Self-assembled electrical contacts to nanoparticles using metallic droplets

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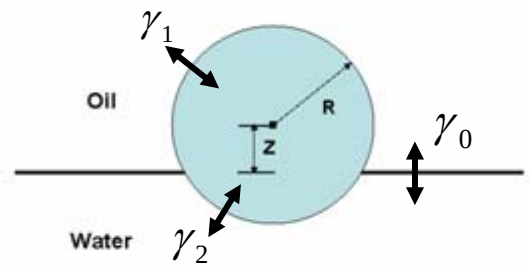
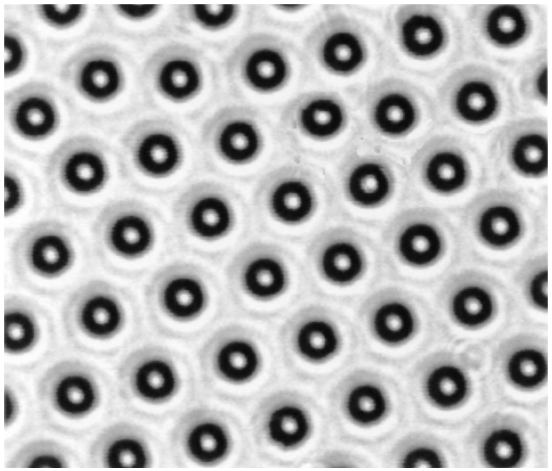
Acknowledge: CUMIRP, NSF-MRSEC and NIRT

Background: Self-assembly at Liquid Interfaces

As a template to fabricate 2-D materials

- *Simple*
- *Fast*
- *Monolayer with long range order*
- *Self healing structure*
- *Interfacial reactions*





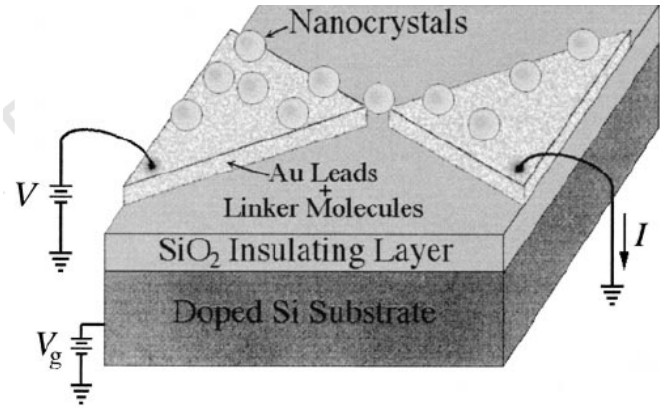
R. Aveyard, B. P. Binks, et al., *PRL*, 2002, 88, 246102

Motivation

Propose a simple approach to form nanoscale electronic devices (transistors) using self-assembly.

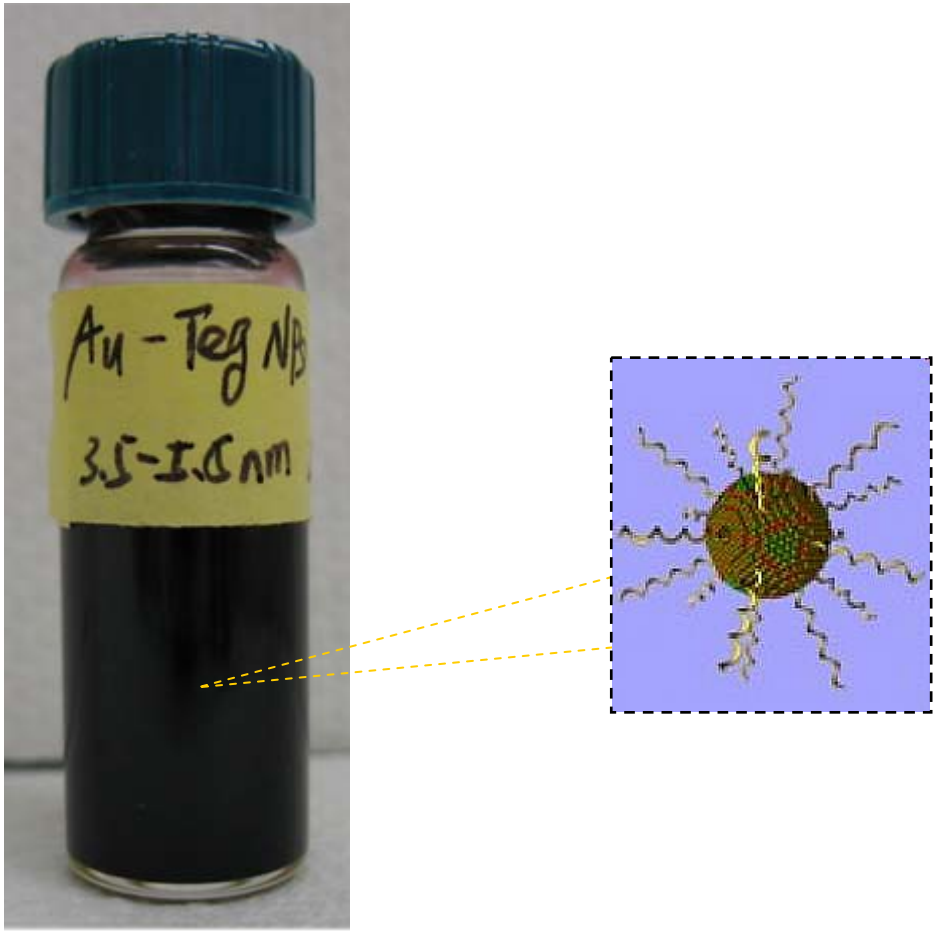
Previous work

- Formed single-electron transistors.
- Nanoparticles were placed between electrodes with nanoscale gaps on a patterned substrate.
- Requires a high-resolution method to form electrodes. (lithography…)



Klein, D. L., et al. (1997). Nature 389: 699

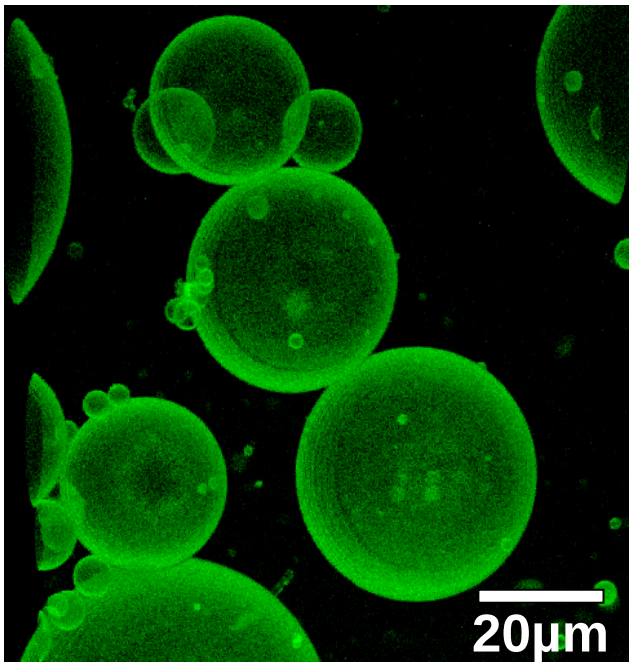
Background: Nanoparticle



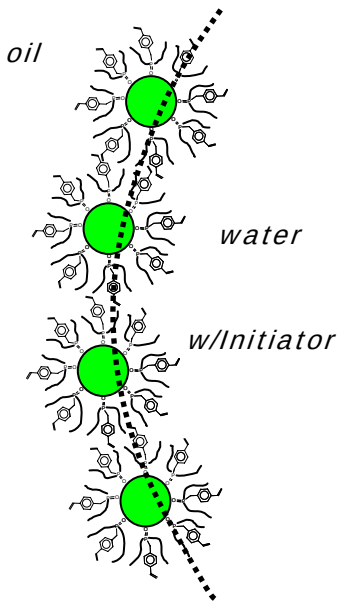
Aqueous solution of gold nanoparticles.

Background: Nanoparticle Interfacial Assembly

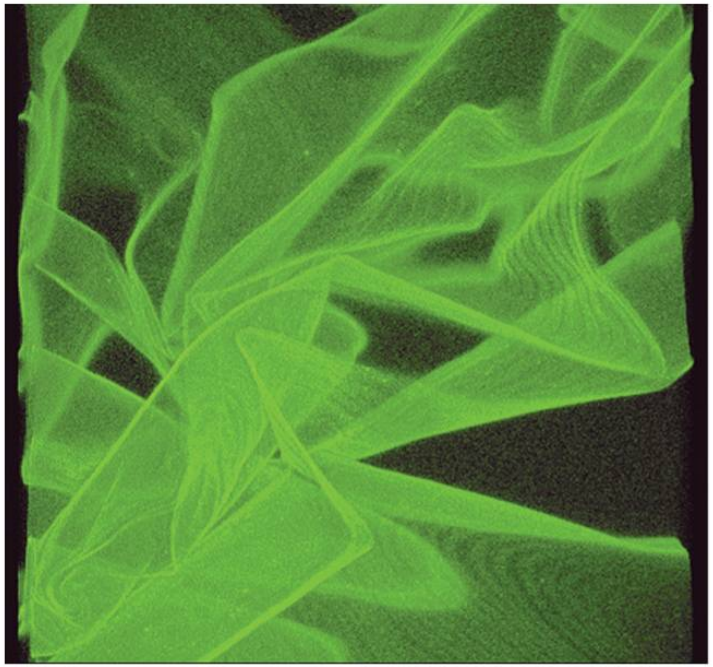
Fluorescence confocal images of TOPO-covered CdSe nanoparticles at O/W Interface



Lin, Y., et al., *Science*, 2003 299, 226

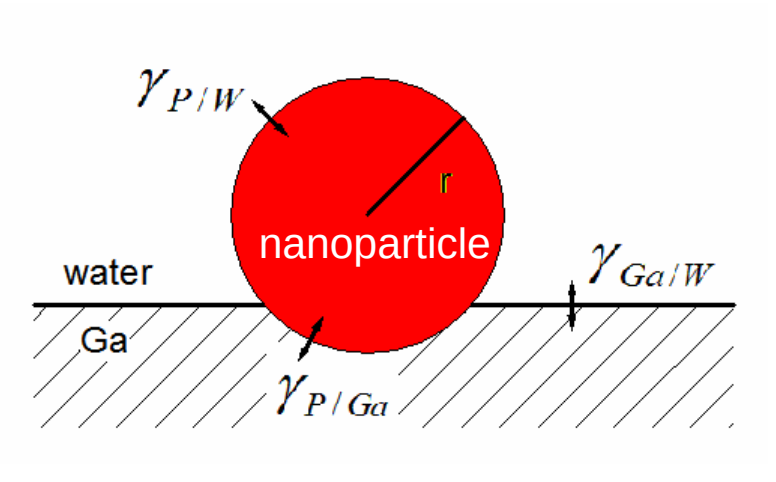


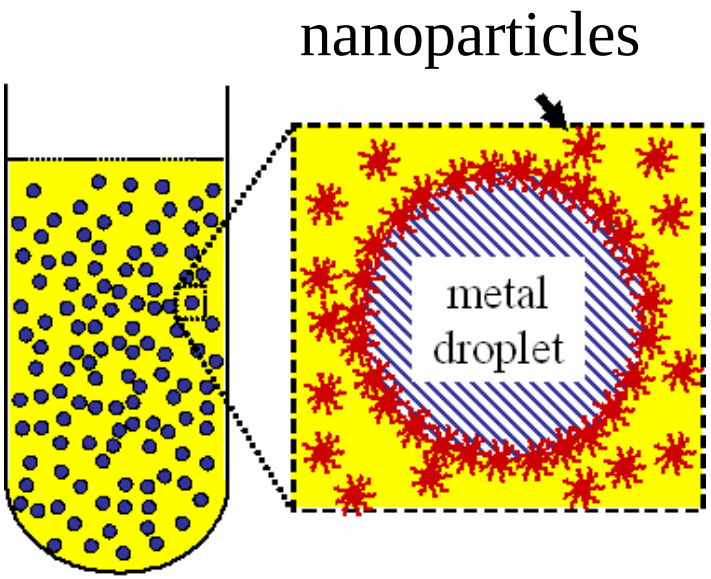
Ultra-thin film taken out from O/W interface



Lin, Y., et al., JACS 2003, 125, (42)

Gallium-Water Interface

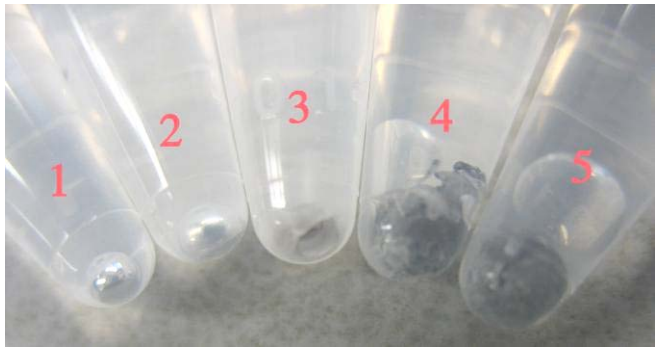




Gallium (Ga)

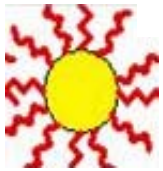
- Liquid metal, T_m =29.8 ^oC
- Supercool (remains liquid below T_m)
- Low electrical resistance.
- Ga oxide can be dissolved in HCl acid.

Ga drop remains shiny at low pH.



Ga in HCl, pH=1 to 5

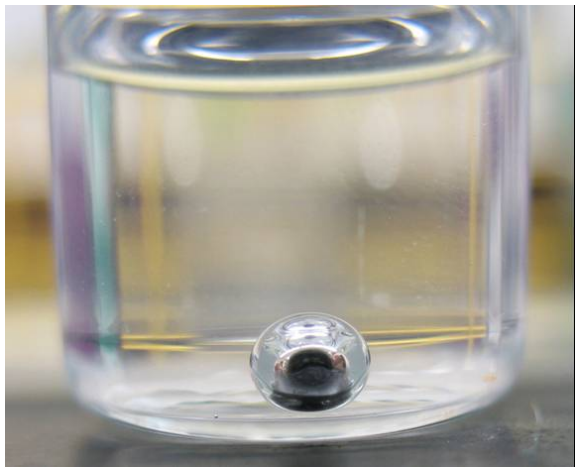
Self Assembly of NPs at Ga-H_2O Interface



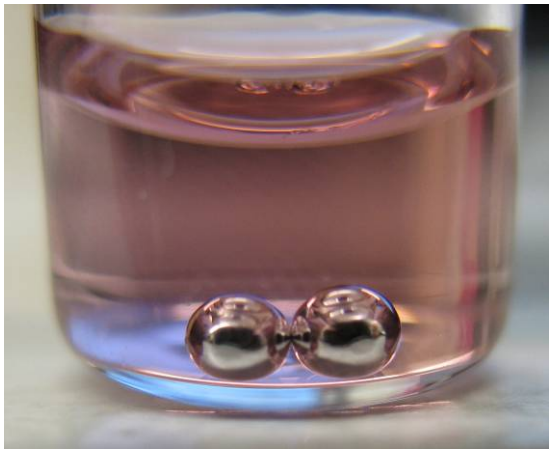
Gold Nanoparticle: (by E. Glogowski, PSE UMass Amherst)

- Size: 2 or 5 nm,
- Ligand: $HS\text{-}C_{11}H_{22}\text{-}[O\text{-}CH_2\text{-}CH_2]_4\text{-}OH$, length~1.5 nm
- Dispersed in water

Au NPs can stabilize Ga droplets in HCl



HCl (pH=1) without NPs:
2 Ga drops coalesce instantly

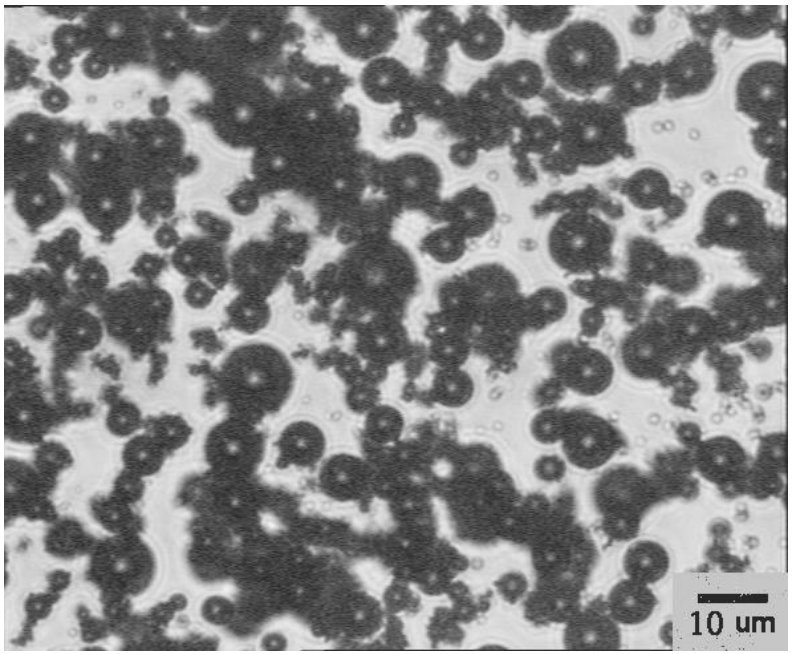


HCl (pH=1) with NPs:
Remain stable for days

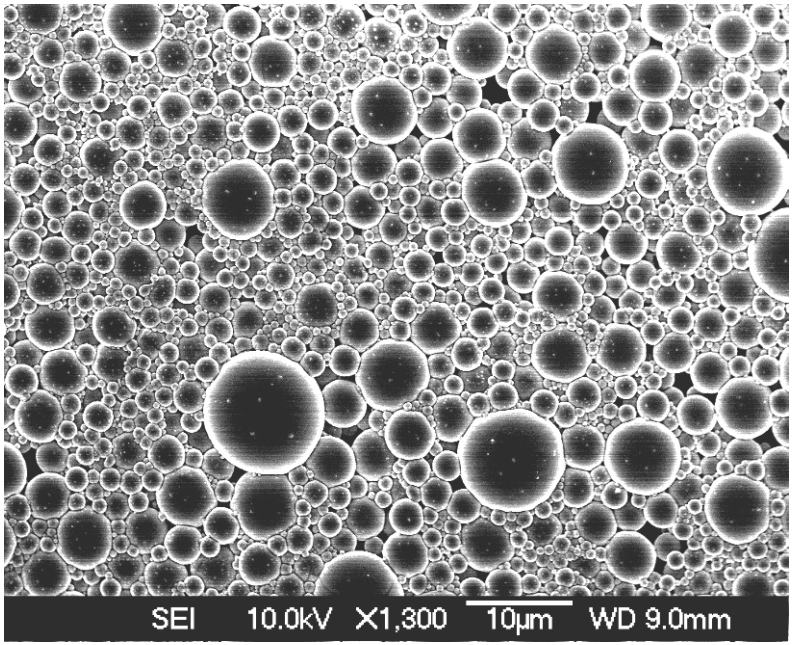
Formation of Ga Emulsion

Ultrasonication for a few minutes at T~40 ^{o}C (above T_m):

Ga + Au NPs + HCl



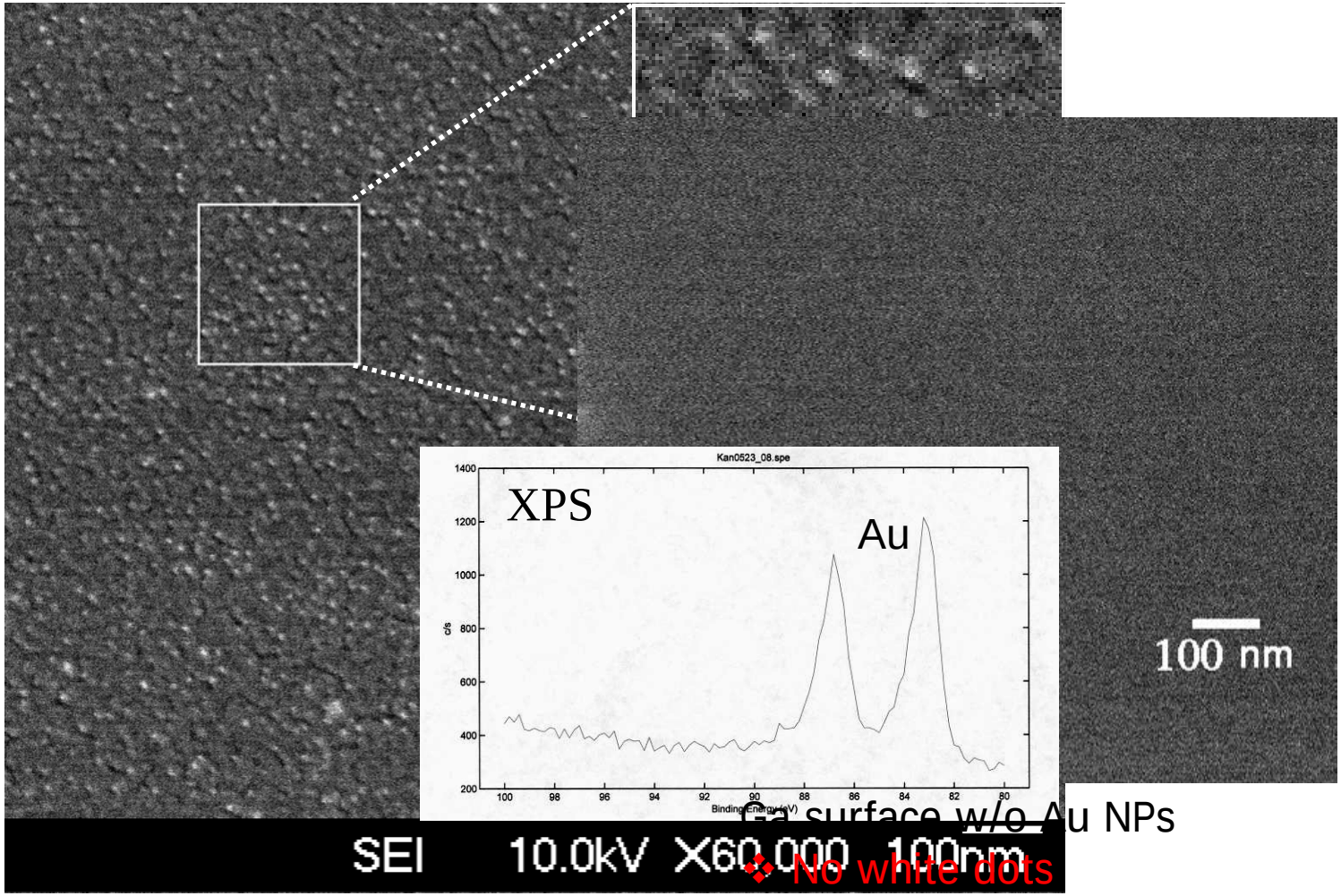
Optical microscopy in solution



SEM image: dry sample

- Polydisperse Ga droplets, size=0.2~10 μm.
- Remain stable in solution , air and high vacuum.

Nanoparticles on Ga surface



Ga surface w/o Au NPs

❖ No white dots

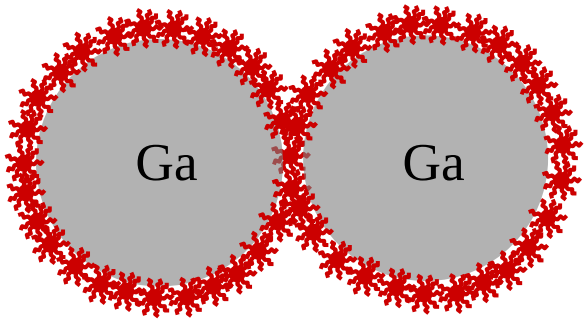
- Au NPs (white dots) uniformly distributed on Ga surface.
- Coverage density ~ 13%.
- XPS data also prove the existence of Au NPs.

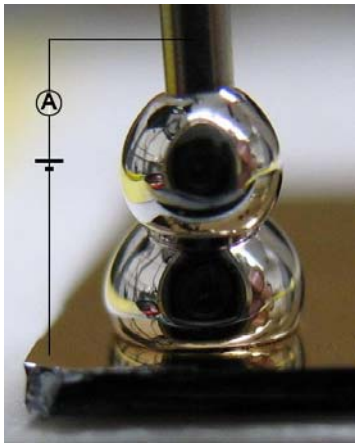
How to form electronic devices?

Simple Answer :

Just push two Ga droplets together !

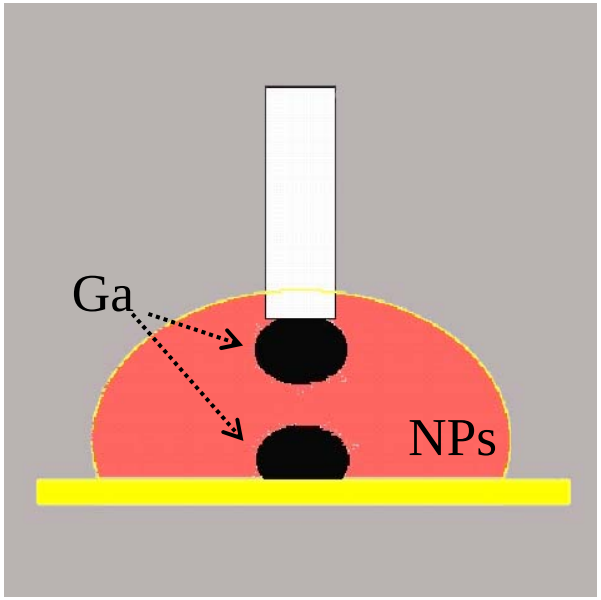
- Electronic device with self-controlled nano-scale junctions
- Electron transport properties similar to solid state devices



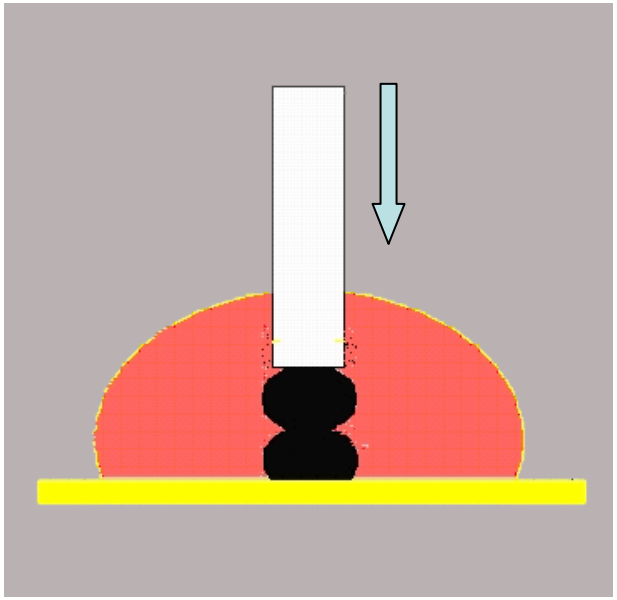


Sample preparation

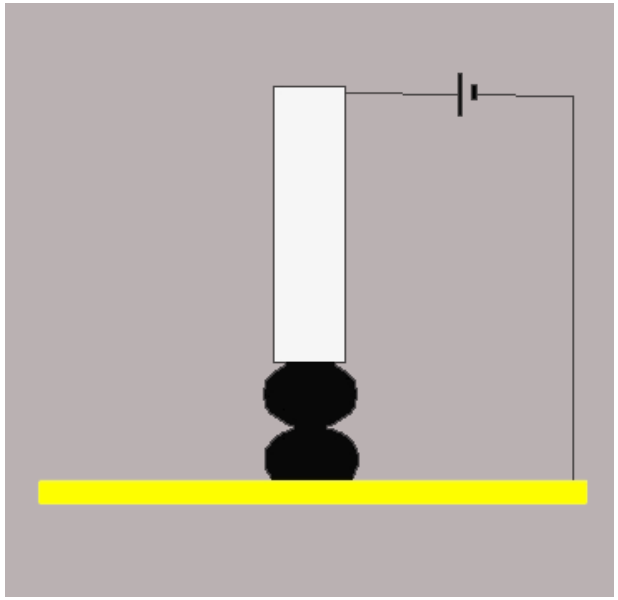
T=32 ^{o}C



2 Ga droplets in HCl with Au nanoparticles

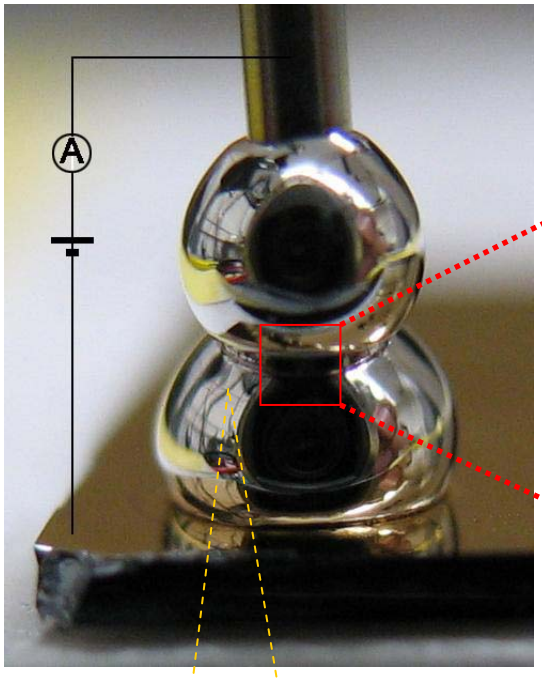


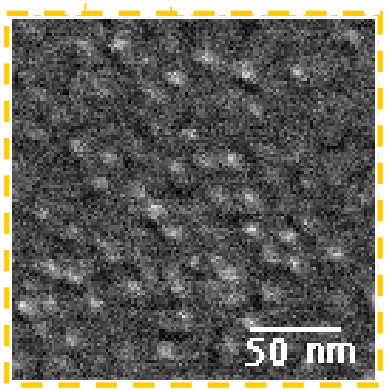
Squeeze 2 Ga droplets, (no coalescence)

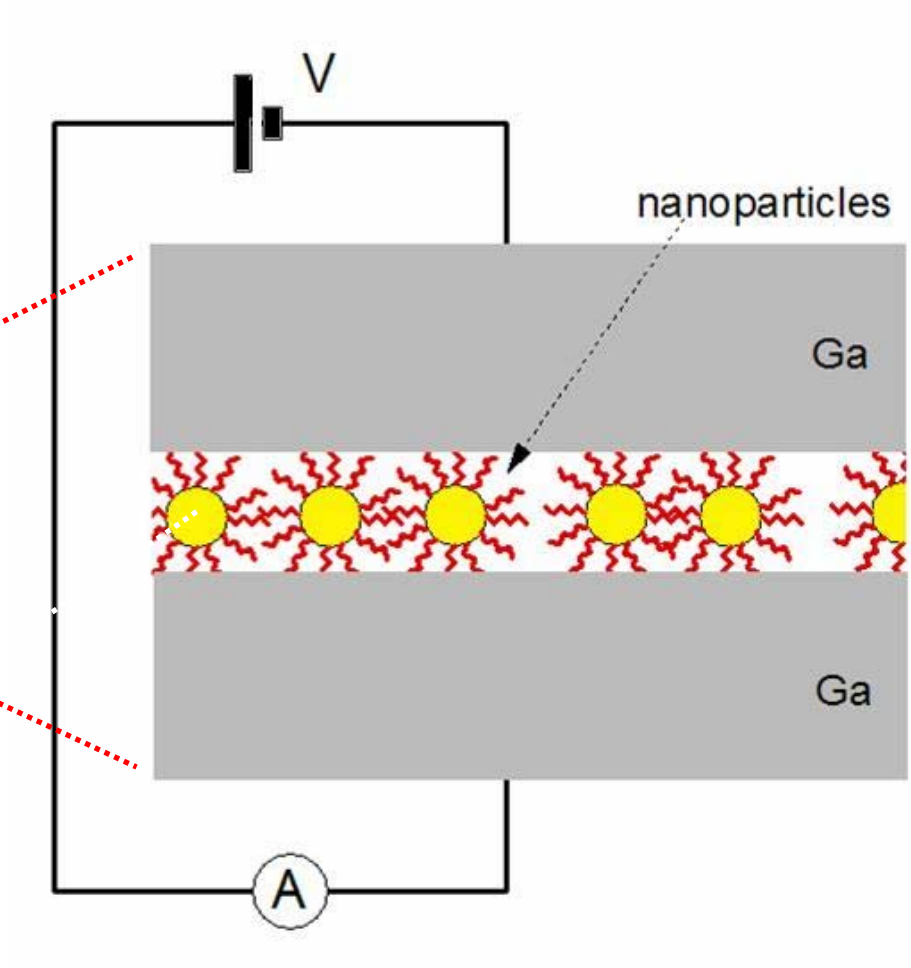


Remove extra solution, Dry the sample

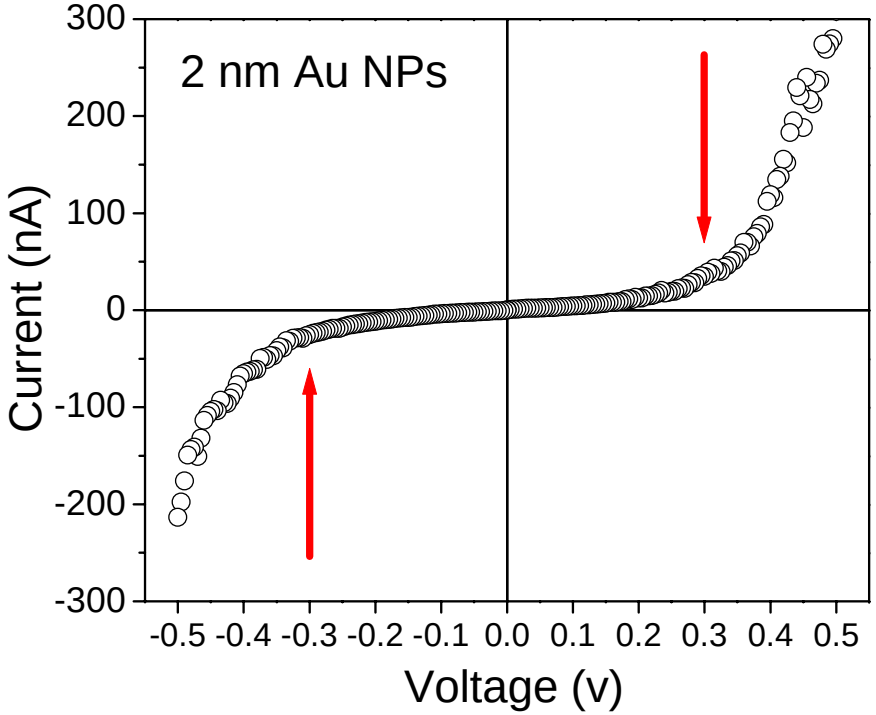
Current Voltage measurement







Coulomb blockade in I-V curve



- Threshold voltage:

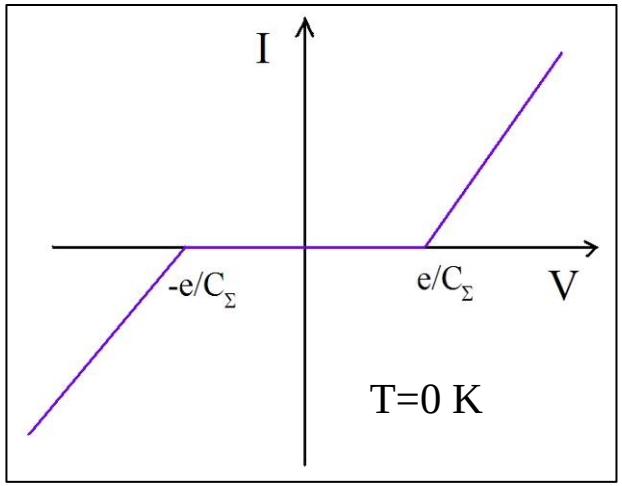
$V_{th} \sim \pm\ 0.3$ V

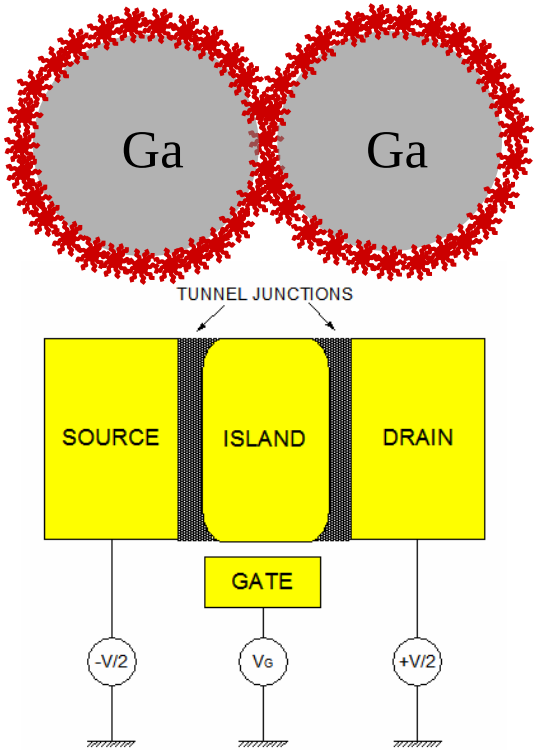
- Close to the theoretical value $V_{th} = \pm\ 0.29$ V

Coulomb blockade theory

- Definition:
  Tunneling current is suppressed below a tunable threshold voltage by the energy of charging individual nanoparticles.

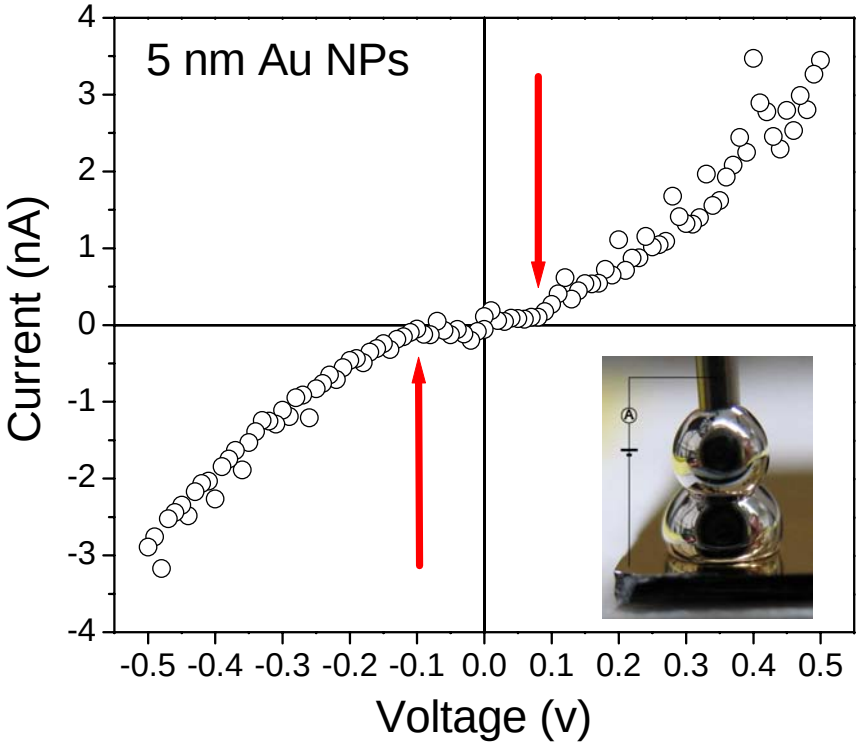
- Threshold Voltage: $V_{th} = \pm \dfrac{e}{C_\Sigma}$





Single electron transistor (SET)

Coulomb blockade in I-V curve

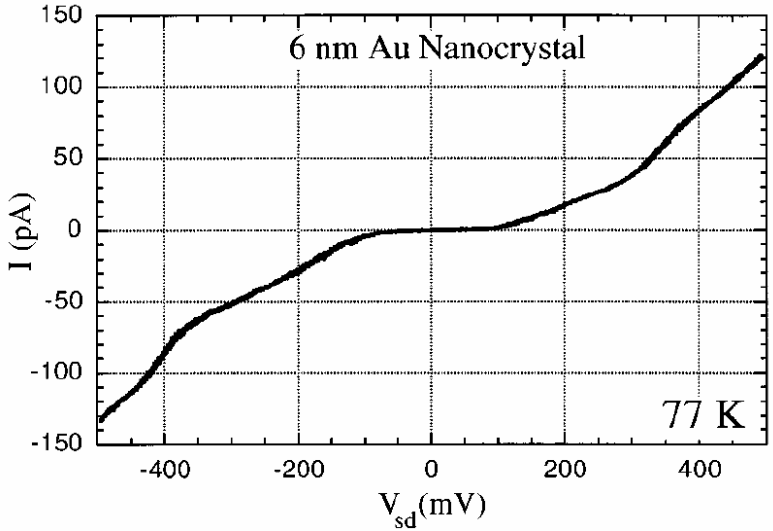


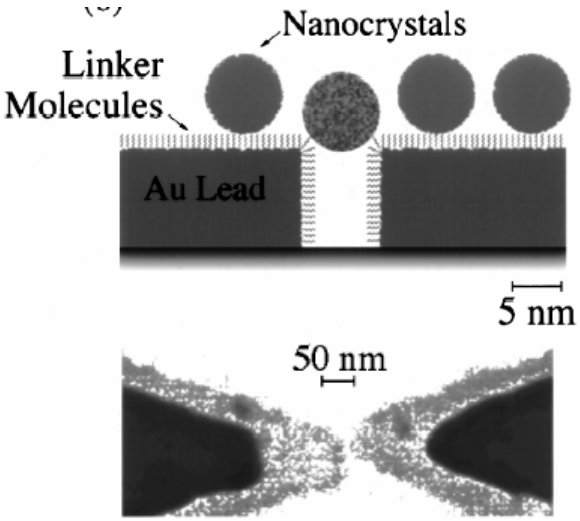
- Threshold voltage:

  $V_{th} \sim \pm 0.1$ V

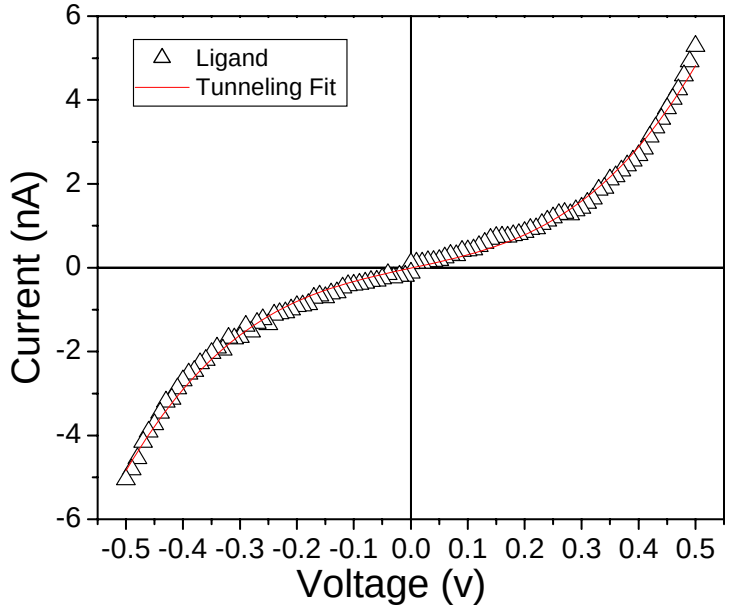
- Agrees with theoretical value

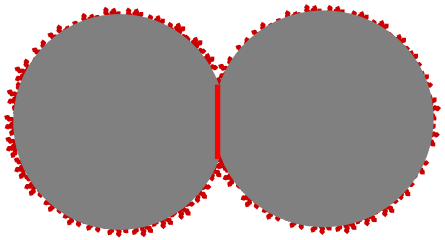
Klein et al, 2574 APL. 68 (18), 1996

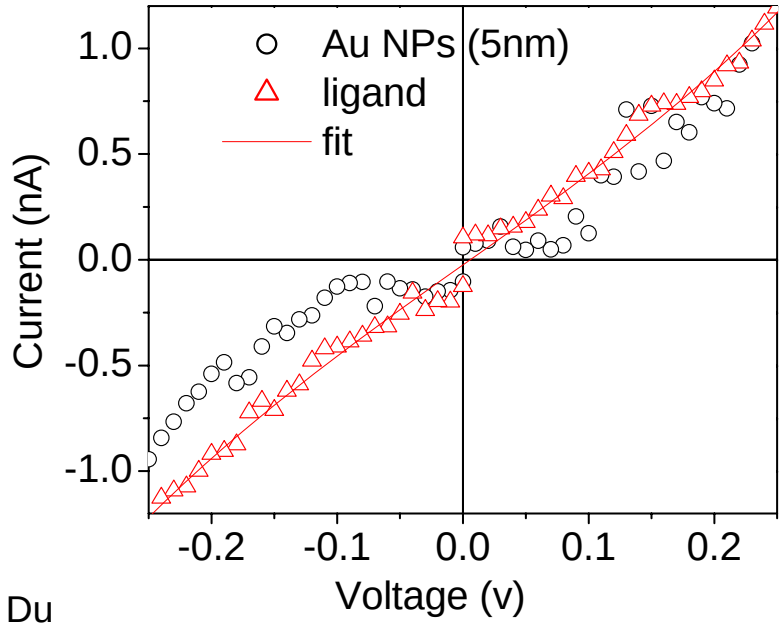




Control experiment: Ga + ligand (no NPs)



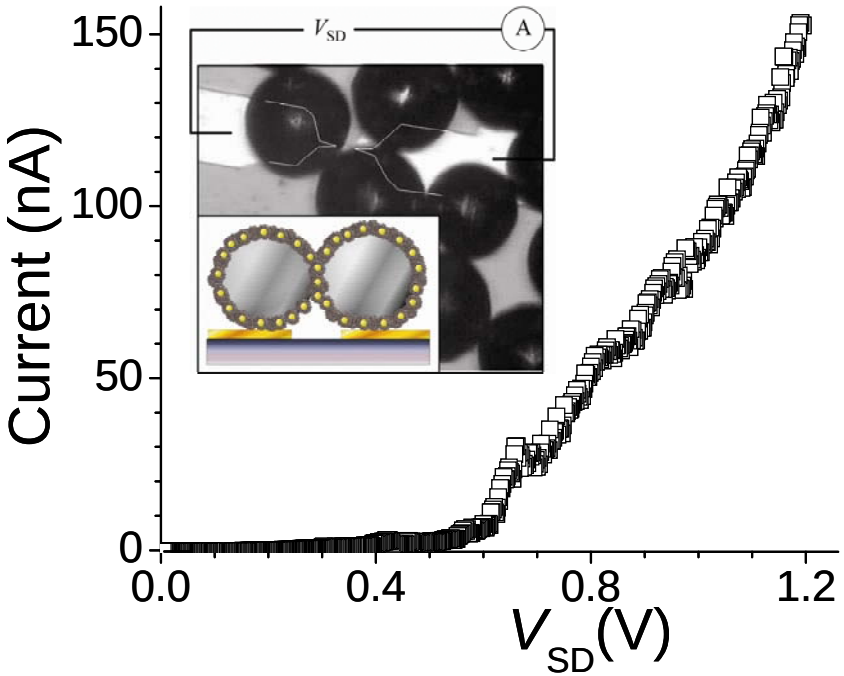




- No coulomb blockade effect
- Fit well to electron tunneling function

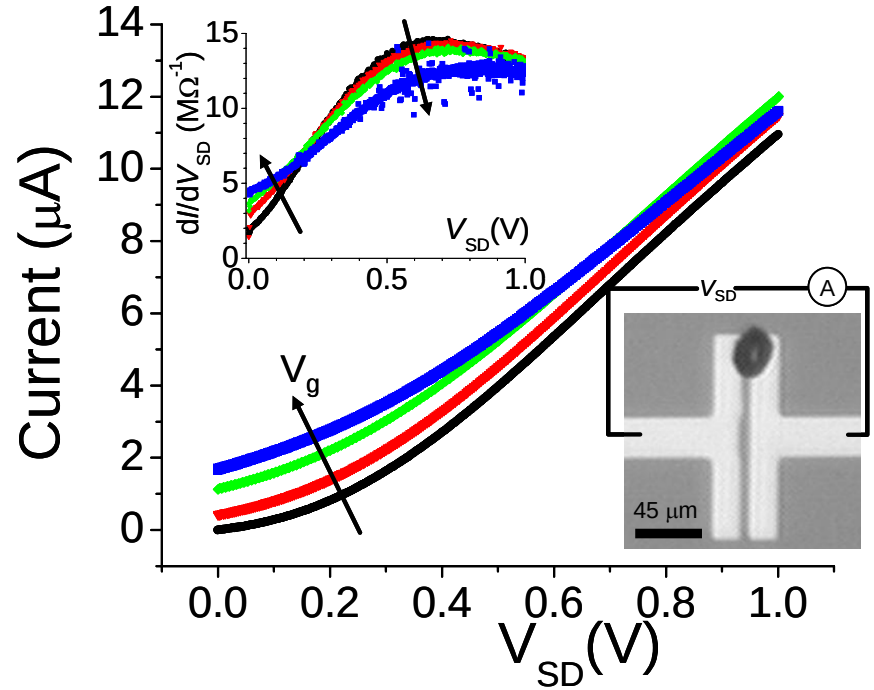
Other experiments (by C. R. Knutson)

Woods Metal



- Alloy: Bi, Pb, Sn, Cd
- T_m=73~77 ^oC
- 120 µm WM droplets
- 1.7 nm Au NPs in toluene
- Deposit on patterned substrate
- I-V measurement at 77k

Aluminum



- Solid particles
- Substrate with buried gate electrode
- Control of conductance by apply gate voltage
- Qualitative agreement with Coulomb blockade model.

Summary

Self-assembled electrical contacts to nanoparticles using metallic droplets

- Self assembly of nanoparticles at Ga-water interface.
- Stable liquid metal emulsion.
- Liquid metal droplet devices: Coulomb blockade
- Micron-size electronic devices on patterned substrate
- A potential in fabrication of large area nano-structured electronic devices at low cost and high efficiency.