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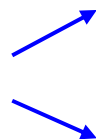
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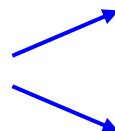
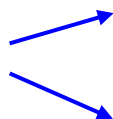






Qbit

Single Photon





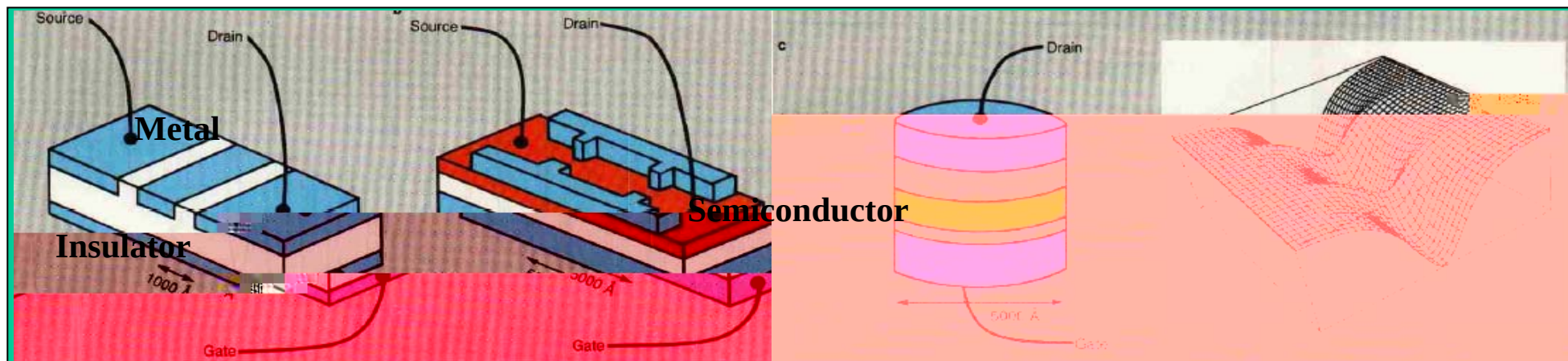
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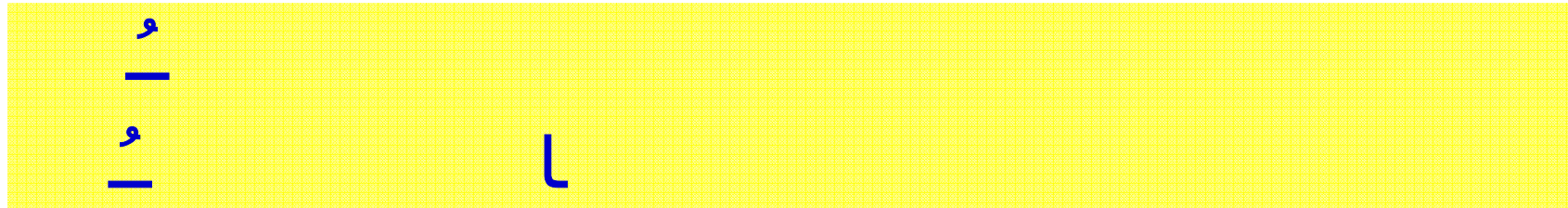
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Charge Quantization

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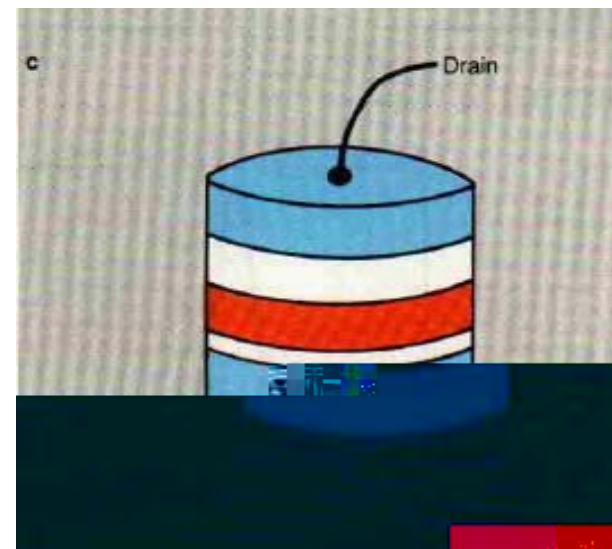
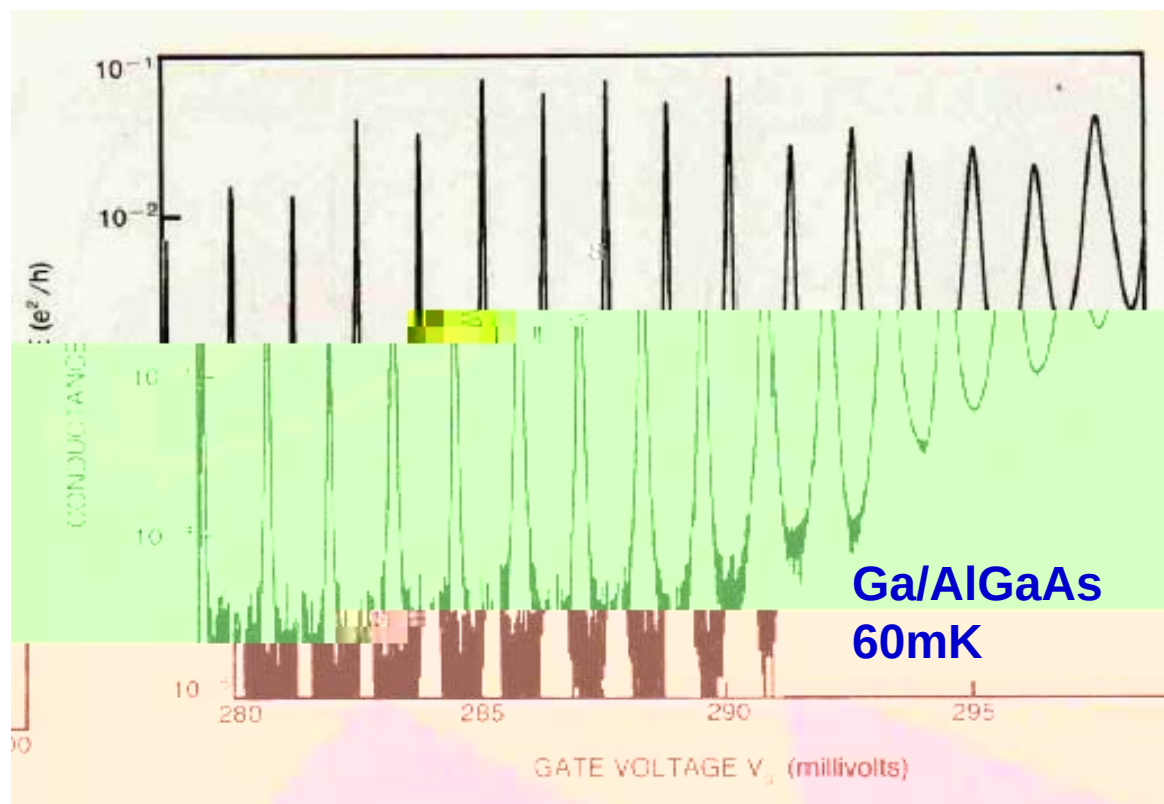
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$$\begin{array}{c} \nearrow \\ \phi \end{array} \quad \begin{array}{c} \leftarrow \rightarrow \\ L \end{array} \quad \begin{array}{c} \nwarrow \\ \phi \end{array}$$

$$\begin{array}{c} V_g \\ \bar{0} \Delta V_g \check{0} \\ \nearrow \Delta V_g \end{array}$$



$Q^2/2C \phi$
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 $e^2/2C \phi$
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$$KT < e^2/2C \quad \underline{\quad}$$

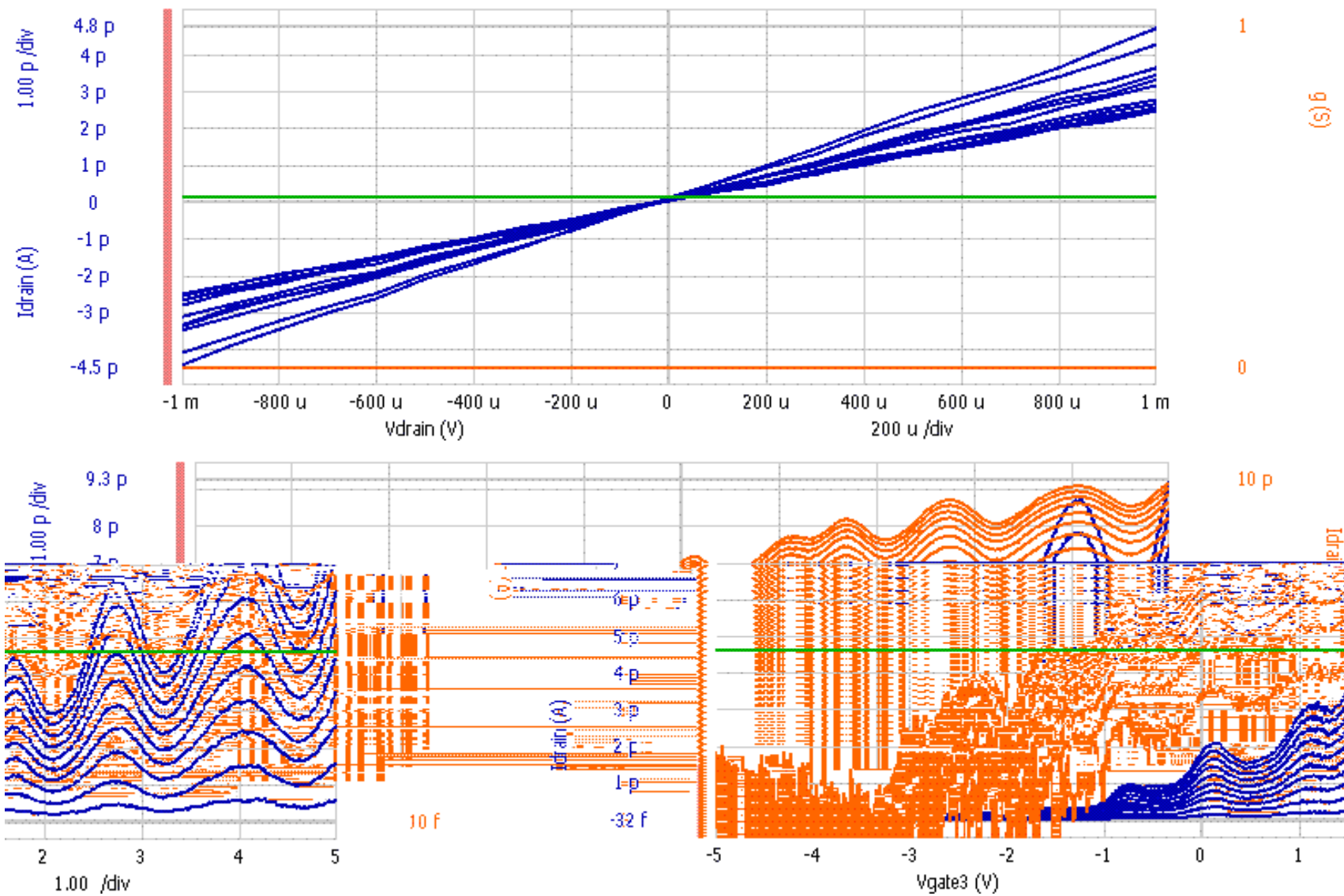
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04-2@25K



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Energy Quantization

de Broglie wave ψ -

50 nm)

ϕ

$\frac{h}{m\lambda}$

ϕ

ξ

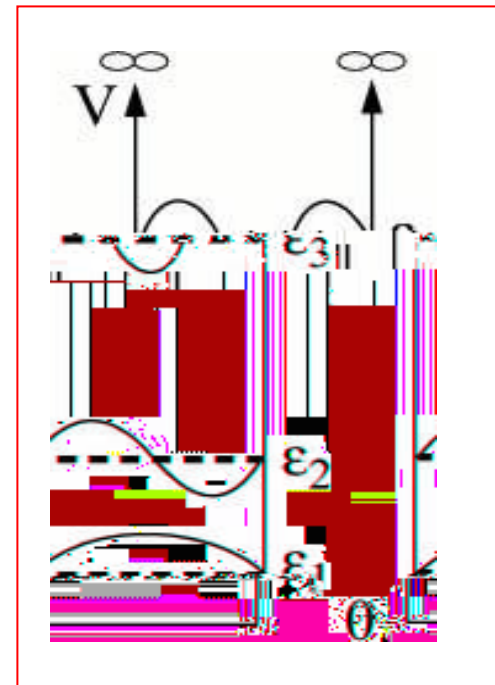
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a “ ”
 $\frac{h^2}{ma^2}$

V_g
 V_{ds}
 ϕ

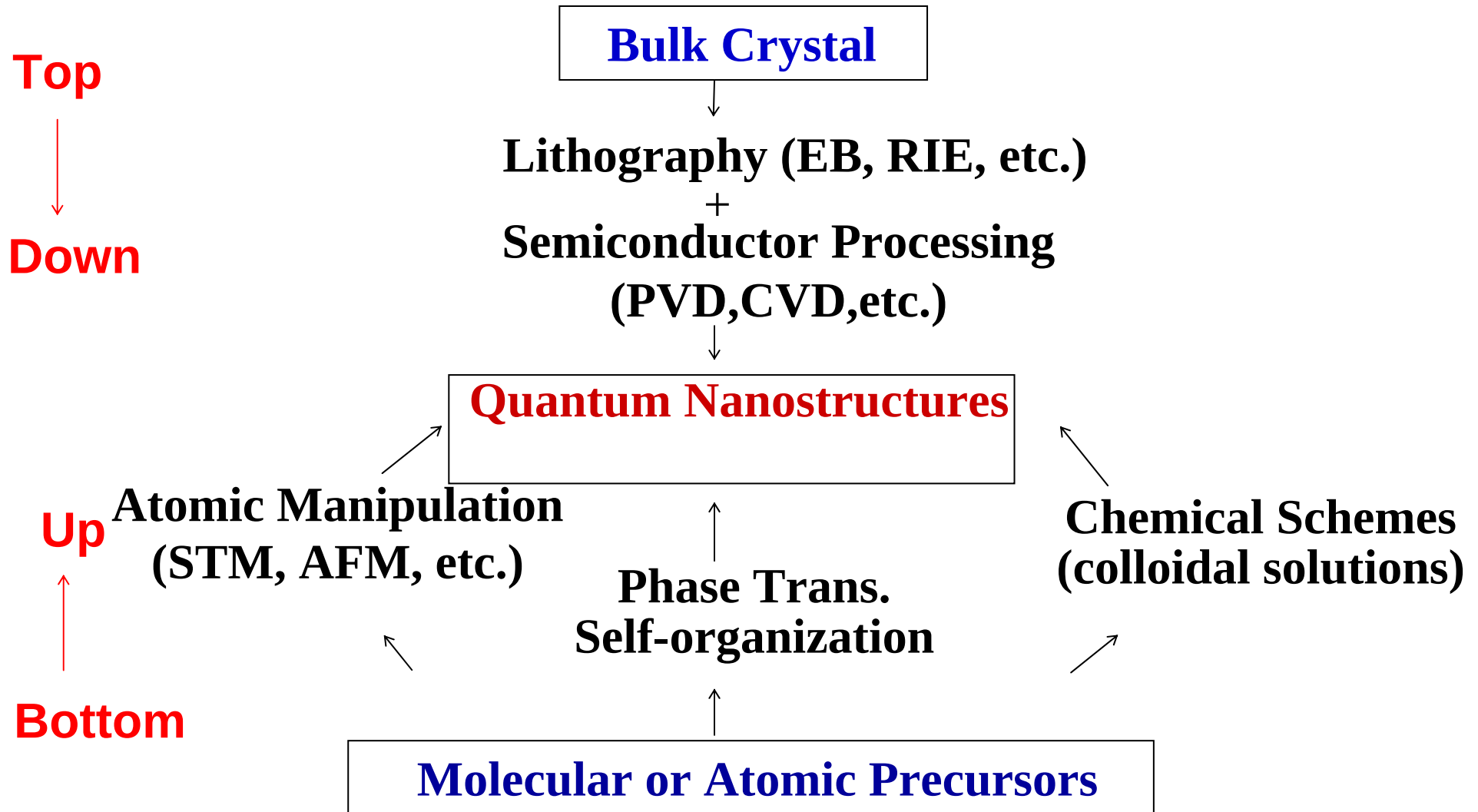
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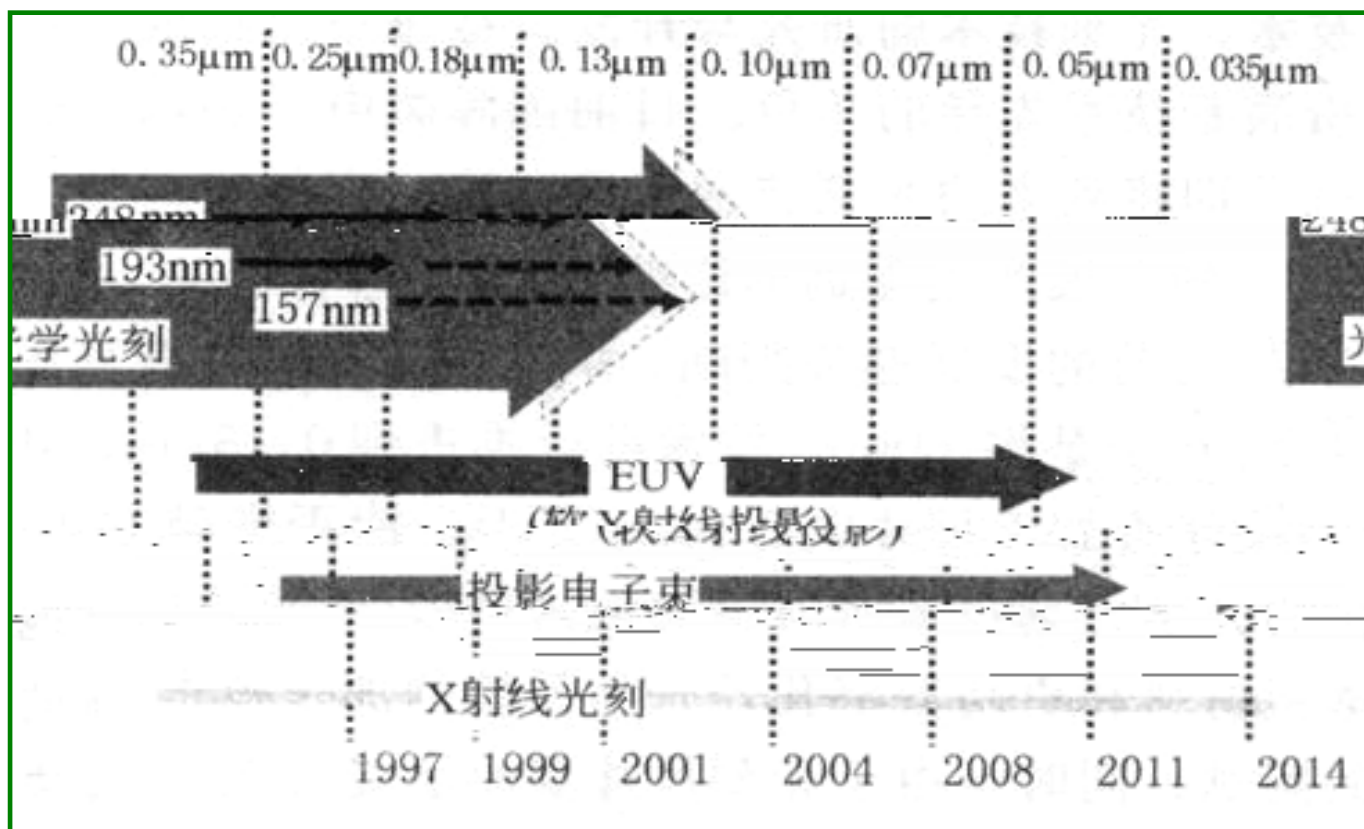


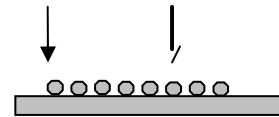
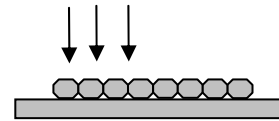




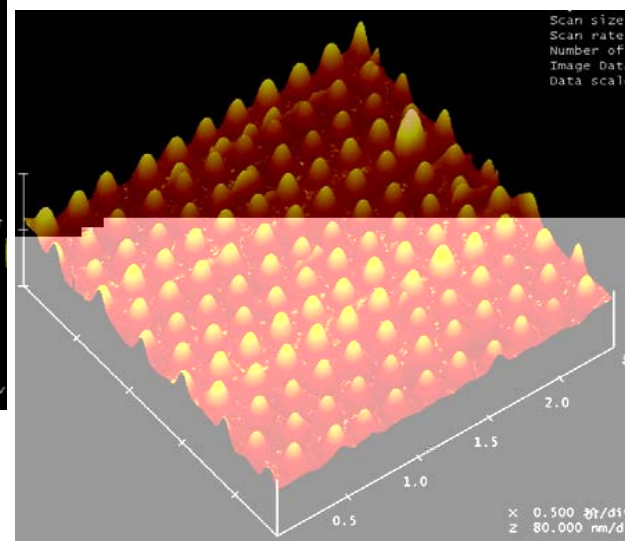
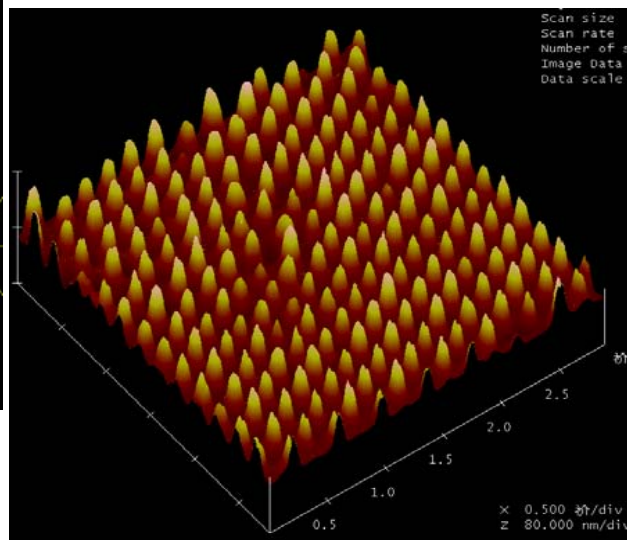
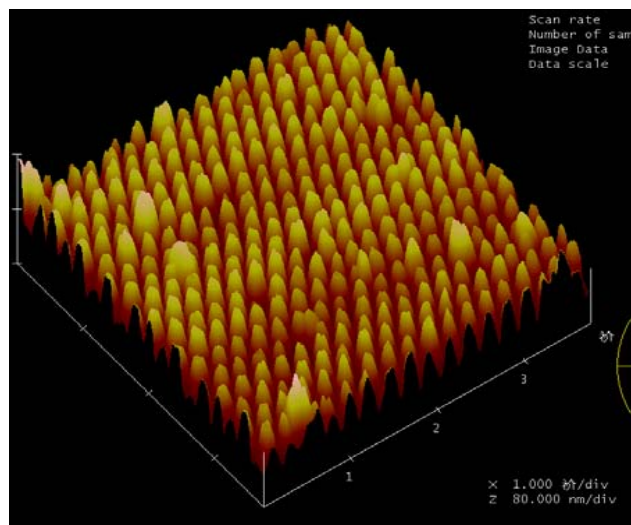
Fabrication of Semiconductor quantum structures, Two distinct approaches







Ordered nc-Si QD Array by Nanolithography



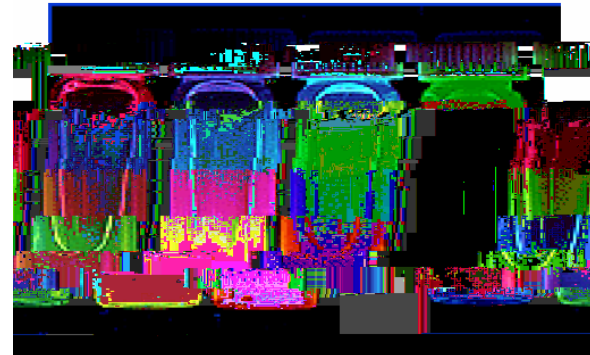
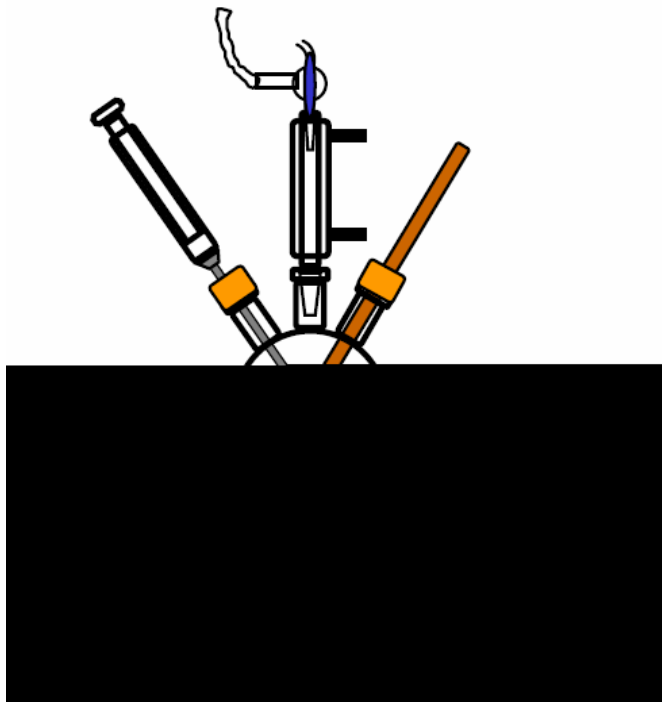
Z 80 nm/div

AFM Image

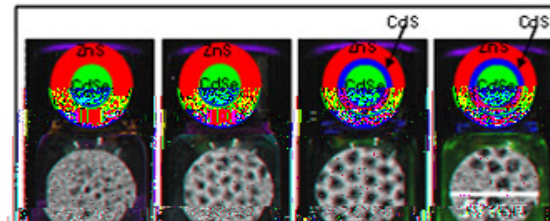


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Chemical Synthesis of Monodisperse Nanoparticles



5 nm σ <5% CdSe Nanocrystals



Technique Challenge

However, the open question is that **can nano-crystal semiconductor leave laboratories and be adopted by a real fabrication line?**

The most important need is to find a preparing technique that can combine

- **precise control of nanocrystal sizes and positions**
- **excellent surface passivation**
- **compatible with the current Si ULSI technology**



Ordered Controllable Array of nc-si Dots

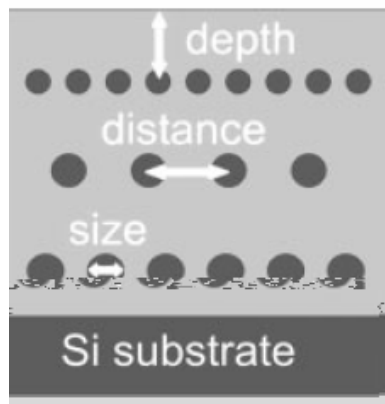
The Idea of Constrained Crystallization for Preparing nc-Si from a-Si

Vertical Constraint:

Multilayer → Control the thickness of a-Si sublayer
→ Longitudinal size of nc-Si

Lateral Constraint:

Phase shift grating → Interference laser beam
→ Local crystallization

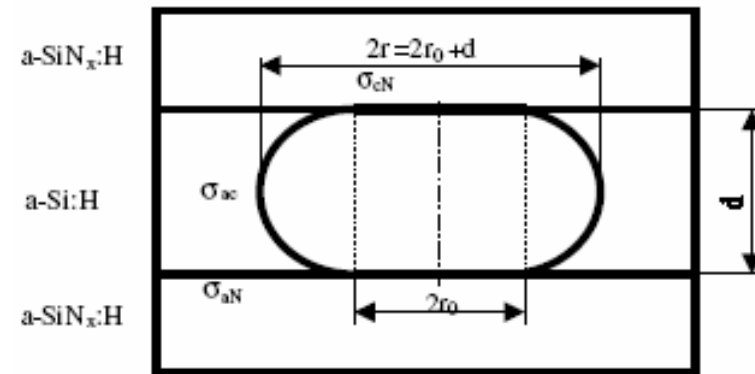
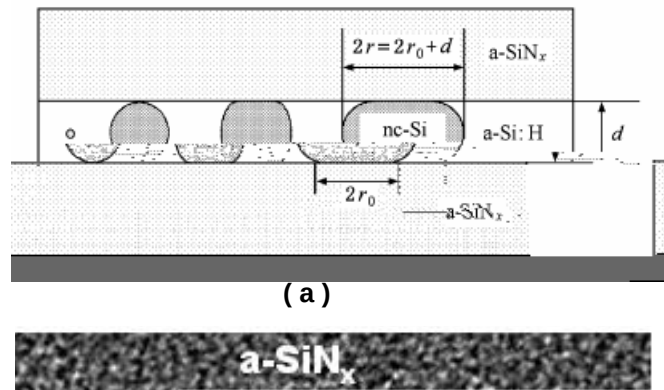


1D 2D and 3D ordered nc-Si array



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MODEL OF INTERFACE CONSTRAINED GROWTH



(c)

- (a) The scheme for the processes of nucleation and growth of nc-Si.
- (b) The cross-section shape of a typical nc-Si grain.
- (c) A cross-section TEM image of the nc-Si sublayer.



MODEL OF INTERFACE CONSTRAINED GROWTH

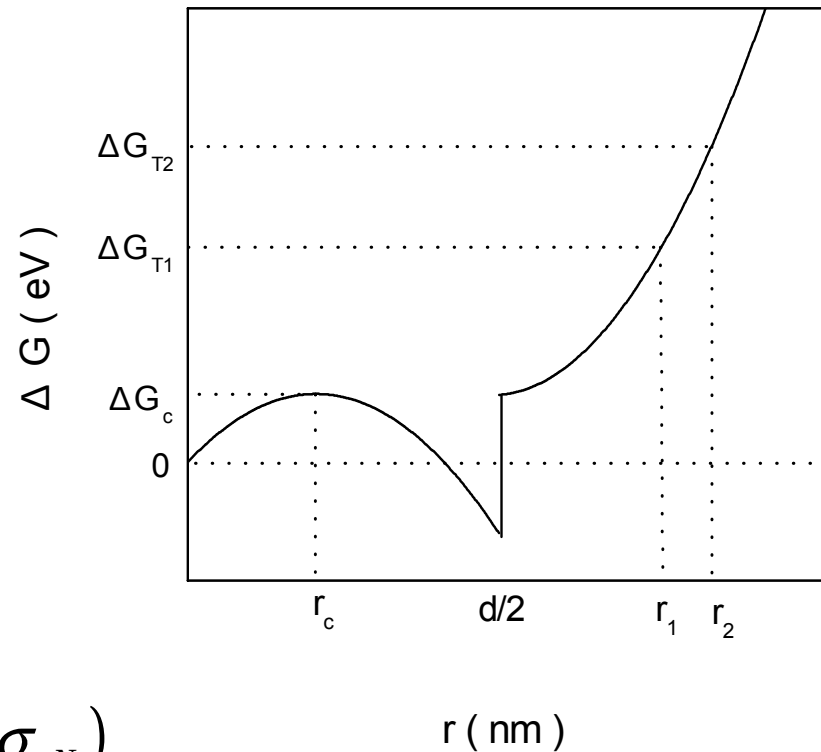
We study quantitatively the effects of the interface and shape of nc-Si on the crystal growth in relation to the **Gibbs free energy G**.

For a spherical crystallite:

$$\Delta G_{sp} = -\frac{4}{3}\pi r^3(\Delta H_{ac} + \Delta H_s) + 4\pi r^2\sigma_{ac}$$

For a cylindrical crystallite:

$$\Delta G_{cy} = -\pi r^2 d \Delta H_{ac} + 2\pi r d \sigma_{ac} + 2\pi r^2(\sigma_{cN} - \sigma_{aN})$$



Schematic diagram of free energy change of nc-Si accompanying the crystallization process



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MODEL OF INTERFACE CONSTRAINED GROWTH

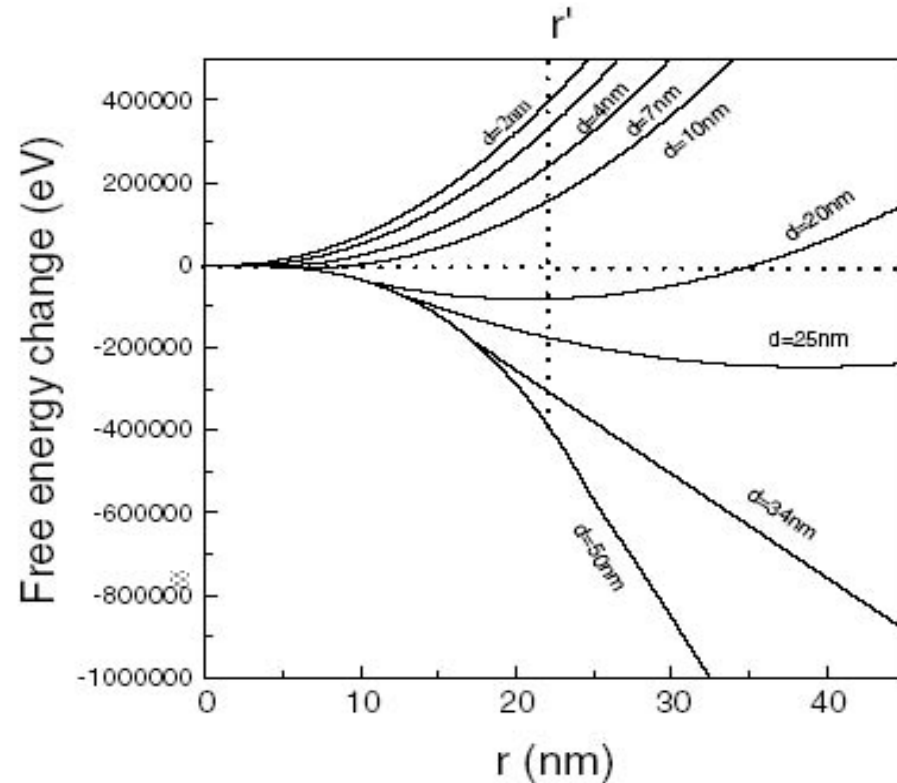
$\Delta G(r)/\Delta r < 0$, the grains can grow continuously

$\Delta G(r)/\Delta r > 0$, the growth halt will occur

$\Delta G(r)/\Delta r = 0$, obtain the threshold thickness d_0

$$d_0 = 2\Delta\sigma / \Delta G_{ac}$$

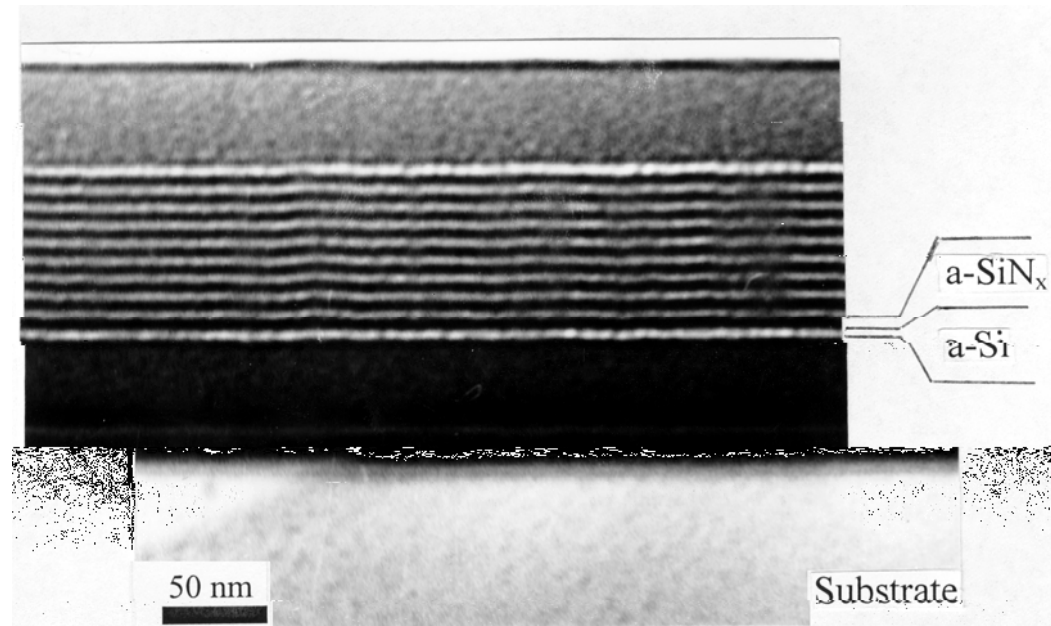
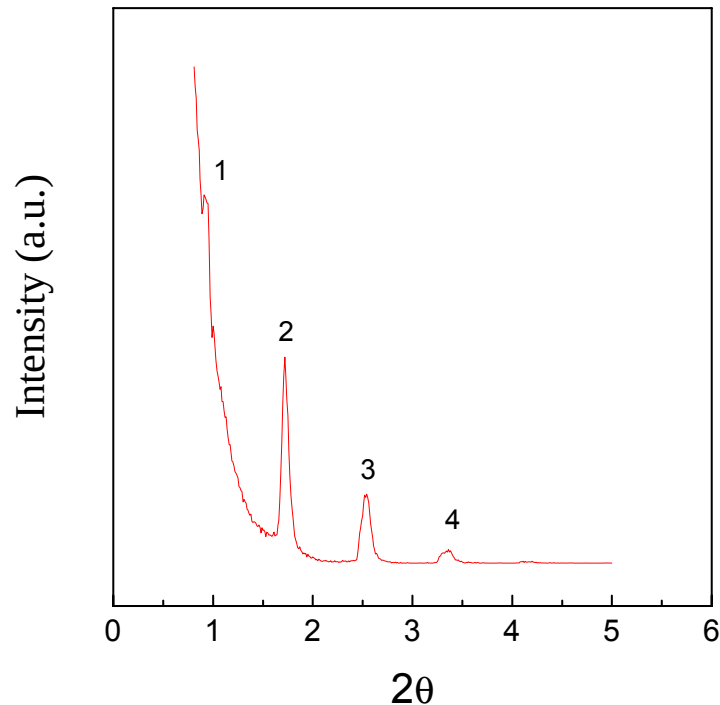
$\sim 25 \text{ nm}$



The free energy change dependence of the nc-Si grain radius at various thicknesses of a-Si sublayers.



Formation of nc-Si Superlattice by Constrained Growth

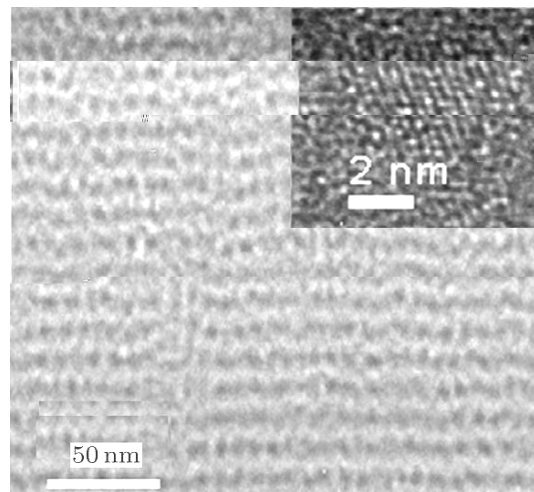


XRD and TEM micrographs of a-Si/a-SiN_x multilayers and Si QDs embedded in SiN_x matrix. The average size of Si QDs is about 4.0 nm.

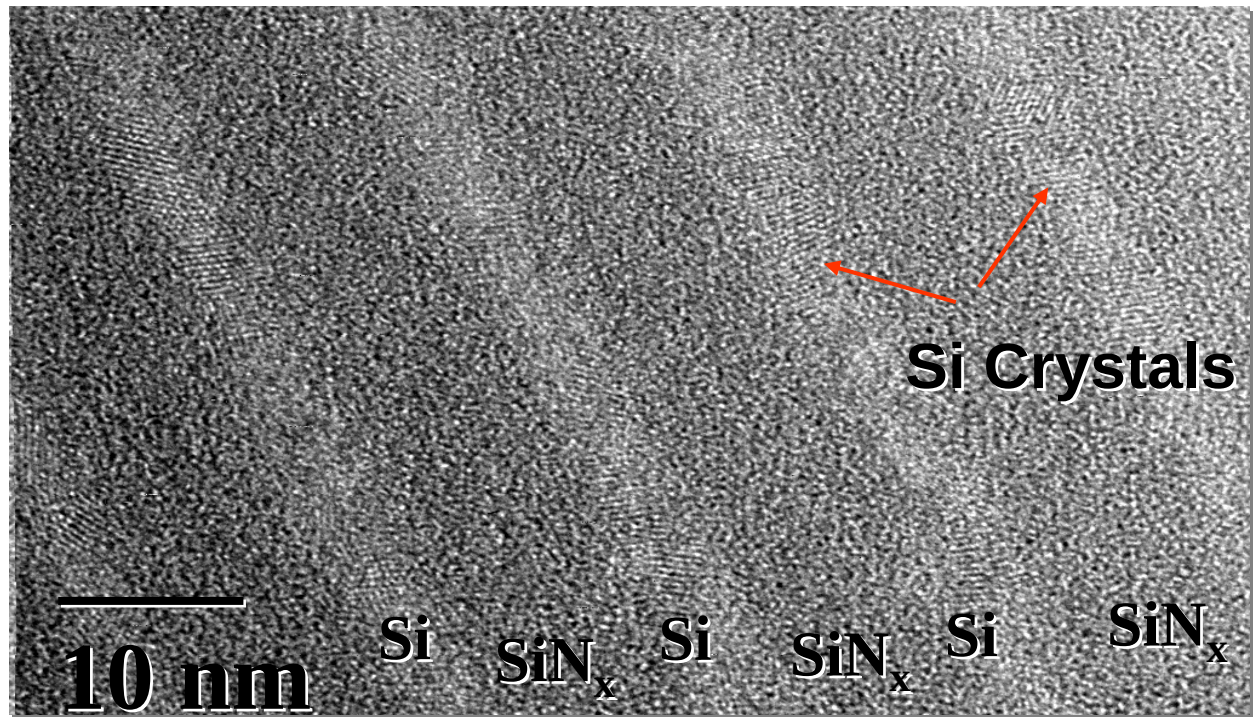


Ordered Controllable Array of nc-si Dots

Formation of nc-Si Superlattice by Constrained Growth



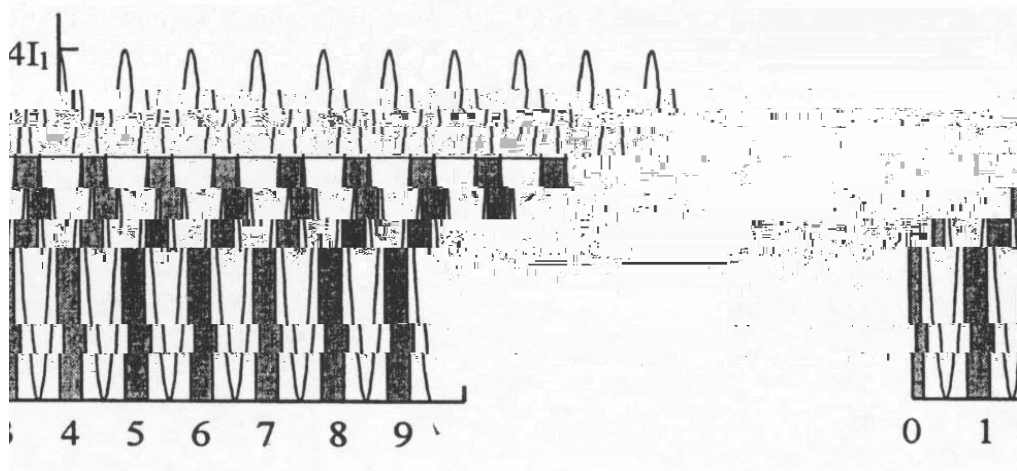
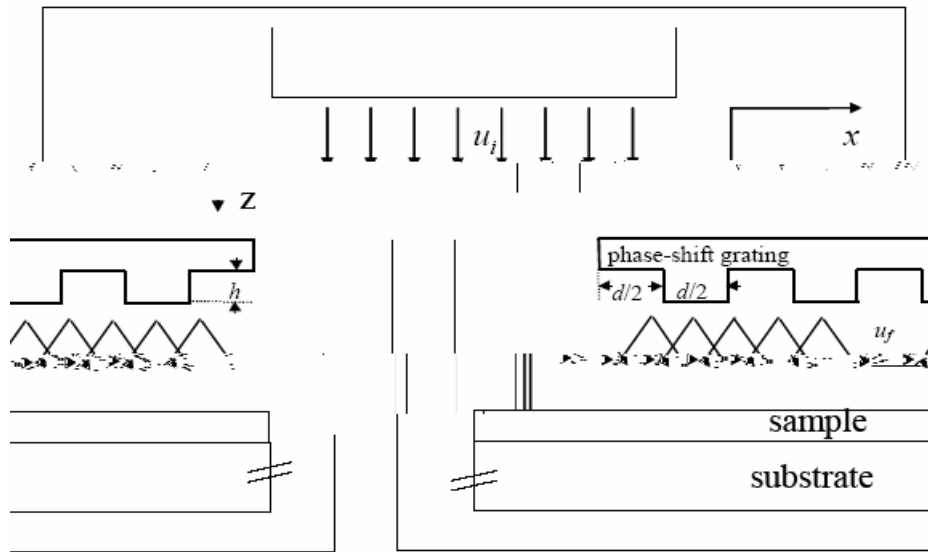
Si/SiO₂ Superlattice



Cross-section HRTEM of nc-Si Superlattice

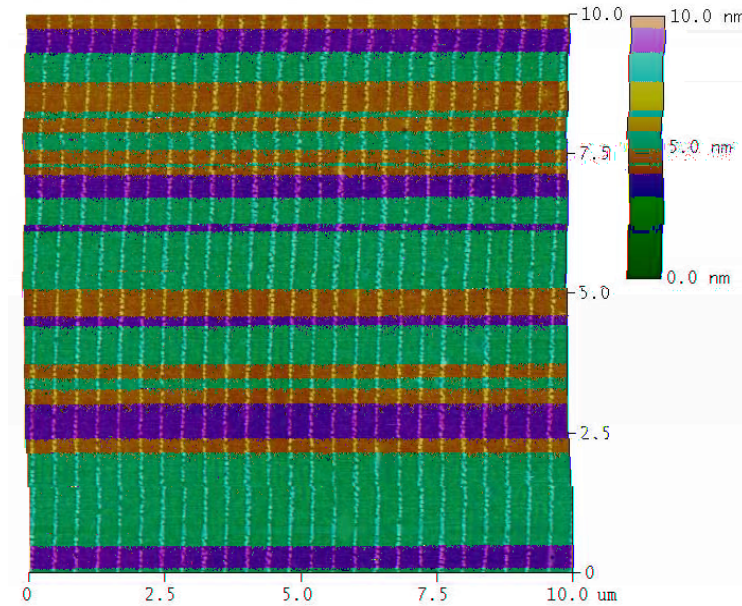
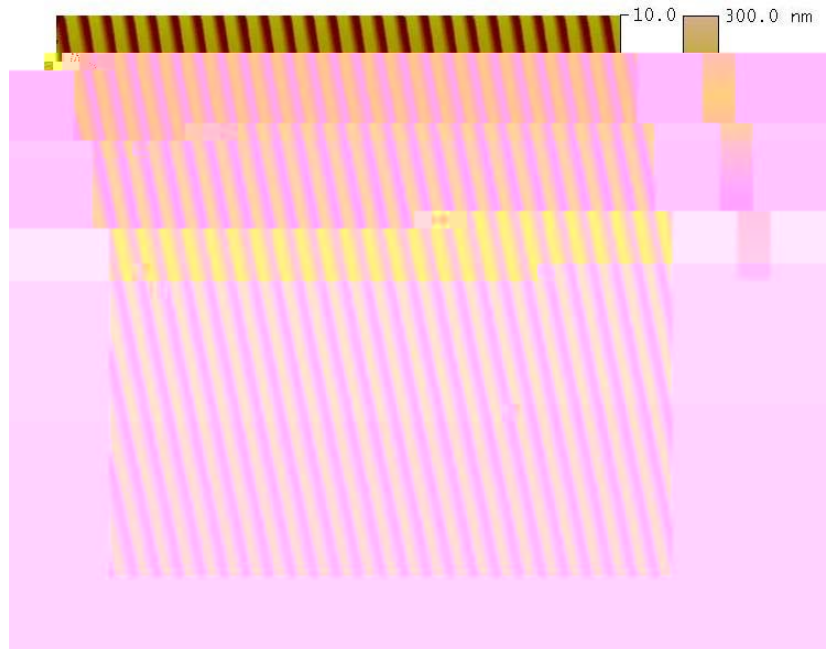


1D 2D and 3D ordered nc-Si structures



The sketch diagram for the laser interference method. **KrF excimer laser beam** passes at normal incident through the **phase-shifting grating** placed on the surface of the sample, then the separate Lorentz-like energy packages are formed due to the multi-beam interference. When the local laser intensity exceeds the **crystallization threshold value**, crystallization process occurs in the shadowed areas.



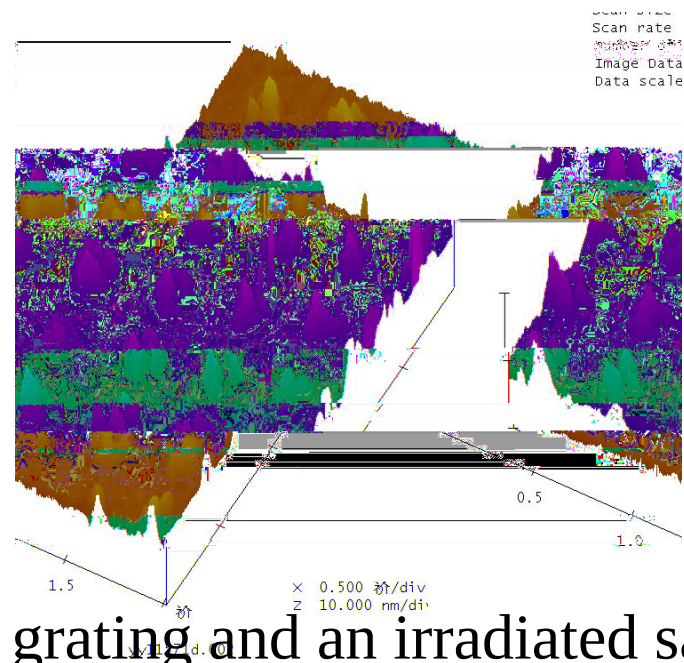
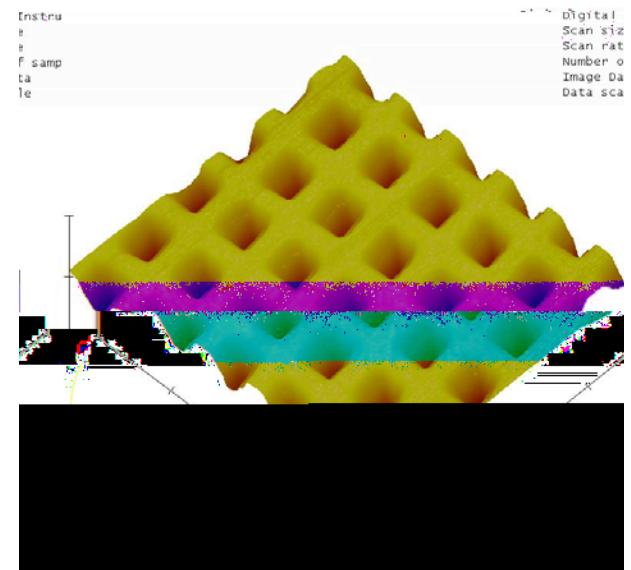
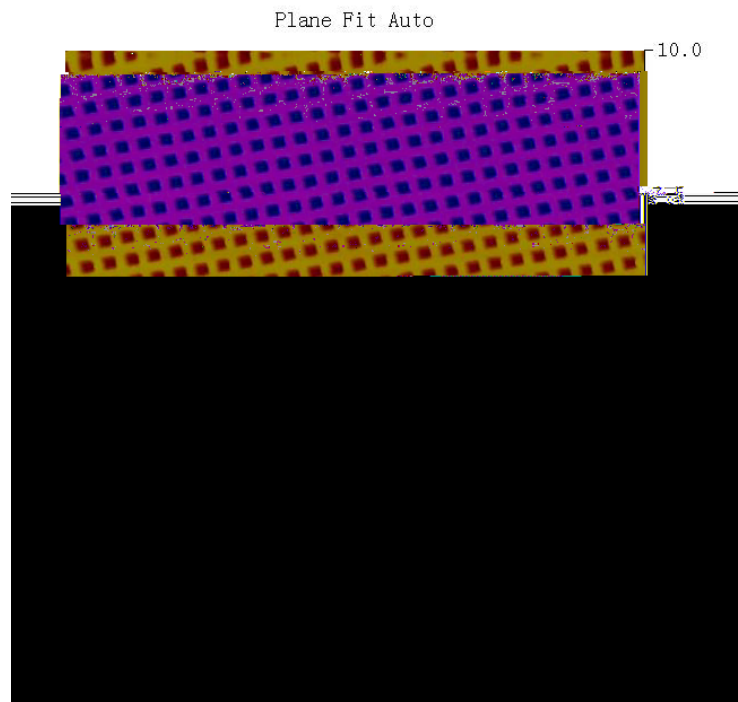


The surface morphology of 1D grating and an irradiated sample.

The bright stripes (crystallized regions)
width < 30 nm, periodicity ~ 400 nm;



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The surface morphology of 2D grating and an irradiated sample.

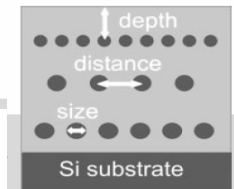


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Silicon Nanocrystals: Size Matters**

By Johannes Heitmann, Frank Müller,
Margit Zacharias,* and Ulrich Gösele

Max-Planck-Institut für Mikrostrukturphysik
Weinberg 2, D-06120 Halle (Germany)



1. Introduction

The first experimental results more than a decade ago demonstrating room-temperature luminescence of silicon nanocrystals (Si-NCs) in silicon-implanted SiO_2 ^[1] or in porous silicon^[2,3] triggered a strong interest in the fabrication of Si-NCs and their properties. Besides fundamental physics questions concerning quantum-confinement effects in the indirect semiconductor silicon,^[4-7] potential applications such as light emission from electrically excited Si-NCs,^[8-13] energy transfer to Er^{3+} ions,^[14-19] and non-volatile memory devices^[20,21] also stimulated a broad interest in this material system. For clarifying

Electroluminescence (EL) measurements on Si-NCs show efficiencies below 1×10^{-3} .^[8-13] This makes ele

[12] M. Wang, X. Huang, J. Xu, W. Li, Z. Liu, K. Chen, *Appl. Phys. Lett.* **1998**, 72, 722.

APPLIED PHYSICS LETTERS VOLUME 72 NUMBER 6 9 FEBRUARY 1998

Observation of the size dependent blueshifted electroluminescence from nanocrystalline Si fabricated by KrF excimer laser annealing of hydrogenated amorphous silicon/amorphous SiN_x superlattices

Mingzeng Wang, Xinfen Huang, Jun Xu, Wei Li, Zhipu Liu, and Kunji Chen*

3. Size-Controlled Silicon-Nanocrystal Synthesis

3.1. Amorphous Silicon/Insulator Superlattices

The use of Si/ SiO_2 superlattices was first introduced by Lockwood and co-workers.^[57,58] In this technique, molecular-beam epitaxy (MBE) combined with oxidization by UV/mass approximation. Later, similar systems could be realized by reactive magnetron sputtering or co-sputtering,^[59-63] plasma-enhanced (PE)CVD or low-pressure (LP)CVD,^[64-66] or reactive evaporation.^[67] After the crystallization of the amor-

[65] Z. Ma, L. Wang, K. Chen, W. Li, L. Zhang, Y. Bao, X. Wang, J. Xu, X. Huang, D. Feng, *J. Non-Cryst. Solids* **2002**, 299, 648.

for bulk silicon.^[62,70] A combination of this controlled deposition method with a patterning of the resulting layered structure comparable to other microelectronic devices is possible.^[71,72]

[71] L. Y. Zhu, X. F. Huang, W. B. Fan, X. W. Wang, W. Li, L. Wang, K. J. Chen, *Superlattices Microstruct.* **2002**, 31, 285.

[76] L. Wang, Z. Ma, X. Huang, Z. Li, J. Li, Y. Bao, J. Xu, V. Li, K. Chen, *Solid State Commun.* **2001**, 117, 239.

[77] H. Huang, L. Wang, J. Li, W. Li, M. Jiang, J. Xu, K. Chen, *J. Non-Cryst. Solids* **2000**, 266-269, 1015.

silicon evaporation and periodic electron cyclotron resonance... pulsed laser deposition... plasma-induced... superlattices were produced and by LPCVD.^[76,77] $\text{Si}/\text{Si}_3\text{N}_4/\text{Si}$

These controlled deposition methods led to a number of diode-like structures for electrically pumped devices.^[12,81-83]

Also, for the EL measurements, different signal wavelengths... 1900 nm were reported; these were mainly attributed to hot-electron recombination. The reported quantum efficiencies of electroluminescence do not exceed 1×10^{-3} .

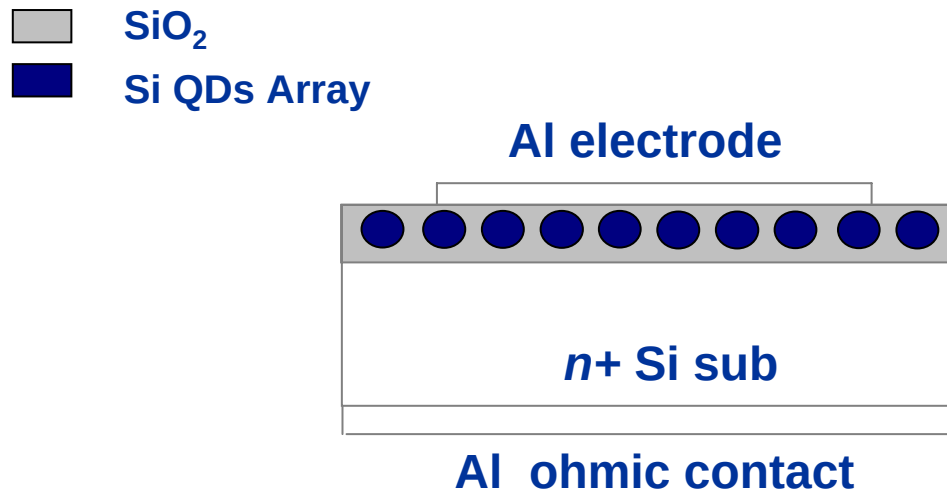
between 500 and 1000 nm were reported; these were mainly attributed to hot-electron recombination. This explanation could not be proved in detail and is still under discussion. The reported quantum efficiencies of electroluminescence do not exceed 1×10^{-3} .



The collective single-electron Coulomb blockade effects in the single layer nc-Si array

➤ Structure

The $\text{SiO}_2/\text{nc-Si QDs array}/\text{SiO}_2/\text{n}^+\text{-Si}$ structure is fabricated in a plasma enhanced chemical vapor deposition (PECVD) system.



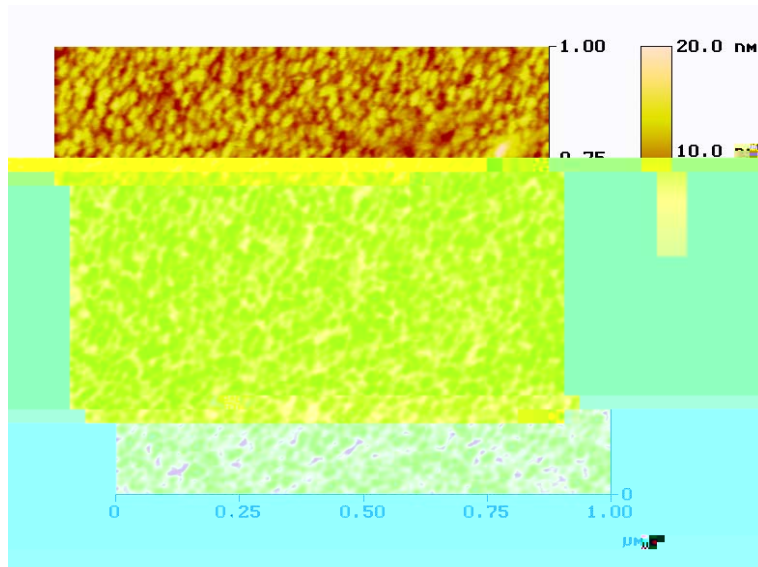
Electrode area:
 $0.8 \times 10^{-3} \text{ cm}^2$

Substrate:
 n^+ - Si (100)
 p - Si (100)

Schematic diagram of the structure

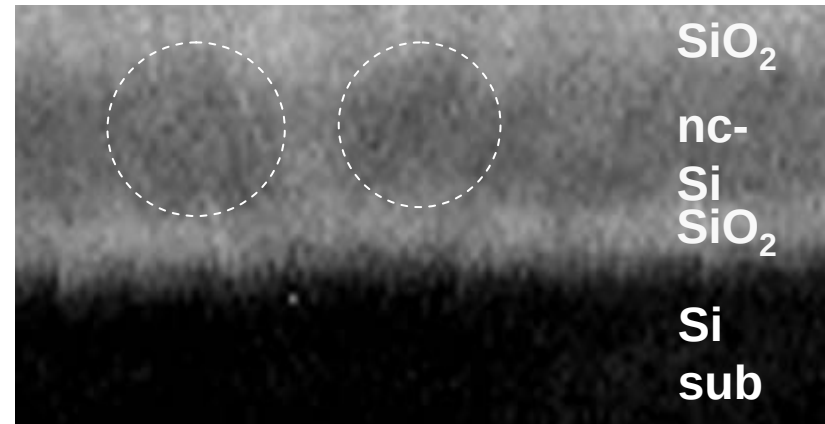


➤ AFM image



AFM image of nc-Si after removing the gate oxide.

➤ X-TEM

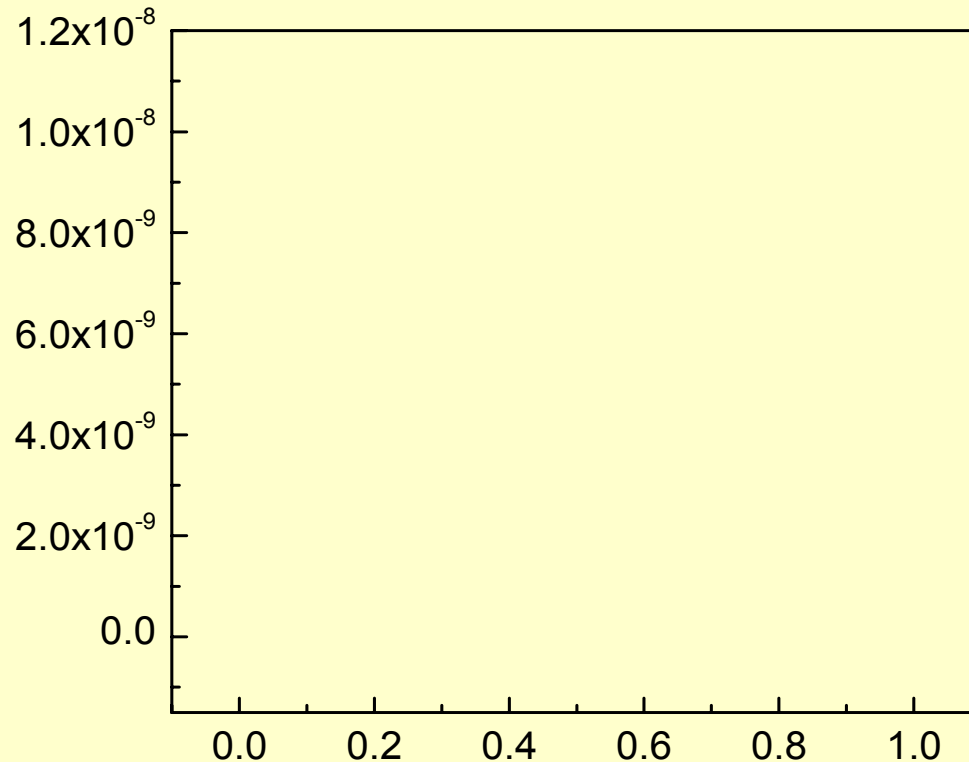


Cross section TEM photograph of sample structure

The density and the mean diameter are $2 \times 10^{11} \text{ cm}^{-2}$ and 6 nm, respectively.



➤ I-V characteristics



* Unique platform-like peaks

* Distribution

- Spacing between peaks
- Spacing between regions

GS: Ground State

FES: First Excited State

CBE: Coulomb Blockade Energy

A typical I-V curve with “sharp-edged platform-like” peaks, which are divided into two regions according to their positions in voltage. The schematic band diagram is shown in the up-left inset.

CBE and QCE

Confinement Levels	GS (2)		FES (6)					
Peak No.	1	2	1	2	3	4	5	6
Peak Position (V)	0.38	0.43	0.64	0.70	0.76	0.81	0.87	0.93
Between Peaks(V)	---	0.05	---	0.06	0.06	0.05	0.06	0.06
Between Region(V)	---	---	0.14	---	---	---	---	---

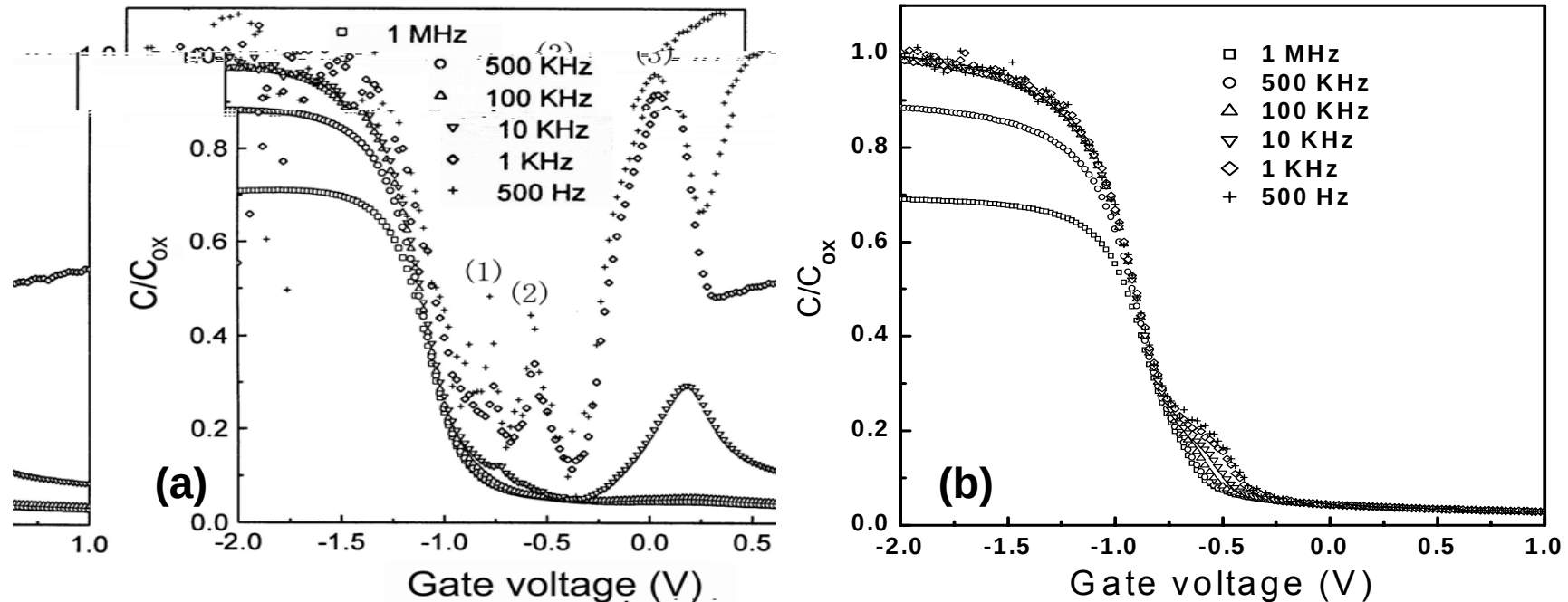
Deduced from the peak structure:

CBE The average spacing between the peaks in the same region : **60 meV**,

QCE The spacing between the regions: **140 meV**

Compared with the estimations : unit meV

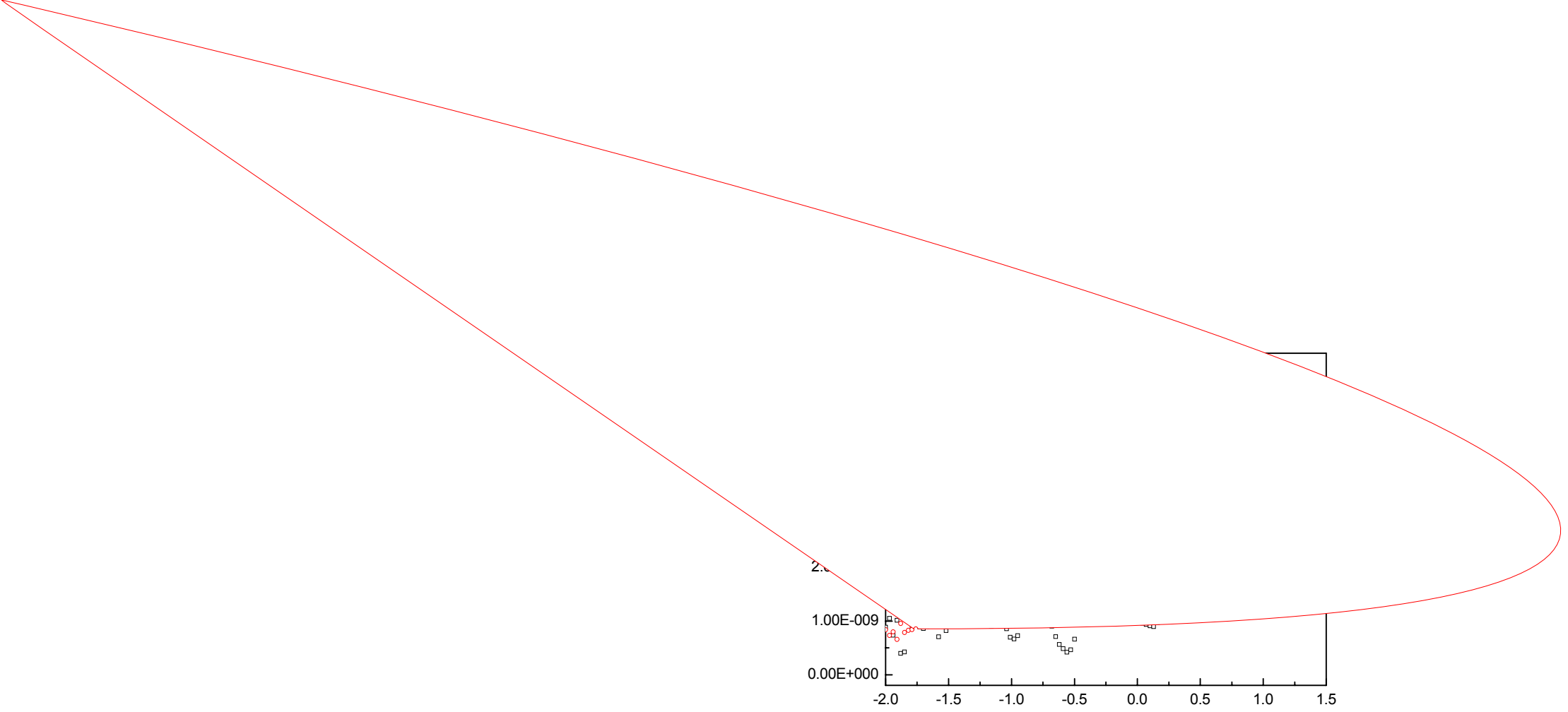
➤ C-V characteristics



Frequency-dependent C-V characteristics of the samples

- (a) with **well-defined Si-QDs**, in which **discrete capacitance peaks** are observed;
- (b) The reference sample **without Si-QDs**, in which no peaks are observed.





➤ C-V characteristics

Comparisons of theoretical evaluations and experimental results:

Conversion formula between gate voltage difference (ΔV_G) and energy spacing (ΔE):

$$\Delta E = \frac{t_{tun}}{t_{tot}} q \Delta V_G$$

Theoretical evaluations based on Coulomb blockade model

The Coulomb charging energy:

$$E_c = \frac{e^2}{2 C_{dot}} \quad \text{where} \quad C_{dot} = 4\pi\epsilon_0\epsilon_{SiO_2}r$$



➤ C-V characteristics

for radius = 7 nm $C_{dot} = 1.49$ aF $\Delta V_G = 0.17$ V

for radius = 3 nm $C_{dot} = 0.64$ aF $\Delta V_G = 0.40$ V

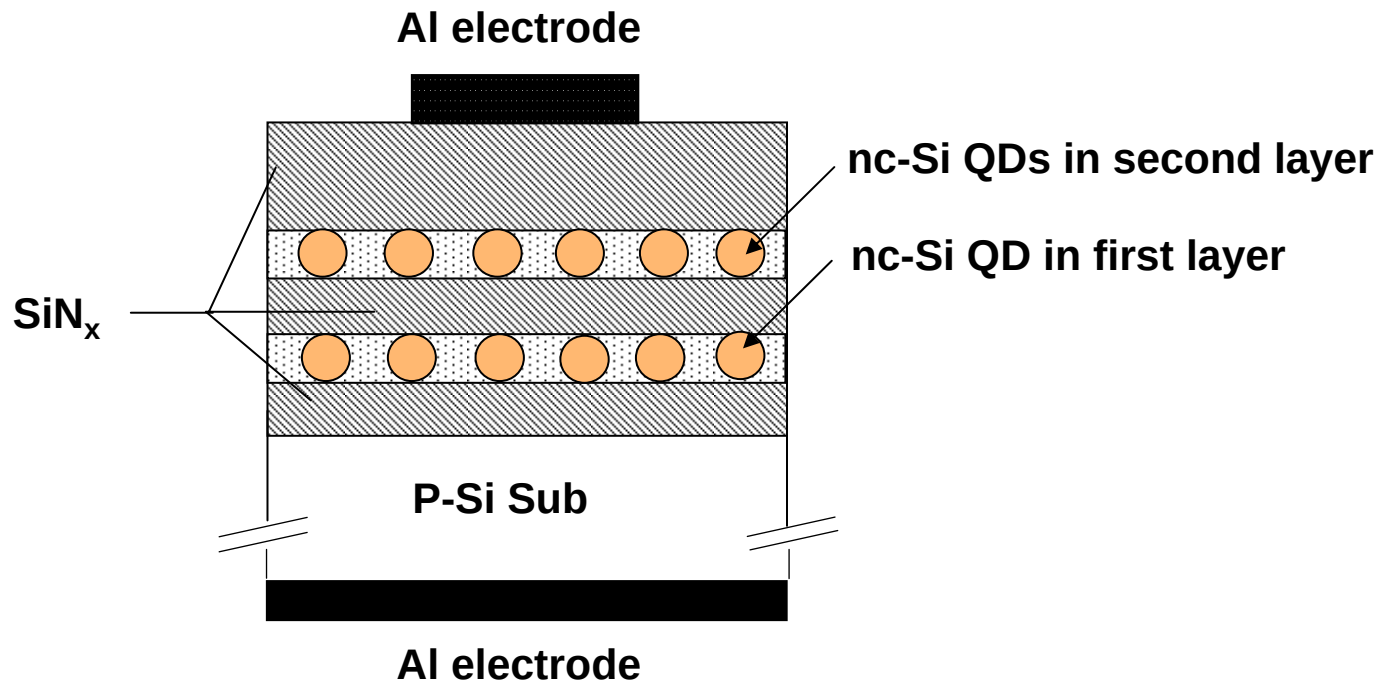
Calculation results:

	7 nm	3 nm
Experiment	50 meV	114 meV
Theoretical	53 meV	125 meV

Experimental results are in accordance with the theoretical evaluations.



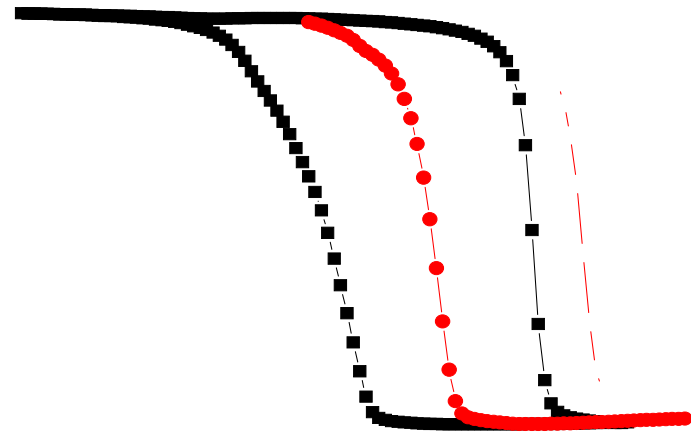
Multilevel charge storage in doubly-stacked nc-Si layers

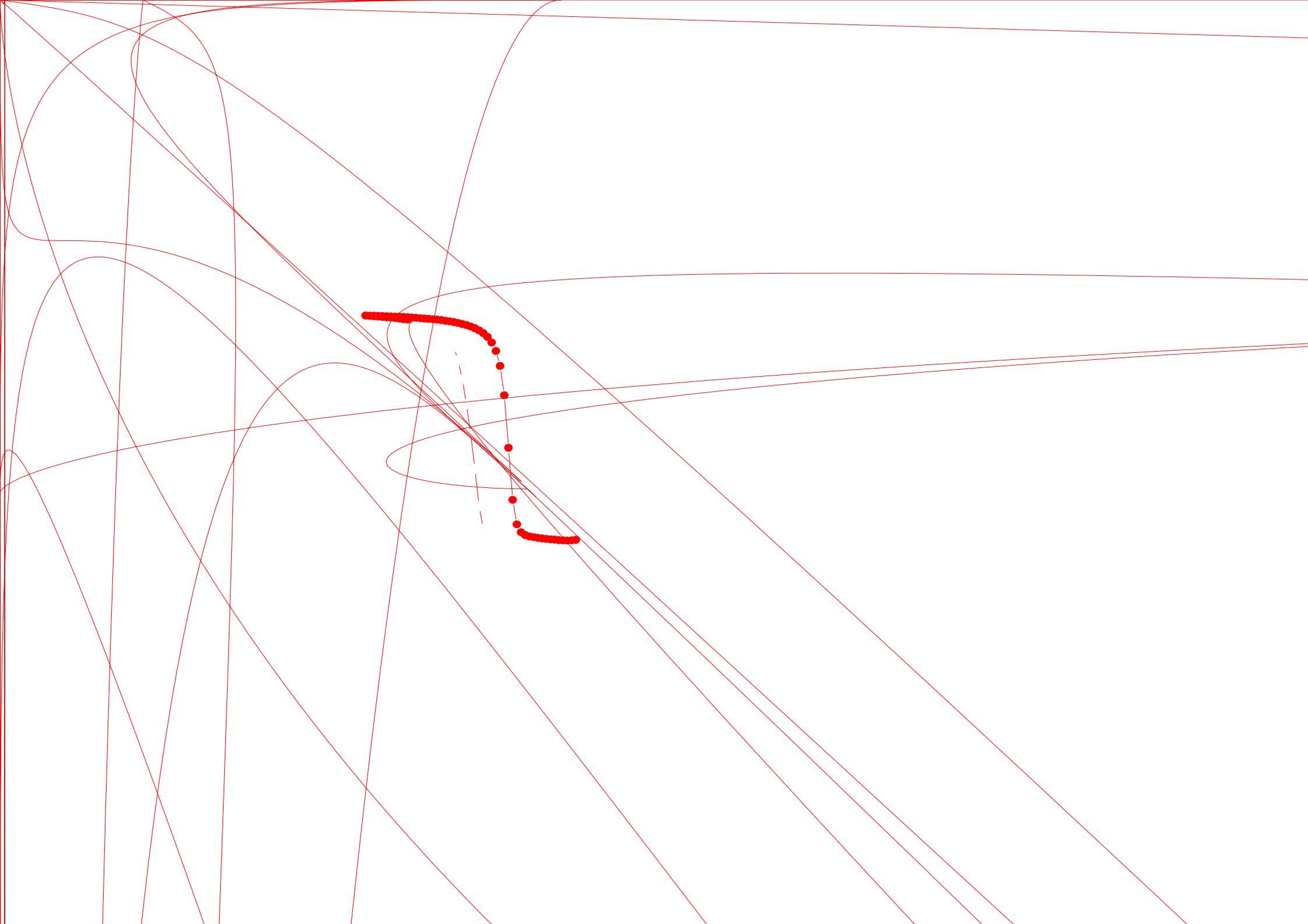


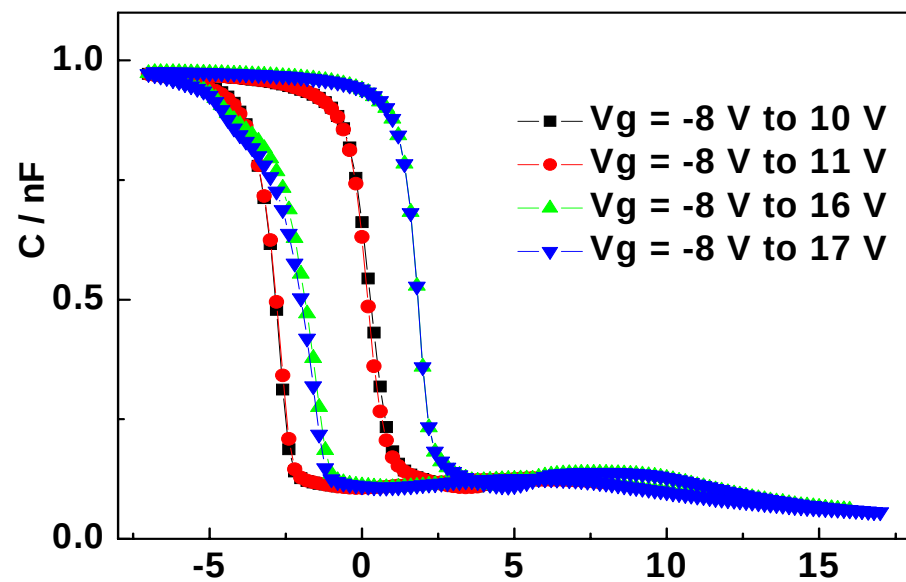
a-SiN_x/nc-Si/a-SiN_x/nc-Si/a-SiN_x structure



➤ Charge storage in nc-Si samples







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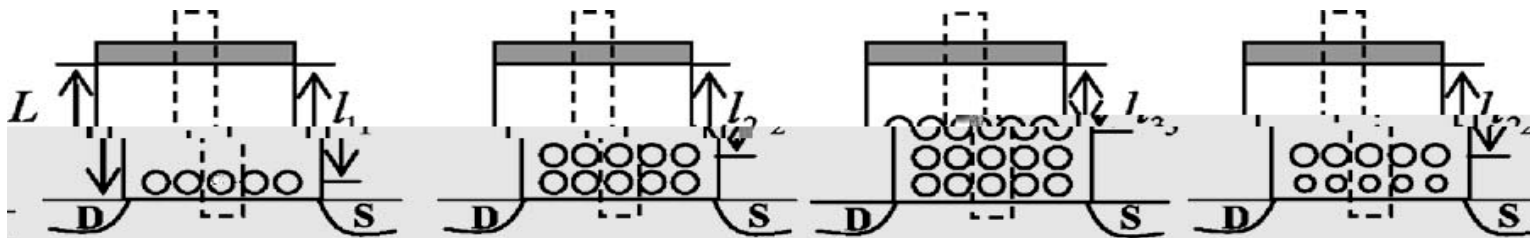
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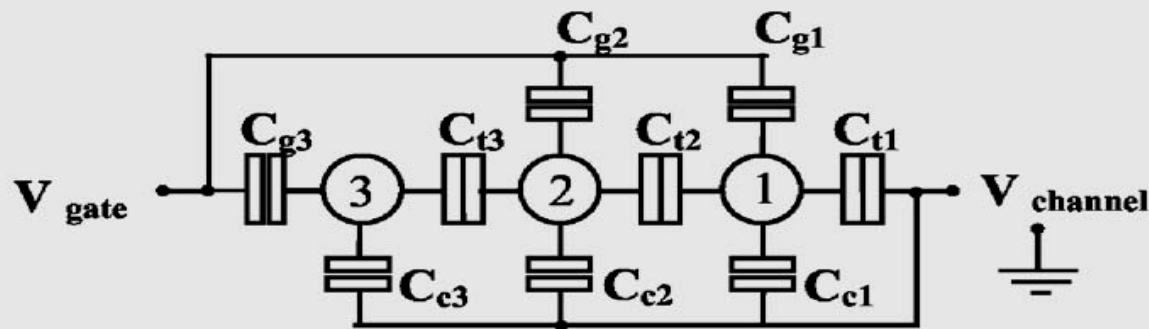
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Multilevel Charge Storage In Doubly-stacked Nc-si Layers

➤ Simulation of multilevel charge storage



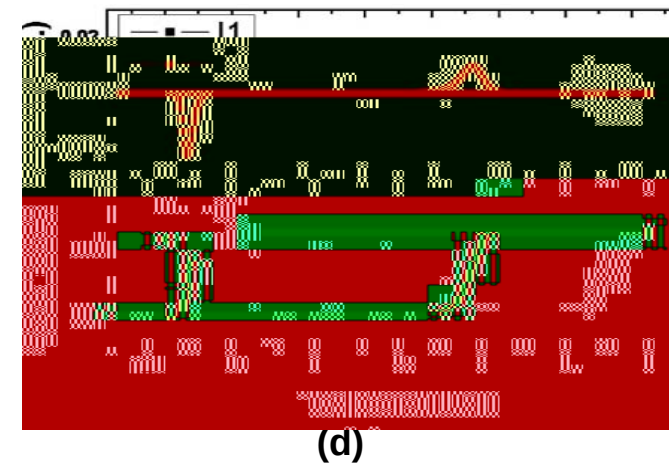
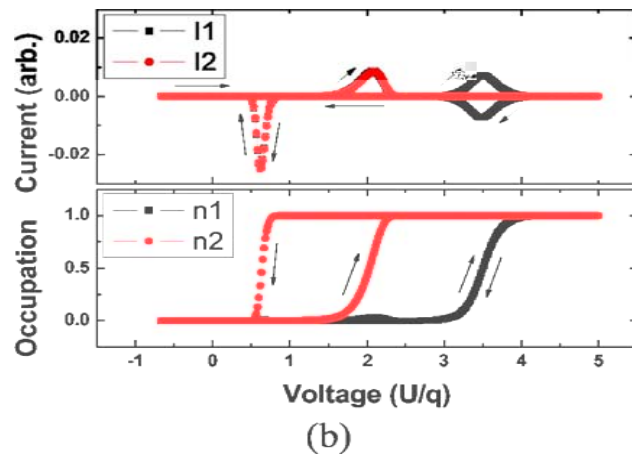
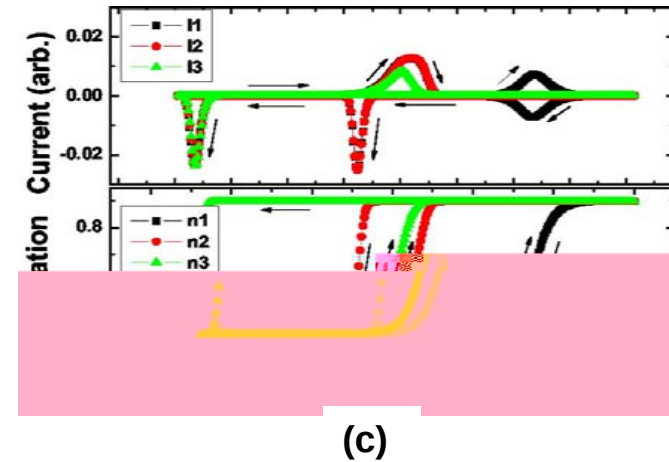
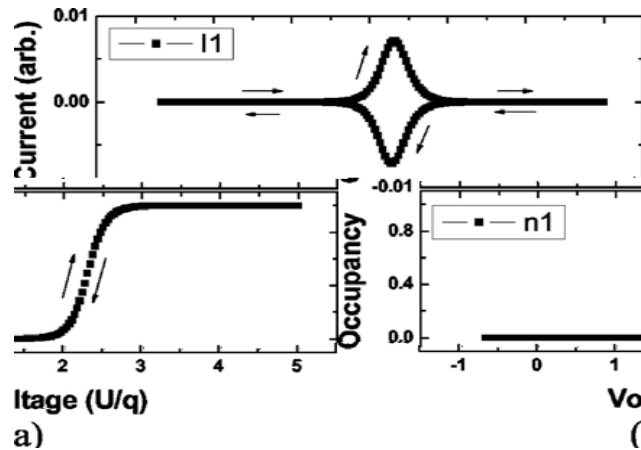
(a) Single layer (b) Double layer (c) Triple layer (d) Asymmetric Double layer

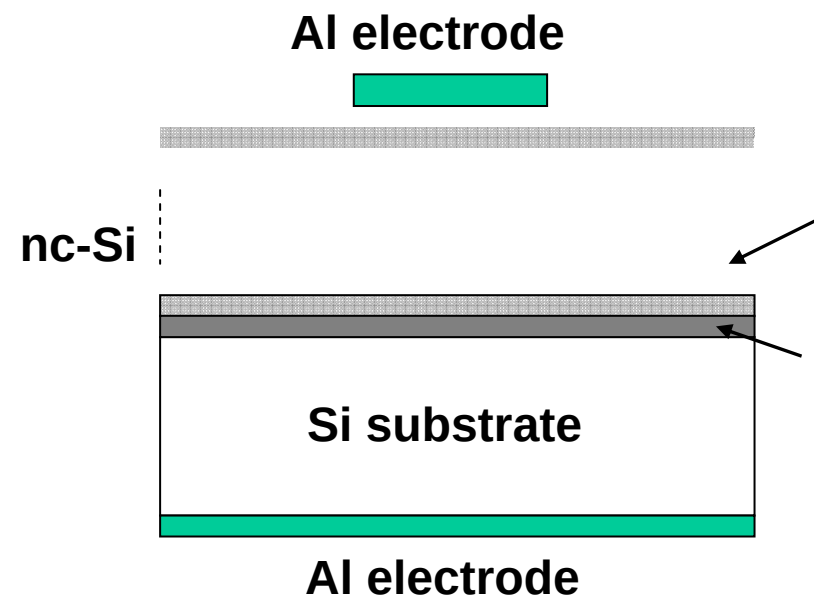


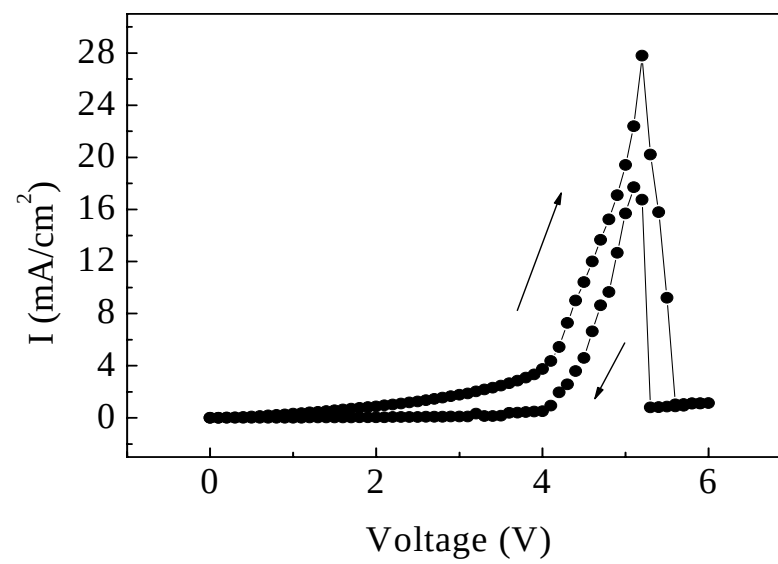
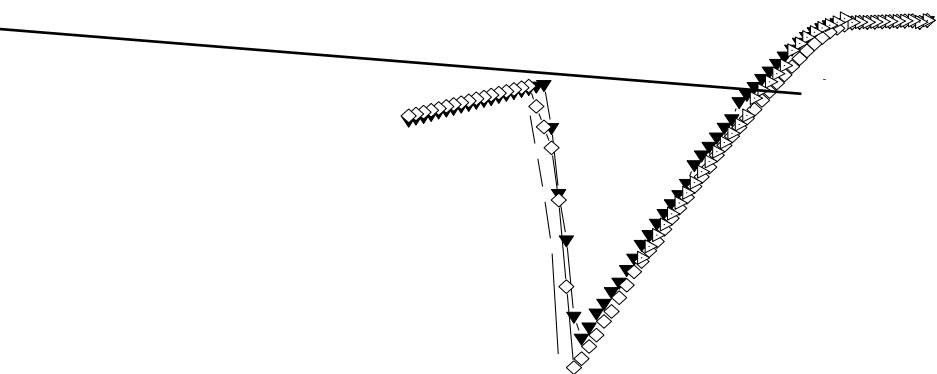
(e) Equivalent circuit for the self-aligned nc-Si unit.



➤ Charging & discharge processes of electrons







**The collective single-electron Coulomb
blockade effects o**



Si

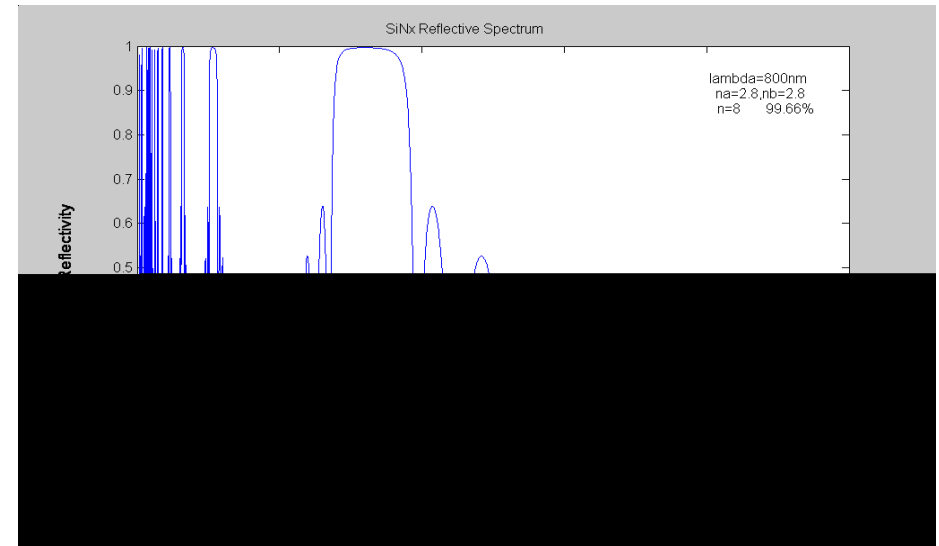
§

Bragg

(DBR)

$$t = \left| T_{11}^N - T_{12}^N T_{21}^N / T_{22}^N \right|^2$$

$$r = \left| T_{21}^N / T_{22}^N \right|^2$$



$$P_l(d_l) = \begin{pmatrix} e^{ik_l d_l} & 0 \\ 0 & e^{-ik_l d_l} \end{pmatrix}$$

$$Q_{l,l-1} = \begin{pmatrix} 1/2 + k_{l-1}/2k_l & 1/2 - k_{l-1}/2k_l \\ 1/2 - k_{l-1}/2k_l & 1/2 + k_{l-1}/2k_l \end{pmatrix}$$

k_l

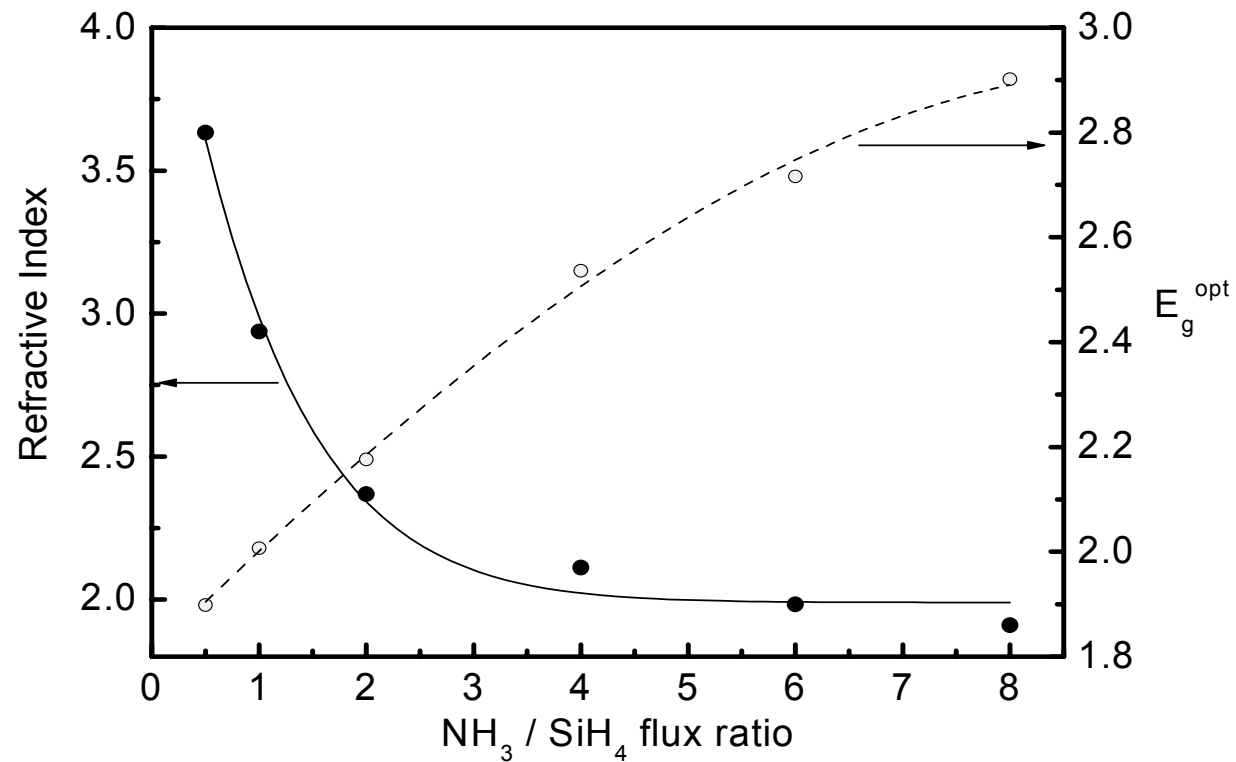
l

n 2.8 1.86 6

98.6 1.4 ¢



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a-SiN_x refractive indices n and optical bandgap versus NH_3/SiH_4

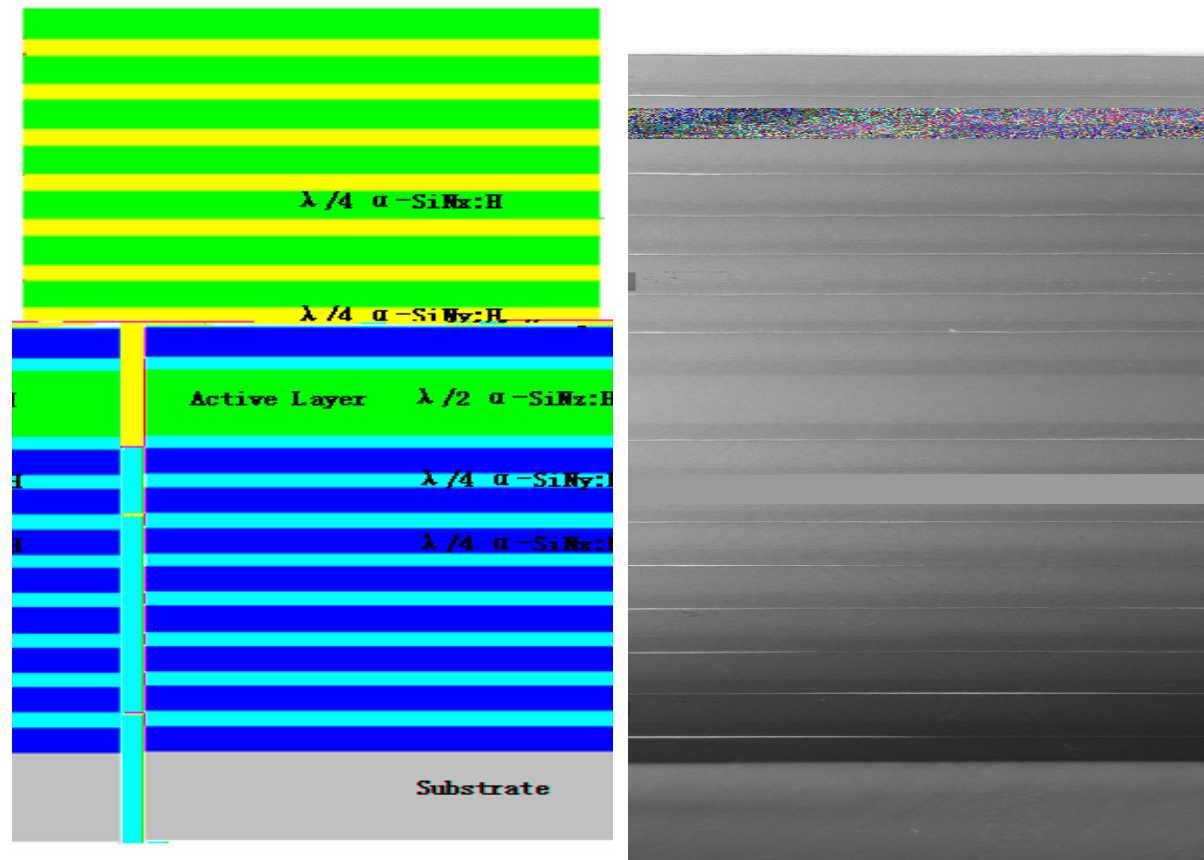
E_g^{opt}

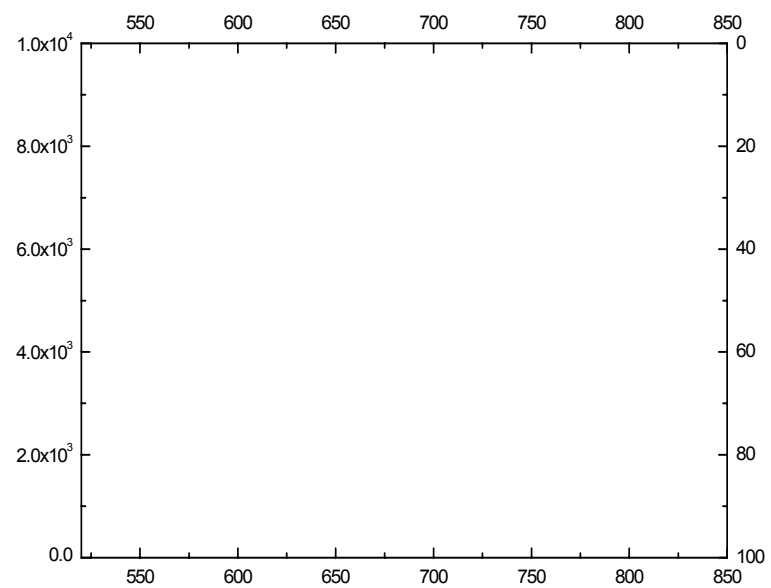


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$a\text{-SiN}_x$

TEM





1.0×10^4

8.0×10^3

6.0×10^3

4.0×10^3

2.0×10^3

550

600

650

700

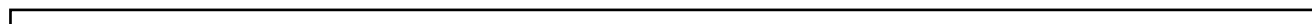
750

800

850

0.0

2.0×10^3



1.

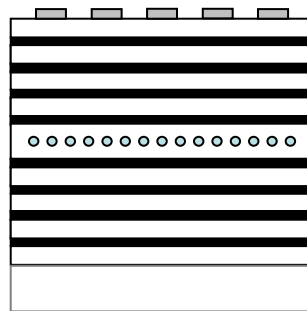
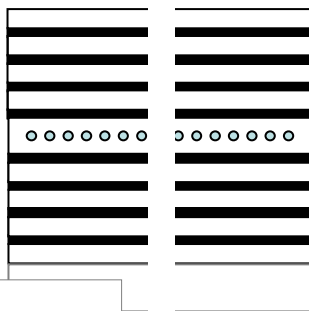
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$\hat{w}$

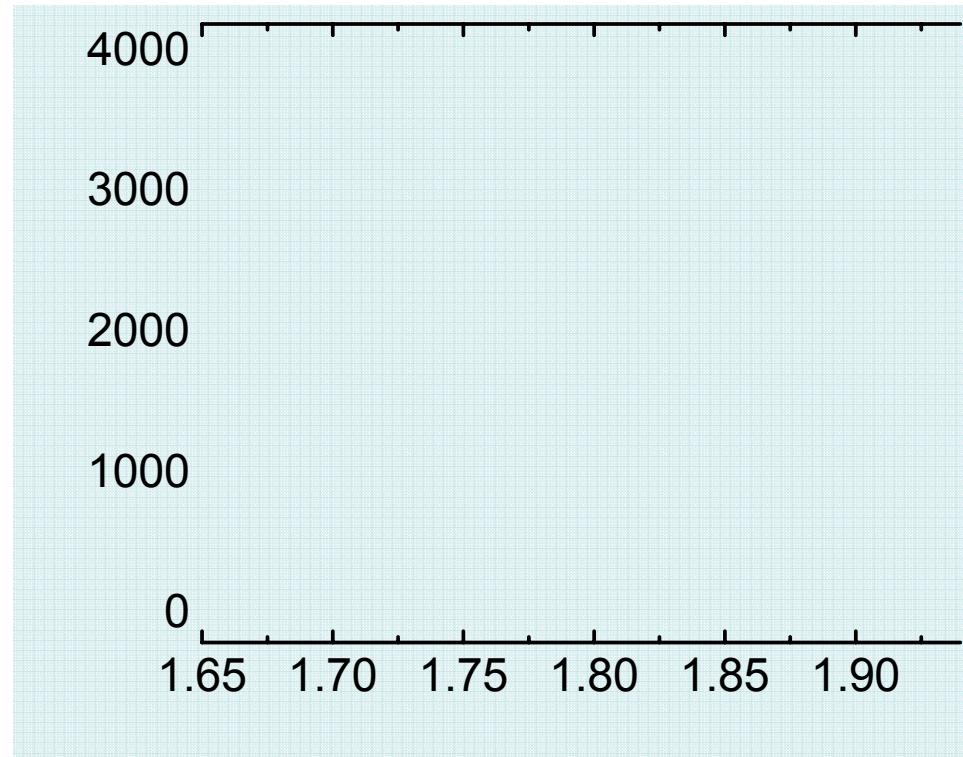
,

$\dot{H}$

f

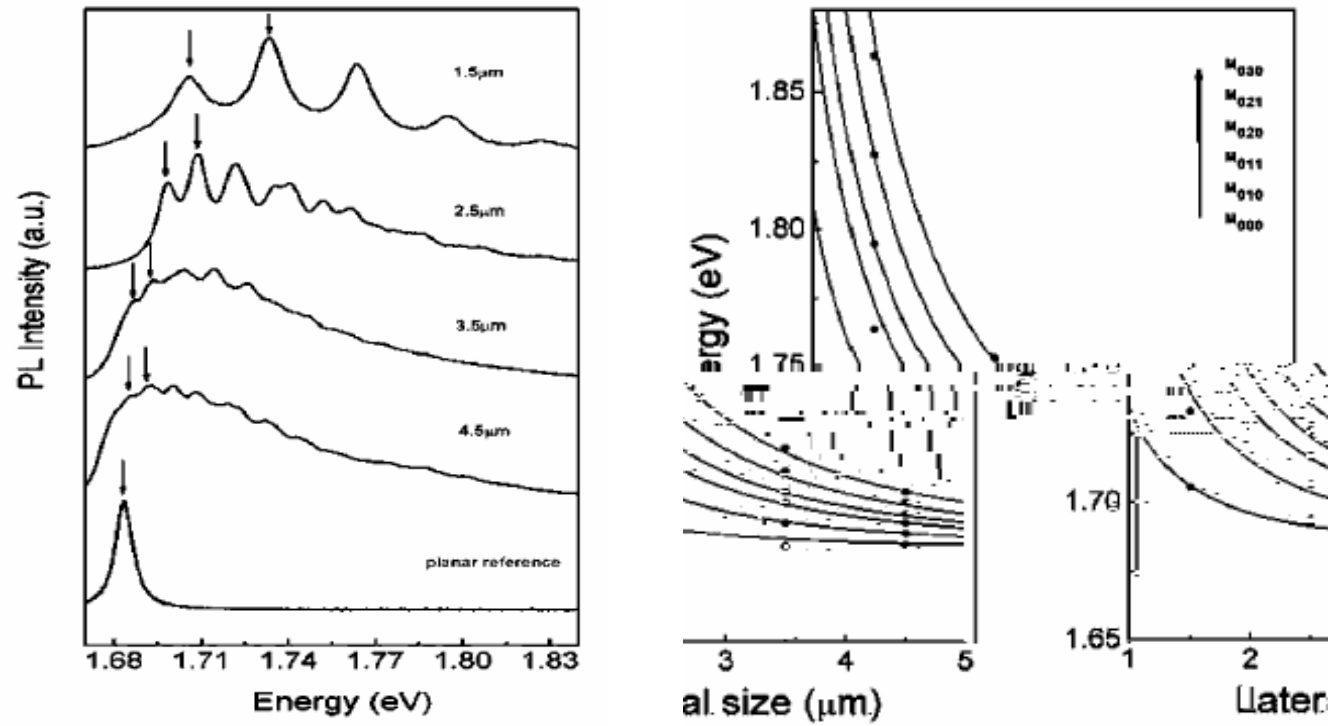


1 m m





Si 3D



$$E_{ph} = \frac{\hbar c}{n} \sqrt{k_0^2 + k_x^2 + k_y^2},$$

$$k_0 = 2\pi n / \lambda_0, \quad k_{x,y} = (m_{x,y} + 1) \frac{\pi}{L}.$$

Here $m_{x,y} = 0, 1, 2, 3, \dots$ correspond to the lateral quantum numbers.



Si 3D

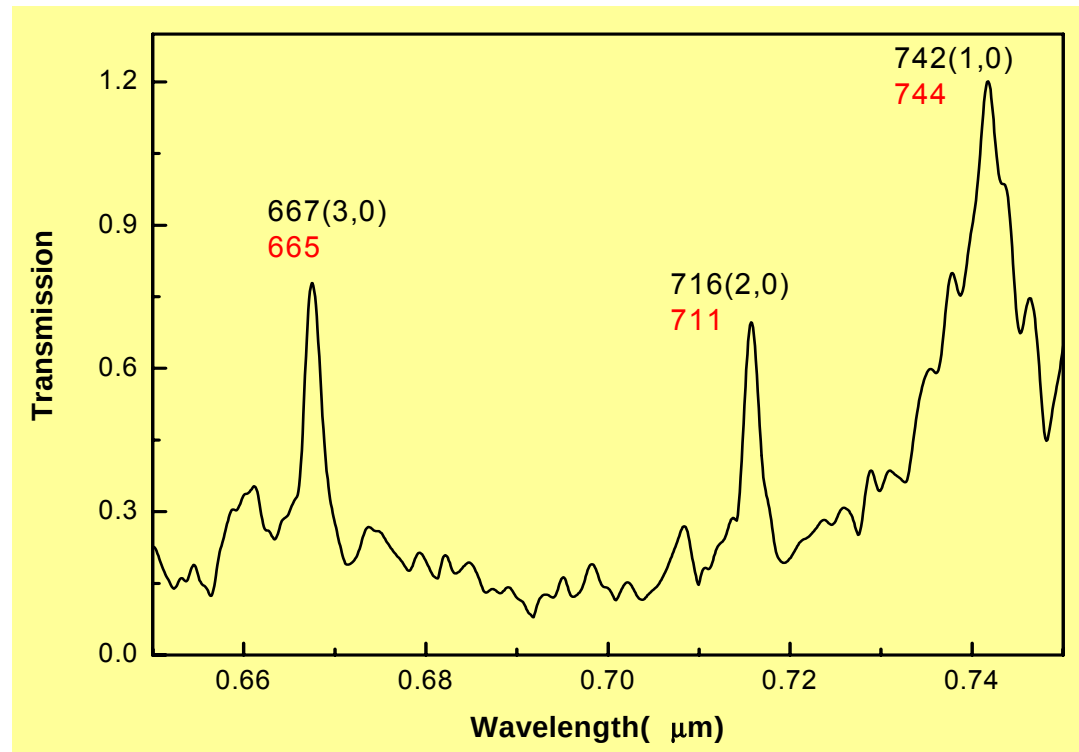
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Lateral size (nm)	M_{000} (eV)	M_{010} / M_{001} (eV)	M_{011} (eV)	M_{020} / M_{002} (eV)	M_{012} / M_{021} (eV)	M_{022} (eV)
1.5	<u>1.705</u>	<u>1.733</u>	<u>1.764</u>	<u>1.795</u>	<u>1.827</u>	<u>1.863</u>
	1.706	1.734	1.773	1.794	1.826	1.868
2.5	<u>1.693</u>	<u>1.706</u>	<u>1.717</u>	<u>1.726</u>	<u>1.737</u>	<u>1.753</u>
	1.691	1.704	1.716	1.724	1.736	1.752
3.5	<u>1.685</u>	<u>1.693</u>	<u>1.701</u>	<u>1.705</u>	<u>1.712</u>	<u>1.721</u>
	1.686	1.694	1.700	1.704	1.710	1.719
4.5	<u>1.685</u>	<u>1.689</u>	<u>1.693</u>	<u>1.697</u>	<u>1.701</u>	<u>1.704</u>
	1.686	1.690	1.693	1.696	1.700	1.705

Table II listed the results of measured energy of the resonant modes for the dots with different lateral sizes compared with calculated values based on 3D confinement model.



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FDTD

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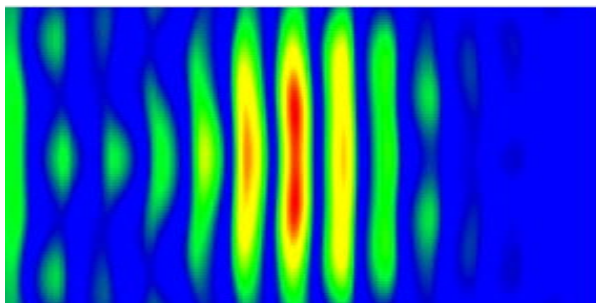
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FDTD چ ä

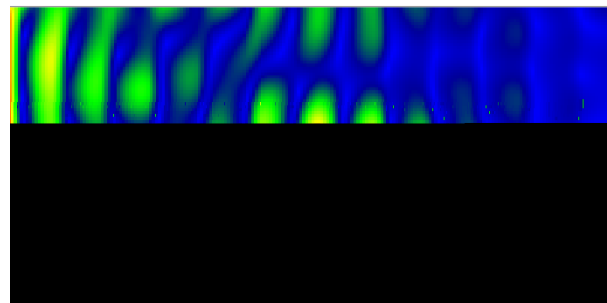
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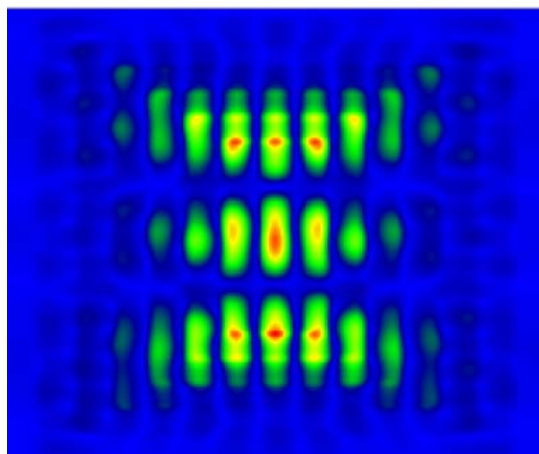
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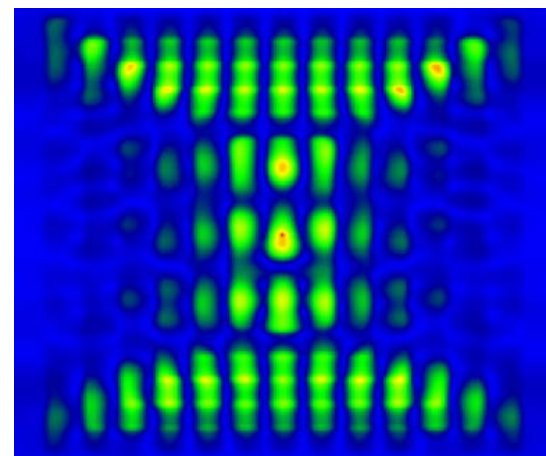
7

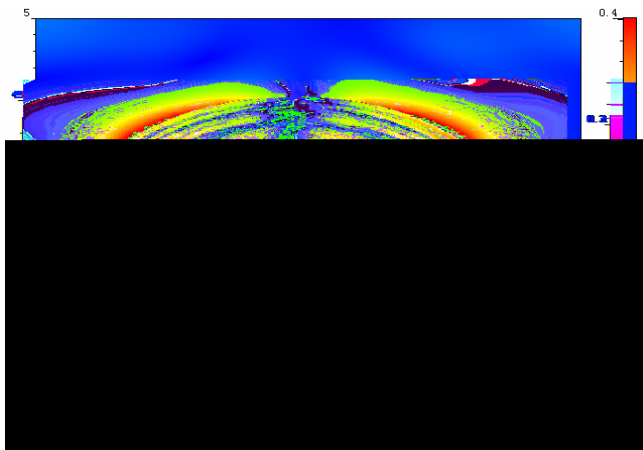
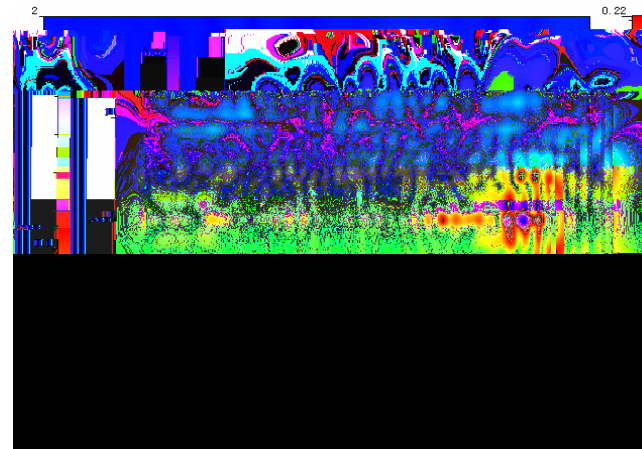
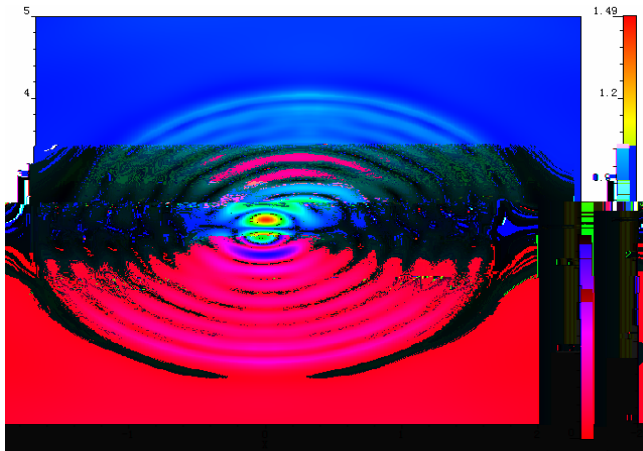


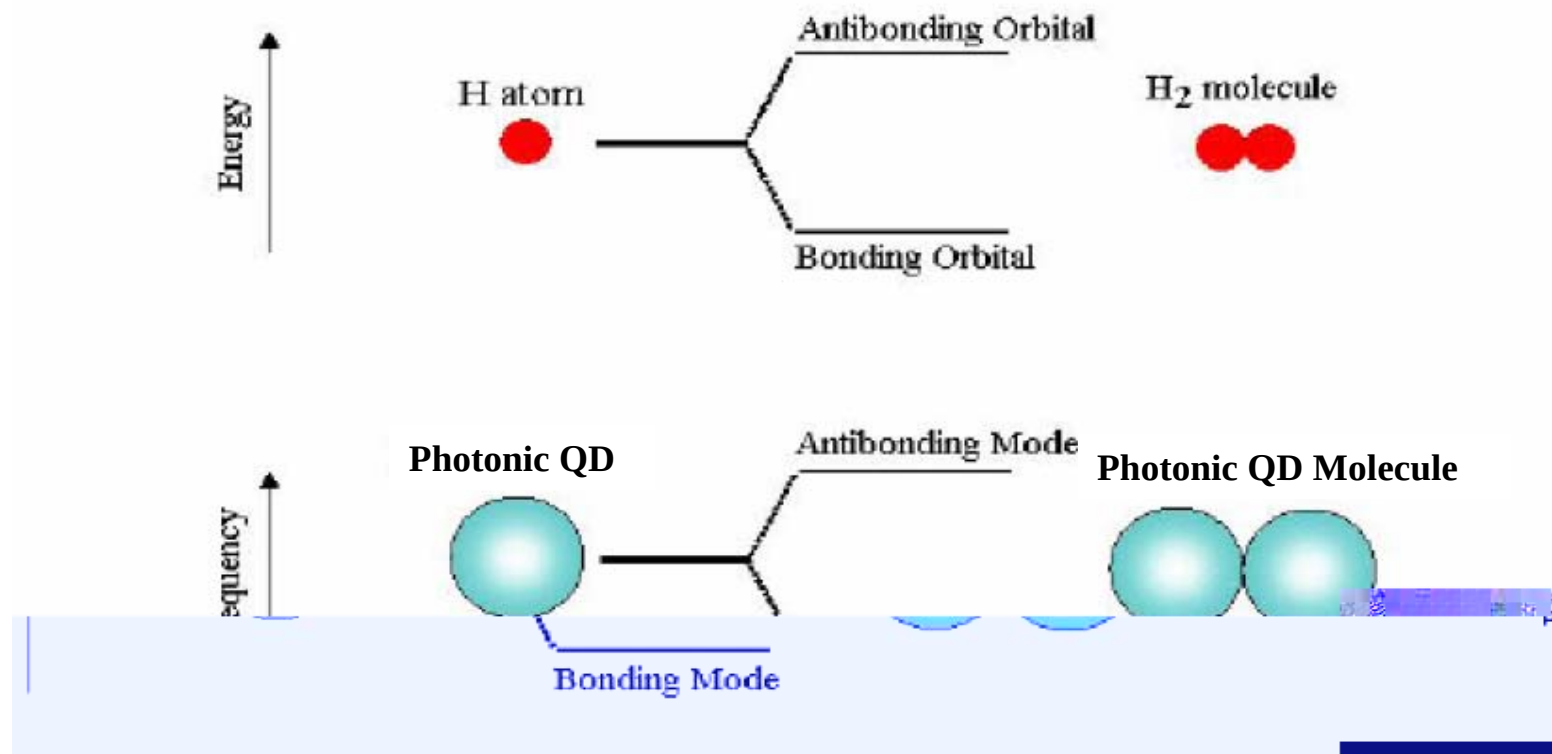
7



7



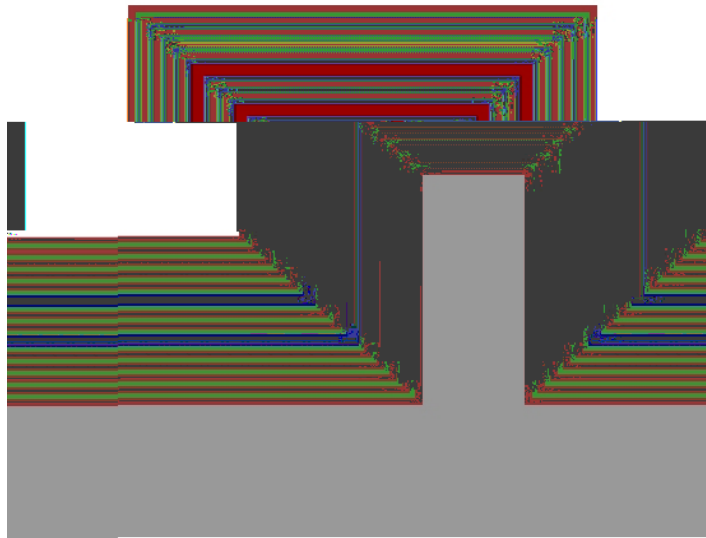




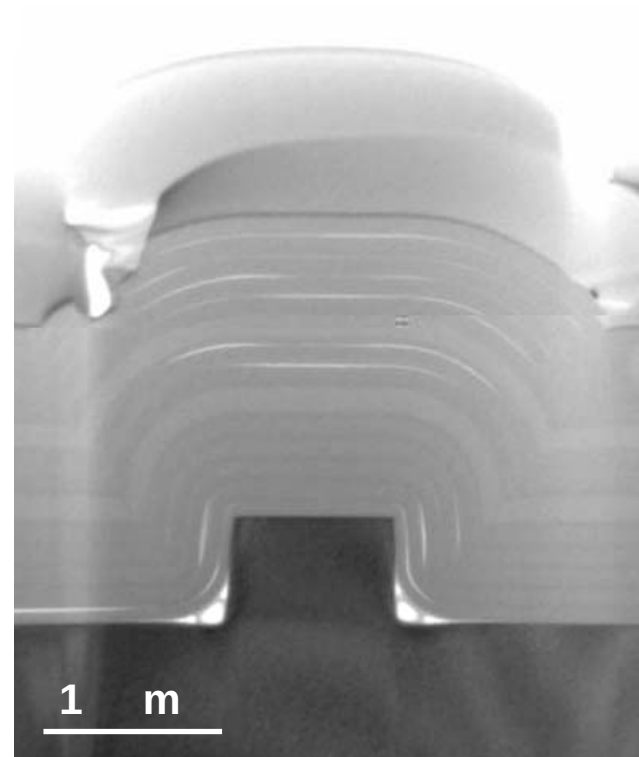
H_2



TEM



2.5

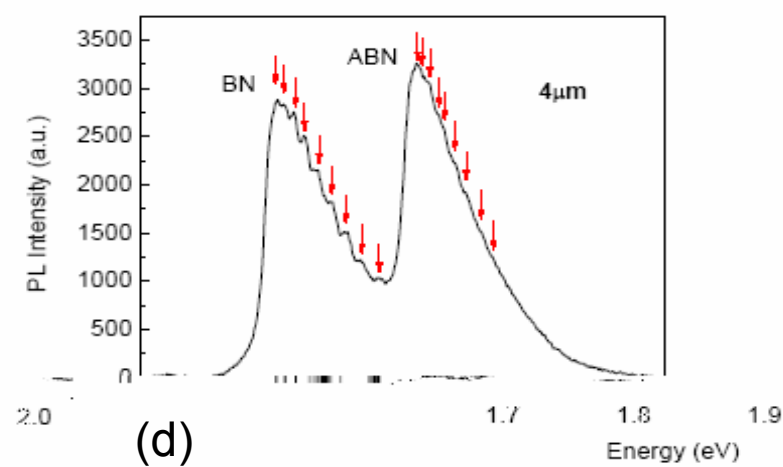
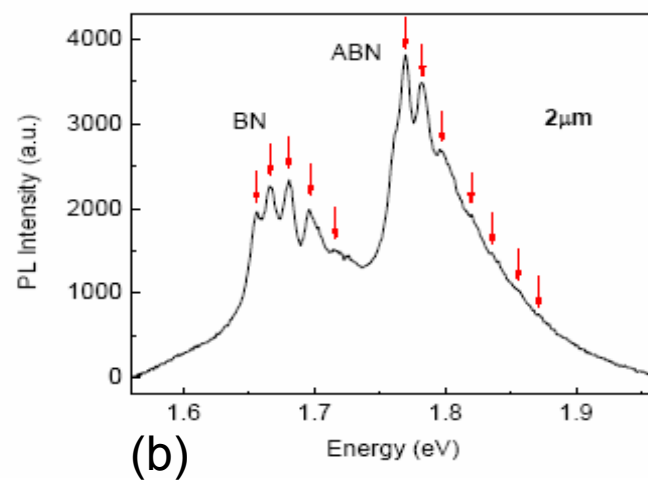
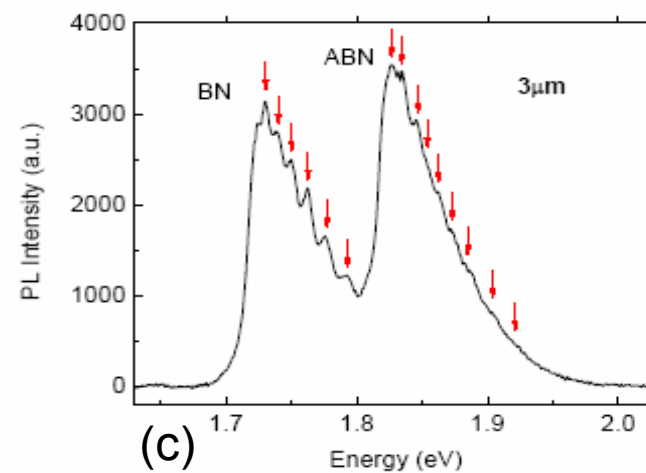
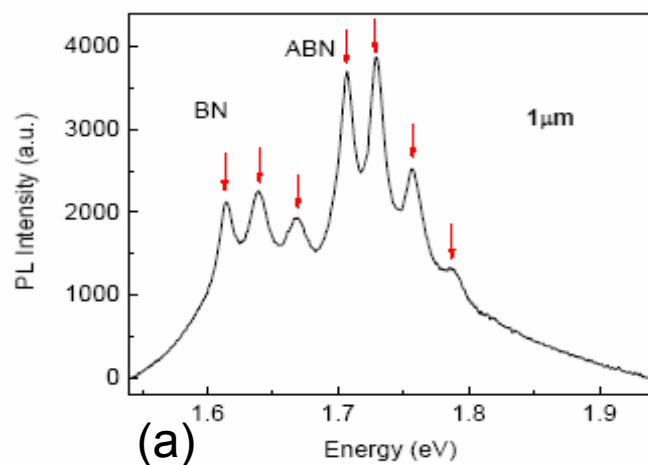


DBR



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PL



2.5

DBR A

PL



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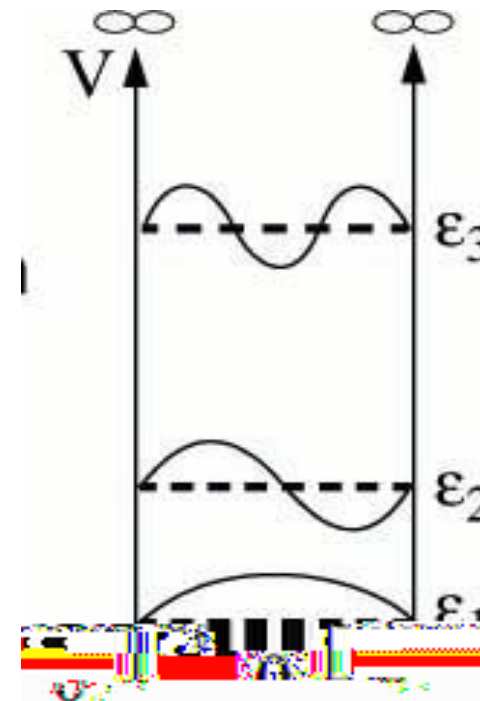


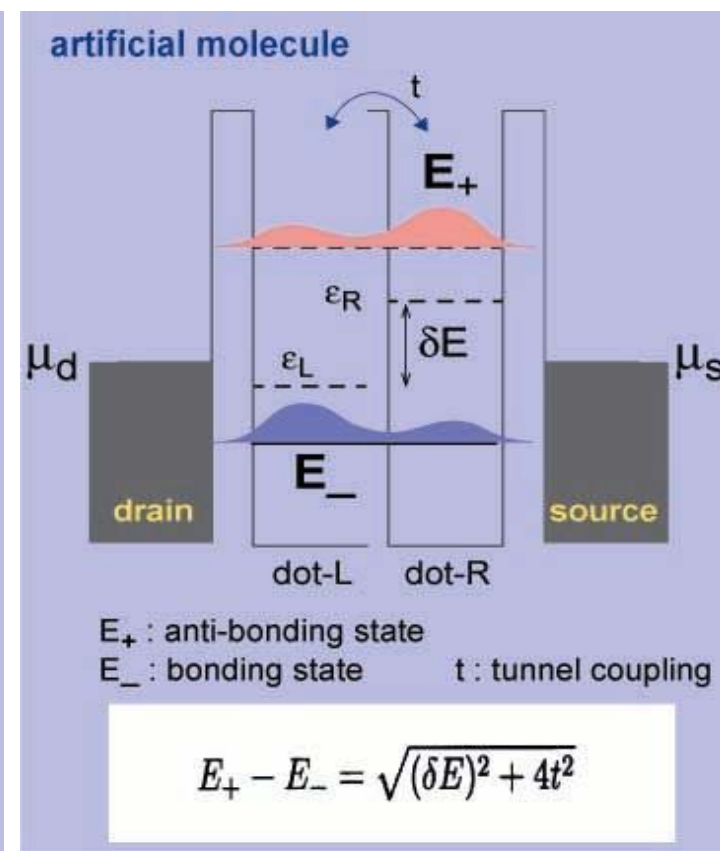
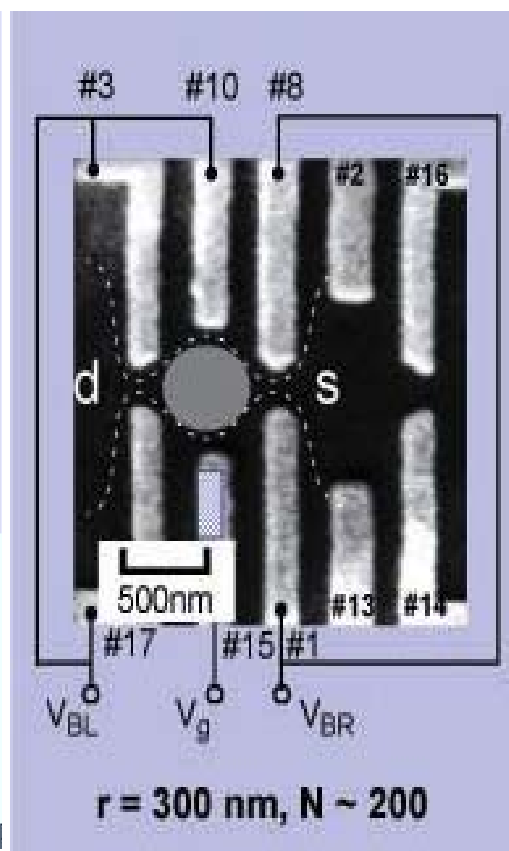
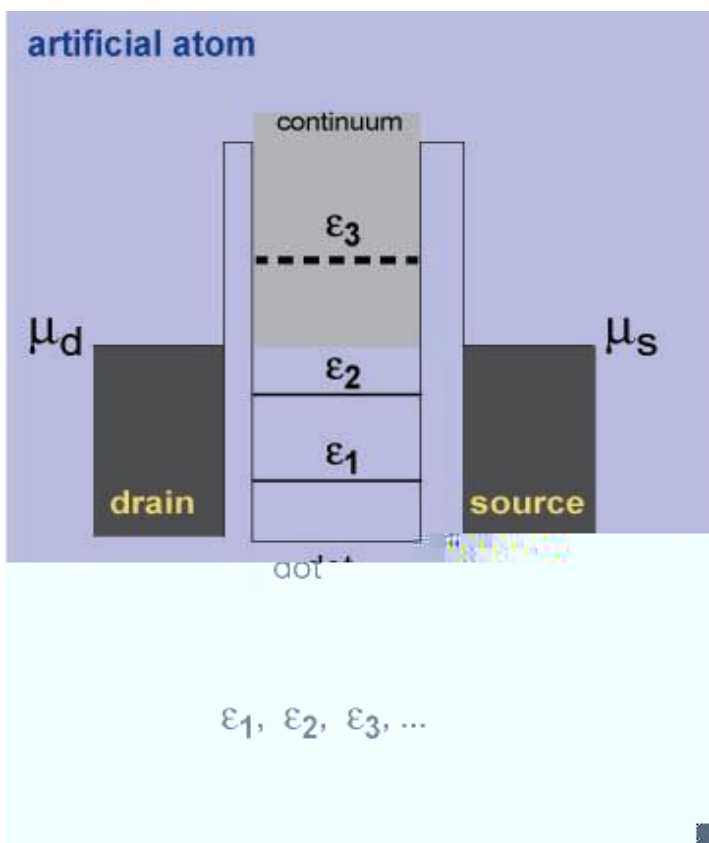
A quantum dot size $L \sim \lambda_F < l_\phi$

λ_F : Fermi wavelength

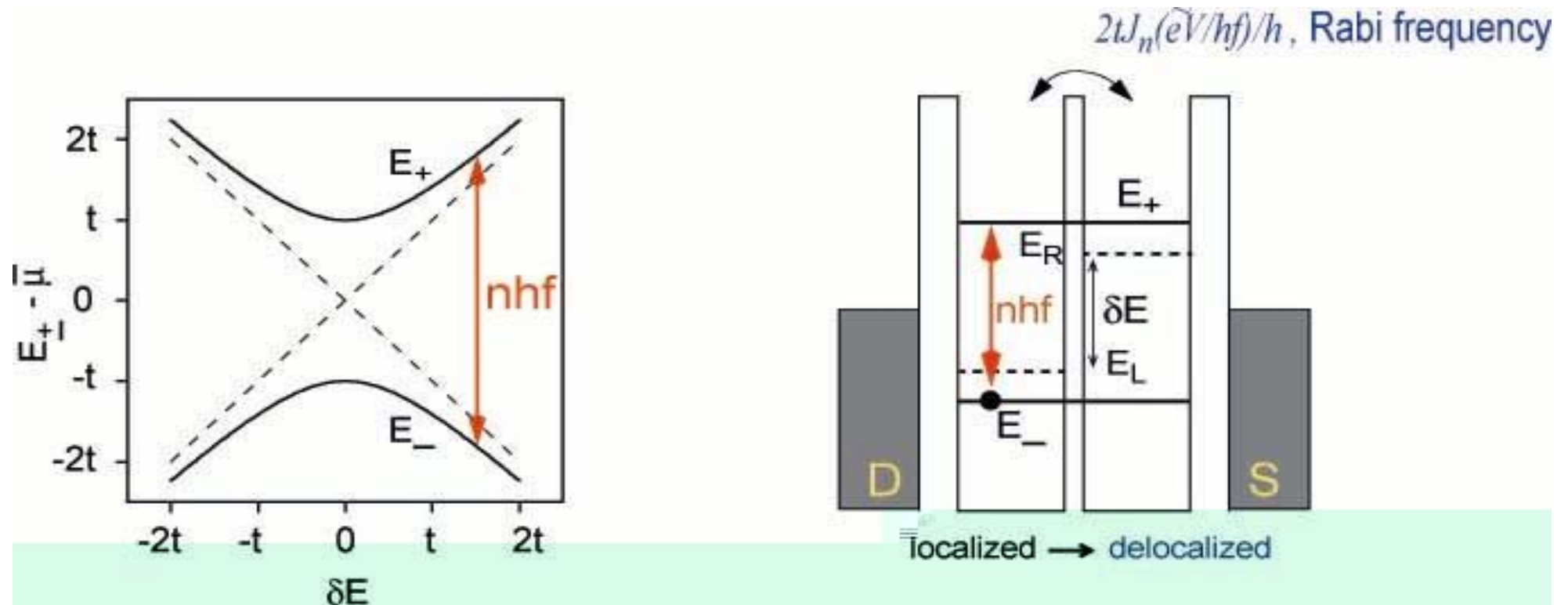
l_ϕ : phase coherence length

cm $\rightarrow$ mm $\rightarrow$ μ m $\rightarrow$ nm





quantum bit



In an artificial molecule, the two electron states can be coupled by external microwave photons when

$$nhf = E_+ - E_- = [(\delta E)^2 + 4t^2]^{0.5}$$



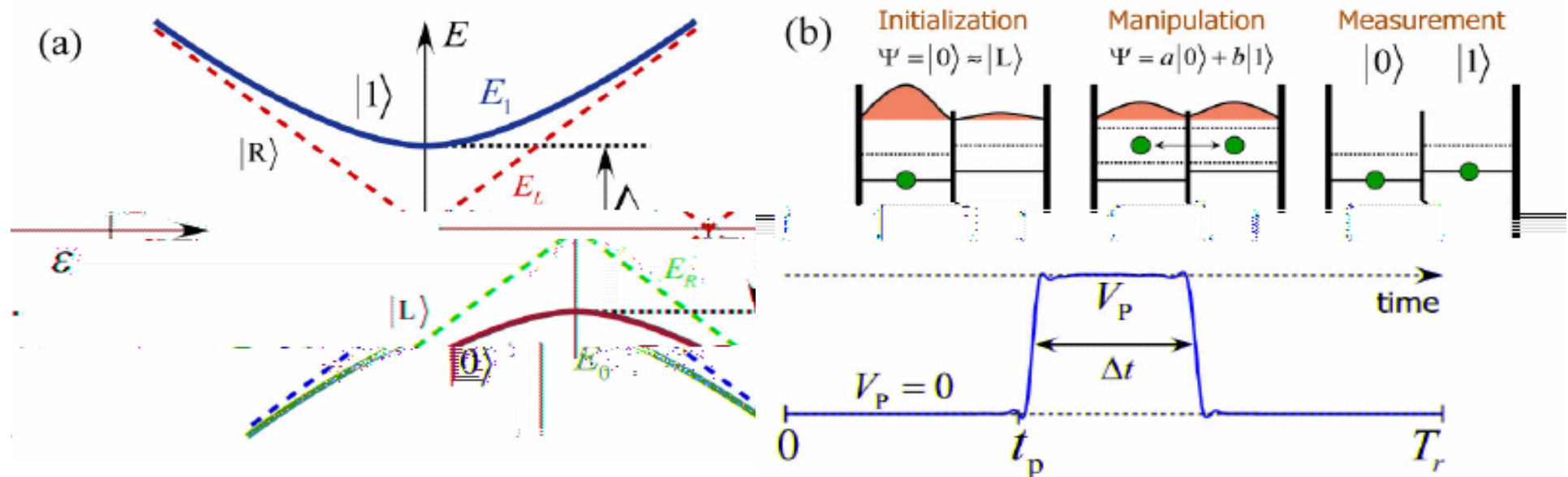
Si

--- Qbit



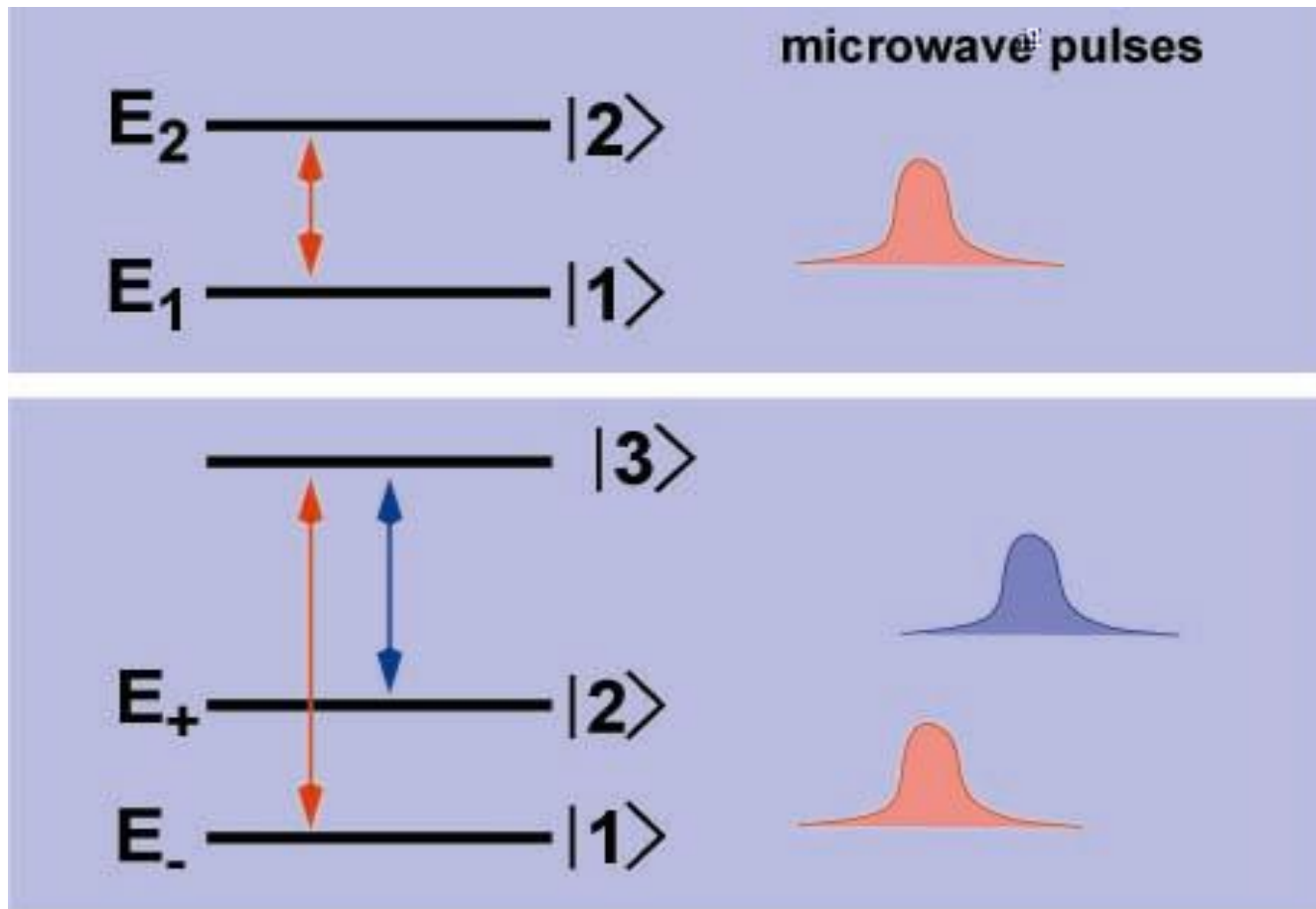
Si

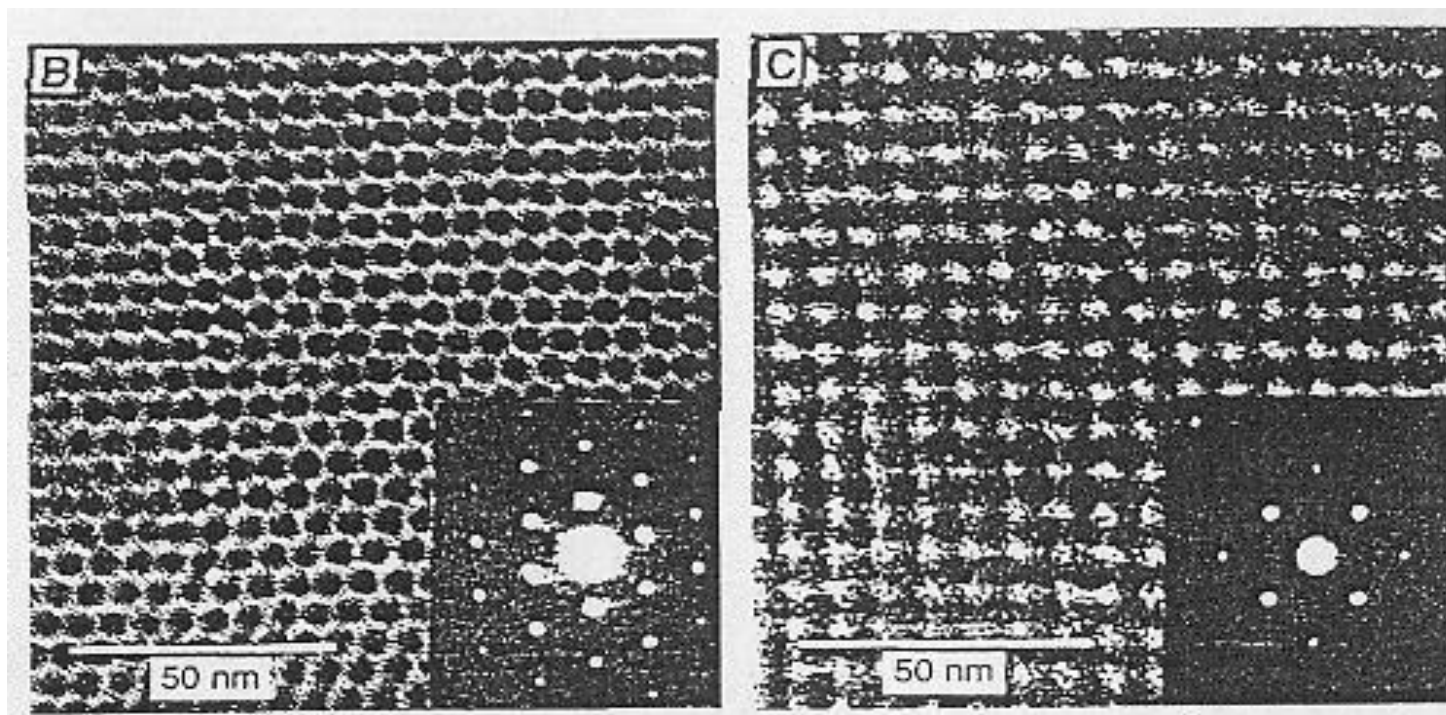
--- Qbit



Quantum bit:

$$|t\rangle = a(t)|1\rangle + b(t)|2\rangle$$





$\langle 101 \rangle$

$\langle 100 \rangle$

CdSe

,

4.8 nm



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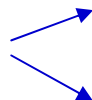


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