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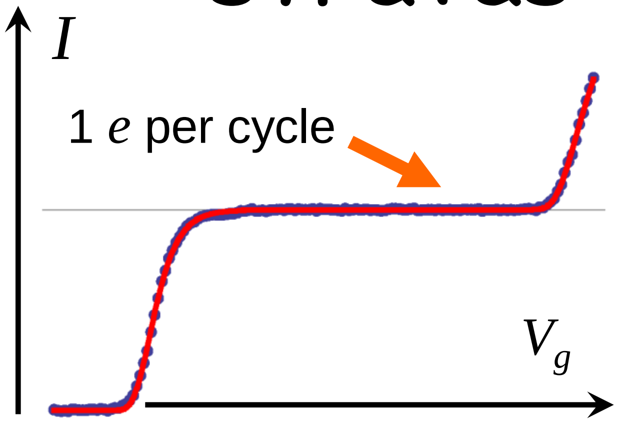
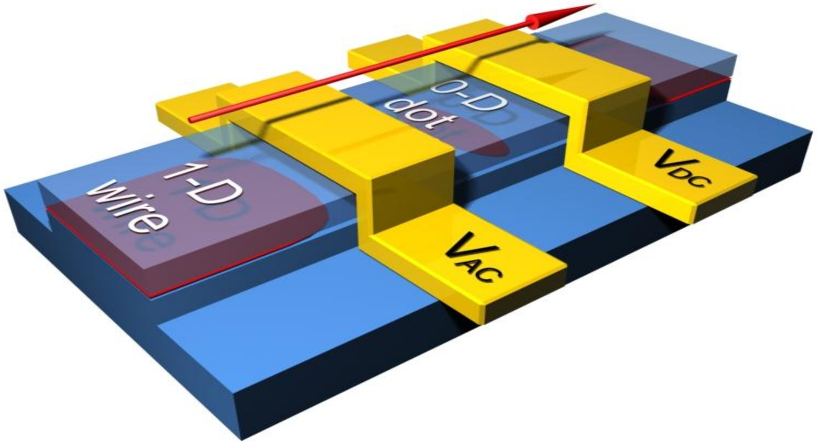
ESF
EIROPAS SOCIĀLAIS FONDS
IEGULDĪJUMS TAVĀ NĀKOTNĒ

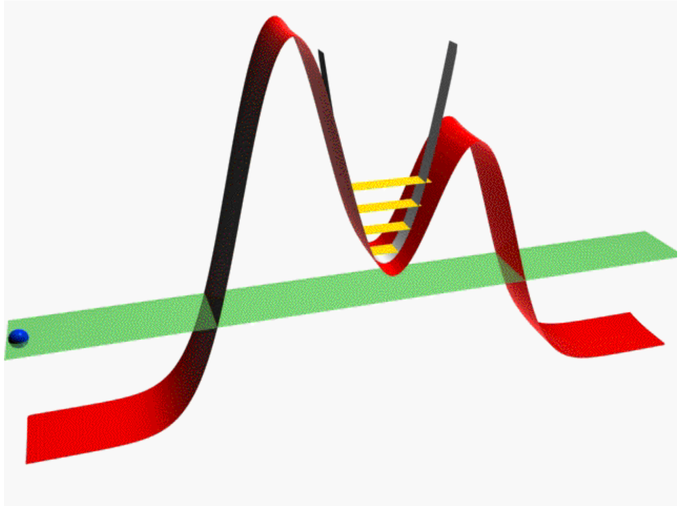
Progress nanoelektroniskā strāvas etalona modelēšanā

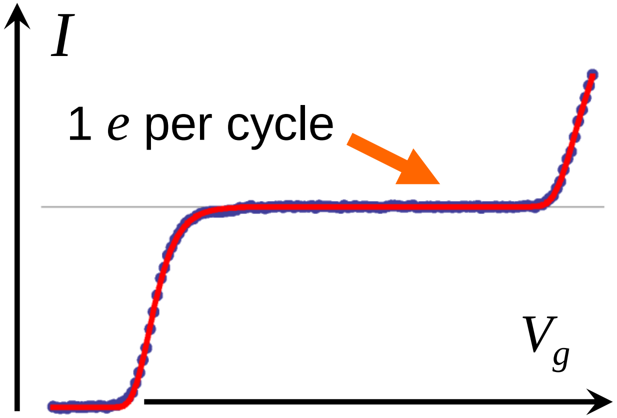


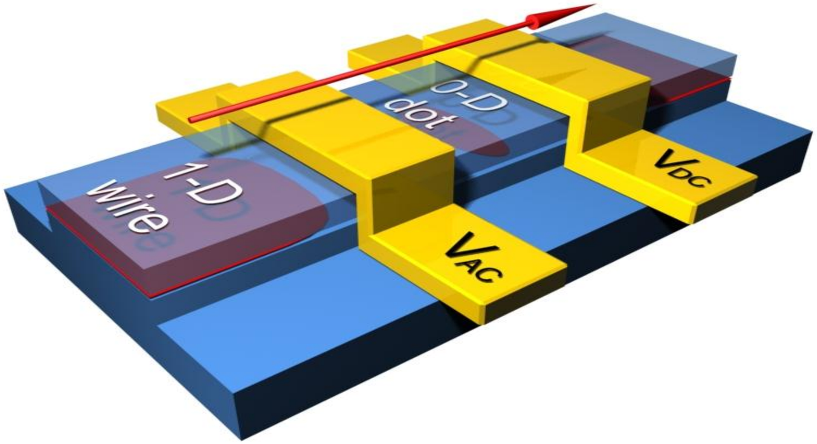


ESF projekts Nr. 2009/0216/1DP/1.1.1.2.0/09/APIA/VIAA/044
„*Datorzinātnes pielietojumi un tās saiknes ar kvantu fiziku*”

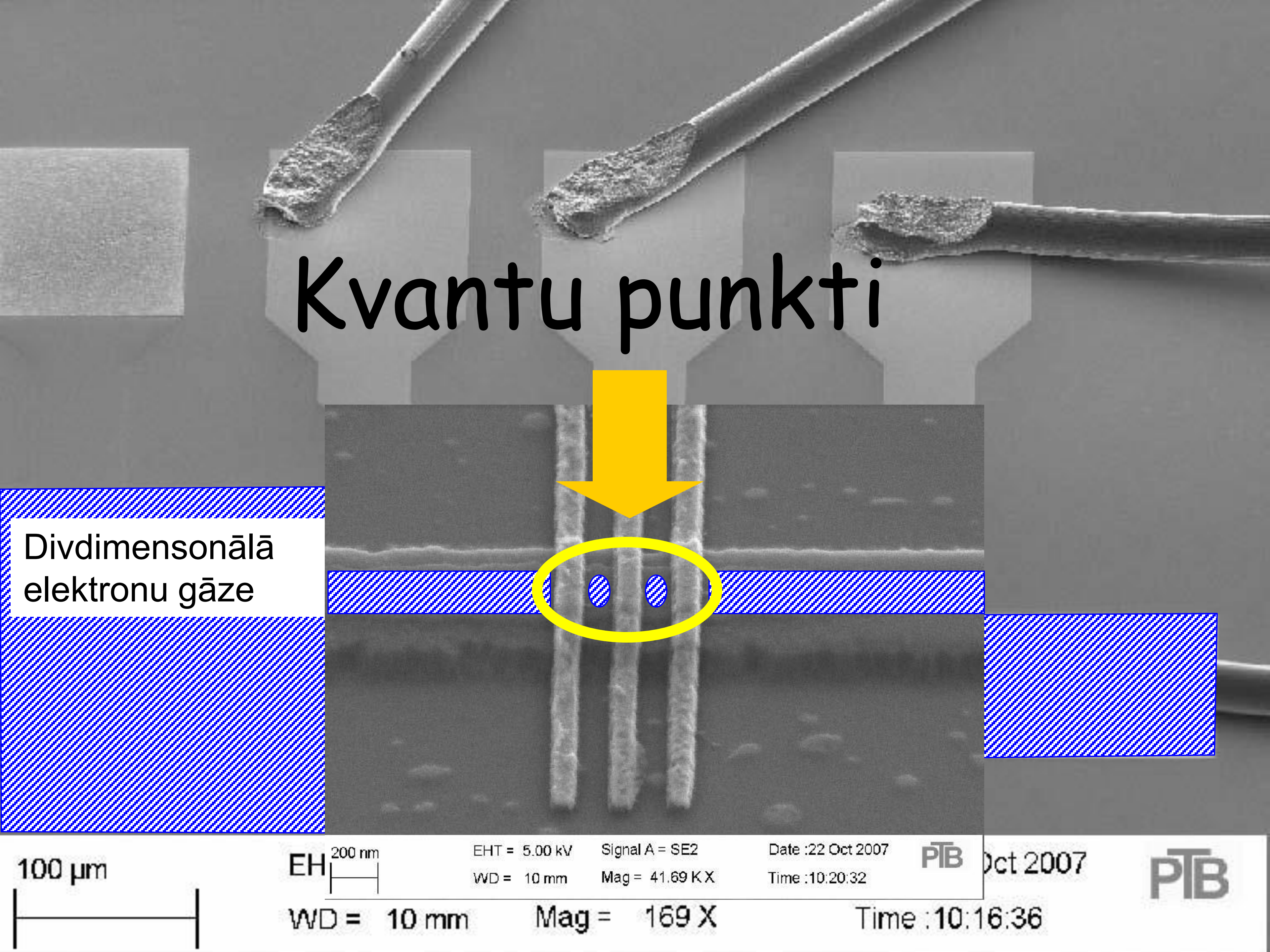
$$\boxed{I = e\,f}$$







Kvantu punkti

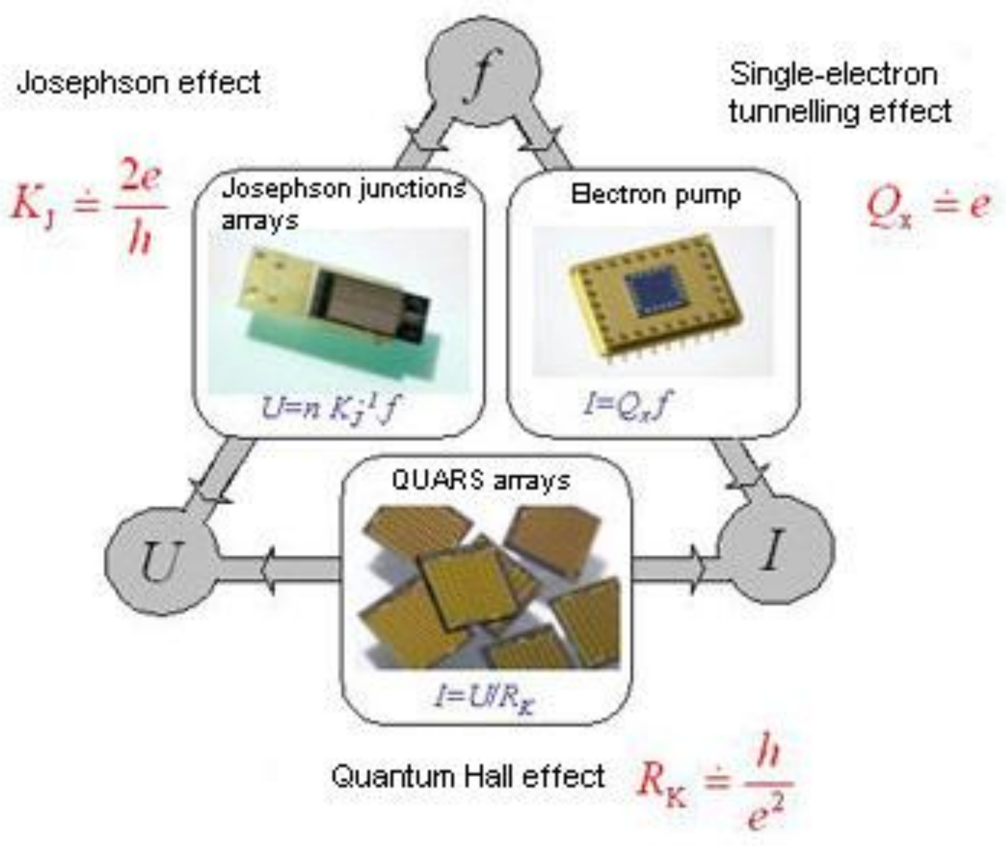


Divdimensonālā elektronu gāze

Kāpēc mēs to darām?

- Metroloģiskais mērķis
  - Ampērs tiks pārdefinēs 2012. gadā
  - Elektrisko vienību kvantu etaloni

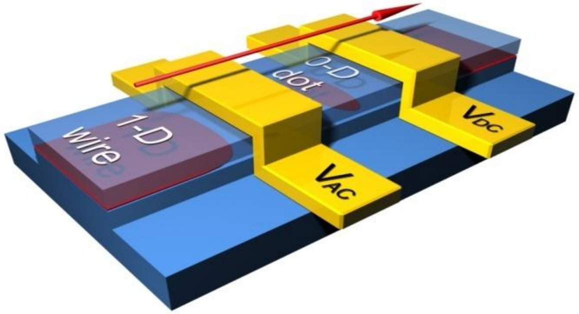
$$\boxed{I = n\,e\,f}$$



- Fu a
  -
  - toru izveidei

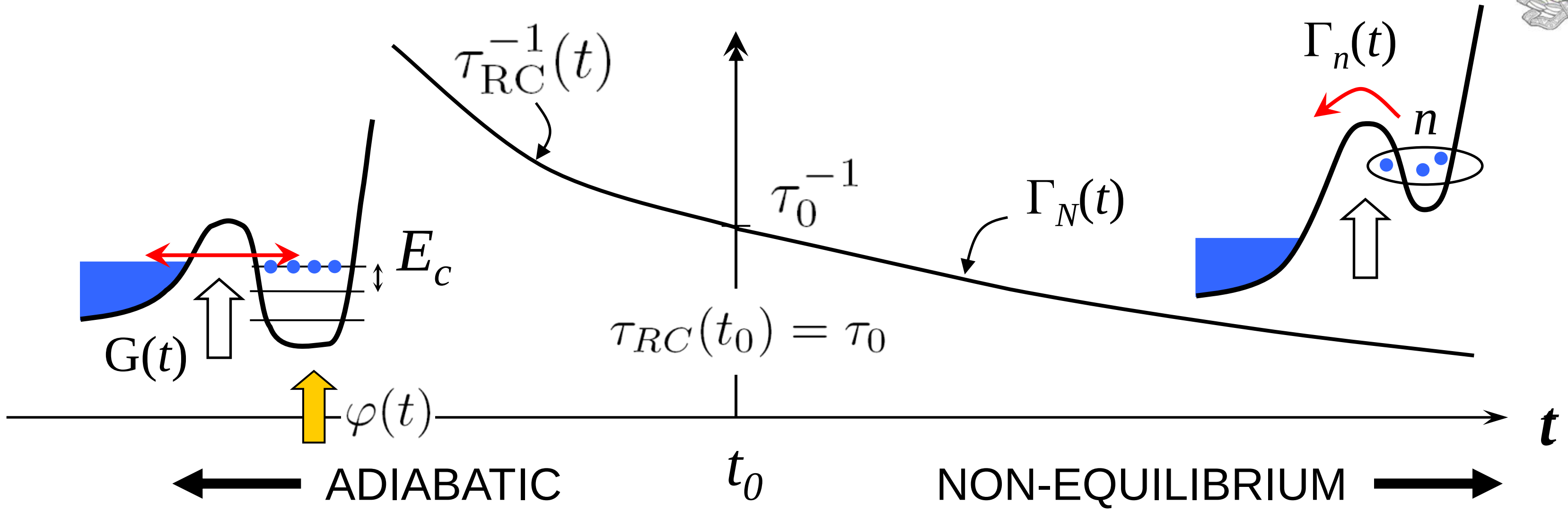
Elektronu sūkņu veidi

- **Turnstiles** – photon-assisted tunneling corrections
- **Adiabatic pumps** – co-tunneling & non-adiabaticity
- **Surface-acoustic-waves**-driven pumps – hard to control
- **Neadibātiskie vienparametra sūkņi**
  - Blumenthal et al. Nature Physics **3**, 343 (2007)
  - **Kaestner et al. Phys. Rev. B 77, 153301 (2008)**
  - Maire et al., Appl. Phys. Lett. 92, 082112 (2008)
  - Fujiwara et al. Appl.Phys.Lett. **92**, 042102 (2008)
  - Wright et al. Phys. Rev. B 78, 233311 (2008)
  - **Kaestner et al, Appl. Phys. Lett. 92,192106 (2008)**
  - **Kaestner et al, Appl. Phys. Lett. 94, 012106 (2009)**
  - Wright et al. Phys. Rev. B **80**, 113303 (2009)
  - **VK & Kaestner, Phys. Rev. Lett .(iesniegts), arXiv:0901.4102**
  - **Zole, Bakalaura darbs, LU (2009)**
  - **Leicht et al., Physica E (pieņemts), arXiv:0909.2778**



- Tehniskās priekšrocības
  (liela tolerance pret kļūdām, paralelizācija, lielas (GHz) frekvences)
- Jauni fizikālie mehānismi

Pinching a droplet from a Fermi sea



- Coulomb blockade: $G(t) < e^2/h$.
- Assume: $G(t) = G_0 e^{-\beta t} \Rightarrow \beta \equiv -\dot{G}/G$ (changing *the barrier* only!)

$T_{\text{eff}} \propto \sqrt{(h\beta)^2 + T^2}\,, |I - enf| \sim e^{-E_c/T_{\text{eff}}}$

Flensberg, Niu & Pustilnik, PRB (1999);
Liu &Niu, PRB (1993)

- Rise both *the barrier* and the quantum dot *potential* $\varphi(t)$!
- Need to remove 1 e per $\tau_0 \equiv E_c/e\dot{\varphi}$ to stay adiabatic
- Crossover from adiabatic to non-equilibrium charge distribution: $\tau_{RC}(t_0) = \tau_0$
- Electrons will continue to escape well above the Fermi energy if $\beta\tau_0 \ll 1$

Decay cascade approach

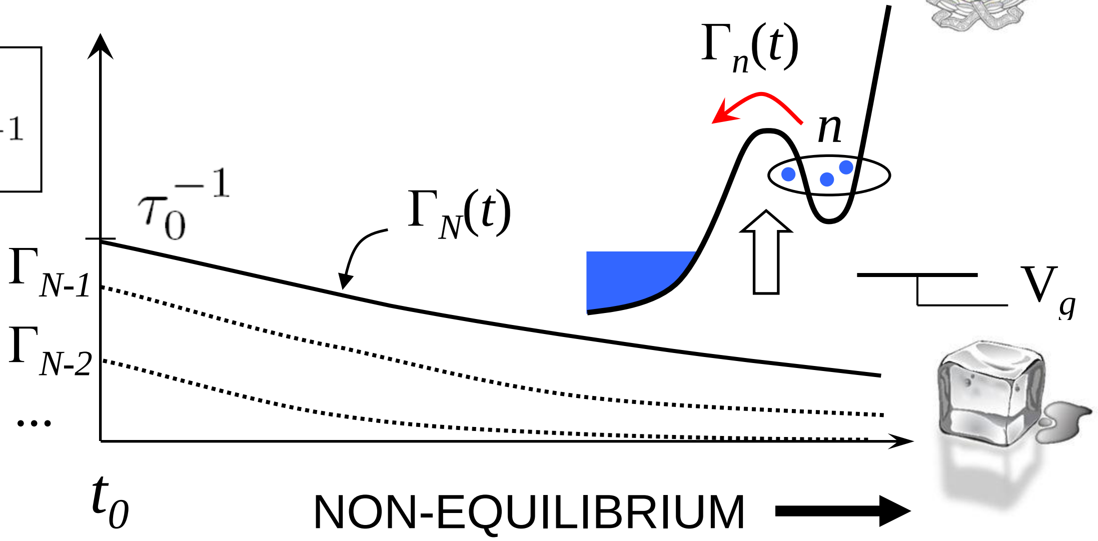
$$\frac{d}{dt}P_n = -\Gamma_n(t)P_n + \Gamma_{n+1}(t)P_{n+1}$$

Decay rate $\Gamma_n(t)$ for n → n-1

Initial condition:

$$P_N(t_0) = 1$$

$$P_n(t_0) = 0 \text{ for } n < N$$



Solve for $t \to \infty$ “FREEZE-OUT”

Route 1 (somewhat restrictive assumptions)

Assume same time dependence of Γ‘s:

$$\Gamma_n(t)/\Gamma_{n-1}(t) = X_n/X_{n-1} \equiv e^{\delta_n}$$

$$X_n \equiv \int_{t_0}^{+\infty} \Gamma_n(t)\, dt$$

Expect exponential parametric dependence:

$$X_n(V_g) = \exp\left[-\alpha V_g + \sum_{m=1}^{n} \delta_m\right]$$

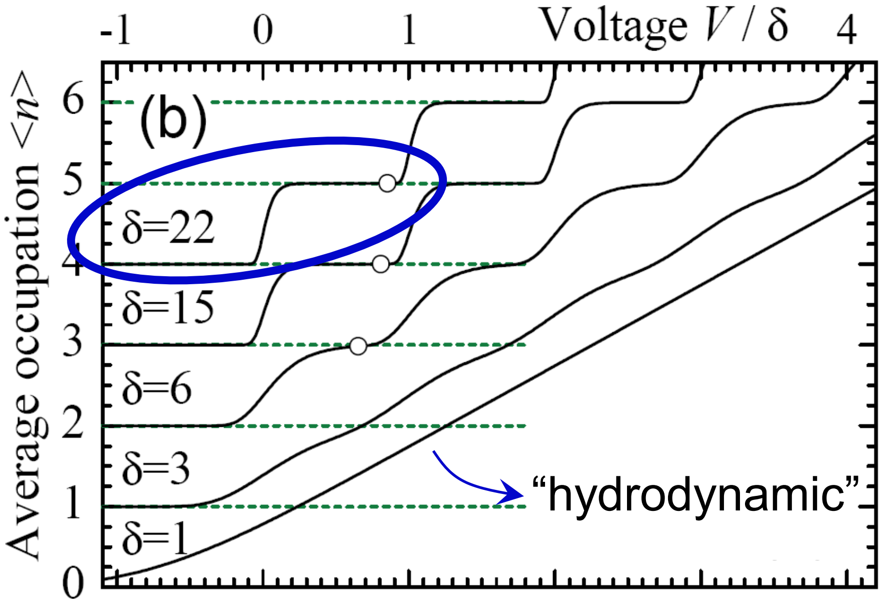
$$P_n(\infty) = \sum_{k=n}^{N} Q_{nk}\, C_k\, e^{-X_k}\,,$$

$$C_k = -\sum_{m=k+1}^{N} C_m Q_{km}\,;\; C_N = 1\,,$$

$$Q_{nk} = \prod_{m=n}^{k-1} \frac{X_{m+1}}{X_m - X_k}\,;\; Q_{nn} = 1\,.$$

Quantization mechanism

Let's plot $\langle n\rangle \equiv \sum_n n\, P_n(\infty)$ as function of V_g for $\delta_n = \delta$



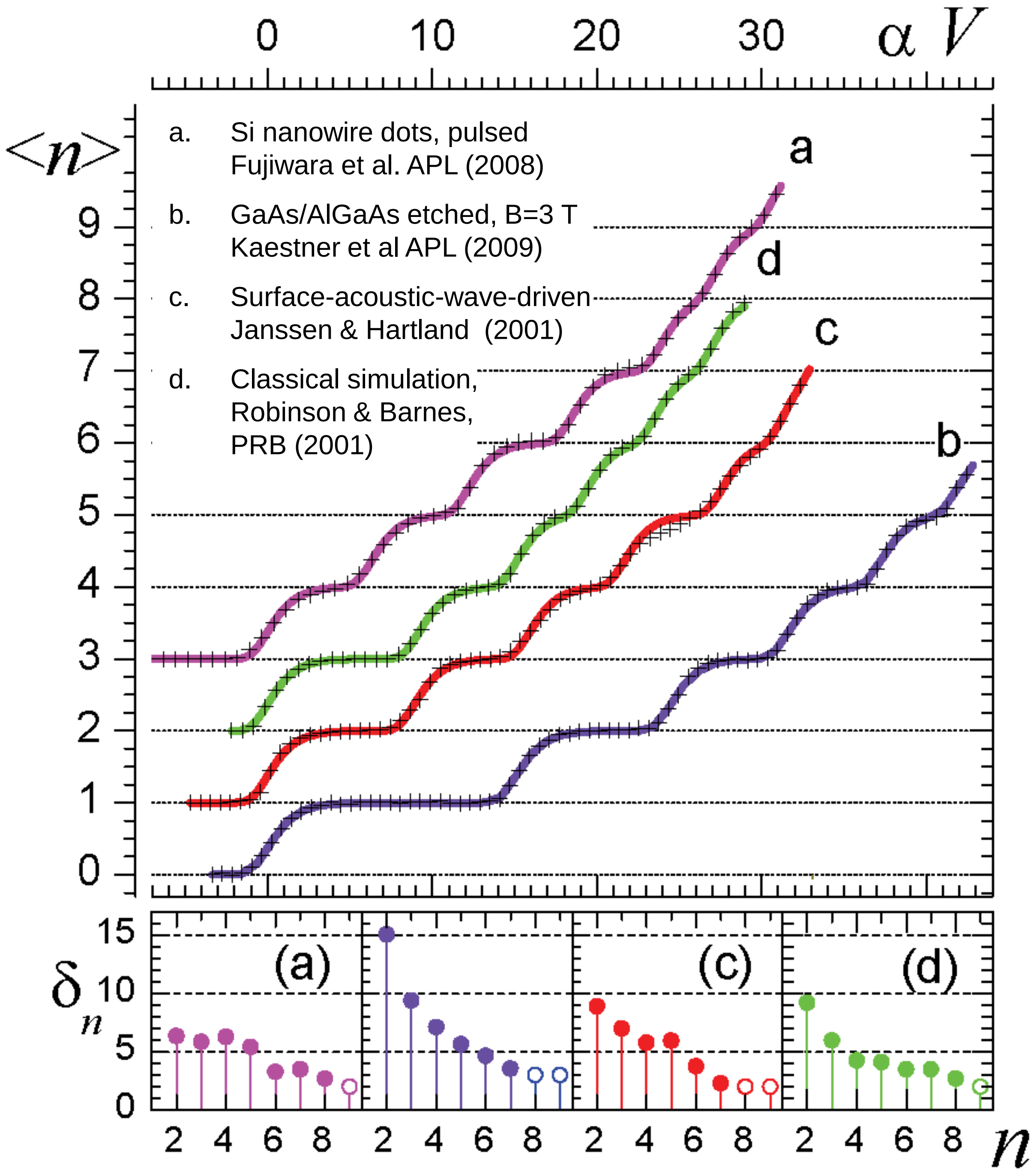
$$X_n \equiv \int_{t_0}^{+\infty} \Gamma_n(t)\, dt$$

$$X_n(V_g) = \exp\left[-\alpha V_g + \sum_{m=1}^{n} \delta_m\right]$$

Quantization = separation of scales!

$$\ldots \gg X_{n+1} \gg X_n \gg X_{n-1} \gg \ldots$$

$$\langle n\rangle \approx \sum_n \exp(-X_n)$$

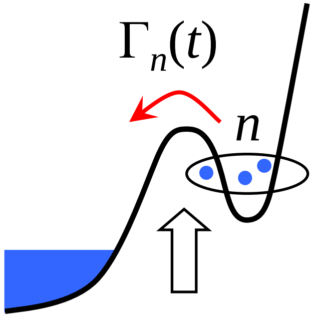


a. Si nanowire dots, pulsed
Fujiwara et al. APL (2008)

b. GaAs/AlGaAs etched, B=3 T
Kaestner et al APL (2009)

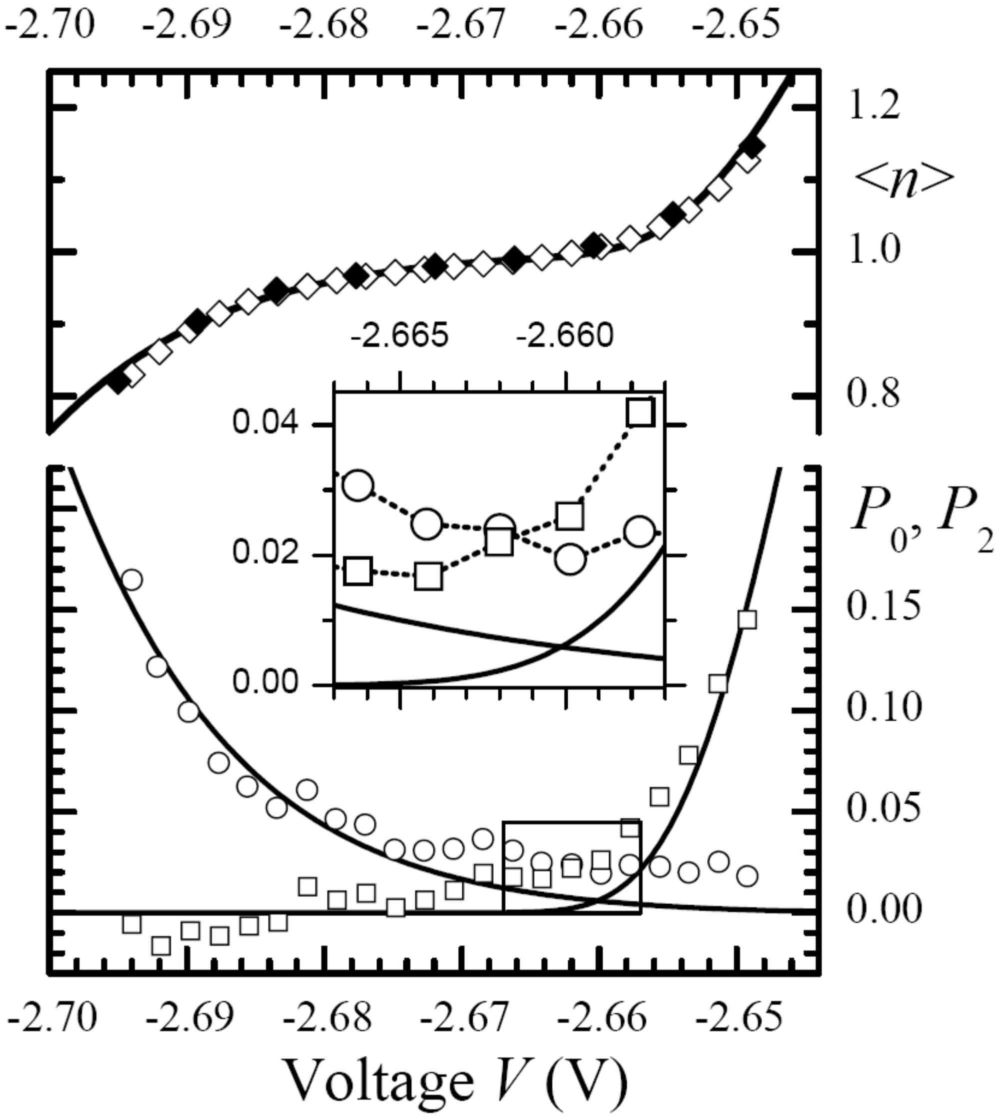
c. Surface-acoustic-wave-driven
Janssen & Hartland (2001)

d. Classical simulation,
Robinson & Barnes,
PRB (2001)



arXiv:0901.4102

More than just current



Experimental data:

Shot noise
measruments
in a surface-acoustic
wave driven pump,

Robinson & Talyanskii,
PRL (2005)

Decay cascade approach II

Route 2 (more general, for long plateus)

Do **not** assume same time dependence of Γ's.

$$\boxed{\frac{d}{dt}P_n = -\Gamma_n(t)P_n + \Gamma_{n+1}(t)P_{n+1}}$$

Consider N=1 (disregarding cascades with n>1):

$$P_1^{(0)}(t) = \exp\left[-\int_{t_0}^{t}\Gamma_1(t')\,dt'\right]$$

Consider N=2 (disregarding cascades with n>2):

$$X_n = \left\langle \int_{t_0}^{+\infty}\Gamma_n(t)\,dt \right\rangle_{t_0}$$

$$P_2(t) = \exp\left[-\int_{t_0}^{t}\Gamma_2(t')\,dt'\right]$$

$$P_1(\infty) = P_1^{(0)}(\infty)\int_{t_0}^{\infty}\underbrace{\Gamma_2(t)\,P_2(t)}_{-\dot{P}_2(t)}\,/\,\underbrace{P_1^{(0)}(t)}_{\approx 1}\,dt \approx P_1^{(0)}(\infty)[1-P_2(\infty)]$$

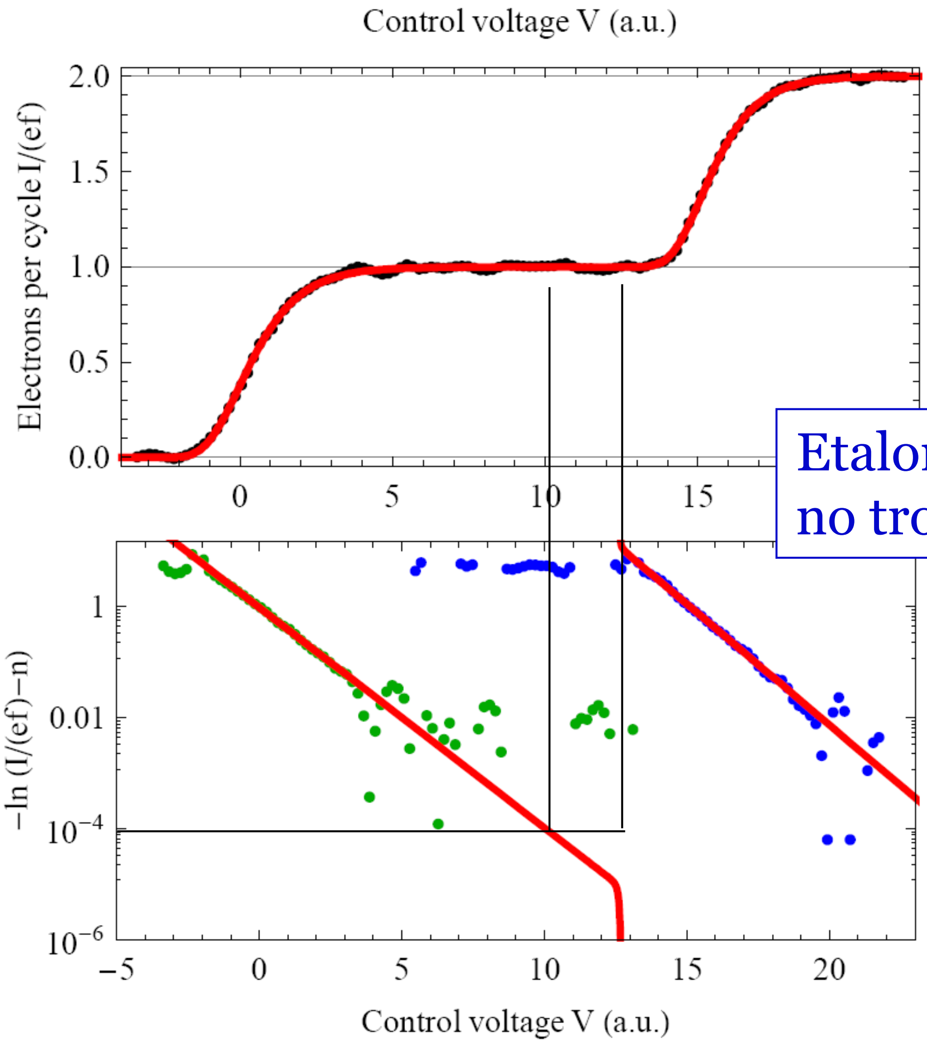
$$\boxed{\langle n\rangle = e^{-X_1} - e^{-X_1-X_2} + 2e^{-X_2}}$$

Ansatz

$$\ln X_1 = -\alpha_1 V_g + \delta_1$$
$$\ln X_2 = -\alpha_2 V_g + \delta_1 + \delta_2$$

... becomes verifiable!

Precizitātes ekstrapolācija



Dati: PTB grupa (B.Kaestner)

Appl. Phys. Lett. **94**, 012106 (2009)

Etalona precizitātes griestus var novērtēt no trokšņainiem mērījumiem!

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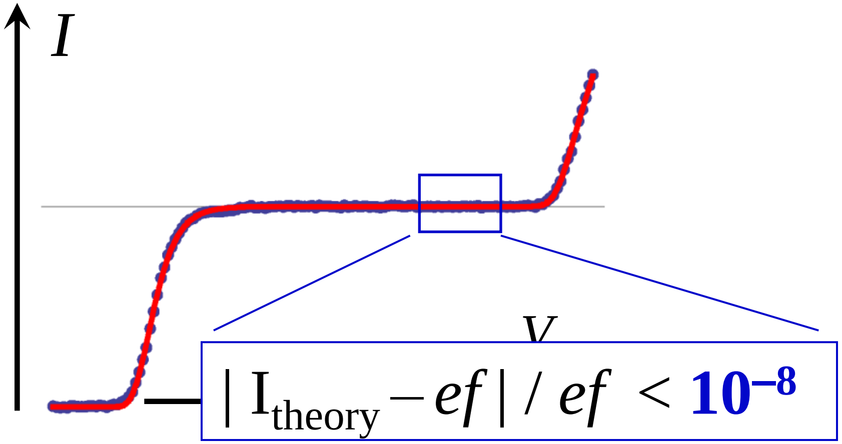
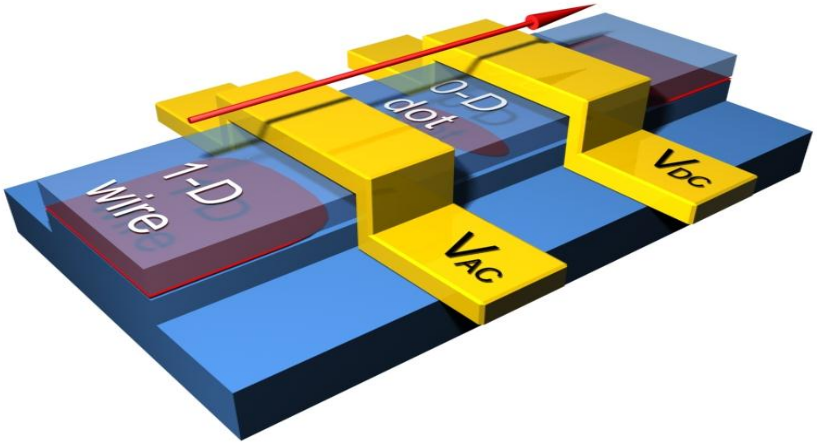


$$| I_{\mathrm{theory}} - ef | / ef < \mathbf{10^{-8}}$$



Dati: BPTB grupa (B.Kaestner),
2009. gada jūlijs, nav publicēts

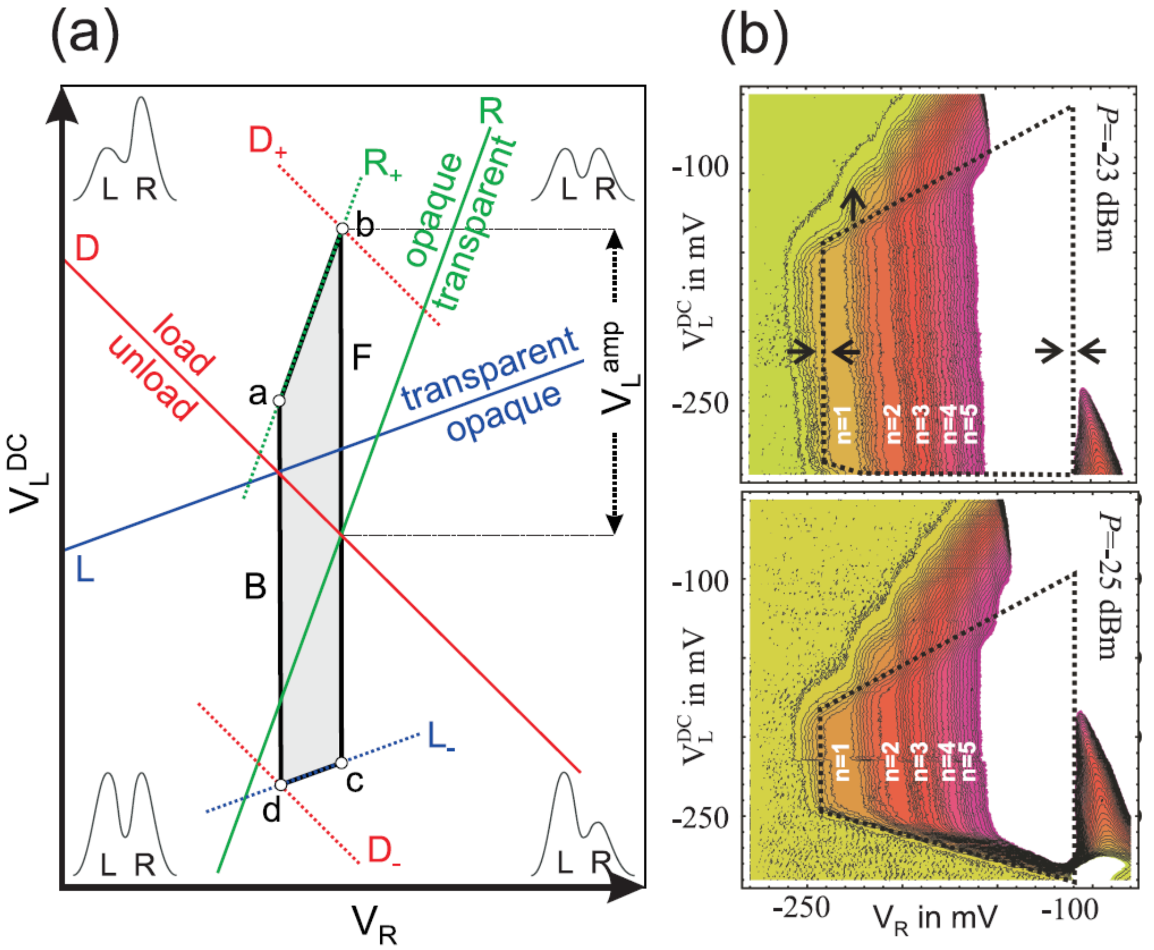


Figure 2: (Color online) (a) The region of V_R and V_L^{DC} where efficient transportation of electrons from source to drain is possible is shaded in gray. The derivation and explanation are given in the text. (b) Typical characteristic of pumped current of device 1 measured as a function of V_L^{DC} and V_R at $f = 500$ MHz, $P = -25$ dBm and $P = -23$ dBm. While the lower and upper line shift with increasing power, the left and right line stay fixed.

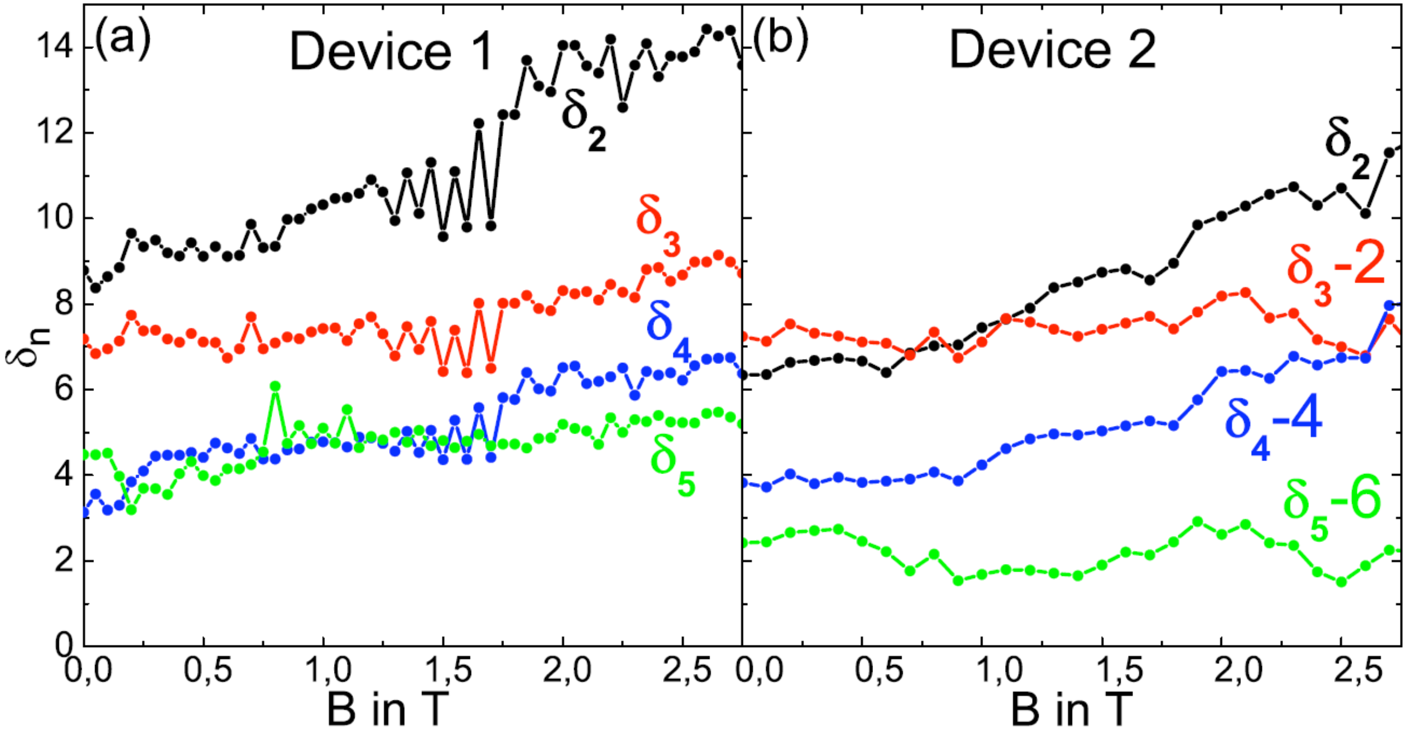


Figure 3: (Color online) δ_n as function of magnetic field strength of two different devices. Device 1 (a) was operated at a pumping frequency $f = 50$ MHz and a power of $P = -16$ dBm. Device 2 (b) was operated at a $f = 100$ MHz and $P = -11.5$ dBm, (b) is shifted for clarity.