For a detailed write-up
See arXiv:condmat/0704.1623
Unified viewpoint: Materials

Quantum Transport Far from Equilibrium

Nanowires

Nanotubes / Graphene

Molecules

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Unified viewpoint: Ballistic to Diffusive

Quantum transport far from equilibrium

\[ \Gamma = i \left[ \Sigma - \Sigma^+ \right] \]

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Need two groups of states: “Red” & “Blue”
Anti-parallel (AP) Spin Valve

Source Channel Drain

Perfect AP

Imperfect AP

Current

Voltage

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Perfect AP with Spin-flip Impurities

Insulating substrate

Spin flip

Current

with spin-flip

w/o spin-flip

Voltage

Source

Drain

Source

Drain
Perfect AP with Spin-polarized gate

Insulating substrate

Source  Channel  Drain

Spin flip

Current

Voltage

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nanoHUB.org
online simulations and more

Perfect AP with Spin-polarized gate
Current at zero voltage !!!

Normalized current --->

Voltage --->
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Device as a "demon"

Normalized current ---\(\rightarrow\)---

Voltage ---\(\rightarrow\)---

No further current

Source Channel Drain

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Where did the energy come from?

Answer: From the contacts
**Second law?**

\[ S = 0 \]

\[ S = k \ln W \]

\[ S = Nk \ln 2 \]

Energy up to \( T \Delta S \) may be extracted.
Resetting the demon takes energy

No energy needed

Need > N kT to “Erase”
Flipping a spin costs energy.

Higher energy vs. normalized energy for different angles of magnetization from the plane of magnet.
The cool demon as a heat engine

Cooled

\[ T_D \]

Source

Channel

Drain

300K

Carnot’s principle

\[ \frac{Q_1}{kT} < \frac{Q_2}{kT_D} \]

Q₁: heat from contacts
Q₂: heat to demon
Q₁ - Q₂: useful work

Current --->

Voltage --->
Carnot's principle

\[ \frac{Q_1}{kT} > \frac{Q_2}{kT_D} \]
Switching a bistable demon

Energy needed to switch from one minimum to another?

Channel

Source

Drain

Transistor

Insulator

\( V_G \)

\( V \)

\( I \)

\[ P = 10^4 \text{ electrons} \times (40 \text{ kT}) \times 10^9 \text{ Hz} = 1 \mu\text{W} / \text{switch} \]

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Transport + Dynamics of Magnetization

- Isolated spins: Bloch equation
- Weakly interacting spins: Many-spin problem
- Nanomagnets: LLG equation

\[ \mu_1 \quad \mu_2 \]

\[ \Sigma_1 \quad \Sigma_2 \]

\[ \Sigma_s(\vec{M}) \]

\[ H \]

Isolated spins: Bloch equation

Weakly interacting spins: Many-spin problem

Nanomagnets: LLG equation
Pentalayer spin-torque device

Salahuddin and Datta (APL, 89, 153504, 2006)

Dynamic demons

\[
\sum_s(\vec{M})
\]

\[
\Sigma_1 \quad H+U \quad \Sigma_2
\]

Current

Voltage

\[
\mu_1 \quad \mu_2
\]

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Quantum Transport far from Equilibrium

Materials

Transport Regimes

Macroscopic dimensions

Atomic dimensions

Reference:
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www.nanohub.org/courses/cqt