JIAN's LABORATORY, NCHU, Taichung, Taiwan (2003)
Moved to NCTU, Hsinchu, Taiwan (2004)

Magnetic Properties of Nanowires and Nanoparticles
PbSe Nanocrystals, ZnCoO Nanowires

1. J. Chem. Phys.124, 064711 (2006).
2. J. Appl. Phys. 99, 08N708 (2006).
3. Phys. Rev. B 73, 233308 (2006).
4. Nanotechnology 17, 5511 (2006).
5. J. Nanosci. Nanotechnol. 8, 202 (2008).
6. New J. Phys. 10, 033017 (2008).
7. J. Phys. Chem. C. 112, 9168 (2008).

Electrical Properties of Nanowire Based Nanoelectronics
ZnO, InP, GaP, RuO2 Nanowires

1. Appl. Phys. Lett. 90, 013105 (2007).
2. Appl. Phys. Lett. 90, 223117 (2007).
3. **Nano Lett. 8, 3146 (2008).**
4. Chem.-Eur. J. 15, 4546 (2009).
5. Adv. Funct. Mater. submitted (2009).

Electronic Structures of Nanocrystals by Using LTSTM
PbSe Nanocrystals, Au Nanoparticles

1. J. Phys. Chem. C (ASAP, 2009). **Cover Art of Issue 18**
2. Nanotechnology accepted (2009).

Size Effects in Collective Transport at Coupled PbSe Quantum Dot Arrays

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[2]Department of Electrophysics, National Chiao Tung University, Hsinchu 30010 Taiwan

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Binghamton, NY 13902-6000

OUTLINE

1. Introduction to Phenomena of Colloidal Quantum Dot
   a) Single Electron Tunneling (orthodox theory)
   b) Memory Effects
   c) Collective Transport (Middleton & Wingreen model)
   d) Artificial Atom States

2. Experiment

3. Results and Discussions
   a) The Array Is Regarded As An Island
   b) The Array Is Regarded As Coupled Quantum Dots

4. Conclusion

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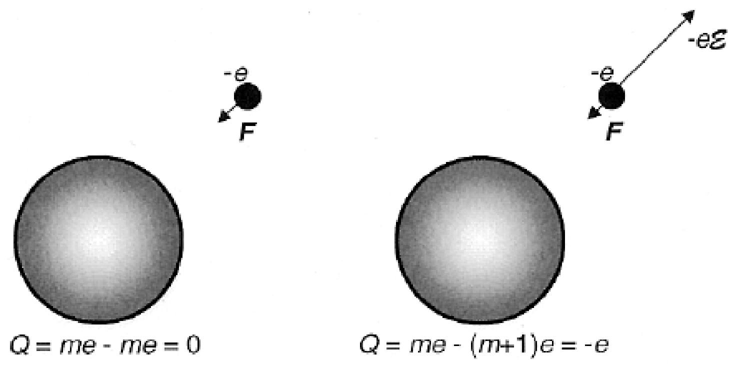
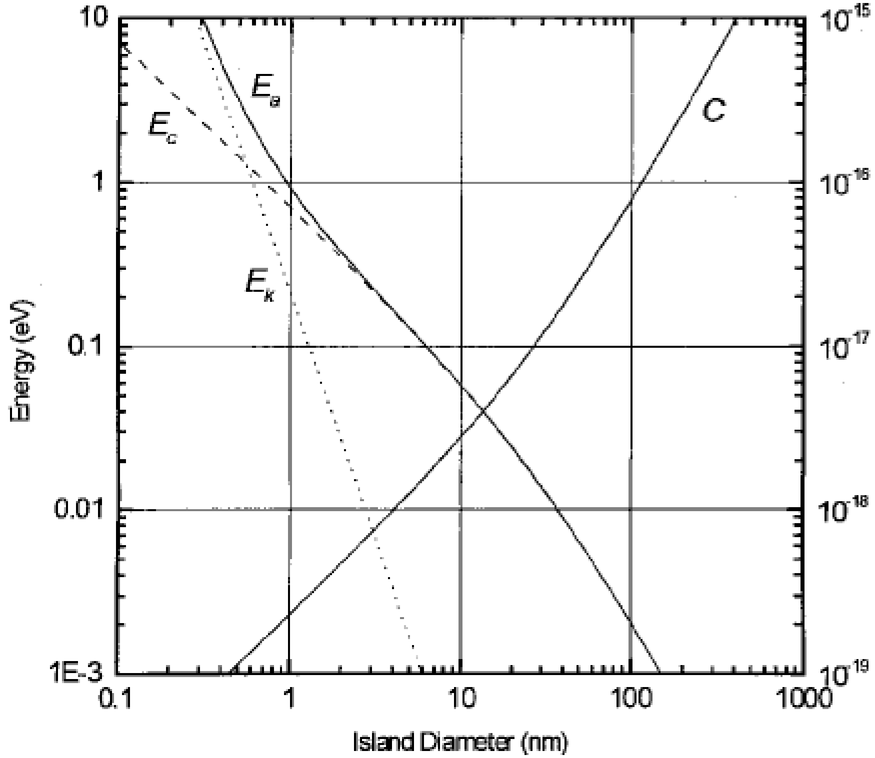
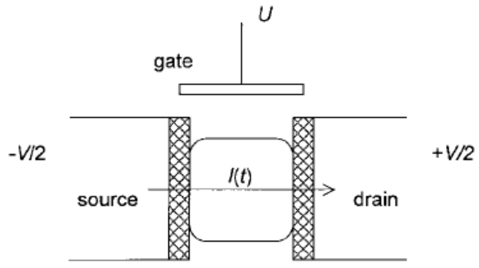
1. Introduction – a) single electron tunneling

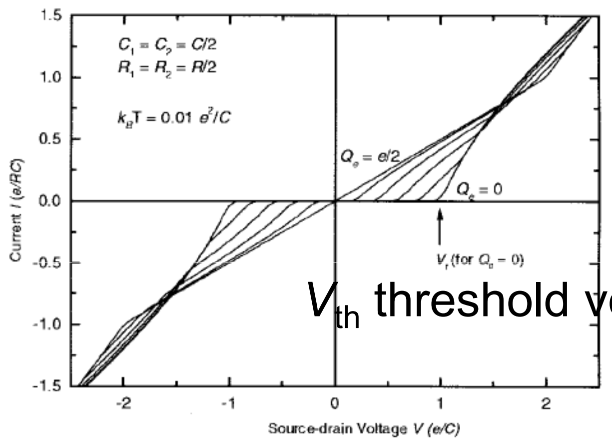


(a) (b)



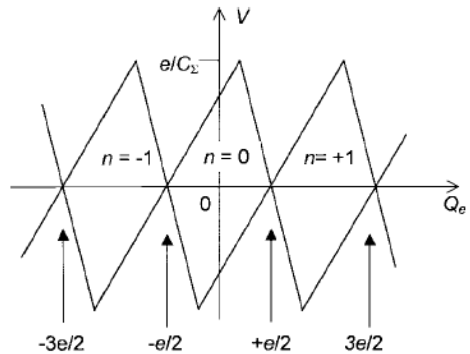


(a)



(b)

V_{th} threshold voltage



(c)

K. K. Likharev, *Proc. IEEE* **1999**, *87*, 606.

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1. Introduction – a) single electron tunneling

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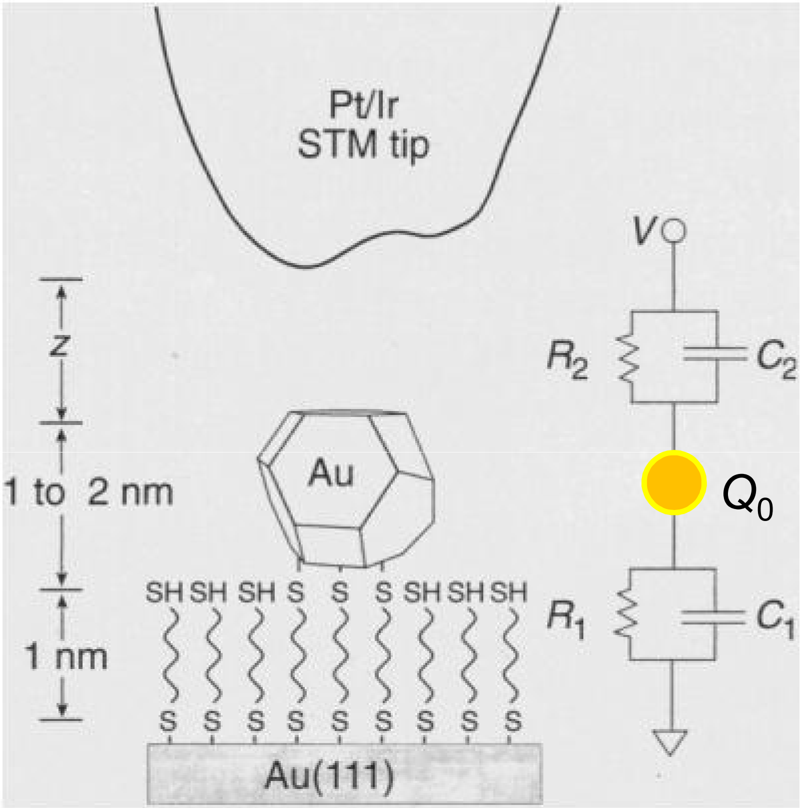
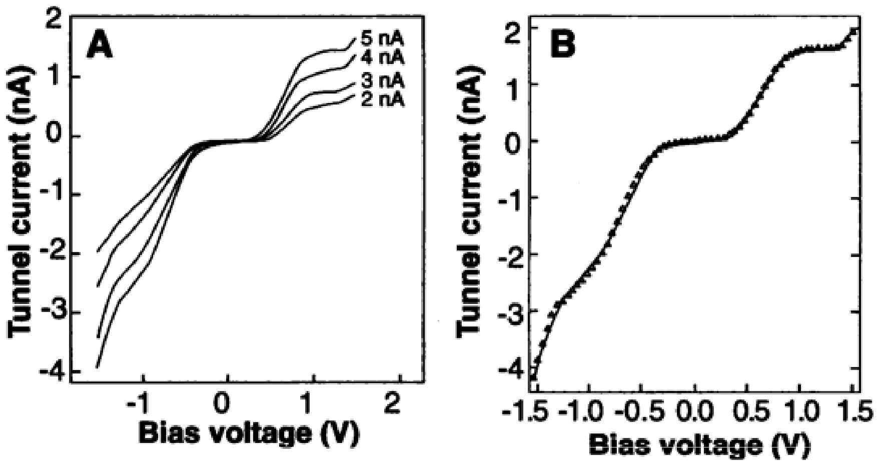


Double-ended aryl dithiol [α,α'-xylyldithiol (XYL) and 4,4'-biphenyldithiol] formed SAM. Semiclassical model (orthodox theory) of Coulomb blockade.



Coulomb staircase at room temperature in a self-assembled molecular (SAM) nanostructure by using STM in a ultra-high vacuum.

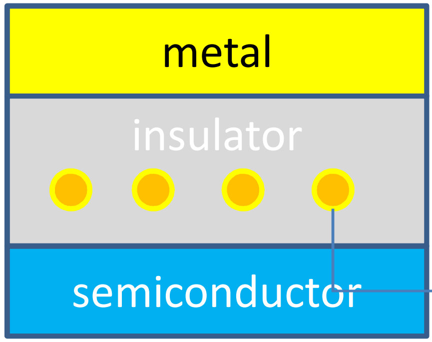
C_2=0.13 aF, C_1=0.08 aF

R_2=V/I, R_1=1.8 MΩ

Q_0=-0.2 e (polarization charge)

R. P. Andres et al., *Science* **1996**, *272*, 1363.

1. Introduction – b) memory effects



Silicon oxide
Aluminum oxide
small metal particle

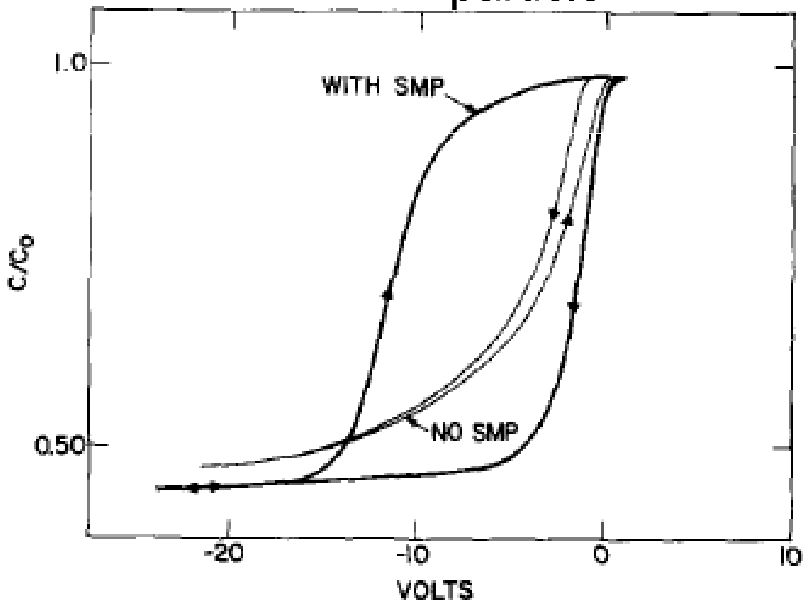
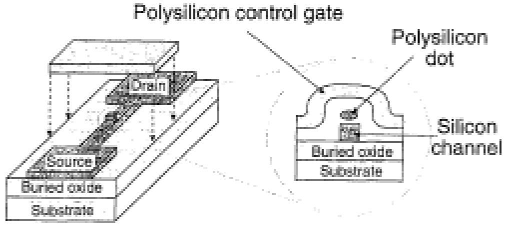
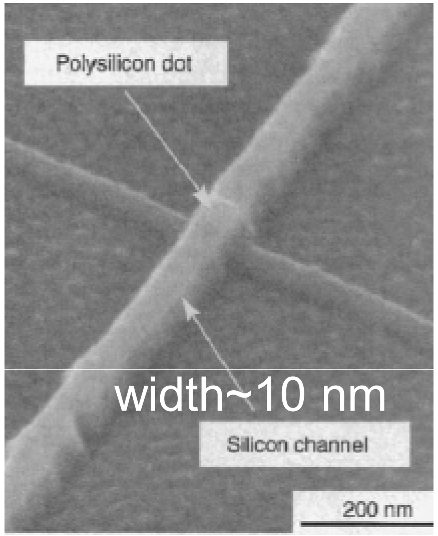
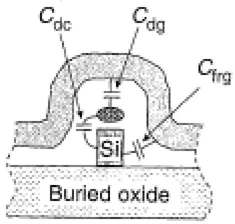


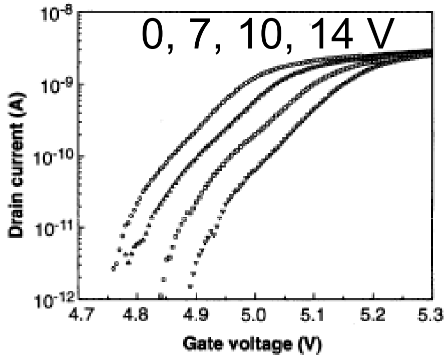
FIG. 1. Capacitance-voltage characteristics for similar samples with and without SMP.

R. B. Laibowitz and P. J. Stiles, *Appl. Phys. Lett.* **1971**, *18*, 267.









The I-V changes after the control gate is pulsed by charging voltage ranging from 0 to 14 V.

L. Guo, E. Leobandung, and S. Y. Chou, *Science* **1977**, *275*, 649.

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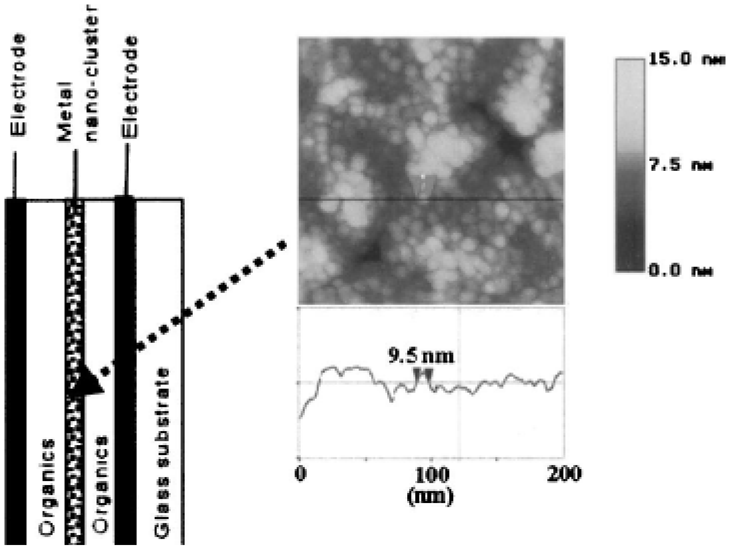
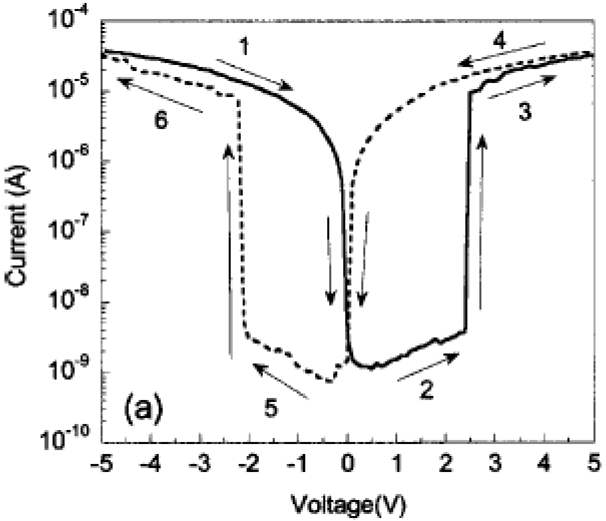
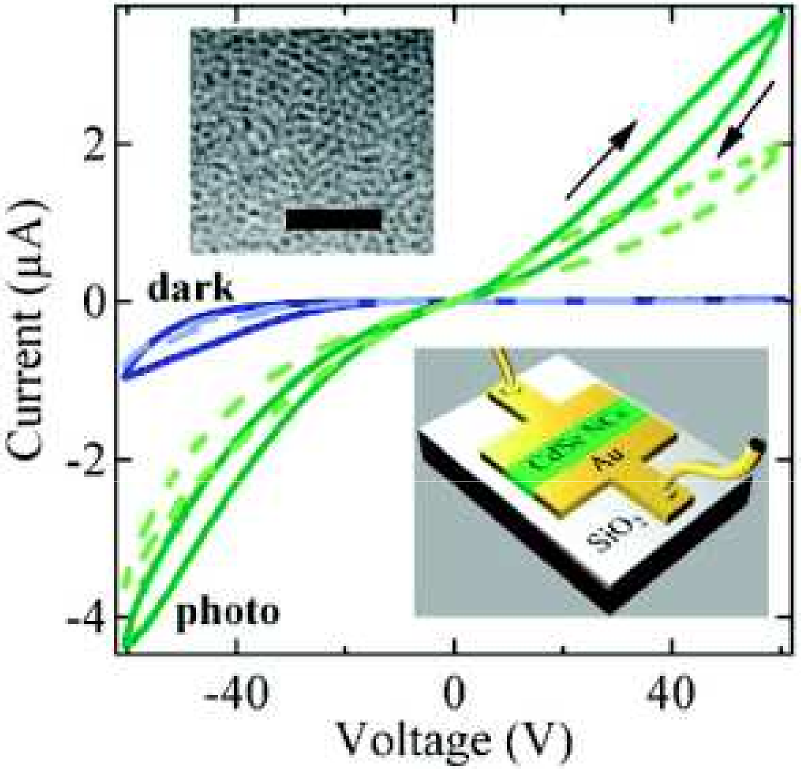
1. Introduction – b) memory effects





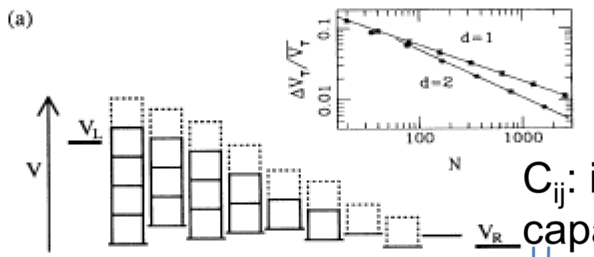
Nonvolatile electrical bistability.
L. Ma, S. Pyo, J. Ouyang, Q. Xu, and Y. Yang, *Appl. Phys. Lett.* **2003**, *82*, 1419.



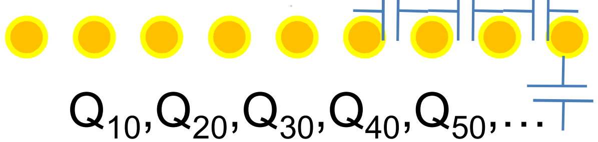
CdSe nanocrystal quantum-dot memory. NCs are photoexcited with a 532 nm wavelength (green) diode laser operating at 1 mW/cm^2.
M. D. Fischbein and M. Drndic, *Appl. Phys. Lett.* **2005**, *86*, 193106.

1. Introduction – c) collective transport

fluctuation of V_{th}



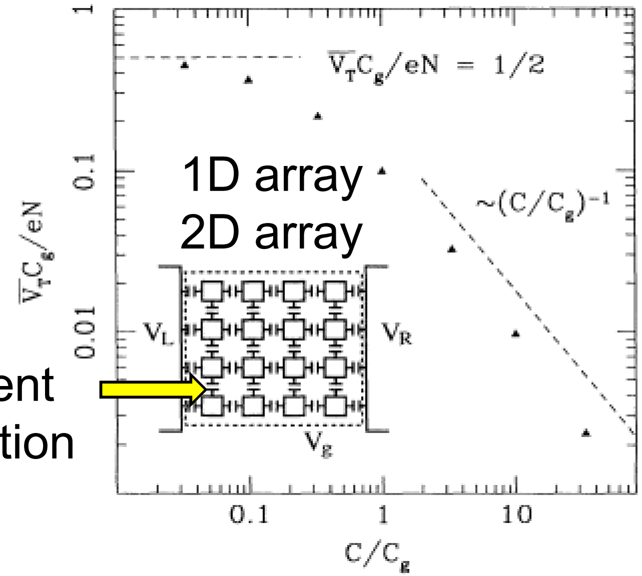
C_{ij}: inter-dot capacitance



C_g

$Q_{10}, Q_{20}, Q_{30}, Q_{40}, Q_{50}, \ldots$

Polarization charges render a disorder distribution

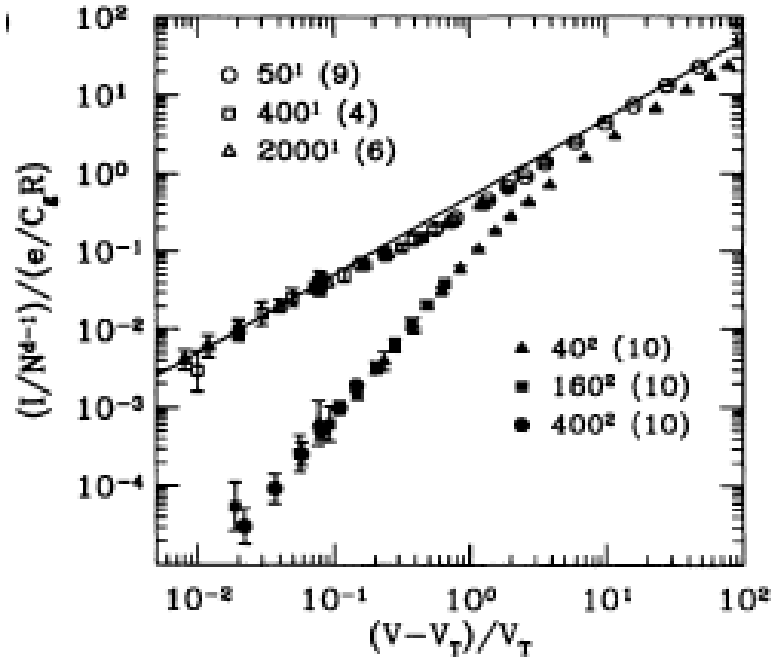


1D array

2D array

Current direction

$C_{ij} >> C_g$: long screening length and strong capacitive coupling



$$I \propto \left(\frac{V}{V_{th}} - 1 \right)^{\zeta}$$

1D: ζ=1

2D: ζ=5/3 or 2…

A. A. Middleton and N. S. Wingreen, *Phys. Rev. Lett.* **1993**, *71*, 3198.

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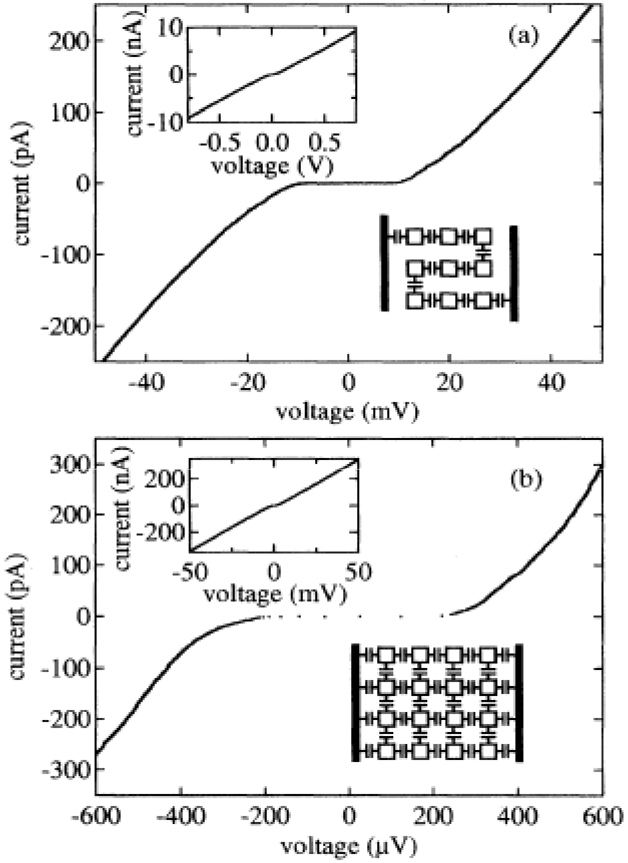
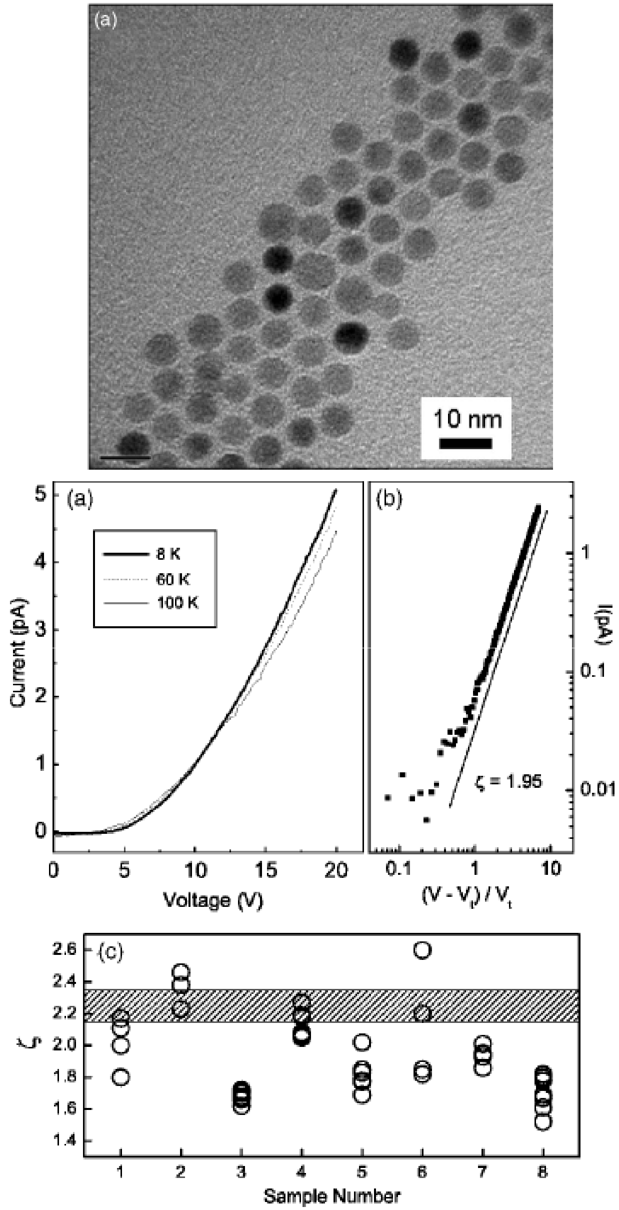
1. Introduction – c) collective transport



IV of 1- and 2D arrays of small metal islands.

A. J. Rimberg, T. R. Ho, and J. Clarke, *Phys. Rev. Lett.* **1995**, *74*, 4714.



K. Elteto, X. M. Lin, and H. M. Jaeger, *Phys. Rev. B* **2005**, *71*, 205412.

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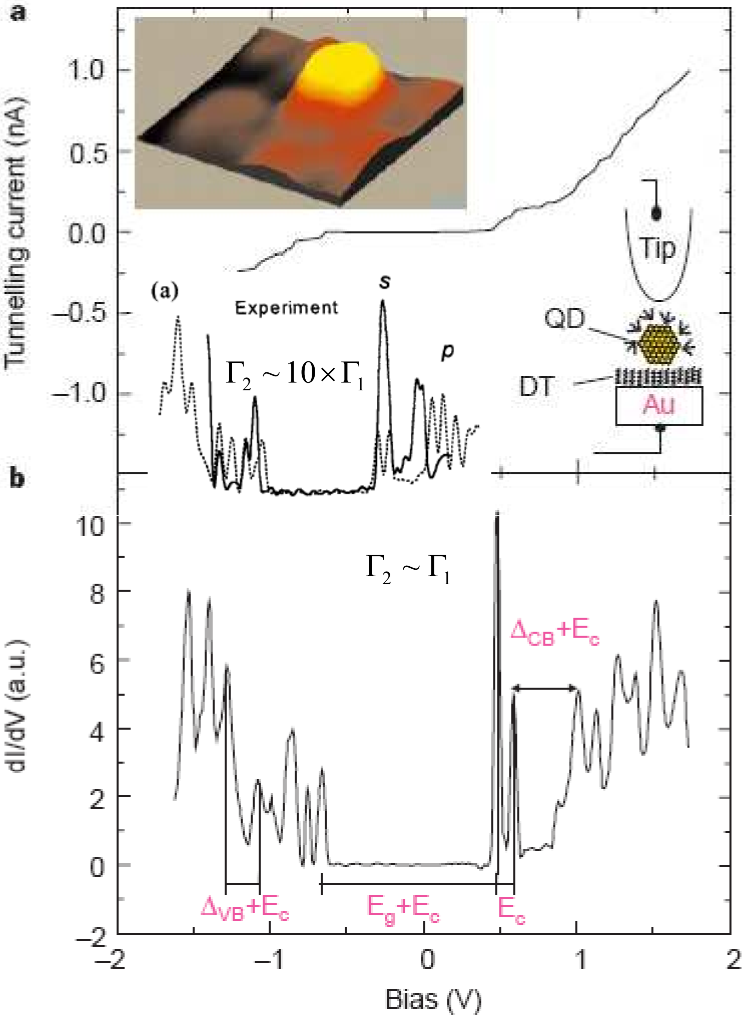
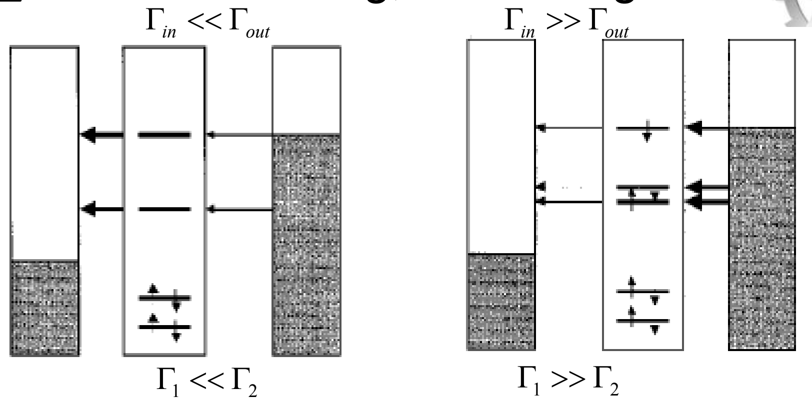
1. Introduction – d) artificial atom states

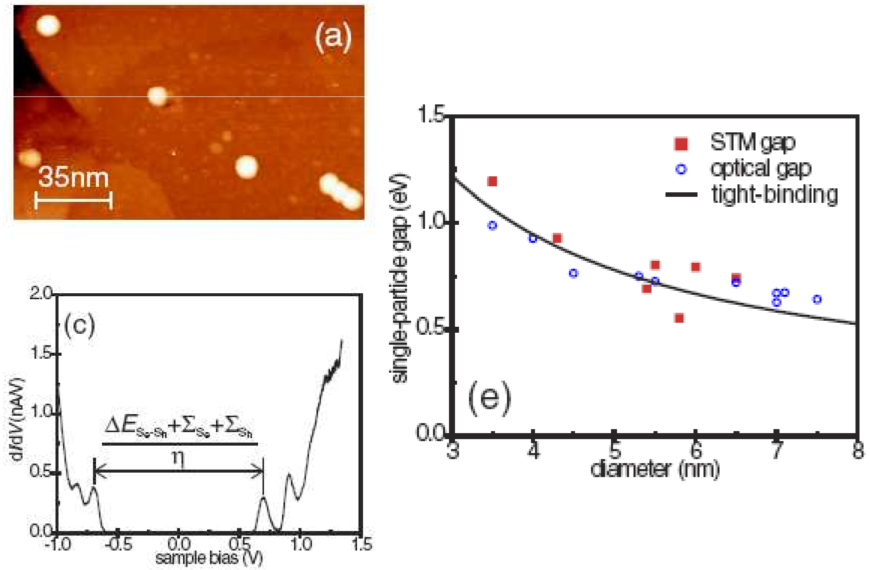


U. Banin, Y. Cao, D. Katz, and O. Millo, *Nature* **1999**, *400*, 542.

shell tunneling, shell filling



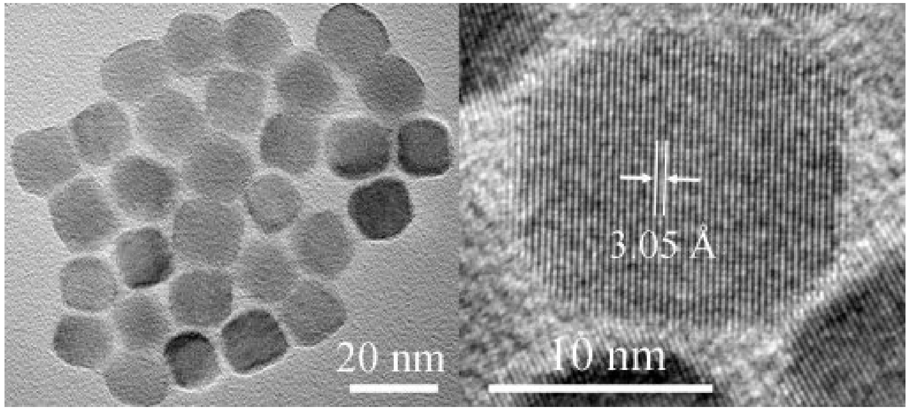
Nano Lett. **2001**, *1*, 551.

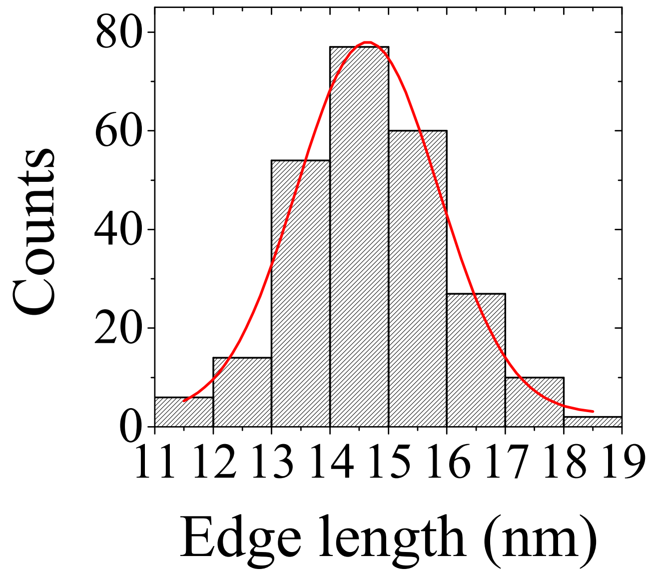


P. Liljeroth, P. A. Z. van Emmichoven, S. G. Hickey, H. Weller, B. Grandidier, G. Allan, and D. Vanmaekelbergh, *Phys. Rev. Lett.* **2005**, *95*, 086801.

2. Experiment

rock salt structure





1. PbSe quantum dots (QDs) were prepared by using a high-temperature organic solution approach.
2. The resultant PbSe QDs were identified using various characterizations including X-ray diffraction study, inductively coupled plasma analysis, transmission electron microscope (TEM, JEOL JEM-2010F) imaging and energy dispersive spectroscopy evaluation.
3. The average diameter and standard deviation of the QDs were estimated to be about **14.6** and 2.4 nm, respectively.

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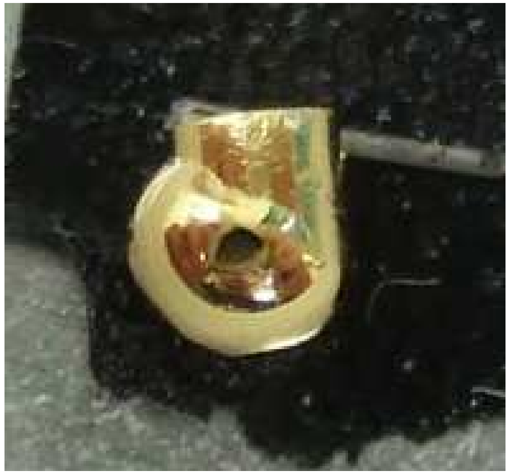
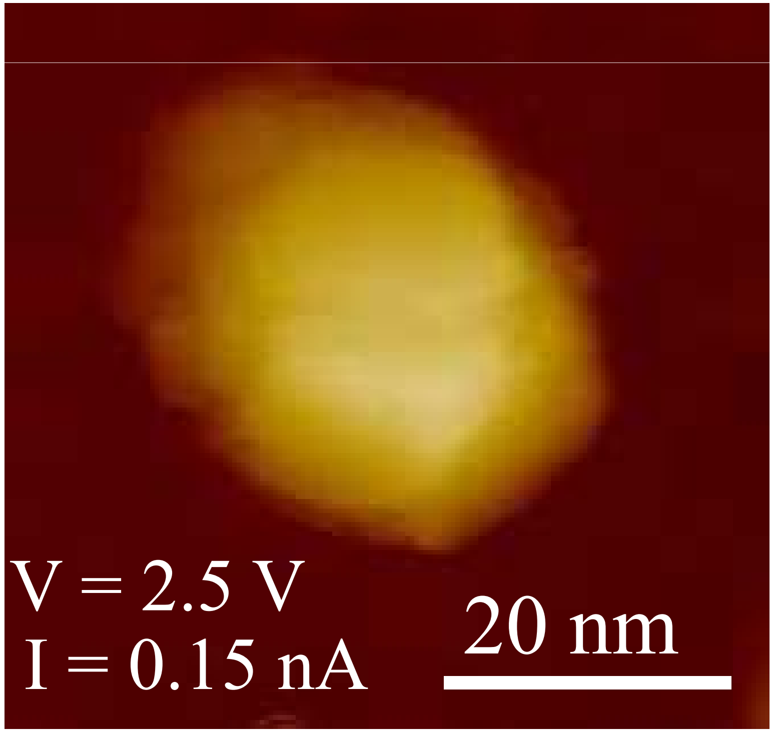
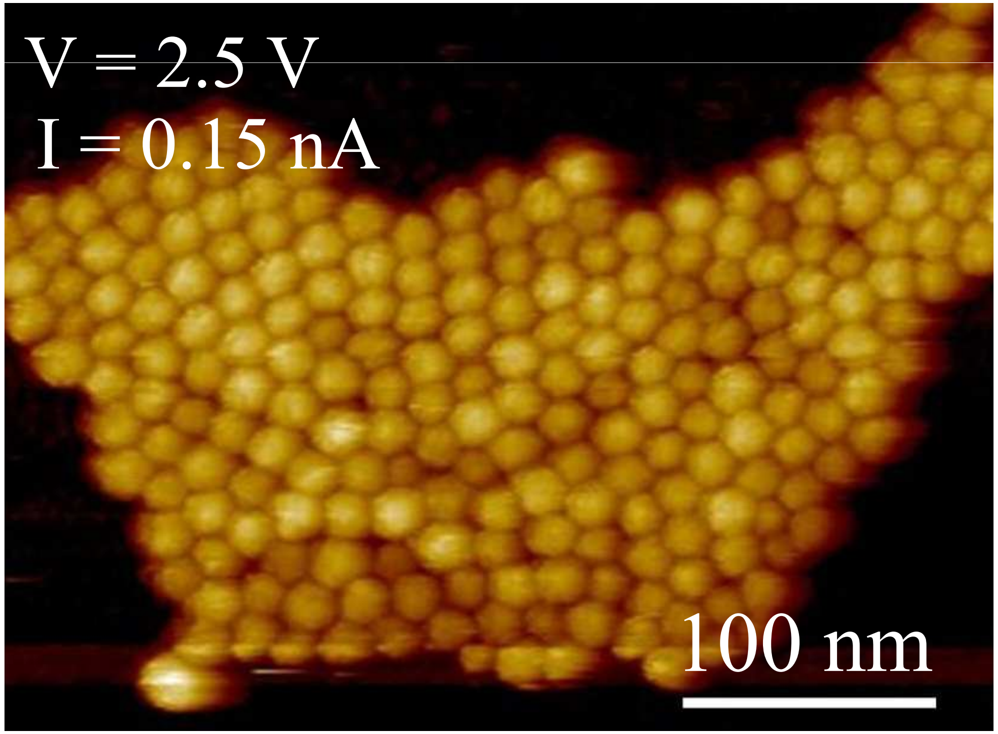
2. Experiment



1. The QDs were dispersed in toluene again to make a dilute QD solution.
2. Several drops of the solution were put on atomically flat Au(111) surfaces on the ball prepared by melting a 2-mm wire in a gas flame.
3. The sample was loaded in a **Omicron LTSTM** chamber in an ultra-high vacuum of 1×10^{-10} torr and it was heated up to 100-150^{o}C for more than 10 h.





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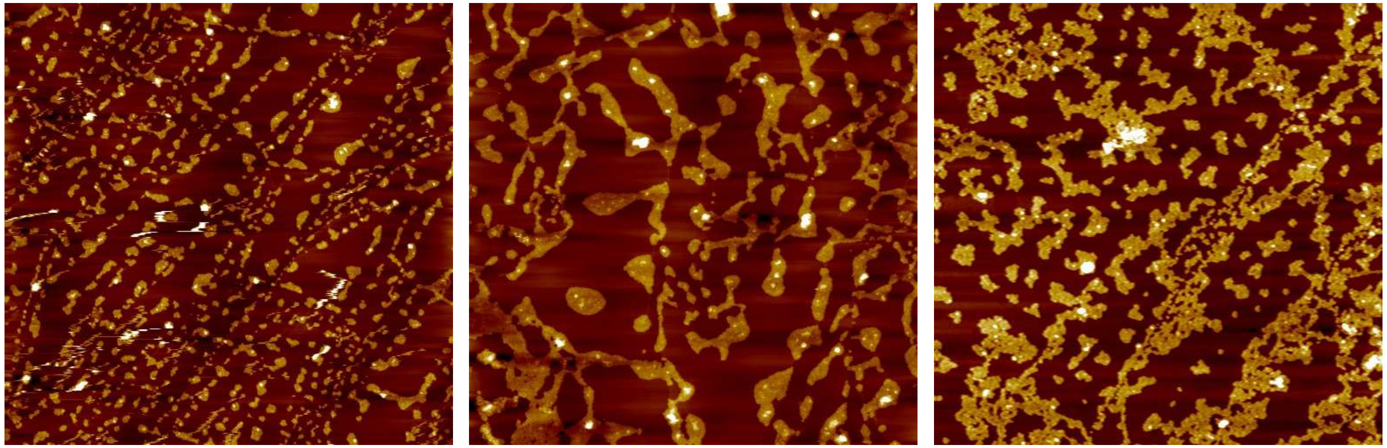
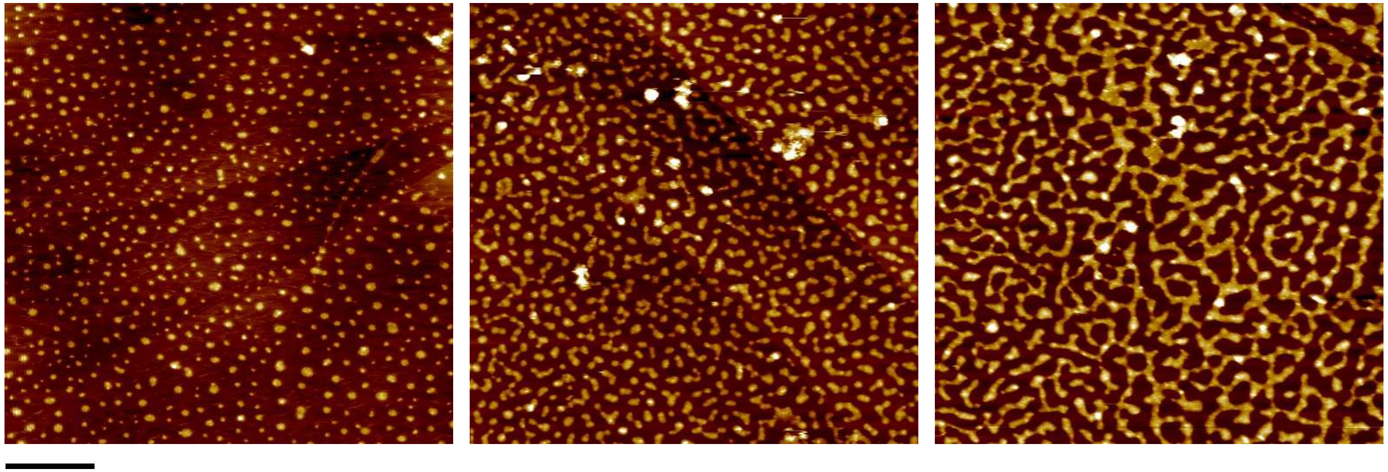
2. Experiment

High temperature



Low temperature



1 μm

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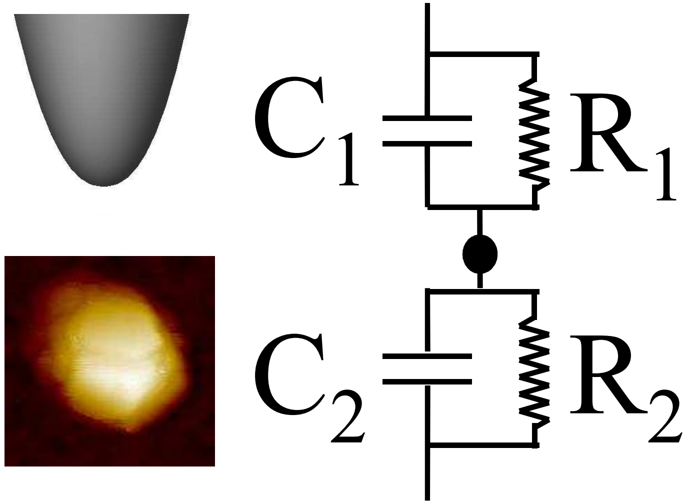
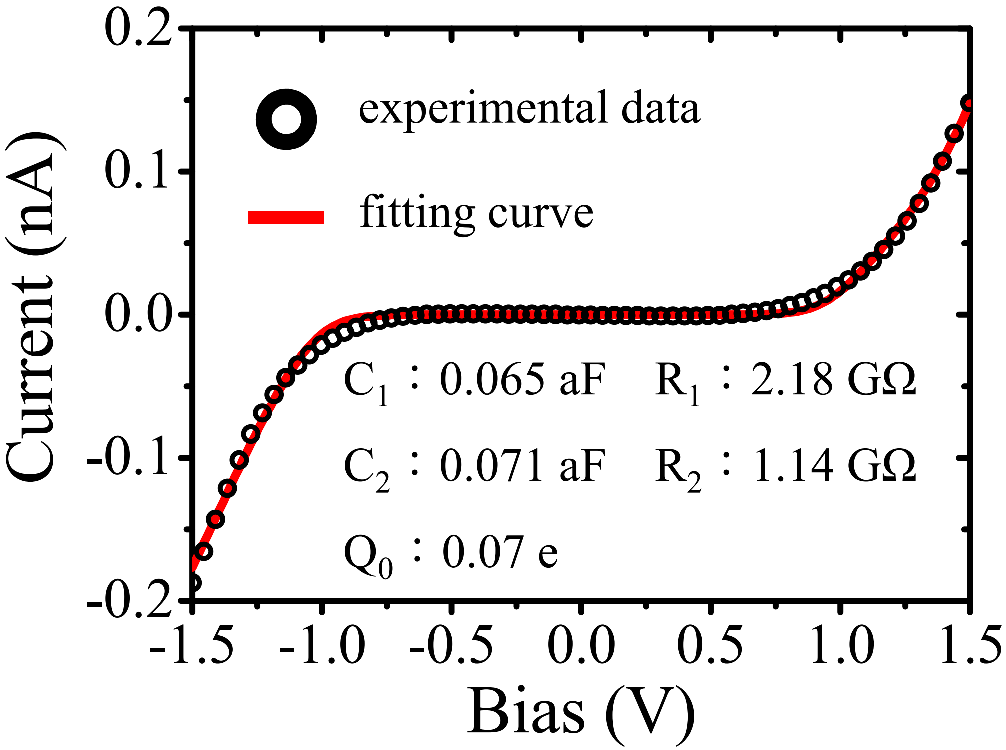
3. Results and discussions – single quantum dot

1. An STM tip is schematically drawn above the single QD to illustrate the corresponding tip-to-dot and the dot-to-substrate resistances (R_1 and R_2) and capacitances (C_1 and C_2) in circuit diagram of the model.
2. The experimental data can be fitted with the orthodox theory at **300 K** to get C_1, C_2, R_1, R_2, and the polarization charge Q_0.

$$E_c = \frac{e^2}{2(C_1 + C_2)} = 0.588\ eV > 25\ meV (300 k_B)$$





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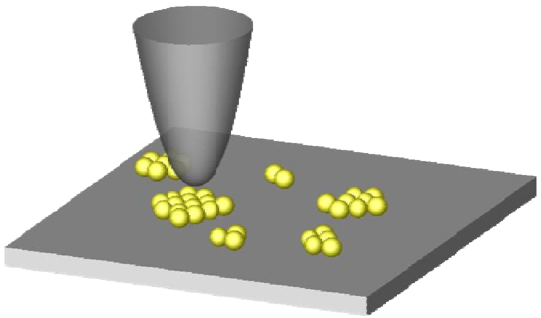
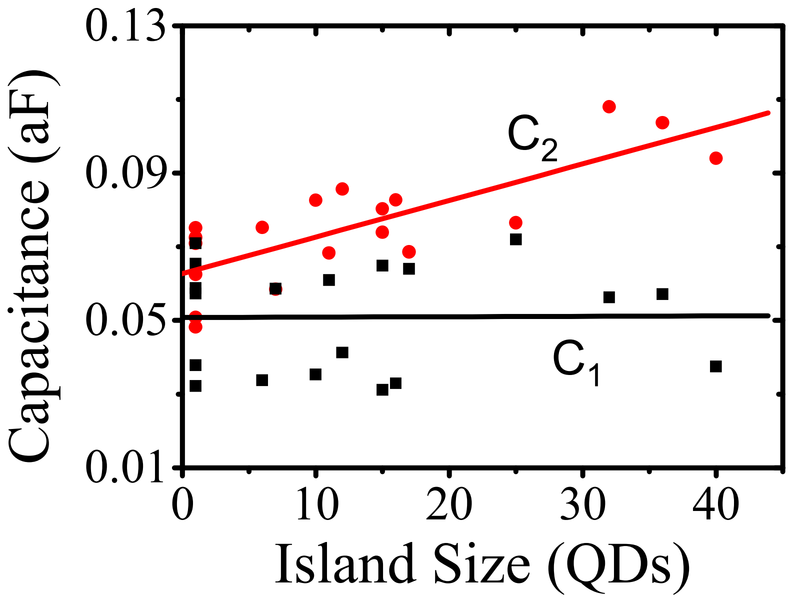
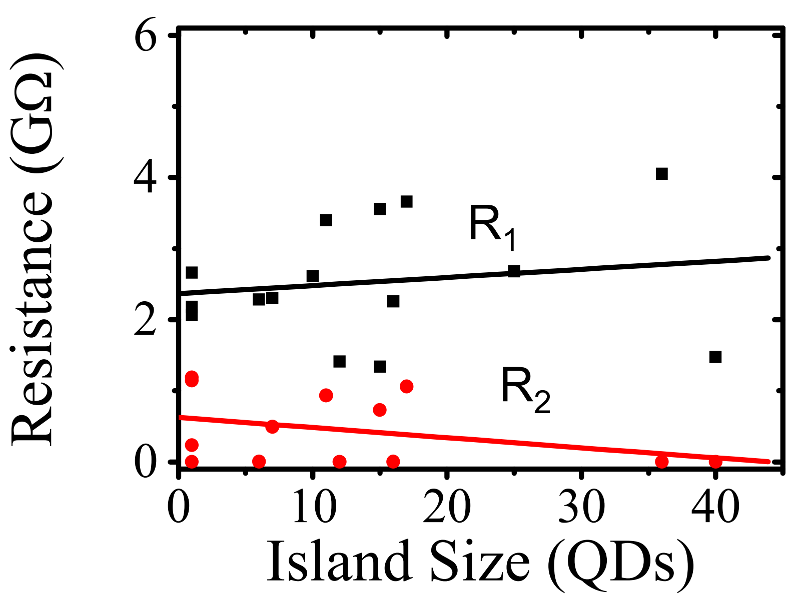
3. Results and discussions – the array is regarded as an island.



1. Hundreds of CITS image points are averaged to get a single characteristic *I-V* curve for analysis to obtain C_1, C_2, R_1, and R_2 for a specified QD array.
2. The area of the array expands about 40 times but C_2 only duplicates its values.
3. The small increase in C_2 implies that the QD array cannot be simply regarded as an island.





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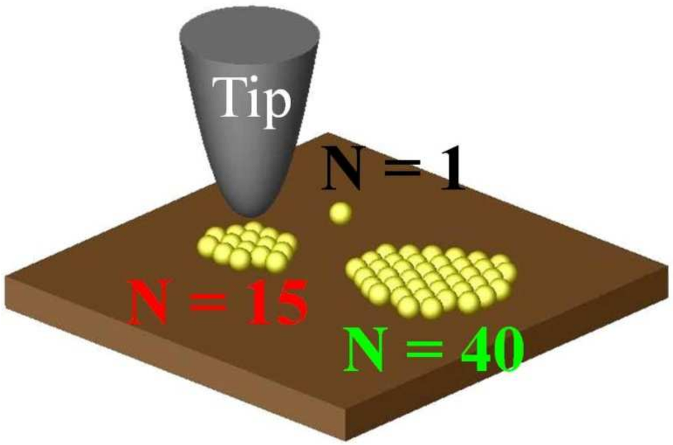
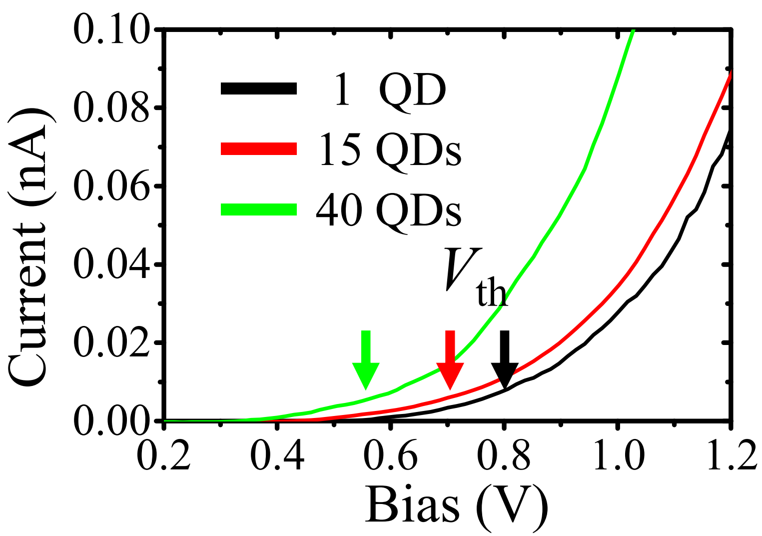
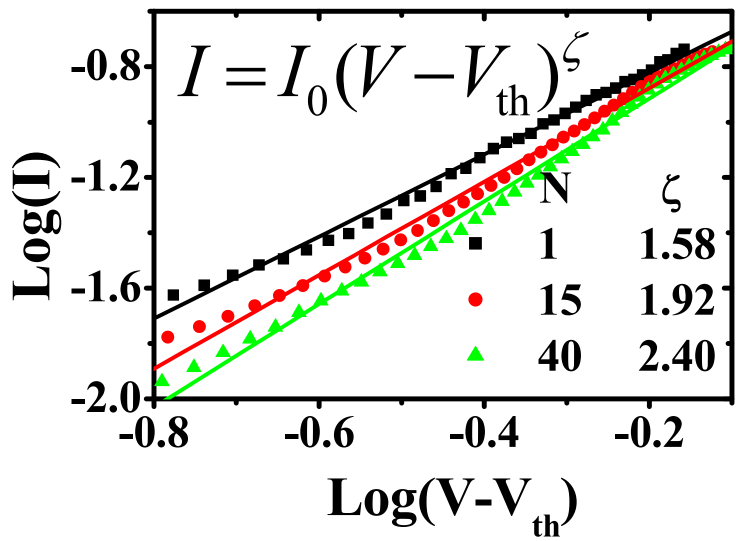
3. Results and discussions – the array is regarded as coupled quantum dots

Use collective transport & MW model to analyze IV data.

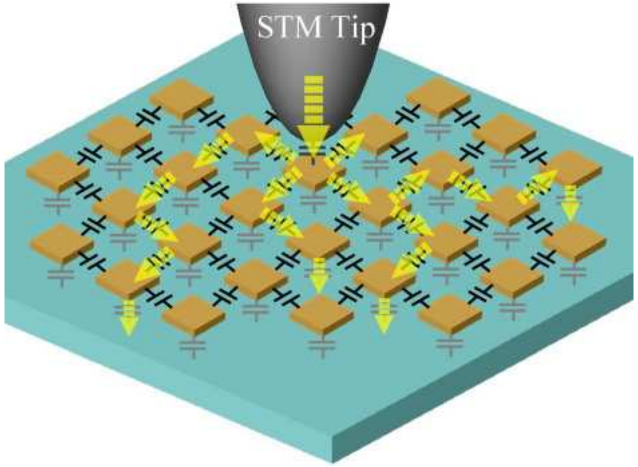


1. The averaged threshold current of ~5.5 pA of the single QD is used to evaluate the V_{th}'s of all the other QD arrays.
2. The IV curve show power law behavior $I(V-V_{th})$ exhibiting linear dependence in a logarithmic scale.

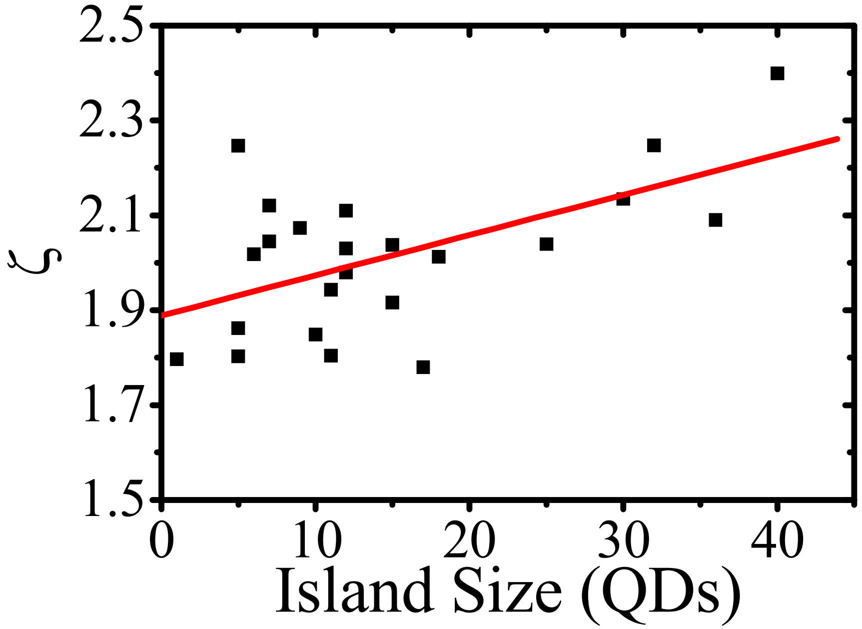


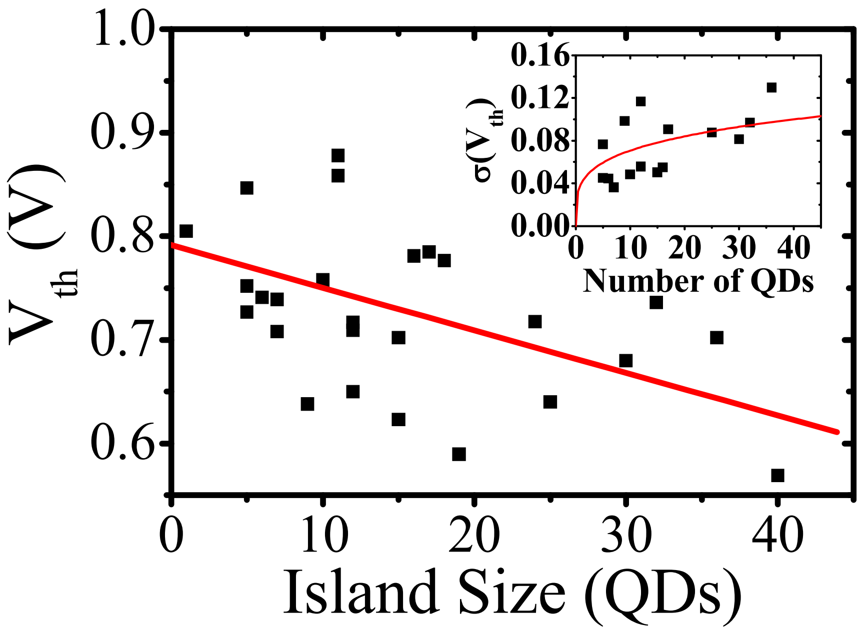


3. Results and discussions



1. The scaling exponent ζ gradually increases with an enlarging size of the PbSe QD array.
2. The threshold voltage V_{th} gradually diminshes from 0.8 to 0.6 V as the number of QDs increases from 1 to 40.
3. The standard deviation $\sigma(V_{th})$ of the fluctuation in V_{th} increases as $N^{1/4}$, where N is the number of QDs in the array.





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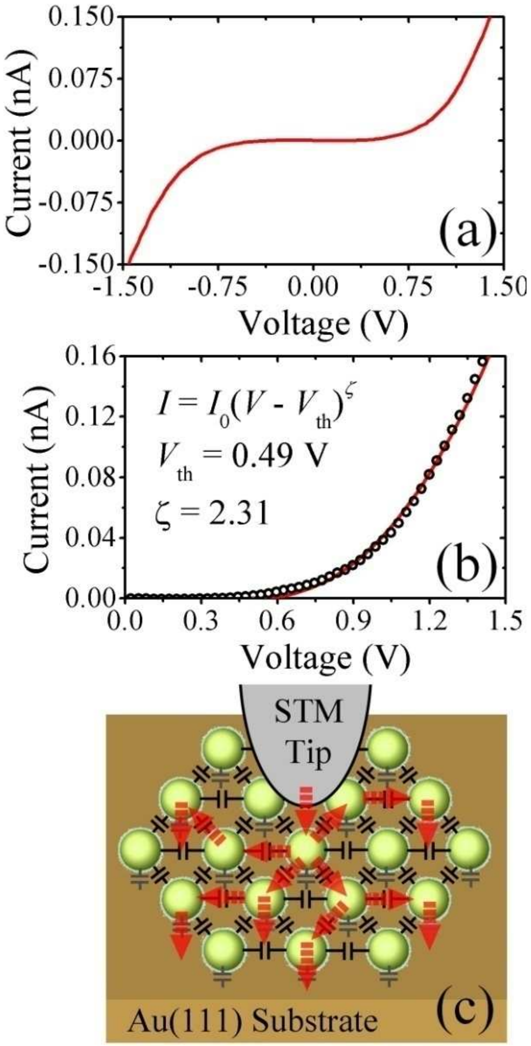
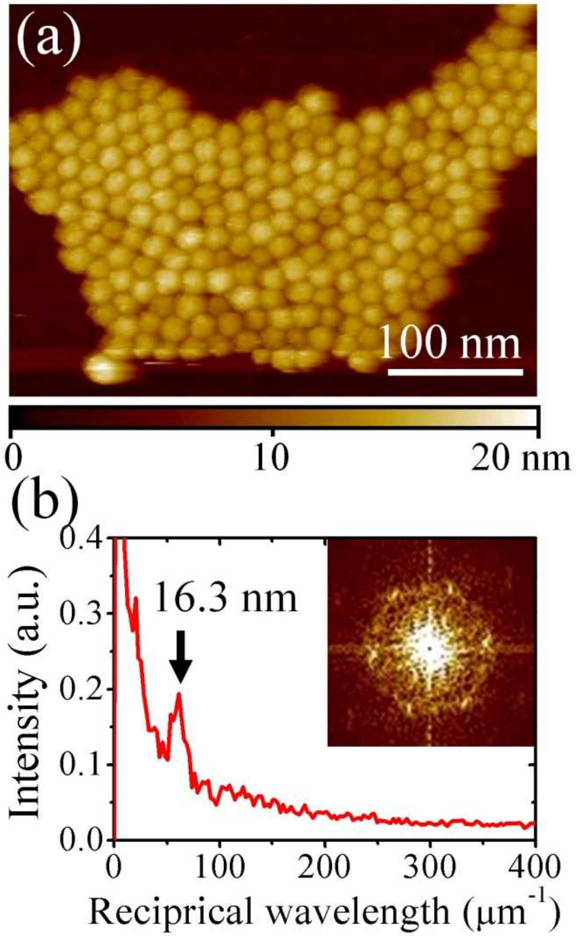
3. Results and discussions

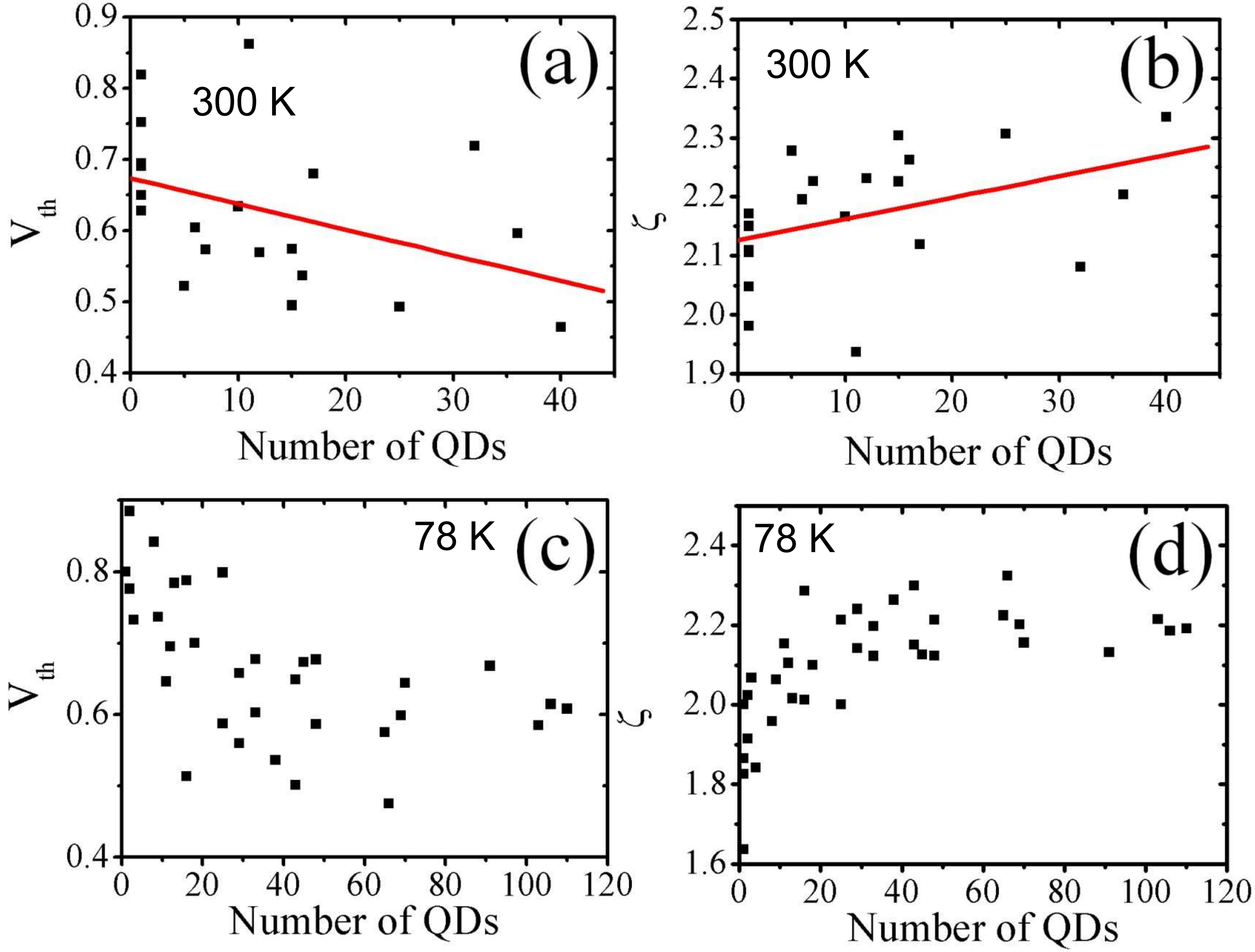
Analyzed by an another method, nonlinear least square fitting.





The average diameter of PbSe QDs is 14.6 nm, so the separation distance between two PbSe QDs is evaluated to be 1.7 nm. Using a parallel plate capacitor model with the interdot spacing 1.7 nm and taking the QDs as cubic with one side 14.6 nm, we can judge the nterdot capacitance to be 2.26 aF. The interdot capacitance gives a Coulomb charging energy of 35.4 meV.

3. Results and discussions



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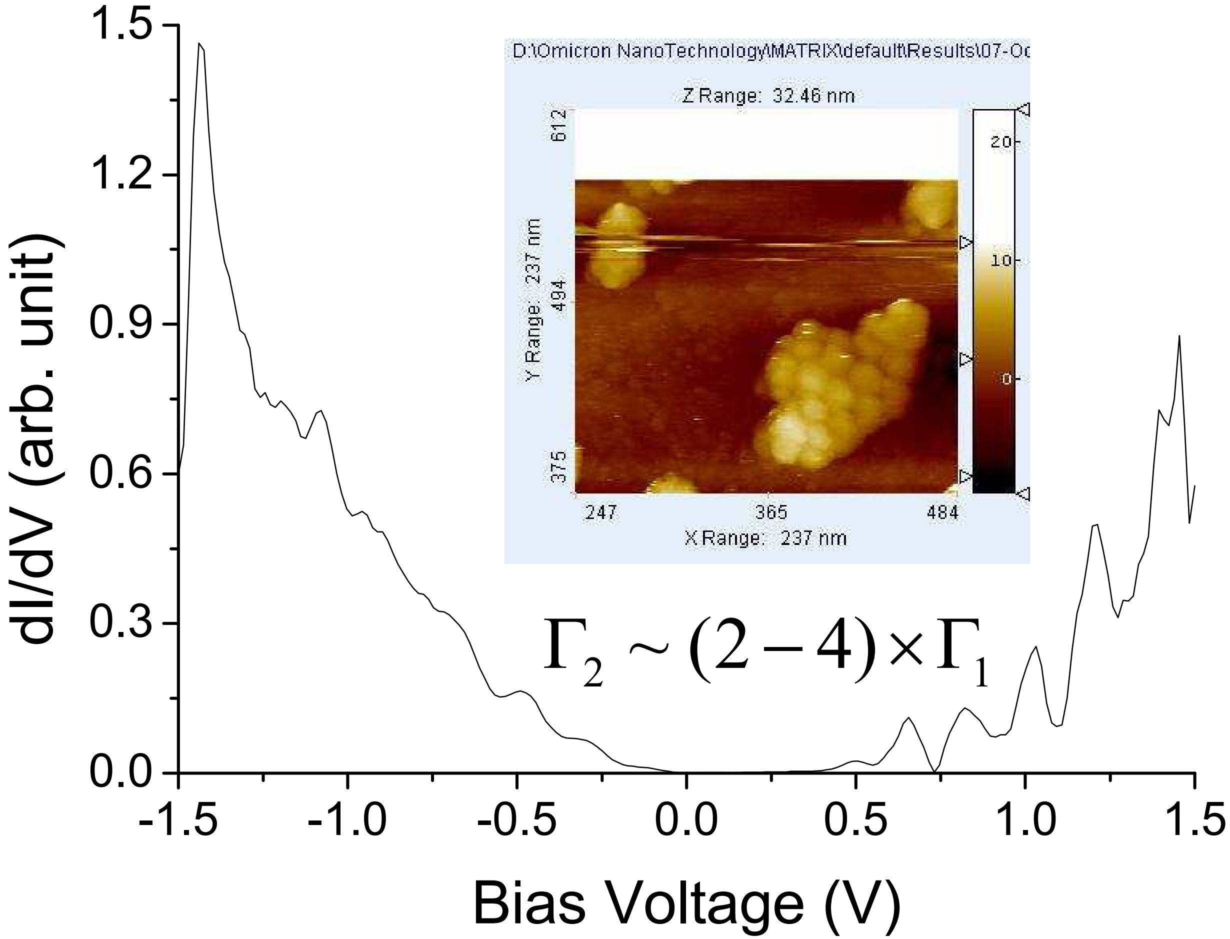
3. Results and discussions

The tunneling spectra show artificial-atom states at ~5 K.



$$\Gamma_2 \sim (2-4)\times\Gamma_1$$

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4. Conclusions

1. We have deposited PbSe QD arrays with different numbers of QDs on the flat Au(111) surfaces and have obtained tunneling spectra on individual QD arrays.
2. The characteristic IV behaviors of the QD arrays have been obtained and analyzed in accordance with the orthodox theory to extract the shunt capacitances and resistances.
3. The array-to-substrate capacitance increase steadily but not rise as fast as the area of the array.
4. The QD arrays can neither be simply treated as an island nor be regarded as independent QDs.
5. We find that, after translation on the voltage scale with the threshold voltage V_{th}, the $I(V-V_{th})$ curves of the QD arrays follow a scaling law with a scaling exponent ζ.
6. The scaling exponent ζ, the threshold voltage V_{th}, and the fluctuation in threshold voltages $\sigma(V_{th})$ strongly depends on the number (size) of the PbSe QD arrays.

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Thank You for Your Attention

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