A Bridge Between Quantum & Thin-Film Nanotechnology

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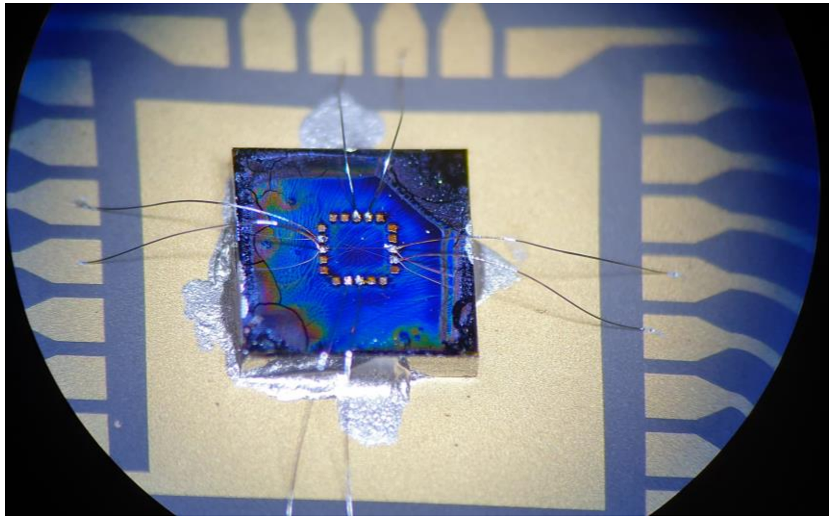


Gökhan Kara, *Quantum Dot Photodetector* (2020)

A Poem About Nanotechnology

Imagine it's like playing with LEGO bricks,
Except the bricks are atoms of solids,
That's how we build nanotechnology,
We play with atoms and stack them together,
Like interlink-able bricks,
Sometimes we can "melt" those bricks together,
This is called diffusion.

-Onri Jay Benally

Background & Motivation

- Reminder that it is generally agreed that **100 nm** or less is considered **nanoscale**.
  - <100 nanometers vertically + micrometer(s) laterally.
  - <100 nanometer dimensions vertically + laterally.
- Making quantum devices involves a balance between:
  - Building up.
  - Tearing down.
  - Inspecting for **desired** or **undesired** defects.
- Focus can be on:
  - (<u>Metals</u> & <u>insulators</u>) or (<u>metals</u>, <u>insulators</u>, & <u>semiconductors</u>).

1. Mandelbrot, *The Fractal Geometry of Nature* (1977)

Viewing Individual Atoms as LEGO Bricks

LEGOs Made of Cake

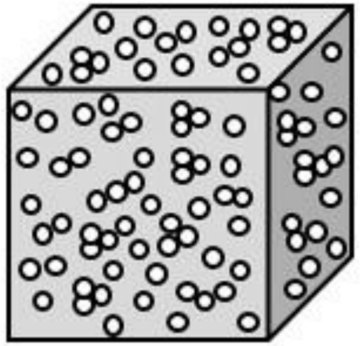
Magnetic Tunnel Junction Made of LEGOs

1. Taken from cakecentral.com

Atoms in a Vacuum Chamber

Rough Vacuum

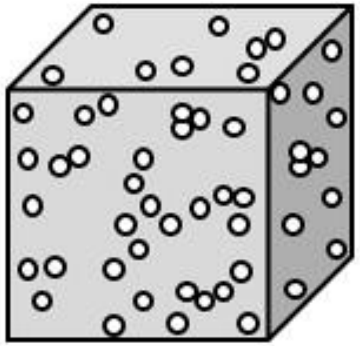
1 atm – 10^{-3} Torr



1.10^{-3} Torr
4.10^{13} atom/cm^3

High Vacuum

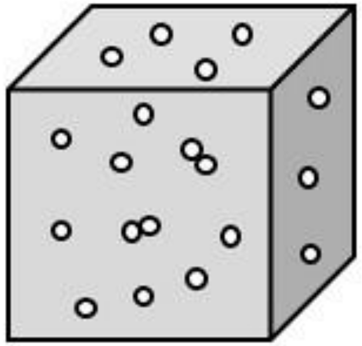
10^{-3} Torr - 10^{-8} Torr



1.10^{-6} Torr
4.10^{10} atom/cm^3

Ultra High Vacuum

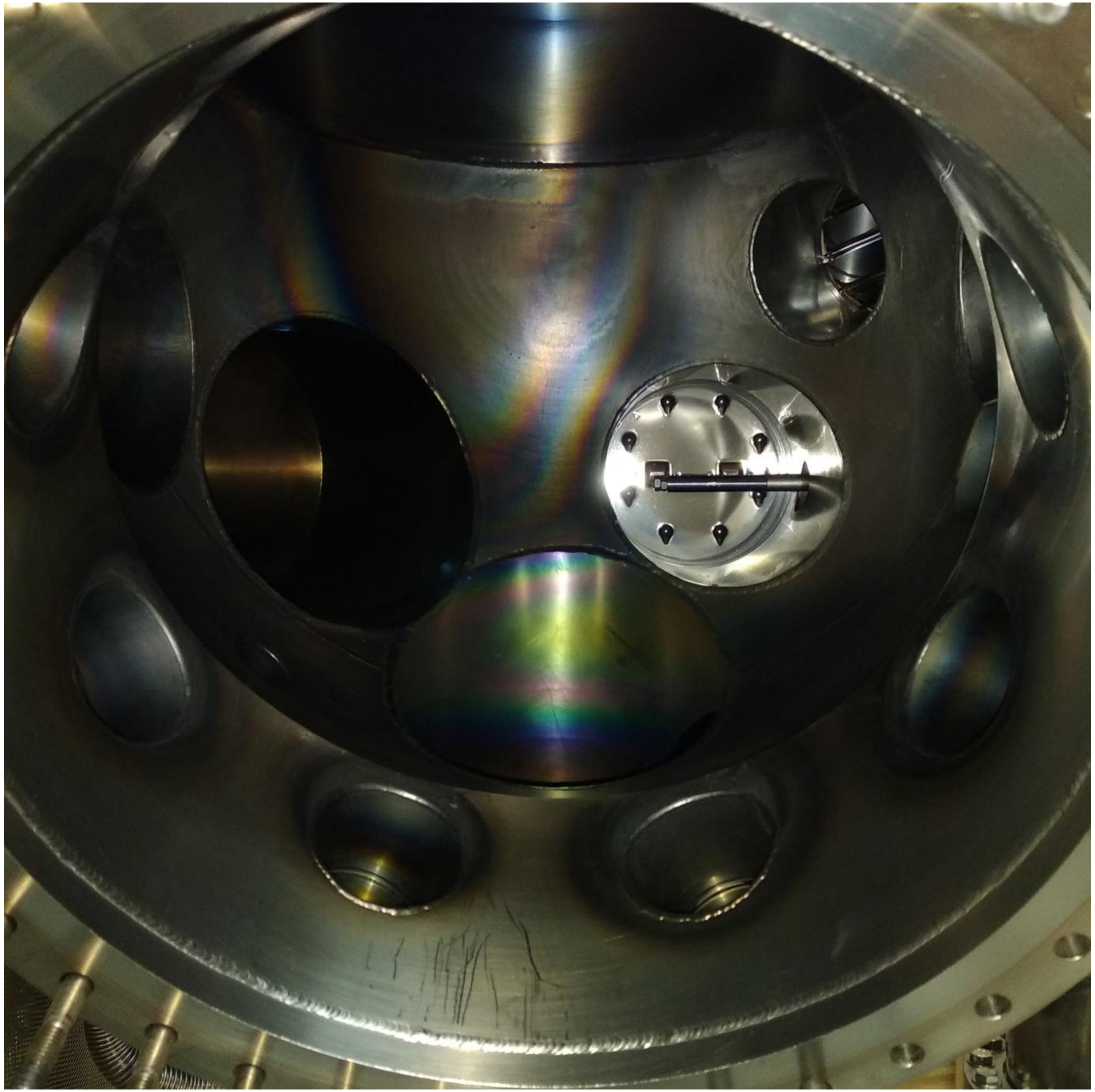
10^{-8} Torr - 10^{-12} Torr

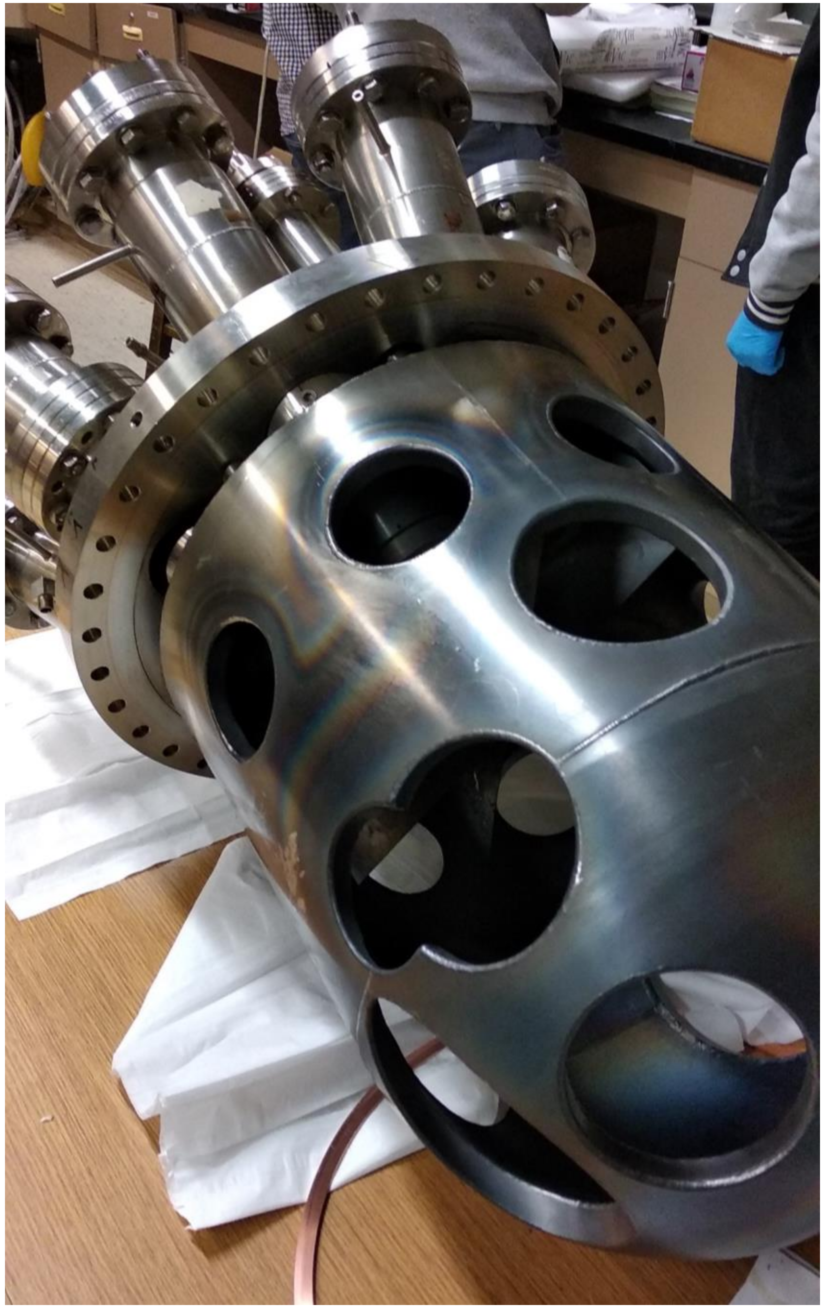


1.10^{-11} Torr
4.10^{5} atom/cm^3

1. Orsay Physics

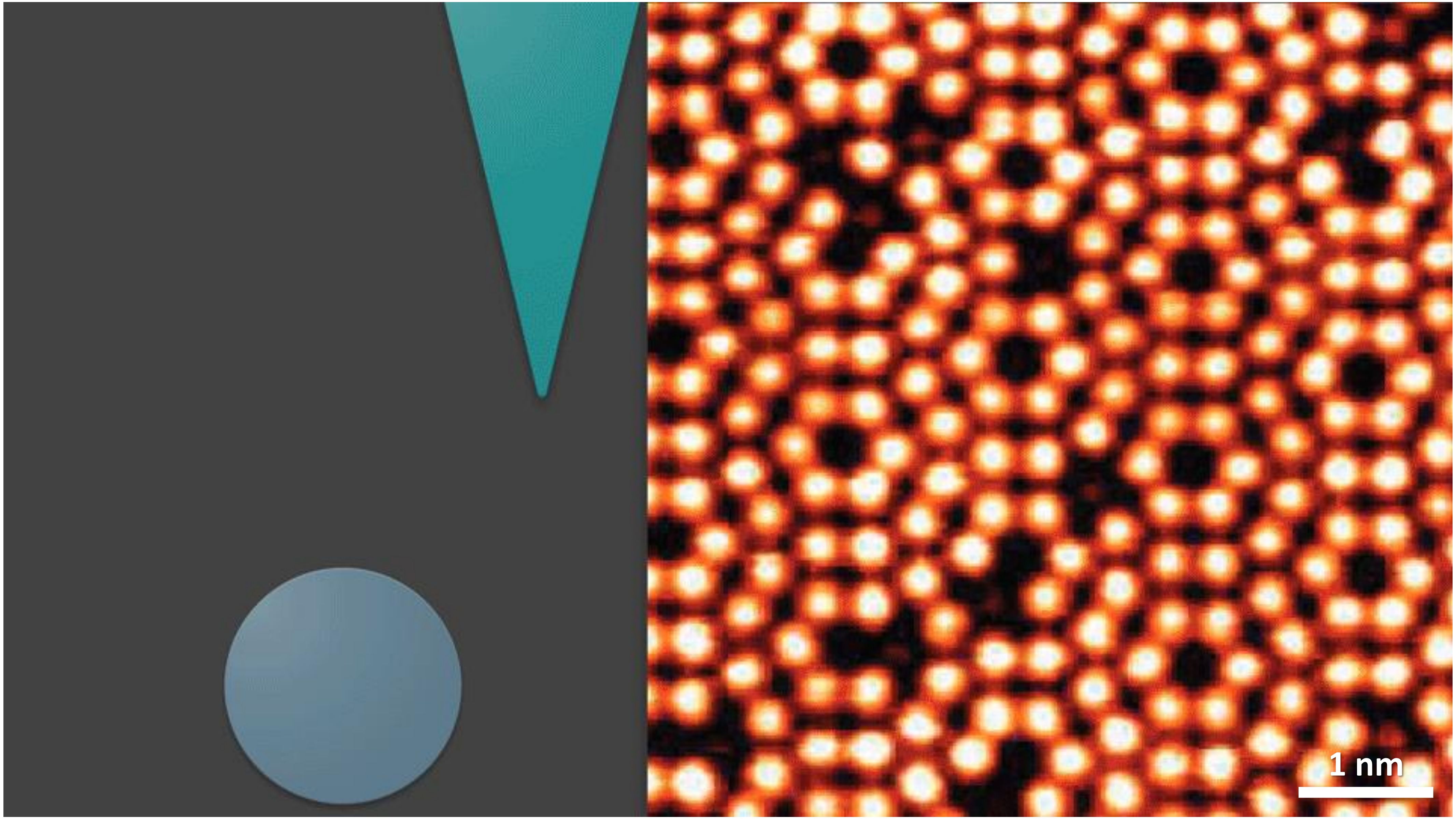
*1 atm = 760 Torr = 101325 ≈ 14.7 PSI





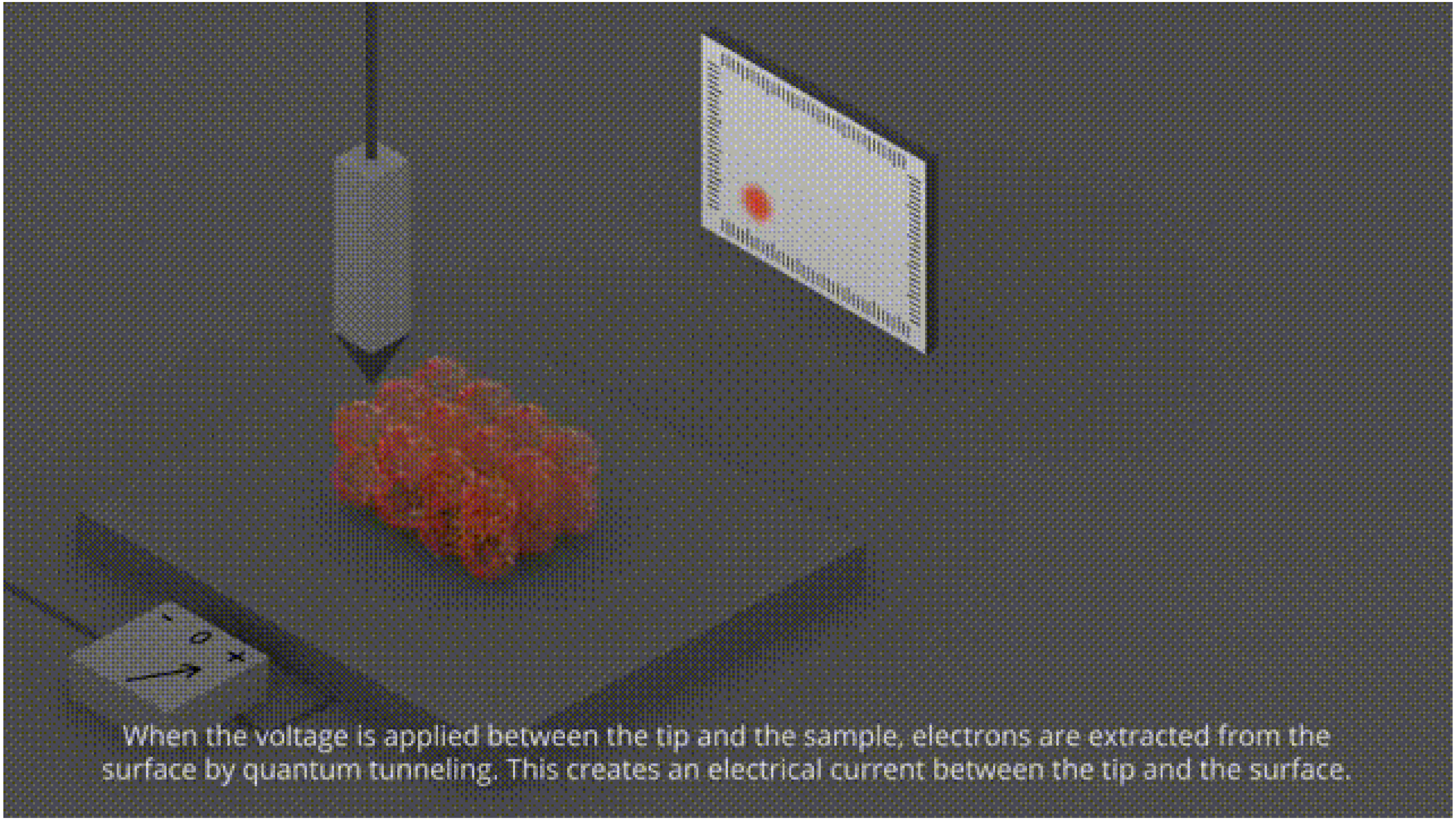
*1 atm = 760 Torr = 101325 ≈ 14.7 PSI

Si Atoms Under an Atomic-Resolution E-Microscope



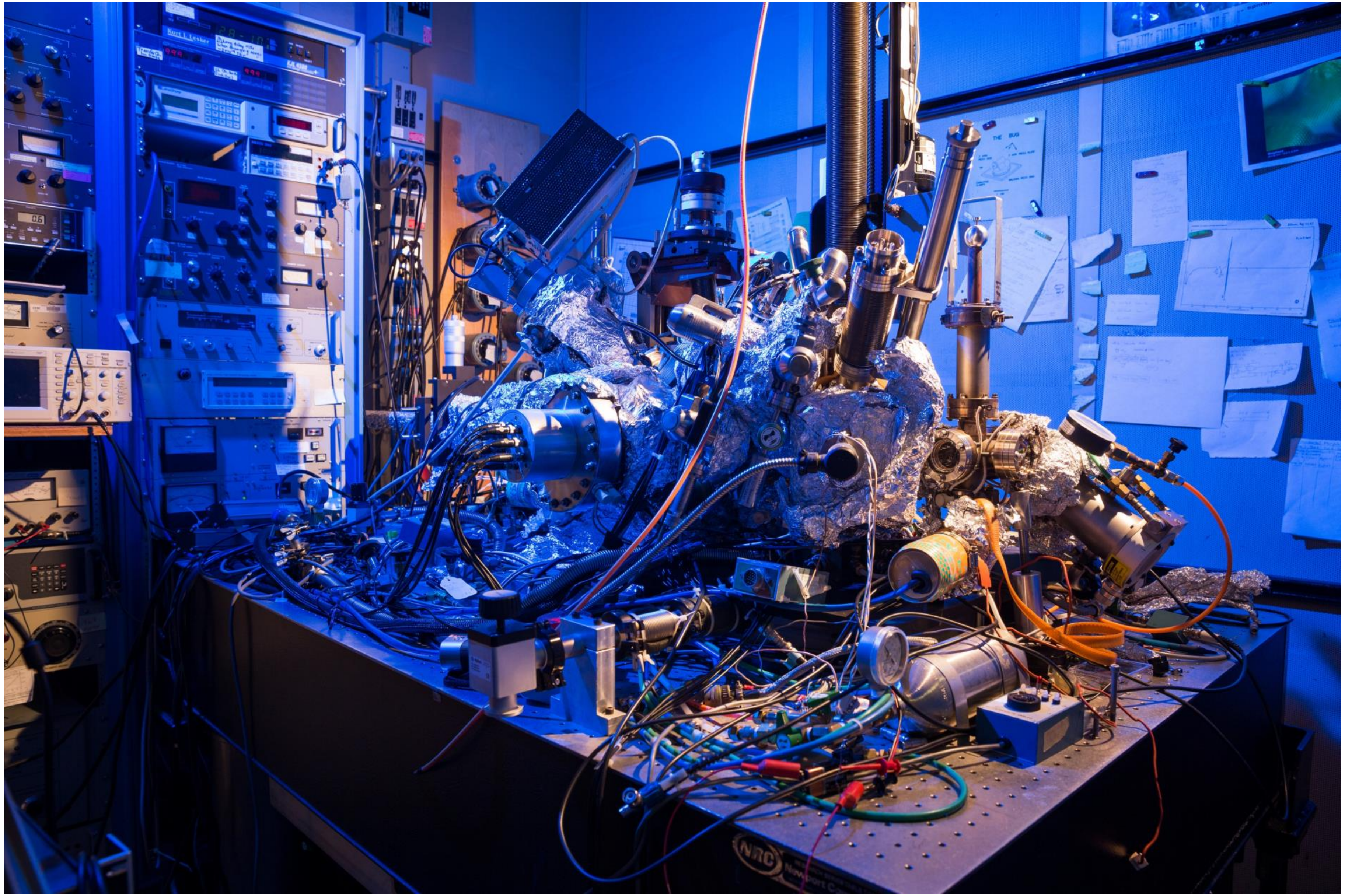
1. Taken from: annex.exploratorium.edu

A Scanning Tunneling Microscope



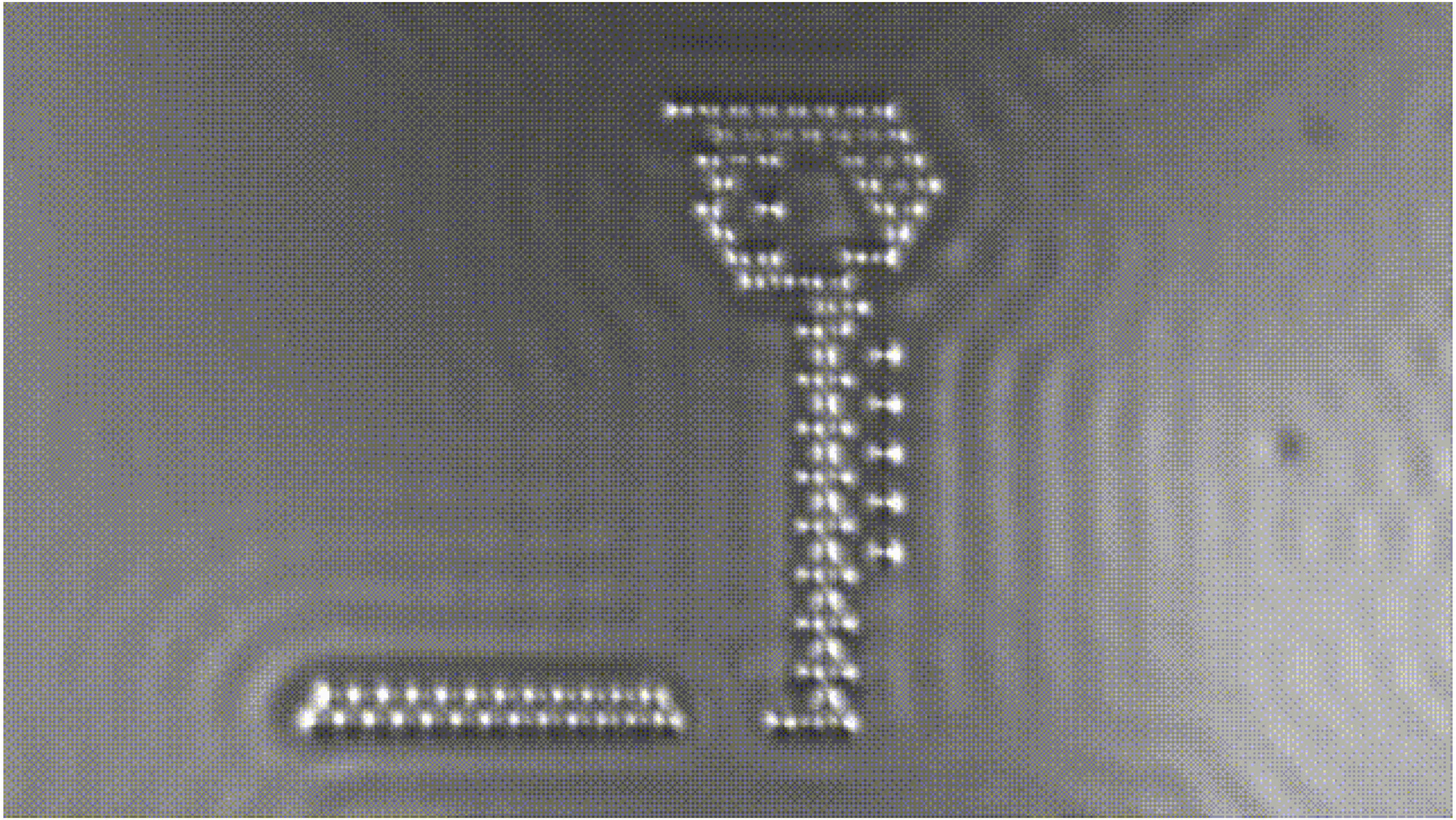
1. Taken from: Bobroff

A Scanning Tunneling Electron Microscope



1. IBM Research

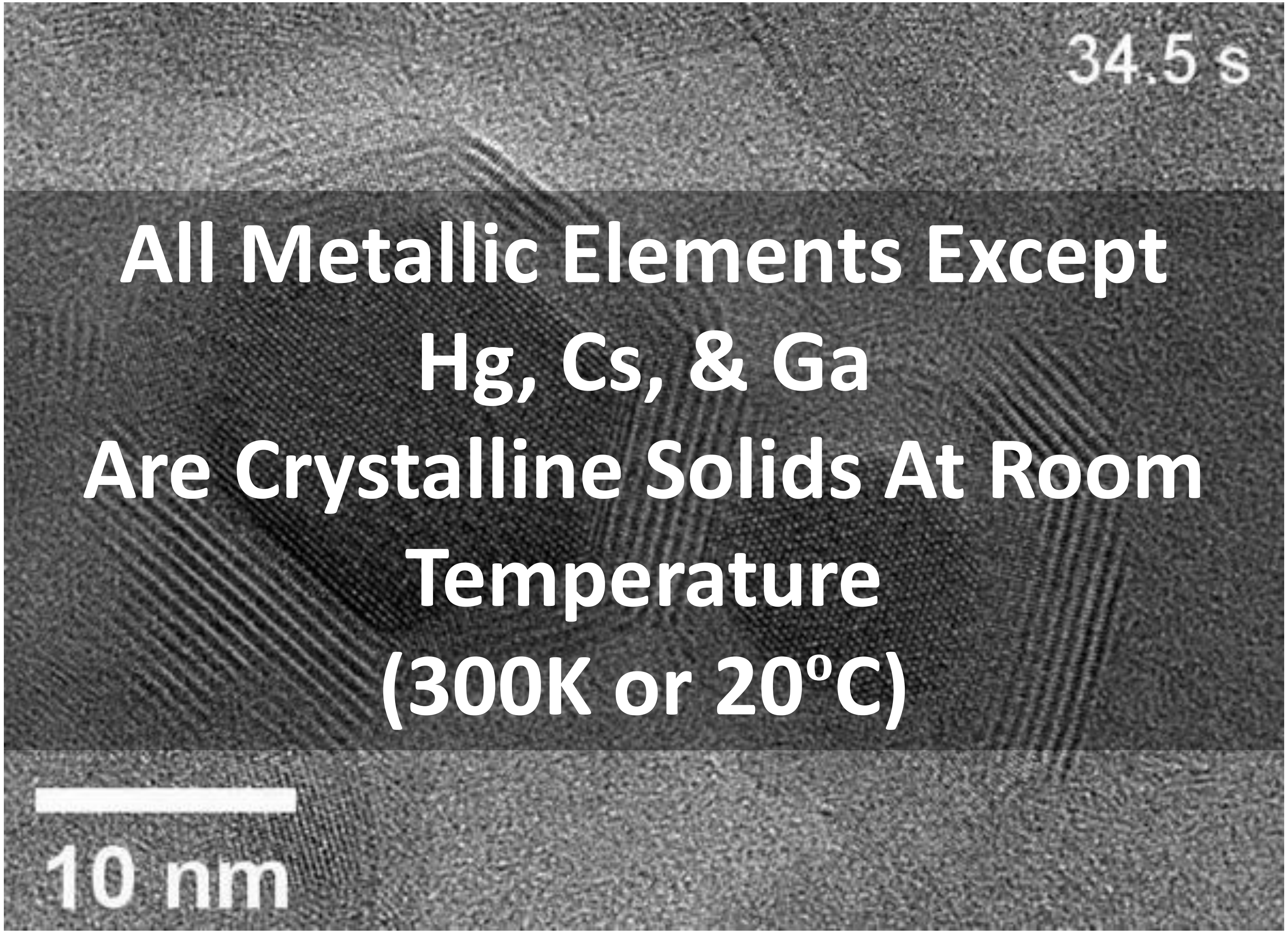
A Boy & His Atom – Via STM*



1. IBM Research

*Scanning Tunneling Microscopy – Carbon Monoxide Atoms

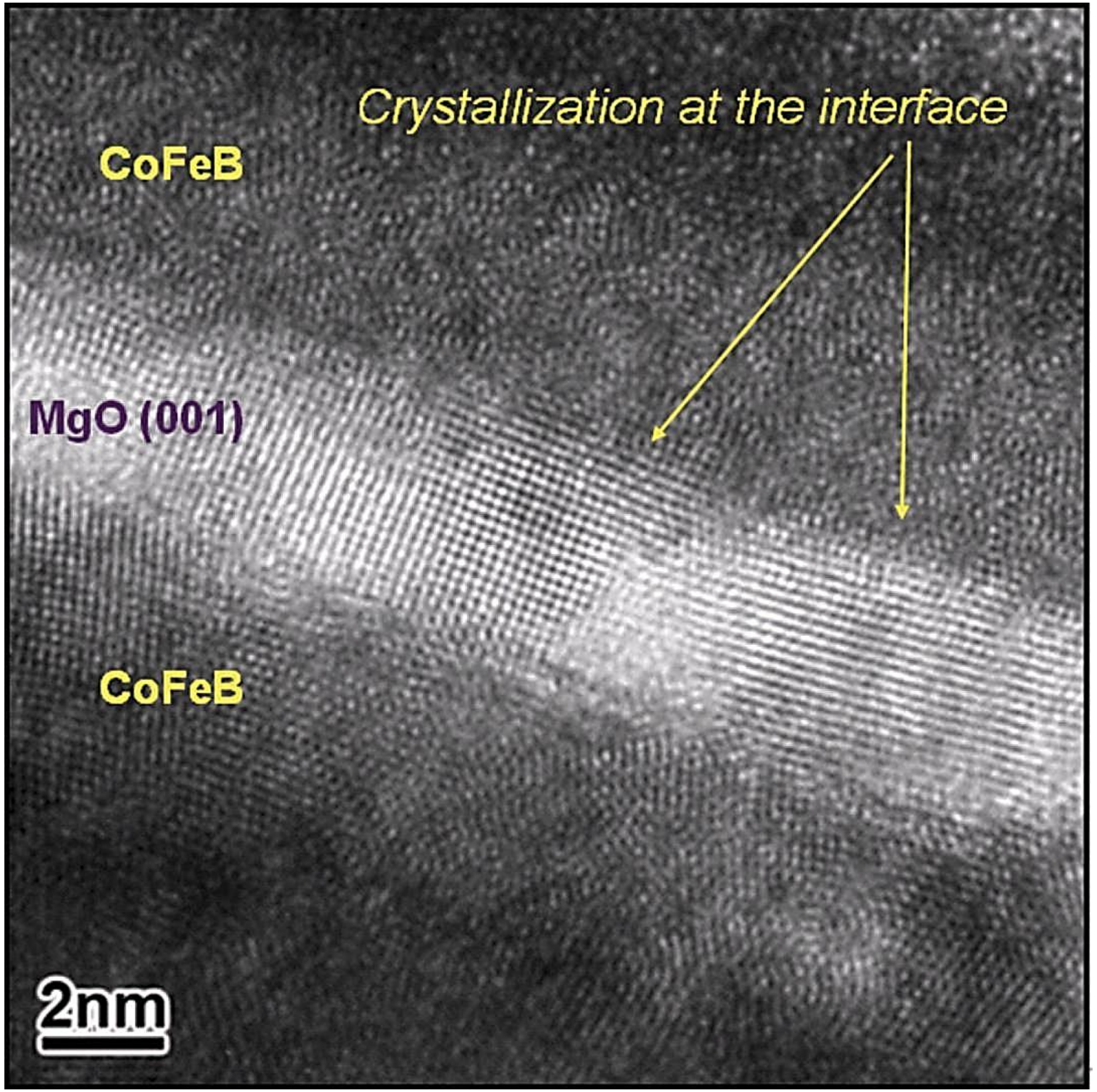
Cd-$CdCl_2$ Core-shell Nanoparticle Growth



1. Zhang, Q. et al., *Nat Comm* (2022)

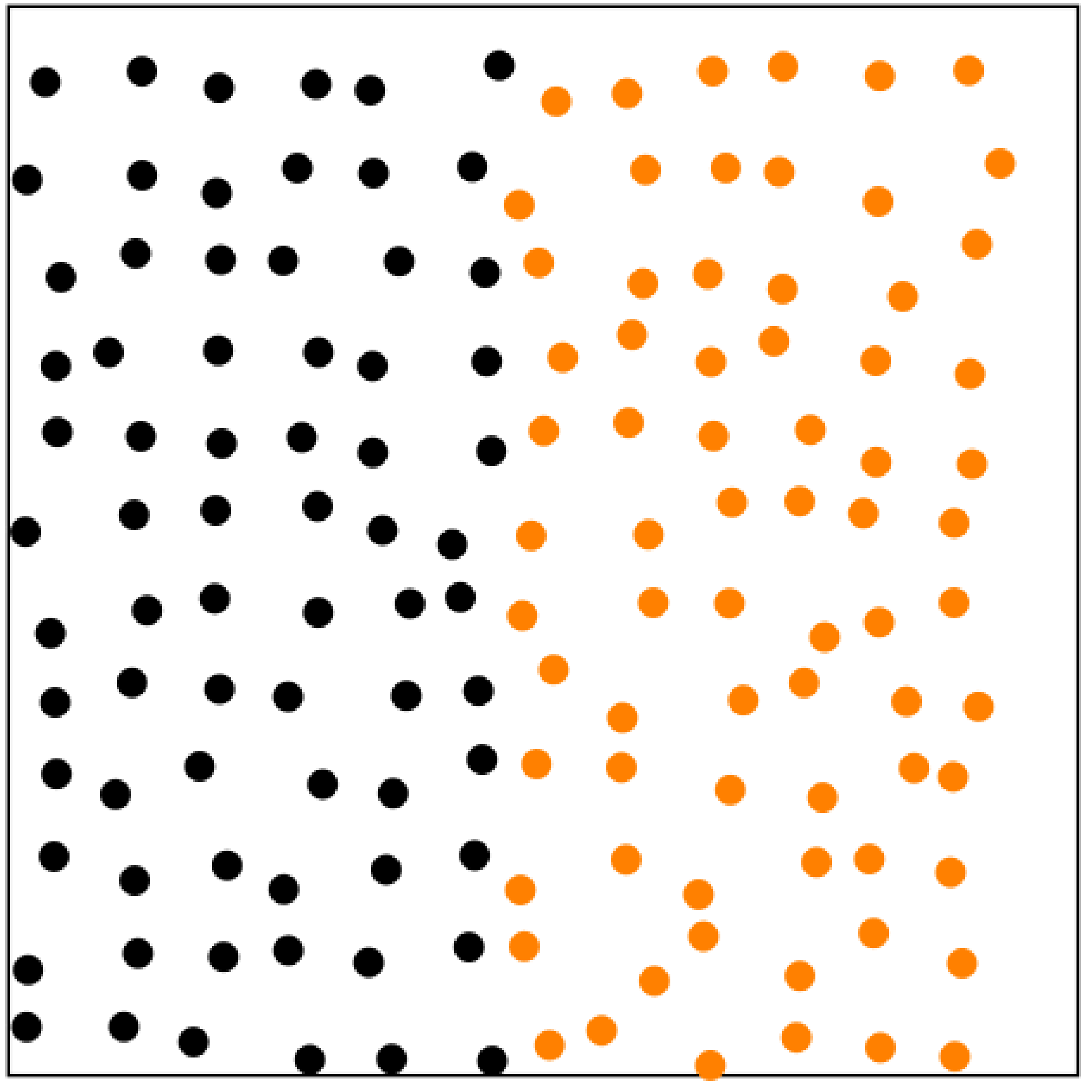
*Liquid Cell-Transmission Electron Microscopy

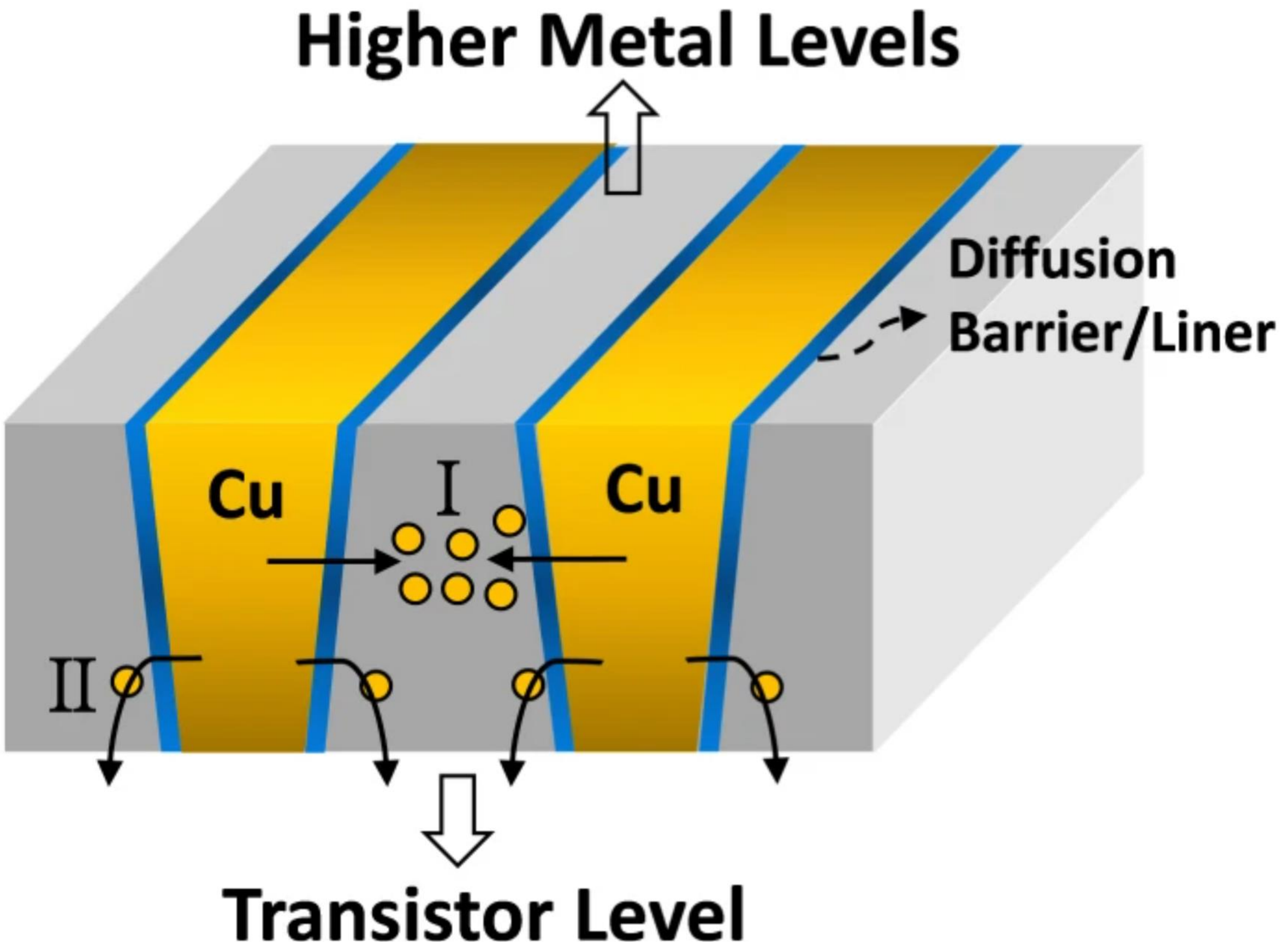
Crystalline vs. Amorphous Layers



1. Park et al., *Journal of Applied Physics* (2006) *

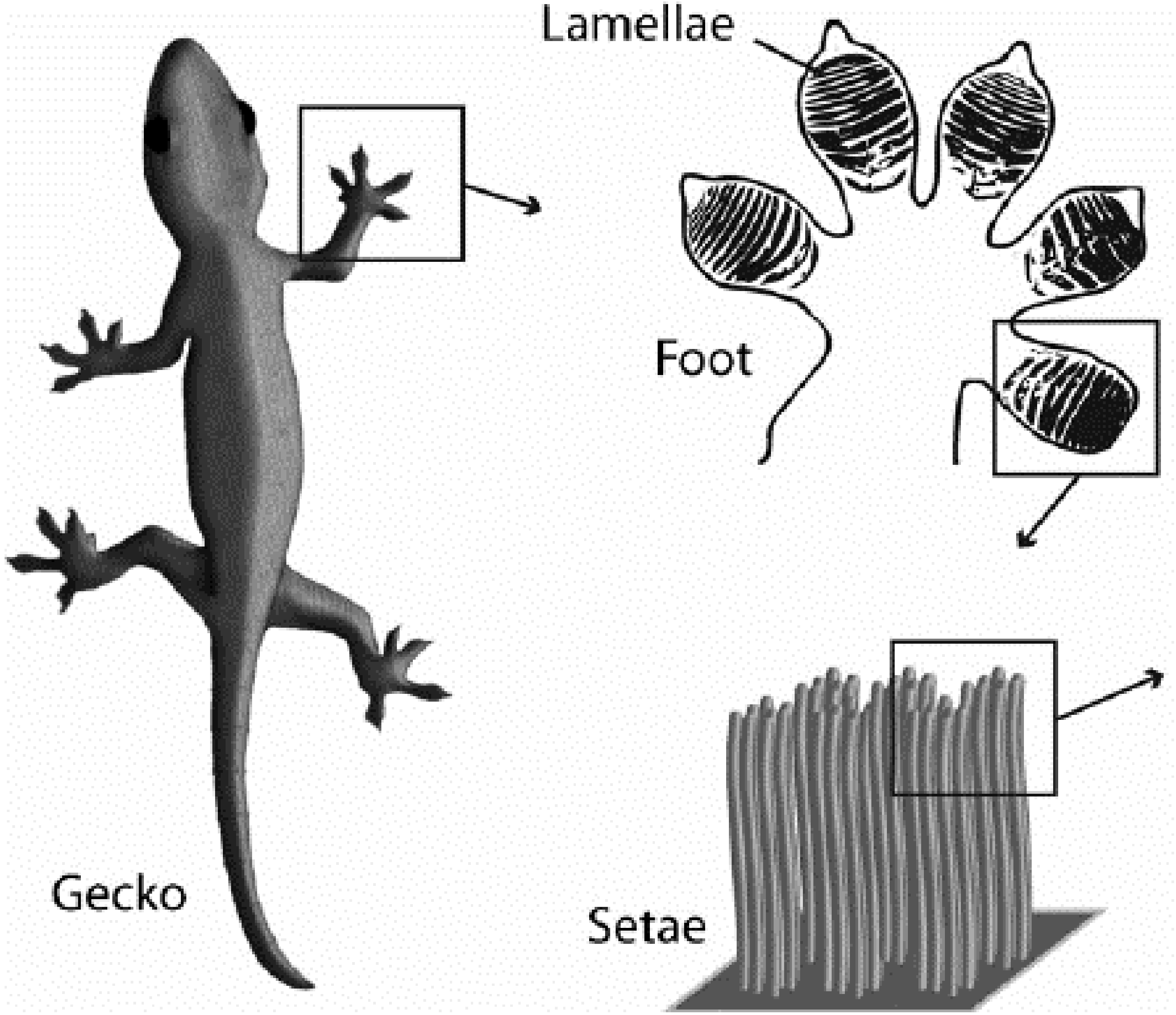
Diffusion vs. Diffusion Barrier

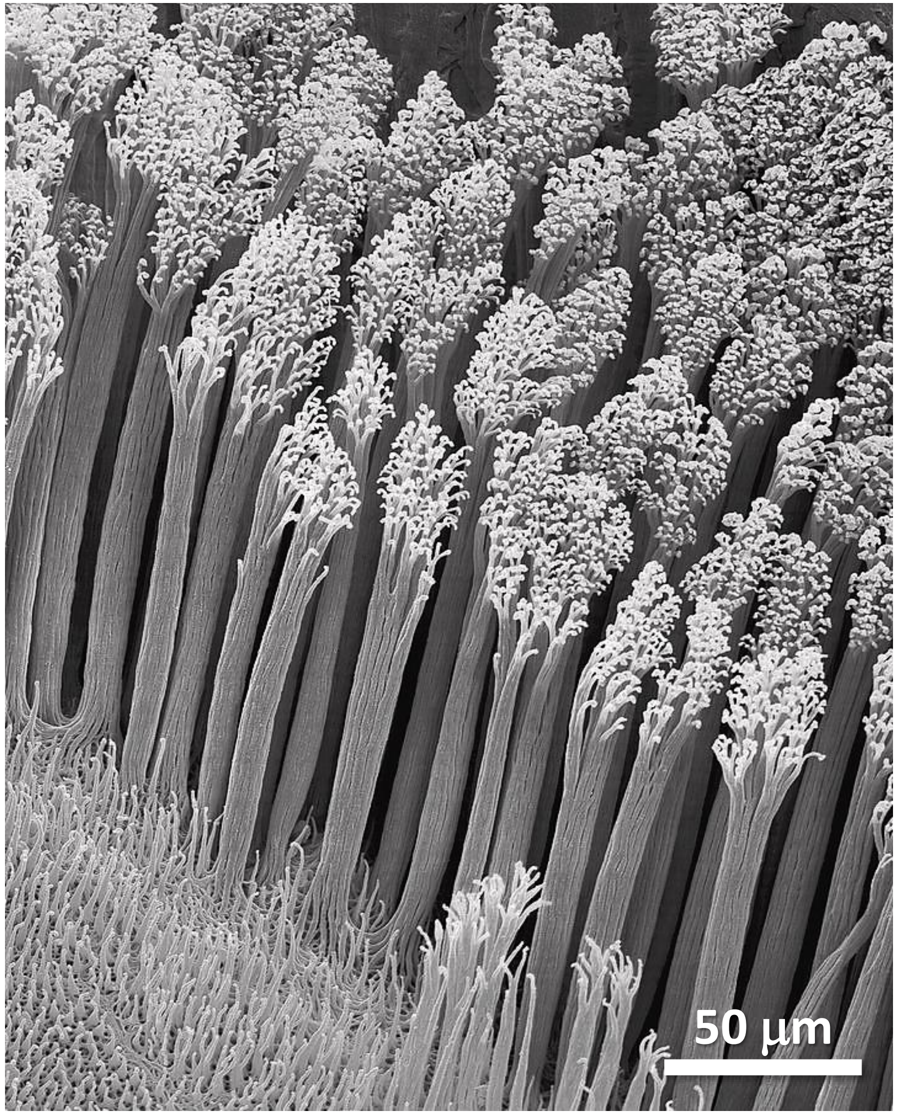




1. Wikimedia Commons
2. Lo et al., *npj 2D Mater Appl* (2017)

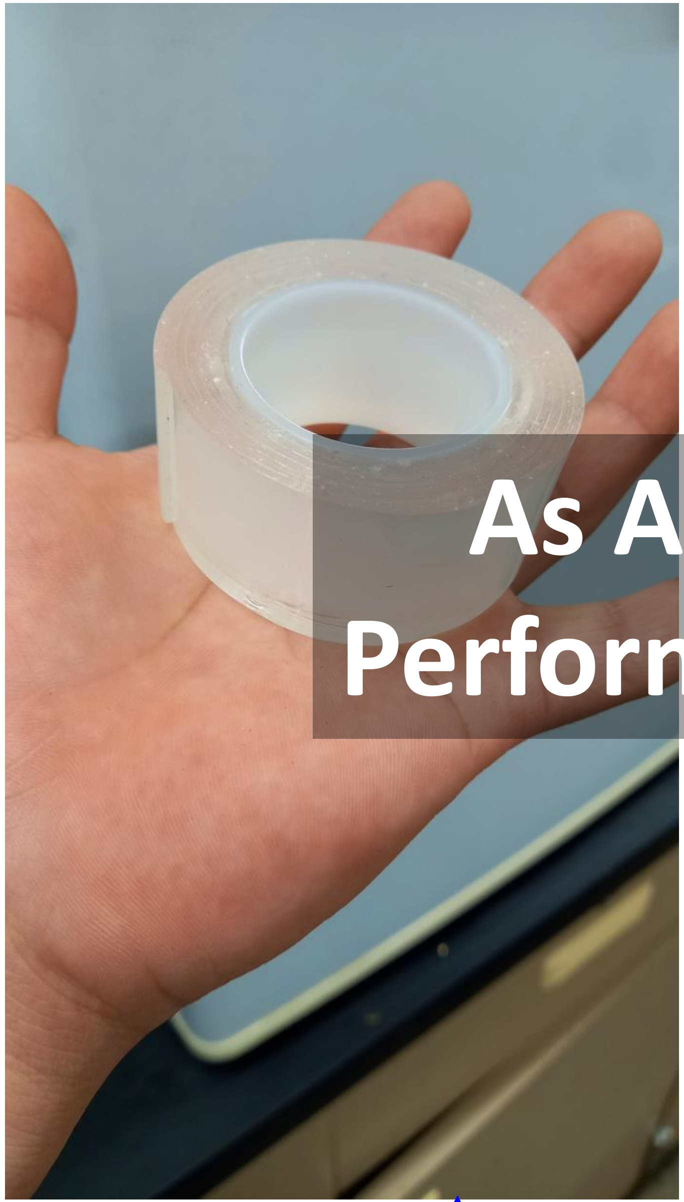
How to Glue Without Using Sticky Glue



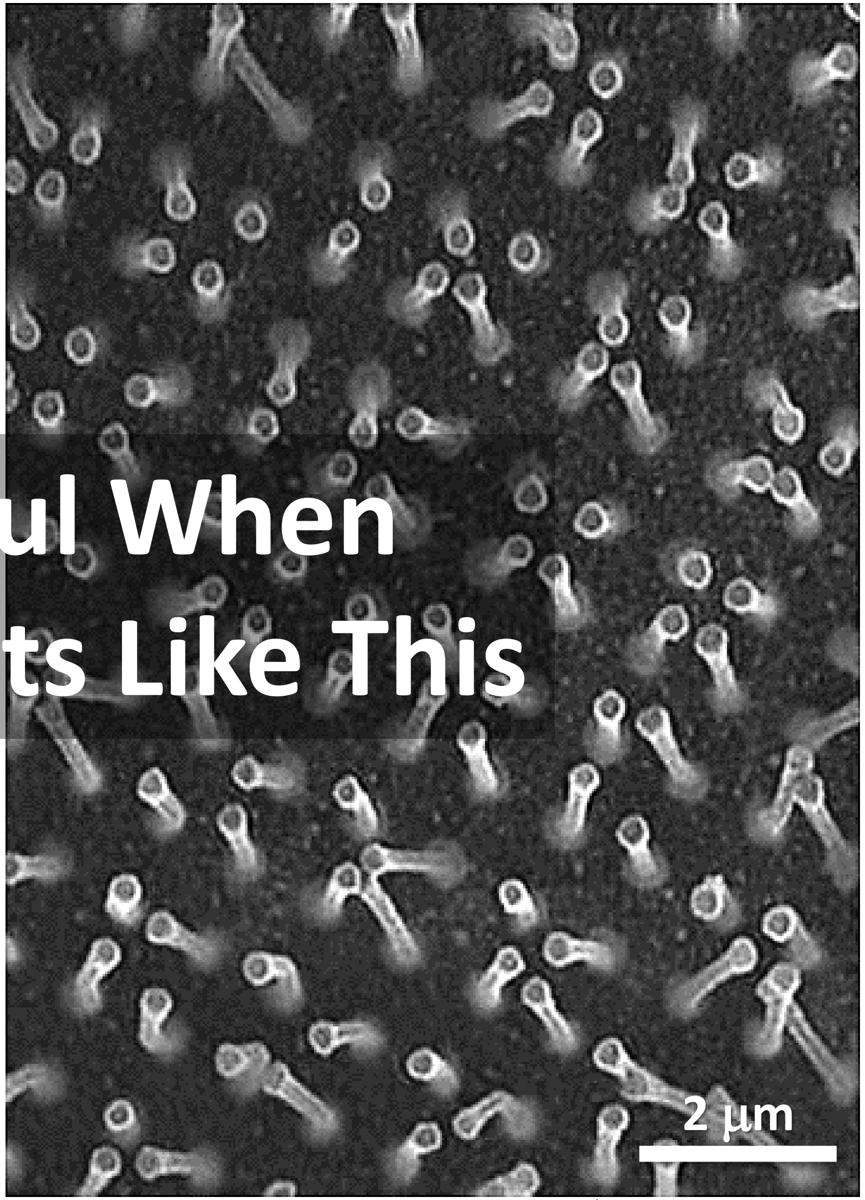


1. Heim et al., *Chem. Soc. Rev.* (2010)
2. Dennis Kunkel Microscopy, *Gecko Foot Hairs* (2018)

Synthetic Setae Used in a "Realistic" Setting



Gecko Tape aka Nano Tape



Polyimide pillars

As Always, Be Careful When Performing Experiments Like This

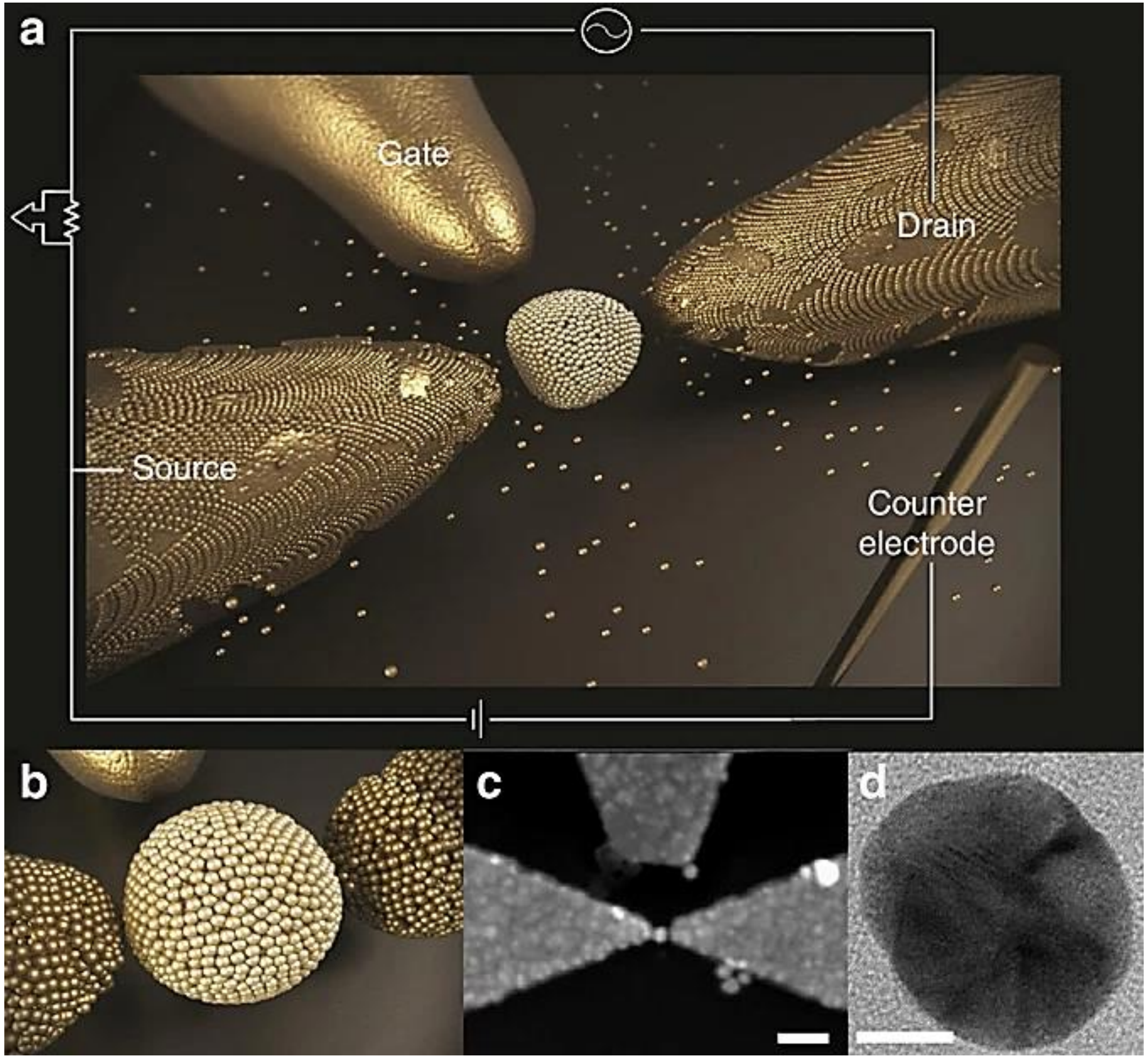
1. Geim et al., *Nat. Mater.* (2003)

Key Ingredients for Thin Films

- Adhesion layer = "**glue**" between 2 different materials.
  - Ex: For every interface of SiO2 and Au, a metal "glue" layer must be added between.
  - Common adhesion metals: Ti, Cr, Al, Ta, Mo, Nb, V.
  - 5-10 nm thickness is used to get good adhesion.
- Diffusion barrier = prevents material or impurities from "**melting**" into nearby layers.
- **Coulomb** blockade = filters or blocks out **charge** type.
- Pauli **spin** blockade = filters or blocks out **spin** orientation.
- **Phonon** blockade = filters or blocks out excitation/ **lattice vibration**.
- Bonus 1: seed layer = help with crystalline growth.
- Bonus 2: thermal annealing = reorganizing atoms using heat.

1. Mandelbrot, *The Fractal Geometry of Nature* (1977)

Nanoparticle-Based Single-Electron Transistor



1. (Bitton et al., Nat. Commun., 2017)

Summary & Brief Announcement

- Nanofabrication uses a lot of material science ideas for obtaining working nanoscale thin films.
- There is a lot of inspection, especially at atomic resolution.
- Nature can be used as inspiration for fabrication approaches.
  - We saw an example of adhesion from Gecko feet.
- Precision control of atoms typically involves vacuum environments.
- Next lecture will cover a range of quantum devices in pictures.