INSTITUTE OF SEMICONDUCTOR PHYSICS, SIBERIAN BRANCH
OF THE RUSSIAN ACADEMY OF SCIENCE

Electron transport via two-dimensional array of tunnel-coupled quantum dots

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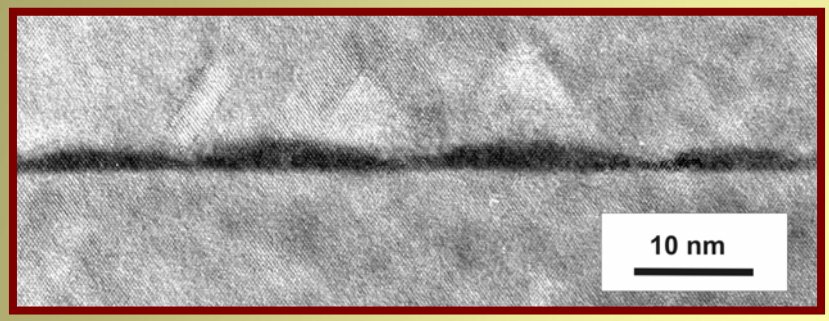
Outline:

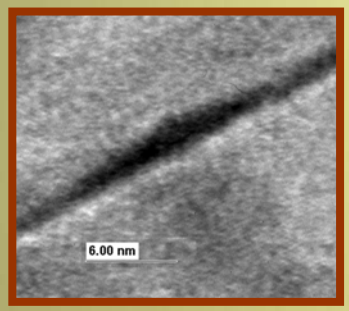
- Quantum dots array properties
- Electron structure of quantum dot system
- Hopping conductance in array of QDs
- Role Coulomb interaction in transport
- Transition from hopping to diffusive behavior
- Photoconductance with slow relaxation
- Relaxation under high-field exitation
- Photo-conductance mesoscopic fluctuations

Ge nanoclusters in Si

Cross-section image of TEM

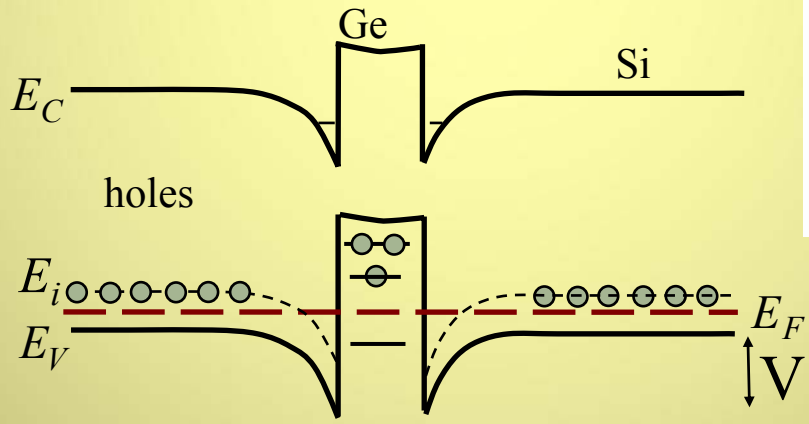


8 ML Ge 300°C

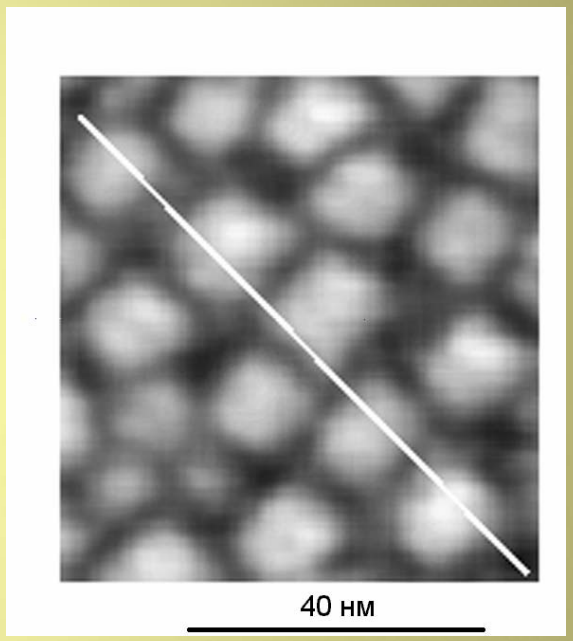


10 ML Ge 300°C

Band structure



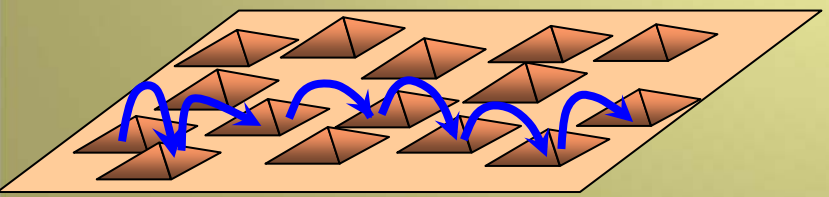
STM image of Ge nanoclusters



Areal density 3-4×10^{11} cm^{-2}

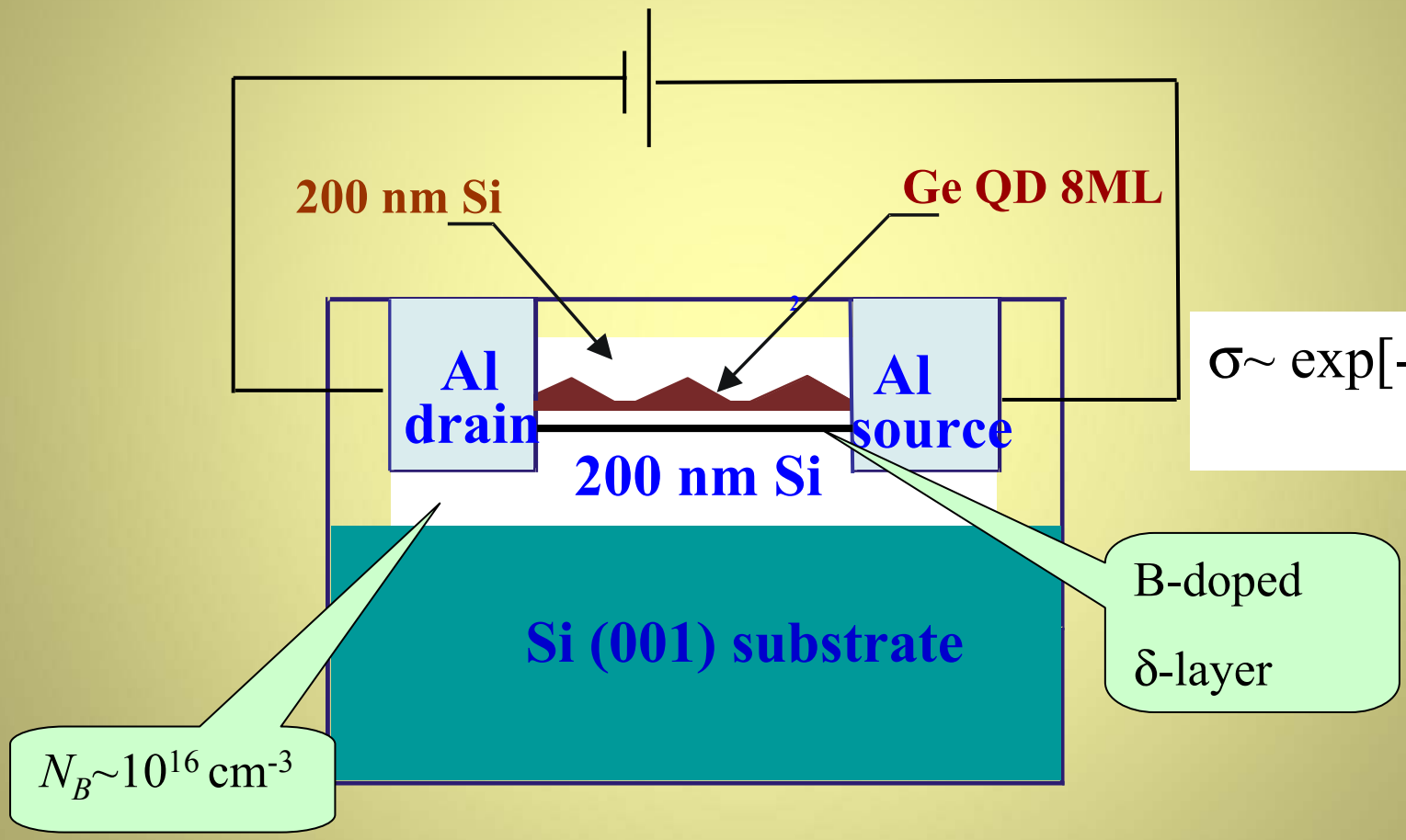
Lateral size 10 -15nm

High 1-1.5 nm



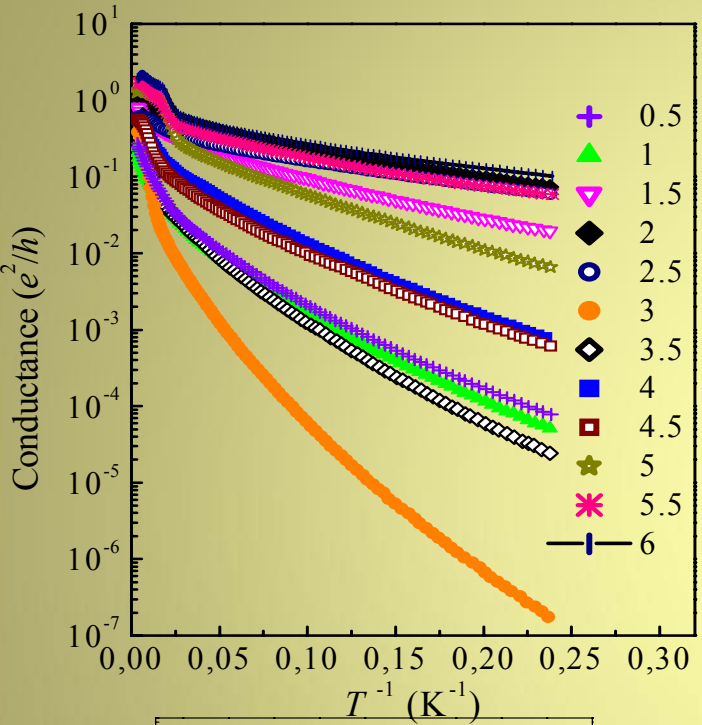
Large density of QD's allows to observe the hopping conductivity along two-dimensional QDs layer

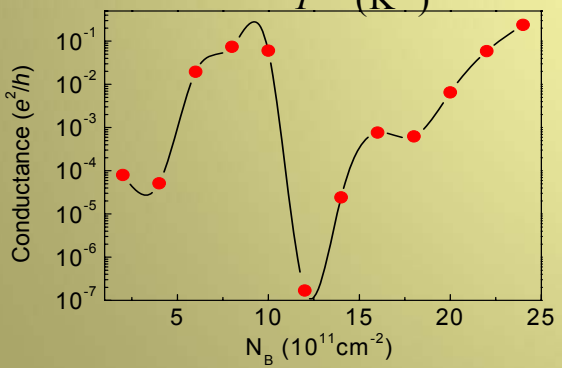
Structure under investigation



$$\sigma \sim \exp[-(T_0/T)^{1/2}$$

Hole hopping





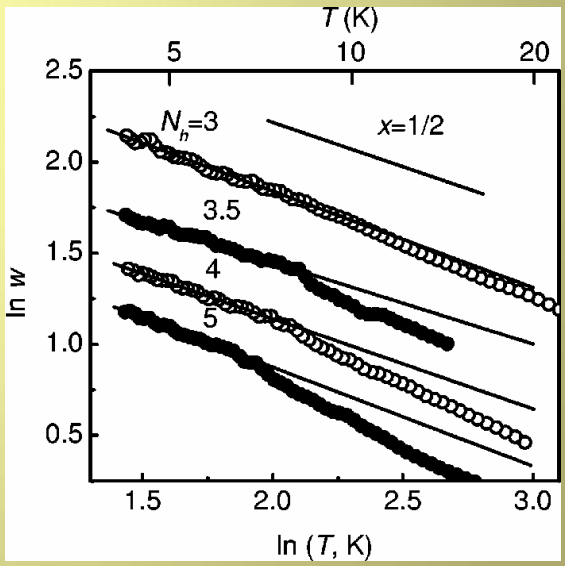
Analysis of reduced activation energy

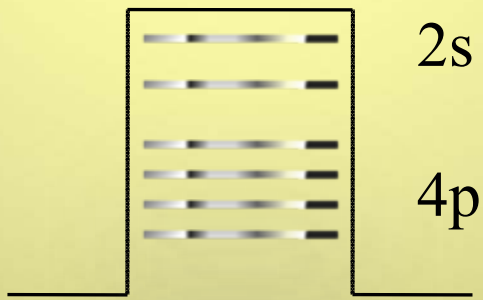
$$G(T) = \gamma T^m \exp\left[-(T_0/T)^x\right]$$

$$w(T) = d\ln G/\ln T \quad w(T) = m + x(T_0/T)^x$$

$m << x(T_0/T)^x$

$$\ln w(t) = A - x\ln T$$



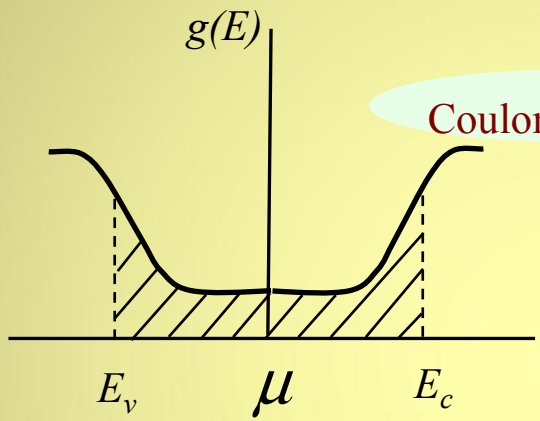


Non-monotonic dependence of hopping conductance on density of state is a characteristic feature of QDs.

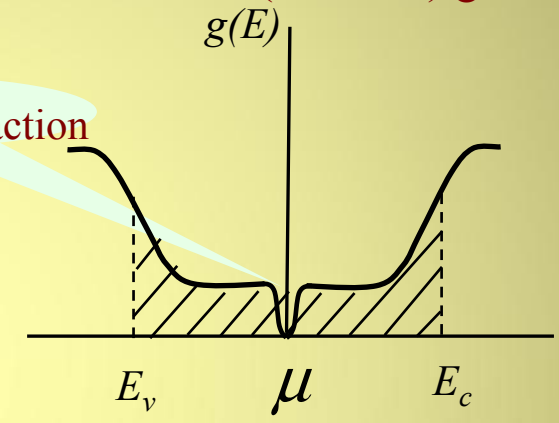
Variable-range hopping

$$G(T) = \gamma T^m \exp\left[-(T_0/T)^x\right]$$

Fermi glass



Coulomb (electron) glass

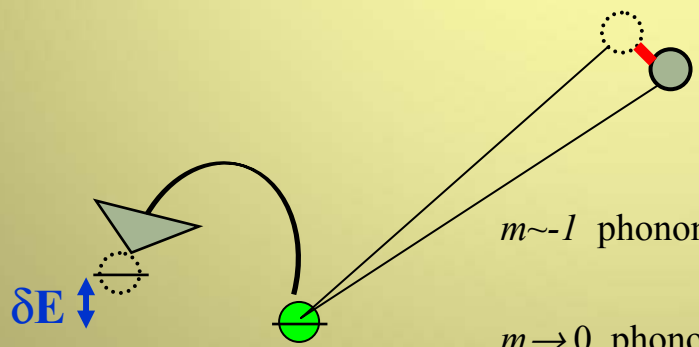


$$G(T) \propto \exp\left[-(T_0/T)^{1/3}\right]$$

Mott law

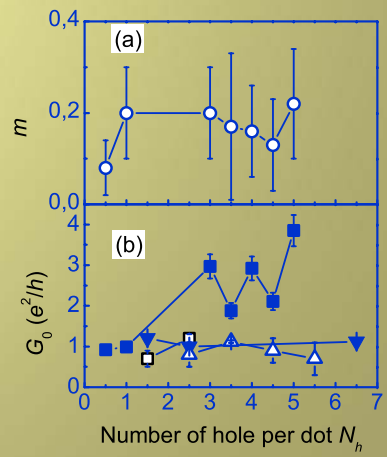
$$G(T) \propto \exp\left[-(T_0/T)^{1/2}\right]$$

ES law



m~*-1* phonon-assisted VRH x=1/3 for Mott
x=1/2 for ES

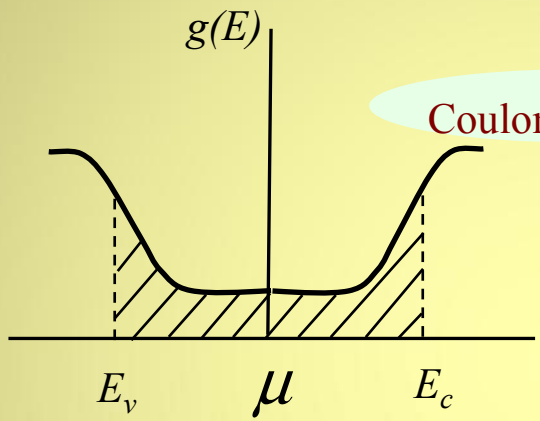
$m \to 0$ phononless hopping, *G0*~ e2/h



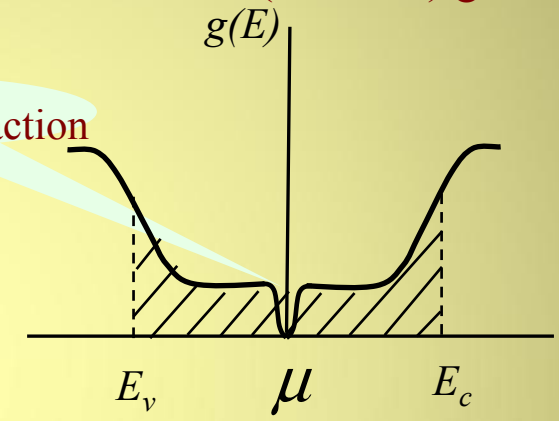
Variable-range hopping

$$G(T) = \gamma T^m \exp\left[-(T_0/T)^x\right]$$

Fermi glass



Coulomb (electron) glass



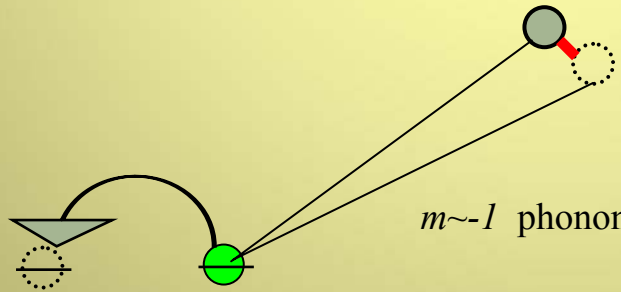
Coulomb interaction

$$G(T) \propto \exp\left[-(T_0/T)^{1/3}\right]$$

Mott law

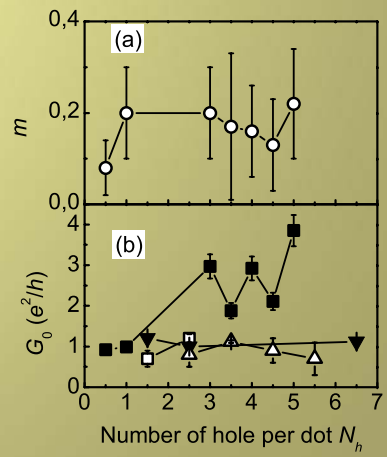
$$G(T) \propto \exp\left[-(T_0/T)^{1/2}\right]$$

ES law

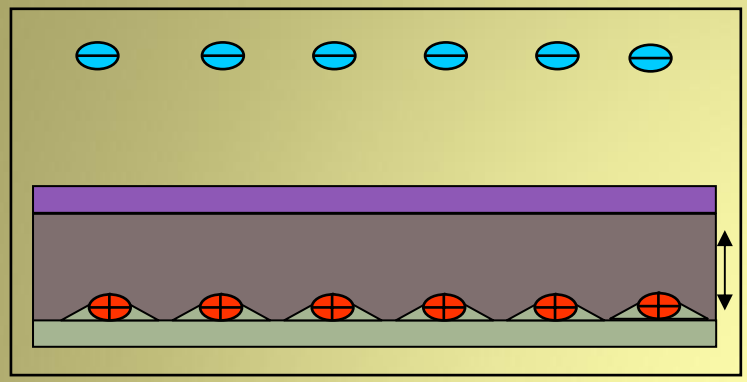


m~-1 phonon-assisted VRH x=1/3 for Mott
x=1/2 for ES

$m \to 0$ phononless hopping, *G0*~ e2/h

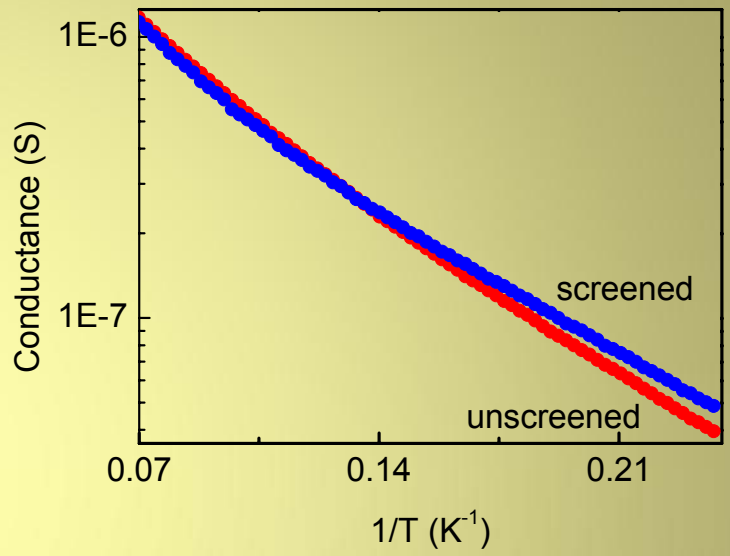


Screening of Coulomb interaction



$l \sim 40$ nm

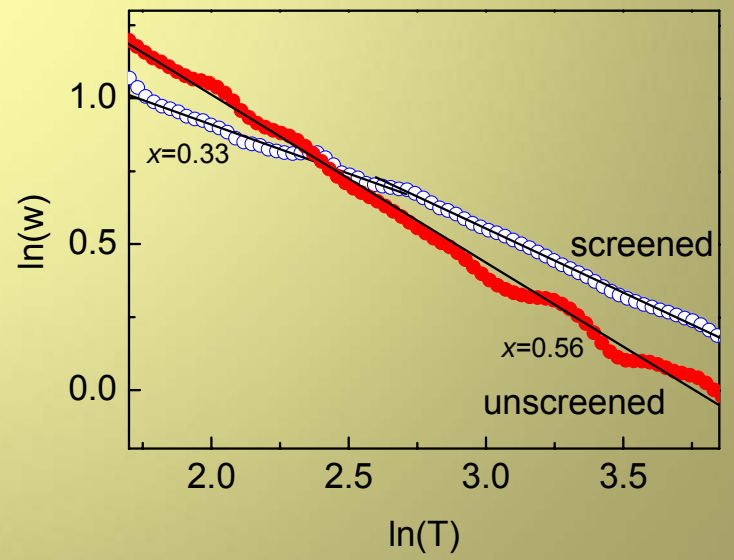
$$U(r) = \frac{e^2}{4\pi\varepsilon\varepsilon_0}\left(\frac{1}{r} - \frac{1}{\sqrt{r^2 + 4l^2}}\right)$$

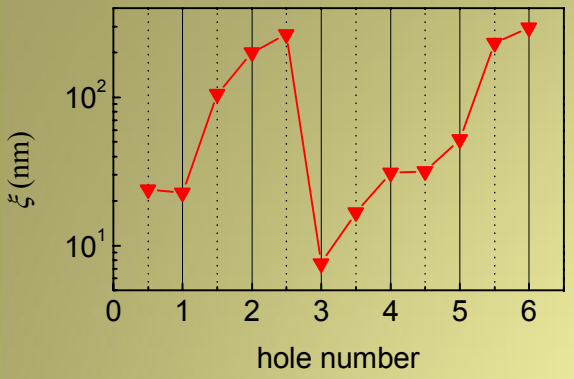


$$G(T) = \gamma T^m \exp\left[-(T_0/T)^x\right]$$

m~*-1* phonon-assisted VRH x=1/3 for Mott in screened sample

$m \to 0$ phononless hopping, $G_0 \sim e^2/h$ in unscreened sample

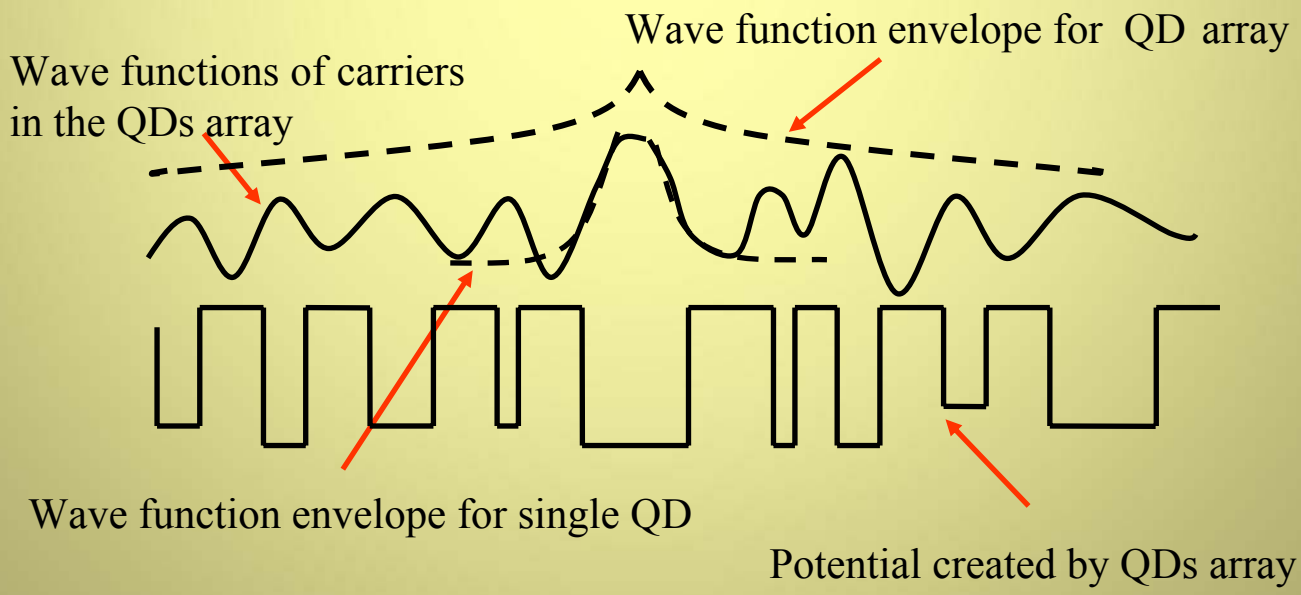




Localization radius in disordered system

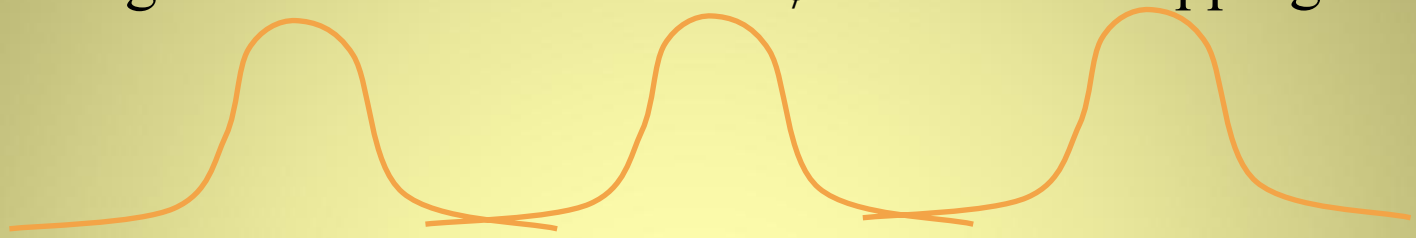
$Z = \frac{I}{W}$ determines the MIT transition

(I – overlap integral, W – the disorder level)

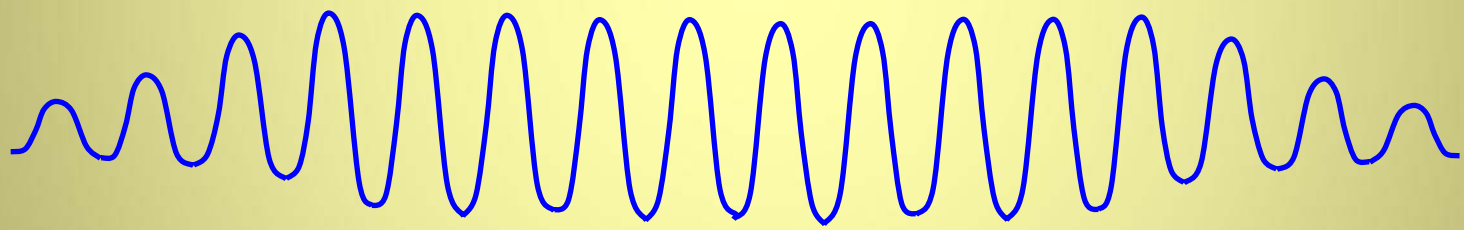


Localization behaviours

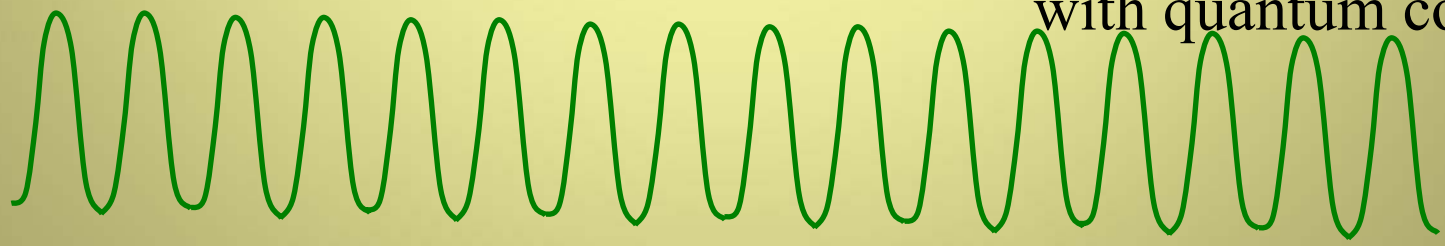
Strong localization $\xi << L_\varphi$ Hopping transport



Intermediate regime $\xi \sim L_\varphi$???????????



Weak localization $\xi >> L_\varphi$ Diffusion transport with quantum corrections



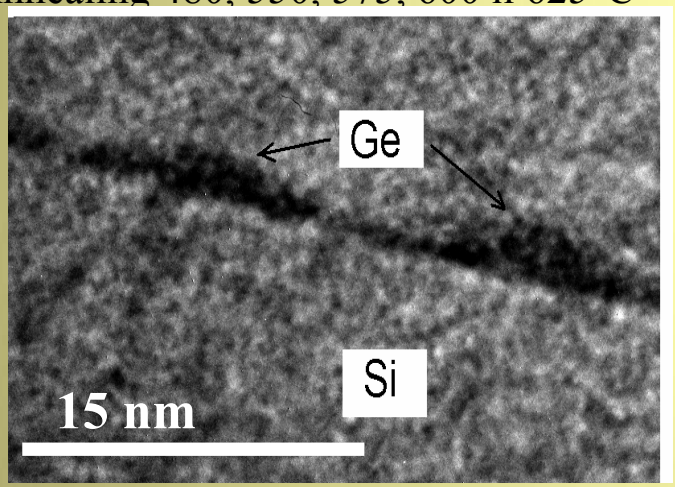
The ways to change disorder and interaction

1. Increase of the QDs array density - to enhance the hopping integral *I* and the interaction without significant change of *W*

QDs density ~4×10^{11} cm^{-2}

Filling factor ν~1.9, 2, 2.1

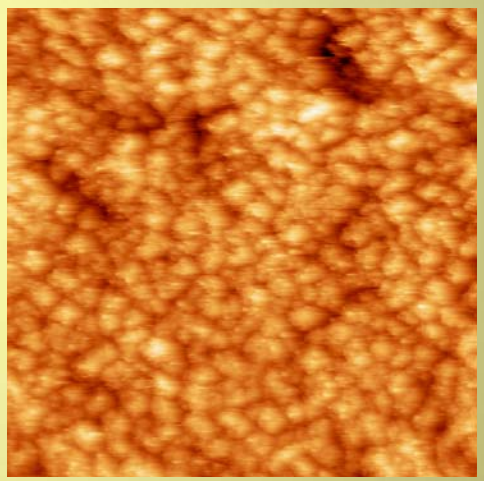
Annealing 480, 550, 575, 600 и 625°C



HTREM image of QDs array with density ~$4\cdot10^{11}$ см $^{-2}$

QDs density 8×10^{11} cm^{-2}

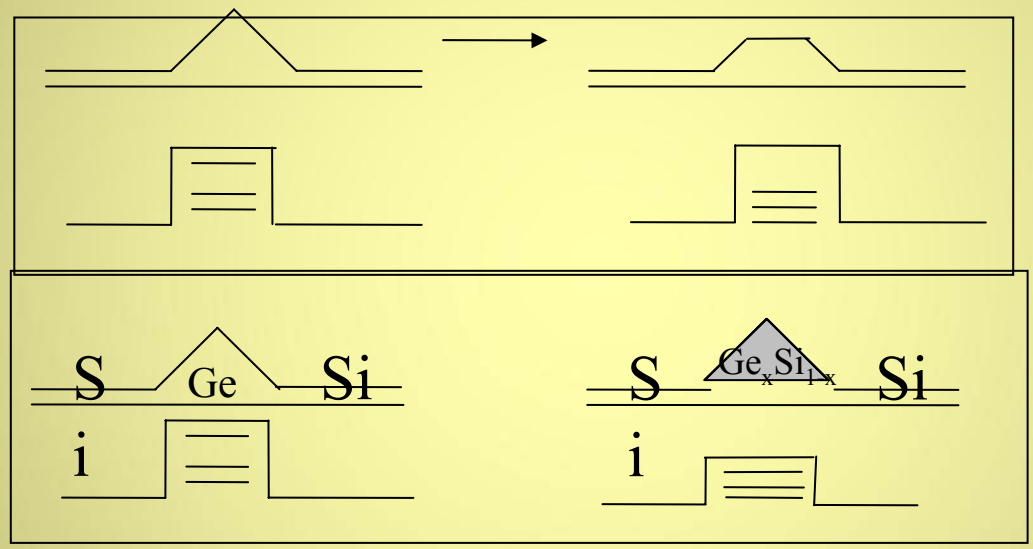
Filling factor ν ~1.8 - 2.6



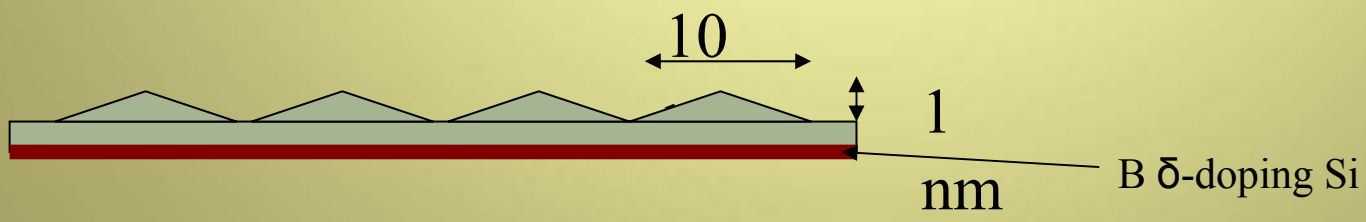
STM image of QDs array with density ~ 8×10^{11} см $^{-2}$ (200×200 nm)

The ways to change disorder and interaction

2. Change the QDs size and composition at annealing- to enhance the overlap of carrier wave functions without seriously effecting the e-e interaction :



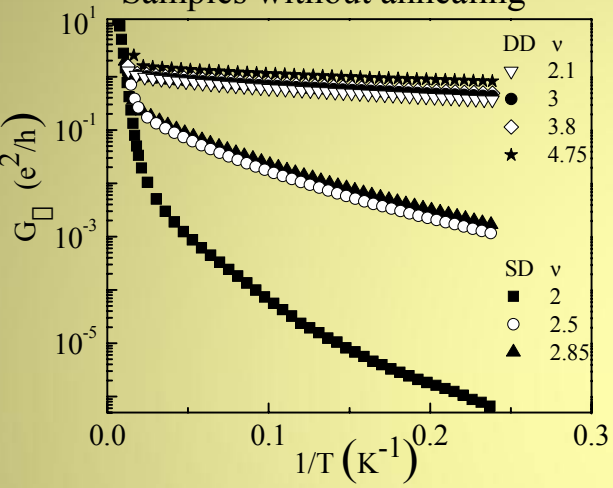
3. Control the filling factor – in opposite way to change interaction and hopping integral



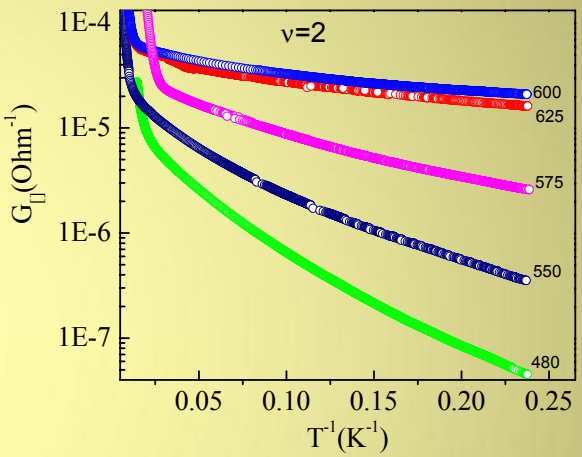
Experimental results

1. Temperature dependence of conductivity (in the frame of hopping transport)

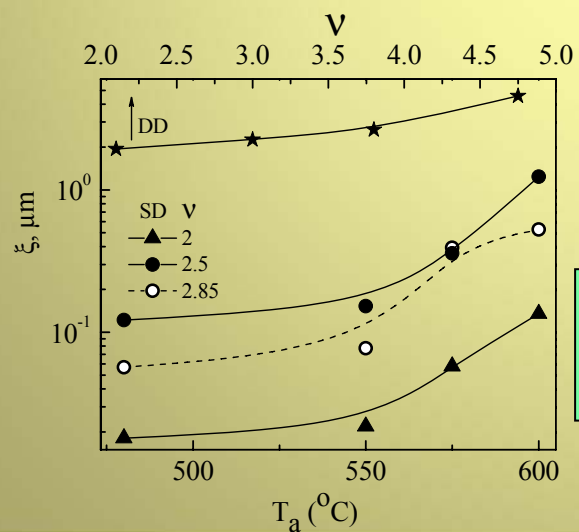
Samples without annealing



Annealing of SD sample, ν=2



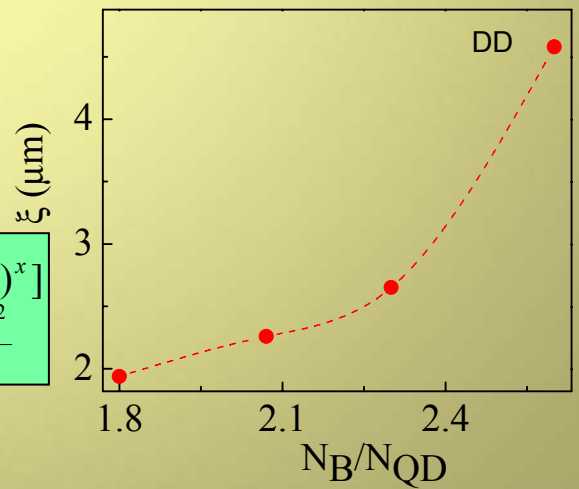
Localization radius for SD samples



$$G(T) \sim \exp[-(T_0/T)^x]$$

$$x = 1/2 \qquad \xi = \frac{6.2e^2}{\varepsilon k T_0}$$

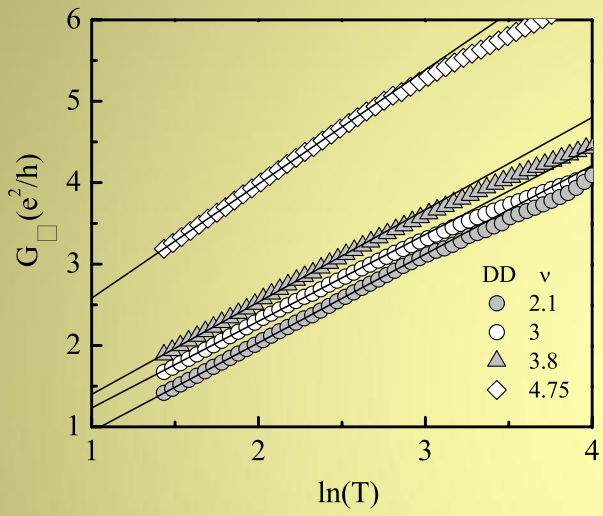
Localization radius for DD samples



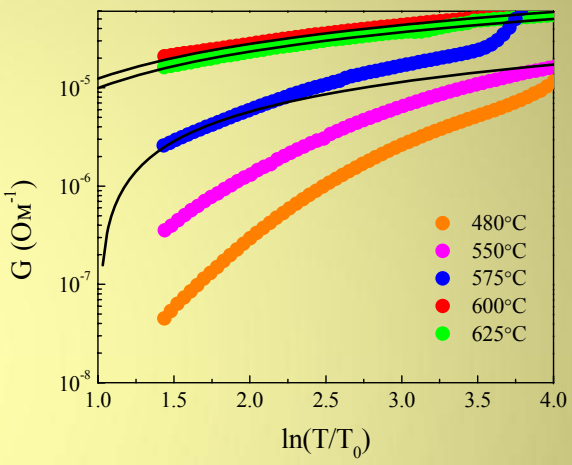
Experimental results

1. Temperature dependence of conductivity (in the frame of diffusive transport)

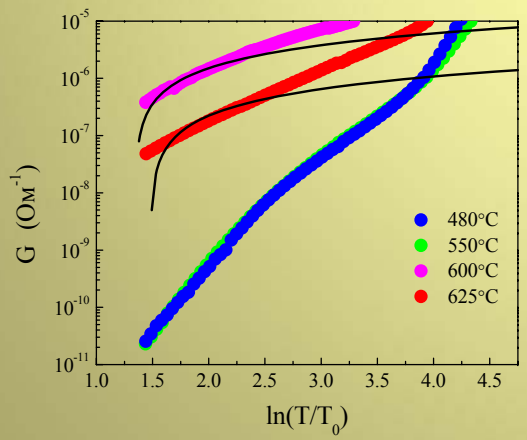
DD samples, different ν



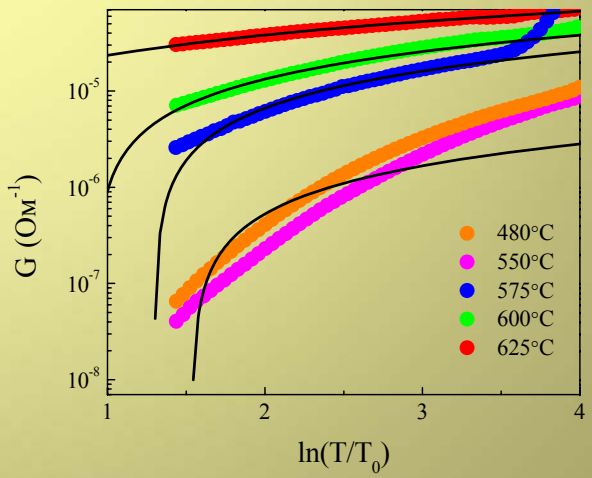
SD samples, ν= 2.5



SD samples, ν= 2

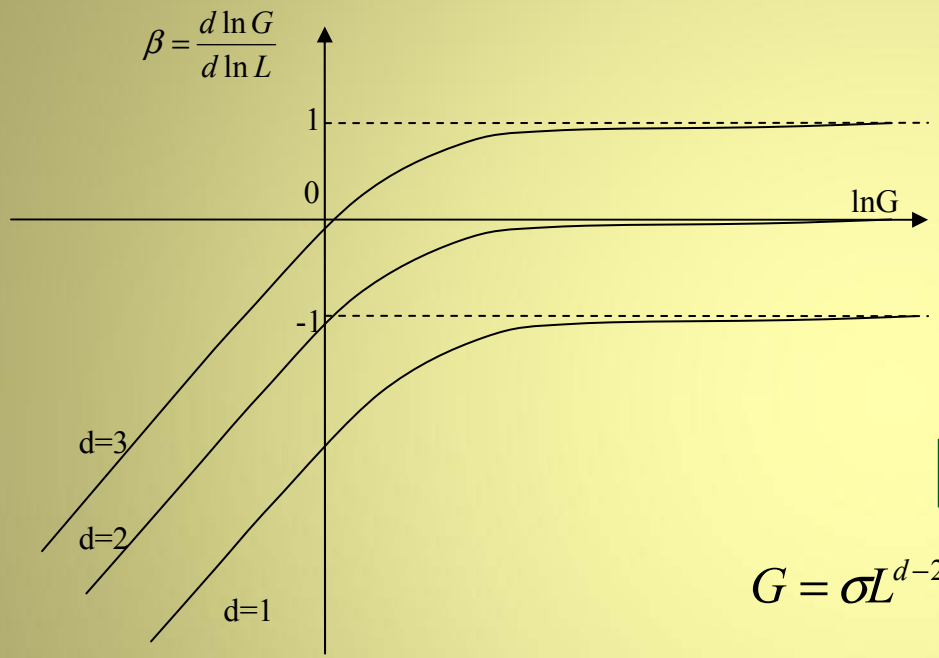


SD samples, ν= 2.85



The methods of the transport behaviour analysis

3. Checking of the scaling theory



Function $\beta(lnG)$ is universal for each dimensionality d, system state is determined by single parameter G (conductance)

β>0 – metal; β<0 - insulator

The limit of high conductance

$$\beta = d - 2$$

$$G = \sigma L^{d-2} \qquad \ln G = \ln \sigma + (d-2) \ln L$$

$$d=2: \qquad \sigma = \sigma_{кл} - \frac{e^2}{h} \ln \frac{L_\varphi}{l}$$

$$\beta = \frac{d \ln G}{d \ln L} = \frac{d \ln \sigma}{d \ln L} = -\frac{e^2}{h} \frac{1}{\sigma} = -\frac{e^2}{h} \frac{1}{G} < 0$$

The limit of low conductance

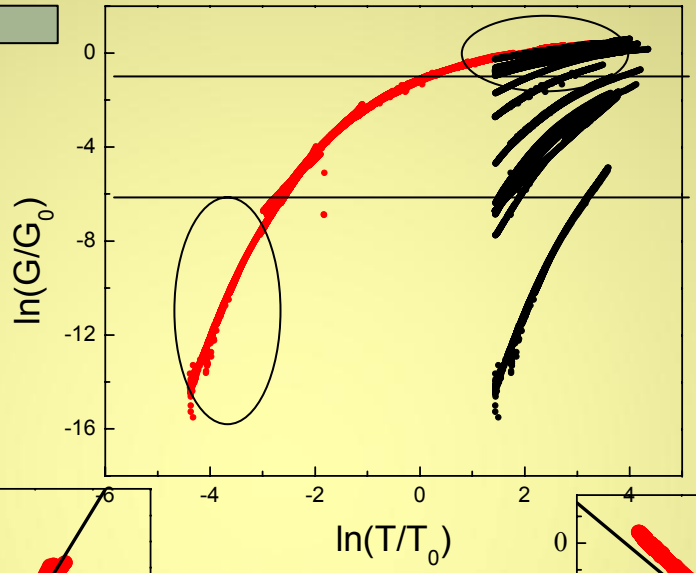
$$G = G_0 e^{-\frac{L}{a}} \qquad \ln G = \ln G_0 - \frac{L}{a}$$

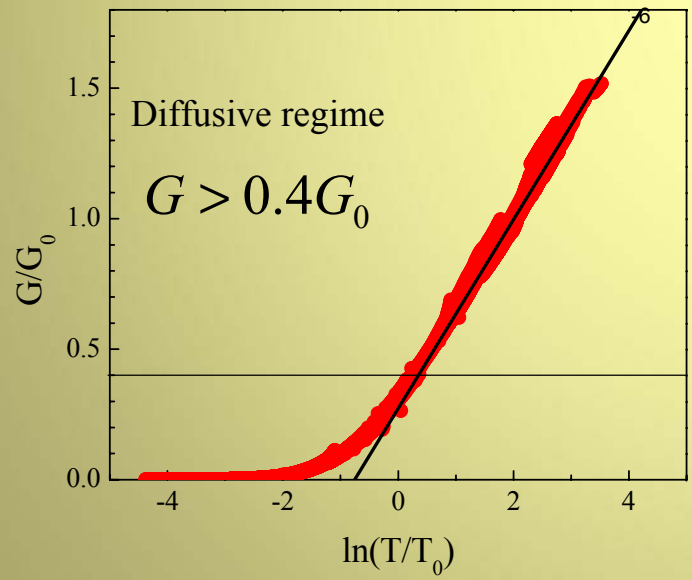
$$\beta = \ln \frac{G}{G_0}$$

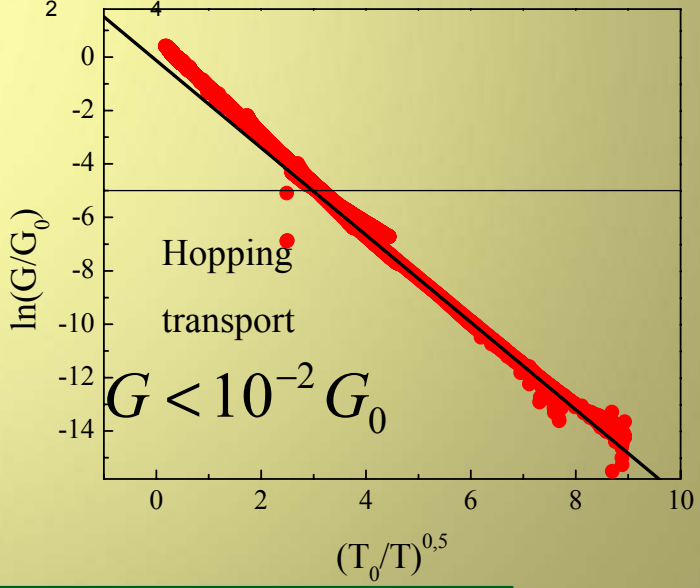
Universality is saved for $\beta = d\ln G / d\ln T$ (because of $\ln L \sim \ln T$)

Experimental results

3. Checking of the scaling theory





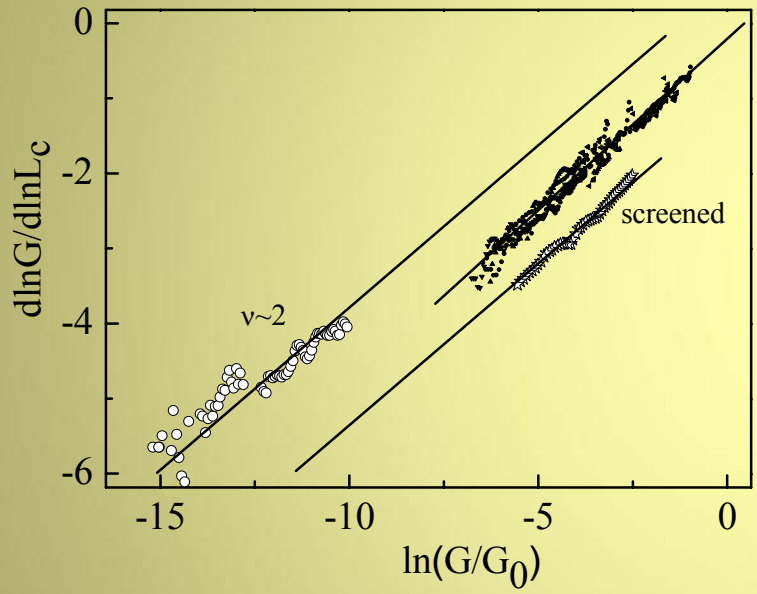


$G_0 = e^2/h = 3{,}876 \cdot 10^{-5}$ Ом$^{-1}$

$G > 0.4e^2/h$	$(G > e^2/h)$	- diffusive transport
$G < 10^{-2}e^2/h$	$(G < 10^{-4}e^2/h)$	-hopping transport

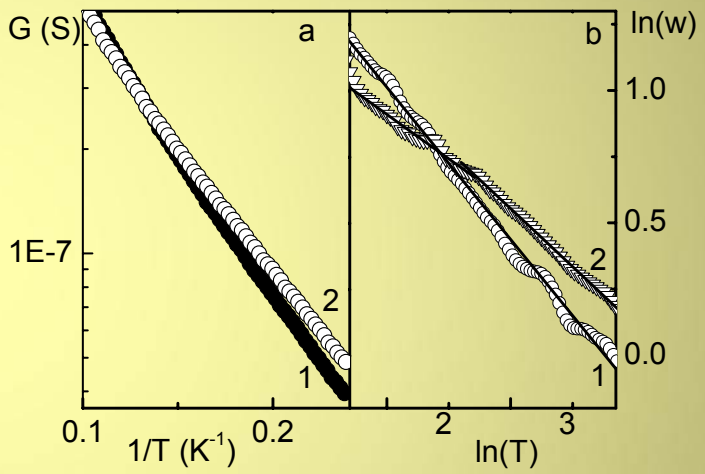
Two-parameter scaling

β-function



$$\beta = \frac{1}{2.3x}\left(-\frac{d\ln G}{d\ln T}\right)$$

Screening of interaction

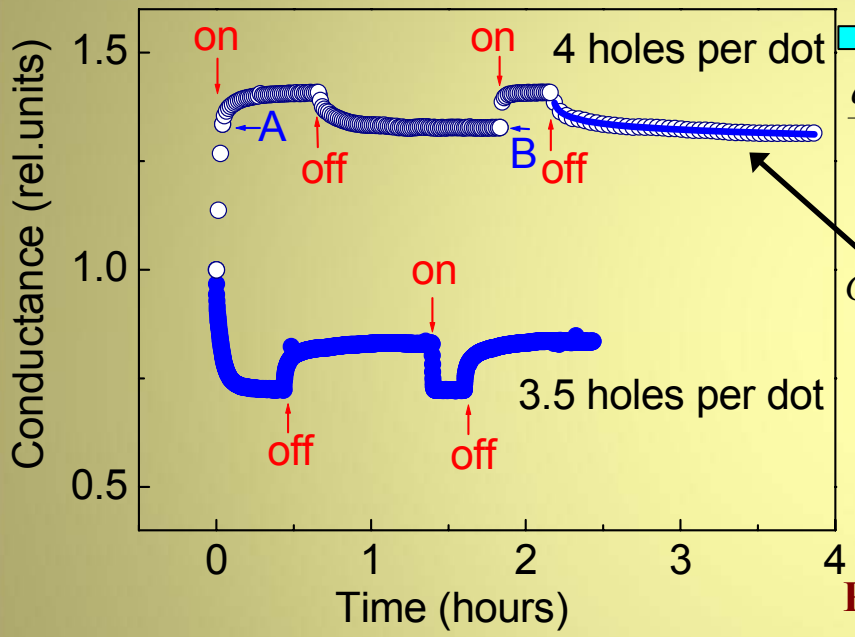


$$G(T) = G_1 \exp\left[-(T_0/T)^{0.5}\right]$$

$$\beta = \frac{1}{2.3}\ln(G_0/G_1) + \frac{1}{2.3}\ln(G/G_0)$$

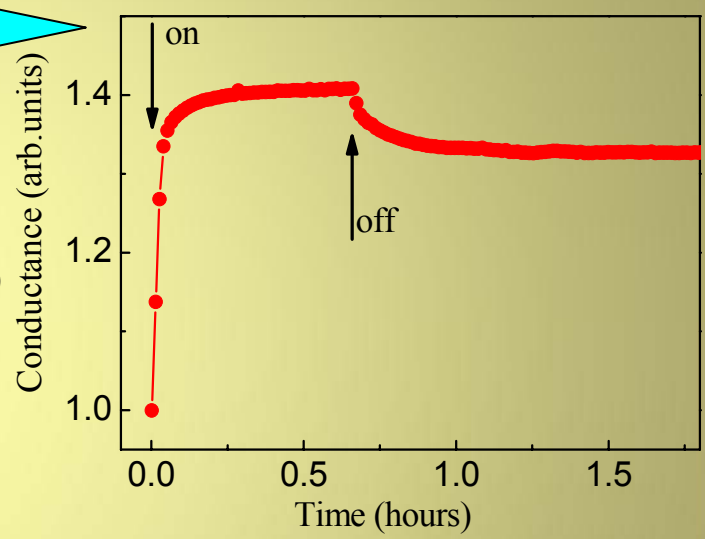
Sign-dependent photoconductance

PC in samples with QDs

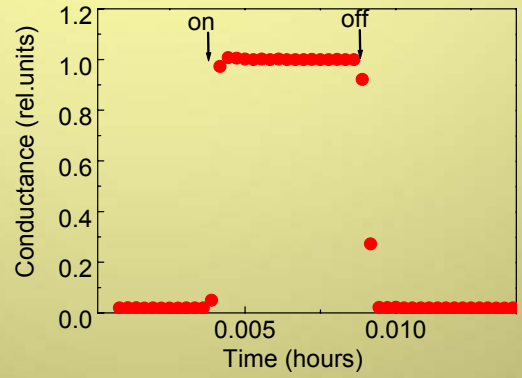


$$\frac{dG}{dt} = B\exp(-\gamma G)$$

$$G(t) = G_0 + C \times \ln(t - t_0)$$

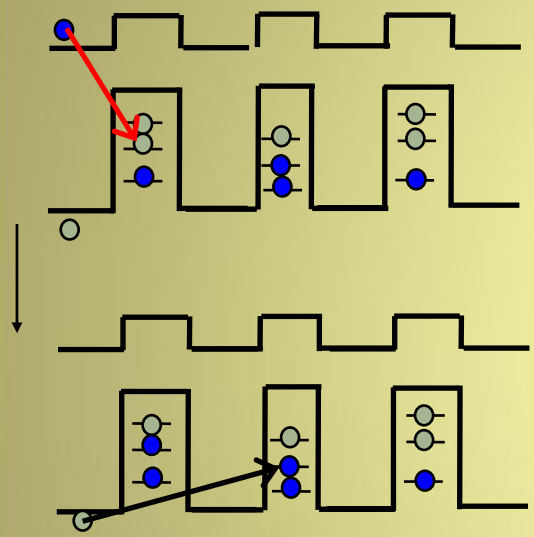


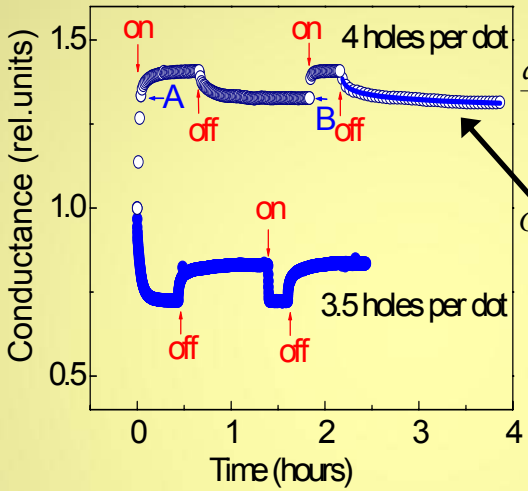
PC in samples without QDs



Interband illumination of sample with $\nu = 1.5$

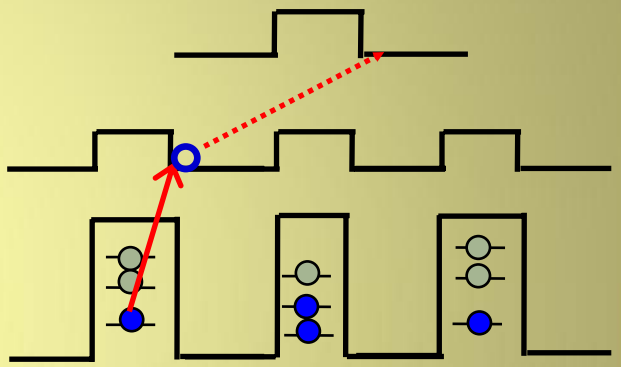
Illumination (1.55 μm) of sample with $\nu = 1.5$

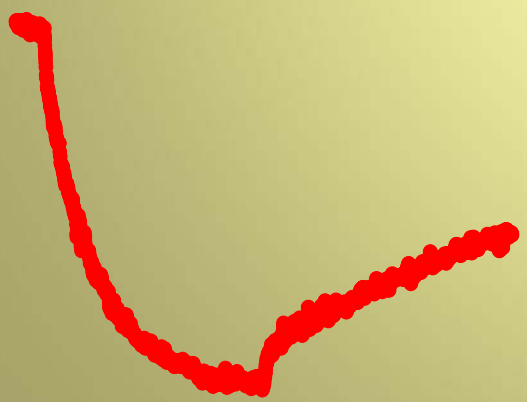


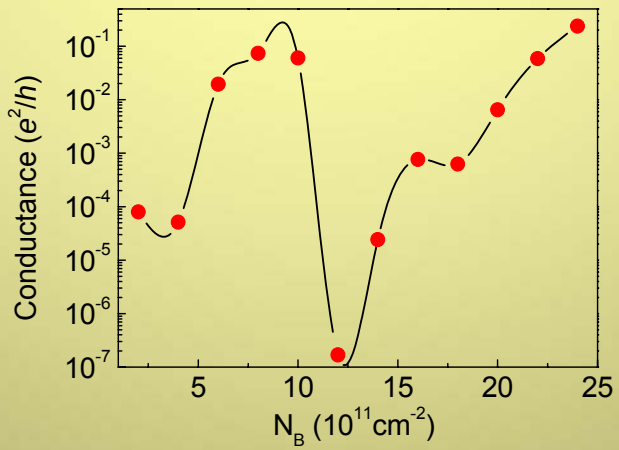


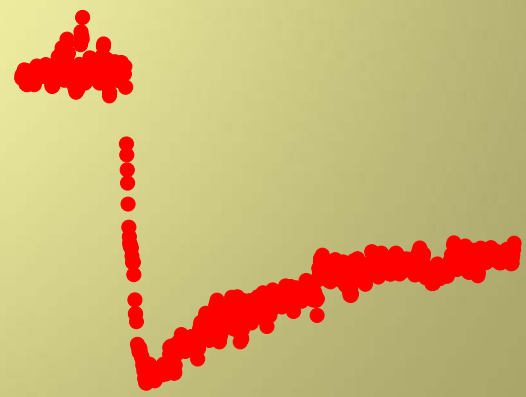
$$\frac{dG}{dt} = B\exp(-\gamma G)$$

$$G(t) = G_0 + C\times\ln(t - t_0)$$

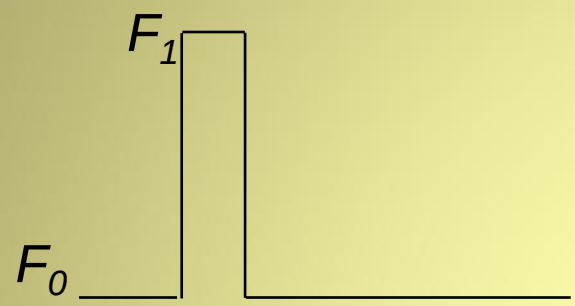


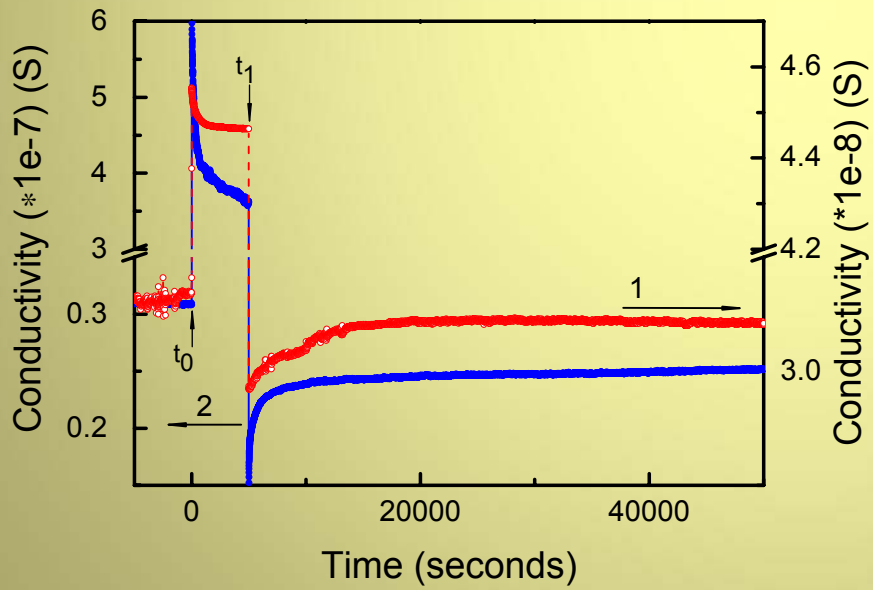


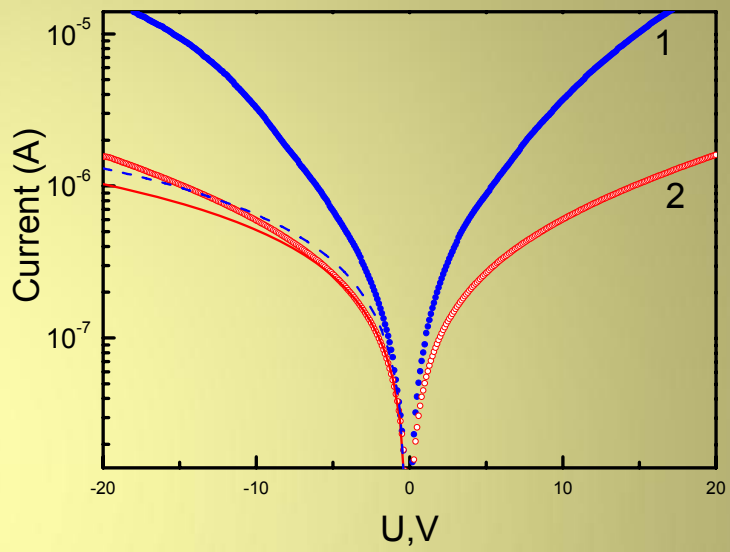




Conductance relaxation under high field excitation







- Glassy behavior can be obtained even in system without interaction due to the exponential dependence of the transition rates *w* on hopping length:

$w = w_0 \exp(-x) \qquad x = 2r/\xi + \varepsilon/kT;$

$\Delta G(t) \propto \ln(w_{\min} t)$

- Interactions may further enhance the glassiness of the system

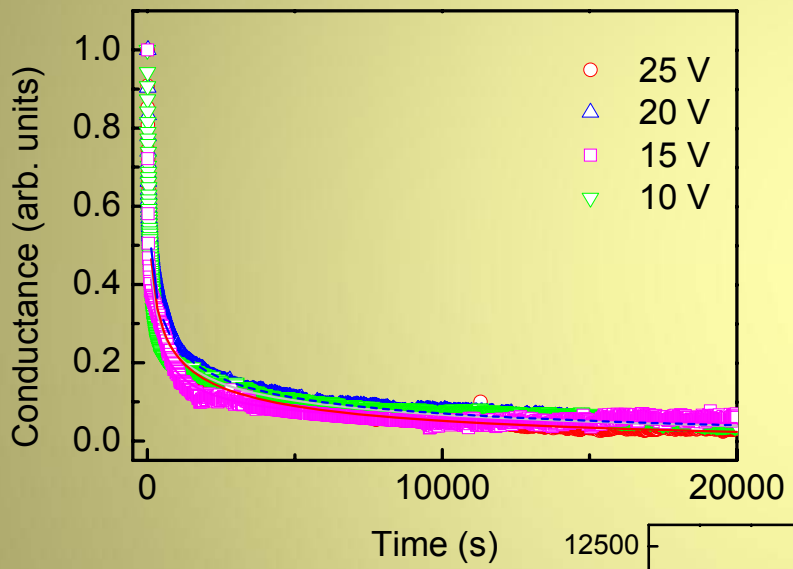
[M.Pollak et al. Phys. Rev. B **59**, 5328 (1999)]

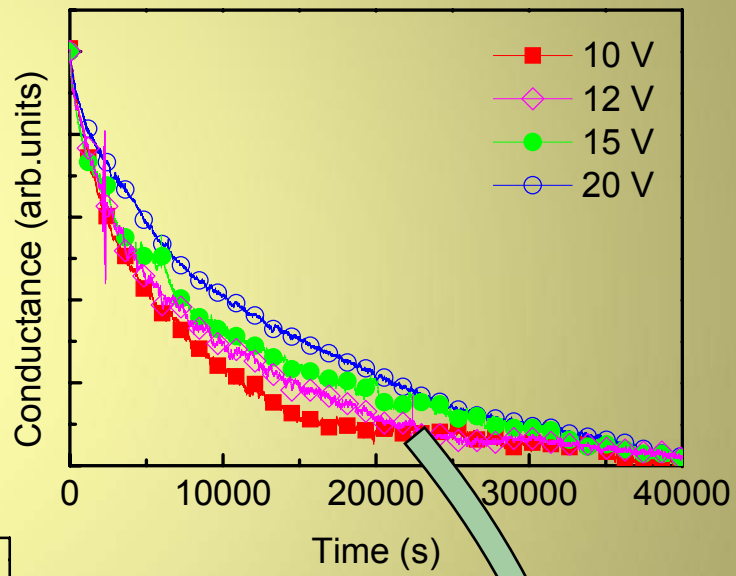
Relaxation law

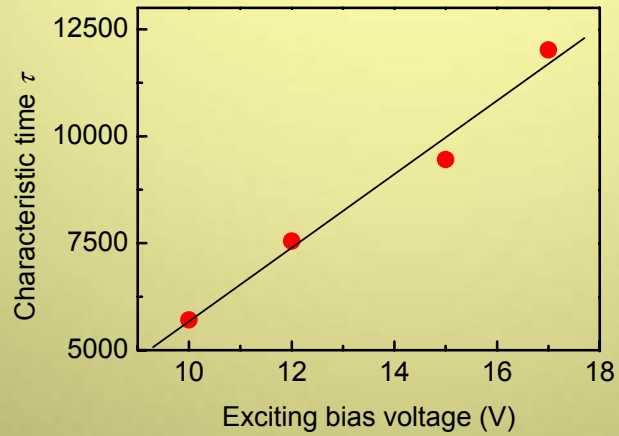
$$F(t) = A\exp[-(t/\tau)^{\beta}]$$

screened
$\beta \sim 0.17 \pm 0.005$

unscreened
$\beta \sim 0.66 \pm 0.005$





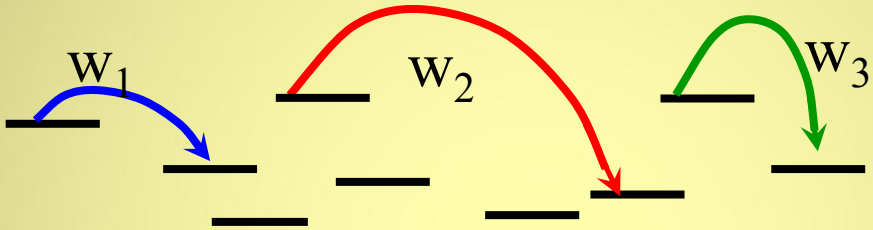


Distribution function

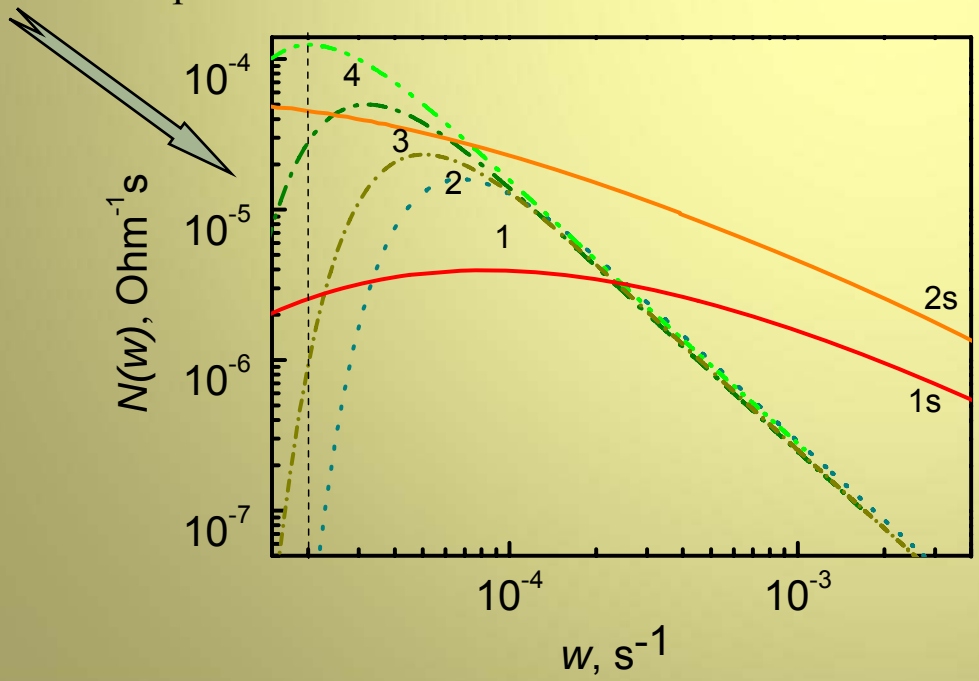
$$F(t) \approx \int N(w) e^{-wt} dw$$

1.Statistical distribution of the relaxation rates *w,* parallel relaxation channels

N(w) –distribution function of the transition rates

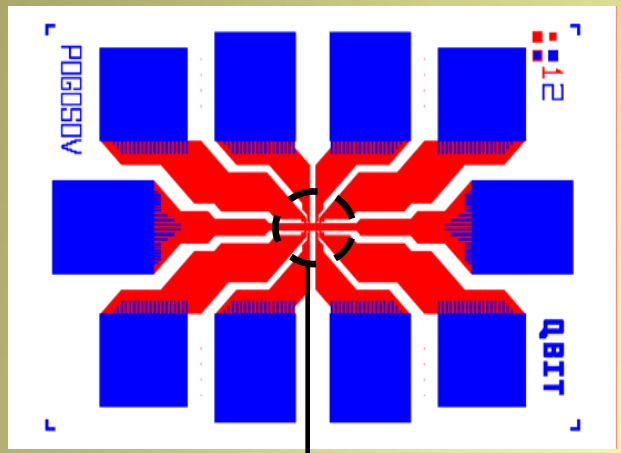


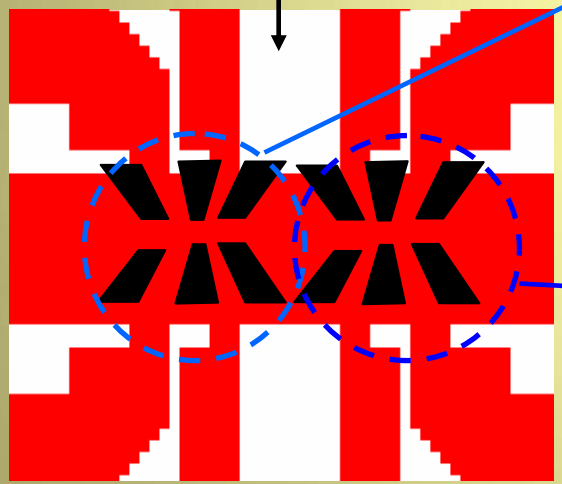
Inverse Laplace transformation of the relaxation law

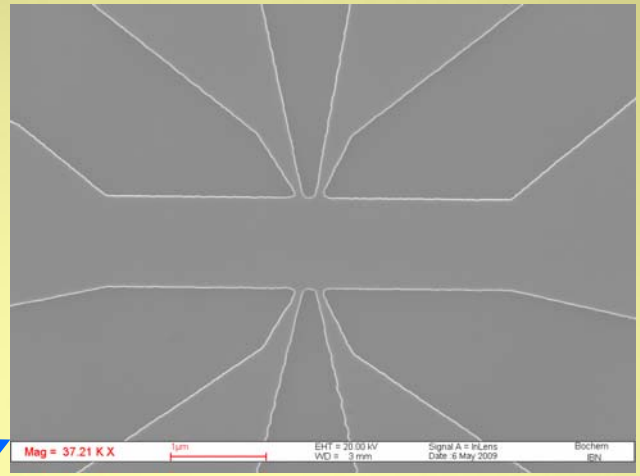


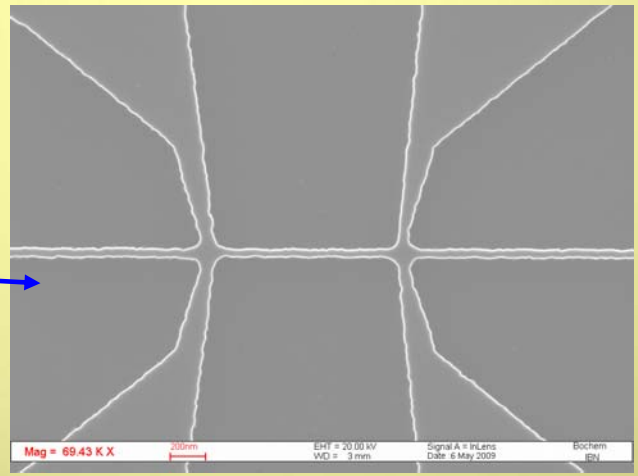
the interaction removes some of the transition events over almost all experimental time range

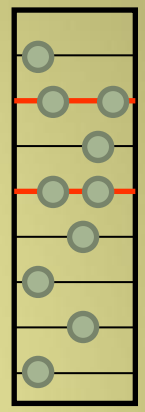
Mesoscopic structures with QDs



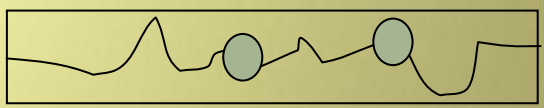








$$G=\Sigma G_i$$

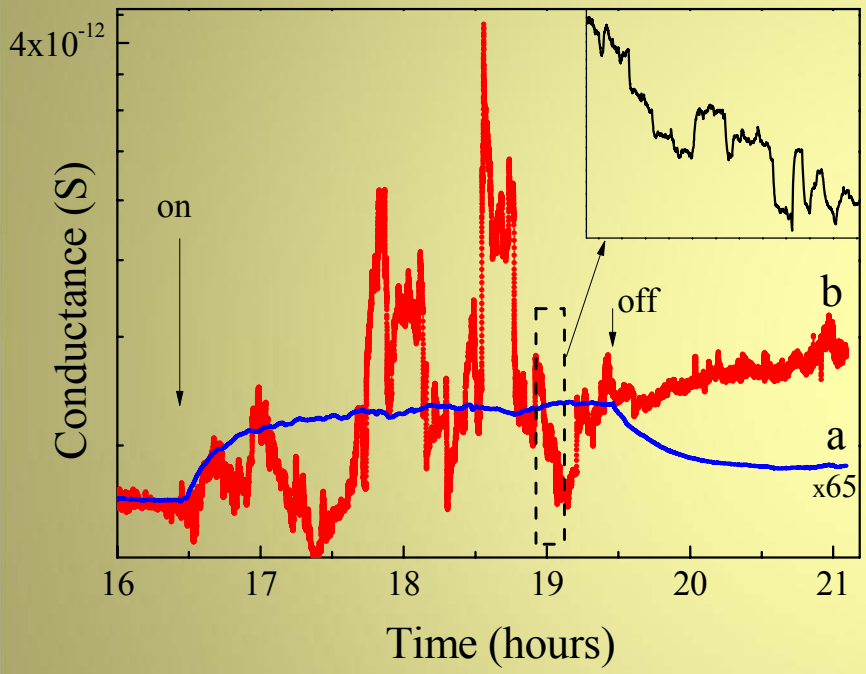


$$R=\Sigma R_i$$

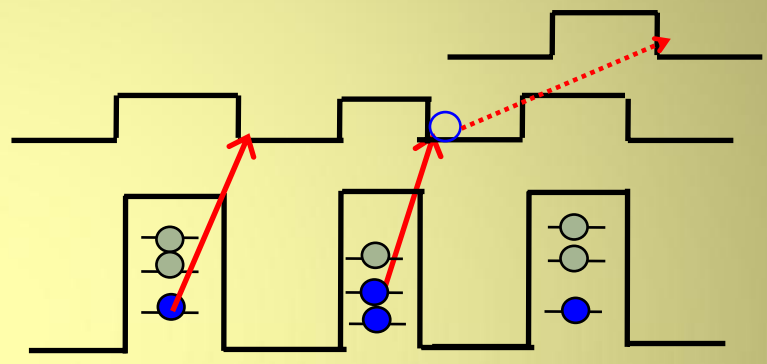
Channel size ~70-500 nm

We present the experimental results of photo-induced conductance fluctuations in nanometer size QDs structures with different width and length of conductance channels under small flux of infrared illumination.

Photoconductance fluctuations in mesoscopic structures



Photoconductance kinetics for meso- (b) and macroscopic (a) samples.

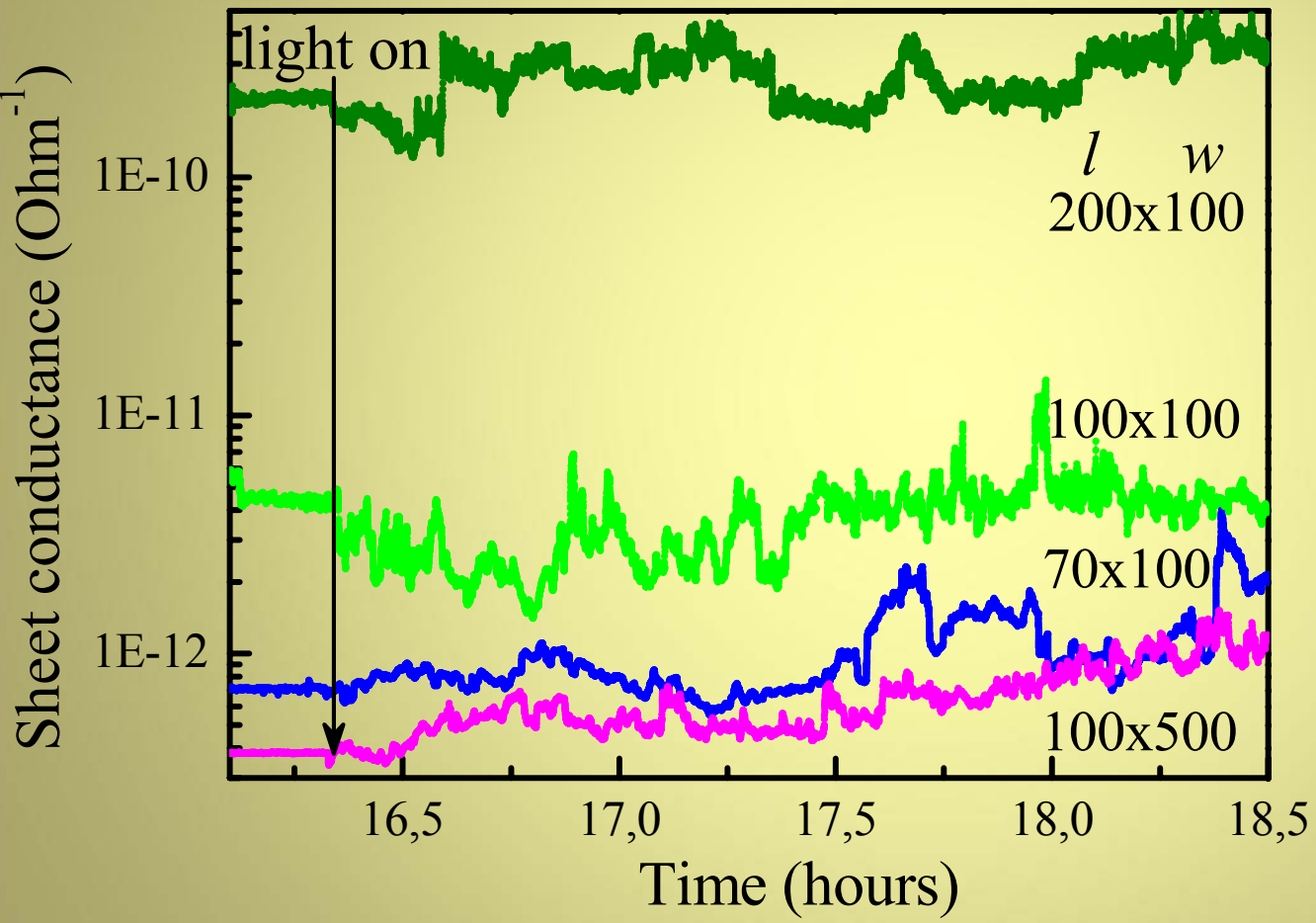


Redistribution of the carriers between different QDs inder illumination

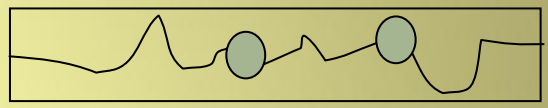
↓

new potential landscape ⟶ new conductive path providing change of the conductance with time.

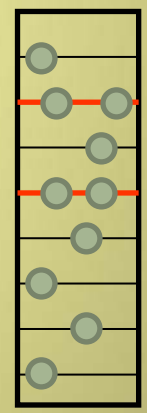
Effect of different structure size and geometry on photoconductance kinetics



Quasi-1D

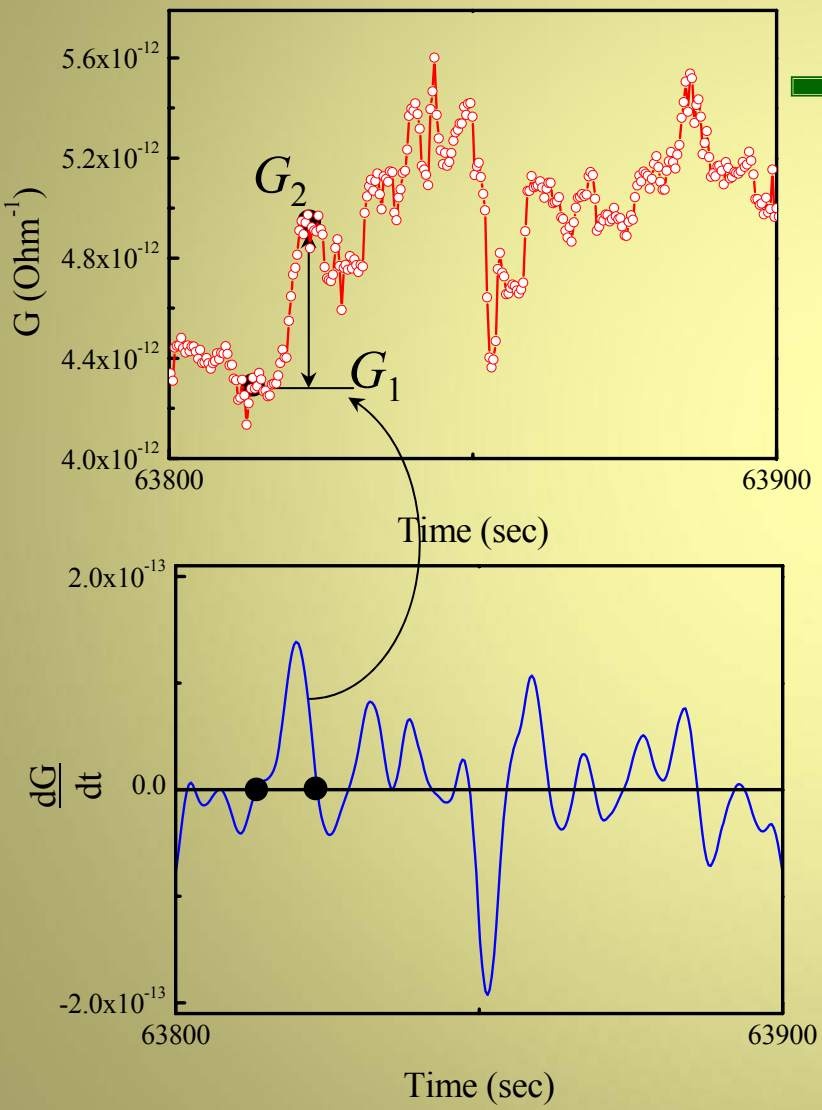


2D-short

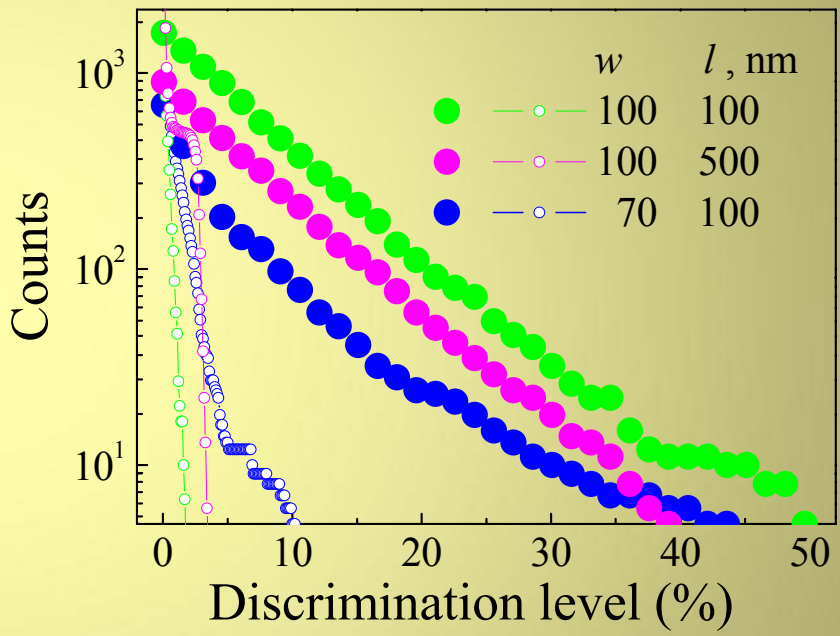


Photoconductance kinetics for samples with different size and geometry.

The method of experimental fluctuation treatment

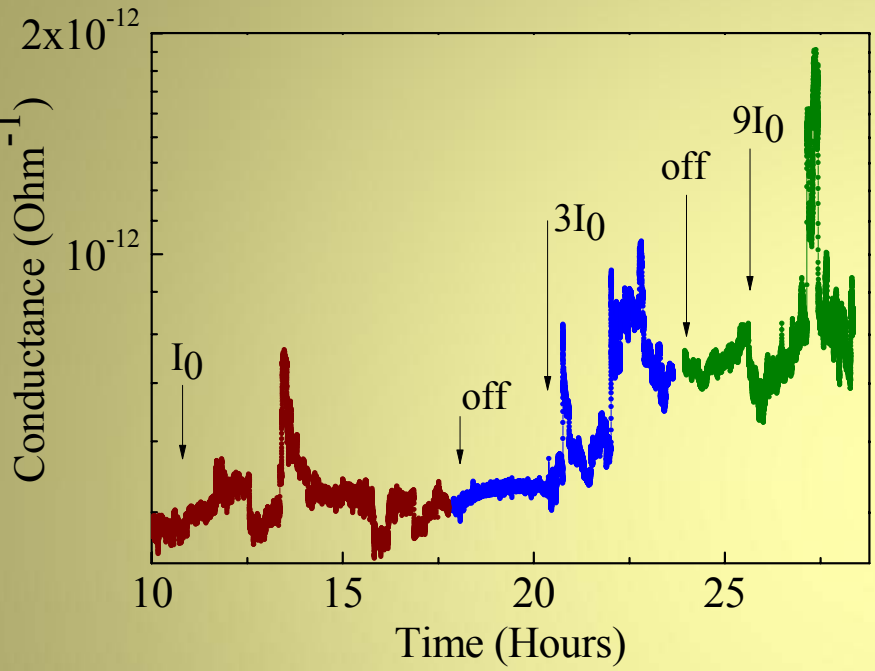


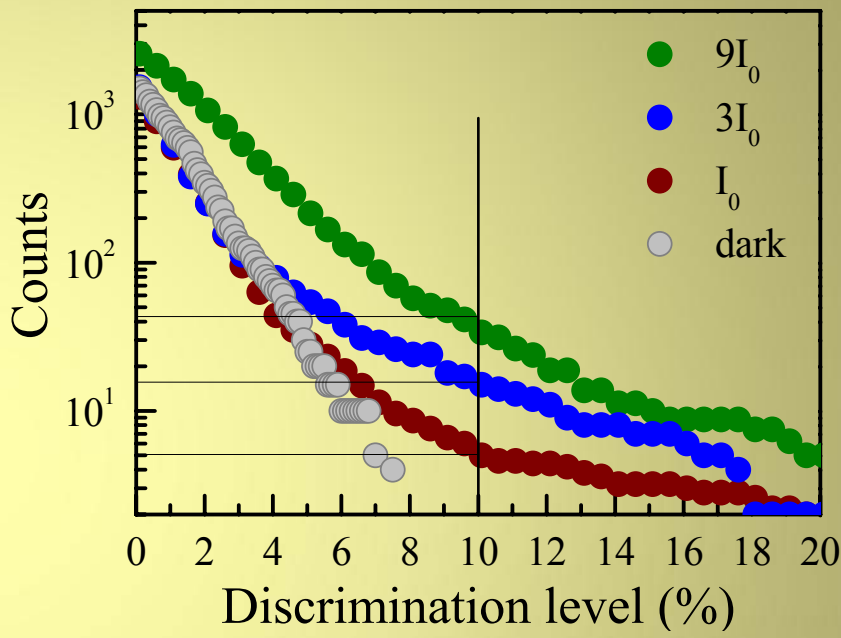
$\Delta G=(G_2-G_1)/G_1$ – discrimination level

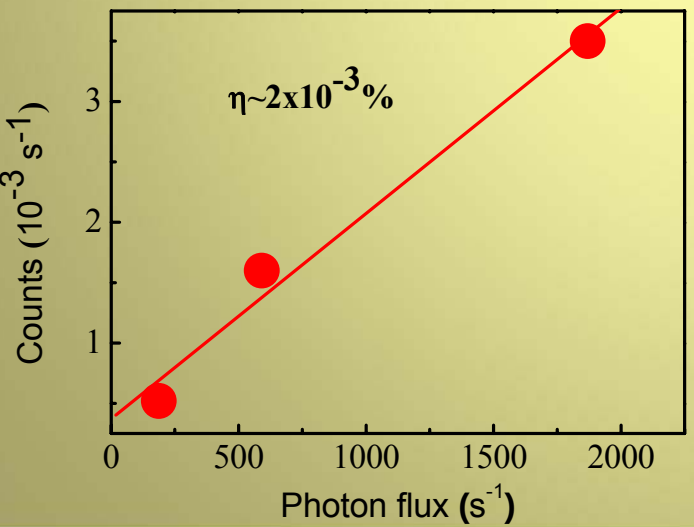


Number of counts with different fluctuation amplitude in dark and under illumination

Dependence of counts on light intensity







Linear dependence of counts on light intensity – as expected for a single-photon process

Conclusion

1.The electron transport in QD array is described by VRH with Coulomb gap.
2. Screening of interaction leads to a the transition to Mott transport; “m” changed from m~0 to m=-1.
3. Conductance and localization radius are strongly and non-monotonously depend on hole number.
4. The crossover from strong to weak localization in the massive of QDs has been observed at the variation of the filling factor of dots with holes and QDs array density, and also after samples annealing allows to change the QDs sizes and composition.
5. It was shown that the system state describes by the single-parametric scaling hypothesis for the samples with small variation of interaction. From the asymptotics of the universal function, the bounds separating the diffusive ($G > 0.4\frac{e^2}{h}$) and hopping ($G < 10^{-2}\frac{e^2}{h}$) regimes were established.
6. PC with sigh depending on initial hole filling factor was observed. Kinetics of the PC has anomalous slow behavior.
7. The relaxation under high field excitation is slowed down in the presence of Coulomb interaction.
8. Mesoscopic behavior in conductance was observed under light illumination of samples with channel size 70-500 nm.
9.The amplitude and number of conductance fluctuations depend on size and geometry of the conductive channel.
10.The number of counts is linearly changes with light intensity as it expected for single-photon process