Low-Dimensional Disordered Electronic Systems (Experimental Aspects)

Lecture II
Electron-Electron Interactions and Dephasing Processes in Disordered Conductors

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Lecture 2: Electron-electron Interactions and Dephasing Processes in Disordered Conductors

- El.-el. interactions in disordered conductors: anomalous corrections to the DoS and conductivity
- Dephasing induced by interactions
- Dephasing at ultra-low temperatures: dephasing by Kondo impurities and high-frequency electromagnetic noise

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from cutting-edge research in organic semiconductors to ultra-low-temperature nanophysics, including quantum computing with ultra-small Josephson junctions

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El.-El. Interactions in disorder-free conductors

Collisions with large and \textbf{T-independent} momentum transfer \( q \sim k_F \) \( \tau_{ee}^{-1} \propto \frac{\mathcal{E}^2}{E_F} \)

El.-el. interactions do renormalize electron parameters at a large energy scale (\( \sim E_F \)), this renormalization does not result in anomalous low-\( T \) behavior of these parameters.

\( T^2 \) term in the resistivity, no anomalous corrections at low \( T \)

Interaction processes in disordered conductors:

Electron scattering by impurities dramatically changes the situation at low energies (\( << E_F \)). Because of the diffusive motion, processes with collisions with a \textbf{small momentum transfer} \( q \sim \left[ \max(T,\varepsilon)/D \right]^{1/2} \ll k_F \) becomes important.

Due to the diffusive motion, the renormalization of all electron parameters becomes \textbf{T-dependent}, and all thermodynamic and transport quantities (including DoS, which is not affected by WL) acquire \textbf{non-trivial T-dependent corrections}.

\[ L_{\varepsilon} = \sqrt{\frac{\hbar D}{\varepsilon}} \]  
\[ \Delta \sigma_{\text{INT}}(T) \rightarrow L_T = \sqrt{\frac{\hbar D}{k_B T}} \]

The dimensionality of a conductor: \( L \leftrightarrow L_T(T) \)

\( l \ll L_T \leq L_\phi \) - a large scale (\( D=10 \text{ cm}^2/\text{s}, T=1\text{K}, L_T \sim 0.1\text{\mu m} \)), \textbf{non-locality} and \textbf{“universality”} of INT effects, similar to the WL effects.

Because of a large characteristic length scale, the interaction corrections are \textbf{“non-local”} and \textbf{“universal”} (similar to the WL correction)
 Corrections to the Tunneling DoS

tunnel junctions (thin disordered) Al-Al\textsubscript{2}O\textsubscript{3}-Al
(magnetic field suppresses SC below $T_{C}$)

MG, Gubankov, Falei ('85,'86)

The dimensionality of a conductor:

$L \leftrightarrow L_{\varepsilon}$ \hspace{1cm} $\varepsilon = \max[T, eV]$

With increasing disorder, the ZBA transforms into the Coulomb gap (the SL regime)

$E_{F}(1) - E_{F}(2) = eV$

$\frac{\Delta \nu(\varepsilon)}{\nu(E_{F})} = \frac{\Delta G(eV)}{G(eV = 0)}$

2D AA theory

the so-called zero-bias anomaly

$\Delta G/G, \%$

$\Delta G/G, \%$

$\Delta G/G, \%$

$\Delta G/G, \%$

$\Delta G/G, \%$

$\Delta G/G, \%$

$\Delta G/G, \%$
The interaction correction to the conductivity - as a result of the interference between wavefunctions of different electrons propagating in a random scattering potential.

Two regimes: **ballistic** \((T\tau > 1 \text{ or } L_T \leq l)\) and **diffusive** \((T\tau << 1 \text{ or } L_T >> l)\).

Metals – mostly diffusive regime, semiconductor structures – both regimes (Lecture 3).

\[ k_Tl >> 1, \text{ all orders in interactions, the leading order in } T. \]

\[ \Delta \sigma_{INT} = f(F_0^a) \frac{T\tau}{\hbar} + g(F_0^a) \ln \left( \frac{\hbar}{T\tau} \right) \]

Functions \( f \) and \( g \) are combinations of the “charge” and “spin” terms, the latter depends on \( F_0^a \) - the Fermi-liquid constant.
“Elasticity” of the processes that contribute to $\Delta \sigma_{\text{INT}}$ should be emphasized: they preserve the time reversal symmetry and do not cause phase breaking. An illustration: one of the contributions to the interaction corrections to the conductivity in the ballistic regime is due to the interference between the waves backscattered off an impurity (a short-range potential) “dressed” by Friedel oscillations. Other contributions, which involve virtual energy exchange processes at a scale $\varepsilon \gg T$, also do not break the time reversal symmetry.

**Sign of the corrections:** depending of the value of $F_0^\alpha$, the corrections could be either *positive* or *negative*. $F_0^\alpha$ can be found from independent measurements of $g^*$, e.g., from the analysis of SdH oscillations in semiconductor structures, or from the ESR with mobile electrons in metals.

Typically, $|F_0^\sigma| < 0.1$ in metals, and the interaction effects *decrease* the conductivity. In semiconductors, the abs. value of $F_0^\sigma$ increases with the strength of interactions: e.g. $F_0^\sigma \cong -0.3$ in Si MOSFETs at low carrier densities (see Lecture 2 by Vladimir Pudalov). In the latter case, the conductivity is *increased* by the interaction effects. For the detailed discussion of the corrections to $\sigma$ at large $|F_0^\alpha|$, see Lecture 3.
Metals: diffusive approximation, $F_0 \sigma \approx 0$

3D:  
$$\Delta \sigma_{INT} \propto (Dt)^{3/2}$$

$$L_T < \text{all dimensions}, \xi$$

2D:  
$$d < L_T \ll \xi$$

$$\Delta \sigma_{INT}^{2D} \propto -\frac{e^2}{h} \ln \left[ \frac{L_T(T)}{l} \right]$$

$$\delta \sigma_C(T) = -\frac{e^2}{2\pi^2 \hbar} \ln \left( \frac{\hbar}{T\tau} \right)$$

Quasi-1D:  
$$d, W < L_T \ll \xi$$

$$\Delta \sigma_{INT}^{1D} \propto -\frac{e^2}{h} L_T(T)$$

$$\delta \sigma_C(T) = -\frac{e^2}{\pi \hbar} \sqrt{\frac{\hbar D}{2\pi T}} \left( \frac{3\zeta(3/2)}{2} \right)$$

$$\zeta(3/2) \approx 2.612$$
WL and INT corrections to the conductivity of quasi-1D conductors

\[ \lambda_F \ll \ell \leq W < L_\varphi, L_T \ll \xi_{1D} \]

How to separate WL and INT corrections?

Echternach, MG et al., PRB 50, 5748 ('94)
Magnetic Field Effect

\[ \Delta \sigma_{INT} = f(F_0^a) \frac{T \tau}{\hbar} + g(F_0^a) \ln \left( \frac{\hbar}{T \tau} \right) \]

Functions \( f \) and \( g \) - combinations of the “charge” and “spin” terms.

ballistic regime \hspace{1cm} \text{diffusive regime}

“Charge” term isn’t sensitive to the field at all, “spin” terms are affected by the field if the Zeeman energy \( g\mu_B \) exceeds \( T \).

**Sloppy** analogy:

\[ \Delta \sigma_{INT}^{\text{diff}} (2D) \propto \left[ 1 + \frac{3}{2} F \right] \ln \left( \frac{\hbar}{T \tau} \right) \]

“charge” \hspace{1cm} “spin”

Note: in a system with interactions, the corrections to the DoS and conductivity are not simply interrelated:

\[ \sigma \neq e^2 v D \]

\[ \sigma = e^2 \frac{d\mu}{dn} D \]

When \( B \) is applied, two (of three) “triplet” contributions to the DoS are “shifted” in energy by \( g\mu_B \) with respect to the Fermi energy, and \( v(E_F) \) increases.
Experimental separation of WL and INT corrections

Let’s apply a magnetic field which, on the one hand, sufficiently strong to suppress the $T$-dependence of WL corrections \( L_H << L_\Phi(T) \), but, on the other hand, too weak to modify el.-el. interactions \( g\mu B << T \).

\[ R(T) \text{ for a 4.2-nm-thick Ag film} \]
\[ MG \text{ et al., JETP 83, 2348 (’82)} \]

(\text{in units } e^2 R_\Omega/2\pi^2 \hbar):

\[ B=1T \text{ is sufficiently strong to suppress } \Delta \sigma_{WL}(T) \text{ but too weak to modify } \Delta \sigma_{INT}(T): \text{ only INT} \]

\[ \Delta \sigma^{2D} = -\frac{e^2}{2\pi^2 \hbar} \ln \left[ \frac{L_\Phi(T)}{l} \right] - \frac{e^2}{2\pi^2 \hbar} \ln \left[ \frac{L_T(T)}{l} \right] \]

\( B=0: \text{ INT } + \text{ anti-WL} \)

(almost compensate each other)
INT corrections close to the WL-SL crossover

Gated $\delta$-doped heterostructures $\text{In}_{0.2}\text{Ga}_{0.8}\text{As/GaAs}$, $n\sim1\times10^{12}\text{cm}^{-2}$, $\mu\sim2,000\ \text{cm}^{2}/\text{Vs}$

Minkov et al., PRB 67, 205306 ('03)

$$\Delta \sigma_{\text{INT}}^{2D} = -K_{ee} \frac{e^2}{2\pi^2 \hbar} \ln \left( \frac{\hbar}{k_B T \tau} \right)$$

$$K_{ee} = \left[ 1 + 3 \left( 1 \frac{\ln(1 + F_0^\sigma)}{F_0^\sigma} \right) \right]$$

$$F_0^\sigma = -\frac{1}{2\pi} \frac{r_z}{\sqrt{2-r_z^2}} \ln \left( \frac{\sqrt{2} + \sqrt{2-r_z^2}}{\sqrt{2} - \sqrt{2-r_z^2}} \right), \quad r_z^2 < 2$$

Observation: INT corrections are suppressed well below the theoretical estimate when $\sigma$ approaches $e^2/h$. (Qualitatively, similar behavior is observed in high-$\mu$ Si MOSFETs).
Dephasing in disordered conductors

"Clean" conductors:
\[ \tau_{\phi}^{-1} \sim \frac{T^3}{\Theta_D^2} + \frac{T^2}{E_F} \]
- e-e term dominates at low \( T \)

\[ \text{e-ph e-e} \]

"Disordered" conductors: static disorder strongly enhances/modify the e-e inelastic processes (while the e-ph scattering rate can be even reduced, e.g., in the case of "vibrating" impurities).

In 1D and 2D, the main contribution to the dephasing rate comes from quasi-elastic collisions with a small energy transfer \( \Delta \varepsilon \approx \tau_{\phi}^{-1} \ll T \). These processes govern the phase relaxation at low temperatures.

\[ \frac{\hbar}{\tau_{\phi}} \propto \frac{T}{g(L_{\phi})} \]

\[ g(L_{\phi}) \equiv \frac{\hbar}{e^2 R(L_{\phi})} \propto L_{\phi}^{d-2} \]

\[ L_{\phi} \propto T^{-1/(4-d)} \]

\[ \tau_{\phi} \propto T^{-2/(4-d)} \propto \begin{cases} T^{-1} & 2D \\ T^{-2/3} & 1D \end{cases} \]
Interactions-induced Dephasing

Collisions with the small momentum transfer \( q \sim L_T^{-1} \) and energy transfer \( \Delta \varepsilon \sim T \) dominate, **the dephasing and energy relaxation rates are similar**:

\[
\tau_{\varphi}^{-1} \approx \tau_{ee}^{-1} = \frac{\sqrt{2}}{12 \pi^2 \hbar} \sqrt{T \hbar D}^{3/2}
\]

In phase relaxation, the collisions with the energy transfer \( \Delta \varepsilon \sim \tau_{\varphi}^{-1} \) dominate. These collisions are equivalent to the interaction of an electron with the fluctuating e.m. field produced by all other electrons (dephasing by Nyquist noise).

(Altshuler, Aronov, and Khmelnitskii ’82).

\[1D \text{ & } 2D\]

**the dephasing and energy relaxation rates are different**. In phase relaxation, the collisions with the energy transfer \( \Delta \varepsilon \sim \tau_{\varphi}^{-1} \) dominate. These collisions are equivalent to the interaction of an electron with the fluctuating e.m. field produced by all other electrons (dephasing by Nyquist noise).

(Altshuler, Aronov, and Khmelnitskii ’82).

\[
\frac{1}{\tau_{\varphi}} = \frac{T}{g} \ln g + \frac{\pi}{4} \frac{T^2}{E_F} \ln (E_F \tau), \text{ where } g = \frac{\hbar}{e^2 \sigma_{2D}}
\]

The first (diffusive) term becomes comparable to the second (ballistic) term when \( T \tau \sim 1 \)

\[
1D \quad \frac{1}{\tau_{\varphi}} = \left( \frac{e^2 \sqrt{D}}{\hbar \sigma_1} \frac{k_B T}{\hbar} \right)^{2/3}
\]
3D disordered metals

Thick disordered metal films, including metal glasses, and heavily doped semiconductors

- 1μm-thick Cu films $\rho=6\times10^{-5} \ \Omega \ \text{cm}$
  (Aronov, MG, Zhuravlev, ‘84)

- $\text{Cu}_{0.9}\text{Ge}_{0.1}$ $\rho=2.8\times10^{-5} \ \Omega \ \text{cm}$
  (Eschner et al., ‘84)

**solid curve** – dephasing due to e-ph collisions in disordered conductors
($D=10 \ \text{cm}^2/\text{s}$)

**dashed lines** – dephasing due to e-e collisions with small momentum transfer

$t_{ph}^{-1} = \frac{\sqrt{2}}{12\pi^2} \frac{\hbar v}{\hbar D} \left( \frac{k_B T}{\hbar D} \right)^{3/2}$
2D metal films

- Mg film, $R_\square = 22.3 \, \Omega$ (White et al., ‘84)
- Al film, $R_\square = 112 \, \Omega$ (MG et al., ‘83)
- Bi film, $R_\square = 630 \, \Omega$ (Komori et al., ‘83)
- Au film, $R_\square = 32.7 \, \Omega$ (Aronov et al., ‘84)
- ultra-thin Ag film, $R_\square = 1.5 \, k\Omega$
Dephasing in Si MOSFETs

The dephasing rate due to both singlet and triplet channels (2D):
Narozhny, Zala, Aleiner, '02

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

Solid lines – 15 triplet components (two degenerate valleys)
Dashed lines – 3 triplet components (single valley)

Despite strong interactions, still a Fermi-liquid system
1D wires

1D:

\[ \tau_\phi \propto T^{-2/3} \]

\[ \tau_\phi = \left( \frac{\hbar^2}{e^2 R_1 \sqrt{D k_B T}} \right)^{2/3} \]

Altshuler, Aronov, and Khmelnitskii, '82; Aleiner et al., '99

<table>
<thead>
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<th>Material</th>
<th>d, nm</th>
<th>W, nm</th>
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<th>R, ( \Omega )</th>
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<td>1.5</td>
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</table>
Validity of the Fermi-liquid approach

Fermi liquid approximation holds (single-particle excitations are well defined)

provided that

\[
T \frac{\tau_\varphi(T)}{\hbar} = g(L_\varphi) > 1
\]

On the “metallic” side of the WL-SL crossover \((L_\varphi << \xi)\) \(g(L_\varphi) << g(\xi) \sim 1\)

Both quasi-1D and 2D conductors behave as Fermi liquids

At the crossover \(g(L_\varphi) \sim 1\)

The upper limit on \(\tau_\varphi\):

\[
\tau_\varphi(T) < \frac{\xi^2}{D}
\]

\(\delta\)-doped GaAs wires \((W=50\text{nm}, R_\square = 1\ \text{k}\Omega)\)
Khavin, MG, Bogdanov, ’98
Puzzle of Low-T Saturation of $\tau_\phi(T)$

Saturation of $\tau_\phi(T)$ at low temperatures was observed in many (but not all!) experiments. A trivial cause – overheating by measuring current – has been ruled out.

Mohanty, Jariwala, and Webb ('97)

What causes the apparent low-T saturation of $\tau_\phi$:

- at least in some cases, the saturation can be attributed to the presence of paramagnetic impurities in a small concentration undetectable by analytical methods (Michigan + Saclay collaboration, ‘02-'07, Bauerle et al., ’05, etc.):

- dephasing by an external high-frequency electromagnetic noise. This effect has not received the deserved attention though it was proposed as an explanation of Webb’s results right after the publication of MJW paper [Khavin, MG, Bogdanov, Phys. Rev. Lett. 81, 1066 ('98)].
With an increase of the dephasing length, the dephasing rate might be affected by magnetic impurities even if their concentration is very low:

\[ L_\varphi \sim 10 \mu m \Rightarrow \text{volume } L_\varphi^2 d \text{ contains } \sim 3 \text{ impurities at the concentration } 1 \text{ ppm.} \]

Pierre et al. (’03)
Experimental Test of the NRG Theory for Dephasing by Magnetic Impurities

The theoretical expression for the $T$-dependence of the dephasing rate, calculated on the basis of the Numerical Renormalization Group (NRG) bridges the gap between the low-$T$ Fermi liquid theory and the high-$T$ Suhl-Nagaoka expansion.

Zarand et al., PRL 93, 107204 ('04)
Micklitz et al., PRL 96, 226601 ('06)

The "quadratically vanishing" dephasing rate appears only well below $T_K$.

C. Bauerle, F. Mallet, F. D. Mailly, G. Eska, and L. Saminadayar, PRL 95, 266805 ('05)
Experimental Test of the NRG Theory for Dephasing by Magnetic Impurities

Alzoubi and Birge, *PRL* 97, 266803 ('06)

\[ \tau^{-1}_\varphi = \tau^{-1}_{in} + \gamma_m \]

Mallet et al., *PRL* 97, 266804 ('06)
Dephasing by external noise?

Though controlling magnetic impurities at a level of a few ppm is a challenge, there were claims that at least in some samples, the observed saturation had nothing to do with magnetic impurities…

One of the suspects – dephasing by external high-frequency electromagnetic noise without overheating.

Altshuler, Aronov, and Khmelnitsky, SSC 39, 619 (‘81)

time-dependent $E$ induces dephasing.

The most efficient dephasing:

$\omega \approx \tau_{\varphi}^{-1}$

(typically, $\tau_{\varphi} \sim 1$ ns, thus $f_{MW}$ in the GHz range)

For an optimal $\omega$, the MW-induced dephasing rate $\tau_{MW}^{-1} \sim \tau_{\varphi 0}^{-1}$ at

$eE_{MW} \sqrt{D\tau_{\varphi}} \sim \frac{\hbar}{\tau_{\varphi}}$
Experimental Challenge: MW Dephasing-w/o-Overheating

To separate $E(t)$–induced dephasing from trivial heating, the electron cooling should be optimized.

$\omega P_{MW}$

$\tau_{MW}^{-1}$ becomes comparable with $\tau_{\phi0}^{-1}$.

Electron heating becomes significant

MW-induced dephasing rate $\tau_{MW}^{-1}$ becomes comparable with $\tau_{\phi0}^{-1}$.

$$eE_{MW} \sqrt{D \tau_{\phi}} \sim \frac{\hbar}{\tau_{\phi}}$$

$P_{MW} \propto \tau_{\phi0}^{-3}$

For observation of the “MW dephasing-without-overheating”:

- **The lower $T$, the better**: at $T > 1K$, dephasing in metal films is mostly due to the el.-ph. scattering ($\tau_{\phi} \sim T^{-3}$) and $P_{MW} \sim T^9$ grows with $T$ much faster than the thermal conductivity ($\sim T^5$).

- **1D is better than 2D**

\[ eE_{MW} \sqrt{D \tau_{\phi}} \sim \frac{\hbar}{\tau_{\phi}} \]

$P_{MW} \propto \tau_{\phi0}^{-3}$
Prior Experiments on MW-induced Dephasing

Wang and Lindelof, 1987 – Mg films
Vitkalov et al., 1988 – Si MOSFETs

In both experiments, the range of $P_{\text{MW}}$ for “dephasing-without-overheating” was very narrow (if any).

“We find that up to 26 GHz this external environment does not cause decoherence without a concomitant increase in the energy relaxation rate”

Webb et al., in “Quantum Coherence and Decoherence” (Elsevier 1999)
Optimization of Sample Geometry

1D wires, ultra-low T

\[ P_{MW}^{\varphi} \approx \frac{T \Delta T}{R} \]

the MW power that results in \( \tau_{MW} \sim \tau_{\varphi} \) (at optimal \( f_{MW} \))

\[ P_{es} \approx \left( \frac{2\pi k_B}{e} \right)^2 \frac{T \Delta T}{R} \]

cooling due to outdiffusion of hot electrons

\[ \frac{P_{es}}{P_{MW}^{\varphi}} \approx \left( \frac{h/e^2}{R} \right)^2 \frac{\Delta T}{T} \]

\( R \) – the total resistance of a wire

Short wires: “dephasing – without – overheating”

Long wires: “dephasing – with – overheating”

ideal samples for probing the intrinsic dephasing mechanisms
Sample Design

**Short wires:**
- efficient outdiffusion cooling
- poor UCF averaging, susceptible to the external noise

**Long wires:**
- better UCF averaging, less susceptible to external noise
- only e-ph cooling, very inefficient at $T < 1$K

**Solution:** long wires with periodically spaced cooling fins.

Distance between cooling fins $d = 30 \, \mu m$, the total length – $1200 \, \mu m$

One can neglect the effect of cooling fins on $\Delta \sigma_{WL}$ if $d > 10 \, L_\phi(T)$.

Effect of Microwave Radiation on the WL MR

MW dephasing + overheating

$T = 0.2 \text{K}$
$f = 1 \text{GHz}$

MW dephasing without overheating

Overheating at $P_{\text{MW}} = 170 \text{pW}$

Wei Jian, Pereverzev, MG, PRL. 96, 086801 (2006)
To compare our experiment with the AAK theory:

- $\tau_{\phi}(T)$, $\tau_{\phi}(T,P_{MW})$ - from the WL magnetoresistance at $P_{MW}=0$ and at $P_{MW}\neq 0$

- $E_{MW}$ (or $P_{MW}$ dissipated in the sample) – by comparing the DC and MW heating

- $T_e$ – from the interaction corrections in strong magnetic fields ($L_H<<L_{\phi}$)

\[ eE_{MW} \sqrt{D\tau_{\phi}} \sim \frac{\hbar}{\tau_{\phi}} \]
In strong magnetic fields \((L_H << L_\phi)\), \(R(T)\) is determined solely by the interaction corrections \(\Delta\sigma_{EEI}(T_e)\).

The measurements of \(R\) in strong \(B\) have been used for the direct measurement of \(T_e\) and calibration of the MW power dissipated in the sample, \(P_{MW}\).
Assumption:  
$dc$ current heating $\equiv$ MW heating  
($\omega \ll 1/\tau$, $\tau$ - the momentum relaxation time)

- the MW power \textit{dissipated} in a wire

At $T = 0.1K$, $P_{\text{MW}} < 1$ pW is sufficient to overheat the electrons in a 1.2 mm-long nanowire with cooling fins. For a typical 1D wire ($L \leq 100 \, \mu m$), this power is in the \textit{fW} range.
\[ \tau_{\phi}(T) \text{ at } P_{MW} = 0 \]

\[ \Delta \sigma_1 = \frac{e^2 L_\phi}{\pi \hbar} \frac{Ai\left(\tau_{\phi} / \tau_H\right)}{[Ai\left(\tau_{\phi} / \tau_H\right)]^2} \]

- dephasing by magnetic field

\[ \tau_H = \frac{12 L_H^4}{D \omega^2} \]

\[ \tau_{\phi} \text{ "saturates" below } T \sim 0.1 \text{ K} \]

\[ \tau_{\phi}(T) \text{ depends on the coupling of a sample to its "environment"} \]
The total dephasing rate:

\[ \tau_{\phi}^{-1}(\omega, P_{MW}) = \tau_{\phi 0}(P_{MW} = 0) + \tau_{MW}^{-1}(\omega, P_{MW}) \]

\( \tau_{MW}^{-1} \) – the MW-induced dephasing rate

\[ \Delta \sigma_{WL}(B = 0, P_{MW}) \]

\[ \alpha \equiv \frac{2e^2 D E^2_{MW}}{\hbar^2 \omega^3} \]

- the normalized MW power

\( f = 1 \text{ GHz} \quad T = 0.5 \text{ K} \)

Wei Jian, Pereverzev, MG, PRL 96, 086801 (’06)

All experimental results are in good agreement with the AAK theory

(no fitting parameters!)
MW-induced Dephasing (cont.)

\[ f = \frac{1}{\tau_\phi(0.2K)} \]

the most efficient
“MW dephasing-without-overheating”

\[ \Delta R(B = 0) = +5\Omega \]
\[ \Delta R(B = 3kG) = -5\Omega \]
Low-$T$ saturation of $\tau_\varphi$

the upper bound on the external noise power $\sim 3 \cdot 10^{-14}$ W

$\tau_\varphi^{-1}(T) = \tau_\varphi^{-1}(T) + (3.3 \text{ ns})^{-1}$

$P_{\text{MW}} = 3 \cdot 10^{-14}$ W leads to $\tau_{\text{MW}} \sim \tau_\varphi(50 \text{ mK}) = 3.7$ ns

Conclusion: in our experiment, the saturation of $\tau_\varphi(T)$ may be caused by the external electromagnetic noise
Summary

Interaction effects in disordered conductors produce quantum corrections to the conductivity, DoS, and other electron parameters.

Dephasing in 1D and 2D conductors at low $T$ is governed by interaction effects.

The observed saturation of $\tau_\phi(T)$ at $T < 0.1K$ - most likely due to scattering by paramagnetic impurities and dephasing by high-frequency electromagnetic noise.
Lecture 3: Quantum Corrections to the Conductivity of High-Mobility Si MOSFETs

Intro: quantum corrections in Si MOSFETs (the most ubiquitous 2D structure) $\Rightarrow$ 25-year-old mystery 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 $\Delta\sigma(T,B)$

The crossover from “metallic” to “insulating” conductivity: role of inhomogeneity?