Large-Scale and Precise Nanoparticle Placement via Electrostatic Funneling

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Hong-Wen Huang

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WHERE DISCOVERIES BEGIN

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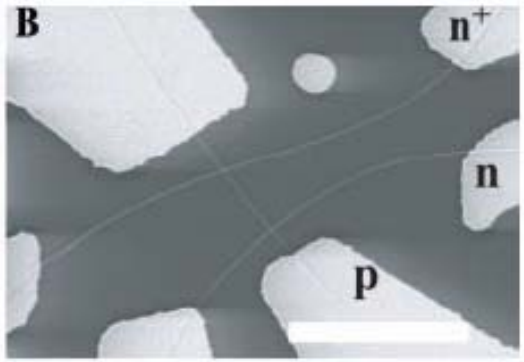
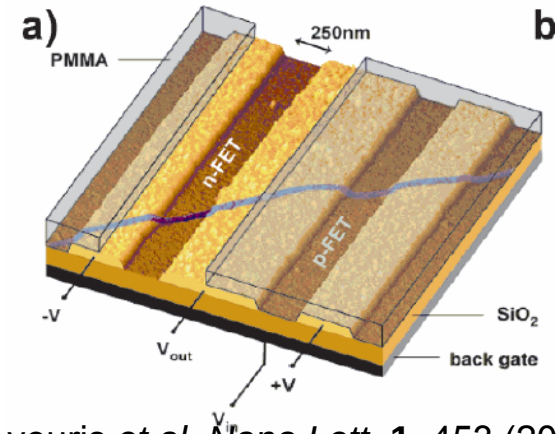
Motivation

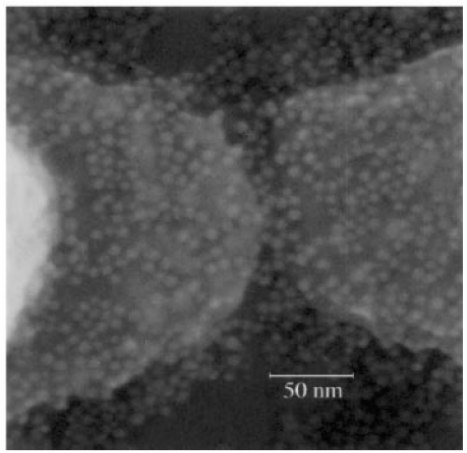
Devices based on nanoscale building blocks: Bottom-Up Approach



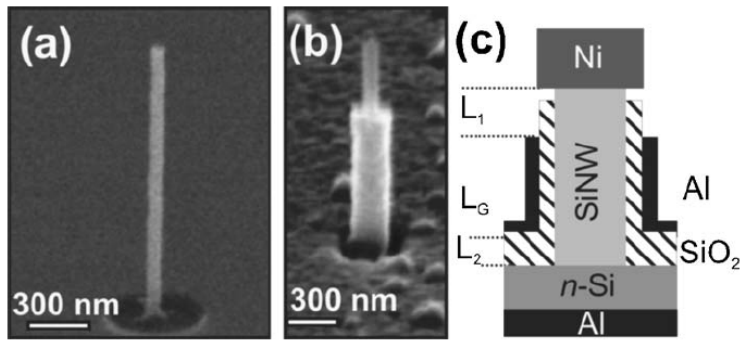
Y. Cui & C.M. Lieber
Science **291**, 851 (2001)



P. Avouris *et al. Nano Lett.* **1**, 453 (2001)



P.L. McEuen *et al, Nature* **389**, 699 (1997)



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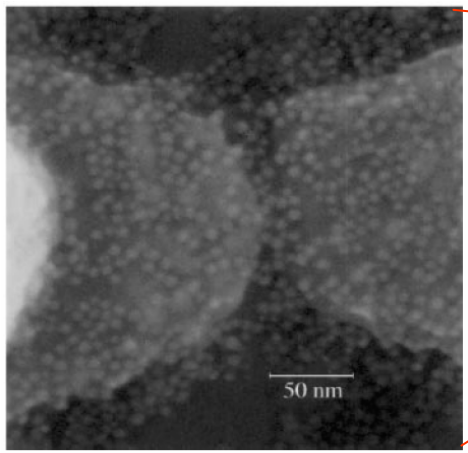

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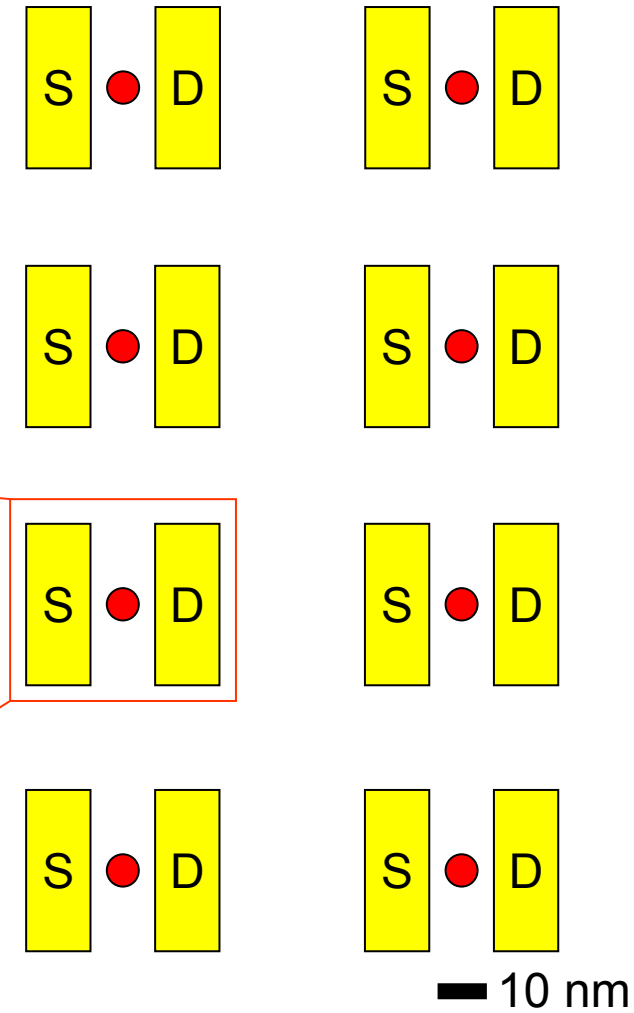

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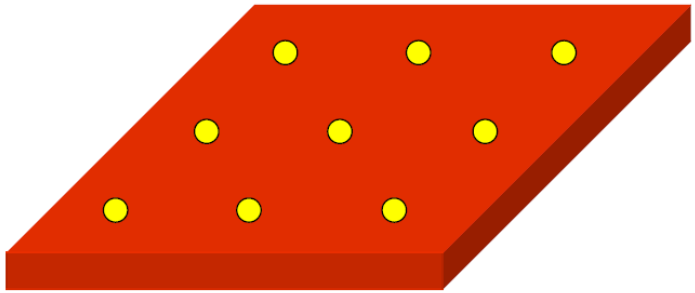

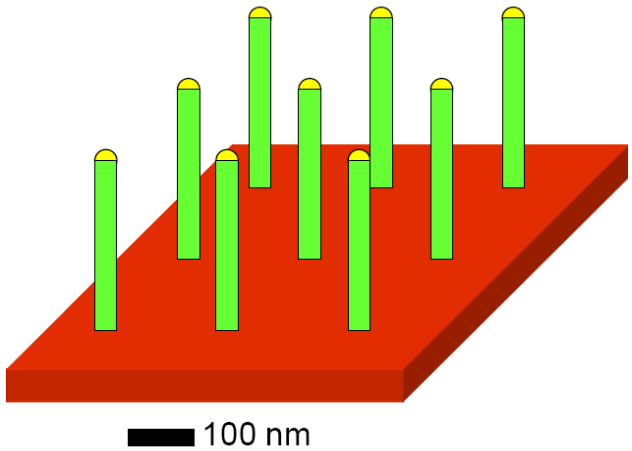

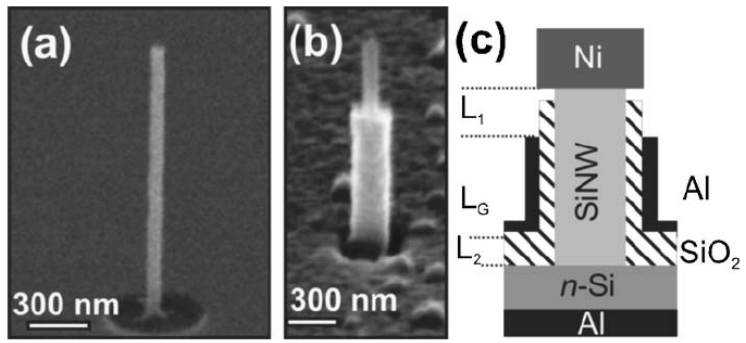

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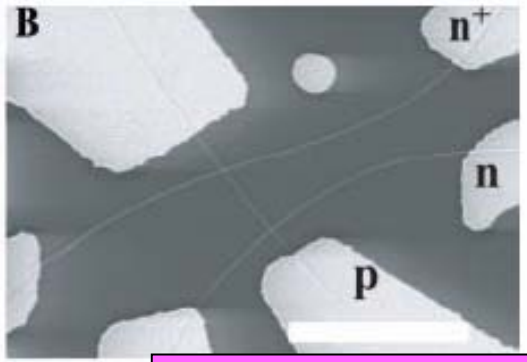
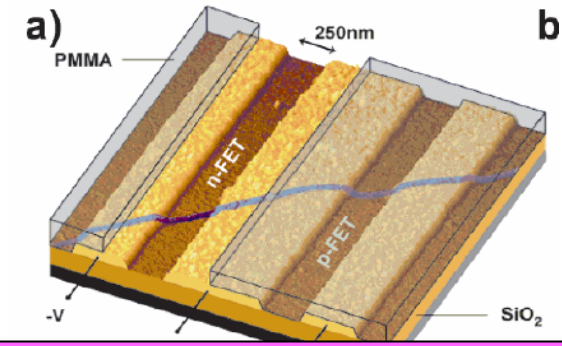
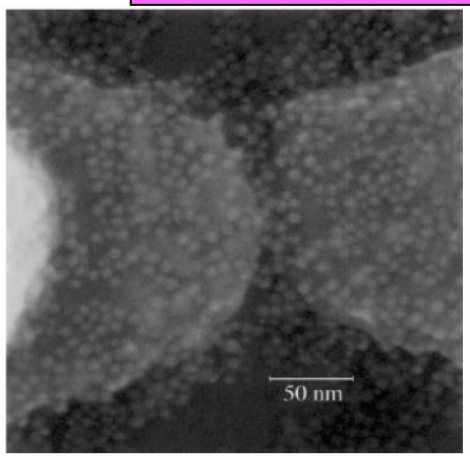




Y. Cui
Scienc

Practical device fabrication require

1. Large-Scale Placement 2. Nanoscale Precision



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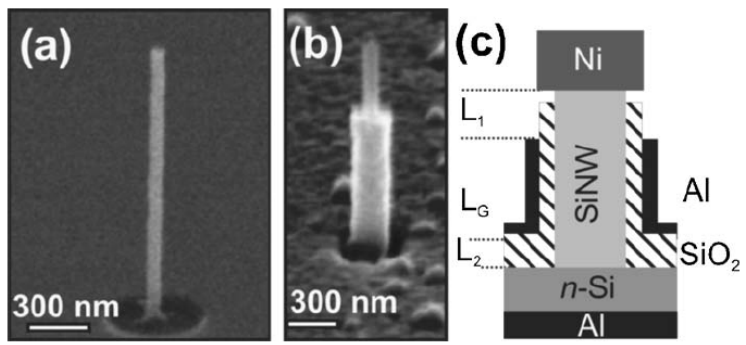

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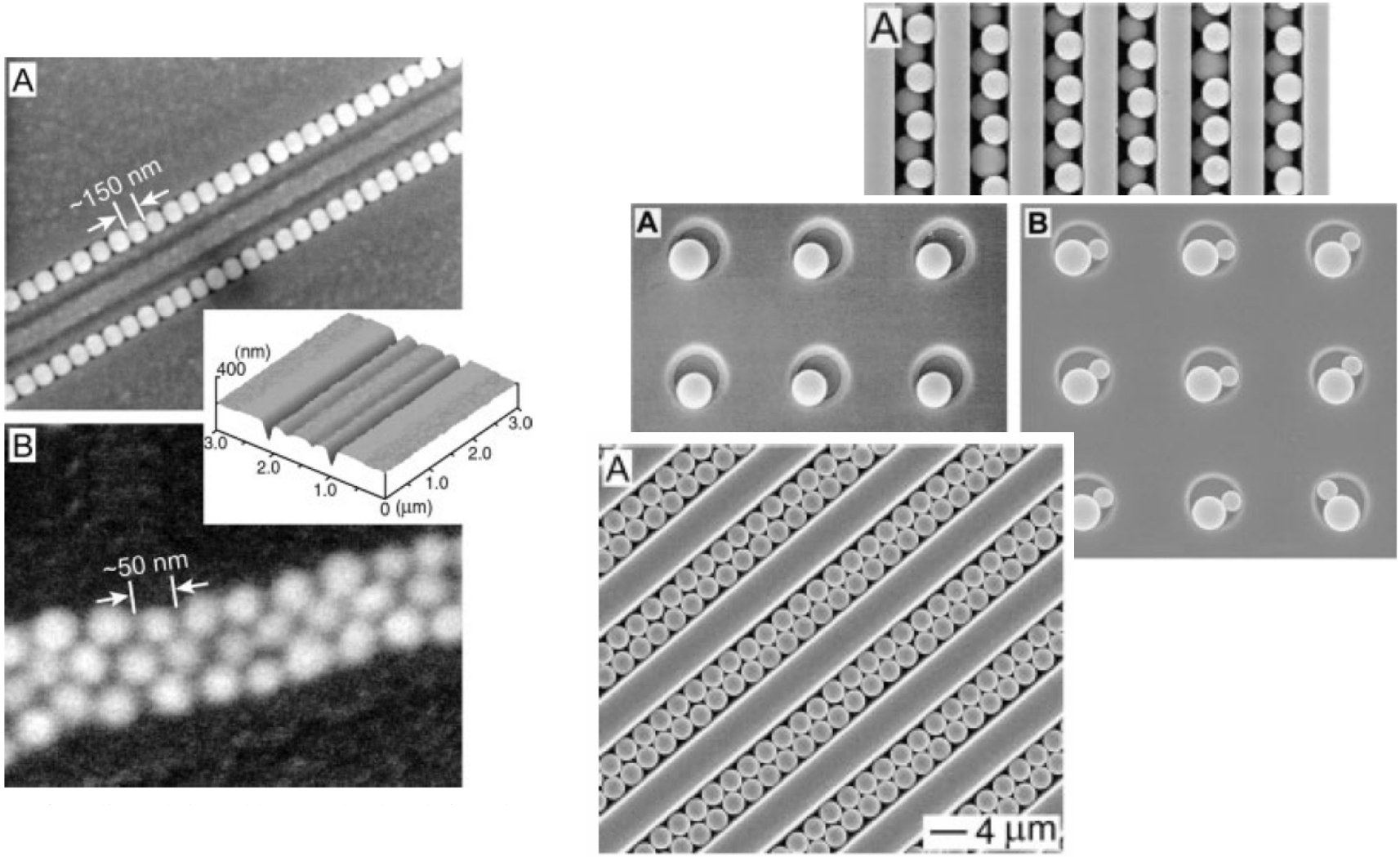
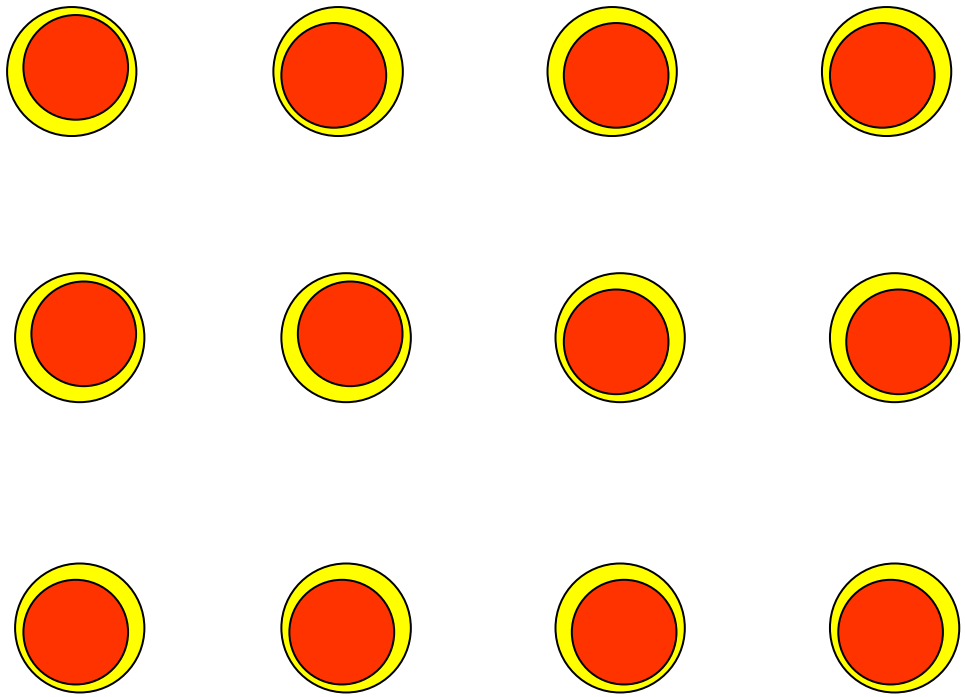
Placement using Templates



Y.N. Xia *et al.,* Adv. Funct. Mater. **13**, 907 (2003).

Placement using Templates

Template size ≈ Particle size

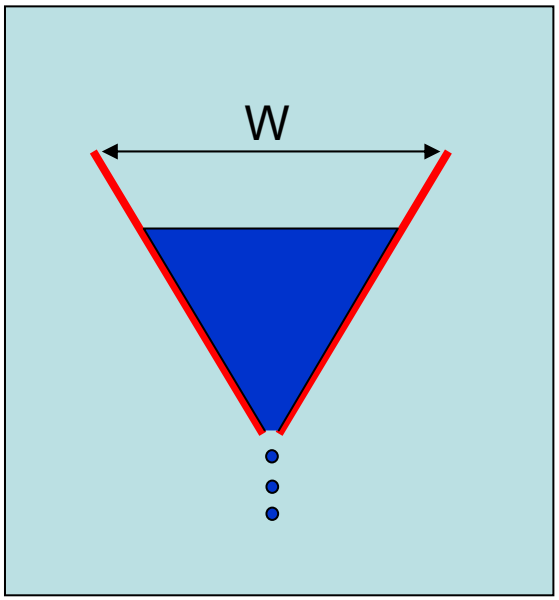


Challenge:
When NP size is below ~20 nm, large-scale processing is difficult.

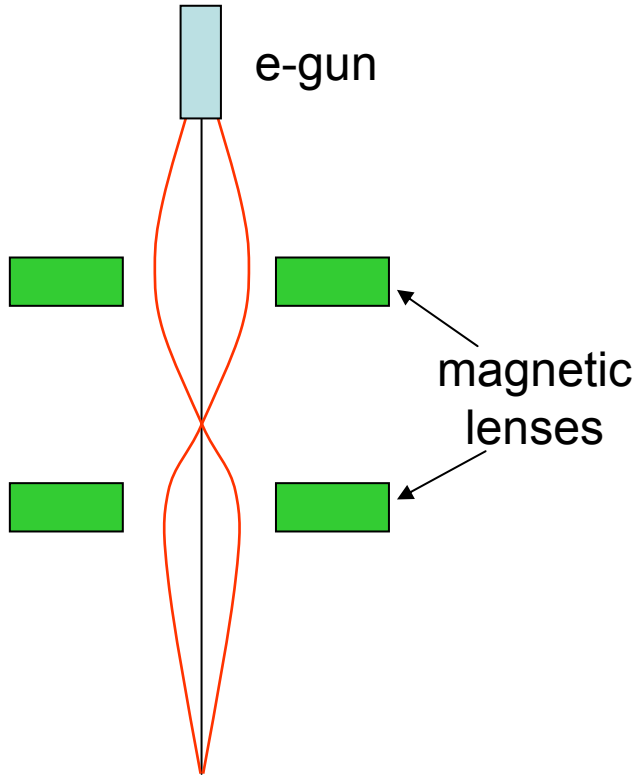
Funneling: Guided Placement

Guiding structure: of macro-scale
Placement precision: of micro-nano scale

Funnel for liquid

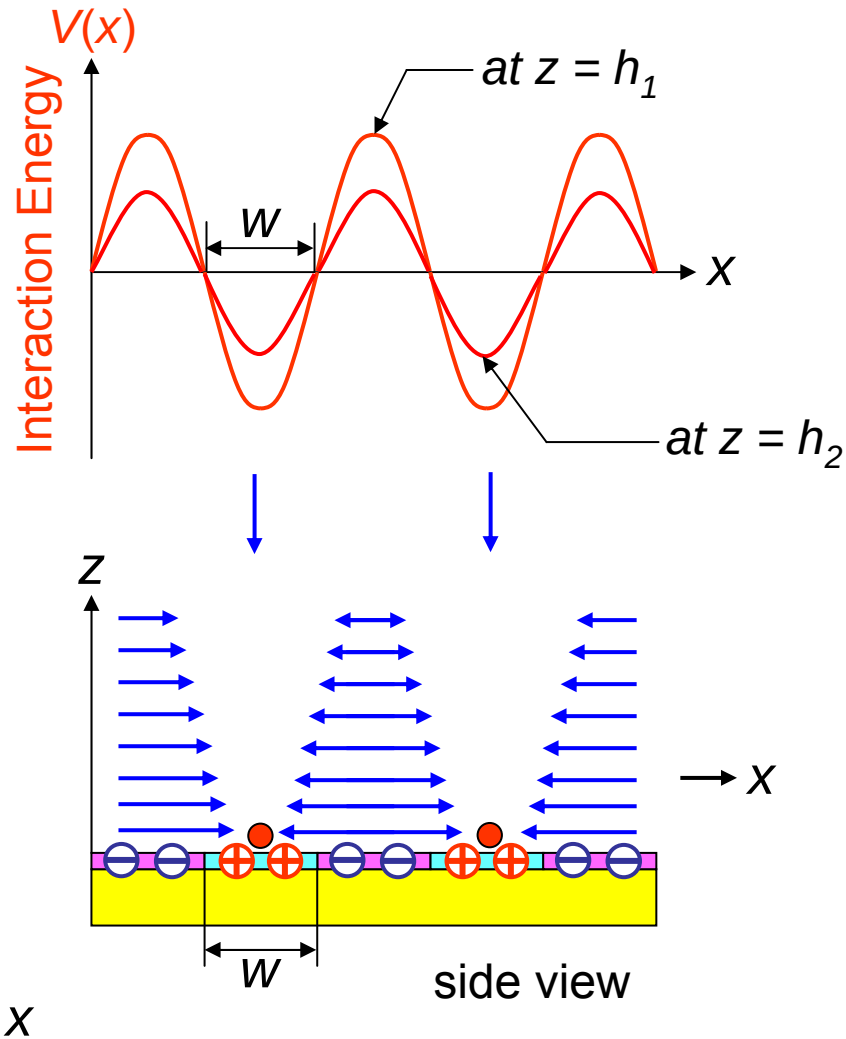


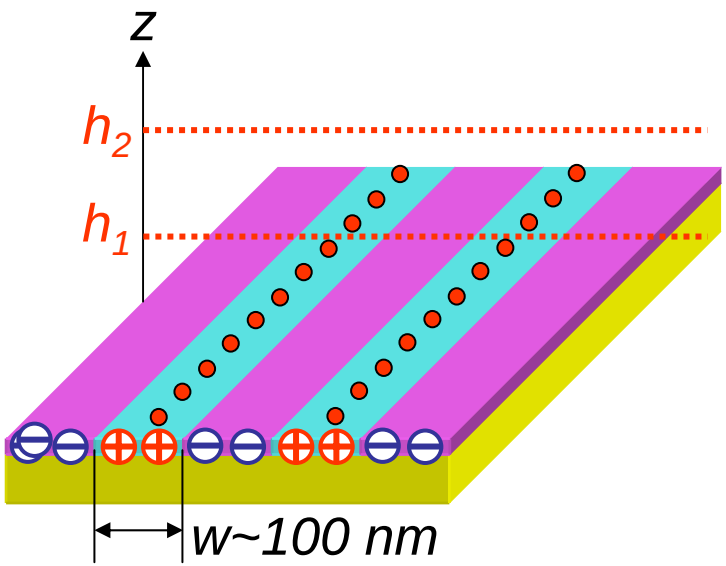
Electron Microscope

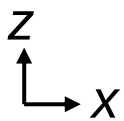


Concept of Electrostatic Funneling

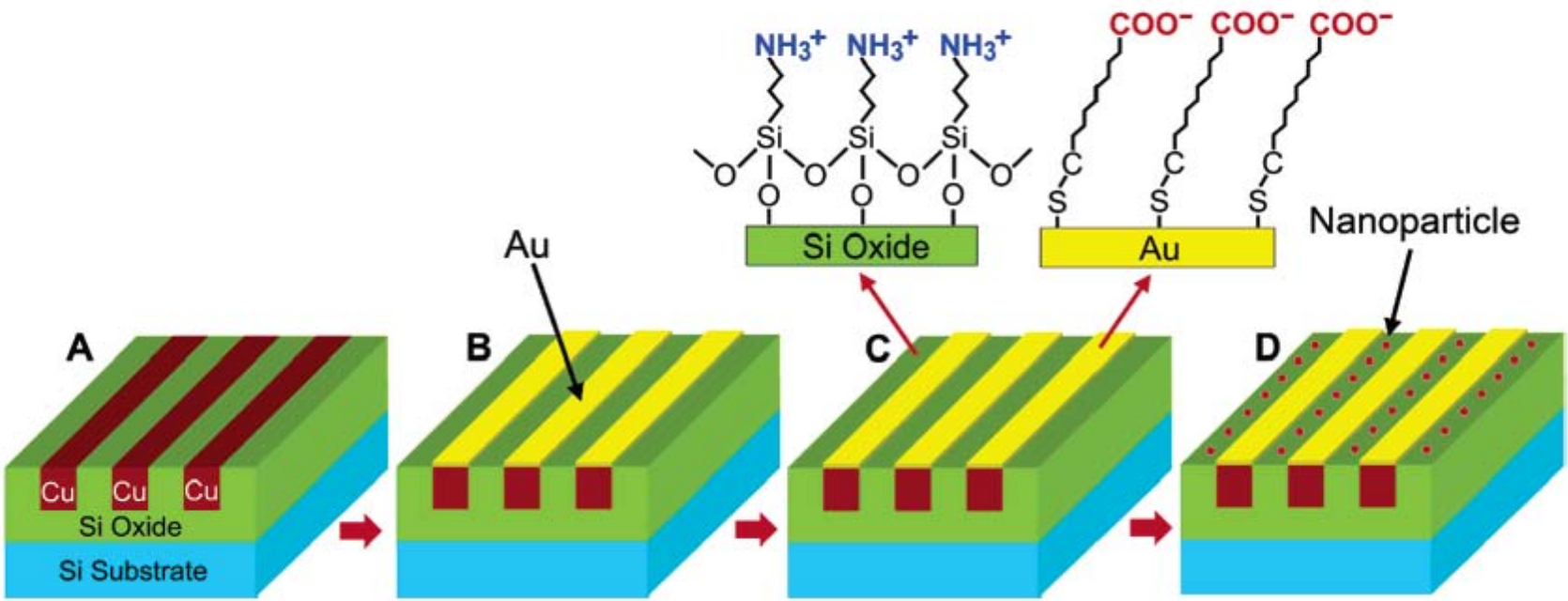
Lateral Force: $F_L = - dV(x)/dx$







Process Flow



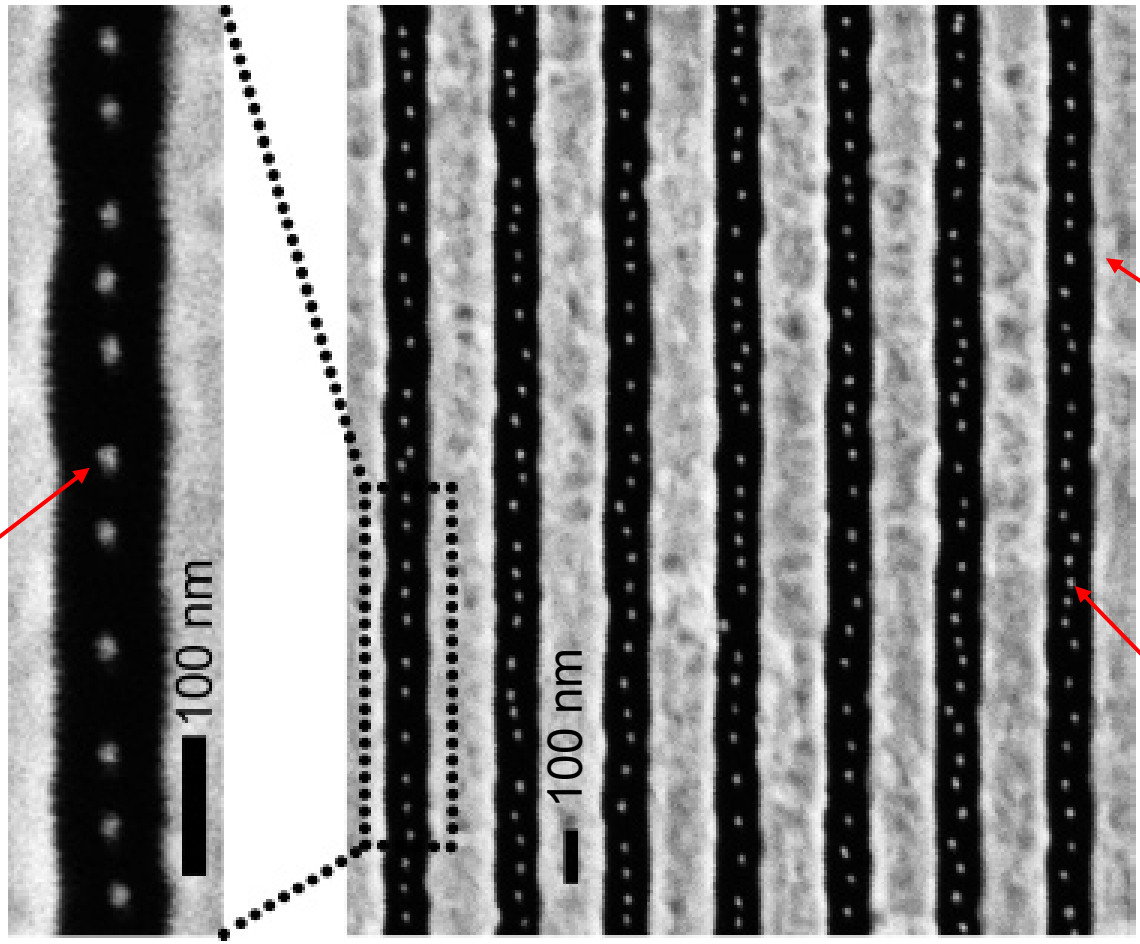
A = Cu interconnect lines in SiO_2 on a 200mm wafer

B = Electroless plating of Au on Cu lines

C = Positive and Negative SAMs formed on SiO_2 and Au respectively

D = Immobilizing negatively charged Au nanoparticles on SiO_2

Large-Scale Placement with Nanoscale Precision

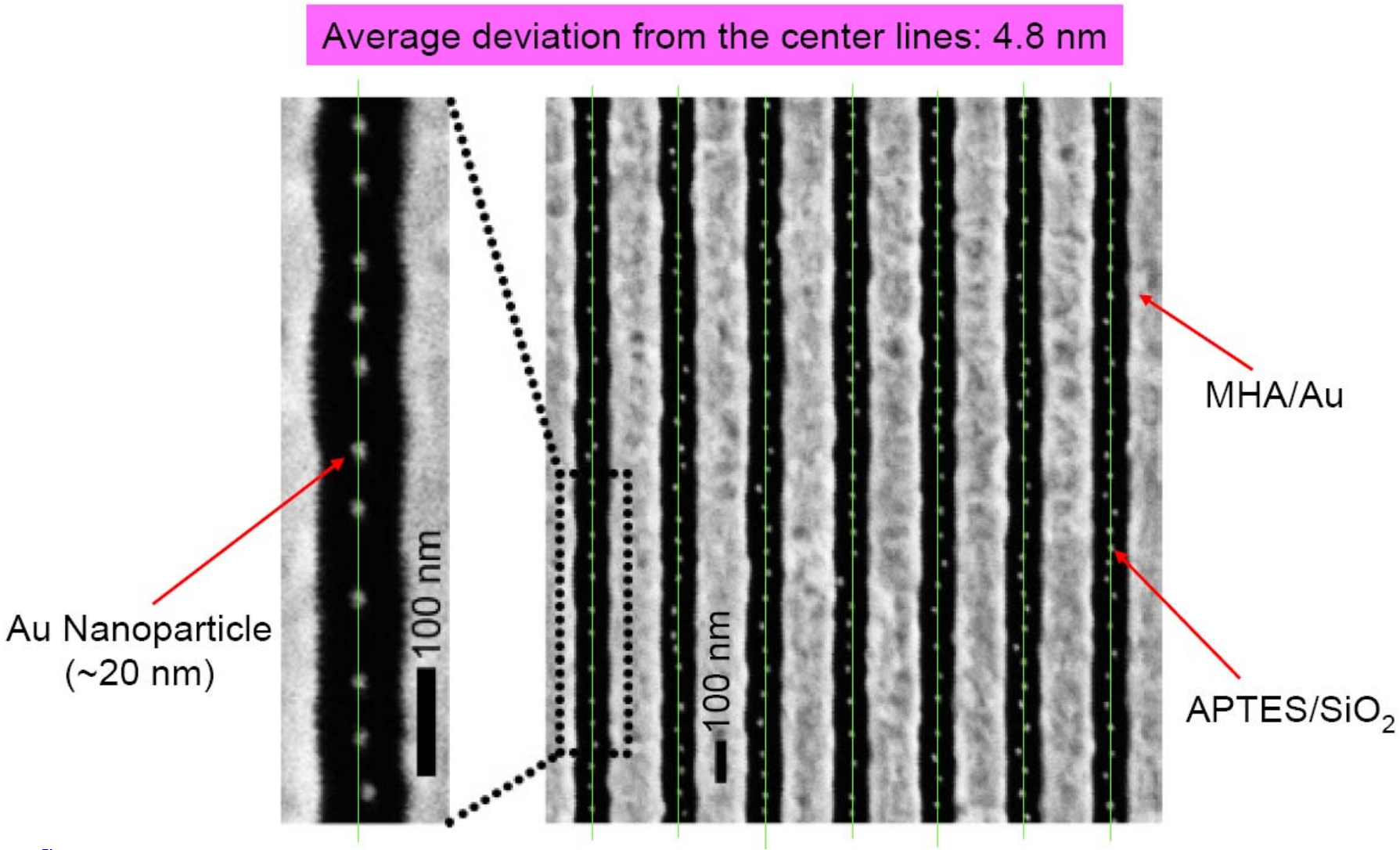


Au Nanoparticle
(~20 nm)

MHA/Au

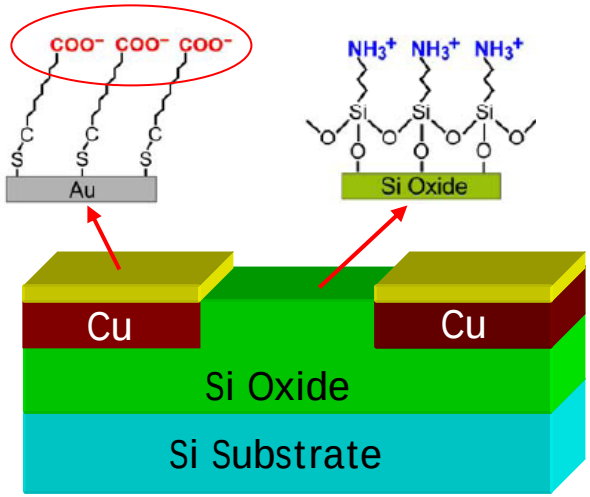
APTES/SiO_2

Large-Scale Placement with Nanoscale Precision

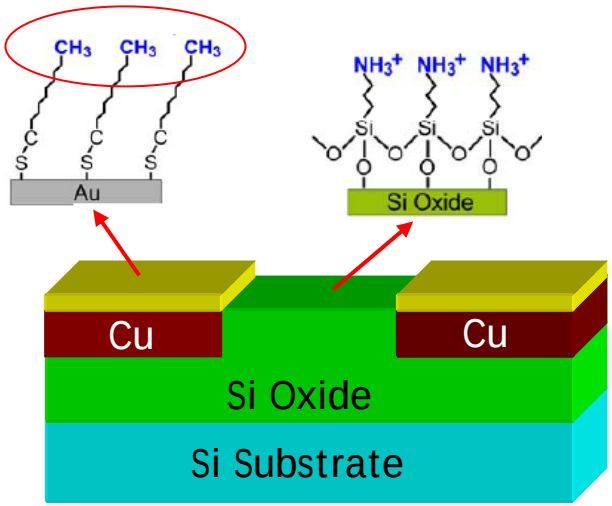


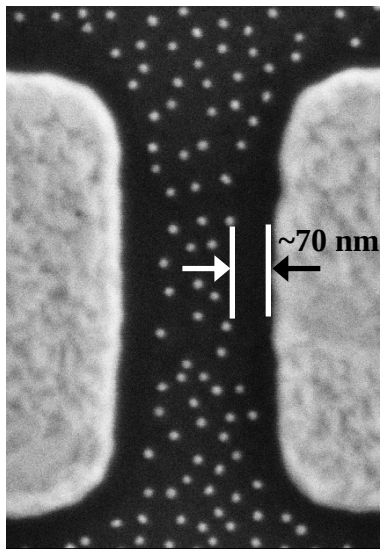
Importance of Interaction Energy *Gradient*

Negatively charged

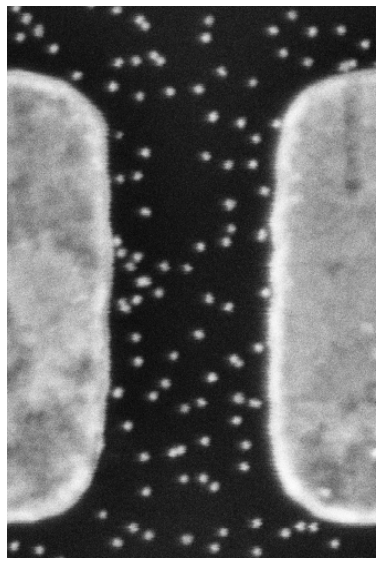


Non-Polar



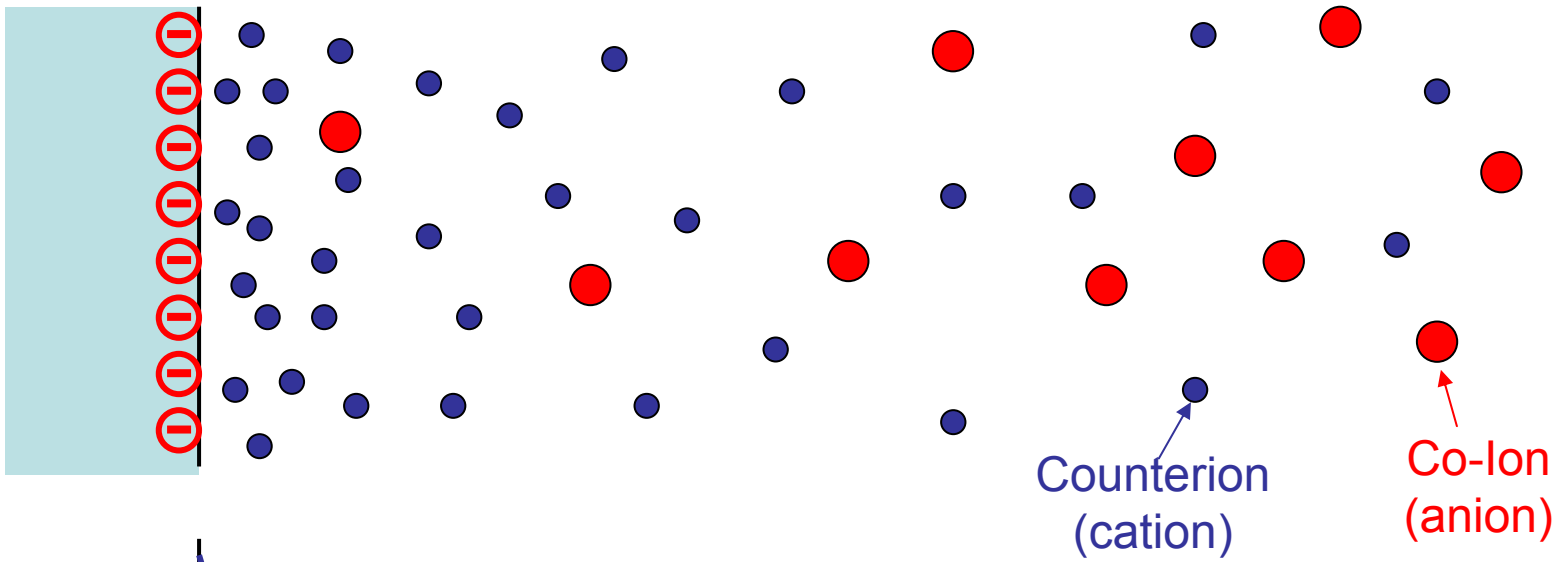


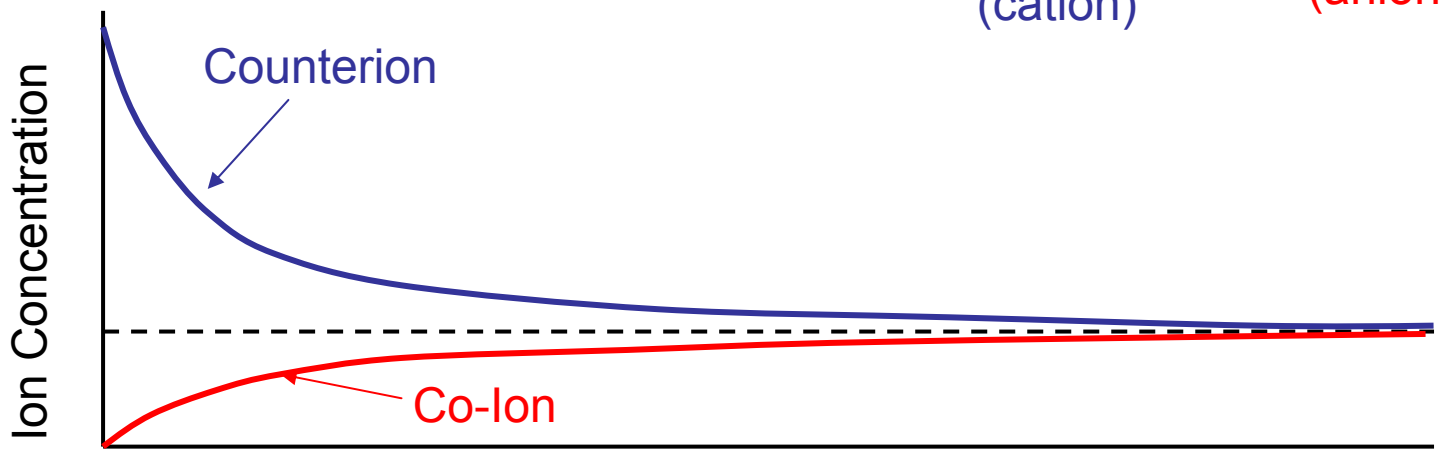
Interactions are Electrostatic and of Long Range



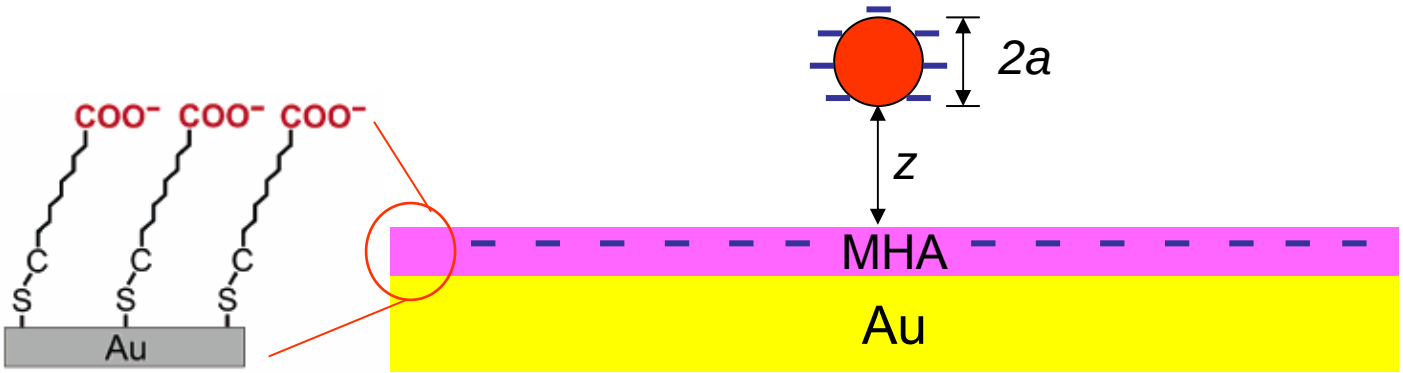
Electrostatic Forces in Liquids

Interaction through Electric Double Layer





Electrical Double-Layer Interaction between a Au NP and Charged Surface



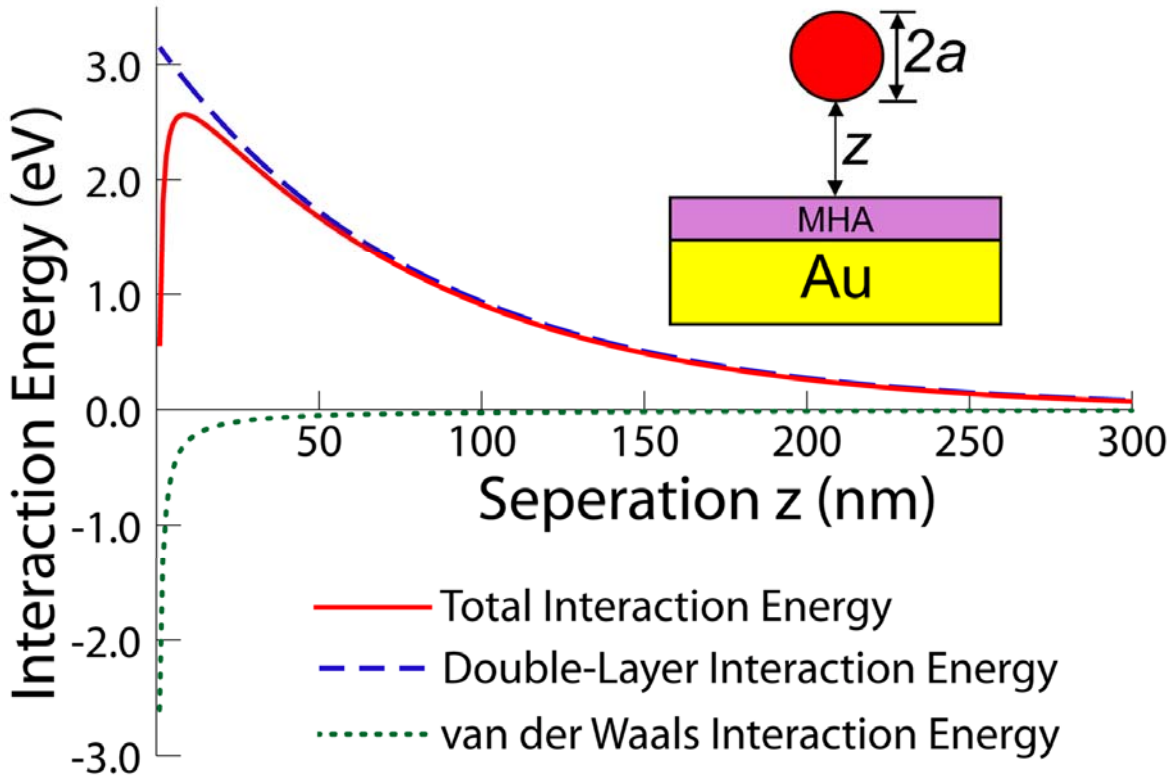
$$V_{MHA}(z) = \Phi_{MHA}(z) + W_{MHA}(z)$$ ← DLVO Theory

$$\Phi_{MHA}(z) = 4\pi\varepsilon\varepsilon_o\, a\, (kT/e)^2\, Y_{Au}\, Y_{MHA}\, exp(-\kappa z)$$ ← LSA

$$\kappa = [(1000\, e^2 N_A / \varepsilon\varepsilon_o kT)\, \Sigma_i\, z_i^2 M_i]^{1/2}$$ ← 1/Debye length

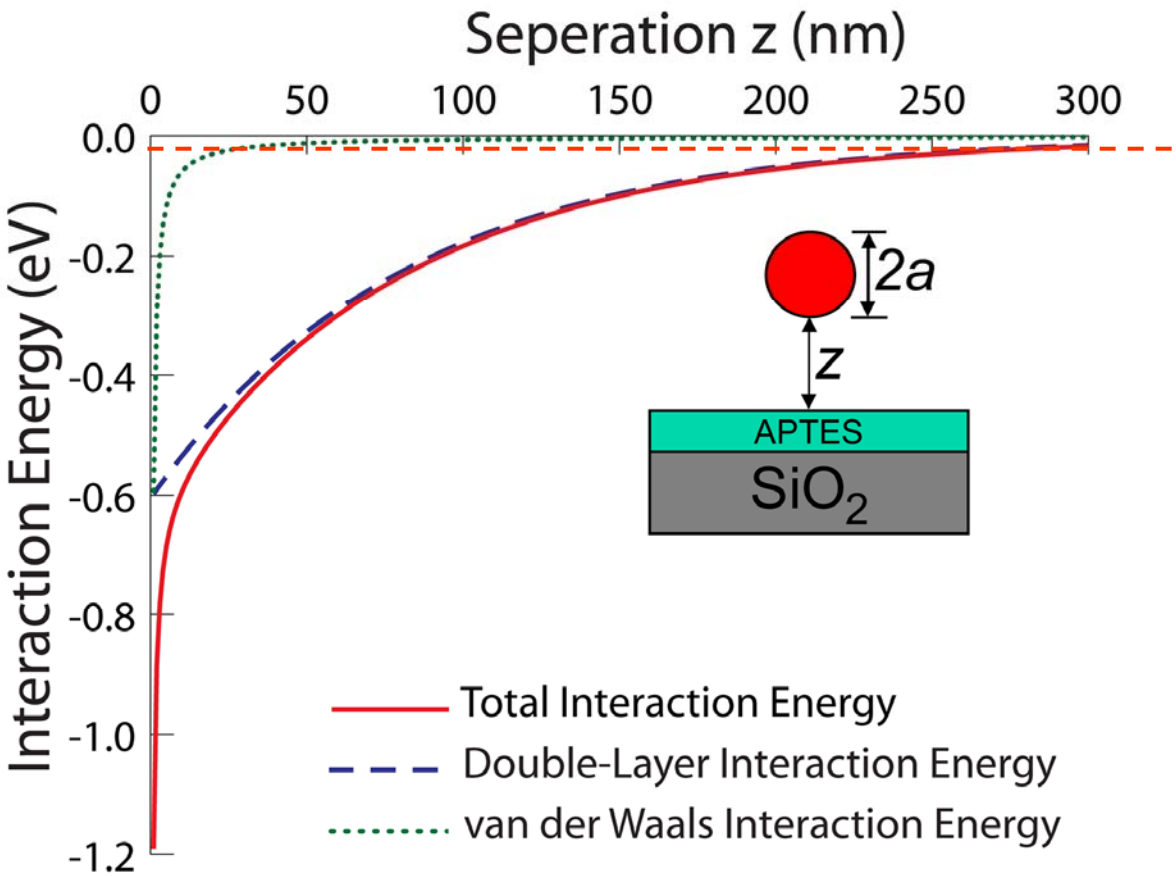
$$W_{MHA}(z) = -A_{MHA}\, a\, /6z$$ ← Van der Waals

Interaction between a Au Nanoparticle and MHA/Au



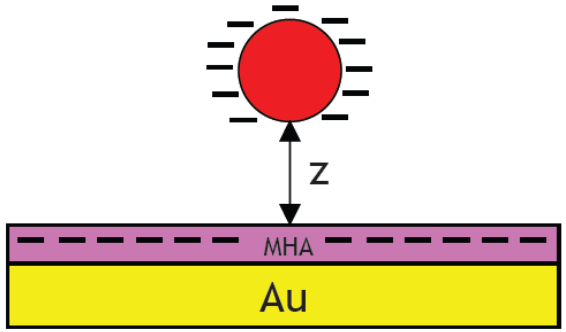
Interactions are of a long range:
Reaches the room temperature thermal energy (~25 meV) at ~370 nm

Interaction between a Au Nanoparticle and APTES/SiO_2

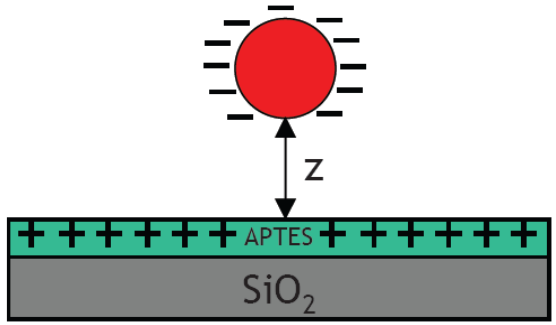


Interactions are of a long range:
Reaches the room temperature thermal energy (~-25 meV) at ~270 nm

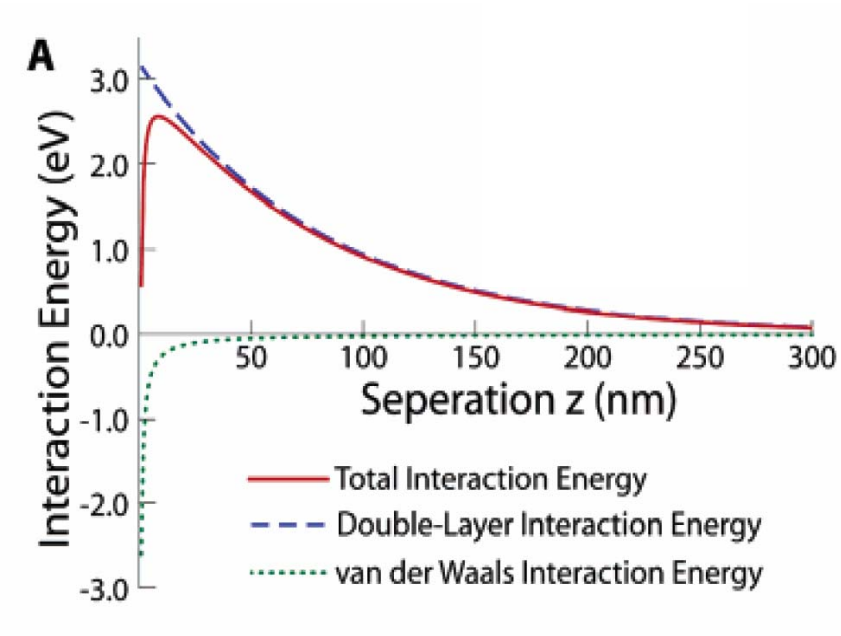
Interaction Energy between a Au NP and Charged Substrate

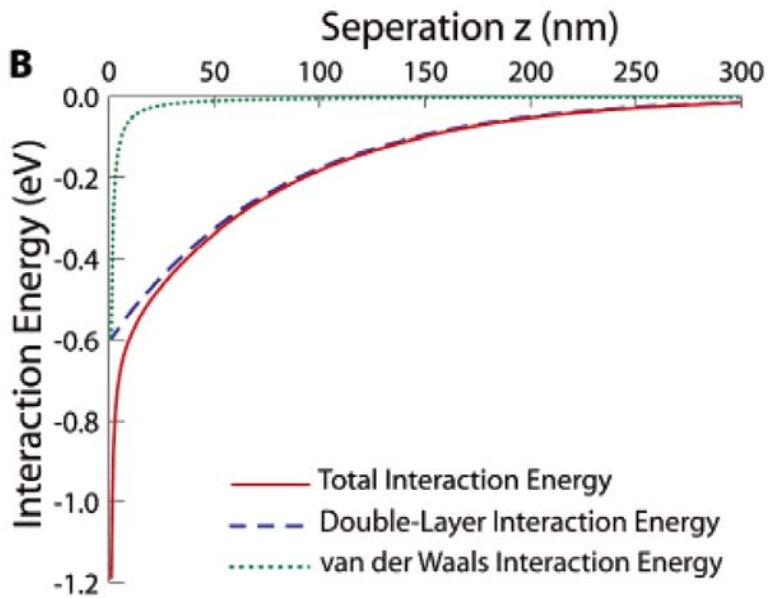


$$V_{\mathrm{MHA}}(z) = \Phi_{\mathrm{MHA}}(z) + W_{\mathrm{MHA}}(z)$$

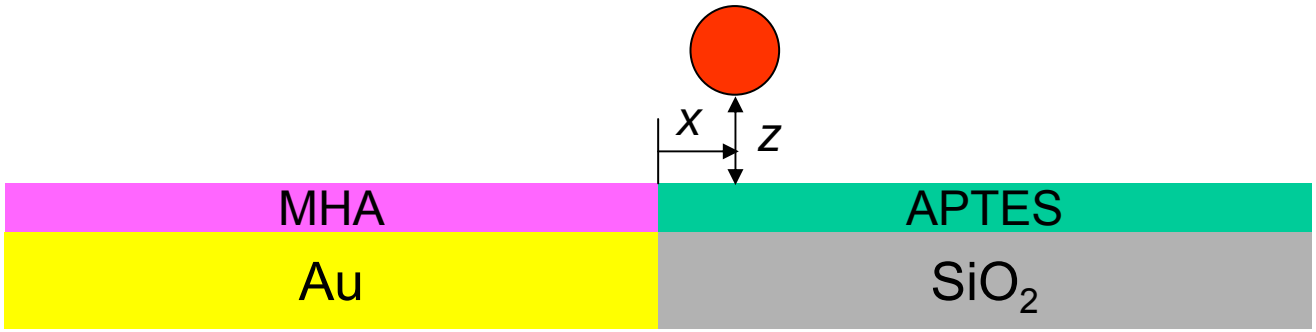


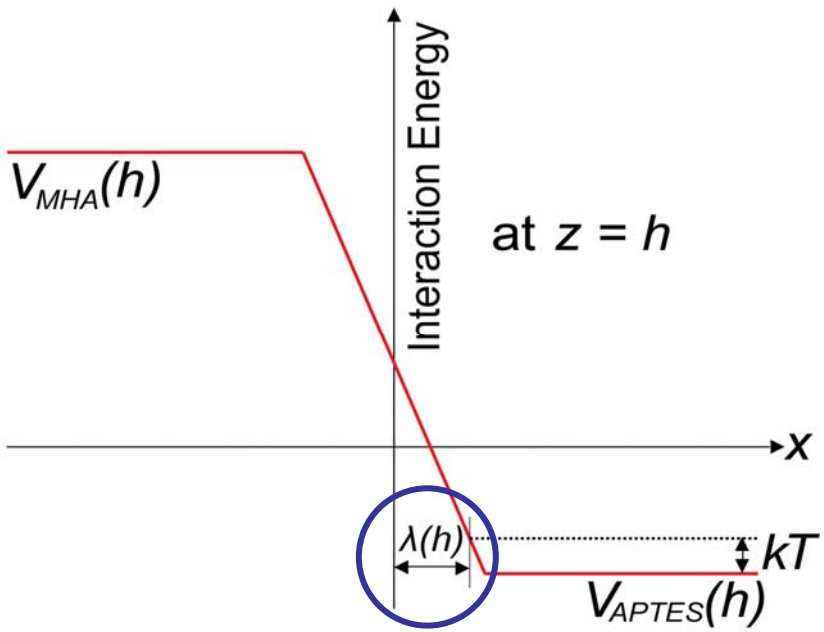
$$V_{\mathrm{APTES}}(z) = \Phi_{\mathrm{APTES}}(z) + W_{\mathrm{APTES}}(z)$$

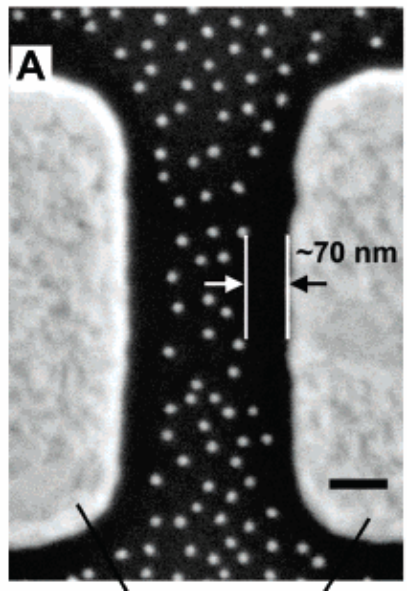




Interaction Energy Near the MHA-APTES Boundary

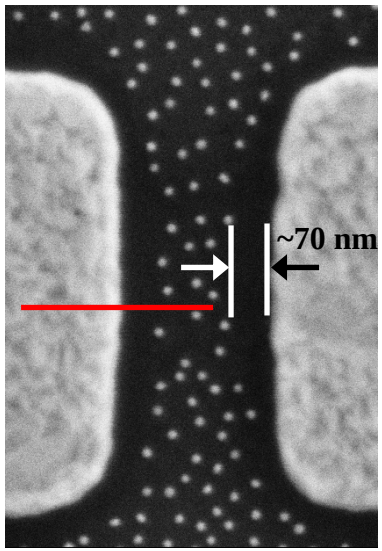


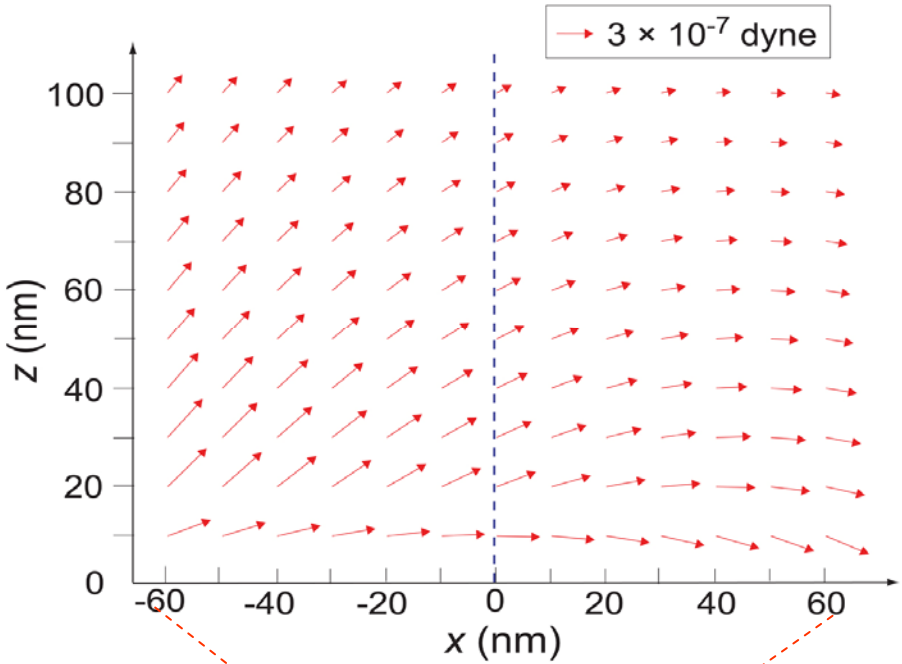


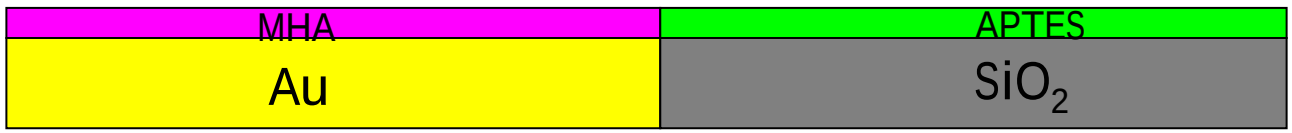


Forces Exerted on a Au Nanoparticle (diameter: 20nm)

$$\vec{F} = -\partial V(x,z)/\partial x\,\vec{X} - \partial V(x,z)/\partial z\,\vec{Z}$$

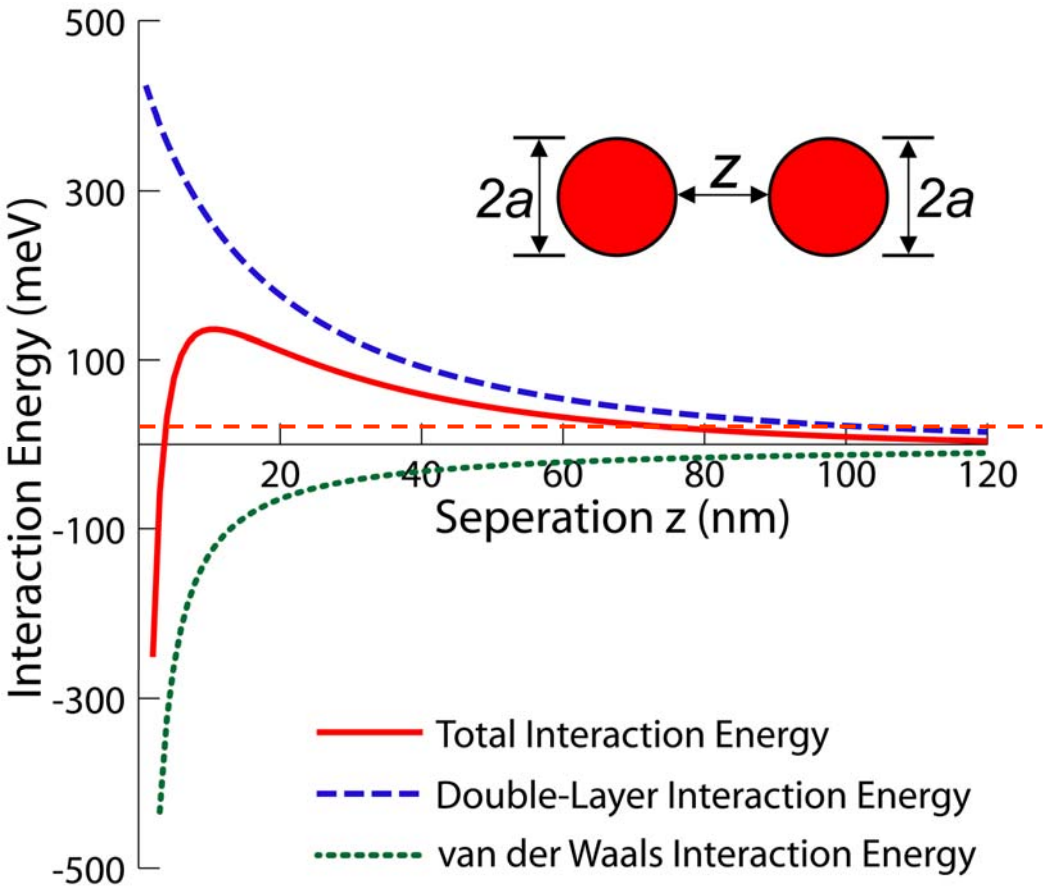




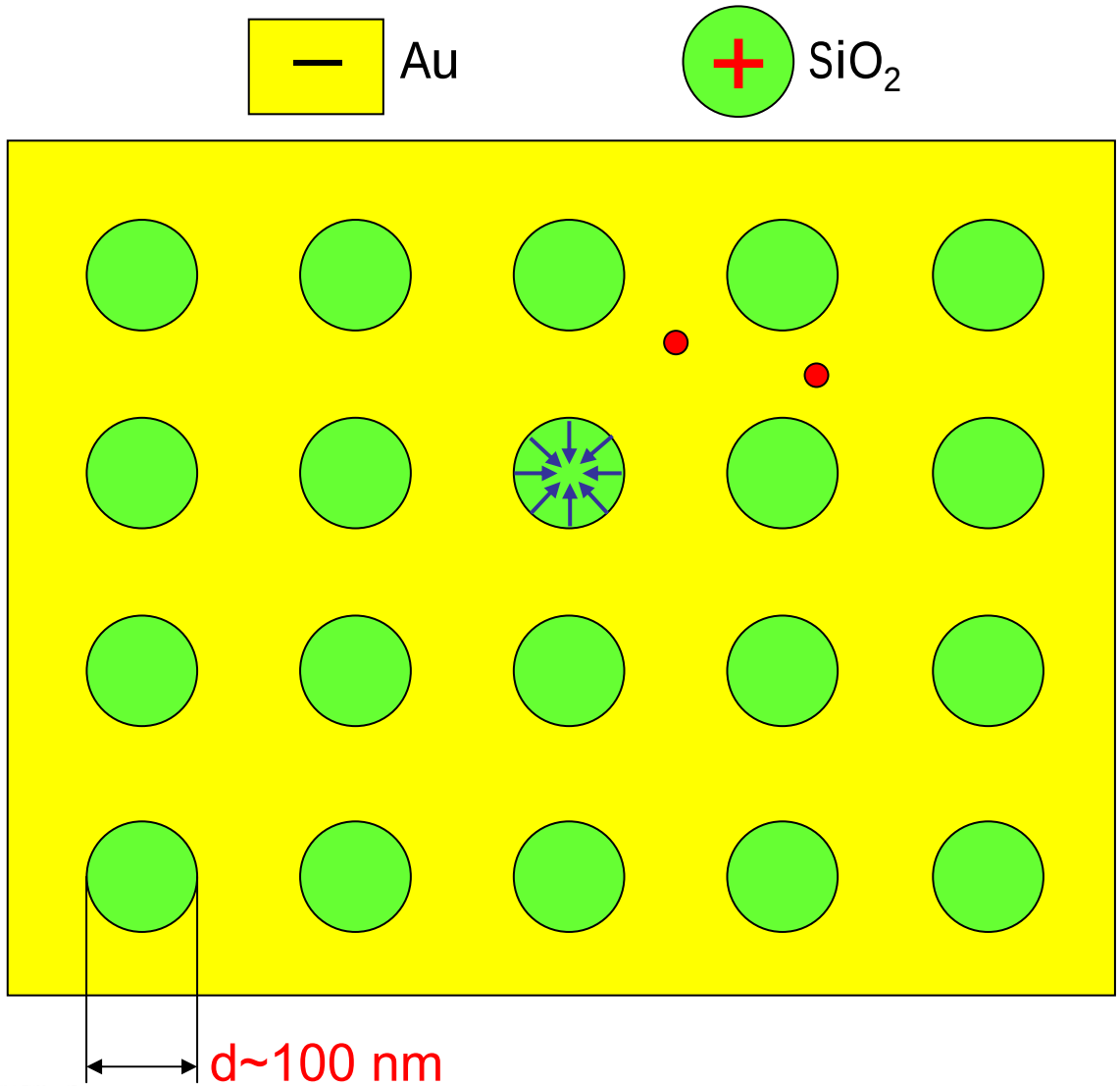


Strong *lateral* forces are responsible for the denuded zone

Interactions between Two Au NPs (20 nm diameter)



Single Particle Placement via Electrostatic Funneling



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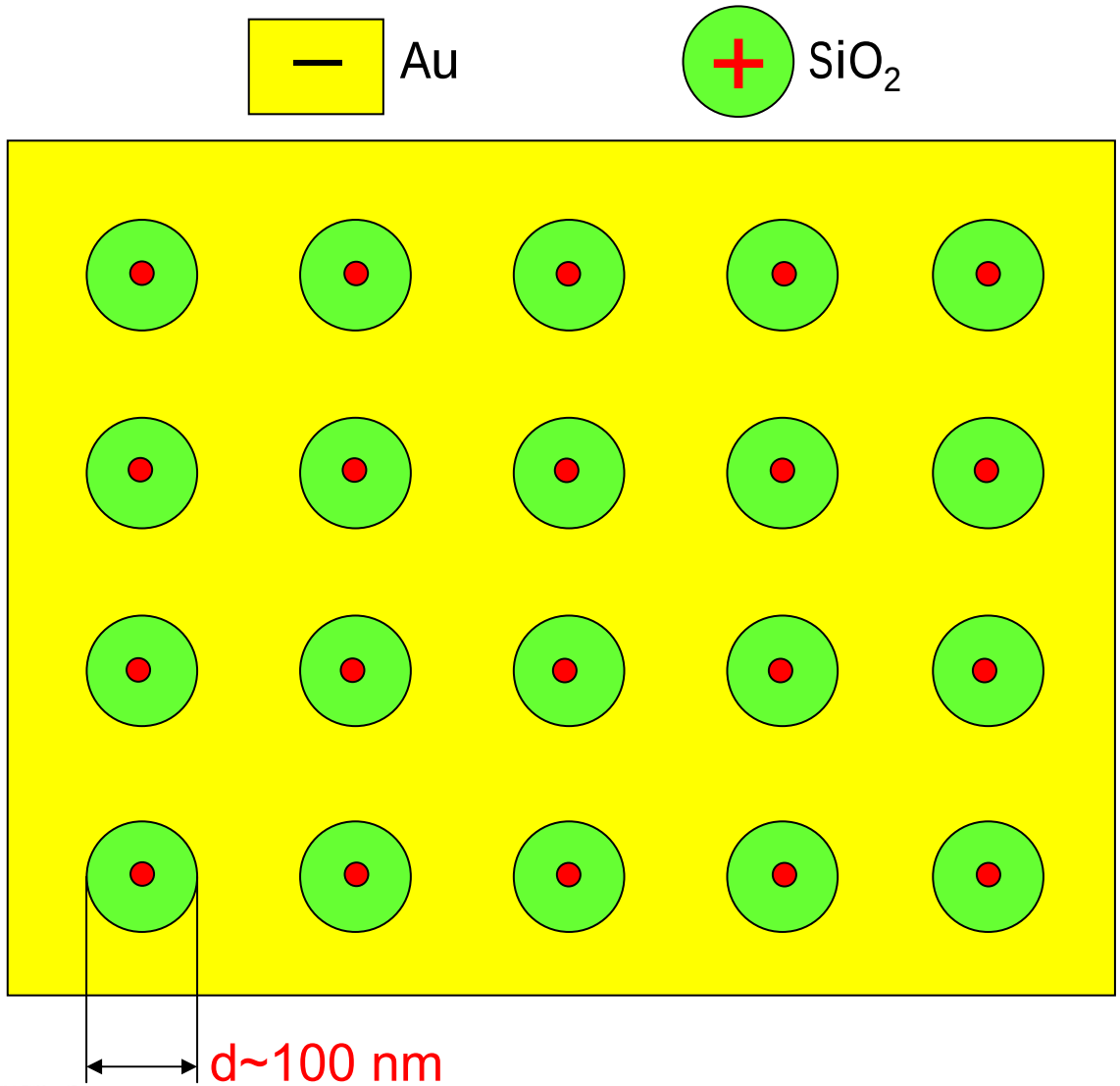

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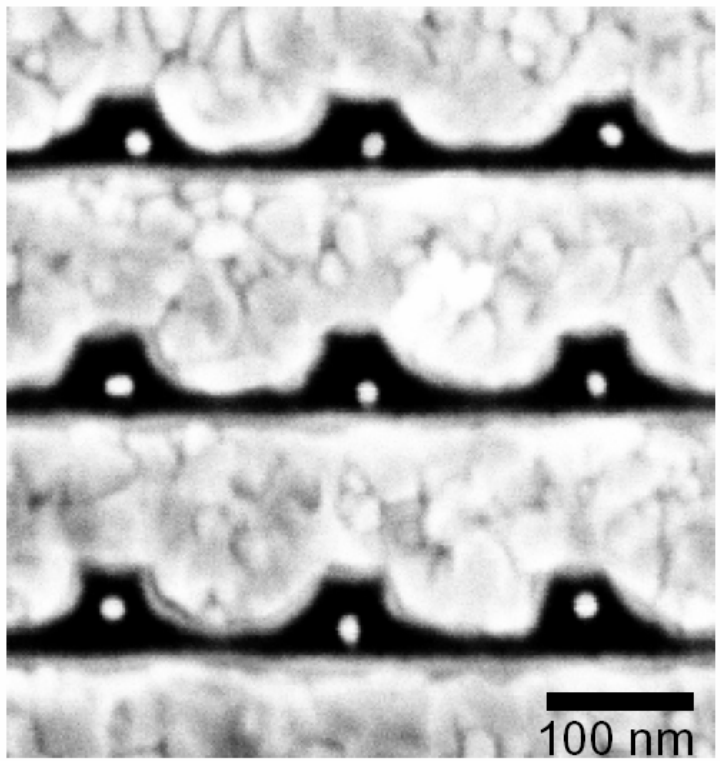

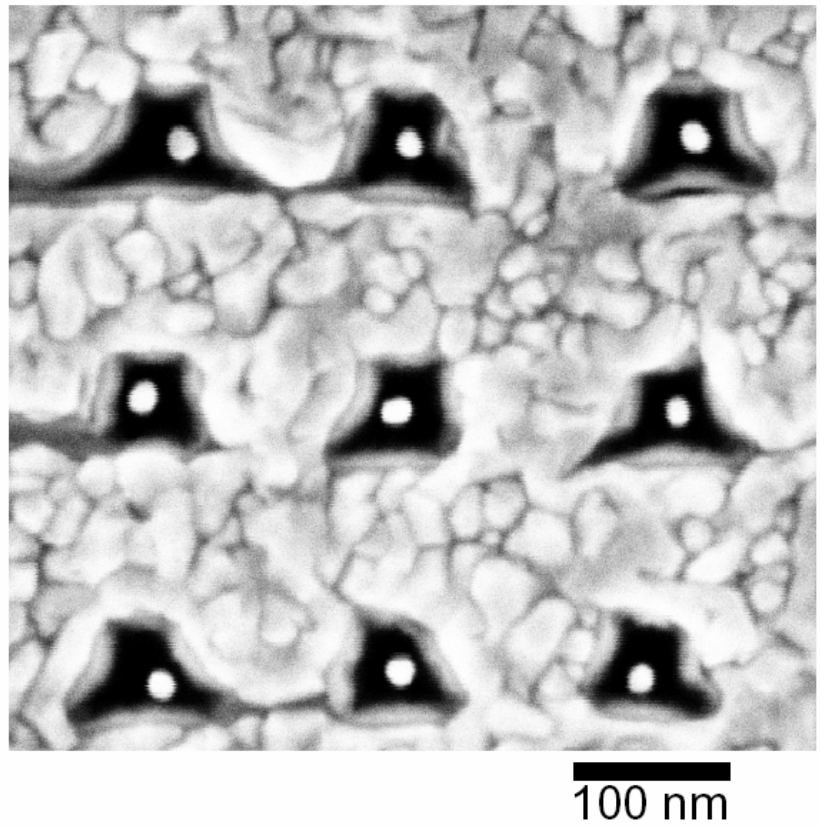

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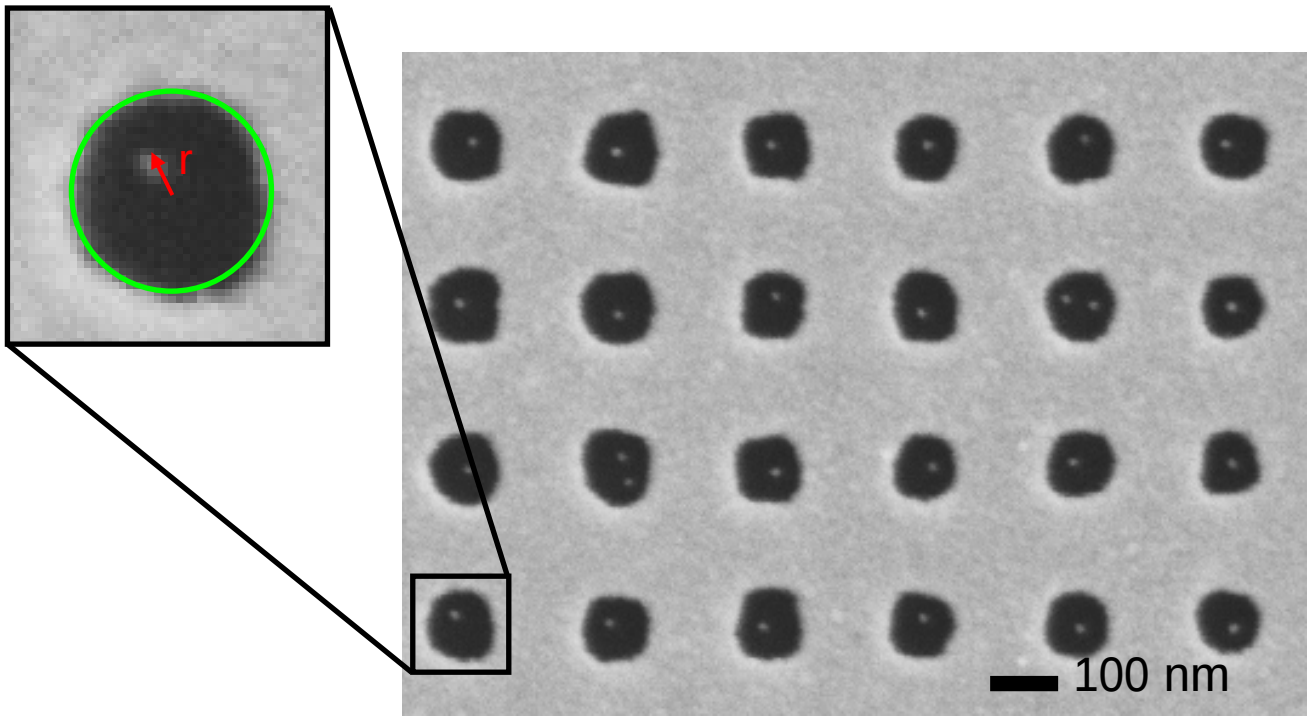
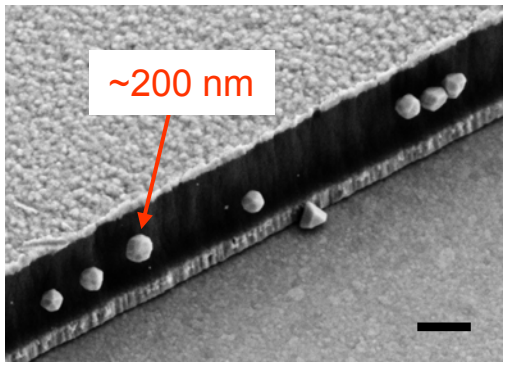
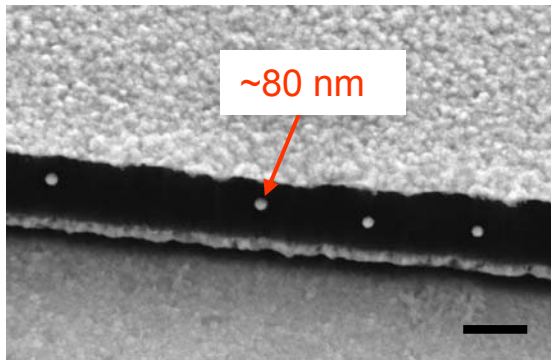


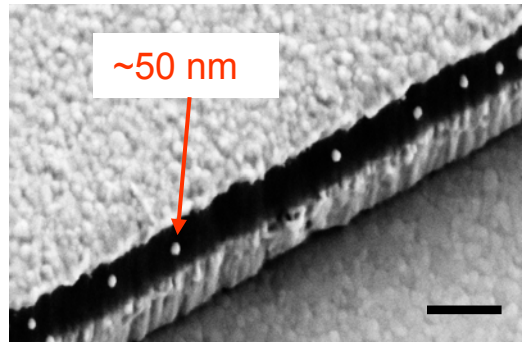
Yield = 22/24 = 92%

Average deviation from the Center of holes: 13.1 nm

Nanoparticle Placement for a 3-D Step Structure





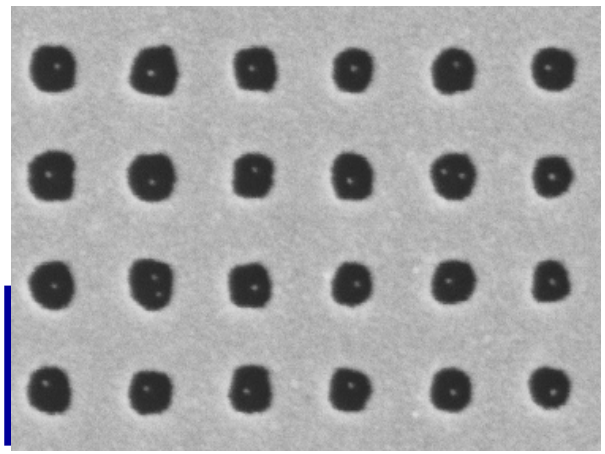


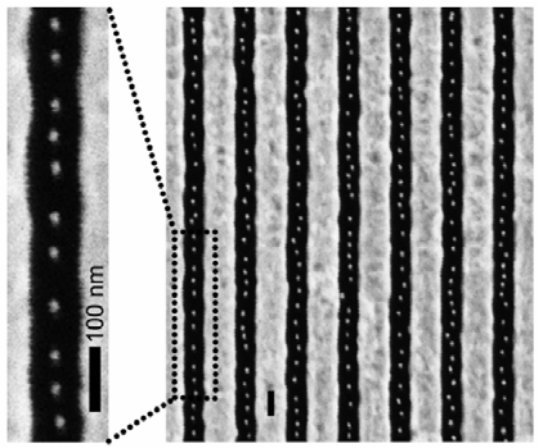
Scale bars: 400nm

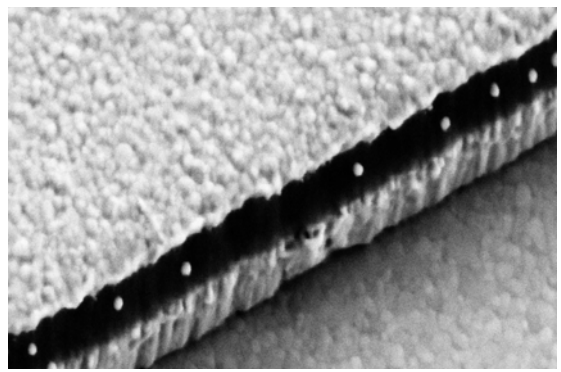
Effective guidance of nanoparticles which are precisely placed in the center of the SiO_2 layer sandwiched between Au layers

Summary and Future Work

- Electrostatic Funneling Scheme has been demonstrated.
  - 1-D, 0-D, and 3-D placement
- Compatible with standard CMOS fabrication technology
- Large-scale Assembly
- Placement Precision >> Lithography Limit
  - Placement precision: ~5 nm using ~100 nm guiding structure
- Future work: Placement of other nanoscale building blocks
  - nanowires, carbon nanotubes, DNA, proteins







- Part of this work has appeared in *Nano Lett.* Vol.7, p.439 (2007)

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