Self-assembled electrical contacts to nanoparticles using metallic droplets

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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

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… )
Background: Nanoparticle

Aqueous solution of gold nanoparticles.
Background: Nanoparticle Interfacial Assembly

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

Ultra-thin film taken out from O/W interface


Lin, Y., et al., JACS 2003, 125, (42)
Gallium-Water Interface
Gallium (Ga)

- Liquid metal, $T_m = 29.8 \, ^\circ C$
- 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$_2$O Interface

**Gold Nanoparticle:** (by E. Glogowski, PSE UMass Amherst)
- Size: 2 or 5 nm,
- Ligand: HS-C$_{11}$H$_{22}$-[O-CH$_2$-CH$_2$]$_4$ 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 °C (above T_m):
Ga + Au NPs + HCl

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

Optical microscopy in solution

SEM image: dry sample
**Nanoparticles on Ga surface**

- 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 °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

2 nm Au NPs

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Coulomb blockade theory

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

• Threshold Voltage: $V_{th} = \pm \frac{e}{C_{\Sigma}}$

Single electron transistor (SET)
Klein et al, 2574 APL. 68 (18), 1996

- Threshold voltage: $V_{th} \sim \pm 0.1 \text{ V}$
- Agrees with theoretical value

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Control experiment: Ga + ligand (no NPs)

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

![Graph showing current vs voltage for Au NPs and ligand](image)
**Other experiments** (by C. R. Knutson)

- Alloy: Bi, Pb, Sn, Cd
- $T_m = 73\sim77 \, ^\circ\text{C}$
- 120 µm WM droplets
- 1.7 nm Au NPs in toluene
- Deposit on patterned substrate
- I-V measurement at 77k

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**Woods Metal**

- $V_{SD}(V)$ vs. Current (nA)
- $dI/dV_{SD}$ (M$\Omega^{-1}$)

**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.