Single Electron Transistor

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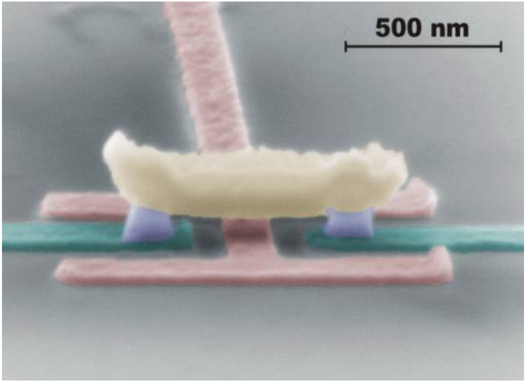
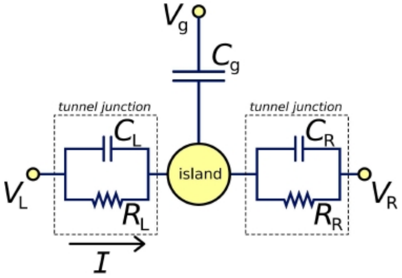
history

- 1985 conceptional proposal by Averin and Likharev
- 1987 realisation by Fulton und Dolan at Bell Labs



picture: Bell Labs, 1998

schematical view



picture: Norbert Nemec, 2005

condition for charge discretization

Which condition has to be fullfiled to observe discretization of charge?

- $E_c = \frac{e^2}{2C} \overset{!}{\gg} k_B T$

  $\rightarrow$ small size $\rightarrow$ small capacities $\rightarrow$ high energy

- example: sphere $C = 4\pi\epsilon_0 R$
  - $R = \mu m \ \rightarrow \ T \cong 4$ K
  - $R = nm \ \rightarrow \ T \cong 300$ K

calculation of charging energy:

- assumption: $V_l = -V_r$

  $$\Rightarrow \; Q_0 = -eN_0 = C_l V_l + C_r V_r + C_g V_g = C_g V_g$$

- $\mu_I(N) = \frac{e^2(N-N_0)^2}{2C_{tot}}$ with $C_{tot} = C_l + C_r + C_g$

charging energy

- calculation:

$$\mu_I(N+1) - \mu_I(N) = \frac{(e(N+1)+C_g V_g)^2}{2C_{tot}} - \frac{(eN+C_g V_g)^2}{2C_{tot}} =$$

$$= \frac{e^2 N}{C_{tot}} + \frac{e^2}{2C_{tot}} + \frac{eC_g V_g}{C_{tot}}$$

Energy Considerations (T=0): Tunneling from Source to Island (and vice versa)

Tunneling from Source to Island:

- $E_i = \sum_k^{\mu_s} \epsilon_k + \sum_k^{\mu_d} \epsilon_k + \mu_I(N)$
- $E_f = \sum_k^{\mu_s} \epsilon_k - \epsilon_{\tilde{k}} + \sum_k^{\mu_d} \epsilon_k + \mu_I(N+1)$
- Conservation of Energy:

$$E_i \overset{!}{=} E_f \quad \Rightarrow \quad \epsilon_{\tilde{k}} = \mu_I(N+1) - \mu_I(N) := \Delta\mu_I(N+1)$$

- tunneling:

$$\epsilon_{\tilde{k}} = \Delta\mu_I(N+1) \leqq \mu_s = \frac{eV}{2}$$

Energy Considerations (T=0): Tunneling from Source to Island (and vice versa)

Tunneling from Island to Source:

- $E_i = \sum_k^{\mu_s} \epsilon_k + \sum_k^{\mu_d} \epsilon_k + \mu_I(N)$
- $E_f = \sum_k^{\mu_s} \epsilon_k + \epsilon_{\tilde{k}} + \sum_k^{\mu_d} \epsilon_k + \mu_I(N-1)$
- Conservation of Energy:
$$E_i \stackrel{!}{=} E_f \quad \Rightarrow \quad \epsilon_{\tilde{k}} = \mu_I(N) - \mu_I(N-1) := \Delta\mu_I(N)$$
- no tunneling:
$$\epsilon_{\tilde{k}} = \Delta\mu_I(N) < \mu_s = \frac{eV}{2}$$

Energy Considerations (T=0): Tunneling from Source to Island (and vice versa)

Coulomb Blockade:

- Voltage range in which Coulomb blockade effects (N is constant) can be observed:

$$\Delta\mu_I(N) < \frac{eV}{2} < \Delta\mu_I(N+1)$$

- For the voltage V one obtains:

$$\Delta\mu_I(N) \cdot \frac{2}{e} < V < \Delta\mu_I(N+1) \cdot \frac{2}{e}$$

- and respectively:

$$\frac{2C_g}{C_{tot}} V_g + \frac{2Ne}{C_{tot}} - \frac{e}{C_{tot}} < V < \frac{2C_g}{C_{tot}} V_g + \frac{2Ne}{C_{tot}} + \frac{e}{C_{tot}}$$

Energy Considerations (T=0): Tunneling from Island to Drain (and vice versa)

Tunneling from Island to Drain:

- $E_i = \sum_k^{\mu_s} \epsilon_k + \sum_k^{\mu_d} \epsilon_k + \mu_I(N)$
- $E_f = \sum_k^{\mu_s} \epsilon_k + \sum_k^{\mu_d} \epsilon_k + \epsilon_{\tilde{k}} + \mu_I(N-1)$
- Conservation of Energy:

$$E_i \overset{!}{=} E_f \quad \Rightarrow \quad \epsilon_{\tilde{k}} = \mu_I(N) - \mu_I(N-1) := \Delta\mu_I(N)$$

- no tunneling:

$$\epsilon_{\tilde{k}} = \Delta\mu_I(N+1) < \mu_d = -\frac{eV}{2}$$

Energy Considerations (T=0): Tunneling from Island to Drain (and vice versa)

Tunneling from Drain to Island:

- $E_i = \sum_k^{\mu_s} \epsilon_k + \sum_k^{\mu_d} \epsilon_k + \mu_I(N)$
- $E_f = \sum_k^{\mu_s} \epsilon_k + \sum_k^{\mu_d} \epsilon_k - \epsilon_{\tilde{k}} + \mu_I(N+1)$
- Conservation of Energy:

$$E_i \stackrel{!}{=} E_f \quad \Rightarrow \quad \epsilon_{\tilde{k}} = \mu_I(N+1) - \mu_I(N) := \Delta\mu_I(N+1)$$

- tunneling:

$$\epsilon_{\tilde{k}} = \Delta\mu_I(N+1) \leqq \mu_d = -\frac{eV}{2}$$

Energy Considerations (T=0): Tunneling from Island to Drain (and vice versa)

Coulomb Blockade:

- Voltage range in which Coulomb blockade effects (N is constant) can be observed:

$$\Delta\mu_I(N) < -\frac{eV}{2} < \Delta\mu_I(N+1)$$

- For the voltage V one obtains:

$$-\Delta\mu_I(N+1)\cdot\frac{2}{e} < V < -\Delta\mu_I(N)\cdot\frac{2}{e}$$

- and respectively:

$$-\frac{2C_g}{C_{tot}}V_g - \frac{2Ne}{C_{tot}} - \frac{e}{C_{tot}} < V < -\frac{2C_g}{C_{tot}}V_g - \frac{2Ne}{C_{tot}} + \frac{e}{C_{tot}}$$

Energy Considerations (T=0): Overview

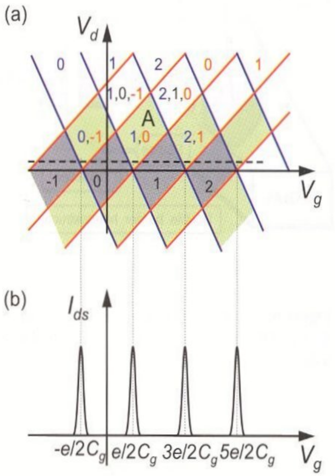
Conditions to observe Coulomb blockade effects::

- From Source/Island:

$$\frac{2C_g}{C_{tot}}V_g + \frac{2Ne}{C_{tot}} - \frac{e}{C_{tot}} < V < \frac{2C_g}{C_{tot}}V_g + \frac{2Ne}{C_{tot}} + \frac{e}{C_{tot}}$$

- From Island/Drain:

$$-\frac{2C_g}{C_{tot}}V_g - \frac{2Ne}{C_{tot}} - \frac{e}{C_{tot}} < V < -\frac{2C_g}{C_{tot}}V_g - \frac{2Ne}{C_{tot}} + \frac{e}{C_{tot}}$$



picture: Applied Physics, 1999

Numerical results

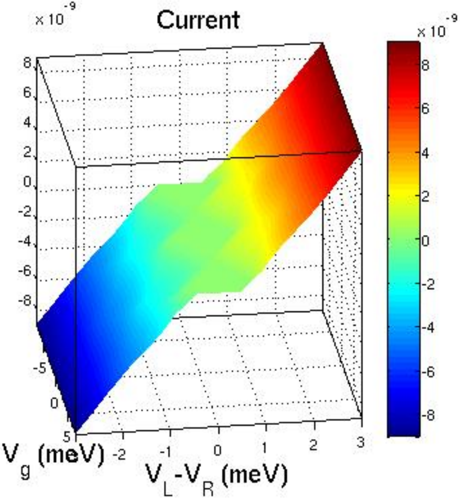
What we did:

- SET-routine with matlab
- playing with parameters
- try to explain results by theory

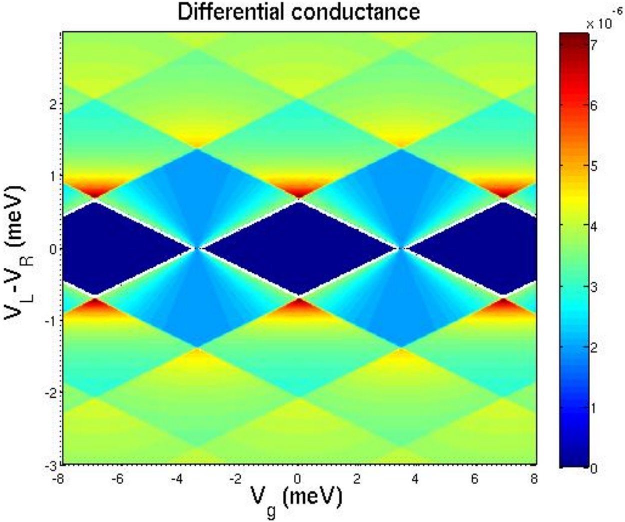
1. standard conditions

$$R_l = R_r$$
$$C_l = C_r$$
$$C_g \approx 1/4 \cdot C_{l/r}$$
$$T = 20mK$$

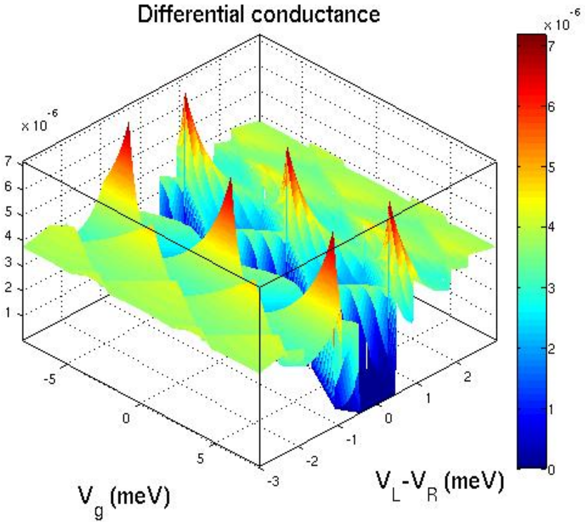
Resulting current



Differential conductance

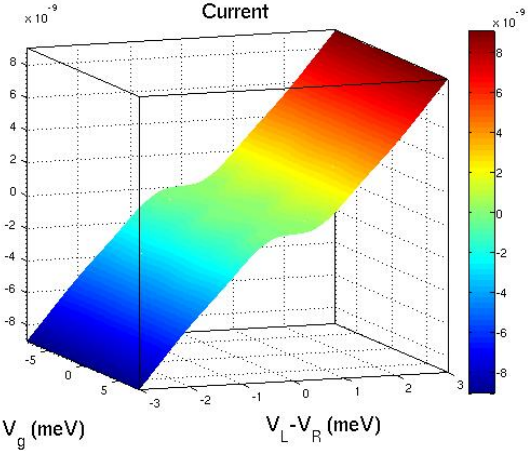


Differential conductance

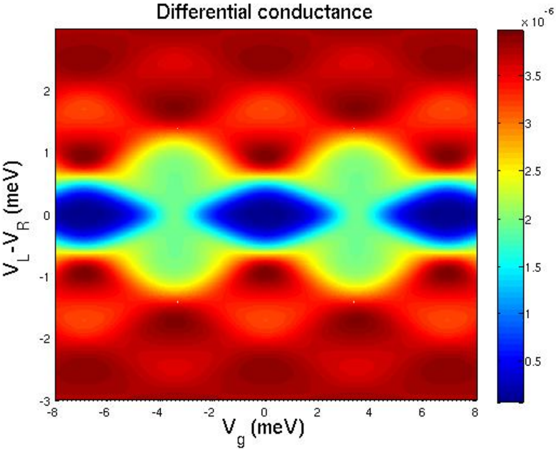


2. standard conditions, consideration of temperature dependency

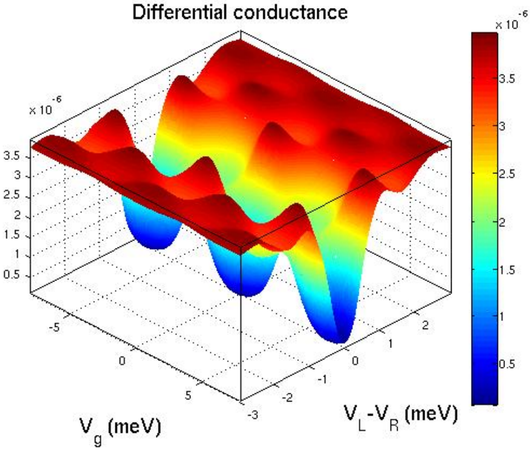
Resulting current at $T = 0.6K$



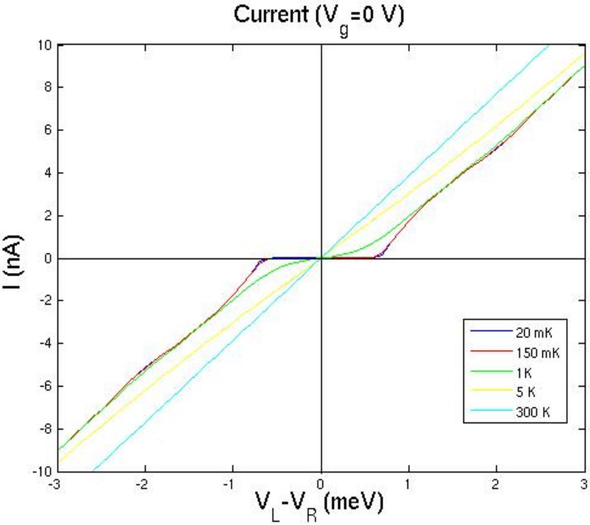
Differential conductance at $T = 0.6K$



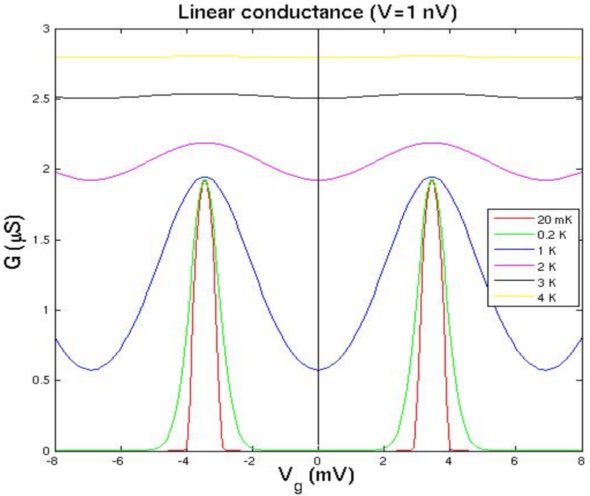
Differential conductance at $T = 0.6K$



Current vs. bias at different temperatures



Coulomb oscillations



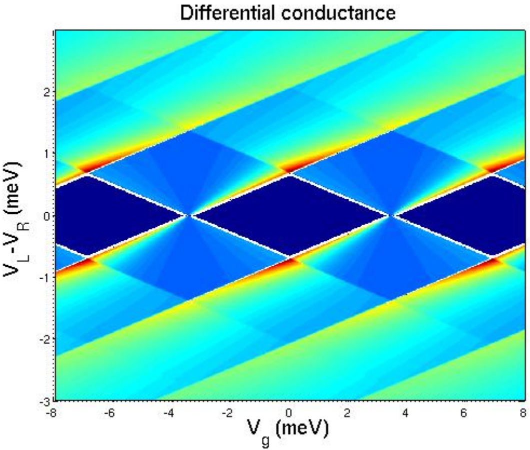
3. different proportions of resistances

$$C_l = C_r$$

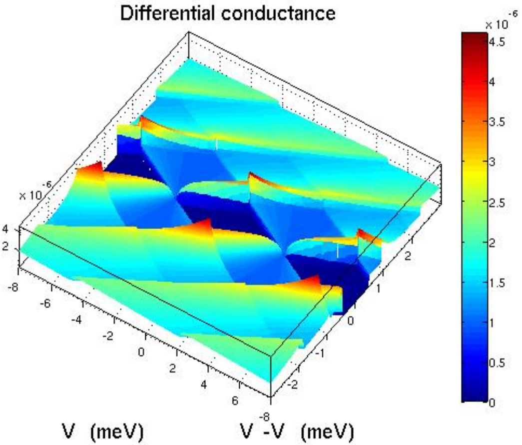
$$C_g \approx 1/4 \cdot C_{l/r}$$

$$T = 20mK$$

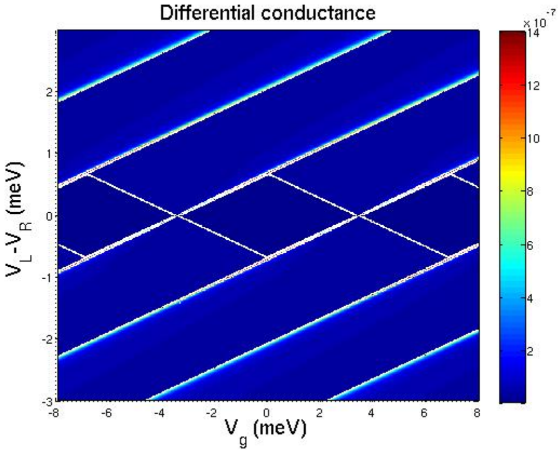
Differential conductance at $R_l = 3 \cdot R_r$



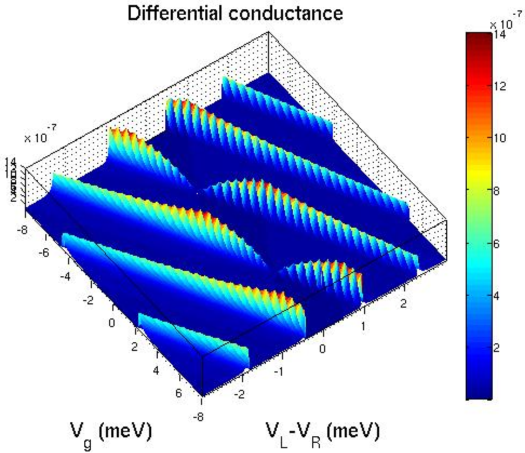
Differential conductance at $R_l = 3 \cdot R_r$



Differential conductance at $R_l = 1000 \cdot R_r$



Differential conductance at $R_l = 1000 \cdot R_r$

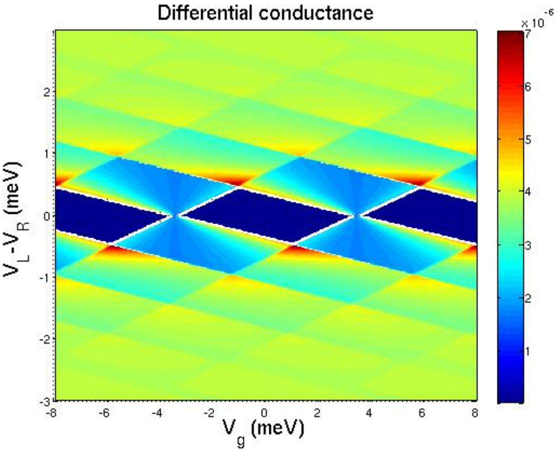


4. different proportions of capacities

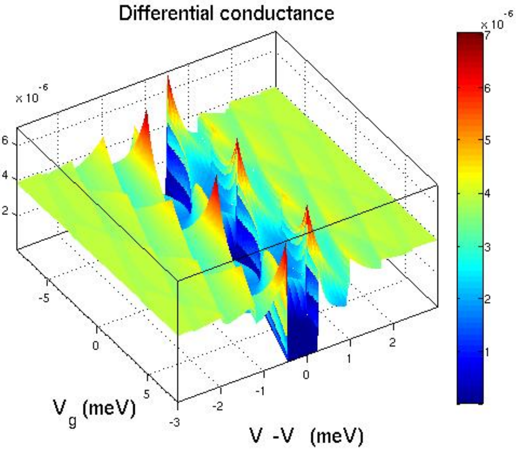
$$R_l = R_r$$

$$T = 20mK$$

Differential conductance at $C_l = 2 \cdot C_r$



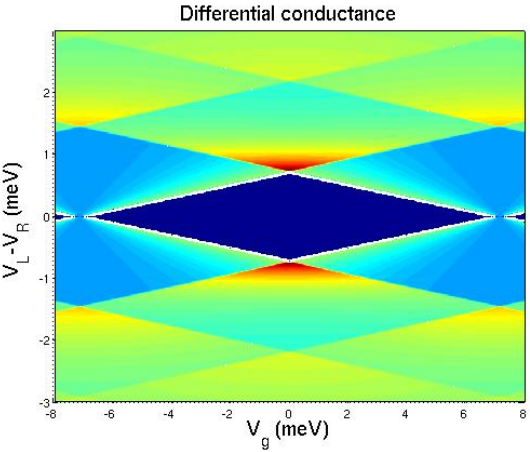
Differential conductance at $C_l = 2 \cdot C_r$



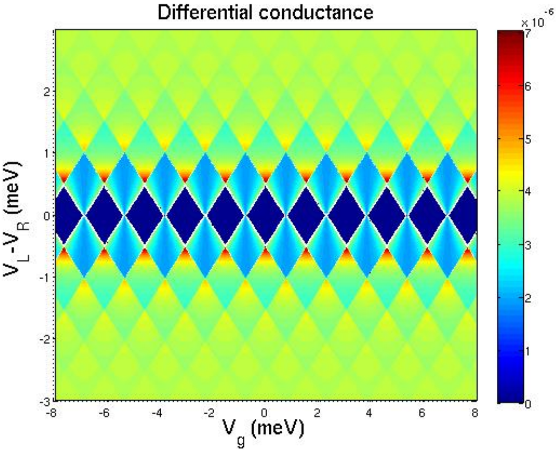
5. Altering the gate-capacity

$$C_l = C_r$$
$$R_l = R_r$$
$$T = 20mK$$

Differential conductance at $C_g = 1/2 \cdot C_{g(standard)}$



Differential conductance at $C_g \gg C_{g(standard)}$



What's the gain of this worksheet?

- short insight to numerical physics
- first step for further studies in quantum electronics
- interesting results despite a low level of theory