Fabrication of nanostructures and nanoscale devices.
Part 6.

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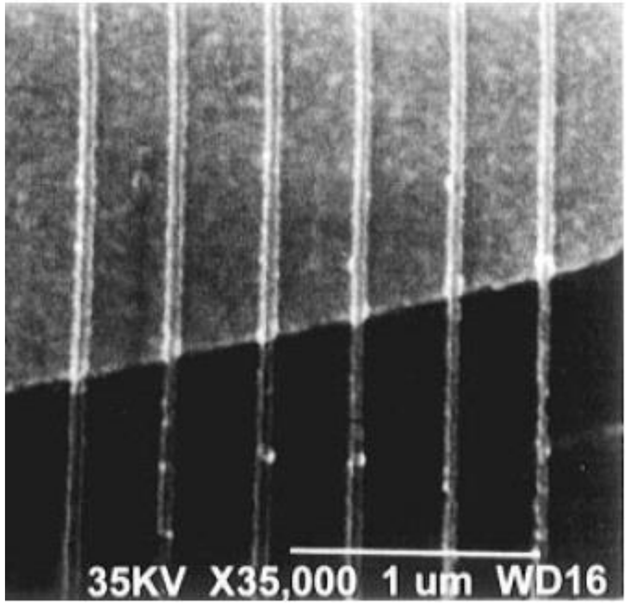
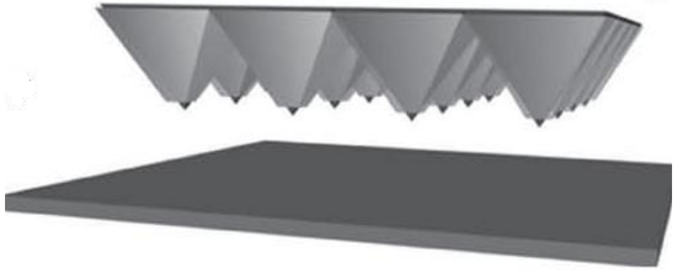
See the lectures at https://www.nanocenter.si/qt-future/education-2/

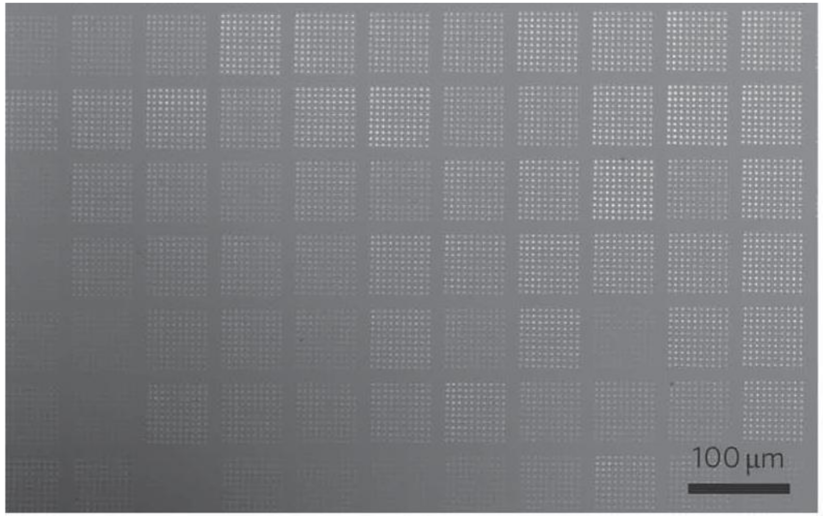
Polymers treatment in atomic force microscope (AFM) configuration

ca. 40 nm resolution

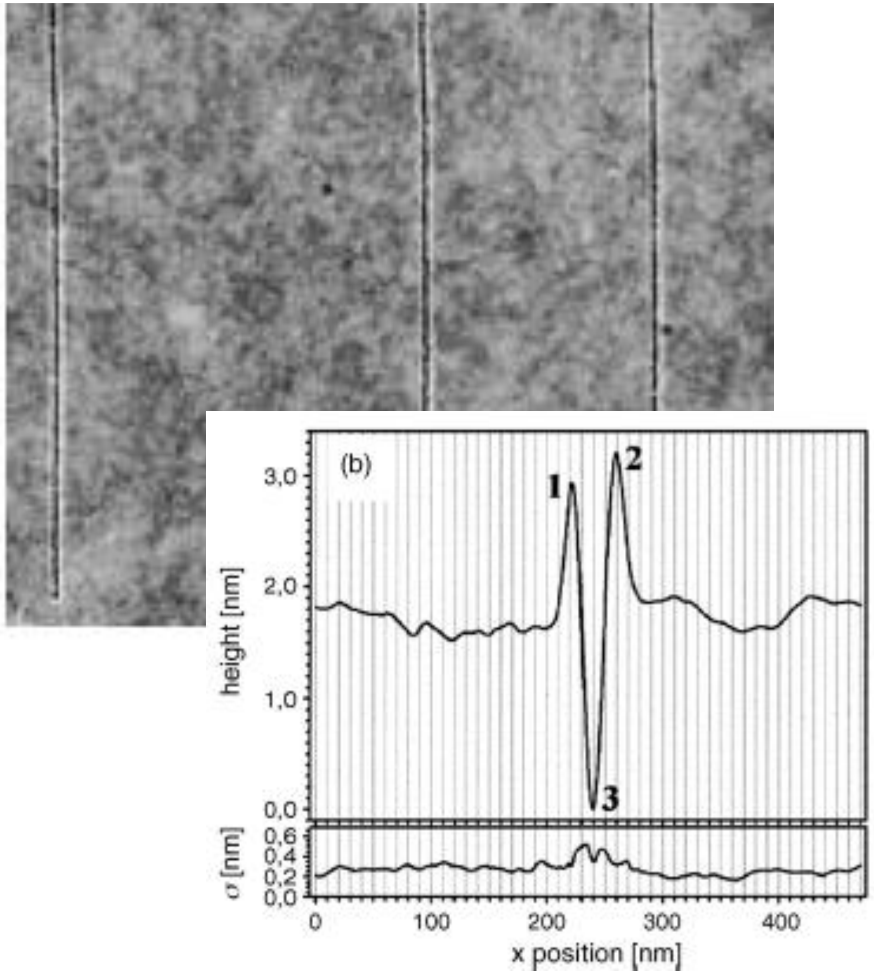


Chem. Rev. 97 (1997) 1195





Macromol. Rapid Commun. 33 (2012) 359



Mechanical + thermal effect on the polymers

Mater. Sci. Eng. R54 (2006) 1

Parts 5-6, Outline

Principle technological schemes

Part 5 Optical and Electronic Lithography

Polymer and inorganic resists (composition, solubility, microstructure)
Spin-coating, adhesion, roughness
Light and beam interactions with positive and negative resists; amplification
Post-exposure procedures (developers, thermal effects, wetting)
Maskless lithography

Part 6 Assembling of low-dimensional objects

- Dry transfer methods

- Wet transfer methods

- Junctions, contacts

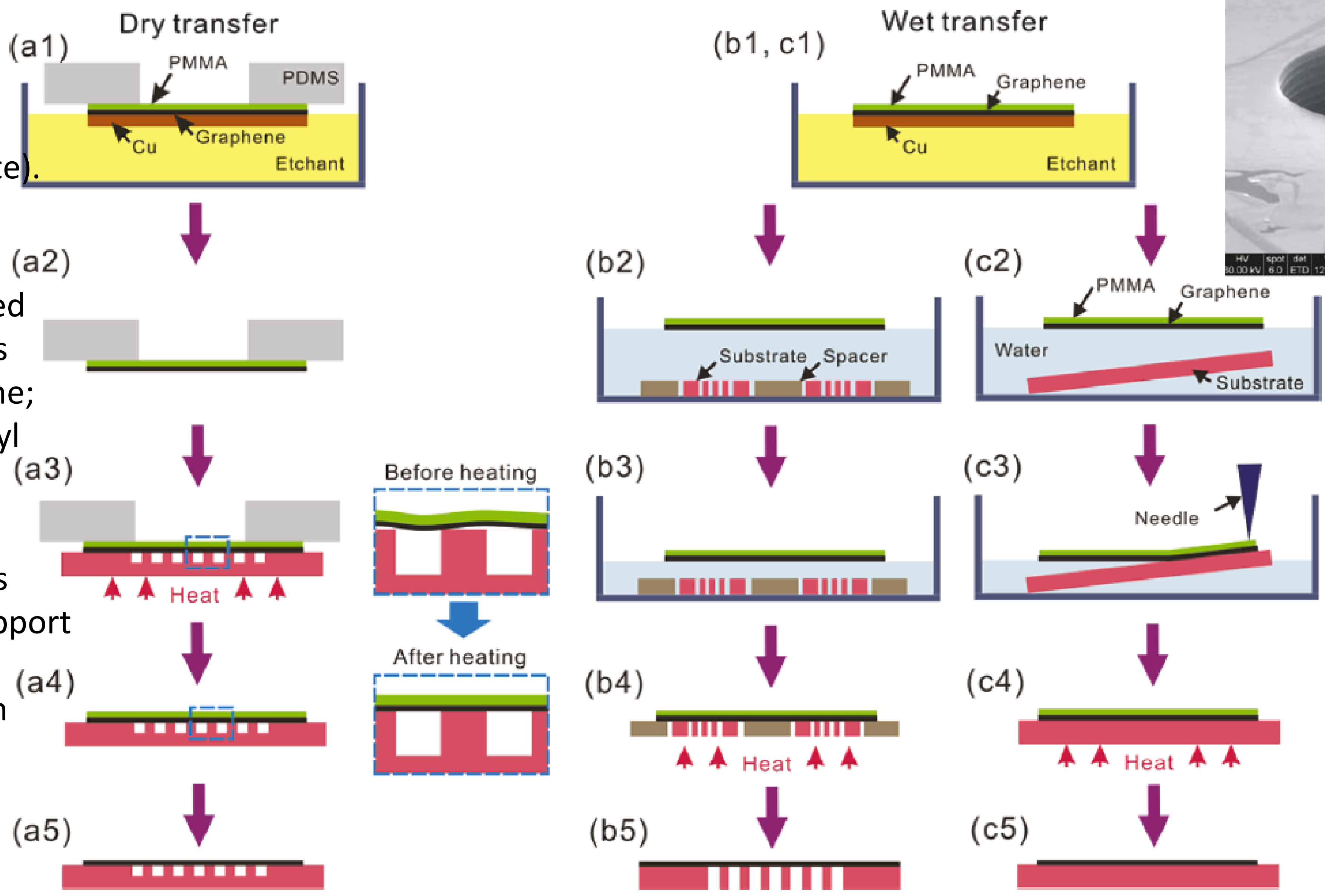
- nm-size gaps

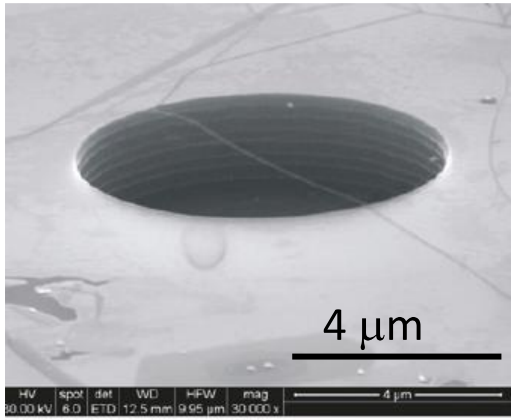
General schemes of the transfer of a single flake (example for CVD graphene grown on Cu)

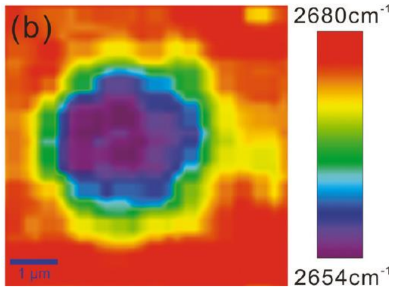
Etchant is oxidizer (e.g. peroxodisulfate).

Polymers are deleted by heating (PDMS is polydimethylsiloxane; PMMA is polymethyl methacrilate).

Perforated supports
- decrease flake-support Interaction;
- allow transmission microscopy;
- are helpful to delete traces of liquid



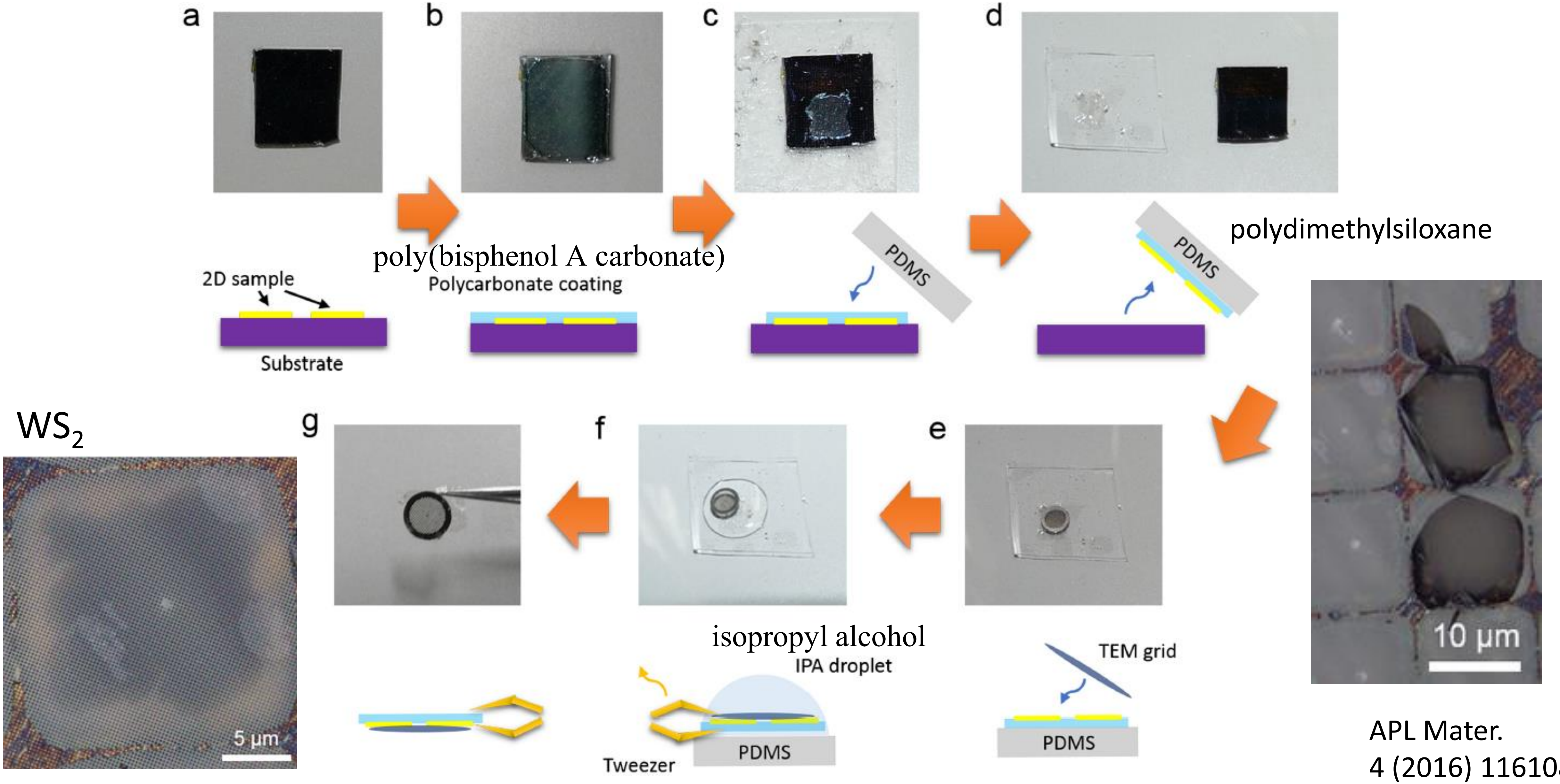




Strain near edges of holes (Raman mapping)

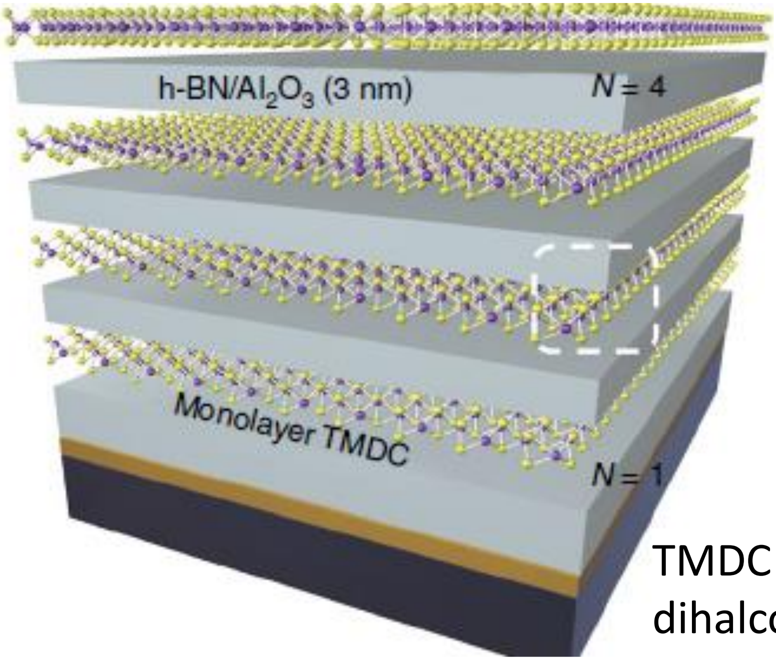
ACS Nano
5 (2011) 6916

Transfer of a single flake avoiding etching (example of transfer to TEM grid)



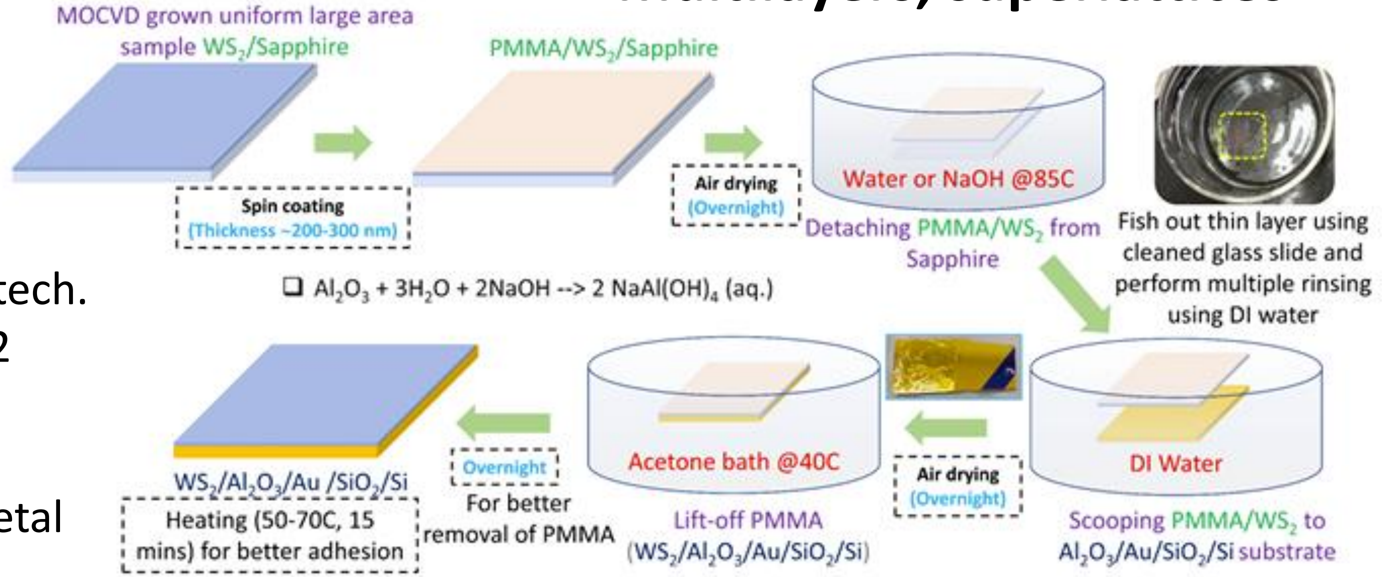
APL Mater.
4 (2016) 116108

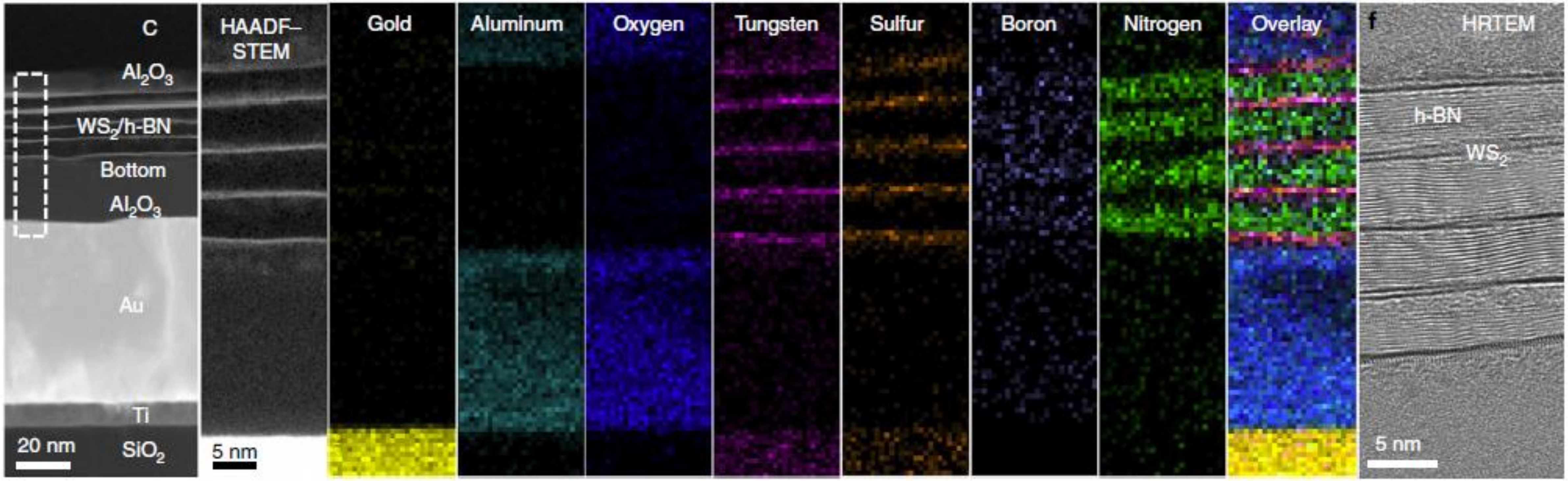
Multilayers, superlattices



Nature Nanotech. 17 (2022) 182

TMDC = transition metal dihalcogenides (MX_2)

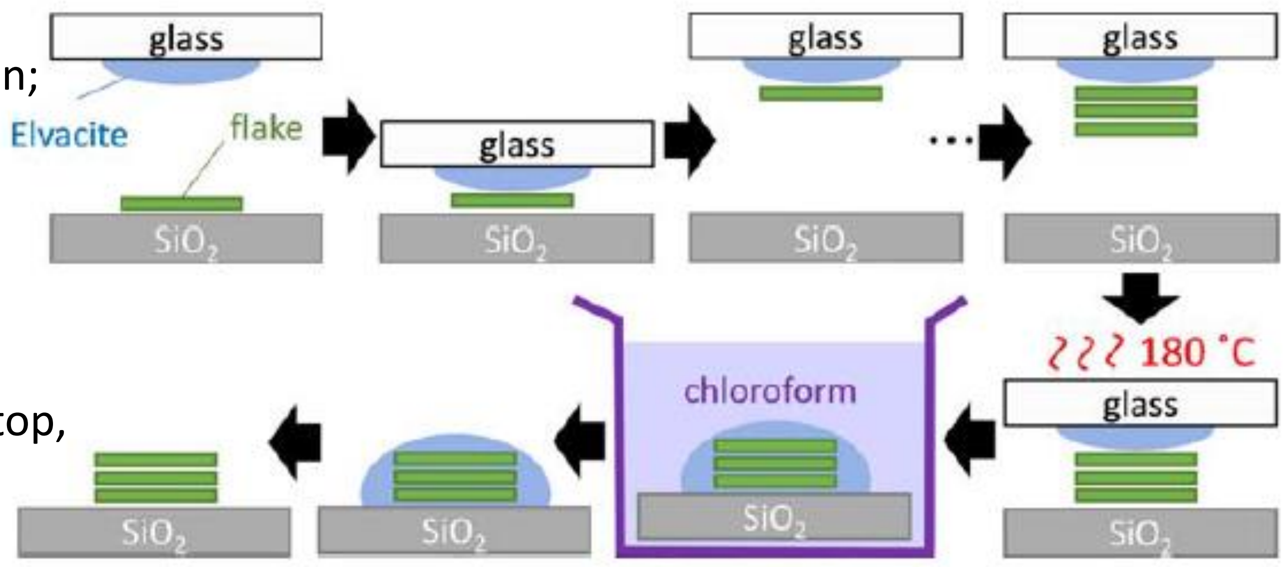




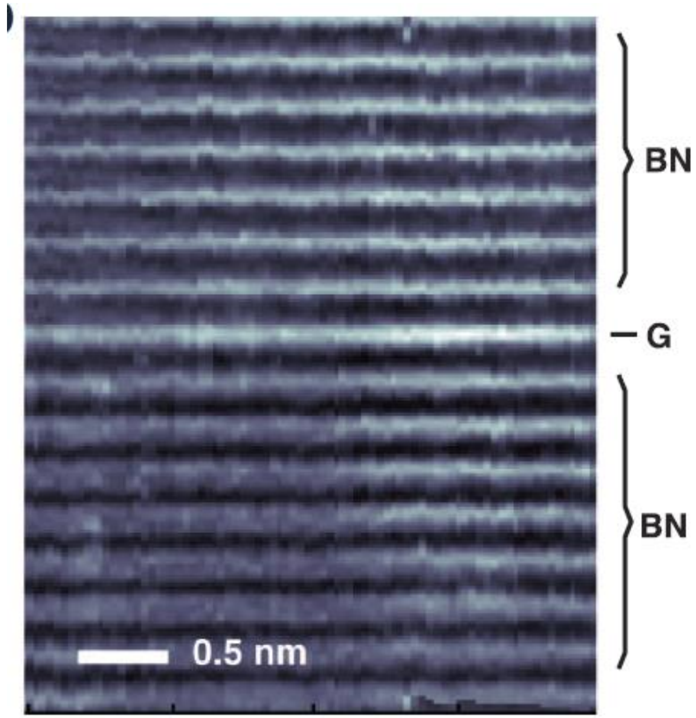
“Pick-up” approach to stacking

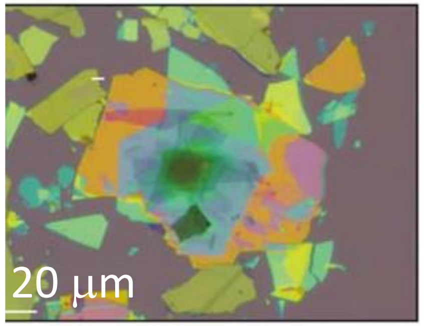
Elvacite is acrylic resin; propylene carbonate based polymers can be used as well.

Flake pocked up first will finally be at the top, so the structure is not contaminated by polymer stamp



Jap. J. Appl. Phys. 59 (2020) 010101



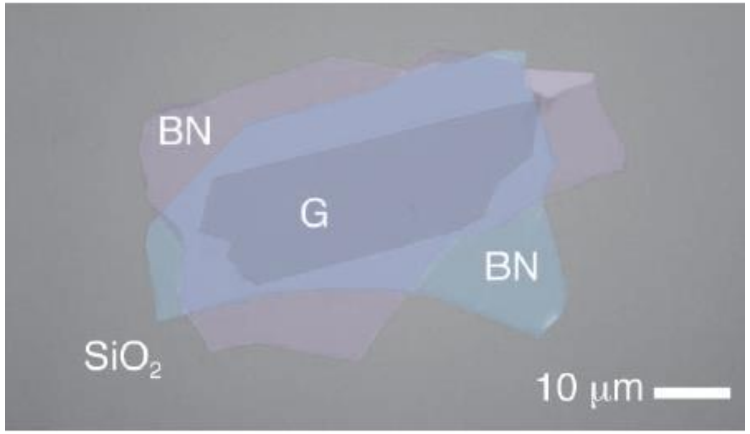


Jap. J. Appl. Phys. 59 (2020) 010101

Dozens of flakes can be stacked, but the size of each flake is occasional.

Optical microscopy is required to combine the central parts of all flakes.

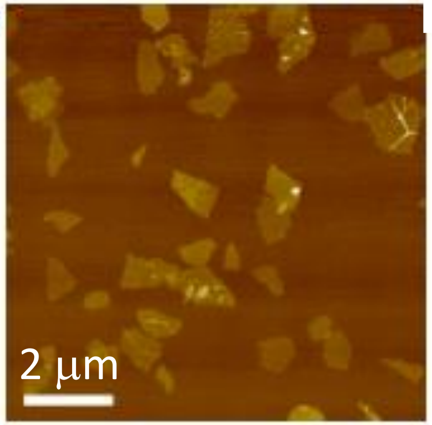
Automatic tools are already developed, but all **single-flake technologies** still work **mostly for laboratory prototype devices**.

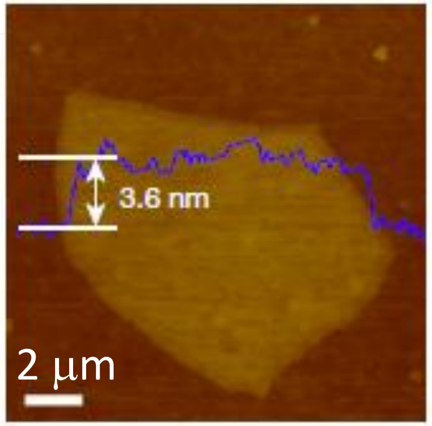


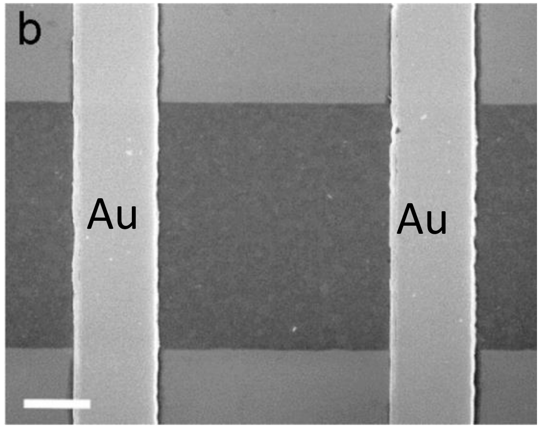
Science 342 (2013) 614-617

Ink-based assembling of 2D flakes (several atomic layers): simple, suitable for any support

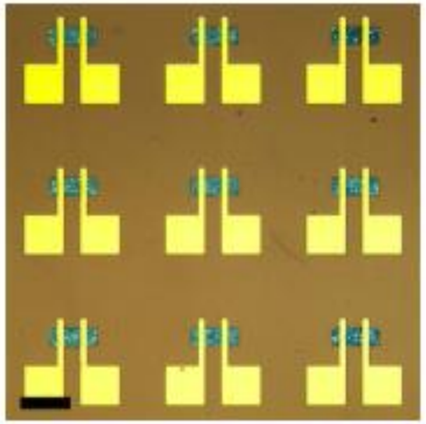
Suspension spin-coating, then lithography



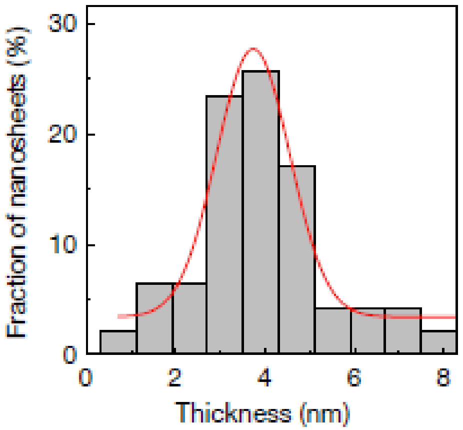




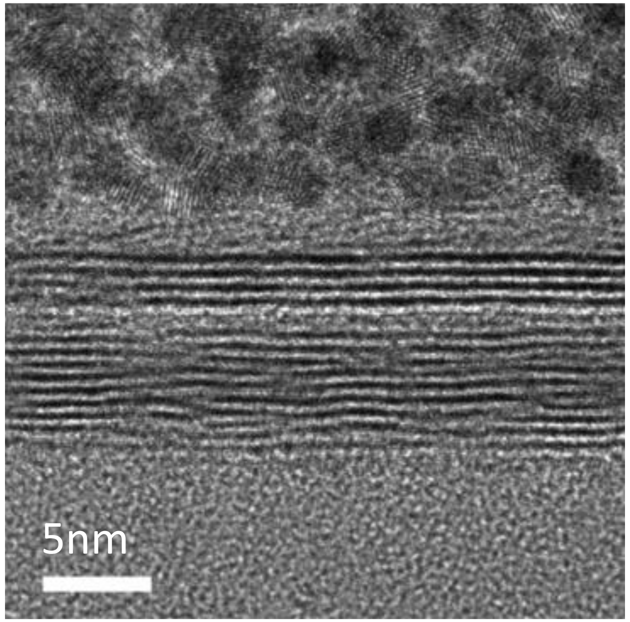
10 μm

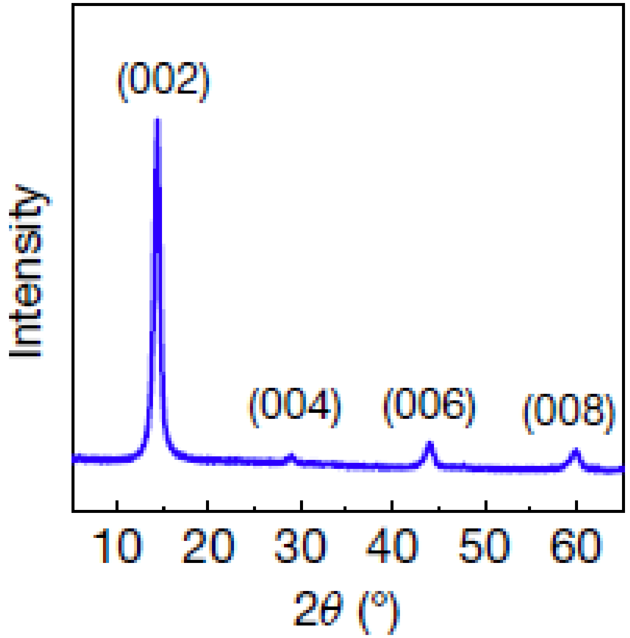


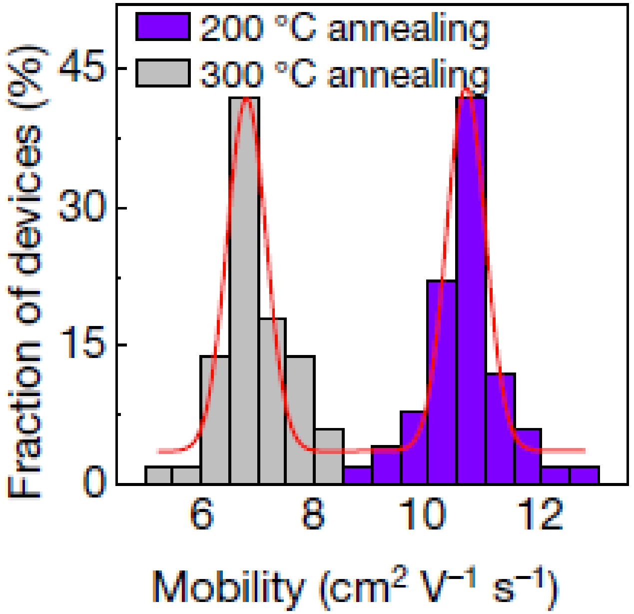
100 μm



(0.61 nm/layer)



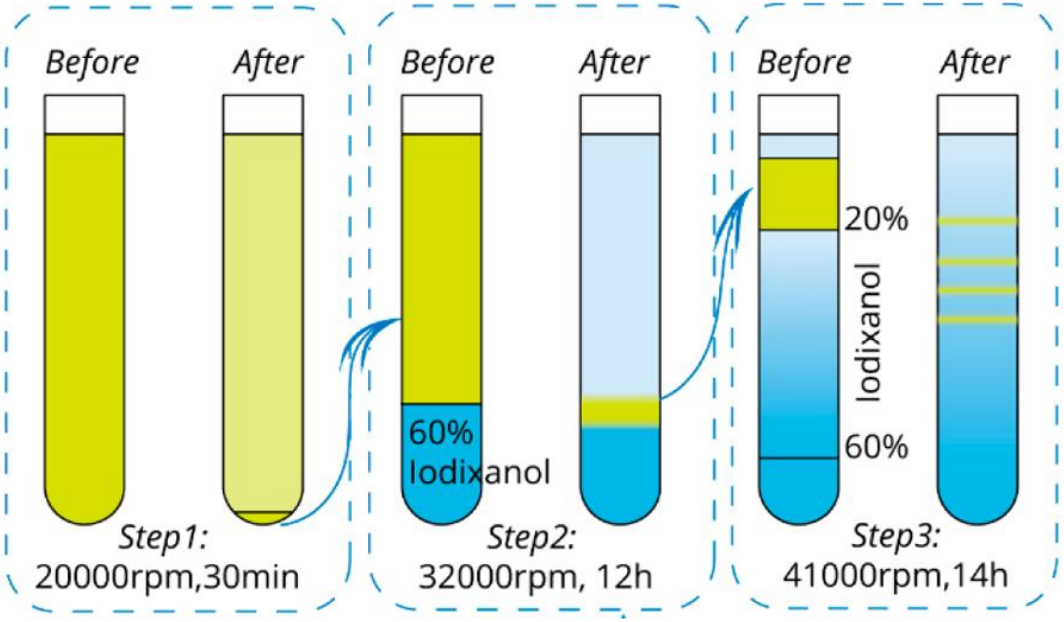


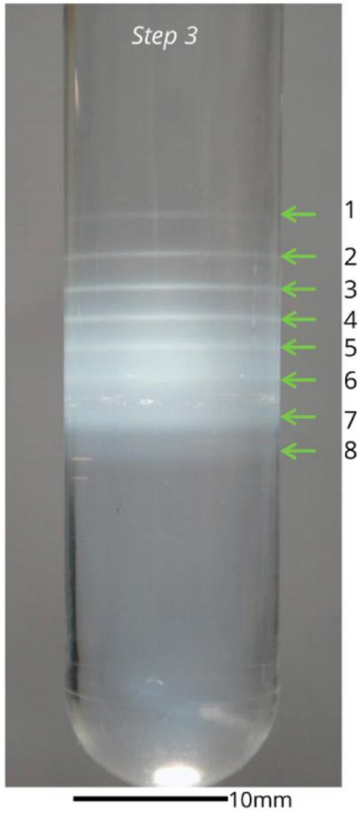


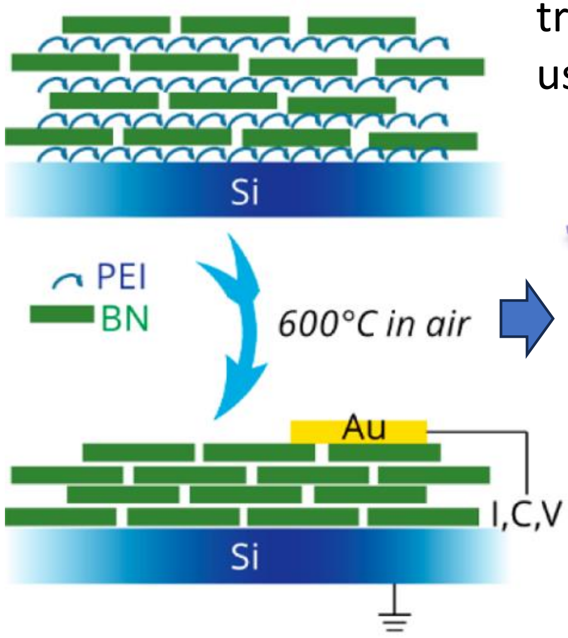
Nature 562 (2018) 254

Ink-based assembling of 2D flakes: size/thickness sorting

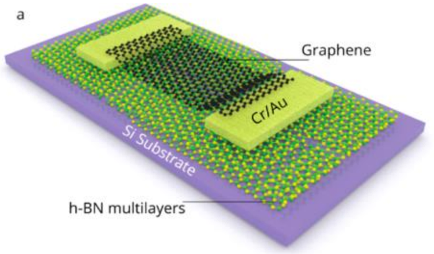
Centrifugation + extraction, **hexagonal BN:**



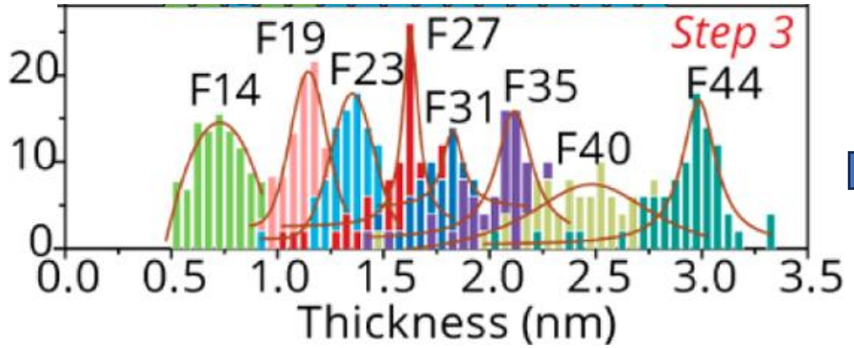




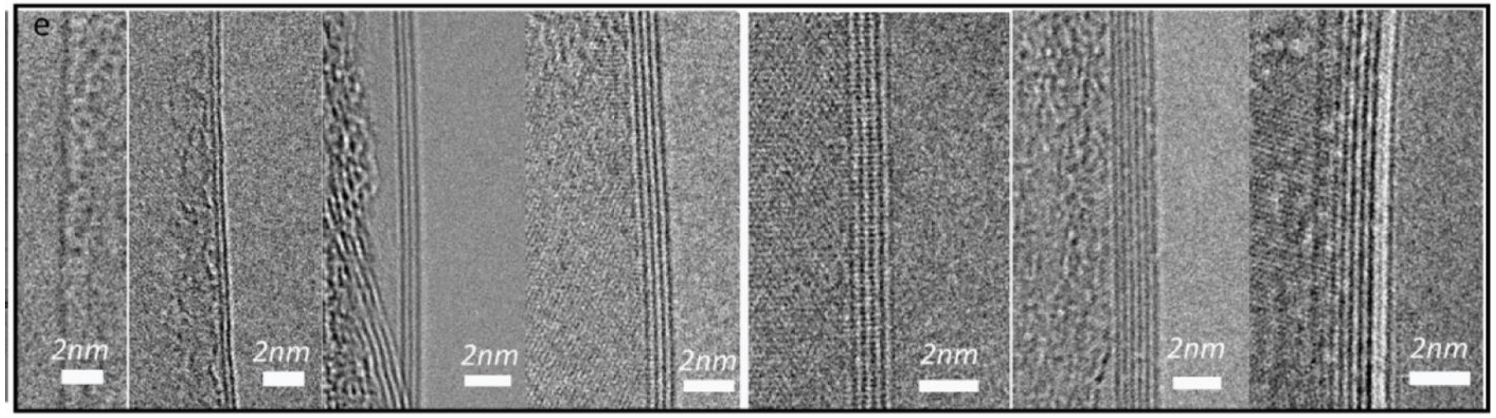
CVD Graphene is transferred from Cu foil using polymer resist



PEI is polyethyleneimine (deleted after heating)

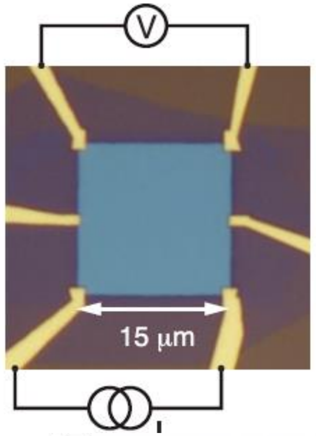


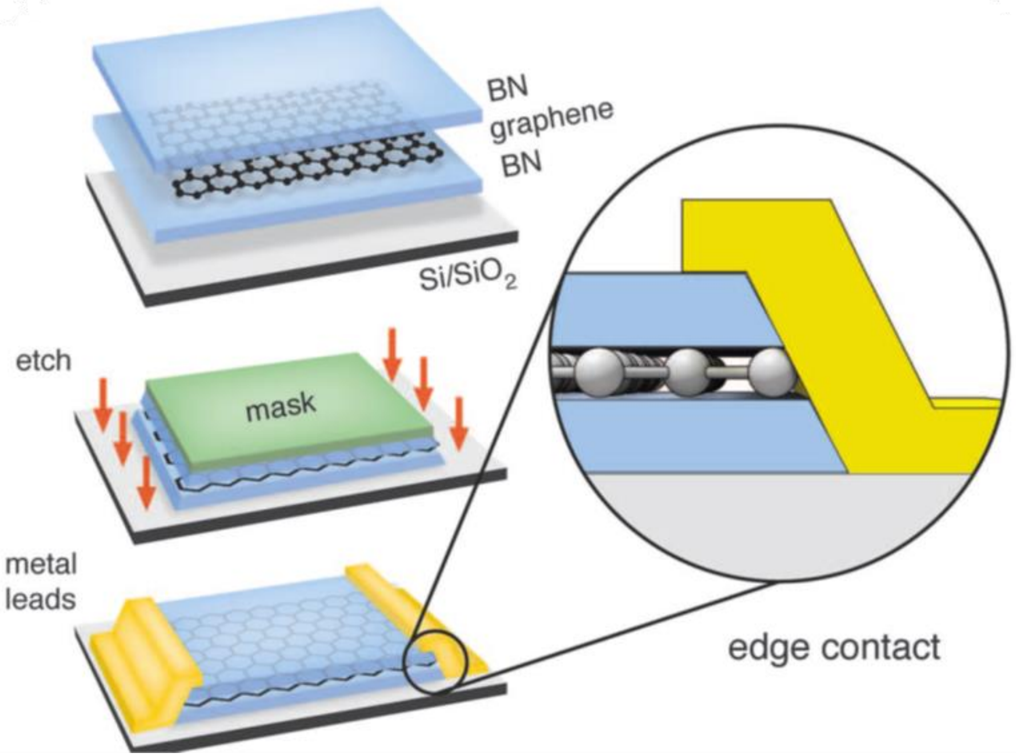
1….7 layers

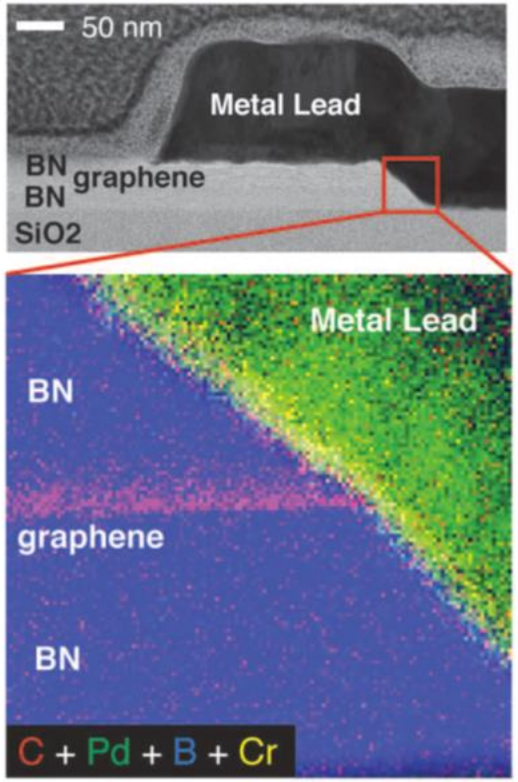


NanoLett. 15 (2015) 7029

Edge-contacts to 2D structures

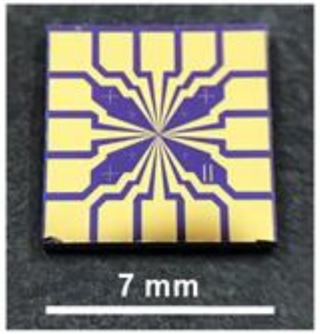


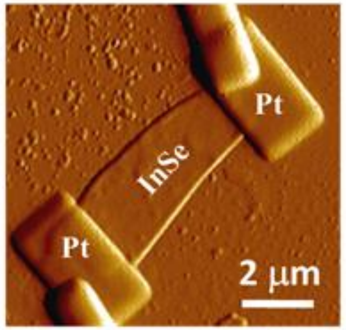


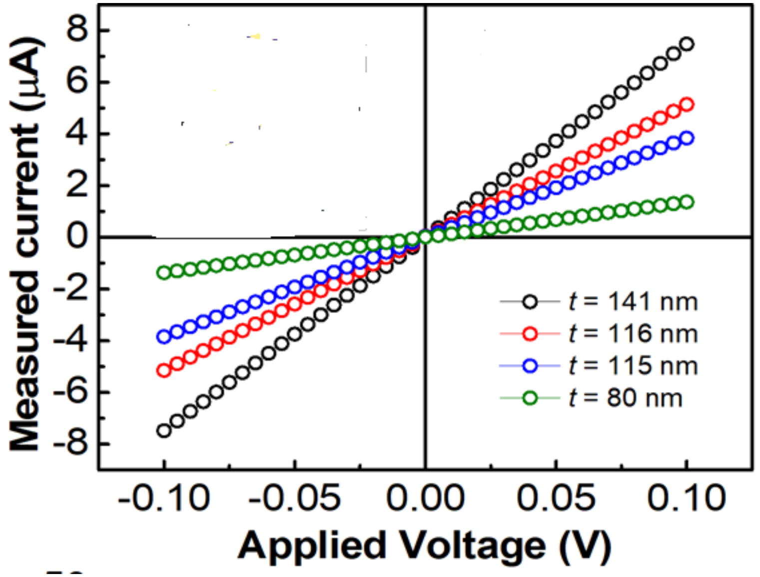


Science 342 (2013) 614-617

Contacts formed using focused ion beam (FIB)







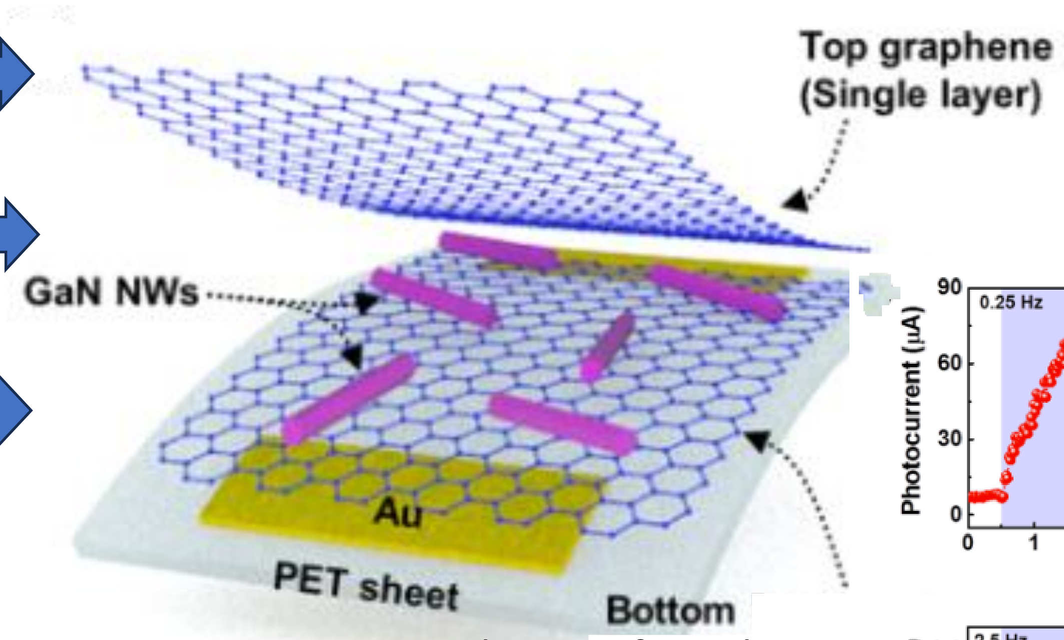
ACS Appl. Mater. Interfaces 10 (2018) 5740

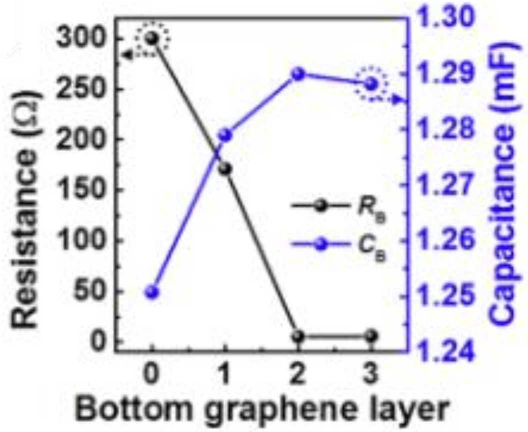
Structures containing the fragments of various dimensions: 2D and 1D

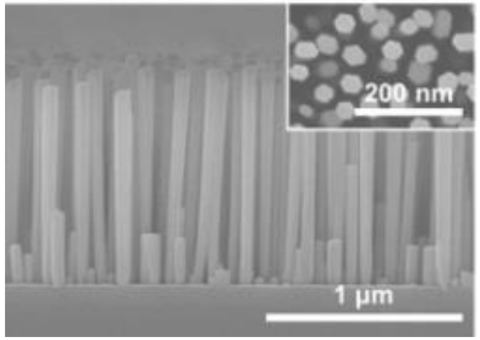
Au sputtering on flexible support (PET = polyethylene terephthalat), 1x0.5mm^{2}x27nm; **60 μm** between two Au contacts.

ACS Appl. Mater. Interfaces 12 (2020) 970

Graphene, up to 3 layers, wet transfer.

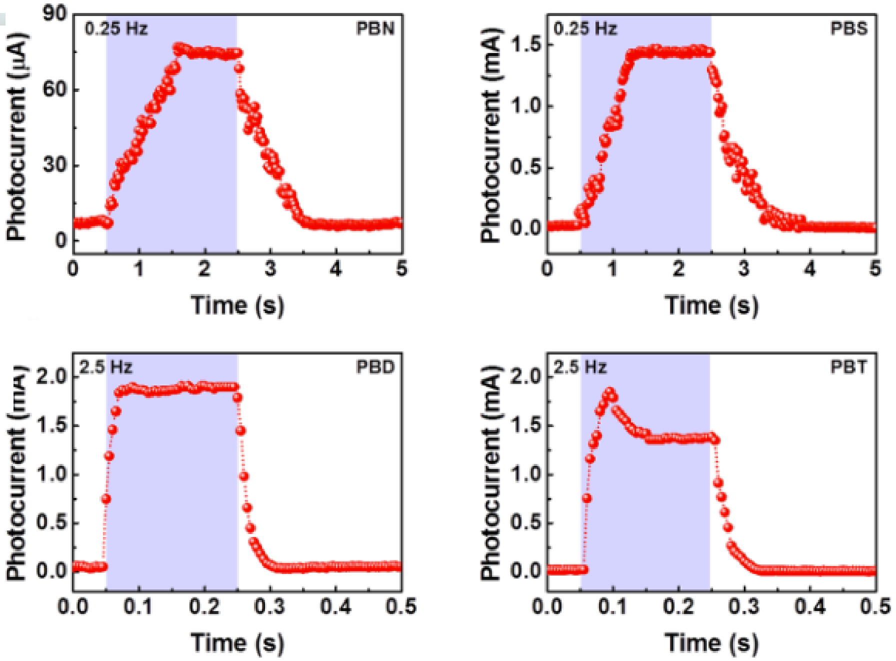




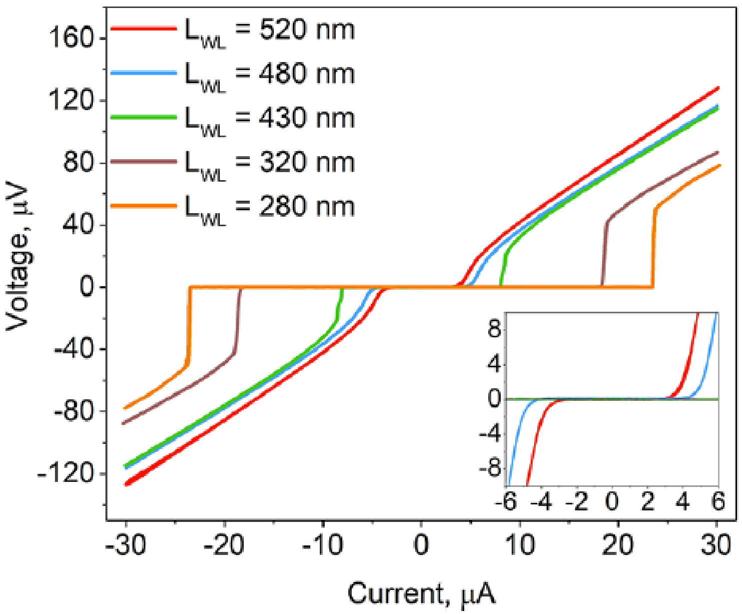


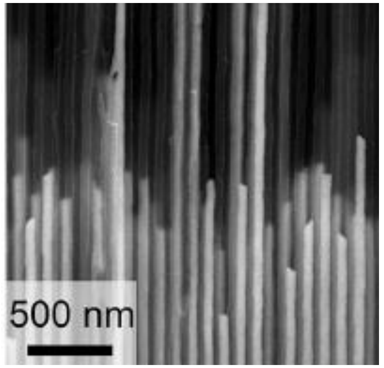
GaN wires grown on Si:
- **suspended**,
- randomly deposited.

layers of graphene:
0 (PBN), 1 (PBS),
2 (PBD), 3 (PBT)

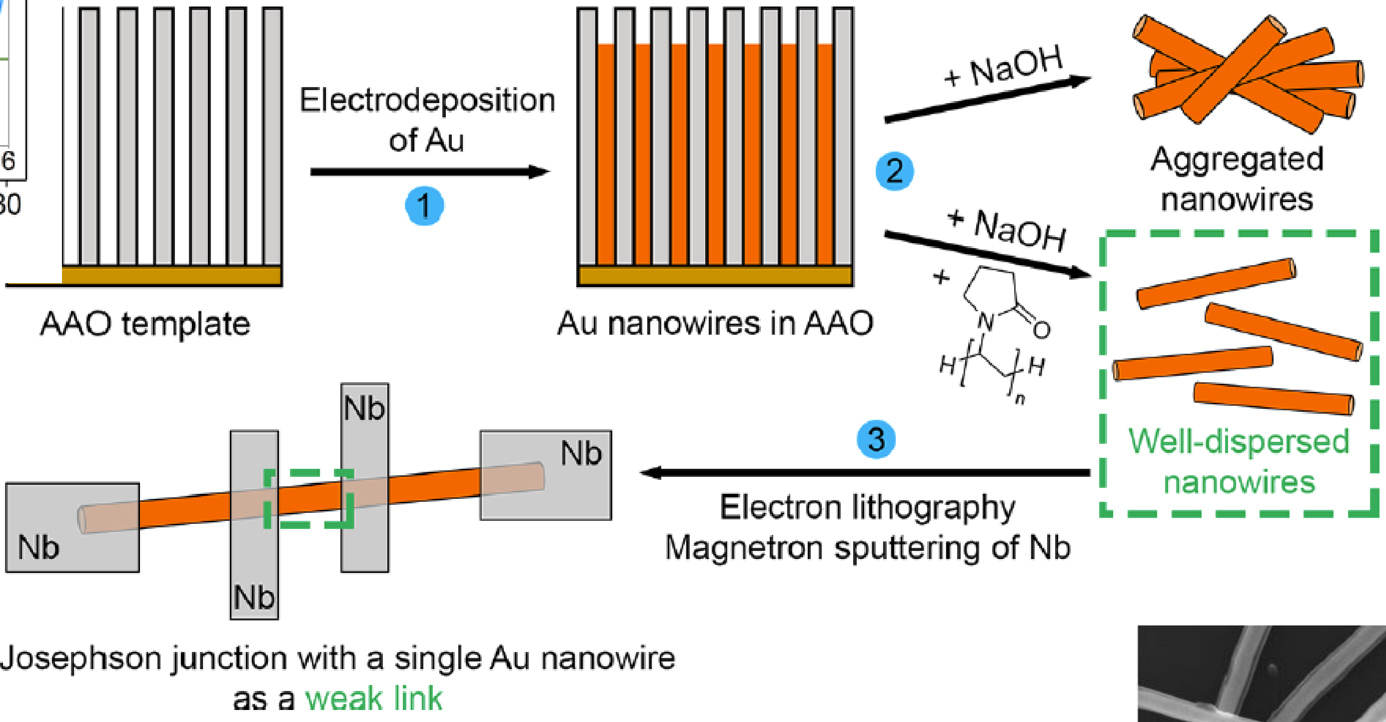


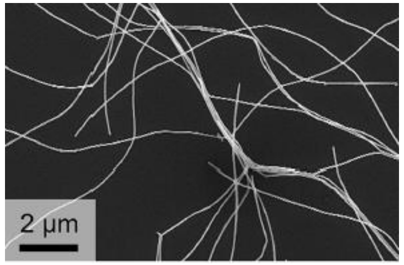
Single wire devices requiring contacts (example of Josephson junction)

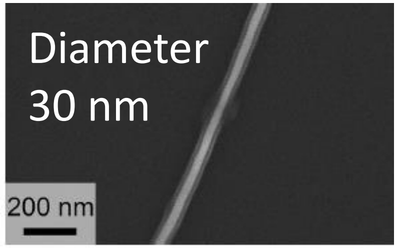


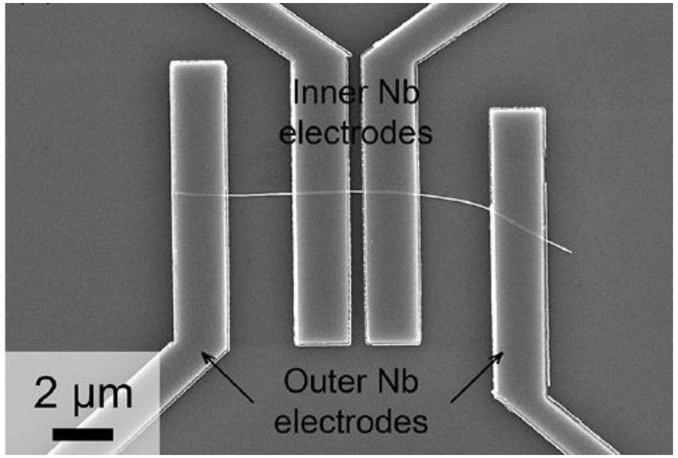


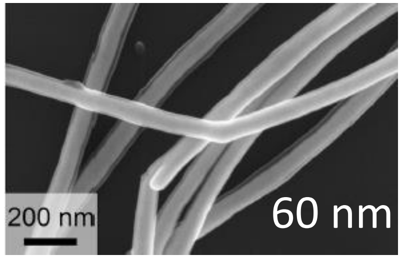
after AAO dissolution, surfactants are necessary to suppress wires aggregation; in this example, polyvinylpyrrolidone (PVP) is applied as surfactant











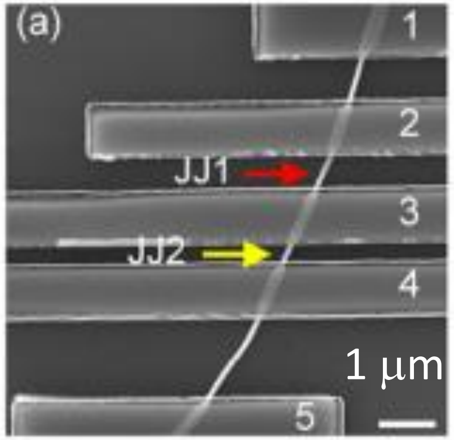
ACS Appl. Nano Mater. 5 (2022) 17059

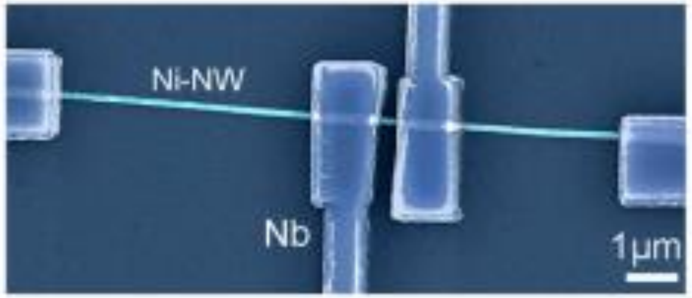
Single wire devices … macroscopic contacts

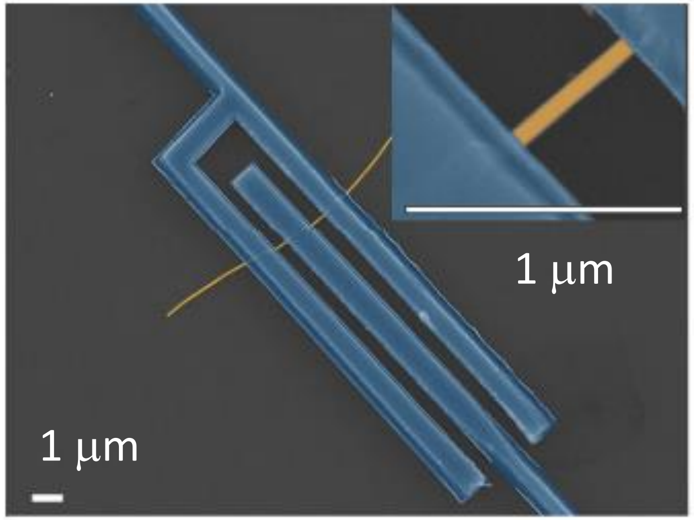
Sci. Rep. 9 (2019) 14470;
11 (2021) 17042

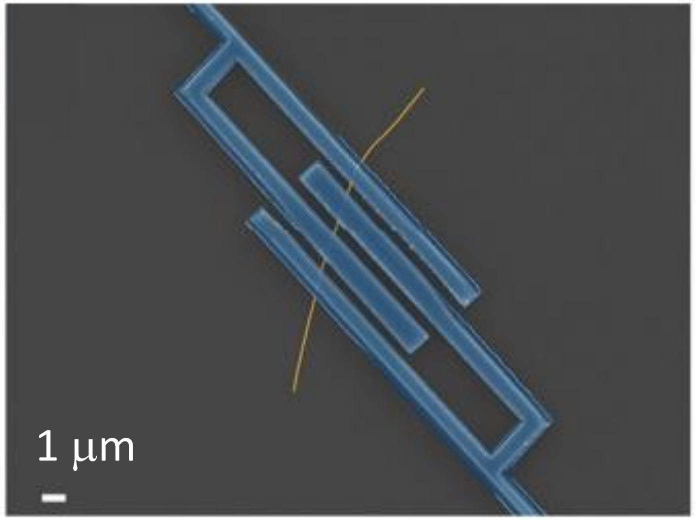
Macroscopic bonding (welding)

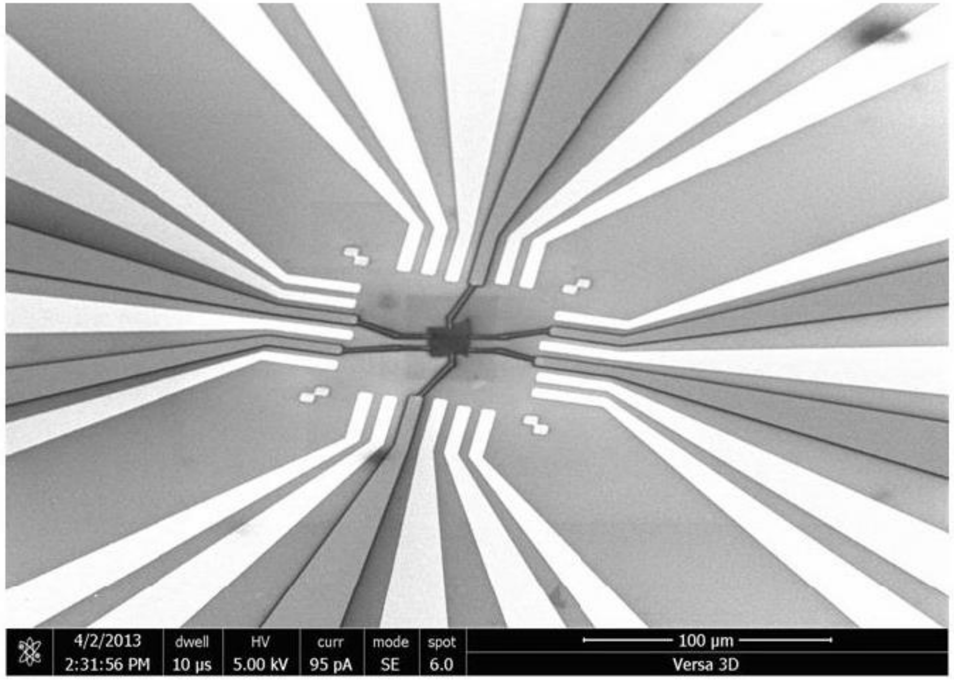
Macroscopic contact pads





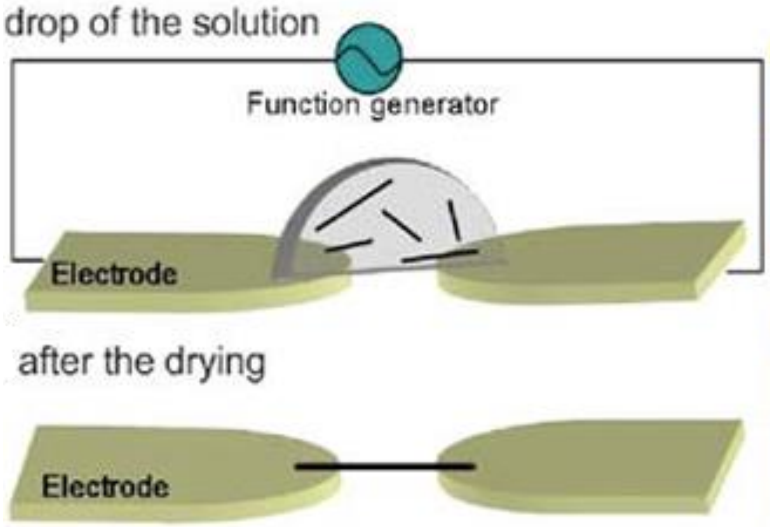


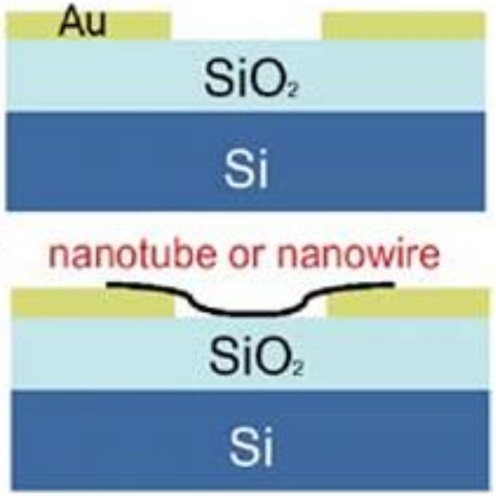




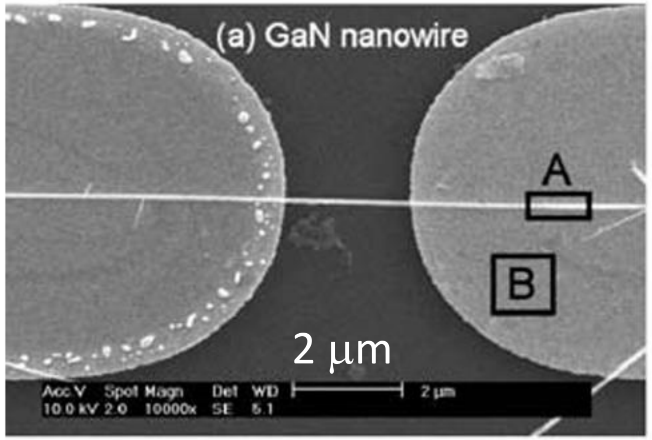
100 μm

Electrophoresis as manipulation tool for 1D fragments

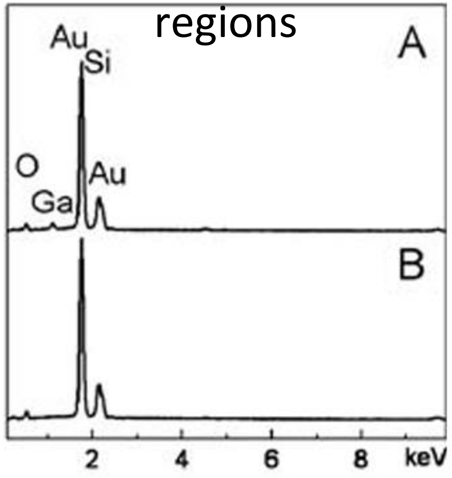


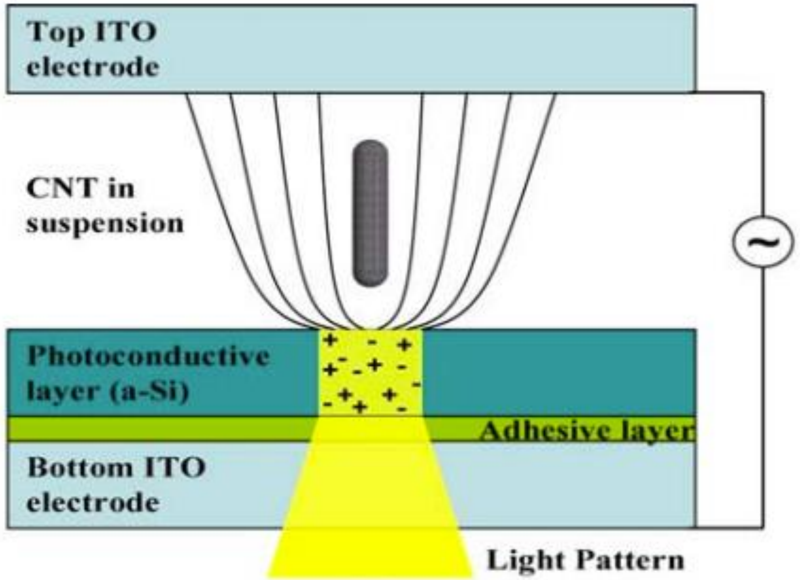


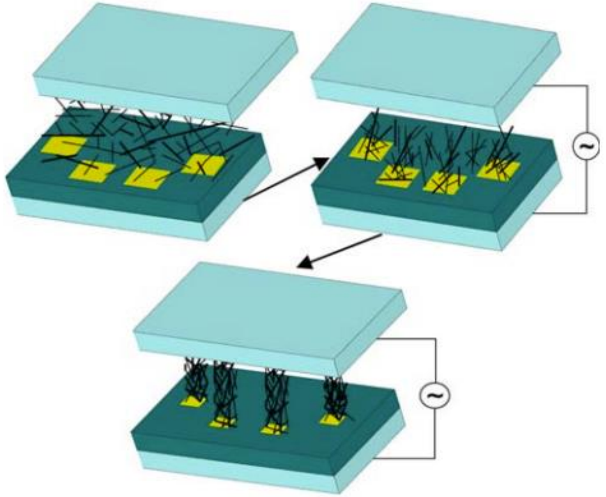
Curr. Appl. Phys. 6, Suppl. 1 (2006) e216-e219

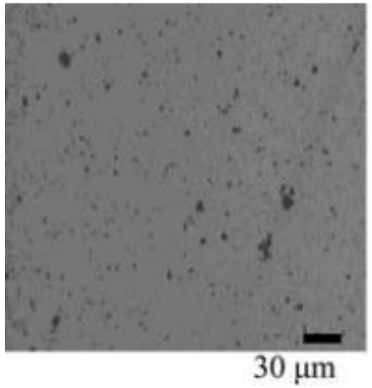


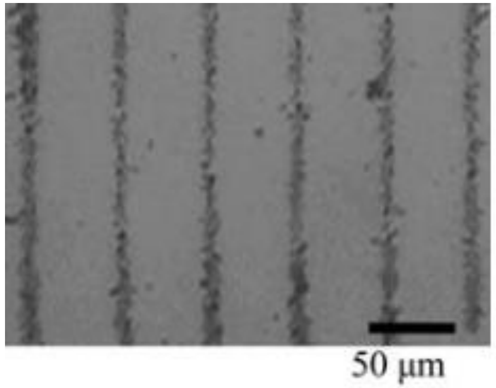
EDX analysis for A and B regions





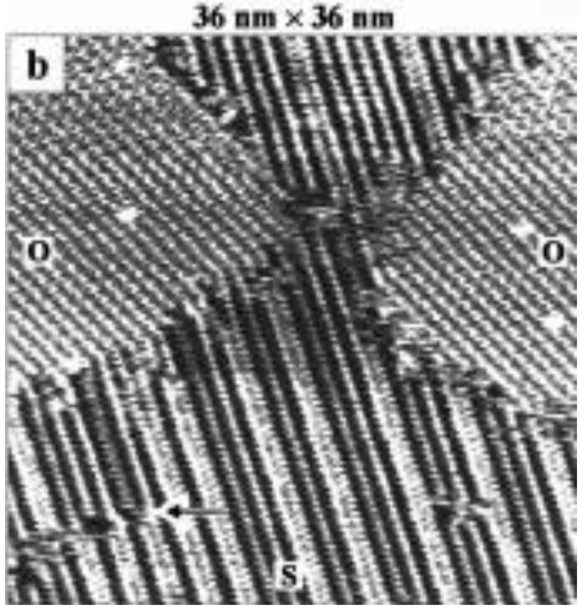


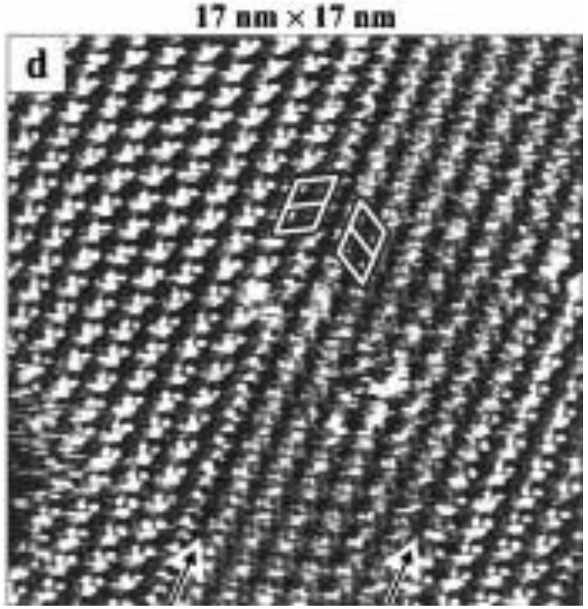




Microfluid Nanofluid 8 (2010) 609

Thiols (R-SH): molecular linkers for surfaces and 0D fragments (nanoparticles)

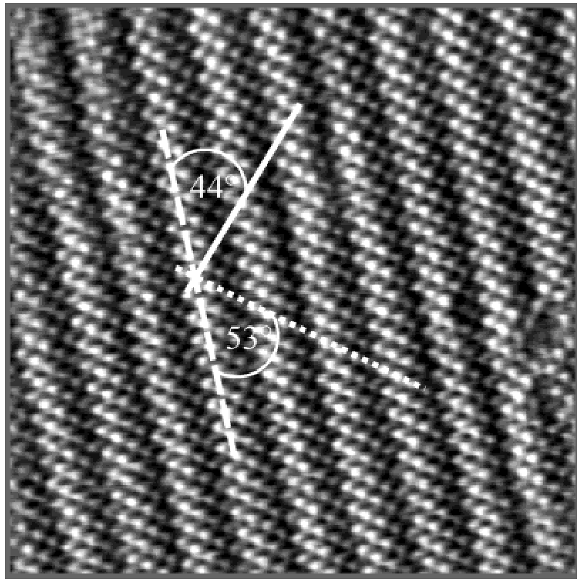


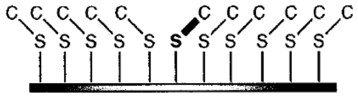


Ethane thiol on Au(111)

Butane thiol on Au(100)

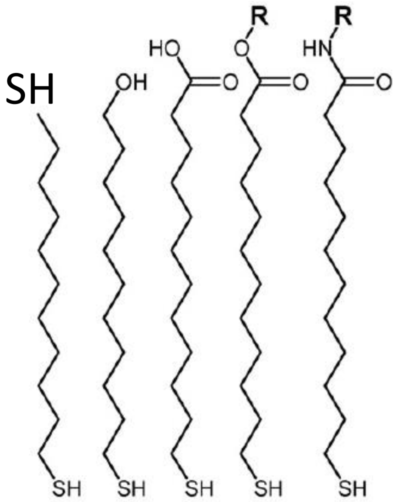
15x15 nm^2





Mirror domains

Langmuir 15 (1999) 2435;
19 (2003) 830

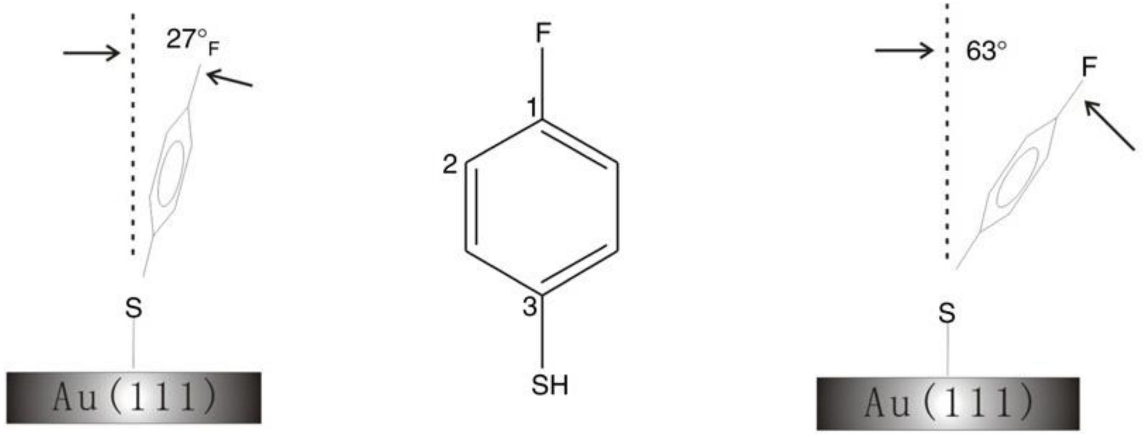


- SH groups and terminal functional groups of one and the same molecule can link to support surface and to nm-size particle respectively

very usual linkers are dithiols

From solution:

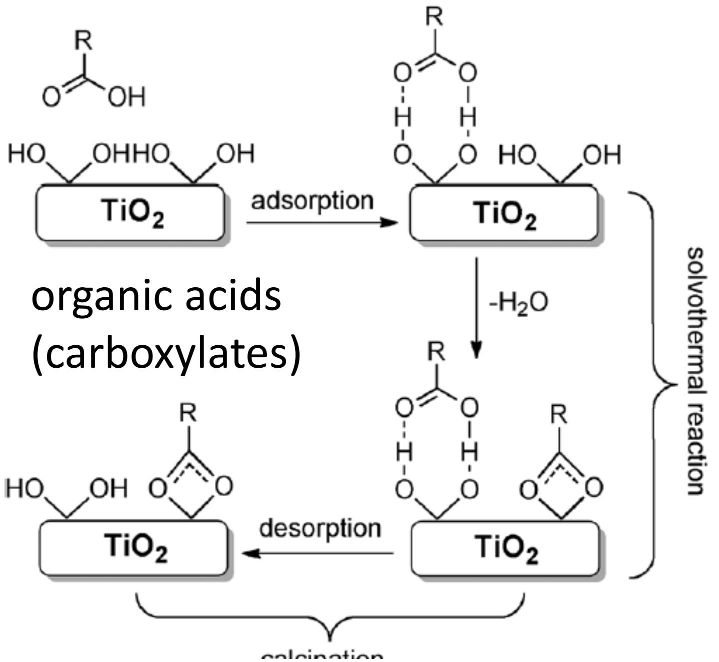
From vapor:



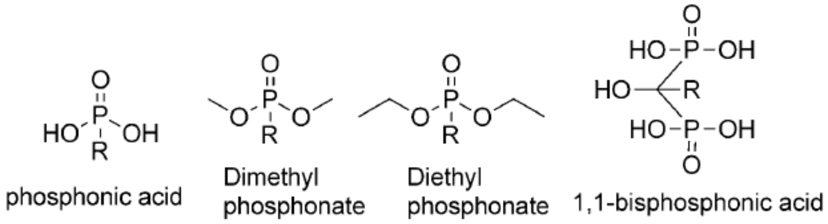
Surface coverage affects orientation (tilt angle)

Surface Sci. Rep.63 (2008) 465

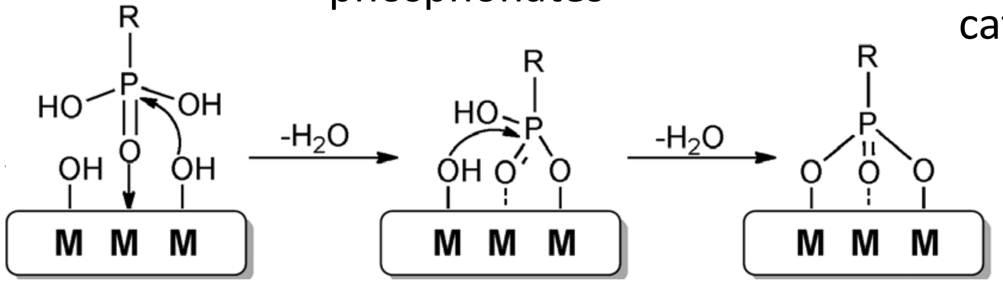
Molecular linkers for oxide surfaces (when thiols are less effective)

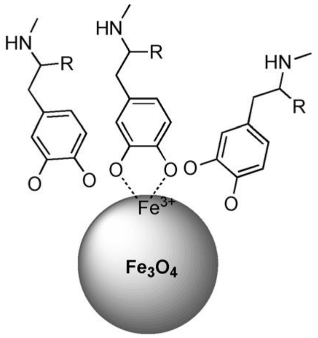


organic acids (carboxylates)



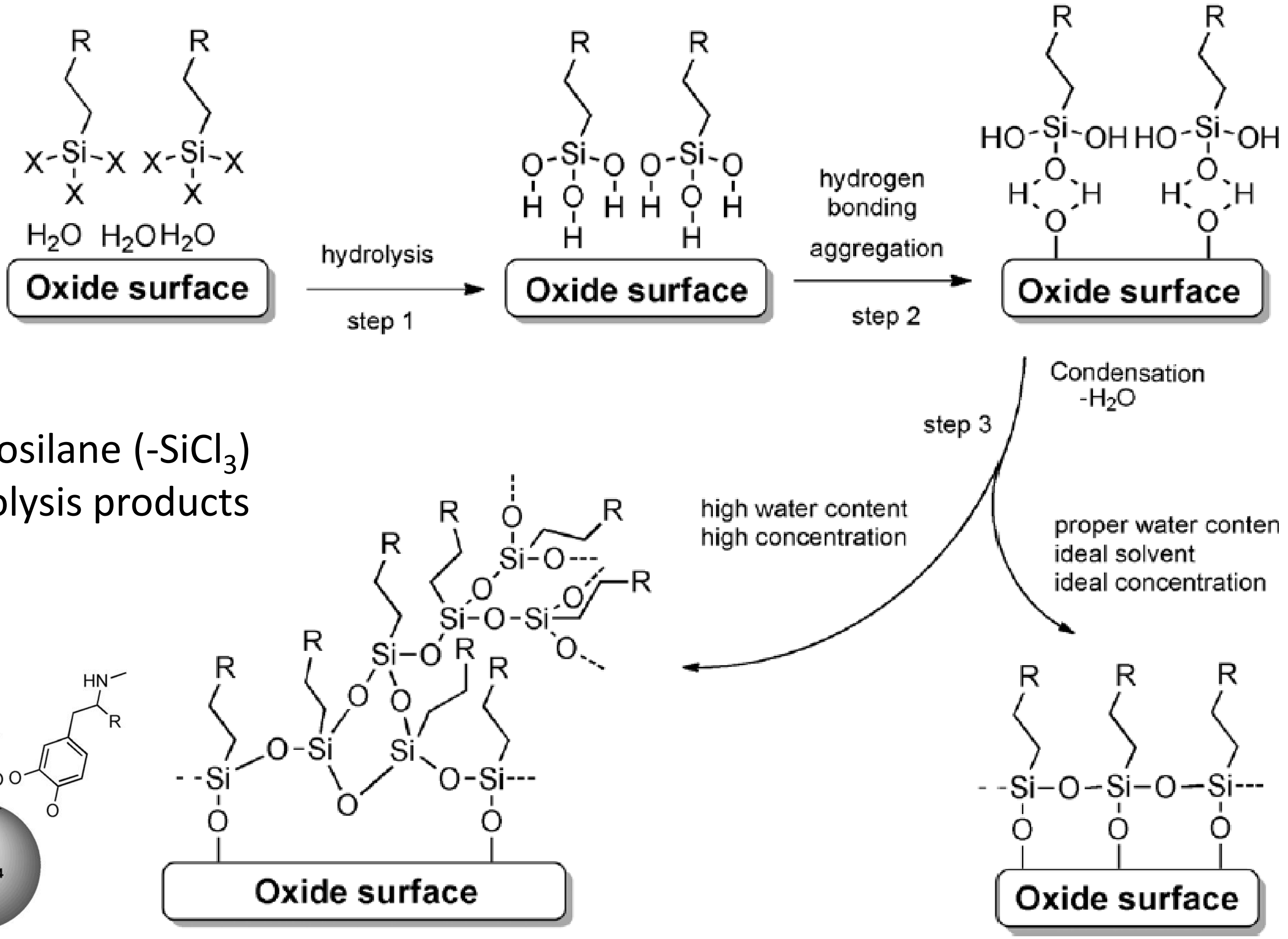
phosphonates





catecholes

chlorosilane (-$SiCl_3$) hydrolysis products

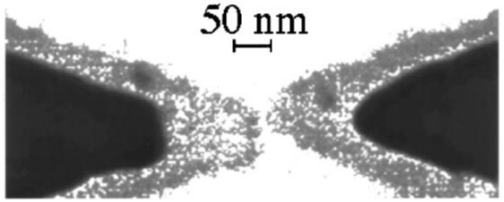


Angew. Chem. Int. Ed. 53 (2014) 6322

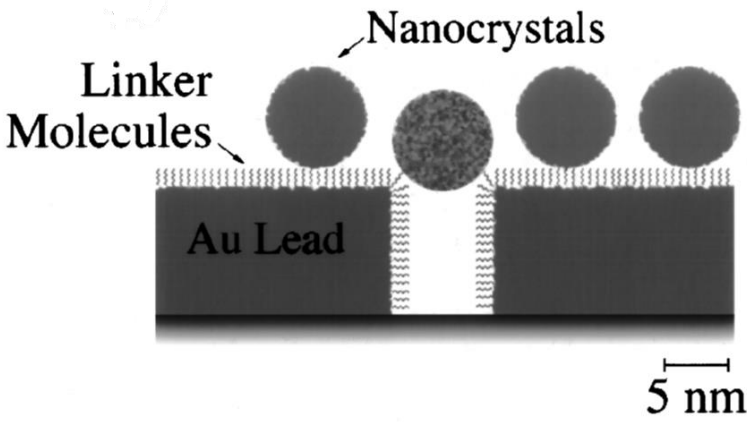
0D particles for single electron transfer

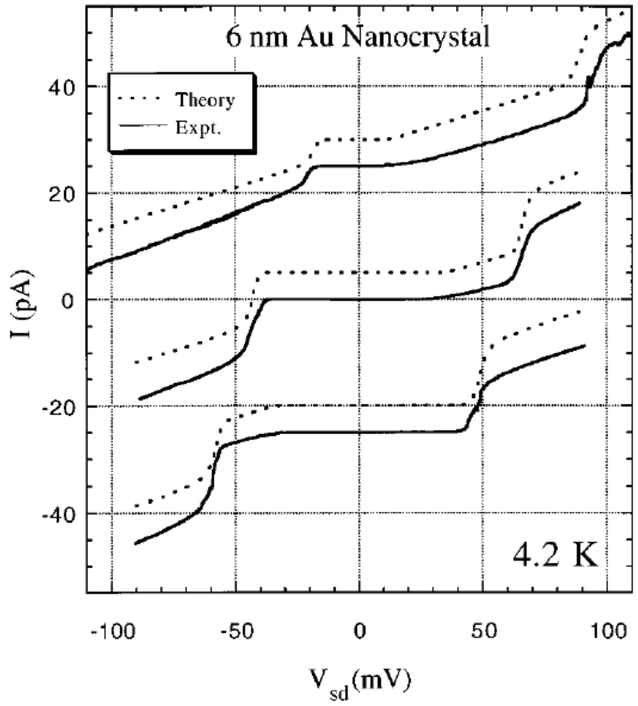
1,6-hexanedithiol linker

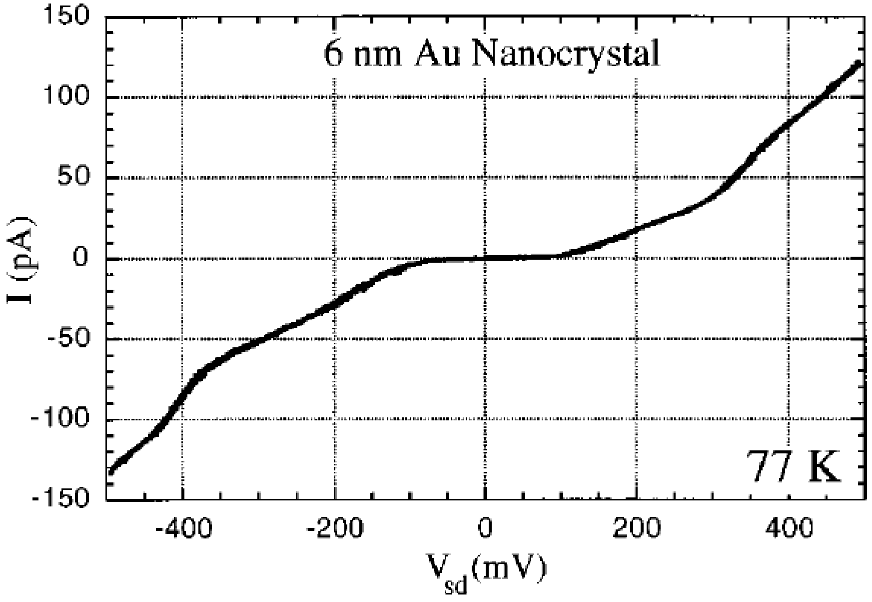
Appl. Phys. Lett 68 (1996) 2574

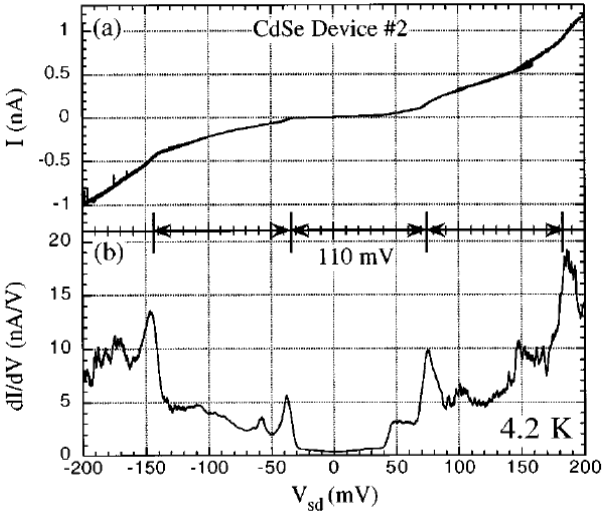


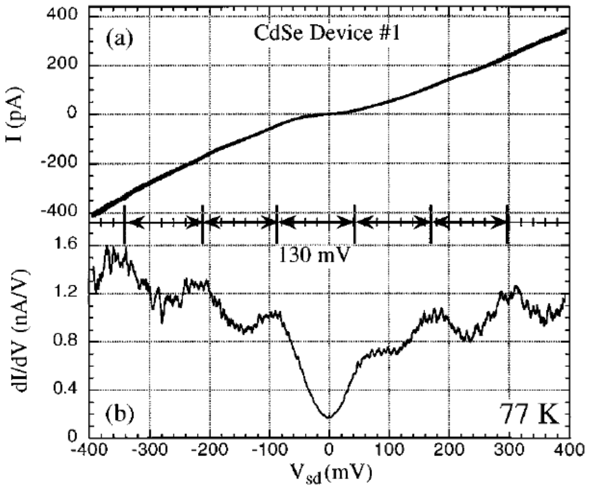
gap is created by shadow evaporation

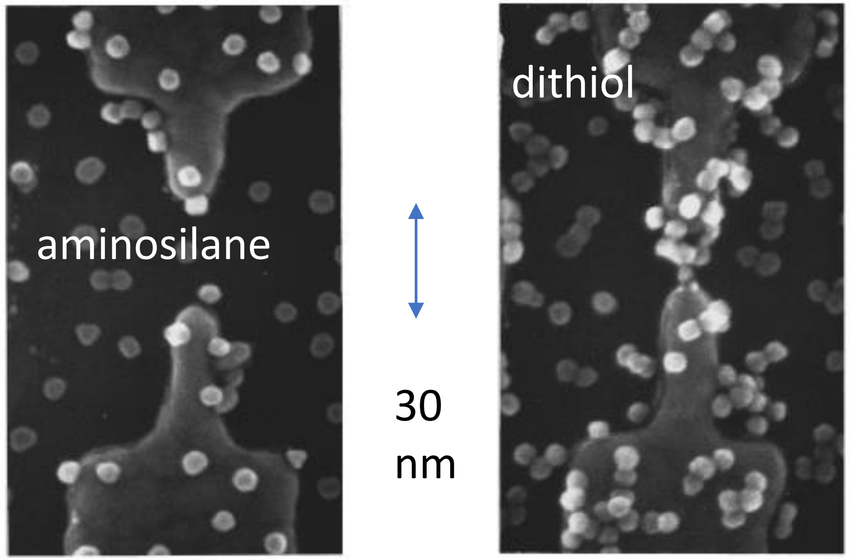






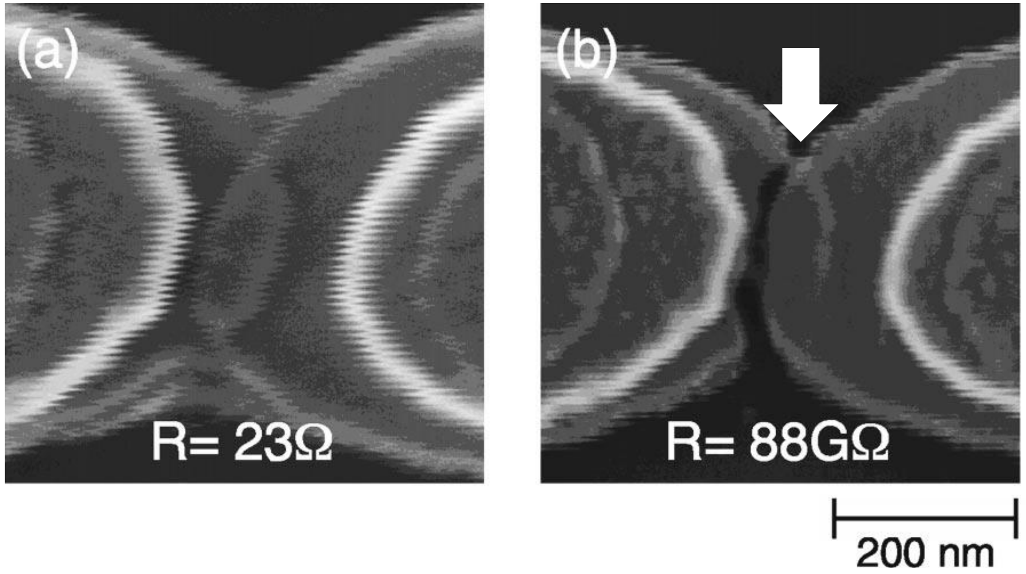


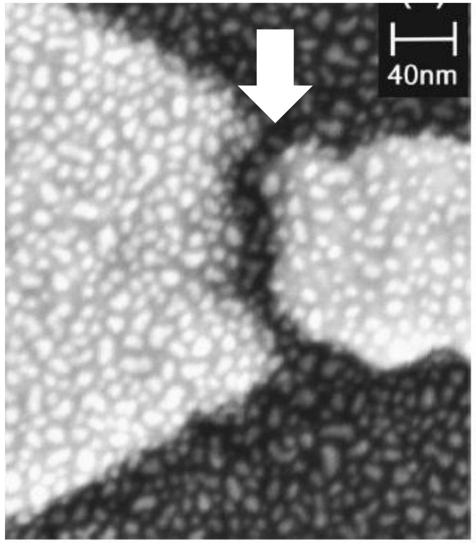




Appl. Phys. Lett 70 (1997) 2759

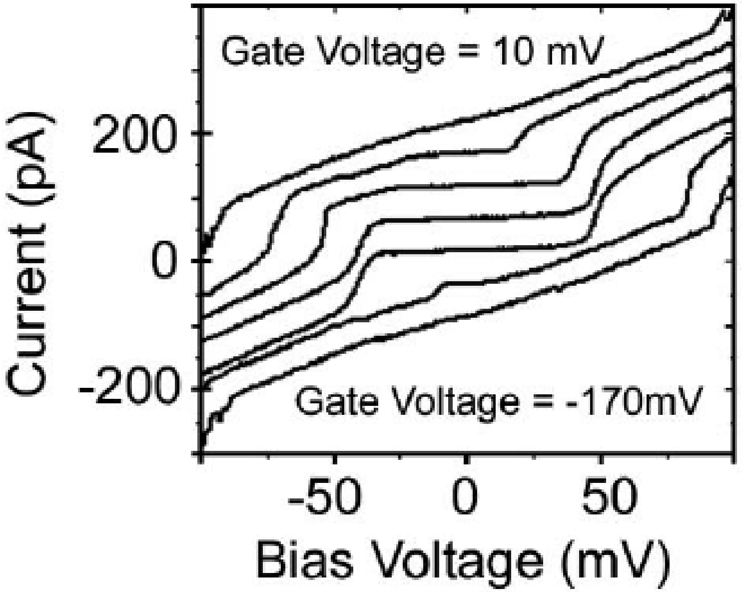
nm-size gaps: fabricated by electromigration, for single electron transistors

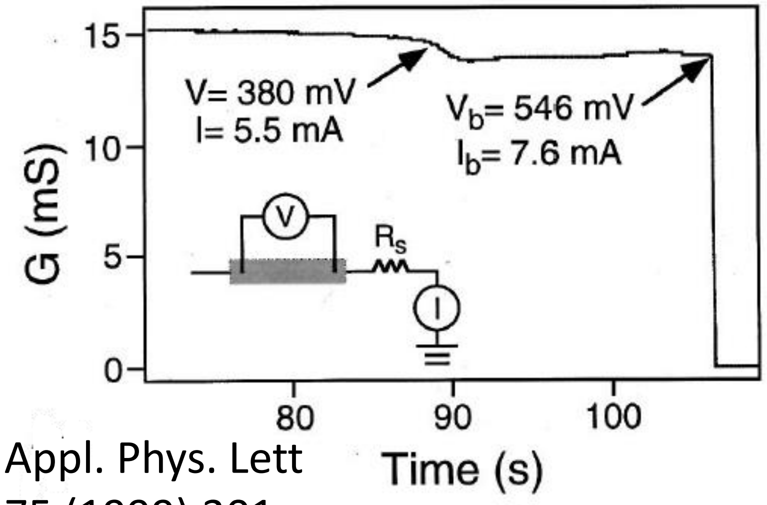




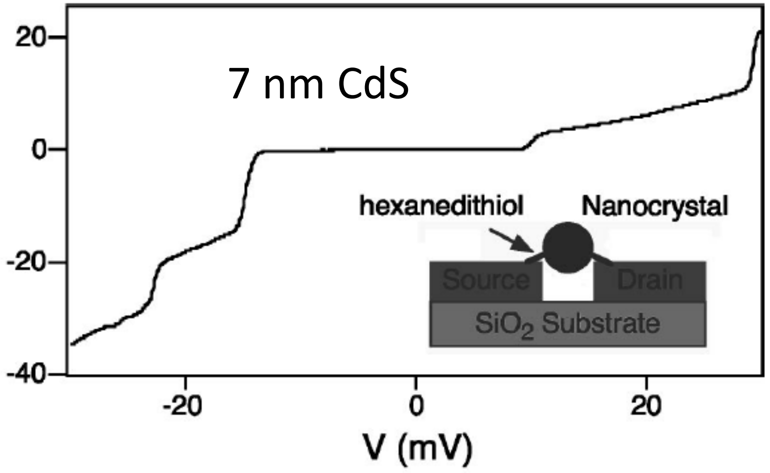
Appl. Phys. Lett
84 (2004) 3154

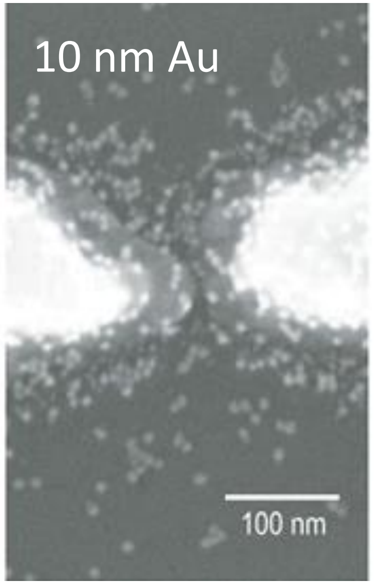
Evaporated Au islands, 5 - 15 nm





Appl. Phys. Lett
75 (1999) 301

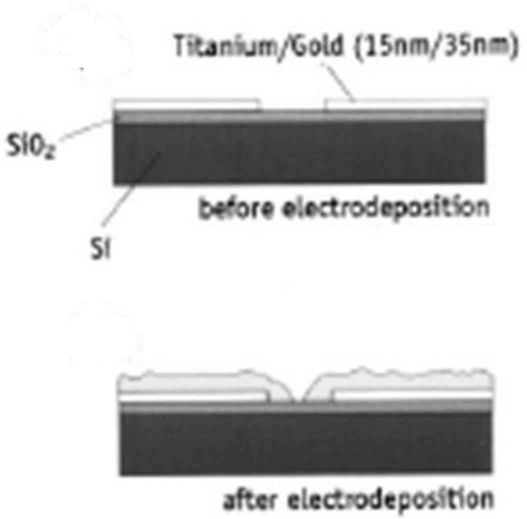


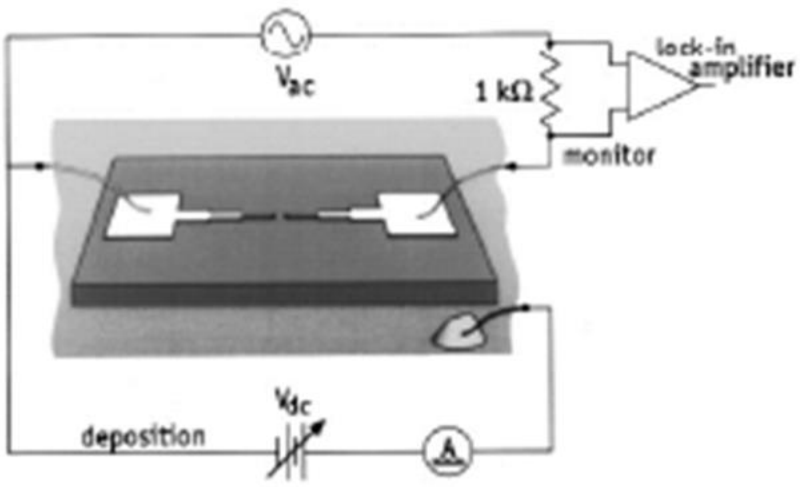


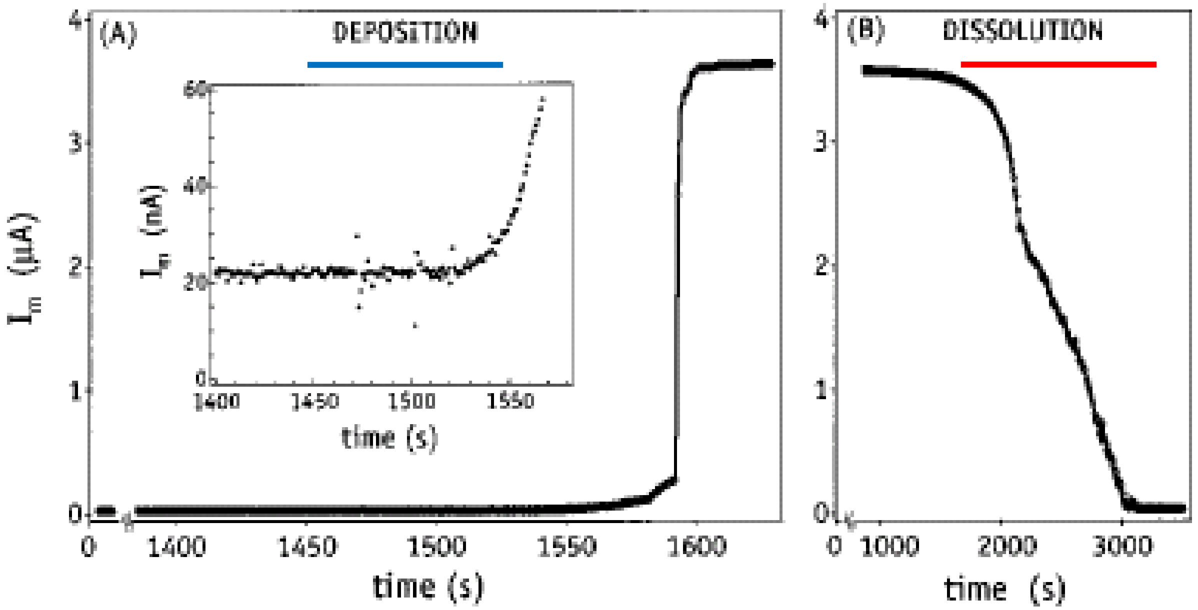
5 nm gap,
aminosilane
linker

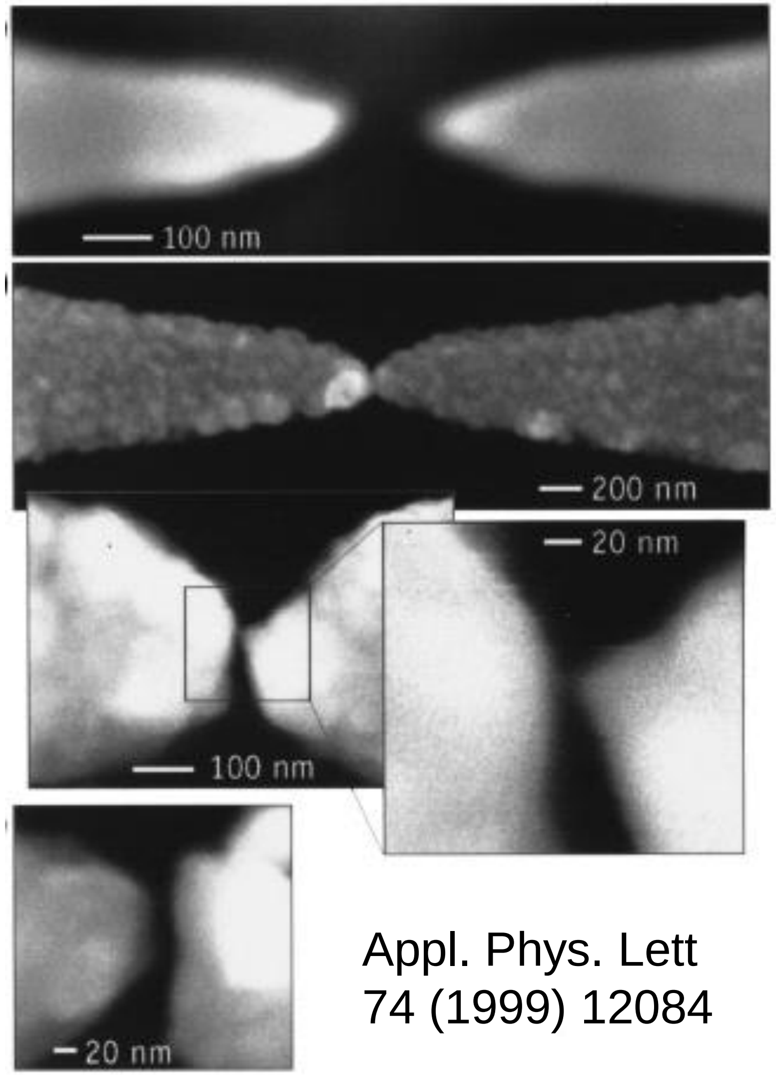
AIP Conf. Proc.
850 (2006) 1438

Gaps formed by electrodeposition and dissolution $[Au(CN)_4]^- + 3e \Leftrightarrow Au + 4CN^-$









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