Lecture 3: Quantum Effects in the Conductivity of High-Mobility Si MOSFETs

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"Low-Temperature Nano-Physics"
Chernogolovka, August 2007

The State University of New Jersey
Rutgers
Department of Physics and Astronomy

Outline:

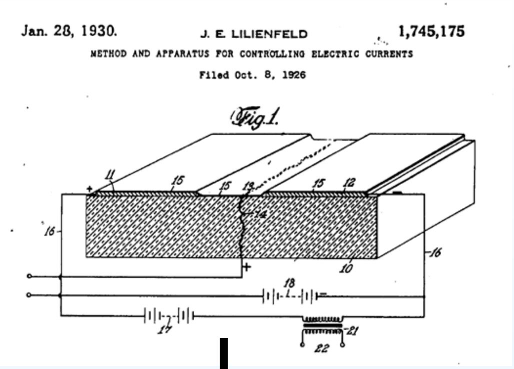
- Intro: quantum corrections in Si MOSFETs (the most ubiquitous 2D structure) ⇒ 25-year-old puzzle, and the work is still in progress

- Ingredients essential for better understanding of interaction effects in Si MOSFETs:
  - interaction parameters in high-mobility Si MOSFETs
  - valley splitting and inter-valley scattering

- Analysis of $\Delta\sigma(T,B_{||})$: (semi)-quantitative agreement with the theory

- The crossover from “metallic” to “insulating” conductivity: role of large-scale potential fluctuations?

Si MOSFET timeline


Jan. 28, 1930. J. E. LILIENFELD 1,745,175

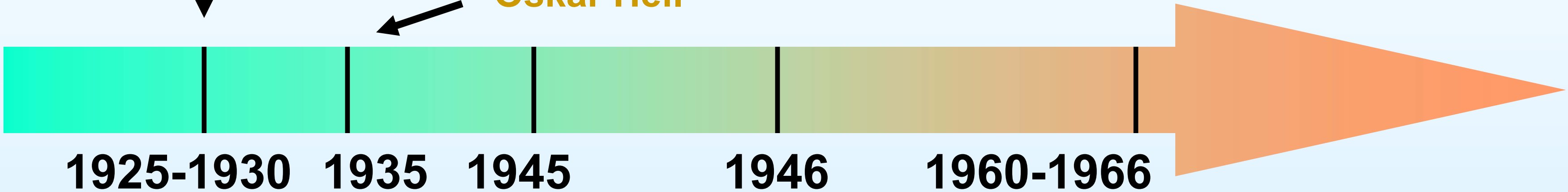
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

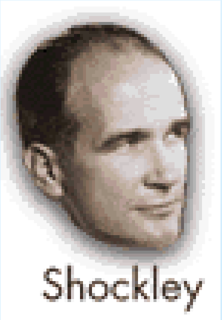
Filed Oct. 8, 1926

Julius Lilienfeld proposed FET, but never constructed a working device…


M. “John” Atalla

Oskar Heil

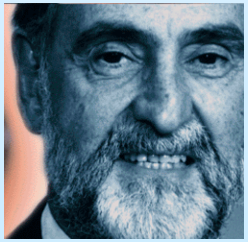

1925-1930 1935 1945 1946 1960-1966



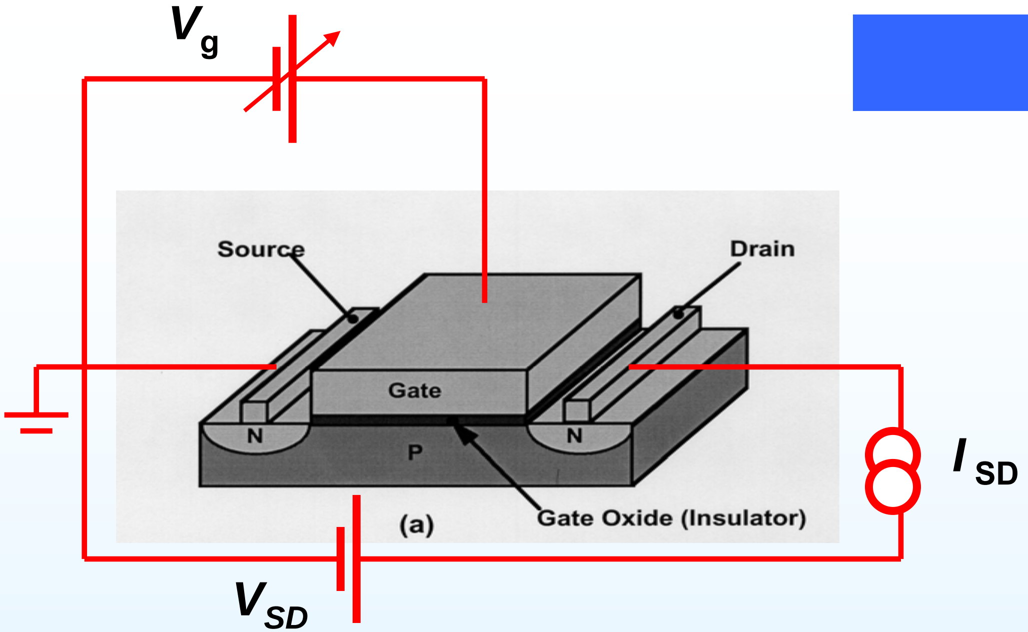

Shockley and Brattain attempted to make FET, but failed…

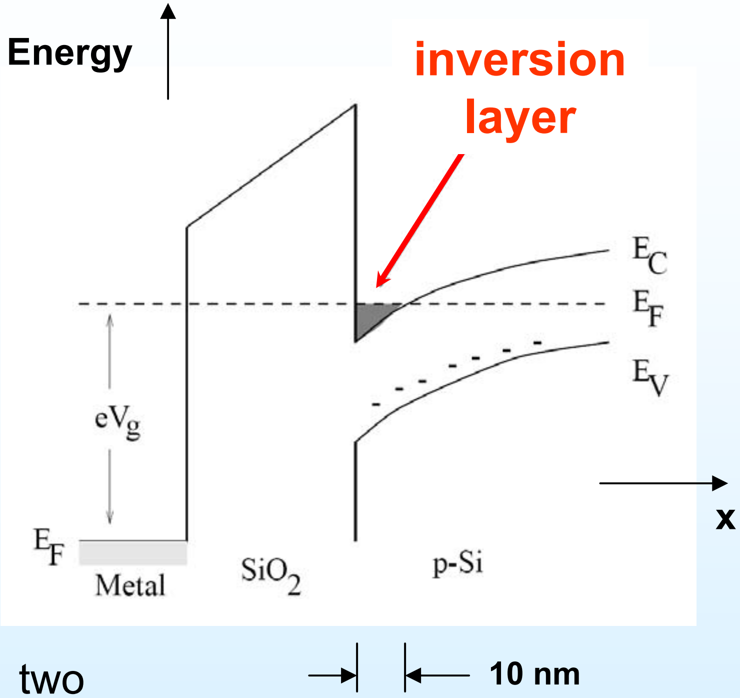
attributed the failure of Shockley’s efforts to the surface states

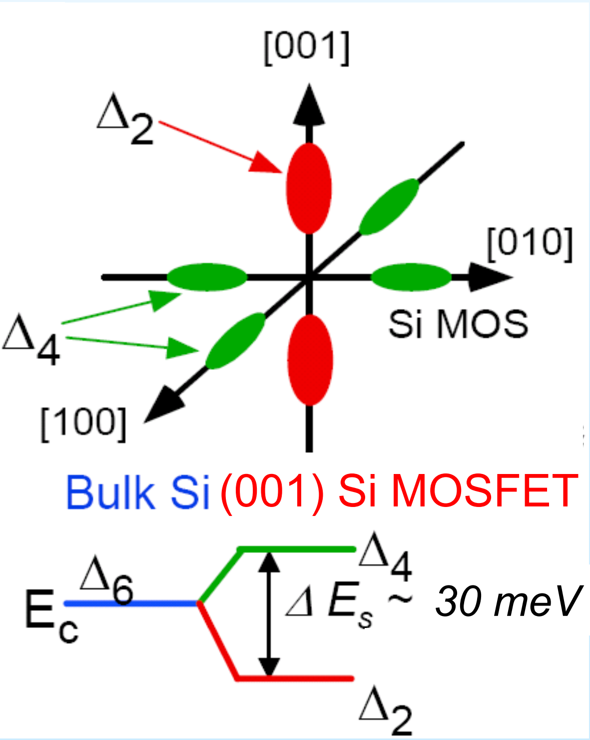
D. Kahng, M. Atalla (Bell)
S. Hofstein, F. Heiman (RCA Sarnoff)
created practical Si FETs


F. Heiman

Si MOSFETs





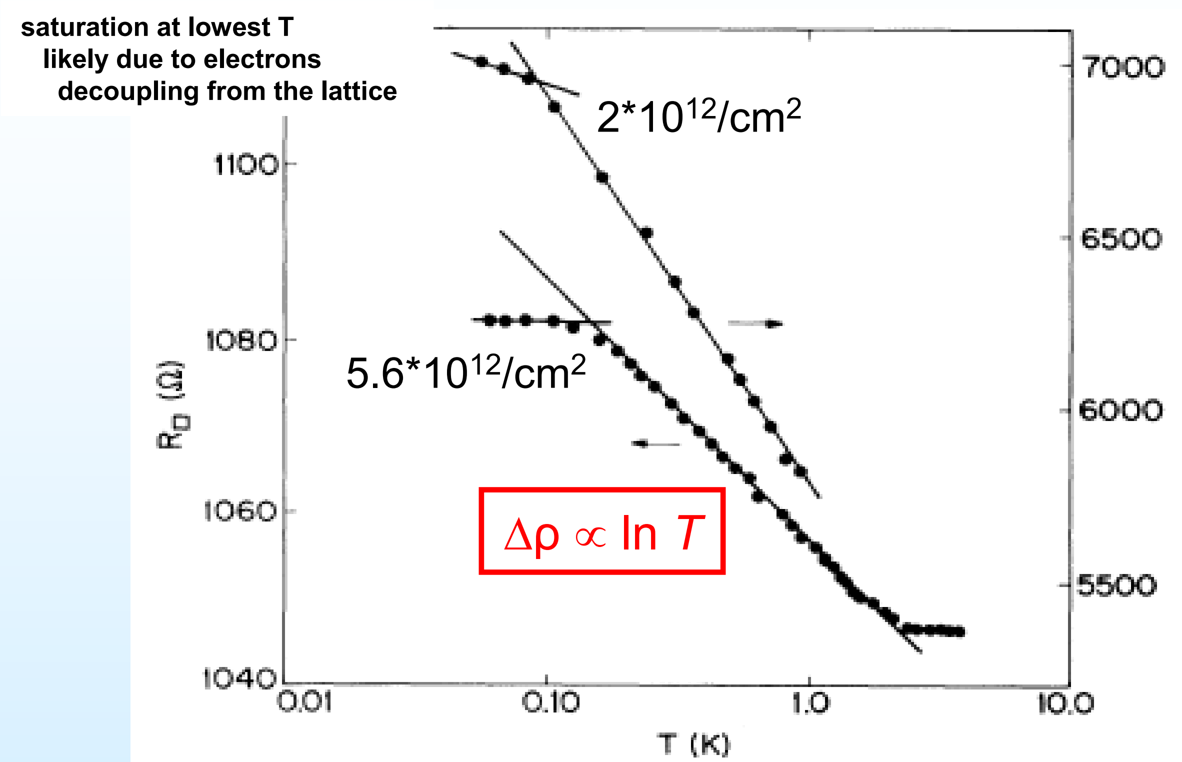


(001) Si MOSFETs – two ***almost degenerate*** valleys, the other four valleys are lifted by ~ 30 meV and do not participate in transport at low densities/temperatures. The degeneracy can be lifted: e.g., the wafer cut is not perfectly aligned along (001).

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2E_F m^*}} \sim 10 nm$$

$$E_F \approx 7 \times \left(\frac{n}{1 \times 10^{11} cm^{-2}} \right) \quad [K]$$

Low-μ devices, high carrier densities



saturation at lowest T likely due to electrons decoupling from the lattice

$2*10^{12}/cm^2$

$5.6*10^{12}/cm^2$

$\boxed{\Delta\rho \propto \ln T}$

$\mu \sim 10^3$ cm²/V·s

Bishop, Tsui, and Dynes, ‘80

Qualitatively – in line with the QC theory, quantitatively – not quite…

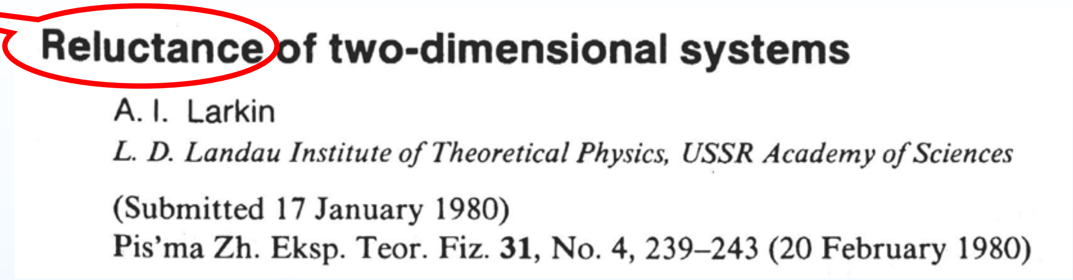
Bishop, Dynes, and Tsui, *Phys. Rev*. B **26**, 773 (1982)
Dolgopolov, Dorozhkin, Shashkin, *Sol. State Commun*. **50**, 273 (1984)
Burdis and Dean, *Phys. Rev*. B **38**, 3269 (1988)

unreasonably large values of the triplet-channel parameter *F*, lack of B/T scaling in MR, etc.

High-μ devices, high carrier densities

- very limited supply of the devices!

(instead of "resistance")



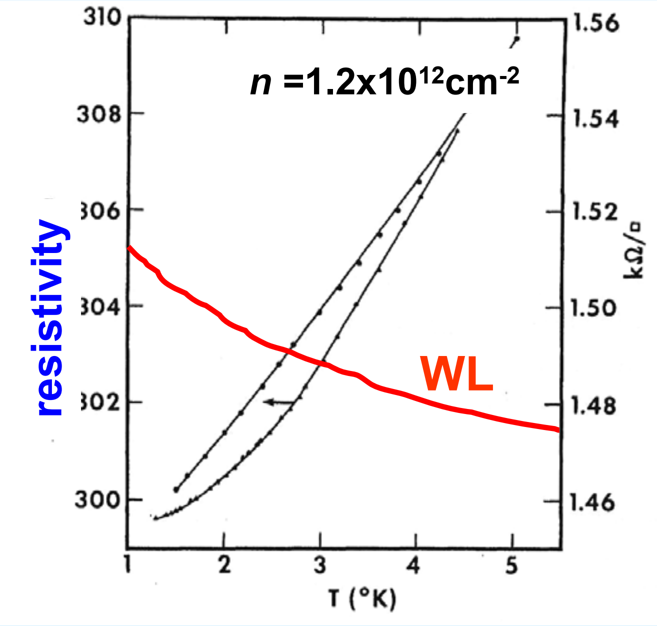
Reluctance of two-dimensional systems

A. I. Larkin

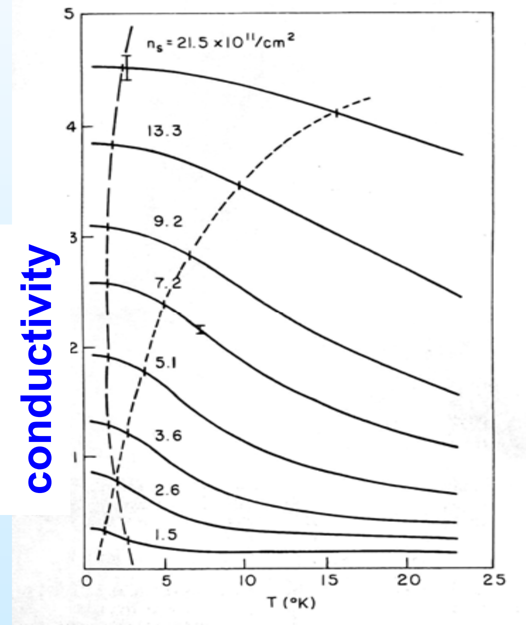
L. D. Landau Institute of Theoretical Physics, USSR Academy of Sciences

(Submitted 17 January 1980)
Pis'ma Zh. Eksp. Teor. Fiz. **31**, No. 4, 239–243 (20 February 1980)

25+year-old puzzle: σ (T,$B_{||}$) of the most ubiquitous 2D system – electrons in Si MOSFETs – defied predictions of the WL+Int. theory

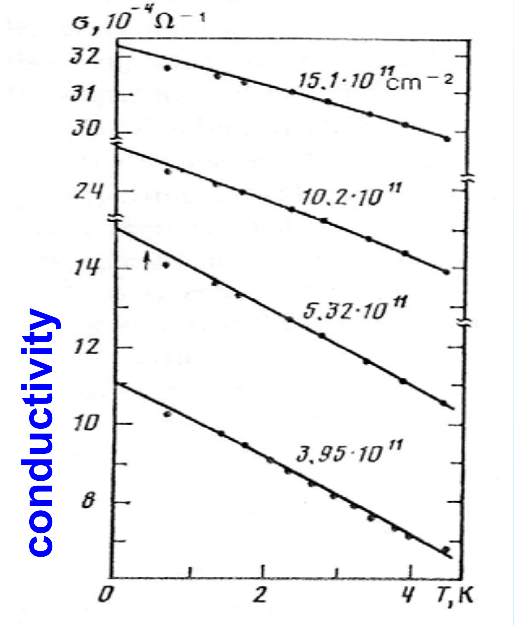


Cham and Wheeler,
PRL **44**, 1472 ('80)



Smith and Stiles,
SSC **58**, 511 ('86)

μ = 2.5x10⁴ cm²/Vs @ 0.2K

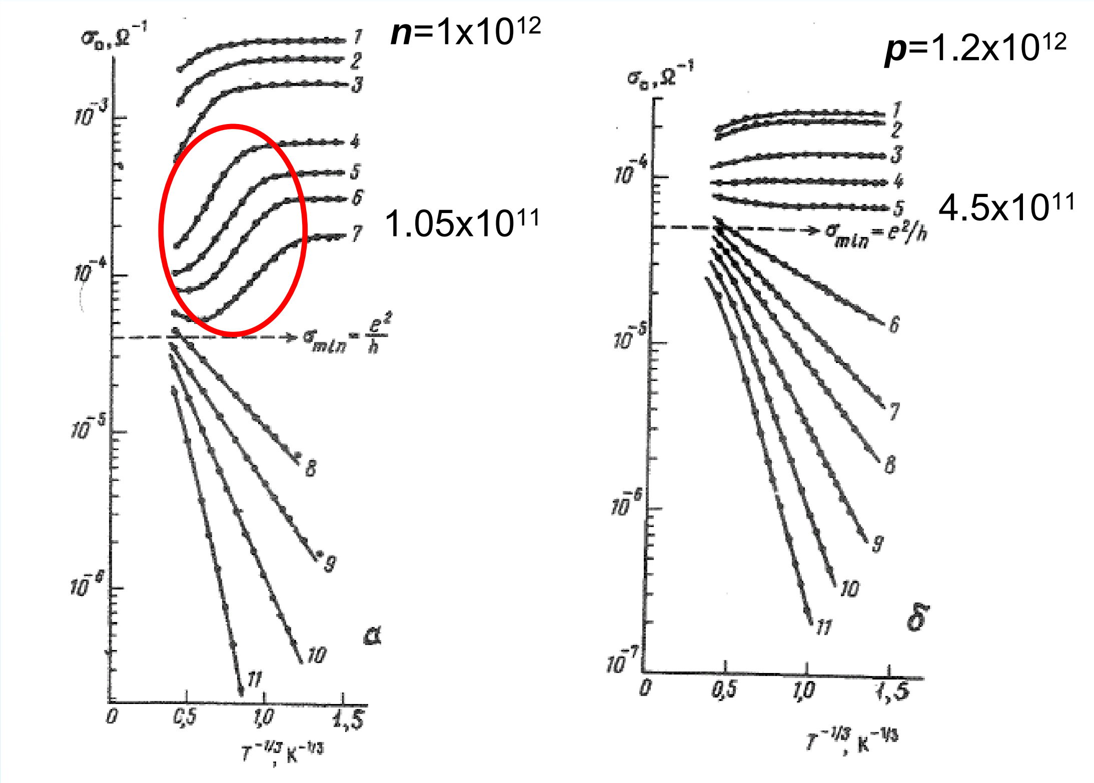


Vyrodov *et al*.,
JETP **67**, 998 ('88)

μ = 1.7x10⁴ cm²/Vs

High-μ devices, low carrier densities

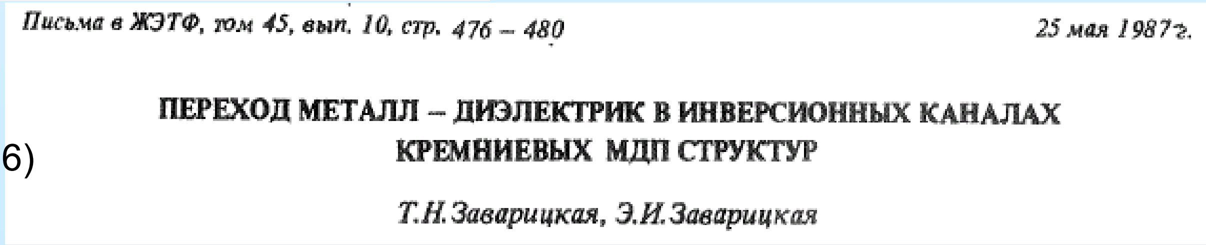
The discrepancy became more dramatic as lower densities became accessible in high-mobility structures (μ ~ 20,000 cm^2/Vs).



Observation of an apparent 2D MIT –

no excitement yet…

n- and ***p***-type Si MOSFETs
Zavaritskaya and Zavaritskaya ('86)



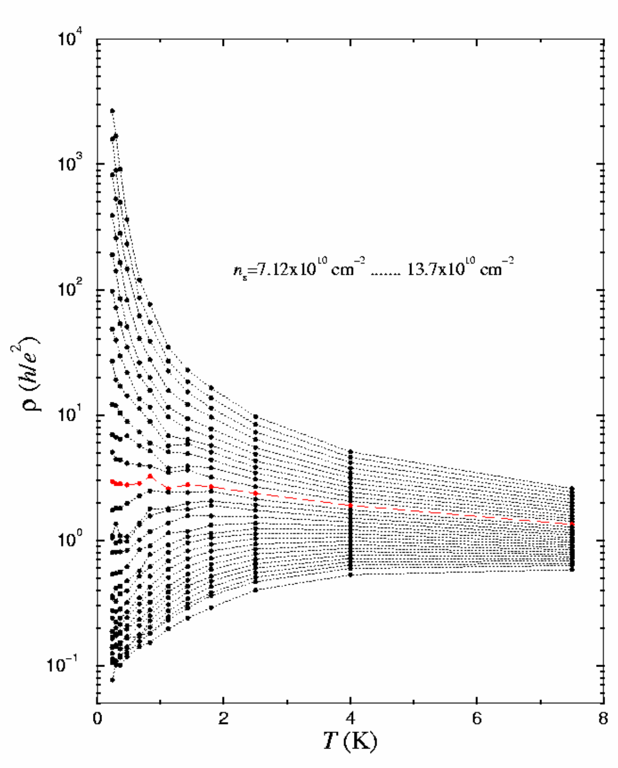
Письма в ЖЭТФ, том 45, вып. 10, стр. 476 – 480 *25 мая 1987 г.*

ПЕРЕХОД МЕТАЛЛ – ДИЭЛЕКТРИК В ИНВЕРСИОННЫХ КАНАЛАХ КРЕМНИЕВЫХ МДП СТРУКТУР

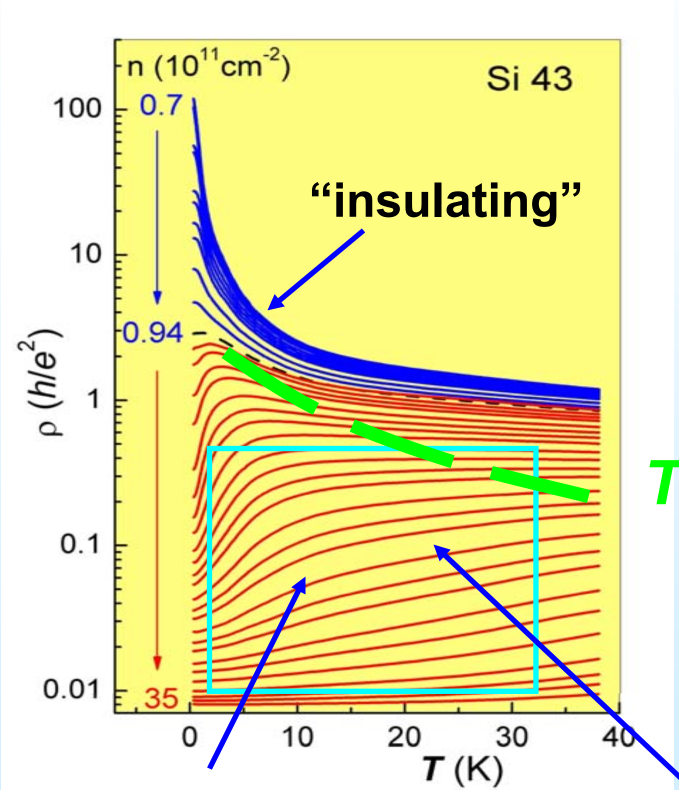
Т.Н.Заварицкая, Э.И.Заварицкая

High-μ devices, low carrier densities (cont'd)

Finally, some excitement…



Kravchenko, Mason, Bowker, Furneaux, Pudalov, and D'Iorio ('95)



"insulating"

"metallic"

$T=T_F$

Pudalov *et al.*, circa 2000

puzzling - the "metallicity" rather than the "2D MIT"

"Metallic" Behavior of 2D Holes

density $p=1\times10^{10}/\mathrm{cm}^2$ r_s= **30**

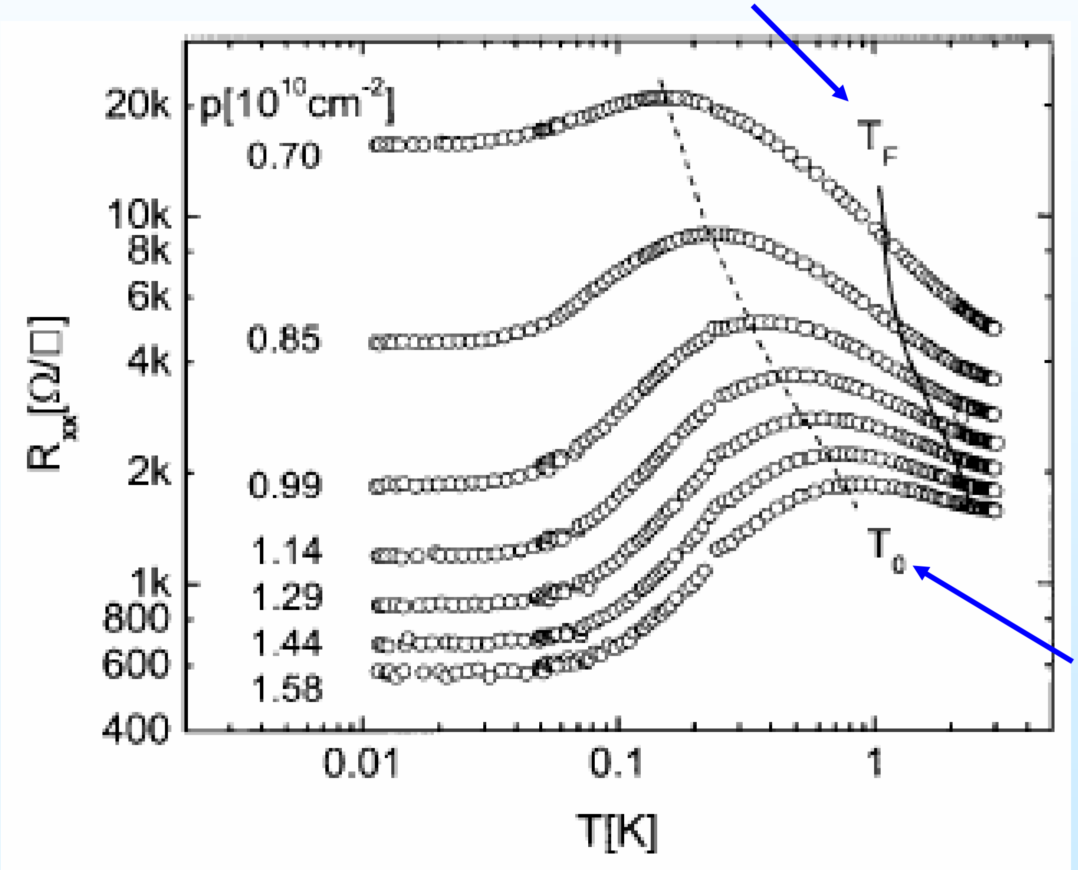
Fermi temperature

T_F = **0.77 K** at "2D MIT"

mobility

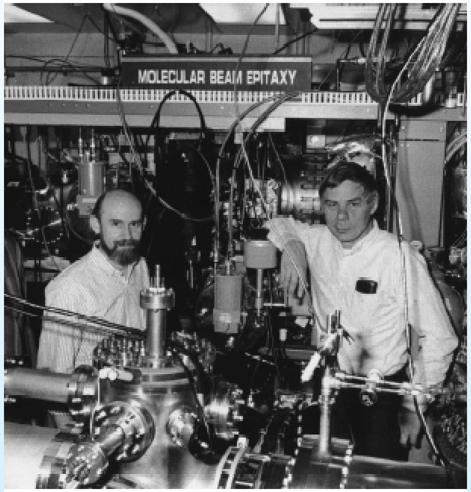
$\mu \sim 1\times10^6$ cm²/Vs

T_F = Fermi temperature



T_o = temperature at which "metallic" behavior begins

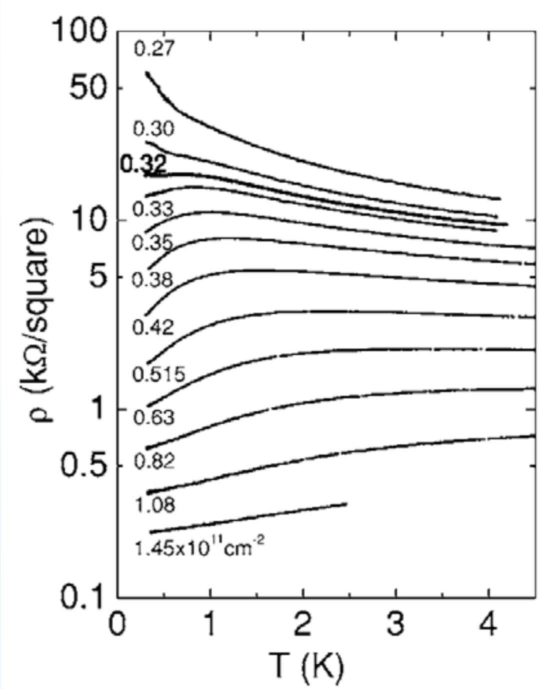
Loren Pfeiffer, Ken West and the MBE chamber at Bell Labs



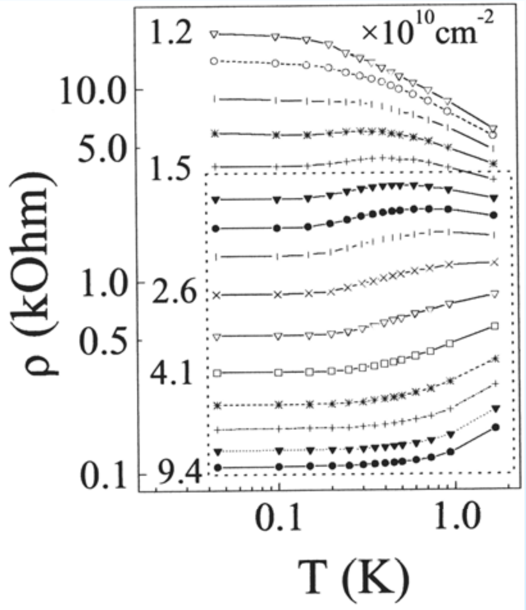
Gao *et al.*, PRL **89,** 016801 ('02)

Other high-μ, low-n systems

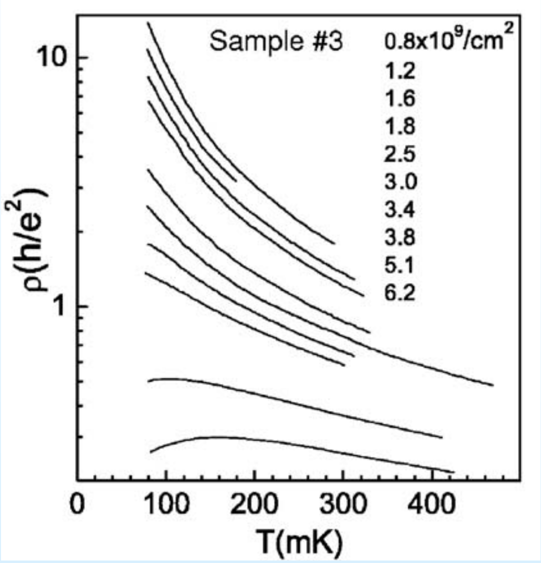
The “metallic” behavior has been observed in many ***high-mobility*** systems at ***low densities*** (> 500 publications over the last 10 years).



Lai *et al.*,
PRB **72**, 081313 (‘05)
strained Si quantum well
μ = 1.9x10^5 cm^2/Vs

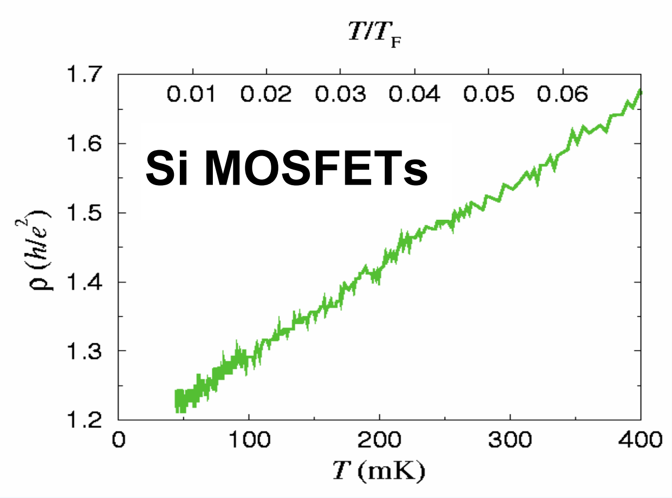


Proskuryakov *et al.*,
PRL **89**, 076406 (‘02)
p-type GaAs/GaAlAs
μ = 5.6x10^5 cm^2/Vs



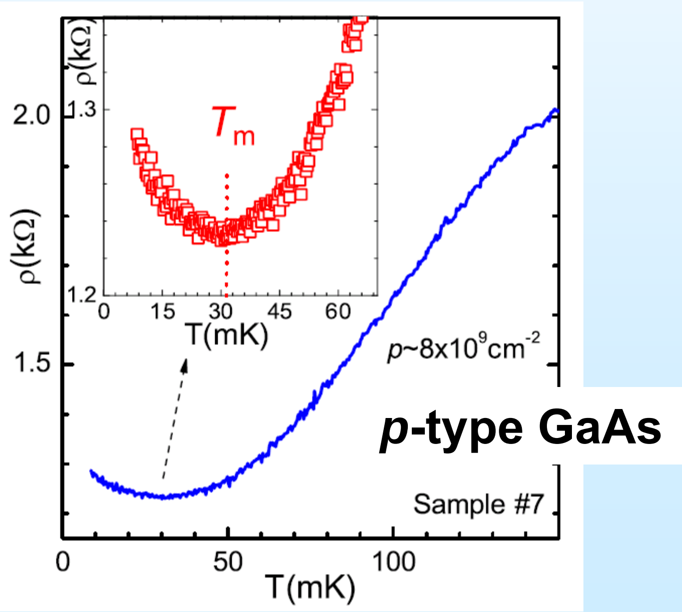
Huang *et al.*,
PRB **74**, 201302 (‘06)
p-type GaAs/GaAlAs FETs

Ultra-low-*T* conductivity

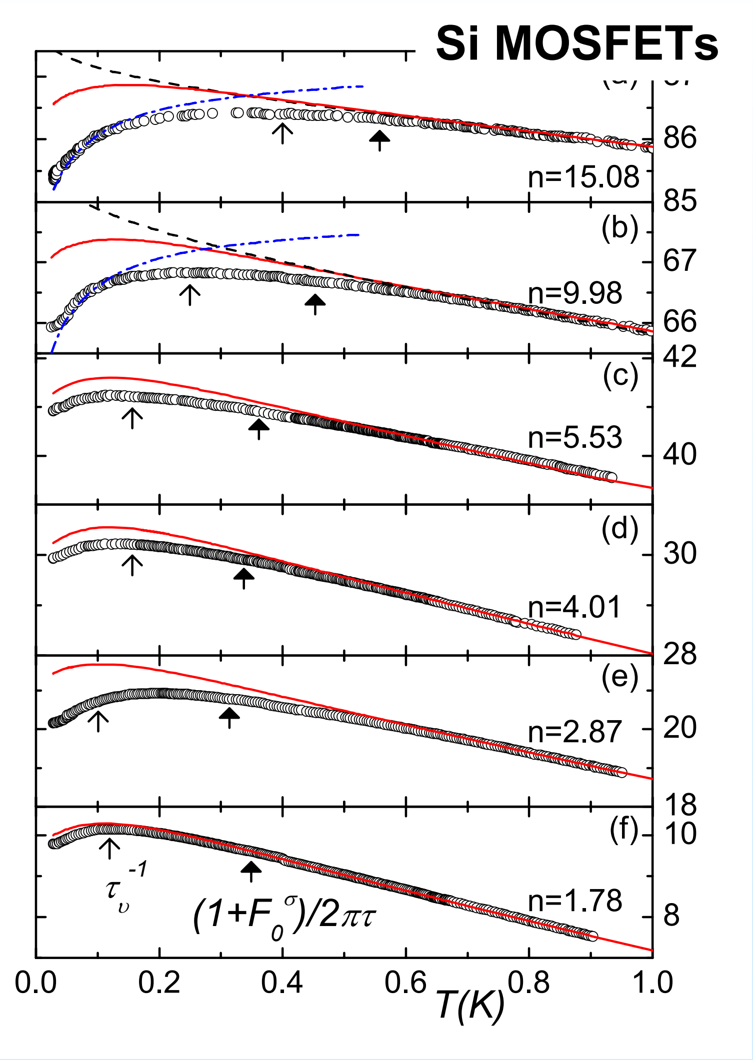


No upturn down to at least 50 mK

Kravchenko and Klapwijk, ‘00:



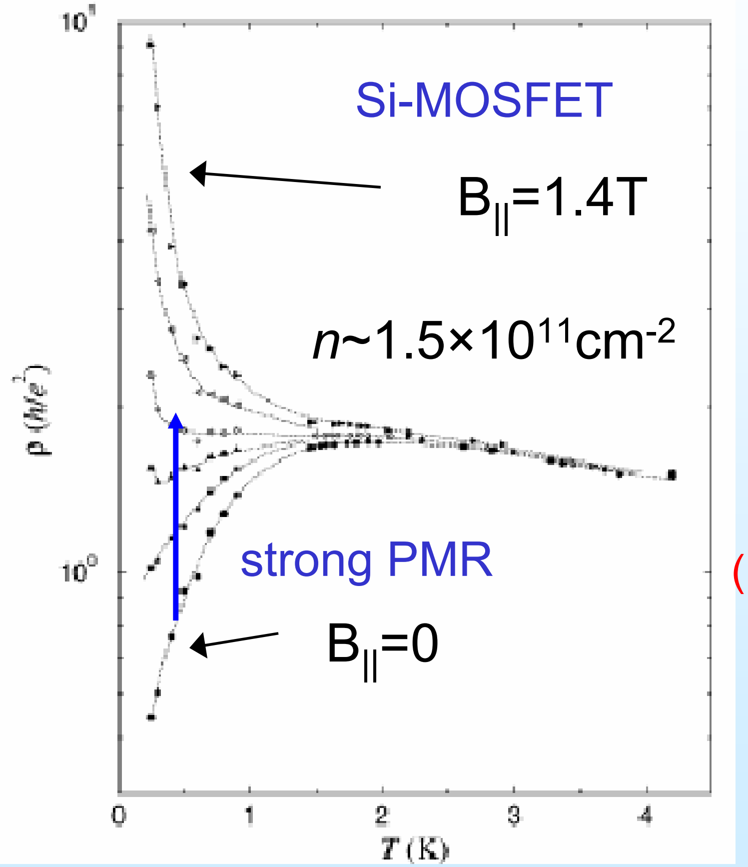
Huang *et al.*, PRL 98, 226801 (‘07)



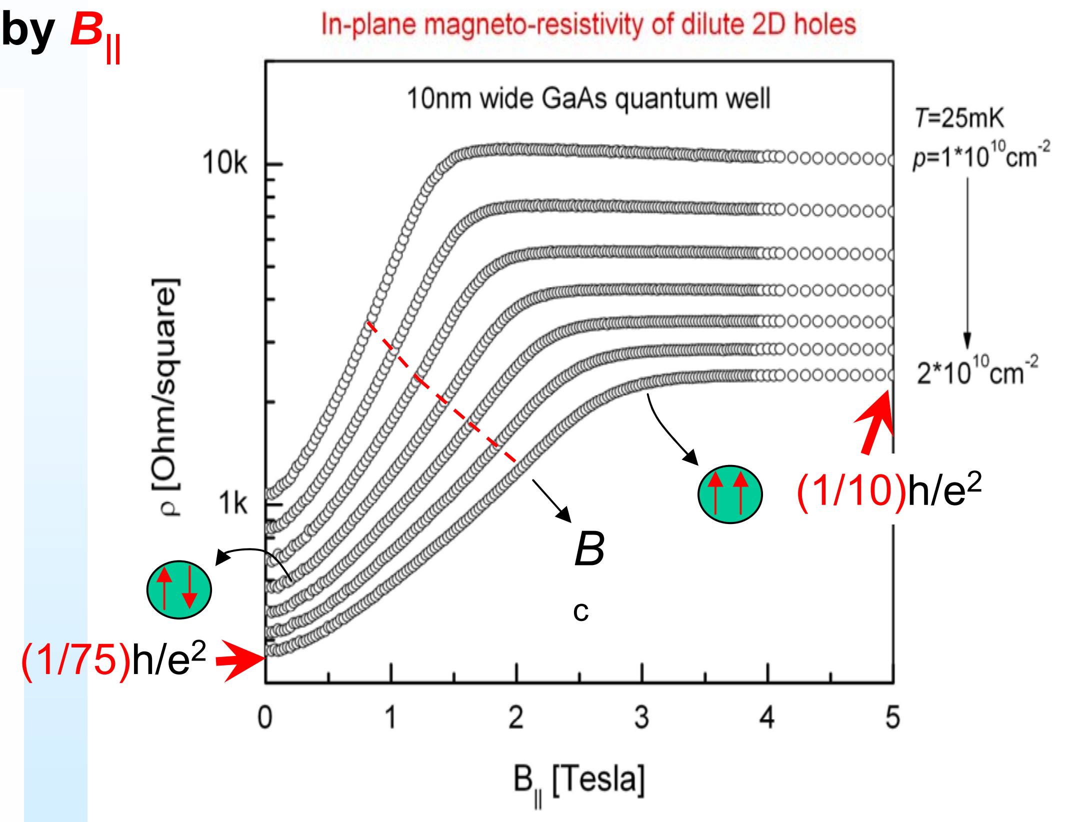
Klimov *et al.* (‘07) unpublished

Anomalous Magnetoconductivity near the apparent 2D MIT

Destruction of 2D “metallic” state by $B_{||}$



Simonian *et al.*, *PRL* **79**, 2304 (‘97)
“*the metallic state is suppressed by an arbitrarily small magnetic field…*”.



Gao *at al*. (‘06)

Conclusion: spin effects play prominent role

Interactions as the primary suspect

distance to the gate > $1/\sqrt{n}$

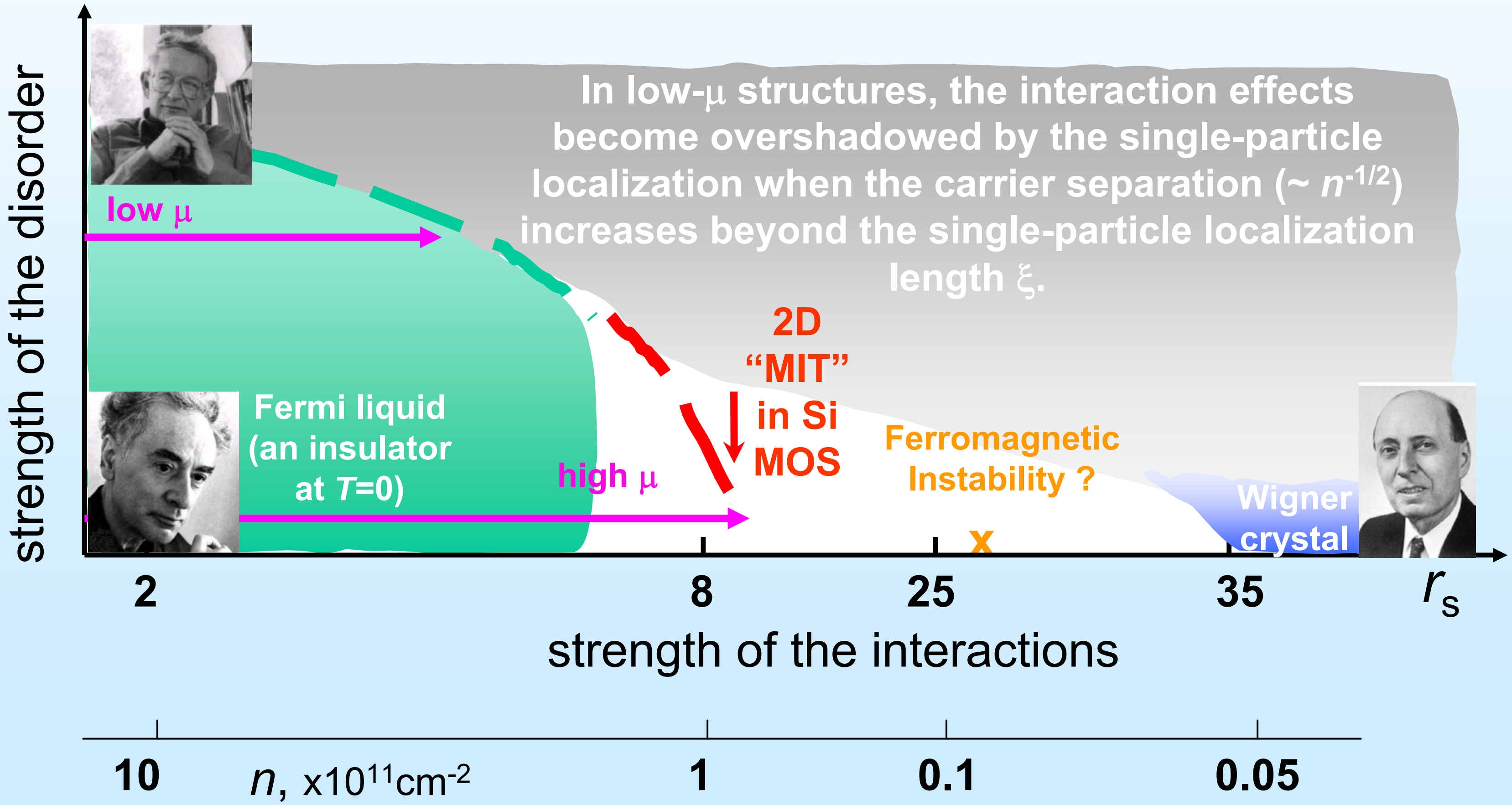
⇒ Coulomb potential $1/r$

Strength of interactions is characterized by the parameter r_s

$$r_s = \frac{E_C}{E_F} \left(\frac{\propto \sqrt{n}}{\propto n} \right) = \frac{a_B}{\sqrt{\pi n}}$$

The lower *n*, the stronger the effective interactions

In particular, the most pronounced “metallicity” is observed in Si MOSFETs at $r_s \sim 2\text{-}7$



In low-μ structures, the interaction effects become overshadowed by the single-particle localization when the carrier separation ($\sim n^{-1/2}$) increases beyond the single-particle localization length ξ.

Not-too-low densities ($n > 2\cdot 10^{11}\,\mathrm{cm}^{-2}$, $R_\square < 5\mathrm{k}\Omega$, $r_S<5$): is the low-T $\sigma(T,B)$ in line with the theory of quantum corrections?

We seek an explanation for:

- "metallic" $\partial\rho/\partial \boldsymbol{T}$ over a wide T range down to ~ 0.5K, upturn at lower T
- positive MR in parallel magnetic fields

What should be taken into account:

- the most pronounced "matellicity" – in the ballistic regime $\boldsymbol{T\tau > 1}$
  (Zala, Narozhny, Aleiner, '01)
- two valleys (Punnoose, Finkelstein, '02)
- independent measurements of F_0^σ
  (Okamoto *et al*., '99, Pudalov, MG *et al*., '02, Shashkin, Kravchenko *et al*., '02)

The main message:

At not-too-low densities ($n > 2\cdot10^{11}$cm^{-2}, $\sigma > 10e^2/h$), the anomalous "metallic" behavior of Si MOSFETs is consistent with the theory of interaction corrections.

The interaction corrections in Si MOSFETs are enhanced by the valley degeneracy and the interaction-driven renormalization of Fermi-liquid parameters.

Can “metallicity” be explained by the interaction effects?

“Metallicity” is observed mostly in the ballistic regime ($T\tau > 1$) – modification of the Altshuler-Aronov theory of interaction corrections was required.

Two (complimentary) theoretical models based on the Fermi liquid theory

Stern (’80), Gold & Dolgopolov (’86), Das Sarma (’86), Das Sarma & Hwang (’99,’04)

The growth of ρ with $\boldsymbol{T}$ (or with $\boldsymbol{B}_{\parallel}$) is due to the weakening of screening with increasing $\boldsymbol{T}$ (or increasing spin-polarization).

The leading order in interactions, all orders in T

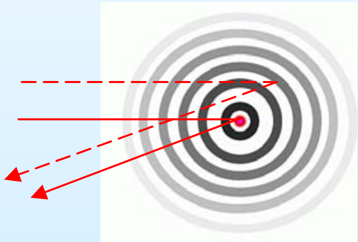
Disorder: screened long-range Coulomb disorder

Applicable at $T_D \ll T \ll T_F$ ($T_D = \hbar/\tau \sim 0.5$K)

Zala, Narozhny, & Aleiner (’01)

The interaction corrections to the conductivity are due to the interference between the waves backscattered off an impurity (a short-range potential) “dressed” by Friedel oscillations.

All orders in interactions,
the leading order in T,
Disorder: short-range disorder



$$\Delta\sigma_{INT} = \boxed{f(F_0^\sigma)\frac{T\tau}{\hbar}} + g(F_0^\sigma)\ln\left(\frac{\hbar}{T\tau}\right)$$

“Metallicity” - if this term becomes ***positive*** with strengthening of the interactions ($|F_0^\sigma| > 0.15$)

Applicable at $T \ll T_F (1+F_0^\sigma)^2$ - potentially, can describe the crossover between the ballistic to diffusive regimes at $T \sim T_D$

Interaction effects in a multi-valley system

***Ballistic regime*:**
Zala, Narozhnii & Aleiner ('01)
$T\tau \gg 1$

$$\partial\sigma_{\text{int}} = -\frac{e^2}{\pi\hbar}\left\{1+\mathbf{15}\,\frac{F_0^{\sigma}}{1+F_0^{\sigma}}\right\}\frac{T\tau}{\hbar}$$

Valley degeneracy
[Punnoose and Finkelstein, '02]

2 spins ⊗ 2 degenerate valleys ⇒ **16 (1 singlet +15 triplets)**

Diffusive regime: Altshuler, Aronov, & Lee ('80); Finkelstein ('83)

$T\tau \ll 1$

$$\partial\sigma_{\text{int}} = -\frac{e^2}{2\pi^2\hbar}\left\{1+\mathbf{15}\left[1-\frac{\ln\left(1+F_0^{\sigma}\right)}{F_0^{\sigma}}\right]\right\}\ln\left(\frac{\hbar}{k_B T\tau}\right)$$

Should work for all $T < (1+F_0^{\sigma})^2 E_F$:

$$\delta\sigma_{ee}^{\;T}(T) = 2\left\{\frac{T\tau}{\hbar}\right\}\left[\left(1-\frac{3}{8}f(T\tau)\right)+15\frac{F_0^{\sigma}}{1+F_0^{\sigma}}\left(1-\frac{3}{8}t(T\tau;F_0^{\sigma})\right)\right] - \left[1+15\left(1-\frac{\ln(1+F_0^{\sigma})}{F_0^{\sigma}}\right)\right]\left\{\frac{1}{\pi}\ln\left(\frac{E_F}{T}\right)\right\}$$

Crossover ⇒
$T\tau \sim (1+F_0^{\sigma})/2\pi$

Mechanisms of “pre-factor 15” reduction:

Magnetic field: $k_B T << g^* \mu B_{||} << E_F \quad (15 \Rightarrow 7)$

$\Rightarrow$ spin-induced positive magnetoresistance in parallel fields

Valley splitting: $\Delta_V > k_B T \quad (15 \Rightarrow 7)$

Inter-valley scattering: $\hbar / \tau_V >> k_B T \quad (15 \Rightarrow 3)$

single-valley result

The ZNA theory takes into account $B_{||}$ and Δ_V, but ignores τ_V.

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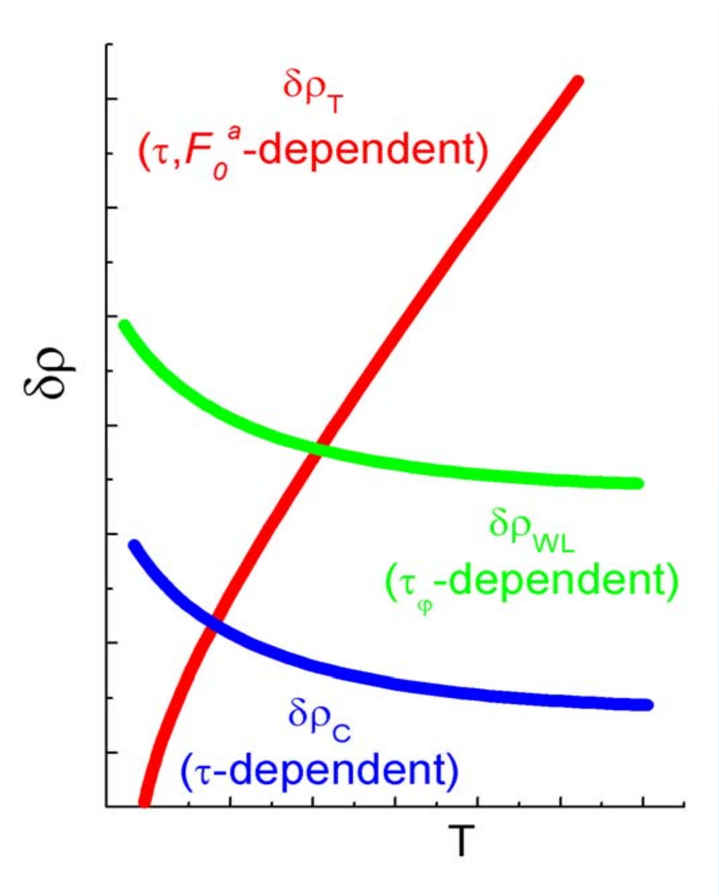
Analysis of Experimental Data

The goal: to compare data with the theory without using any fitting parameters.

$$\sigma(T,B_\parallel)-\sigma_D = \partial\sigma_{WL}(T)+\underbrace{\partial\sigma_C+\partial\sigma_T}_{\partial\sigma_{INT}(T)}$$



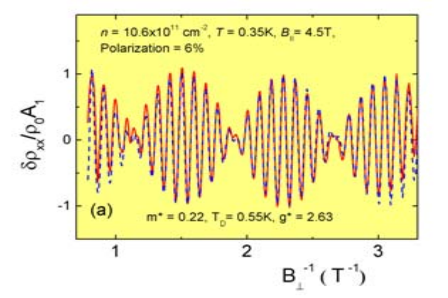
Strategy:

- find all INT-relevant parameters in independent measurements (including the study of WL in weak fields)
- suppress WL by weak perp. magnetic field and study INT effects as functions of temperature and parallel magnetic field

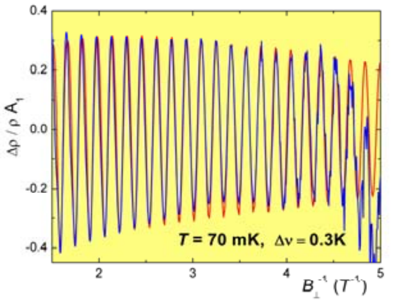
Analysis of Experimental Data (cont'd)

from $\rho_D = m^*/e^2 n\tau$, with m^* from SdH measurements

SdH Oscillations

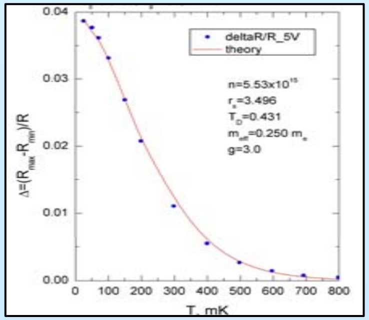


SdH Oscillations

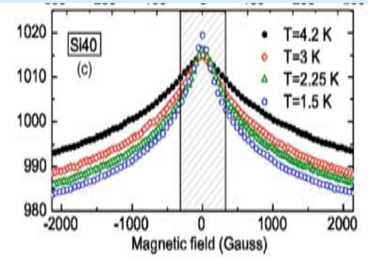


$$\partial\sigma_{INT}\left(T,\tau,F_0^{\ \sigma},g\mu B,\Delta_V,h/\tau_V\right)$$

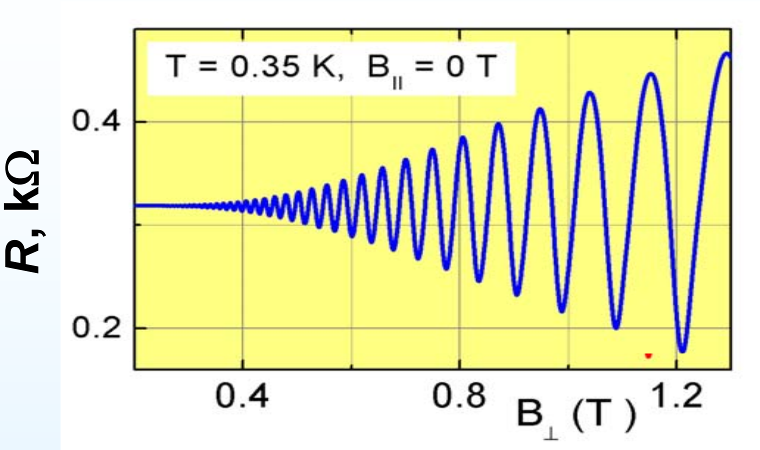
SdH oscillations



WL corrections



Electron Temperature

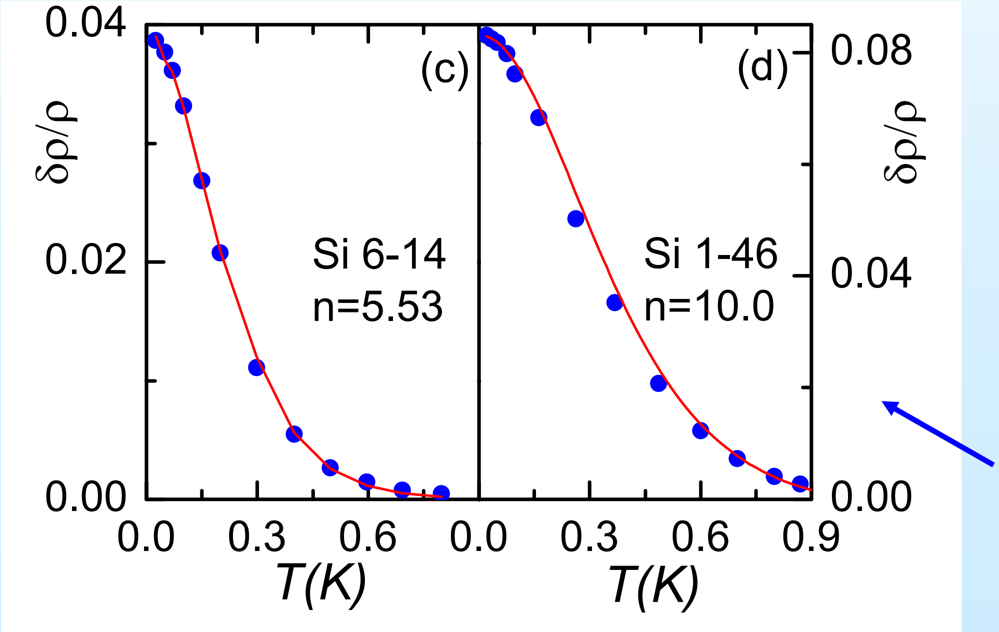


Damping:

averaging over Landau levels within ***$k_B T$***

elastic scattering off impurities

$$A_1(\omega_C, T) \propto \exp\left[-\frac{2\pi^2 k_B (T + T_D)}{\hbar\omega_C}\right]$$



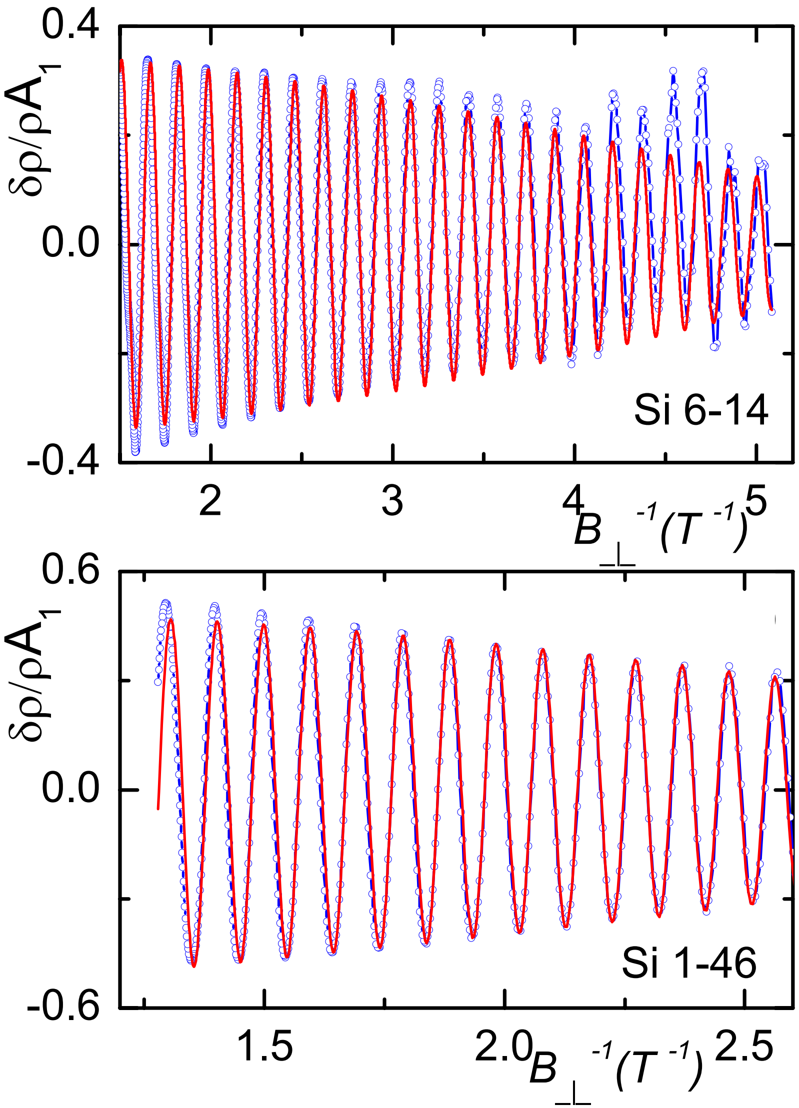
Dingle temperature: $k_B T_D = \frac{\hbar}{2\pi\tau_q}$

τ_q - the "all-angle" scattering time, almost the same as the transport time for a short-range disorder (Si MOSFETs)

T_D ~ 0.3-0.4K in our samples

This "thermometer" works down to ~50mK.

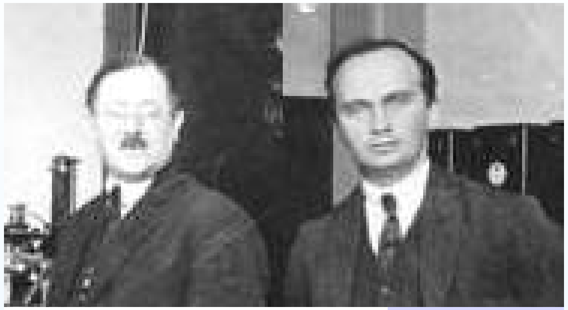
Valley Splitting

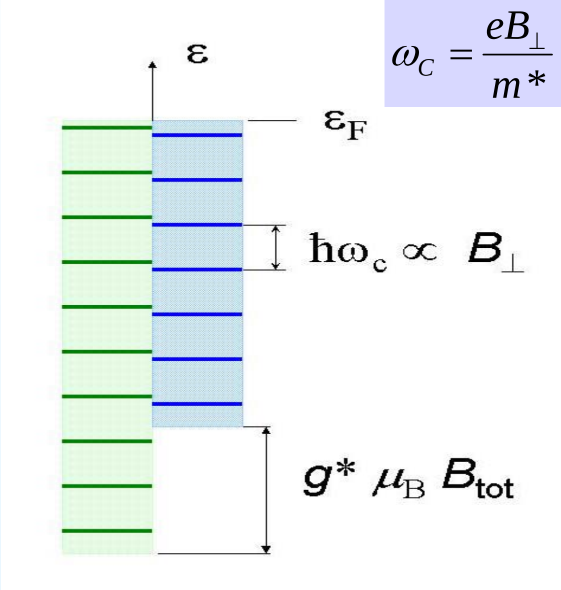


$$\Delta_V = 0.4K$$

$$\Delta_V = 0.7K$$

SdH oscillations
(normalized by the first harmonic A_1):
Si6-14: $n=6.1\cdot10^{11}\text{cm}^{-2}$, $T=36\text{mK}$
Si1-46: $n=10\cdot10^{11}\text{cm}^{-2}$, $T=200\text{mK}$
Klimov *et al.*, '07





$$\omega_C = \frac{eB_\perp}{m^*}$$

Valley splitting:
"minority" and "majority" carriers

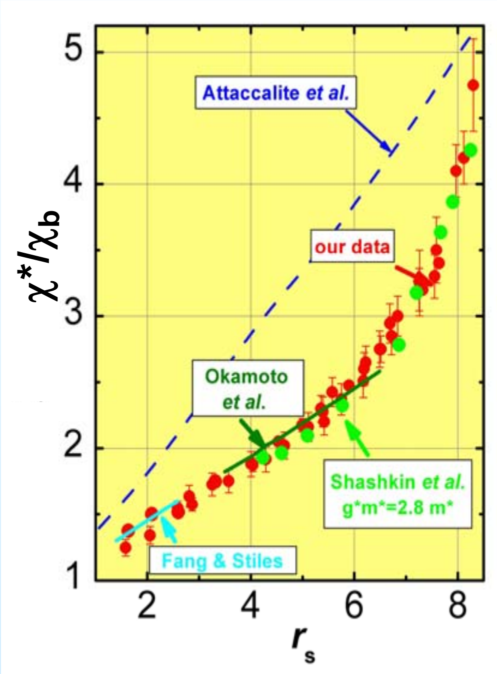
Interaction parameter F_0^σ

The interaction-driven renormalization of m^*, g^*, χ^* is controlled by the Fermi-liquid parameters F_0^σ and F_1^s:

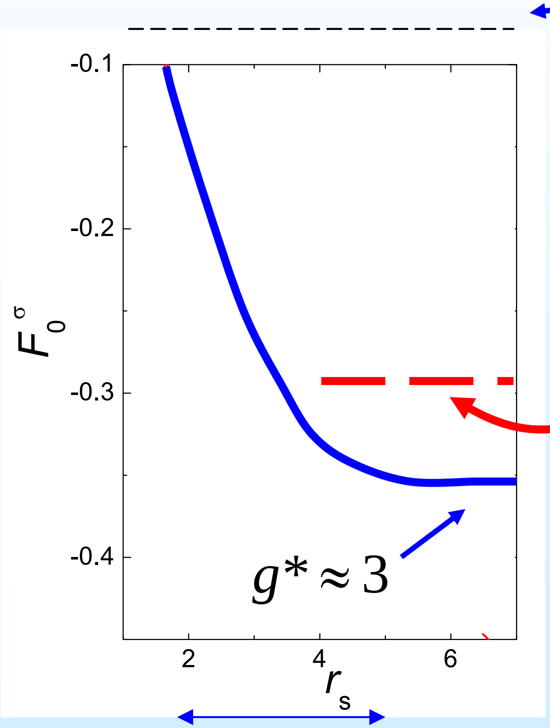
$$\chi^* = g^* m^* \frac{g_b \mu_B^2}{\pi \hbar^2} \qquad m^* = m_b(1+F_1^s) \qquad g^* = \frac{g_b}{1+F_0^\sigma}$$

All parameters can be found from the SdH measurements in crossed magnetic fields

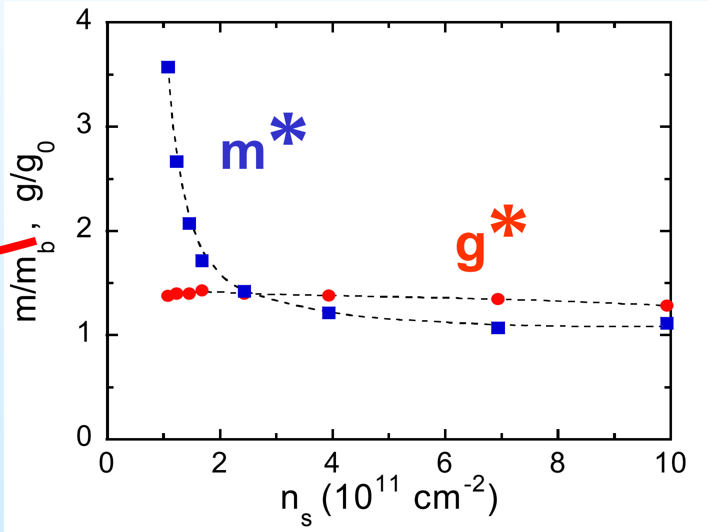
at this F_0^σ, change of sign $[1+15F/(1+F)]$ is expected



Pudalov, MG *et al.* (‘02)



n=(15-2)·10^{11}cm^{-2}



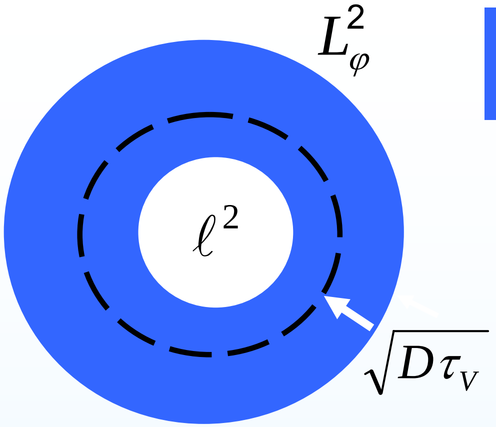
Shashkin, Kravchenko, *et al.* (‘02)

$|F_0^\sigma|$ increases up to ~ 0.3 at large r_s

(still very far from Stoner instability ⇒ $F_0^\sigma = -1$)

sufficient for explanation of “metallicity”

τ_V - from the WL MR



Two-valley system:

$$\partial\sigma_{WL} = \alpha\frac{e^2}{\pi h} f\left(B,\tau_\varphi\right)$$

weak inter-valley scatt. ($\tau_V >> \tau_\varphi$): $\alpha = 2$
strong inter-valley scatt. ($\tau_V << \tau_\varphi$): $\alpha = 1$

Kuntsevich *et al.*,
PRB **75**, 195330 ('07)

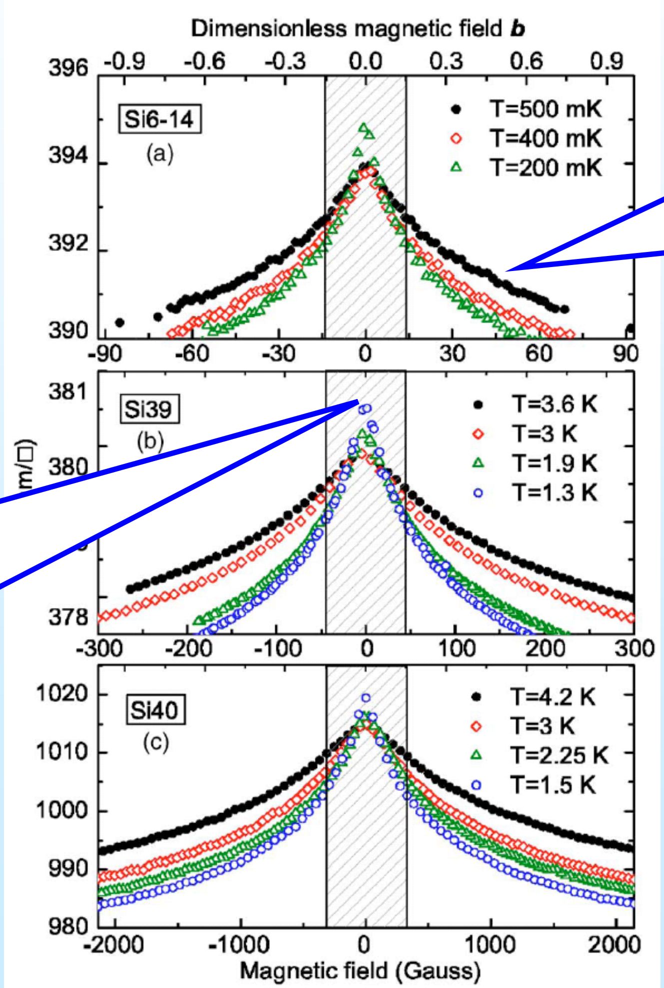
Si 6-14: μ=2 m^2/Vs
Si 39: μ=0.45 m^2/Vs
Si 40: μ=0.18 m^2/Vs

Within the hatched region:
the diffusive approximation holds, α = 1 (valley are intermixed at t < τ_φ)

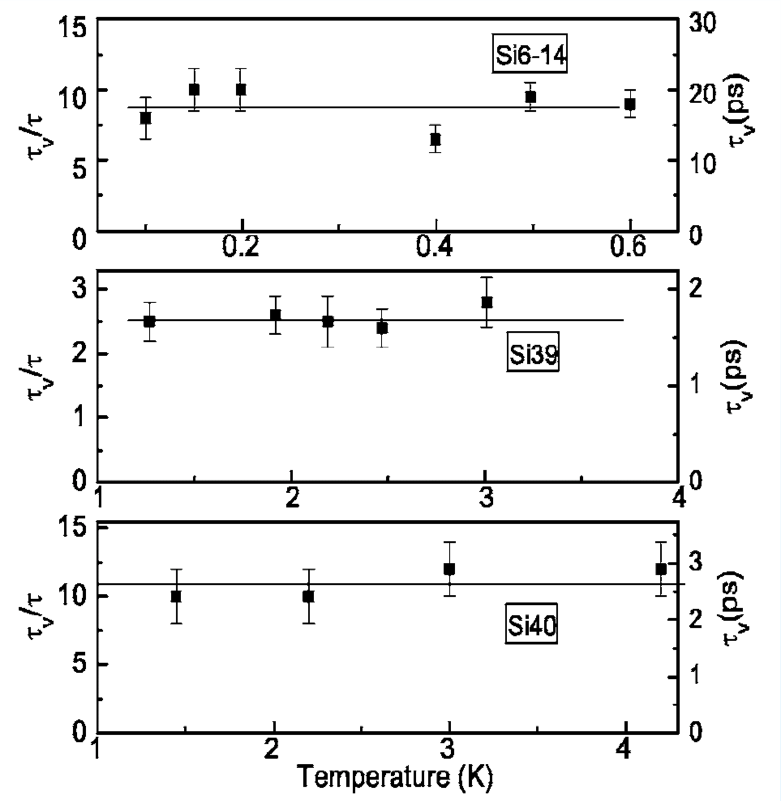
this region was used to extract τ_φ

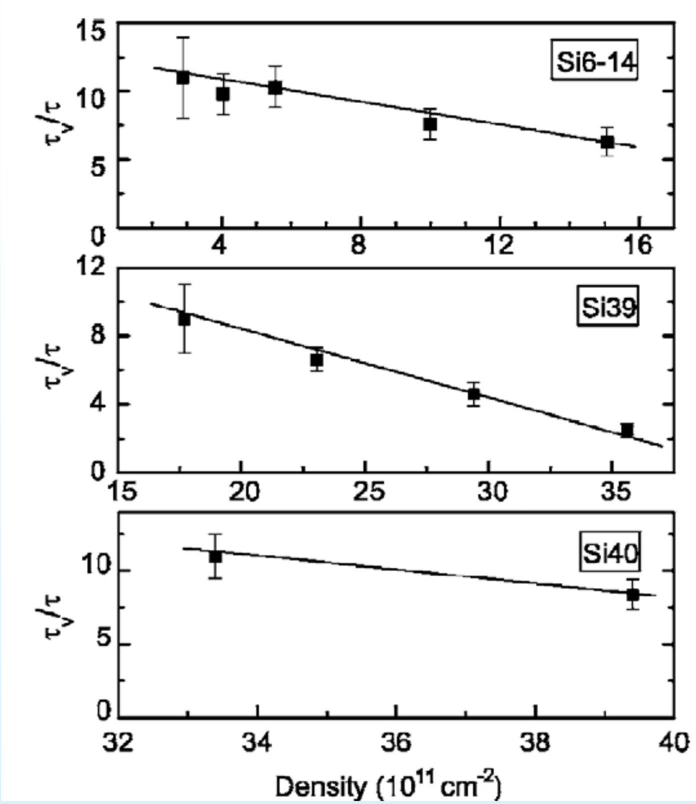
Outside the hatched region:
crossover to the ballistic regime

τ_V was estimated in this region using the theory by Tarasenko and Averkiev ('06) (the WL corrections in a multi-valley system in the ballistic regime)



Intervalley scattering in Si MOSFETs





Inter-valley scattering is *T*-independent and the ratio τ_V/τ decreases with ***n***:
roughness of the Si-SiO$_2$ interface is the dominant factor.

τ_V ~ 20ps $\Rightarrow$ $\hbar/\tau_V$ ~ 0.4K - close to this *T*, the "$3F_0^\sigma \Leftrightarrow 15F_0^\sigma$" crossover in the INT corrections is expected

Dephasing in Si MOSFETs

The dephasing rate due to both singlet and triplet channels (2D):

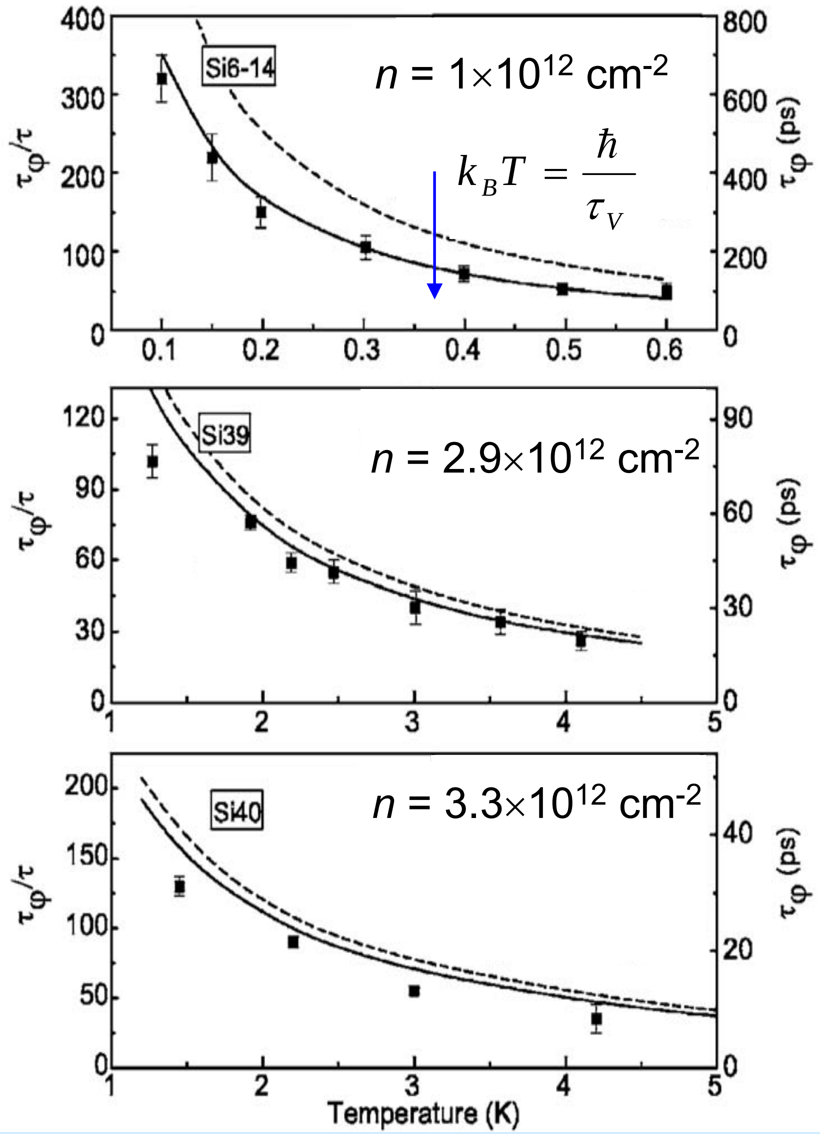
Narozhny, Zala, Aleiner, ’02

$$\frac{1}{\tau_\varphi} = \left[1 + \frac{15(F_0^\sigma)^2}{(1+F_0^\sigma)(2+F_0^\sigma)}\right]\frac{T}{g}\ln\left[g(1+F_0^\sigma)\right] +$$

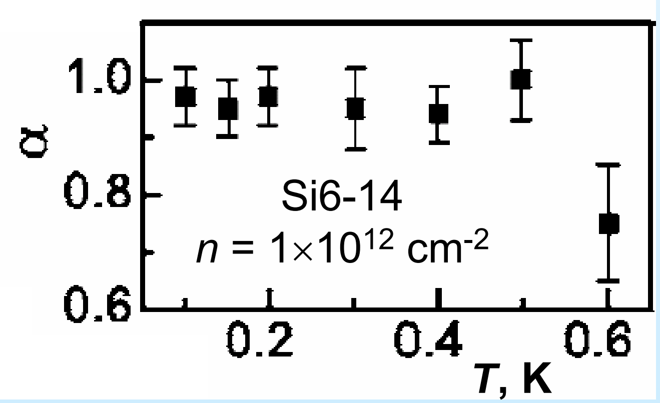
$$\frac{\pi}{4}\left[1 + \frac{15(F_0^\sigma)^2}{(1+F_0^\sigma)^2}\right]\frac{T^2}{E_F}\ln\left(E_F\tau\right)$$

Solid lines – 15 triplet components (two degenerate valleys)

Dashed lines – 3 triplet components (single valley)



Kuntsevich *et al.*, PRB **75**, 195330 (’07)



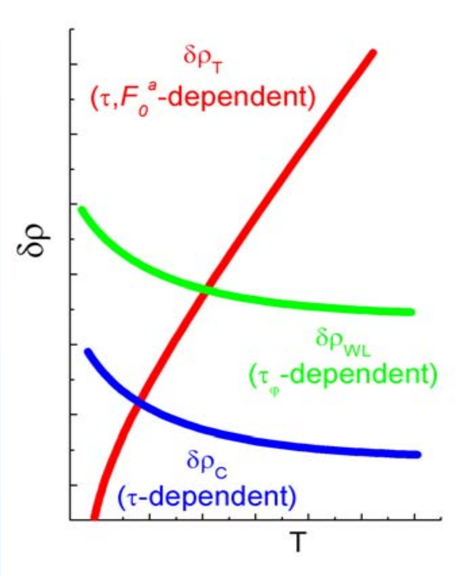
- valleys are intermixed on the time scale τ_φ

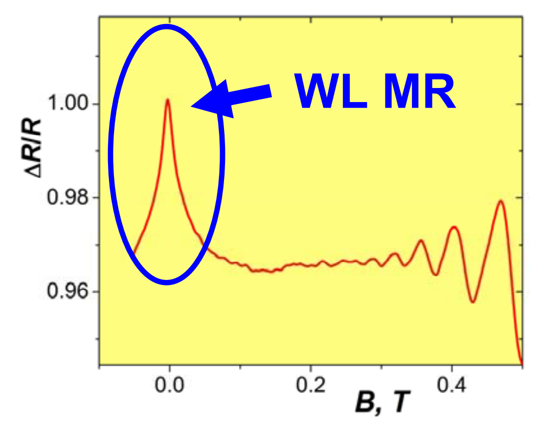
Despite strong interactions (r_S up to ~ 5), Si MOSFETs behave as a Fermi-liquid system.

Analysis of Experimental Data

$$\sigma(T,B_{\|})-\sigma_D = \partial\sigma_{WL}(T)+\underbrace{\partial\sigma_C+\partial\sigma_T}_{\partial\sigma_{INT}(T)}$$

The goal: to compare data with the theory without using any fitting parameters.





Strategy:

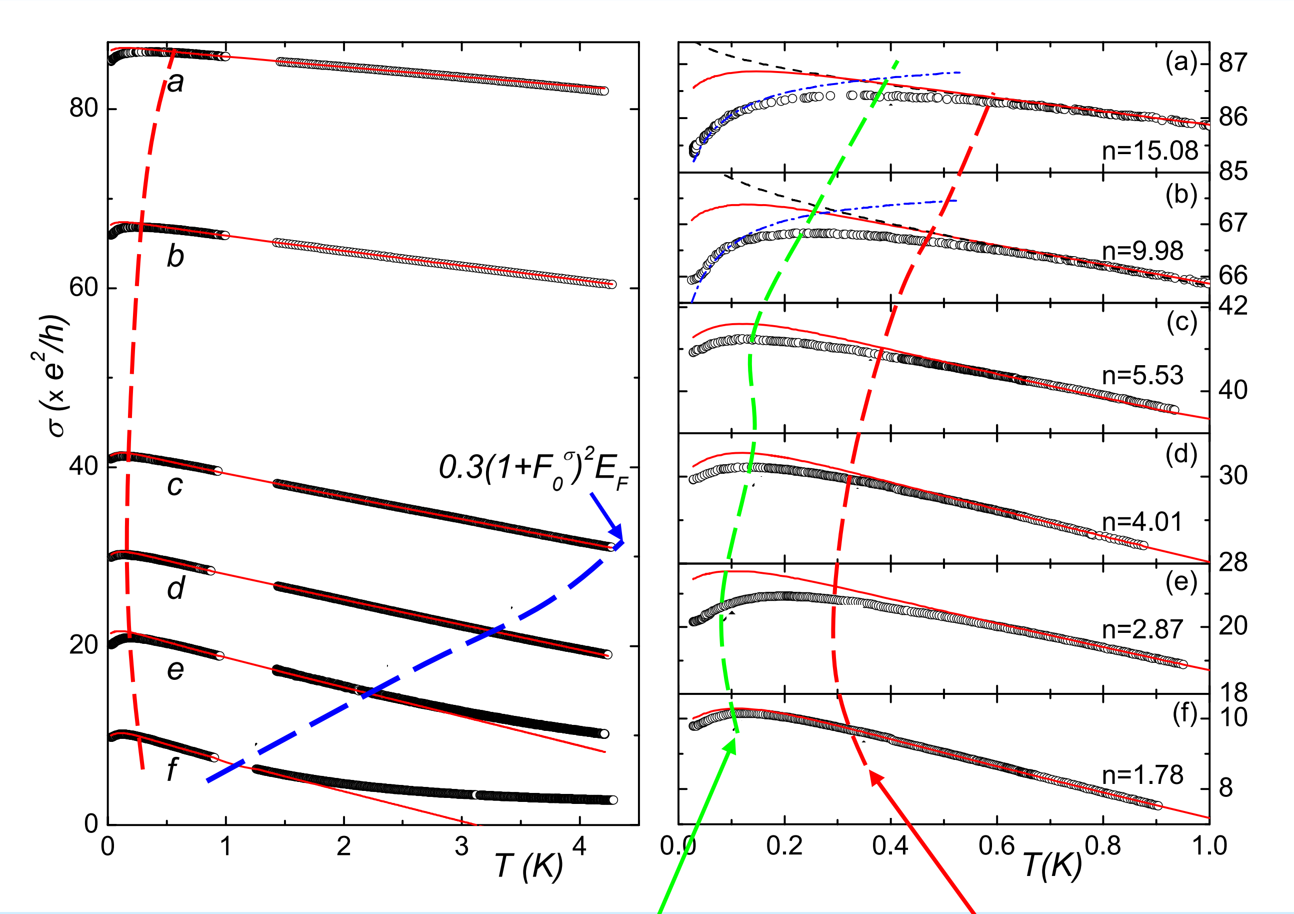
- find all INT-relevant parameters in independent measurements (including the study of WL in weak fields)
- suppress WL by weak perp. magnetic field and study INT effects as functions of temperature and parallel magnetic field

$B_\perp$ separates the WL and interaction corrections (orbital effects)

$B_{\|}$ elucidates the structure of interaction corrections (spin effects)

Zero-$B_{\parallel}$ $\sigma(T)$: fitting

F_0^σ - let's find from the ballistic regime ($T >> \hbar/\tau$, Δ_V, $\hbar/\tau_V$) and compare with the SdH data



Black curves:

$\Delta\sigma_{INT}(\Delta_V < T,\ h/\tau_V < T)$

Red curves:

$\Delta\sigma_{INT}(\Delta_V,\ h/\tau_V < T)$

Blue curves:

$\Delta\sigma_{INT}(h/\tau_V >> T)$

The theory captures all essential features of the observed $\sigma(T)$; for further improvement, the theory consider a finite intervalley scattering rate.

$$T = \frac{\hbar}{\tau_V}$$

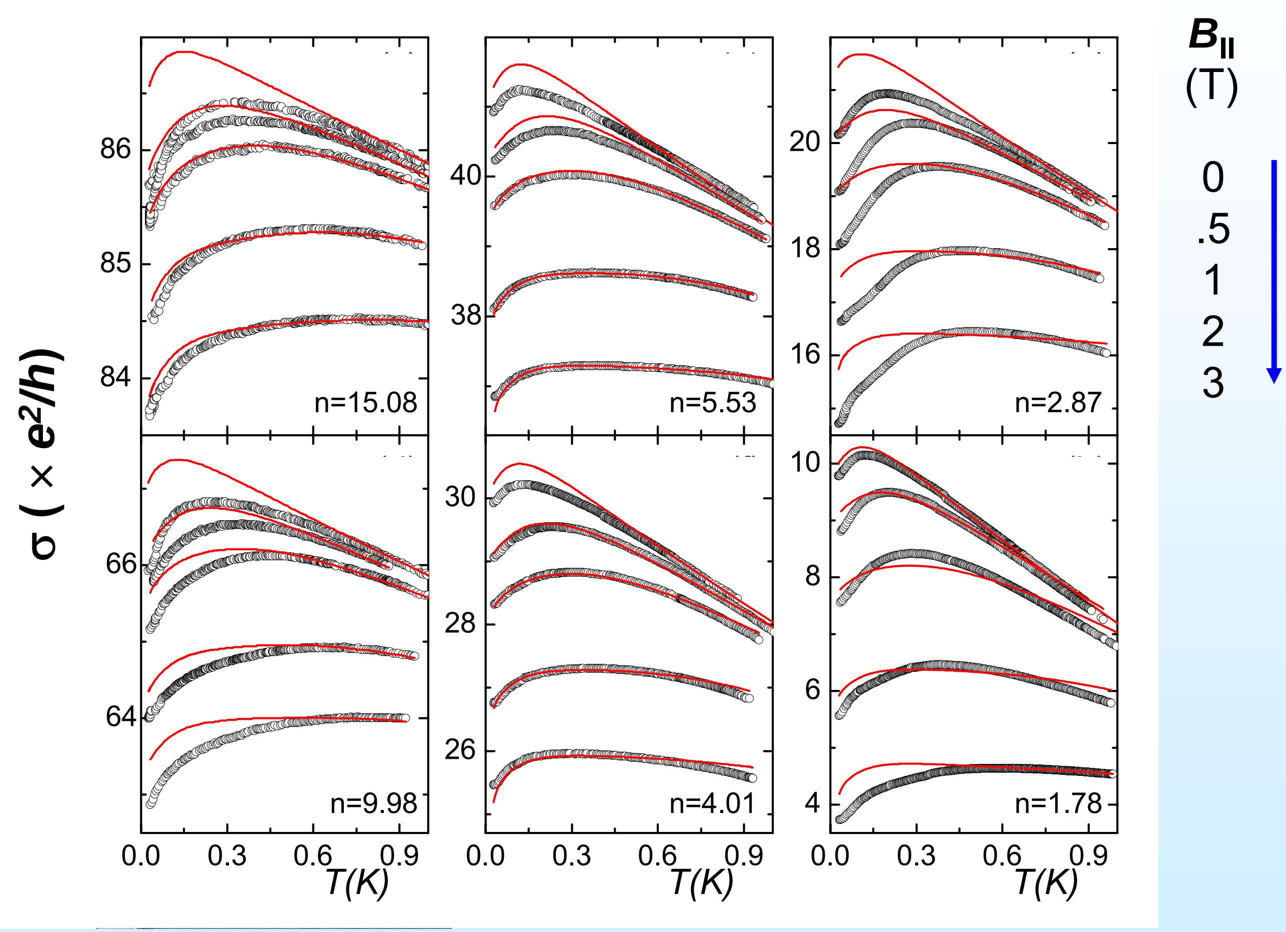
diffusive ⇔ ballistic

$$T = \left(1 + F_0^\sigma\right)\frac{\hbar}{2\pi\tau}$$

Klimov *et al.*, unpublished

THE STATE UNIVERSITY OF NEW JERSEY
RUTGERS

$\sigma(T)$ in strong $B_{\parallel}$



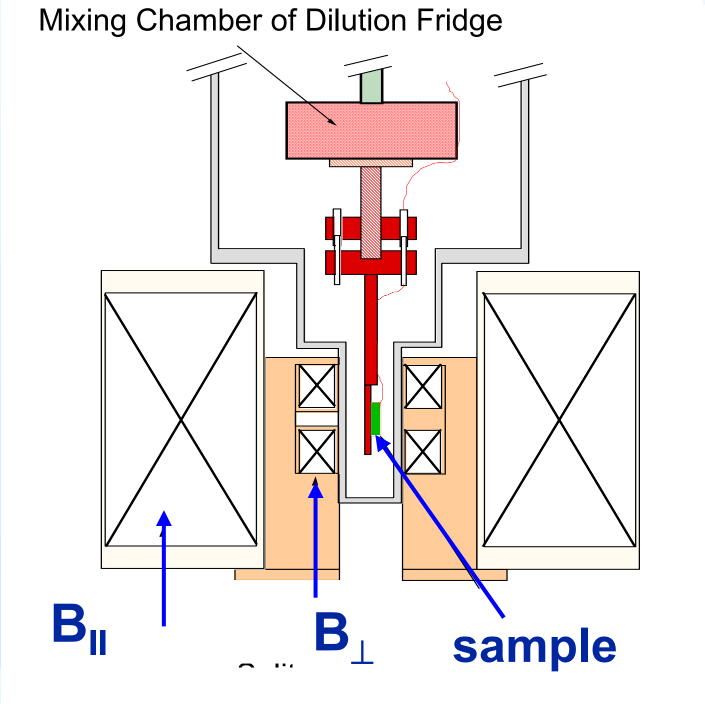
Klimov *et al.,* unpublished

As soon as the Zeeman energy exceeds *T*, the “metallicity” is weakened. (the number of triplet components is reduced from 15 to 7).

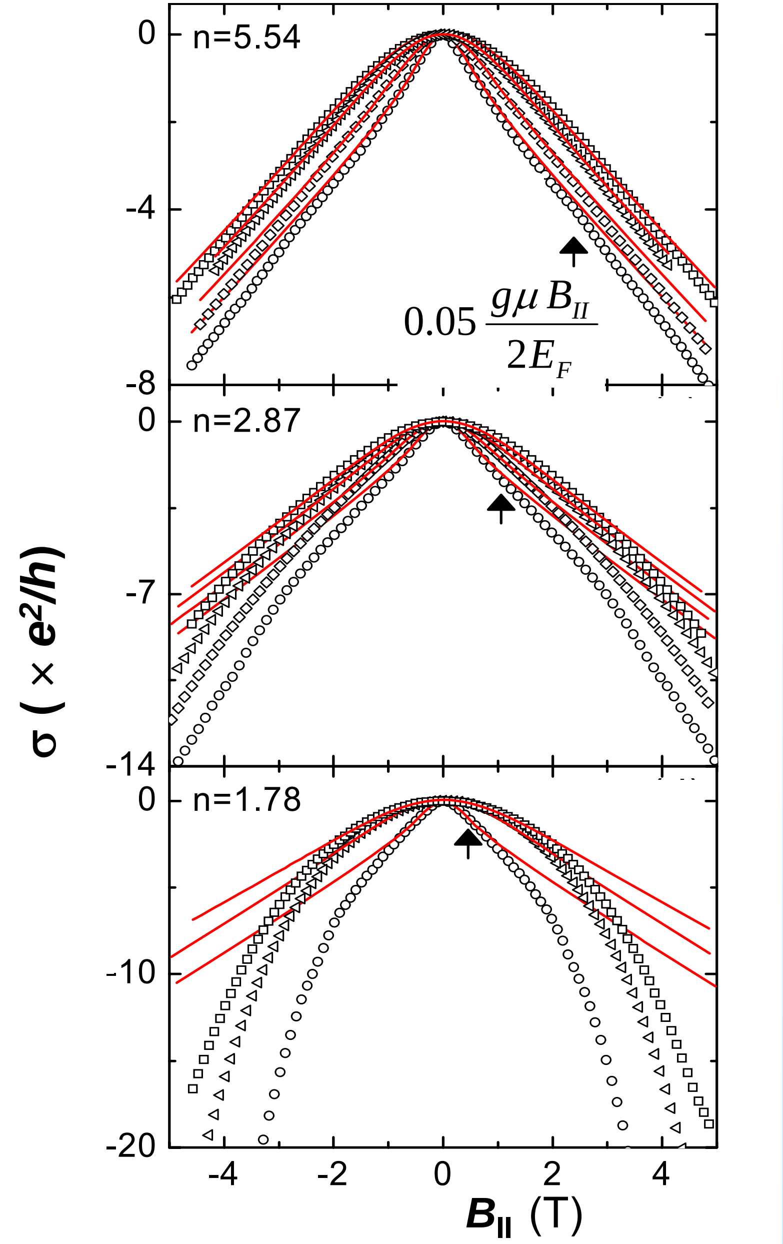
Magnetoconductance $\Delta\sigma(B_{\parallel})$

Experimental difficulty: small misalignment of $B_{\parallel}$ with respect to the 2DEG plane leads to a non-zero $\boldsymbol{B_{\perp}}$ and orbital (WL) magnetoconductance.

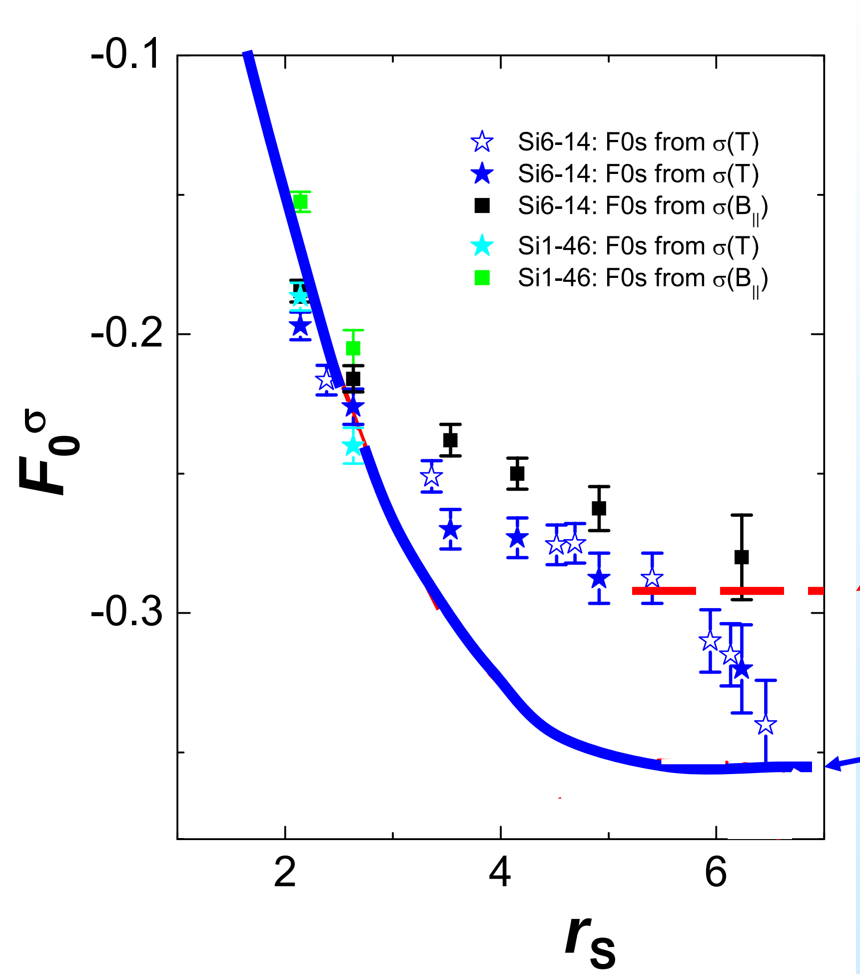
Solution: compensation of $\boldsymbol{B_{\perp}}$ in the set-up with crossed magnetic fields



MG *et al.*, *Physica* E **12**, 585 (‘02)



The Fermi-liquid parameter F_0^σ: comparison



F_0^σ from B*
Shashkin, Kravchenko, *et al*. ('02)

F_0^σ from SdH
Pudalov, MG *et al.* ('02)

Overall, very reasonable agreement !

The main message:

At not-too-low conductances ($\sigma > 10e^2/h$), the anomalous "metallic" behavior of Si MOSFETs (as well as in the other high-mobility and low-density systems) is consistent with the theory of interaction corrections. The interaction corrections in Si MOSFETs are enhanced by the valley degeneracy and the interaction-driven renormalization of Fermi-liquid parameters.

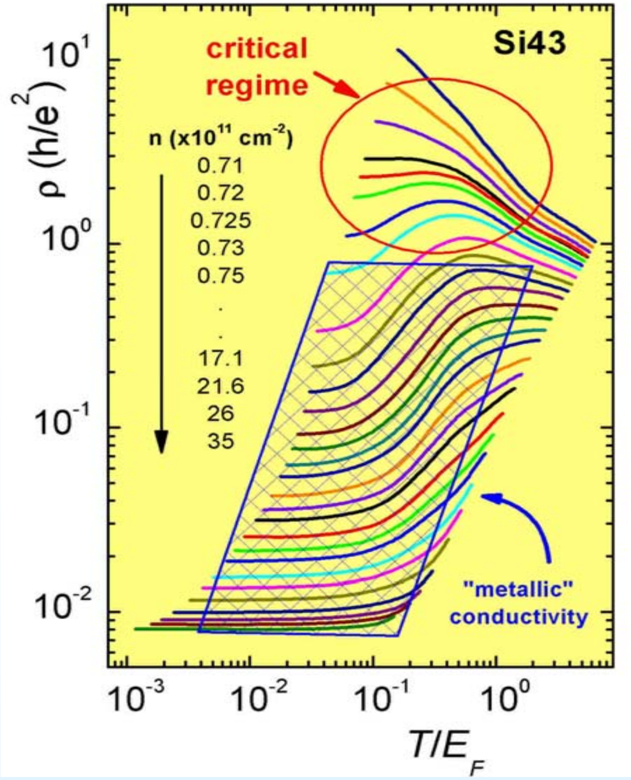
Agreement with the ZNA theory:

***n*-type Si:** Shashkin *et al*., *PRB* **66**, 73303 ('02); Kvon *et al*., *PRB* **65**, 161304 ('02); Vitkalov *et al*., *PRB* **67**, 113310 ('03); Pudalov *et al., PRL* **91**, 126403 ('03)

***p*-type GaAs:** Proskuryakov *et al*., *PRL* **89**, 076406 ('02); Noh *et al*., *PRB* **68**, 165308 ('03); Yasin *et al.*, cond-mat/0403411

***n*-type GaAs**: Li *et al*., *PRL* **90**, 076802 ('03); Yasin *et al.*, cond-mat/0403411

***p*-type SiGe:** Coleridge *et al*., *PRB* **65**, 125328 ('02)



What is the nature of the apparent 2D MIT?

(At least) two schools of thought:

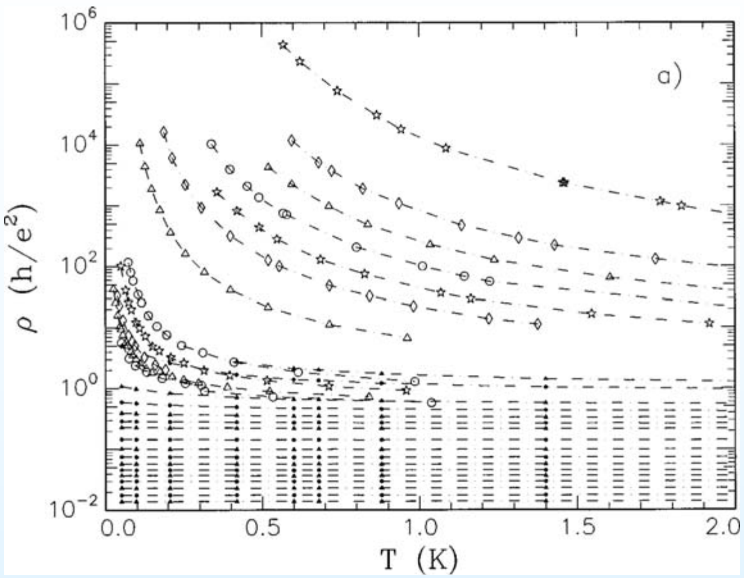
2D MIT - a quantum phase transition between a true 2D metal and an insulator.

A new “metallic” phase is stabilized by the strong electron-electron interactions.

“2D MIT” - a classical (percolation) transition driven by the emerging macroscopic fluctuations at low *n*.

Anomalous “metallic” behavior – a finite-*T* effect associated with the interaction contribution to the resistivity.

What is so special about this crossover ?

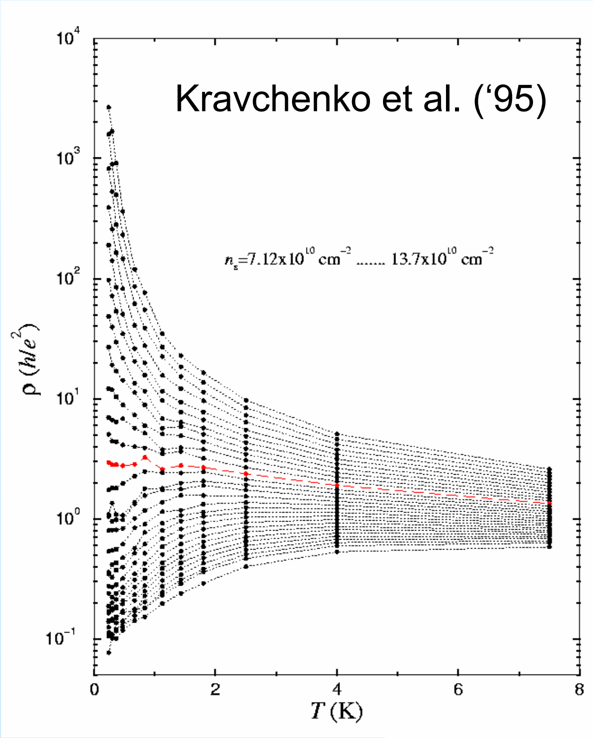


The WL-SL crossover has been observed in many quasi-1D and 2D systems (this does not mean, however, that we know how to describe $R(T)$ at the crossover quantitatively…).

Gated GaAs/AlGaAs structures,
n = (0.65-6)x10^{15} m^{-2}
Van Keuls *et al*., *Phys. Rev*.B **56**, 13263 ('97)

Unusual feature of the "metallic"-"insulating" crossover in high-mobility Si MOSFETs:

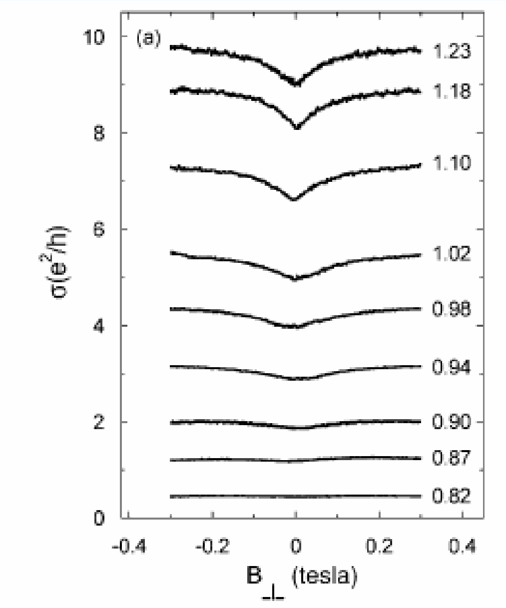
the WL and INT corrections seem to be suppressed near the crossover (at large $\boldsymbol{R}_{\square}$) rather than enhanced...


Kravchenko et al. ('95)

The WL MR near the apparent 2D MIT

Up to ~ 5 kΩ/□, the WL corrections can be well described by the conventional theory. However, at larger $R_□$, the magnitude of the WL MR (but not $\Delta\sigma_{WL}(T)$!!) is ***smaller*** than the predictions for a ***homogeneous*** system with $\boldsymbol{\sigma \gg e^2/h}$.

high-μ Si MOSFET



Rahimi *et al.* ('03)

"Vanishing" WL MR at $\sigma \Rightarrow e^2/h$ is expected for both homogeneous and macroscopically inhomogeneous systems:

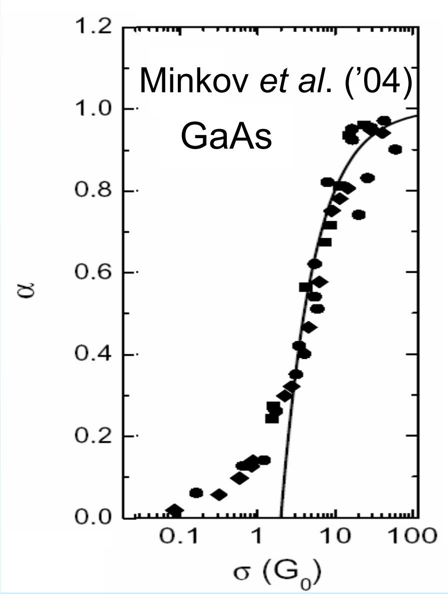
- **homogeneous** – owing to the second-loop corrections

$$\alpha = 1 - \frac{2G_0}{\sigma}$$
$$G_0 = e^2/(2\pi^2\hbar)$$

Gornyi ('04)

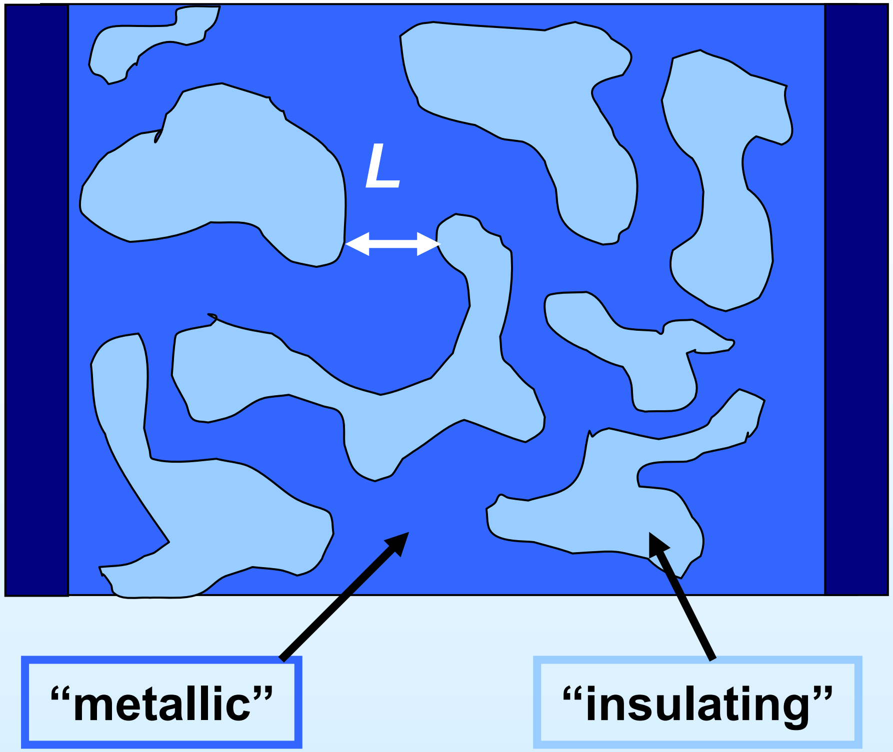
- **macro inhomogeneous** – owing to the percolation effects

Aronov, MG, Zhuravlev ('86)

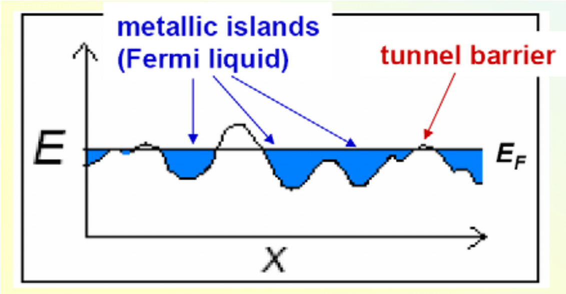

Minkov *et al.* ('04)

This scenario seems more likely - it explains suppression of both $\Delta\sigma_{WL}(T)$ and $\Delta\sigma_{WL}(B)$

Entertaining the non-homogeneous scenario…



In our samples, separation between dopants ~ 0.1 μm.



Emerging macroscopic inhomogeneity at a macroscopic scale $L > L_\varphi$

The screening becomes weaker and strongly non-linear as the density is lowered ⇒ a nominally uniform 2DEG breaks up into isolated puddles.

Efros (’88), Nixon and Davies (’90), Meir, ’99 Das Sarma and Hwang, (’83, ’99, ’04), MG (’02), Fogler (’03), etc.

What would be the consequences of percolation?

- The amplitude of WL corrections is suppressed:

$$\Delta\sigma_{WL} = \frac{\Delta\rho_{WL}}{\rho^2_{macro}}$$ but $R_{\square\ \mathrm{metallic}} << R_{\square\ \mathrm{total}}$ ✓

\- in the conductors with percolation, the quantum corrections are smaller than one might expect for a homogeneous system with the same total resistance.

Aronov, MG, and Zhuravlev, *JETP* **60**, 554 (1984)
MG *et al., Phys.Rev.Lett.* **74**, 446 (1995).

- At the same time, τ_φ would not depend on $R_{\square\ \mathrm{macro}}$ ✓

- The same conclusion would be applicable to the INT corrections – this percolation “reduction” of the quantum corrections might explain why the slope d*R*/d*T* in the vicinity of the apparent MIT becomes smaller instead of getting bigger ($|F_0^{\sigma}|$ remains large near the apparent 2D MIT). ✓

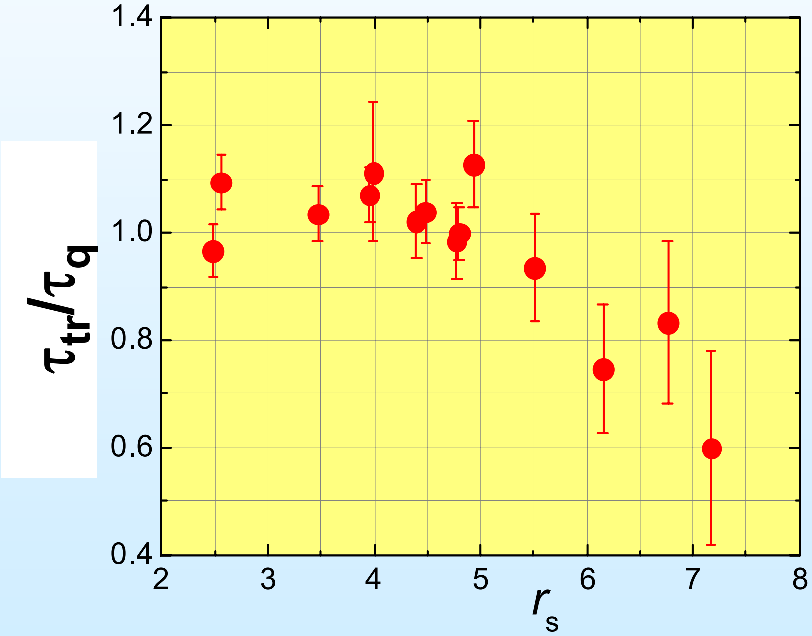
- Enhancement of the 1/f noise near the perc. threshold ✓

  D. Popovic et al., R. Leturcq et al. PRL 90, 076402 (2003)

- The amplitude of SdH oscillations becomes anomalously large: τ_q becomes greater than τ_{tr} ✓

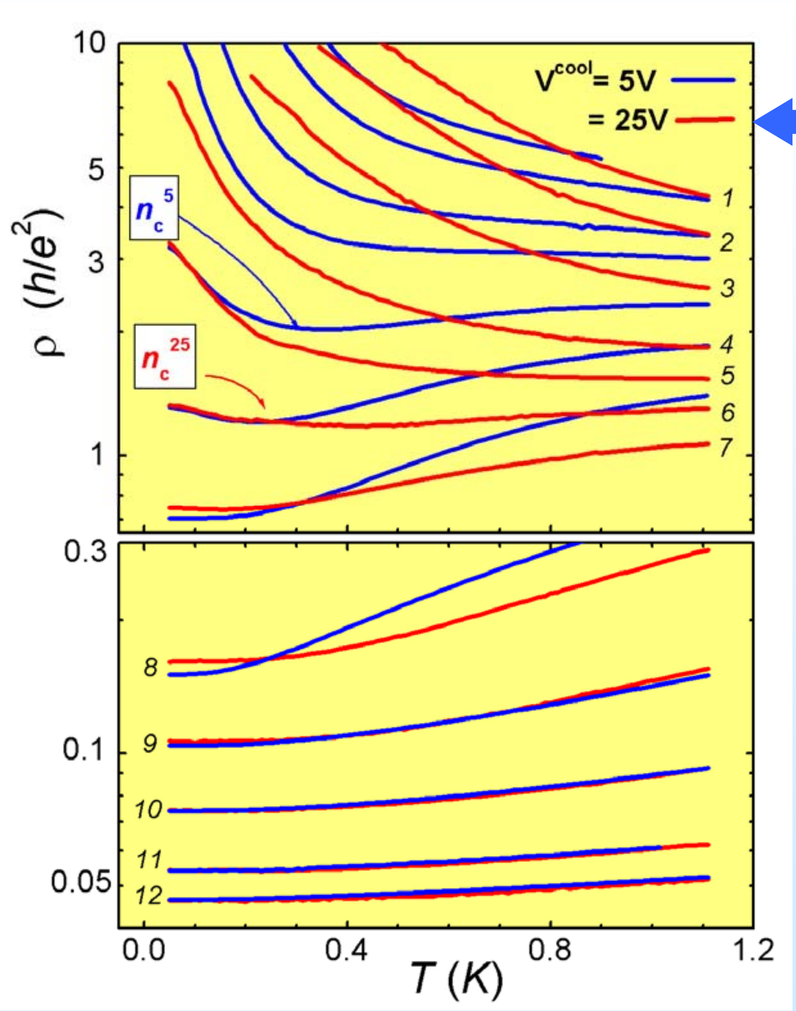
$$\tau_q = \frac{\hbar}{2\pi\, k_B\, T_D}$$

$$\tau_{tr} = \frac{\sigma_{macro} m^*}{e^2 n}$$



(The WL corrections would be reduced by a large factor τ_q / τ_{tr}).

Hysteresis effects at lower densities/higher resistances



Pudalov, MG, Klimov, and Kojima
JETP Lett. **82**, 412 (2005).

The same device, cooled down to 4K at different fixed values of V_g.

Important: different V_g^{cool} did not affect significantly the parameters which control the interaction effects (τ and F_0^a)

Universal behavior $\Rightarrow$ sufficiently far from the apparent 2D MIT
($\rho \leq 0.1h/e^2$, or $n > 1.3x10^{11}$ cm^{-2}).

Part II: Conclusion

The crossover from "metallic" to "insulating" conductivity in high-mobility Si MOSFETs seems to be consistent with a classical percolation scenario.

Close to the crossover, the dilute 2D systems may become non-homogeneous. If this is the case, the temperature and magnetic-field dependences of σ are still due to the quantum corrections, but the magnitude of these corrections is diminished by development of percolation at low electron densities.

In the percolation scenario, the "apparent 2D MIT" has nothing to do with interactions.

Probing the macroscopic homogeneity of dilute 2D systems – the key issue for better understanding of the apparent 2D MIT.