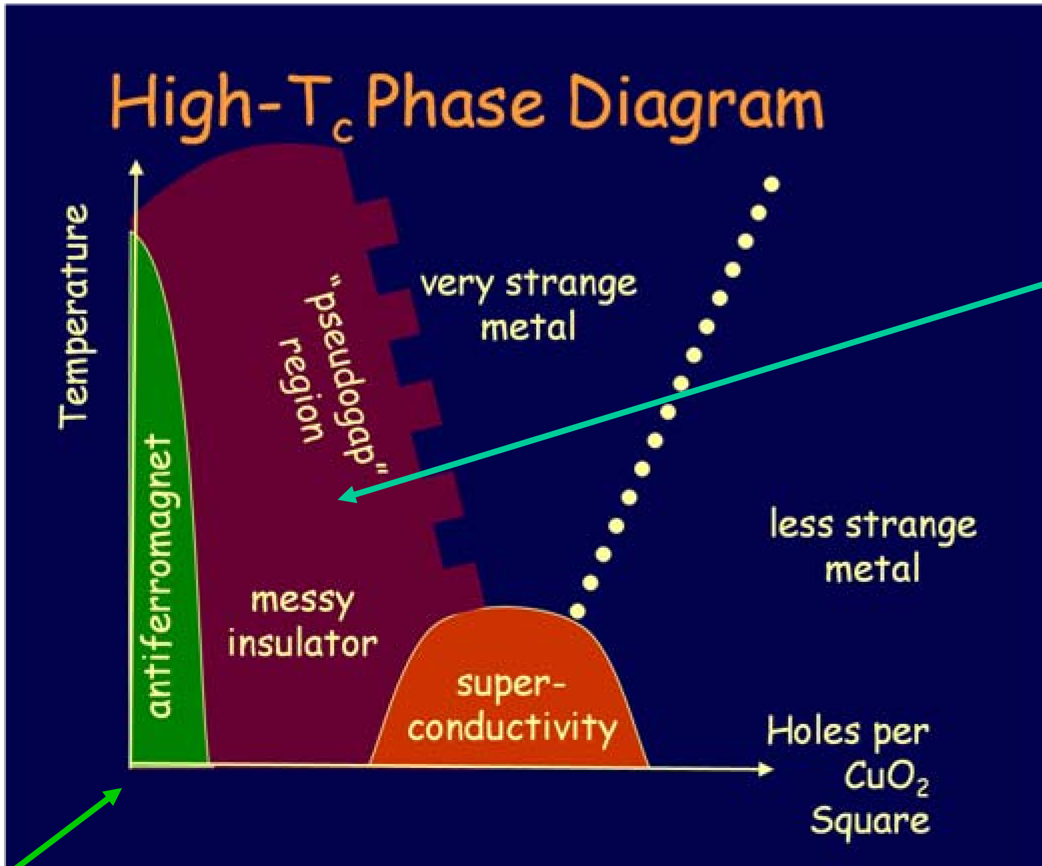
- expected in Anderson insulators with strong electron-electron interactions [M. Pollak (1970); Efros, Shklovskii (1975); Davies, Lee, Rice (1982,84)]

Observations of glassiness in electronic systems – very few:

- slow relaxations in GaAs capacitance (Monroe *et al.*)
- slow relaxations and thermal hysteresis in conductivity of granular films (Goldman *et al.*, Wu *et al.*, Frydman *et al.*)
- slow relaxations of photoconductivity in $YH_{3-\delta}$ (Lee *et al.*)
- slow relaxations, aging, memory in conductivity of InO_x (Ovadyahu *et al.*) and granular Al (Grenet *et al.*)
- 2D electrons in Si (DP *et al.*): slow relaxations, aging, memory; slow, correlated dynamics – from insulating to (poorly) metallic
- lightly doped cuprates (DP *et al.)*

} my work

Complex behavior of high-T_C superconductors



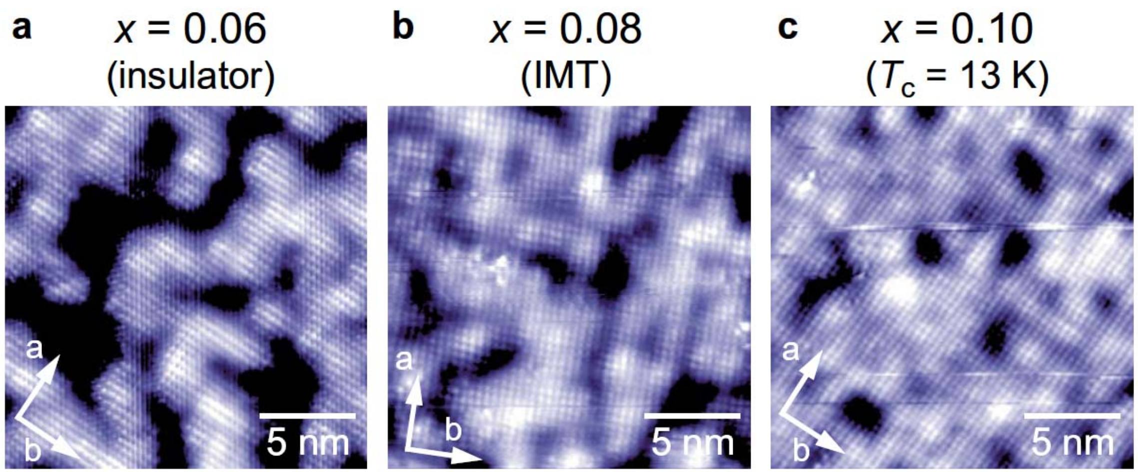
Emergence of nanoscale inhomogeneities!

- **only a few per cent of dopants cause a transition from an insulating to a (super) conducting state**

- **undoped parent compound (*e.g.* La_2CuO_4): Mott insulator, not a metal**
- **single-electron band theory of solids fails also here**

Nanoscale charge inhomogeneities

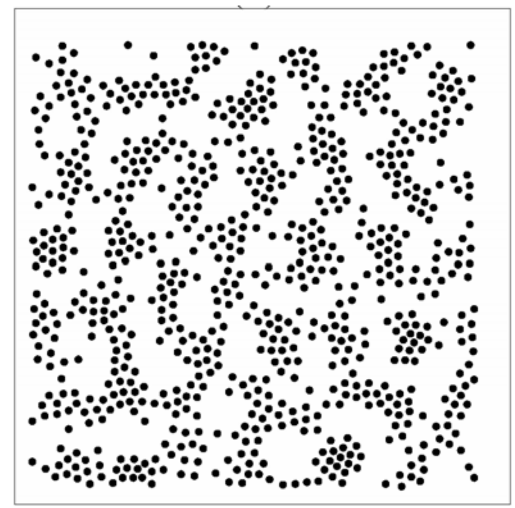
STM images



$Ca_{2-x}Na_xCuO_2Cl_2$

[Kohsaka *et al.*, Phys. Rev. Lett. 93, 097004 (2004)]

Computer modeling

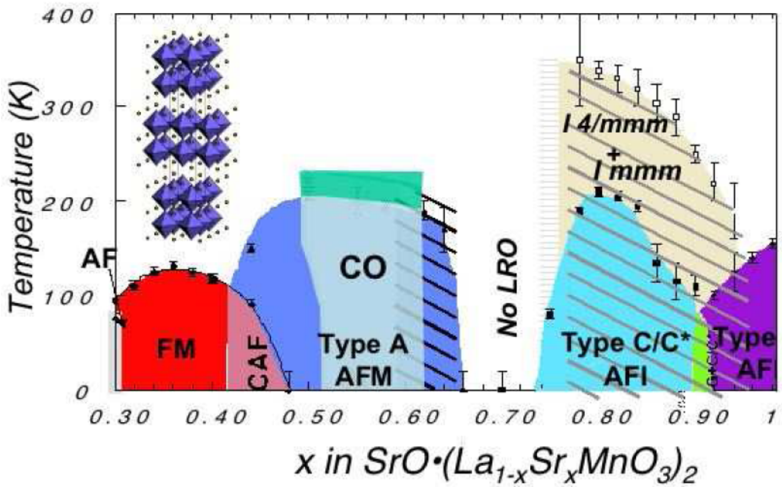


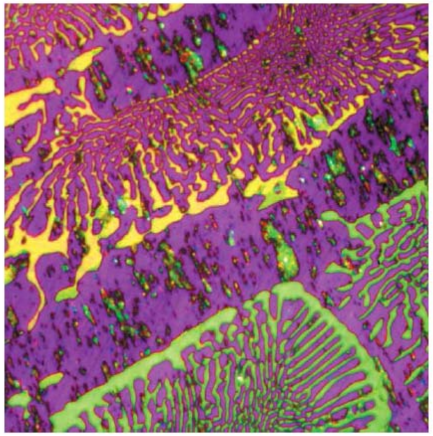
("stripe- and clump-forming systems")

[Reichhardt *et al.*, Europhys. Lett. 72, 444 (2005)]

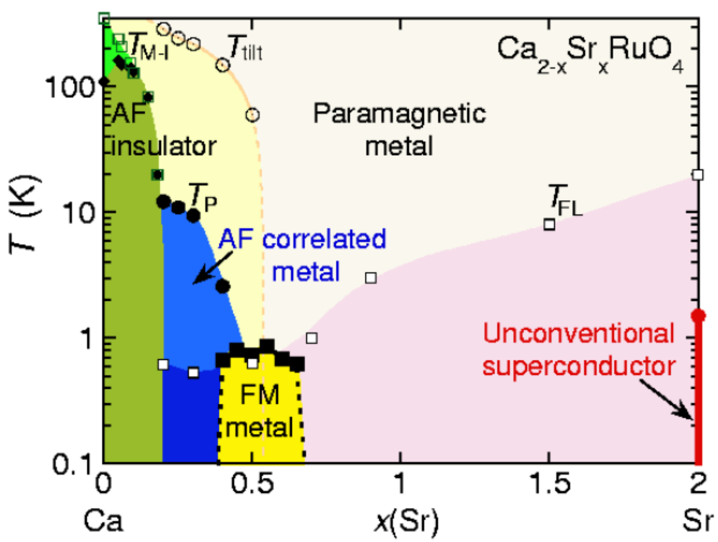
- global phase separation not possible because of <u>charge neutrality</u>
- (infinitely?) many possible arrangements of nanoscopic ordered regions with comparable energies ⟹ charge (Coulomb) glass?

Some other complex, strongly correlated electronic systems





Percolative conduction in half-metallic-FM and insulating-ferroelectric mixture of (La,Lu,Sr)MnO_3 (Park *et al*., 2004).



Emergence of intermediate heterogeneous phases due to the existence of several competing ground states

Dynamics?

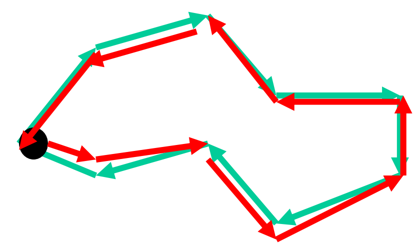
- **quantum effects important**

Metal-insulator transition in two dimensions

Is there a true (T=0) metallic state in 2D?

• **Theoretical arguments from the 1980s:**

no true (T=0) metallic state or MIT in 2D



Noninteracting electrons: always localized

Strong disorder: $\sigma \sim \exp[-(T/T_0)^{1/p}]$ p=1, 2, 3
[strong localization]

Weak disorder: $\sigma = ne^2\tau/m^* + A(e^2/h)\ln(T/T_0)$
[weak localization; Abrahams, Anderson, Licciardello, Ramakrishnan, PRL 42, 673 (1979)]

Weakly interacting electrons: always localized (also ln T)
[Altshuler, Aronov, SSC 39, 115, (1979); JETP 50, 968 (1979)]

Strongly interacting electrons:

No disorder: Wigner crystal (insulator)

But:

- mid 1990s – present: experiments suggesting a true MIT in 2D
- an active research area in both theory and experiment

What about *strongly interacting* systems with weak disorder?
Can *strong* electron-electron interactions cause delocalization?

Theory:

- early calculations perturbative (ln T – leading corrections)
- a hint from theory [Finkel'stein, Z. Phys. B 56, 189 (1984)] that the 2D metal might be possible, but theory uncontrolled at low T…
- Punnoose, Finkel'stein, Science 310, 289 (2005):

  interaction contribution changes sign and wins over weak localization!

2D metal possible!

But:

- this theory probably does NOT describe experiments

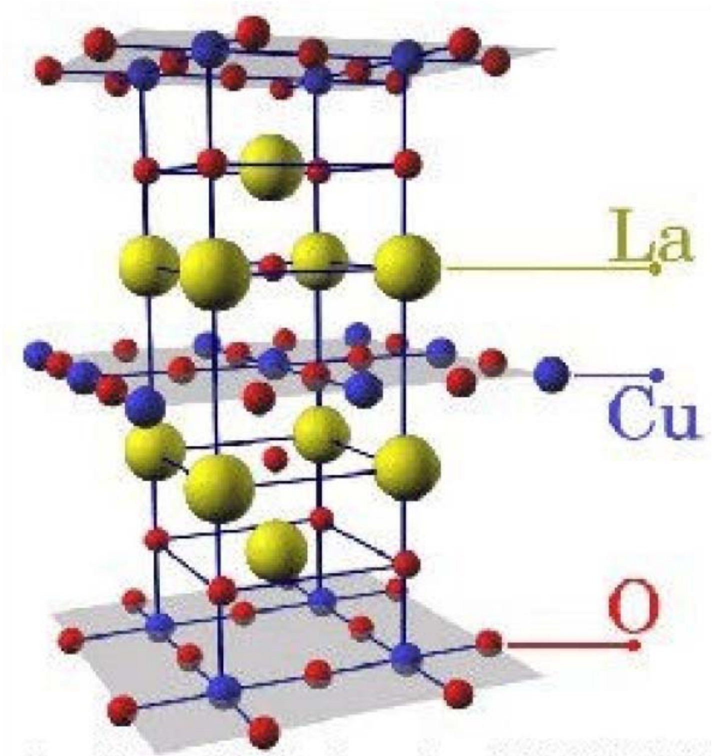
Practical realizations of 2D systems

- thin films

- semiconductor heterostructures at sufficiently low temperatures
  (*e.g.* Si MOSFET and AlGaAs/GaAs)

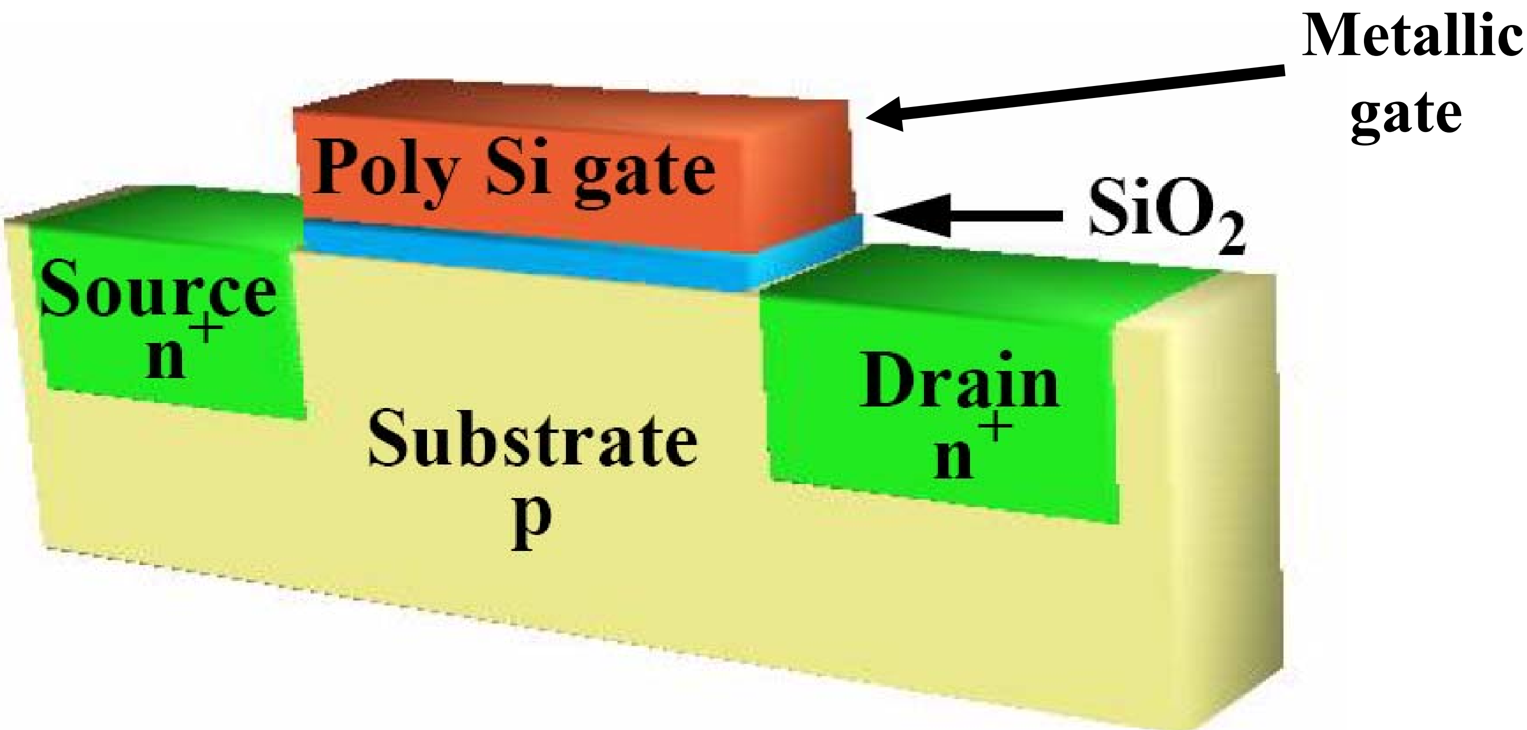
- quasi-2D systems: layered structures
  (*e.g.* cuprates)

La_2CuO_4



Back to transistors…:

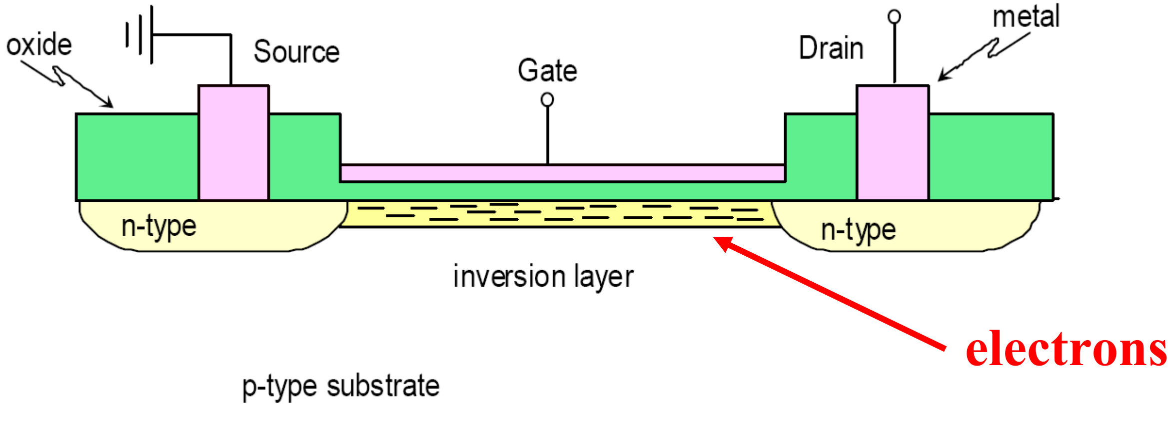
Si MOSFET – the basis of semiconductor technology

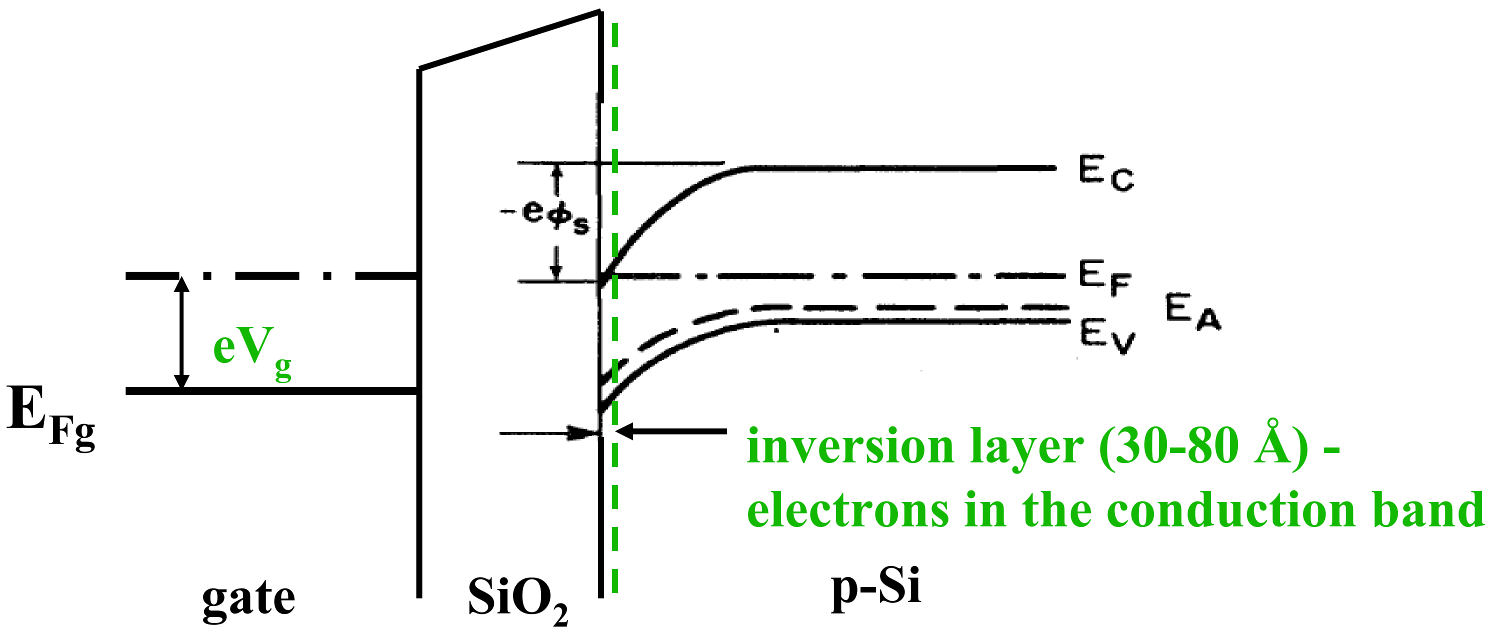


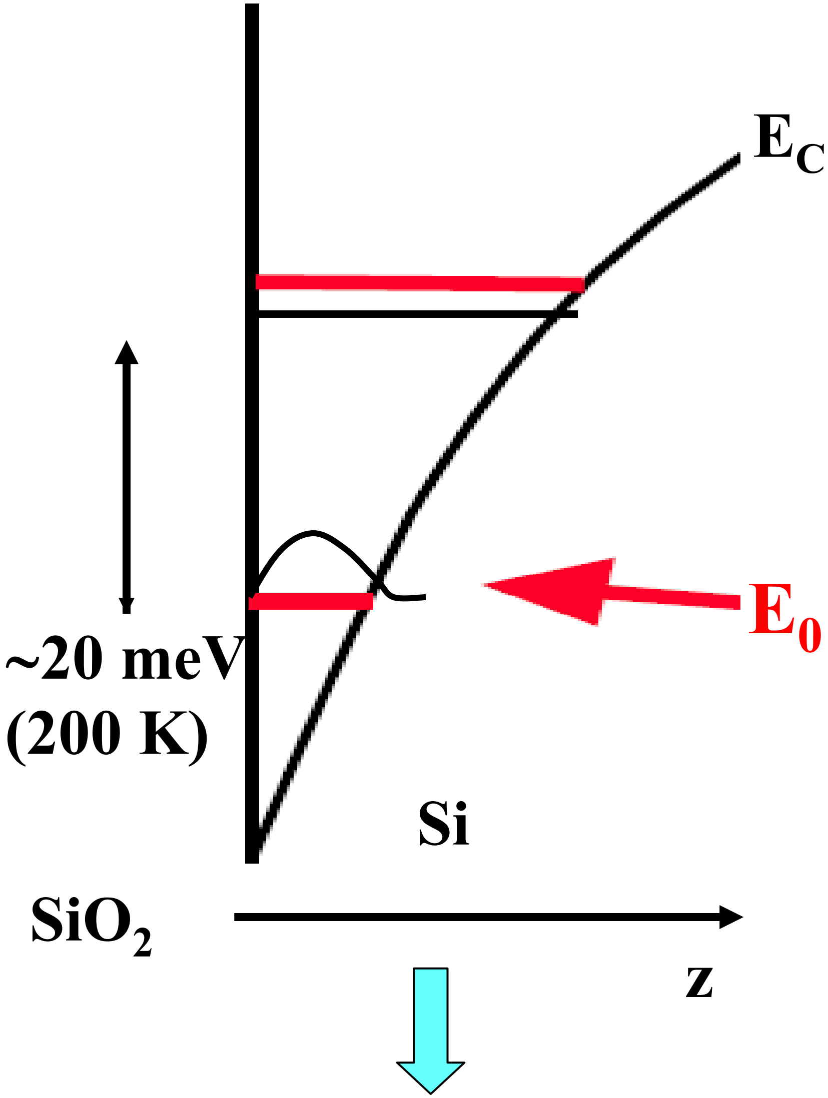
Metal-**O**xide-**S**emiconductor **F**ield-**E**ffect **T**ransistor – conducts current because of the effect of the electric field (V applied to the gate) at the surface of Si

Gate, source, drain, substrate – all doped Si (in the old days, gate was Al)

Si MOSFET: a capacitor!







- electrons confined in a narrow potential well at the interface

→ motion perpendicular to the interface (“z-direction”) is quantized

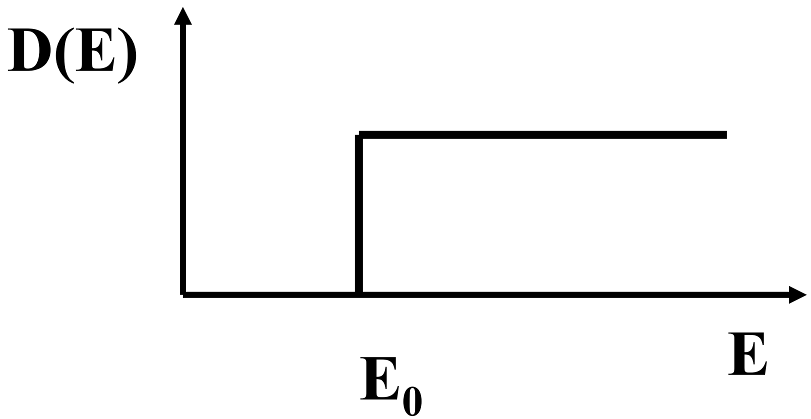
- discrete energy levels (subbands) for motion in the z-direction; energy levels:

$$E = E_n + (k_x^2 + k_y^2)\hbar^2/2m^*, \quad n = 0, 1, 2, \ldots$$

electrons free to move in a plane parallel to the interface

At low enough T, only E_0 is occupied: a 2D system.

2D density of states: $D(E)=g_s g_v\, m^*/2\pi\hbar^2$ = const
(g_s, g_v – spin and valley degeneracies)



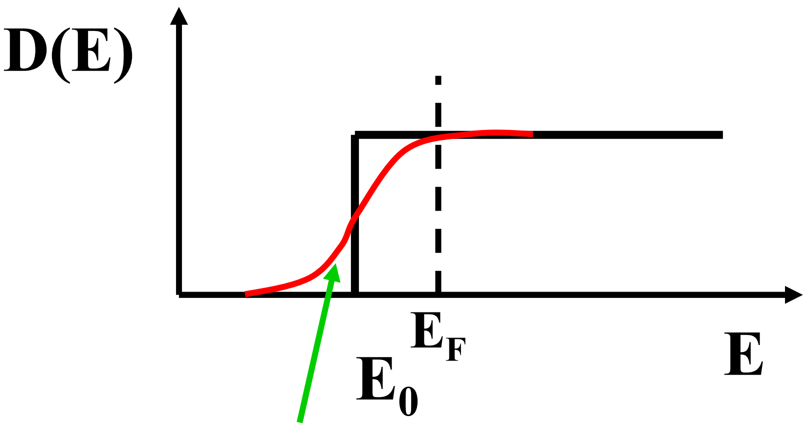
- 2D systems studied extensively since late 1960s
  [Fowler, Fang, Howard, and Stiles, PRL 16, 901 (1966): 2D in Si MOSFETs]

- dimensionality plays a fundamental role in many phenomena (*e.g.* integer and fractional quantum Hall effects observed in 2D systems in high magnetic fields – Nobel prizes in physics, 1985 and 1998)

Room for more???

2D density of states: $D(E)=g_s g_v\, m^*/2\pi\hbar^2$ = const

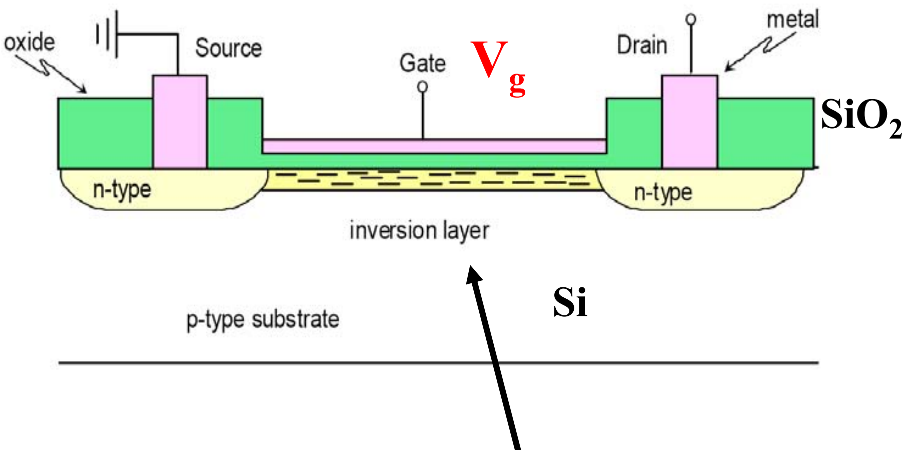
(g_s, g_v – spin and valley degeneracies)



band tail (strongly localized states)

Add disorder

Carrier density n_s (=$D(E)E_F$ at T=0; E_F - Fermi energy) can be tuned continuously over two orders of magnitude (!) by varying V_g

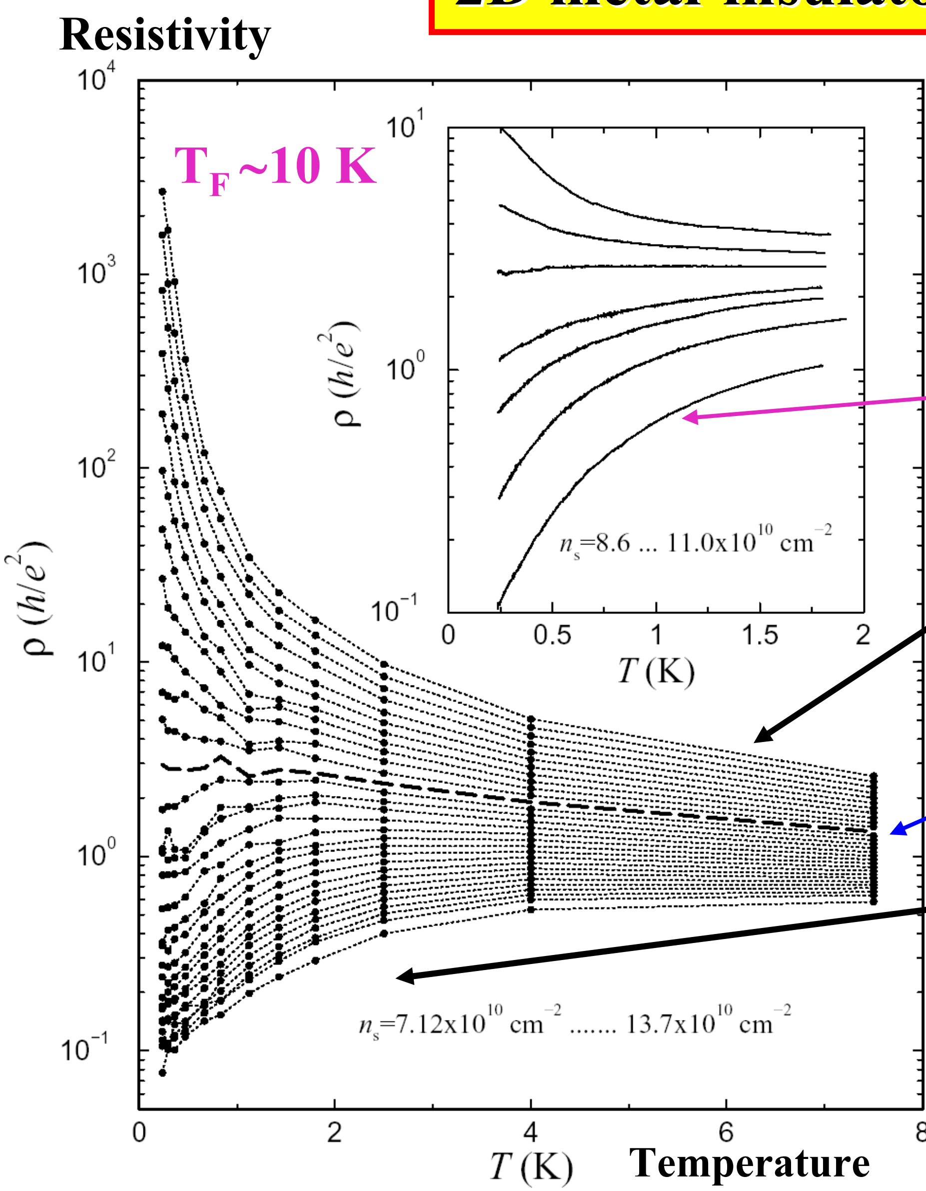


2D at low T

Disorder due to (Na+) ions randomly distributed throughout SiO_2 (frozen out below ~100 K), and to surface roughness

2D electrons move in a smooth random potential

2D metal-insulator transition?



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

Large resistivity drop! (origin?)

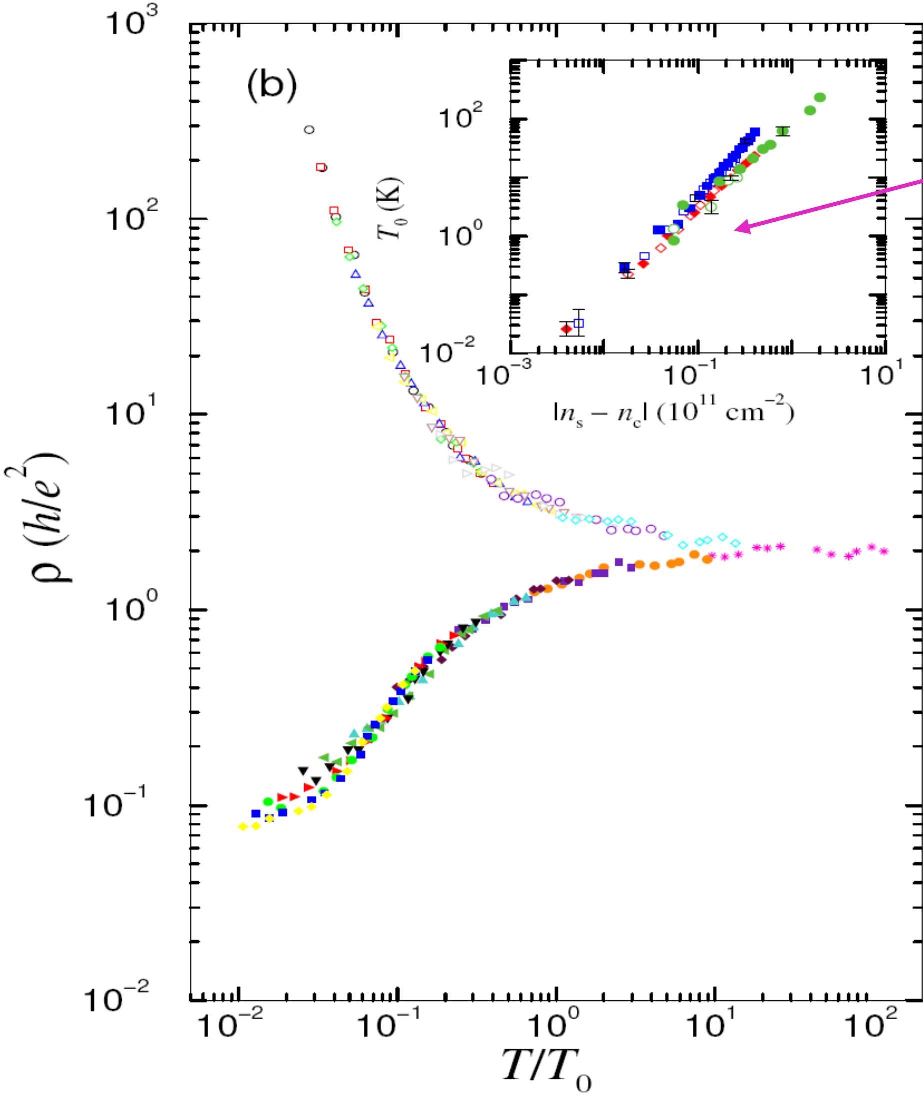
insulating behavior for $n_s < n_s^*$ [exponential ρ(T)]

"separatrix" n_s^* (= n_c? NO! n_c – critical density for the MIT)

metallic behavior for $n_s > n_s^*$

[Kravchenko, Mason, Bowker, Furneaux, Pudalov, D'Iorio, PRB 51, 7038 (1995); 2DES in Si MOSFETs]

The same data:



(rescaled T axis)

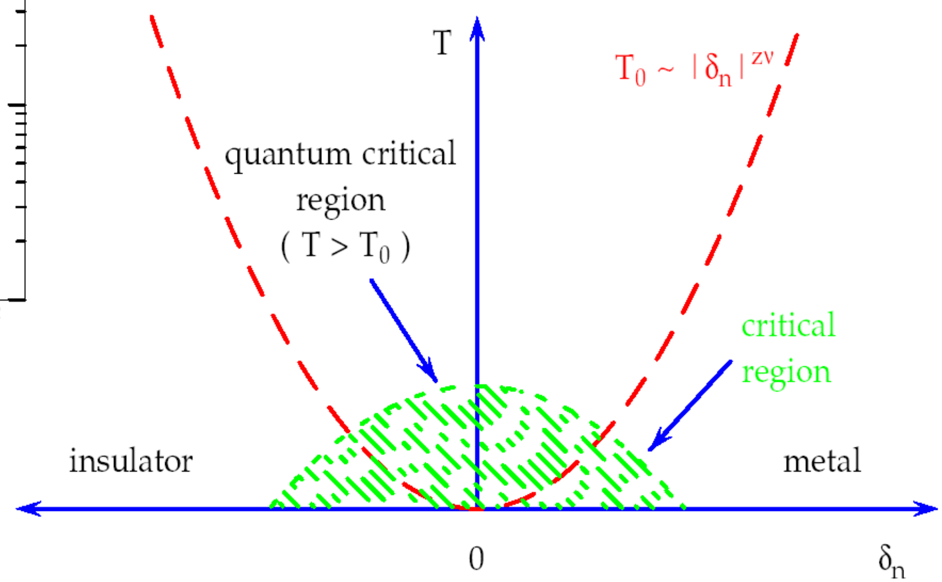
[Kravchenko *et al.*, PRB 51, 7038 (1995)]

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

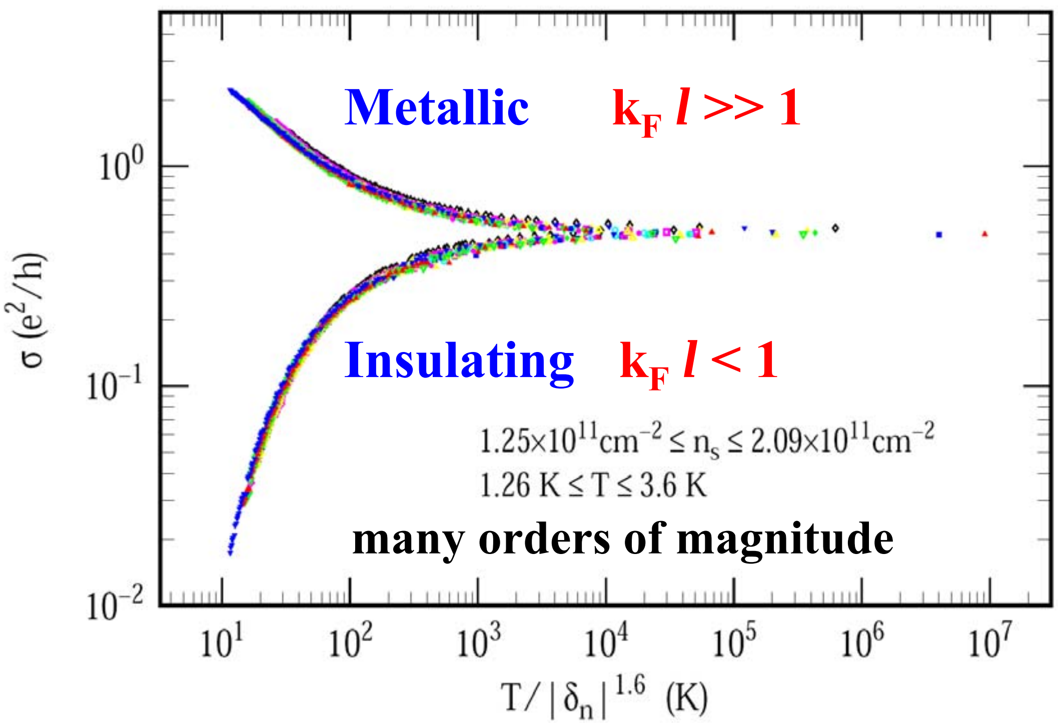
"dynamical scaling":

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

Metal-insulator transition as a quantum critical point:



Conductivity $\sigma = 1/\rho$



[Popović, Fowler, Washburn; PRL 79, 1543 (1997); other Si MOSFETs where disorder was varied]

The race begins!

Change to metallic behavior occurs at:

- low densities ($n_s \sim 10^{11}\ \mathrm{cm}^{-2}$)

Fermi energy: $E_F = \pi\hbar^2 n_s/2m^* \approx 0.6$ meV

Electron-electron interaction energy:

$$E_{e\text{-}e} \sim (e^2/\varepsilon)(\pi n_s)^{1/2} \approx 10 \text{ meV}$$

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

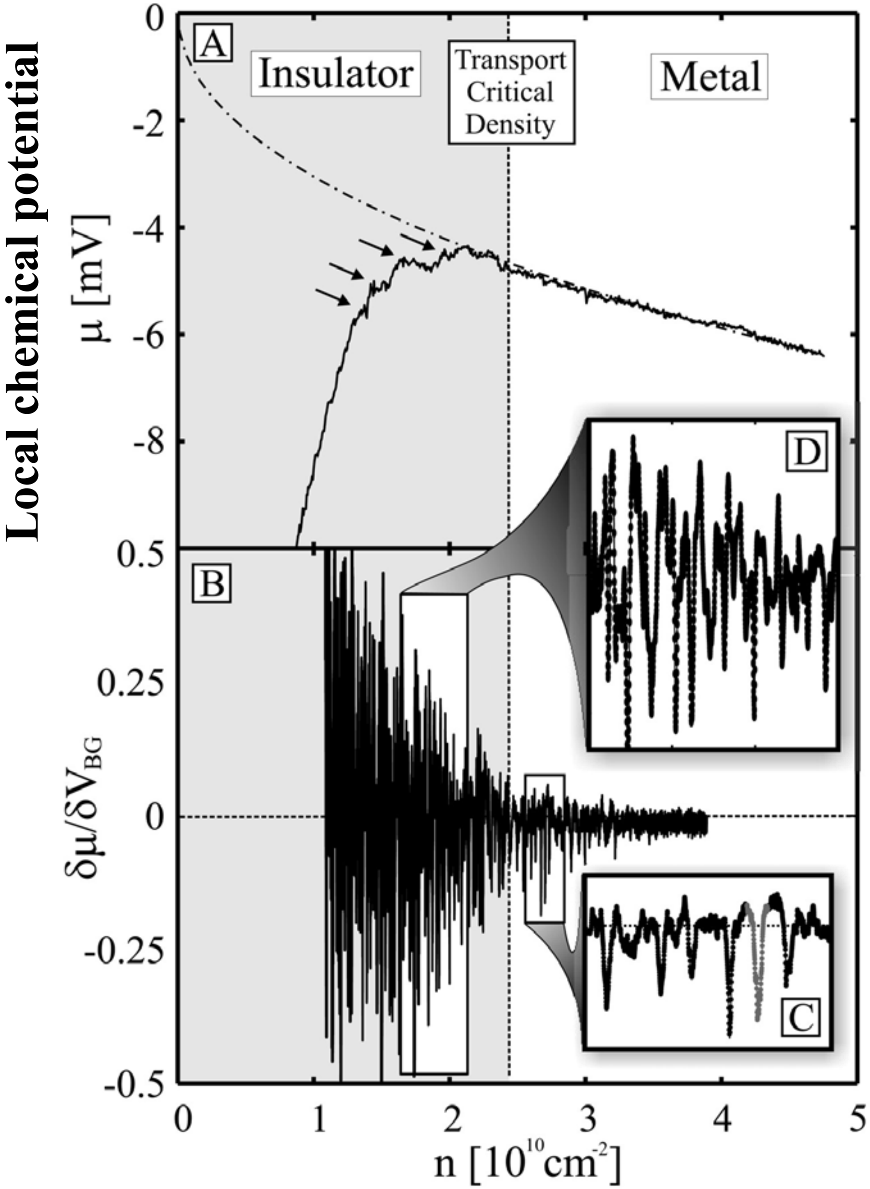
- critical conductivity $\sim e^2/h$

$\sigma \sim (e^2/h)(k_F\, l) \Rightarrow k_F\, l \sim 1$

(l – mean free path; k_F – Fermi wave vector)

Strong Coulomb interactions and disorder!

Local compressibility



- as the density approaches n_c from the metallic side, 2DHG fragments into localized charge configurations that are distributed in space

  ⇒ insulating phase is spatially inhomogeneous

- the structure with sharp spikes emerges already at $n>n_c$ (on the metallic side of the MIT!)

Dynamics? Coulomb glass?

[Ilani, Yacoby, Mahalu, Shtrikman, Science 292, 1354 (2001); also, PRL 84, 3133 (2000); 2D holes in GaAs]

Summary of Lecture I

- **Metal-insulator transition: a fundamental problem of relevance to many interesting materials**

- **Problem: strongly (Coulomb) interacting electrons in a random potential**
  ⇒ expect frustration, dynamic inhomogeneities

- **2D systems in semiconductors:**
  - **easy to use; can be precisely engineered (semiconductor technology!)**
  - **control and vary density (interactions) and disorder <u>independently</u>**
  - **"simple" – no magnetic or structural degrees of freedom (unlike *e.g.* cuprates)**

<u>Lectures II and III:</u> study electron dynamics as n_s is varied through the MIT

Evidence of a phase transition? What can we learn about the MIT and out-of-equilibrium dynamics in general?

Literature I

- Doped semiconductors; strong localization (Anderson and Mott insulators), variable-range hopping transport:
  B.I. Shklovskii and A.L. Efros, *Electronic Properties of Doped Semiconductors* (Springer-Verlag, Berlin, 1984) – out of print; http://www.tpi.umn.edu/shklovskii/

- Disorder and interactions; metal-insulator transition (3D, 2D); inhomogeneous phases; glassy behavior
  E. Miranda and V. Dobrosavljević, *Disorder-Driven non-Fermi Liquid Behavior of Correlated Electrons*, Rep. Prog. Phys. 68, 2337 (2005)

- E. Dagotto, *Complexity in Strongly Correlated Electronic Systems*, Science 309, 257 (2005) – a very brief (few pages) review

- Metal-insulator transition in 2D - basic issues:
  E. Abrahams, S.V. Kravchenko, M.P. Sarachik, *Metallic Behavior and Related Phenomena in Two Dimensions*, Rev. Mod. Phys. 73, 251 (2001)

- Weak localization and e-e interaction effects in metals:
  P.A. Lee and T.V. Ramakrishnan, *Disordered Electronic Systems*, Rev. Mod. Phys. 57, 287 (1985)

- 2D systems in Si and other semiconductors – basics:
  T. Ando, A.B. Fowler, and F. Stern, *Electronic Properties of Two-Dimensional Systems*, Rev. Mod. Phys. 54, 437 (1982)