Non-Equilibrium FES in Mesoscopic Devices

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Non-Equilibrium Effects (T=0)

Impurity state change

\[
\begin{pmatrix}
S^g
\end{pmatrix} \rightarrow \begin{pmatrix}
s^e
\end{pmatrix} = \begin{pmatrix}
r & -te^{-i\phi(s)} \\
te^{i\phi(s)} & r^*
\end{pmatrix}
\]

\[\phi(s) = V_{sd}s\]  gauge transformation

BM+NdA, 2005, PRB

FES effects:

i) Exponent, Friedel sum rule

\[\alpha = (\delta_S/\pi - 1)^2 - 1\]

ii) Fumi shift

\[\epsilon' = \epsilon + \int^{E_F} dE \frac{\delta(E)}{\pi}\]

iii) Non-eqm broadening and shifting

BM+NdA, 2005, PRB

\[R = 0.7\]

\[\sim 1/\omega^{1+\alpha}\]

\[
\omega/V
\]

\[\epsilon'/0.5\]

\[F(\omega)\]
RTS in a dirty MOSFET I

2 Regimes:

i) UCF weak localization

ii) Quantum Hall regime

\[ T = 100 \text{mK}, \]
Channel 0.6-0.8 µm
\[ l \sim 300 \text{Å} \]

Cobden, Muzyk. 1995
Detailed Balance:
\[ \frac{\gamma_2}{\gamma_1} = \exp \frac{\epsilon}{kT} \]

\[
\begin{align*}
\sigma_{12} & \approx 3.6 \mu S \approx 0.1 \frac{e^2}{h} \\
\sigma_1 & \approx 10 \mu S \\
\frac{\sigma_{12}}{\sigma_1} & \approx \left( \frac{A_\phi}{A} \right)^{1/2} \approx 0.45 
\end{align*}
\]

\[ V_{sd}^{ac} = 20 \mu V, \ T = 100 \text{mK}, \ B = 0.06 \text{T}, \ 10.35 \text{T} \]
γ_2/γ_1 = \exp \epsilon/kT

σ_{12} \approx 3.6 \mu S \approx 0.1 \frac{e^2}{h}

σ_1 \approx 10 \mu S

\frac{σ_{12}}{σ_1} \approx \left( \frac{A_φ}{A} \right)^{1/2} \approx 0.45

V_{sd}^{ac} = 20 \mu V, \ T = 100 \text{mK}, \ B = 0.06 \text{T}, \ 10.35 \text{T}
Two Regimes

Weak localization regime:
1 impurity $\rightarrow$ UCF, Altshuler, Spivak ’85

$$S^e = \begin{pmatrix} r & -te^{-i\phi(s)} \\ te^{i\phi(s)} & r^* \end{pmatrix}, r = |r|e^{2i\delta}, t \ll 1$$

High field regime, saddle points, ($\ell_0 < \ell$)

$$r = |r|e^{2i\delta}, |t| < 1$$

Expect $|t|$ to relate to $\sigma_{12}$
Non-equilibrium FES

Core Hole:

\[
\epsilon' = \epsilon + \int_{0}^{E_F + V_{sd}} dE \frac{\delta_l(E)}{\pi} = \epsilon + \Delta(V_{sd})
\]

Fumi Shift:

\[
\Delta_1(V) = \Delta_2(V)^* = \left( \frac{\delta - i \ln |r|}{2\pi} \right) V
\]

Shift \( V\delta/2\pi \) and dephasing \( V \ln |r|/2\pi \)

Line Shape: Fermi Edge Singularity

\[
G_j(t_f) = \langle i | U_0^{-1}(t_f) U(t_f) | i \rangle
\]

\[
\gamma_j(\epsilon, V, \Delta_j) \propto \int dt_f \ G_j(t_f) e^{i\epsilon t_f}
\]

Open Line:
Line-Shape

Equilibrium (no bias voltage):

\[ \gamma_{1,2} \propto CT^{\beta^{-1}} \exp \left[ \pm \frac{\epsilon - \Delta_0}{kT} \right] \frac{\Gamma[\beta/2 + i\epsilon/2\pi kT]^2}{\Gamma[\beta]} \]

\[ \beta = \left( \frac{\delta_1}{\pi} \right)^2 + \left( \frac{\delta_2}{\pi} \right)^2 \quad \text{(diagonalize S)} \]

(Yuval & Anderson '70, Matveev & Larkin '92)

Non-Equilibrium:

\[ \beta' = \left( \frac{\log (S_{11}^e)}{2\pi i} \right)^2 + \left( \frac{\log (1/S_{22}^e)^*}{2\pi i} \right)^2 \quad \text{for } \epsilon < V_{sd} \]

\[ = \beta \quad \text{otherwise} \]

Broadening + Polarity effects
Asymmetries in NFES

$V_{sd}$

$\overline{\epsilon}$

$-V_{sd}$

$\overline{\epsilon}$
Transition Rates - Low Field

Low frequency ac signal: (5kHz)

With \(|r| \leq 0.99, V = 20\mu V,\)

\[-\frac{V \ln |r|}{2\pi} \ll 10\mu s\]

Average transition rates:

\[\gamma_{ac}^j = \left[ \frac{2}{\gamma_j^{-1}(\epsilon, V) + \gamma_j^{-1}(\epsilon, -V)} \right]^{-1}\]

Fumi measures phase shift
**Transition Rates**

\[ B = 0.06T \]

Sensitivity to gate voltage, \( x \), fitted to equilibrium

Access scattering parameters

\[ r = 0.9, \quad \delta = 0.22 \]

\[ V_{sd}^{ac} = 20\mu V \]
\[ T = 100\mu K \]

\[ V_{g} - V_{g0} (mV) \]

\[ \ln(\gamma_1/\gamma_2) \]

\[ \gamma_{1,2} (s^{-1}) \]

\[ \delta = 0.22 \]

\[ V_{ac} = 20\mu V \]
\[ T = 100\mu K \]

\[ B = 10.5T \]

Dephasing: \( T_{eff} > T \)

Asymmetry effects

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Conclusions

Non-eqm effects in RTS:

Observation of Altshuler, Spivak prediction

Access scattering parameters, via Fumi shift

NFES effects not just broadening