ESH Benign Processes for he Integration of Quantum Dots (QDs)

PIs:

- **Karen K. Gleason, Department of Chemical Engineering, MIT**

Graduate Students:

- **Chia-Hua Lee: PhD Candidate, Department of Material Science and Engineering, MIT**
- **Wyatt Tenhaeff, Ph.D Candidate, Department of Chemical Engineering, MIT (NSF Fellow)**

Motivation

- ***Physical limitations of silicon-based devices inhibit continued innovation in IT, communications, and electronics.***
- ***Conventional micro-fabrication techniques are reaching the limits of their capabilities, while fabrication costs and complexity continue to grow.***
- ***Breakthroughs for building electronics at the nanoscale requires new materials and new manufacturing concepts.***
- ***Achieving semiconducting behavior through nanoparticles***
    - eliminates the need high quality Si substrates
    - avoids energy intensive fabrication of high purity silicon wafers.
    - allows for inexpensive, lightweight flexible substrates compatible with roll-to-roll processing.

Quantum Dots (QDs)

• Nanocrystals of a semiconductor compound

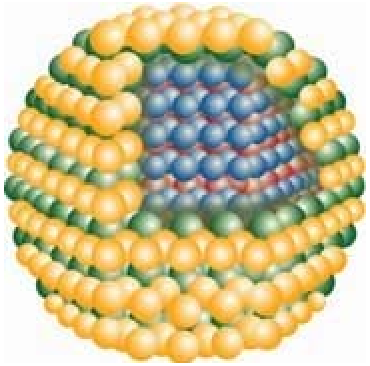
• Quantum dot size is not limited by lithography

• Diameters in the 1 to 10 nm length scale

• Electrons are quantum confined in 3D

• Enable new devices and markets such as quantum information processing:

- spin-transistors,
- nanomagnets
- quantum computing
- electron spin-based memory.



The Quantum Dot

QDs in future electronics

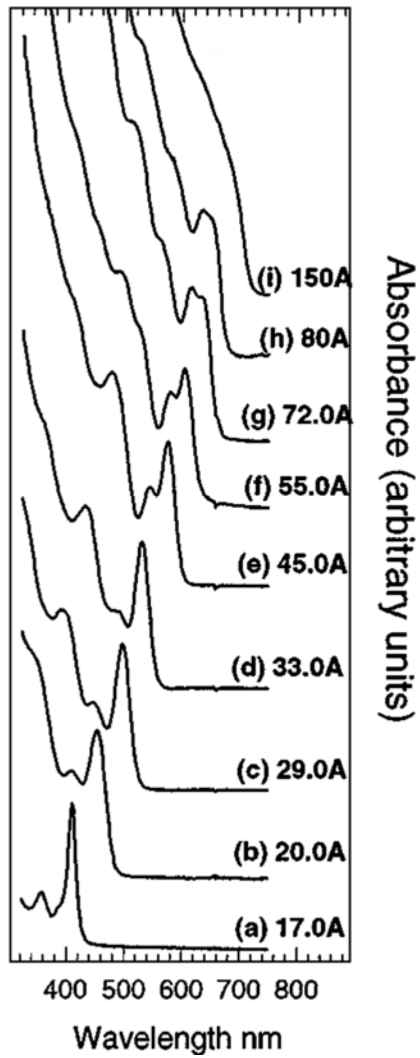
- Linear and nonlinear quantum transport phenomena
- Transitions among quantum confined states
- Control over the behavior of a single or a few electrons as well as that of a single or a few photons
- Switching device structure with the potential for much higher speeds, lower power consumption and higher packing densities than CMOS transistors (Alignment of Epitaxial Quantum Dots: Springer, 2007)
  - resonant tunneling transistors (RTDs
  - single-electron transistors (SETs)
  - spin transistors
- Next generation memory devices (M. Geller et. At: Appl. Phys. Lett. 92, 092108, 2008)
  - storing one terabyte (1000 gigabytes) of data per square inch
  - write information to this memory in just 6 nanoseconds

QDs Optoelectronics

- Frequency of light emission depends on QD size
- Narrow emission band
- High quantum yields: ≤85 %
- Broad excitation spectra
- Chemical/photo stability

Applications

•tunable IR-UV lasers and LEDs
•display luminophores
•optical electro-modulation,
•optical limiting
•DNA site markers
•efficient sensors of explosives and toxic materials.

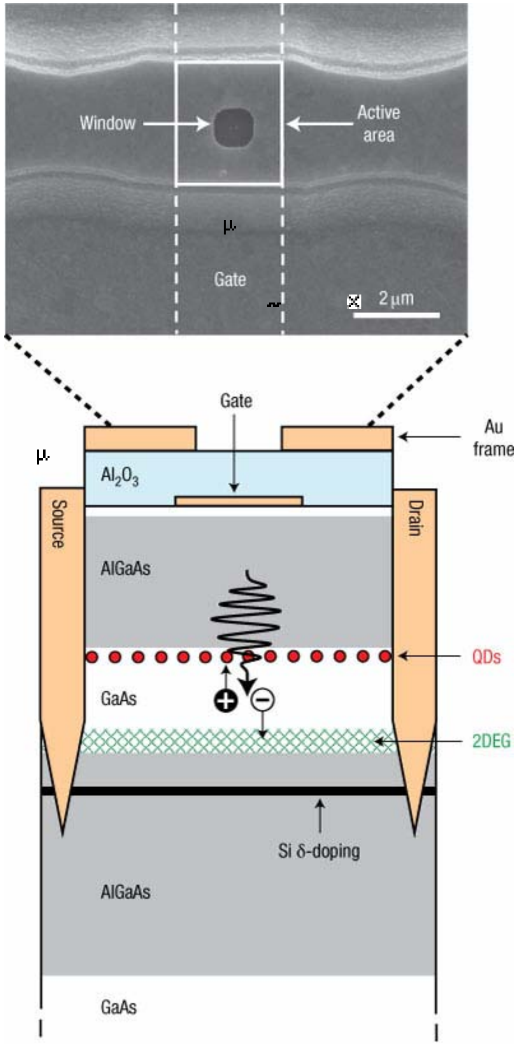


C. B. Murray, C. R. Kagan, and M. G. Bawendi, Annu. Rev. Mater. Sci., **2000**. 30:545–610

Detecting a single photon

"Detectors with the capability to directly measure the photon number of a pulse of light enable linear optics quantum computing, affect the security of quantum communications, and can be used to characterize, and herald non-classical states of light."

E. J. Gansen et. al, Nature Photonics 1***, 585 - 588 (2007)***



ESH

Nanoparticles which are not confined to a surface film are free to transport by diffusion and convection.

The size (typically <10 nm) limits the ability to be filtered or separated efficiently with current technology.

Early consideration the ESH life cycle in the design and development of a new material reduces the total cost of introducing and using a technology compared to revisions made closer to high volume manufacturing.

Developing technology separately from ESH impact and evaluating ESH impact without the capability to affect a technology is inefficient since the two are intimately connected.

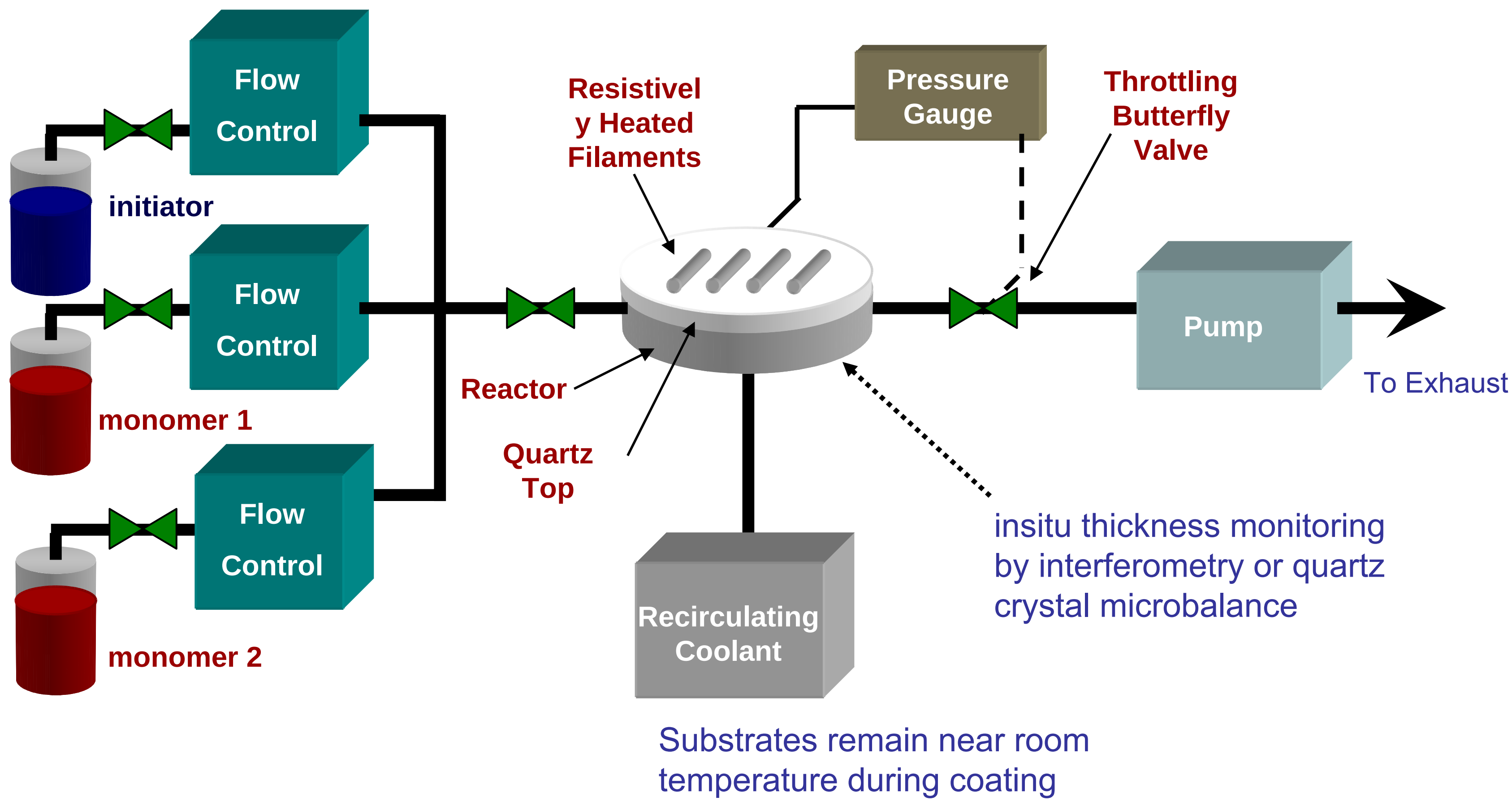
Scope

Processes for tethering QDs to surfaces with precise spatial control is required in order to exploit the novel electronic properties of these nanoparticles

ESH benign fabrication methods are desired which are compatible with wafer processing and also with flexible substrates. The use of flexible substrates is required for roll-to-roll processing, which is a high-volume, low-cost manufacturing method.

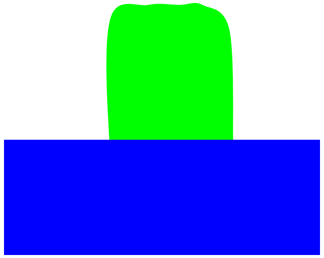
White paper for 2009 with
Dr. Anthony Muscat - ESH benign QD synthesis
Dr. Mark Riley – development and implementation of ESH assesment tools

Initiated CVD of Functionalizable Polymers

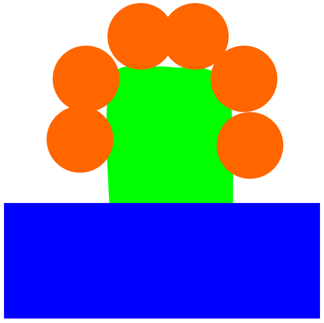


Functional groups in iCVD films can be used to covalently tether nanoparticles

Fabrication Strategy

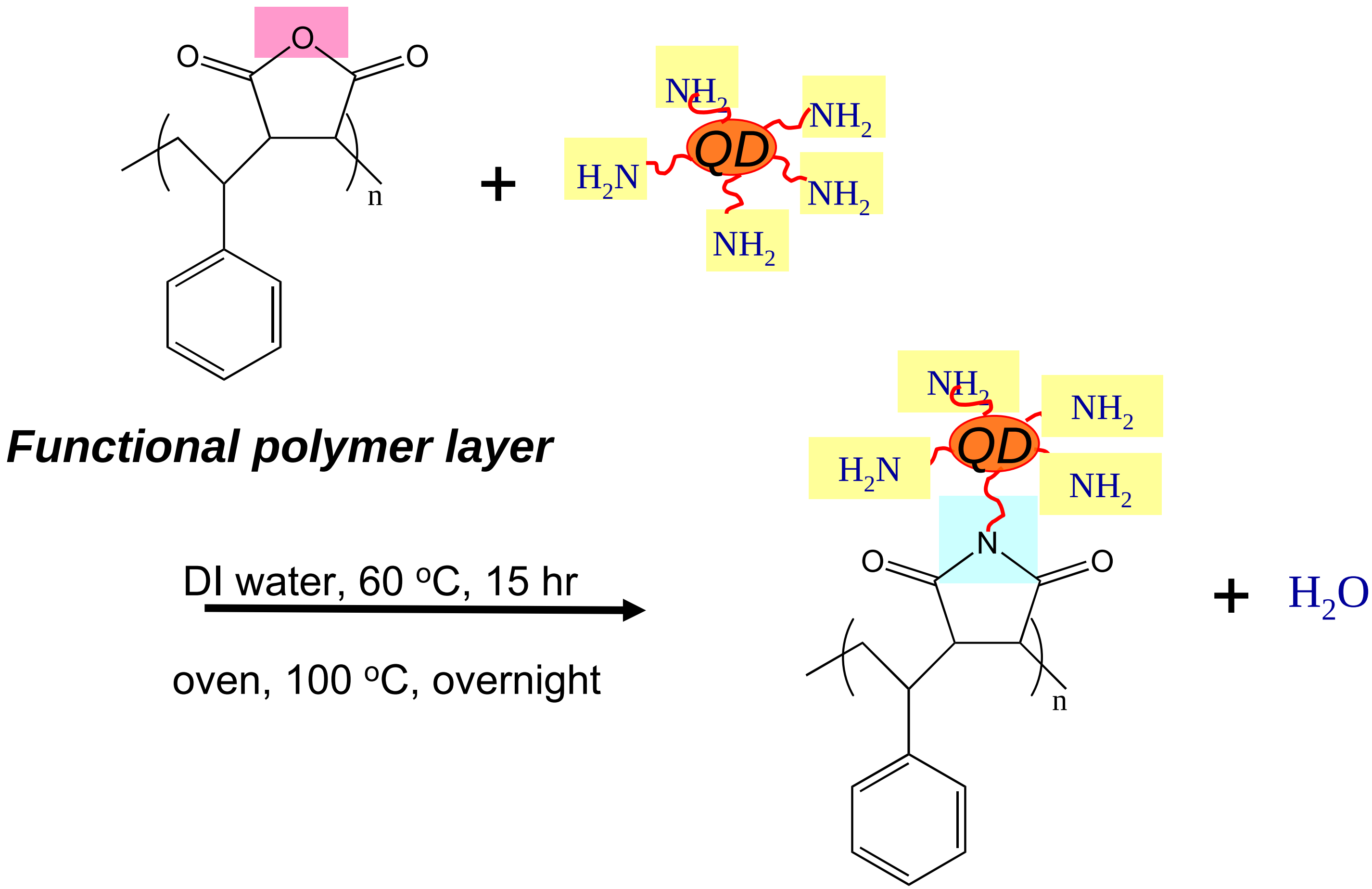


Sub-50 nm patterns of a functional polymer on Si wafer or flexible substrate (avoid use of conventional lithography)

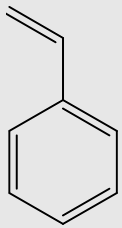


Covalent tethering of QDs

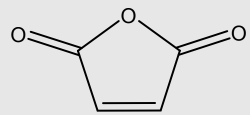
Tethering Chemistry



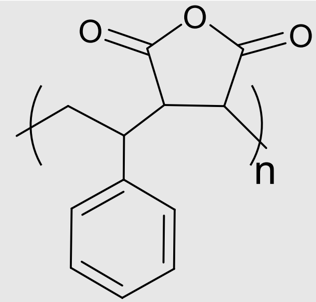
iCVD functional polymer layer



Styrene

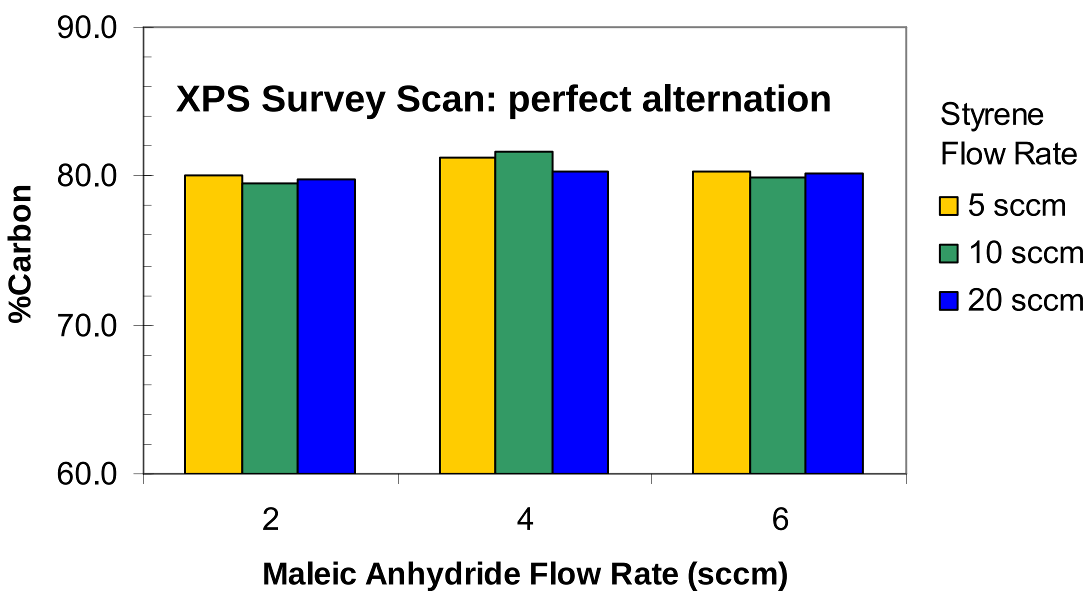


Maleic Anhydride



Poly(styrene-alt-maleic anhydride) (PSMa)

12 C: 3 O per unit (80% carbon)



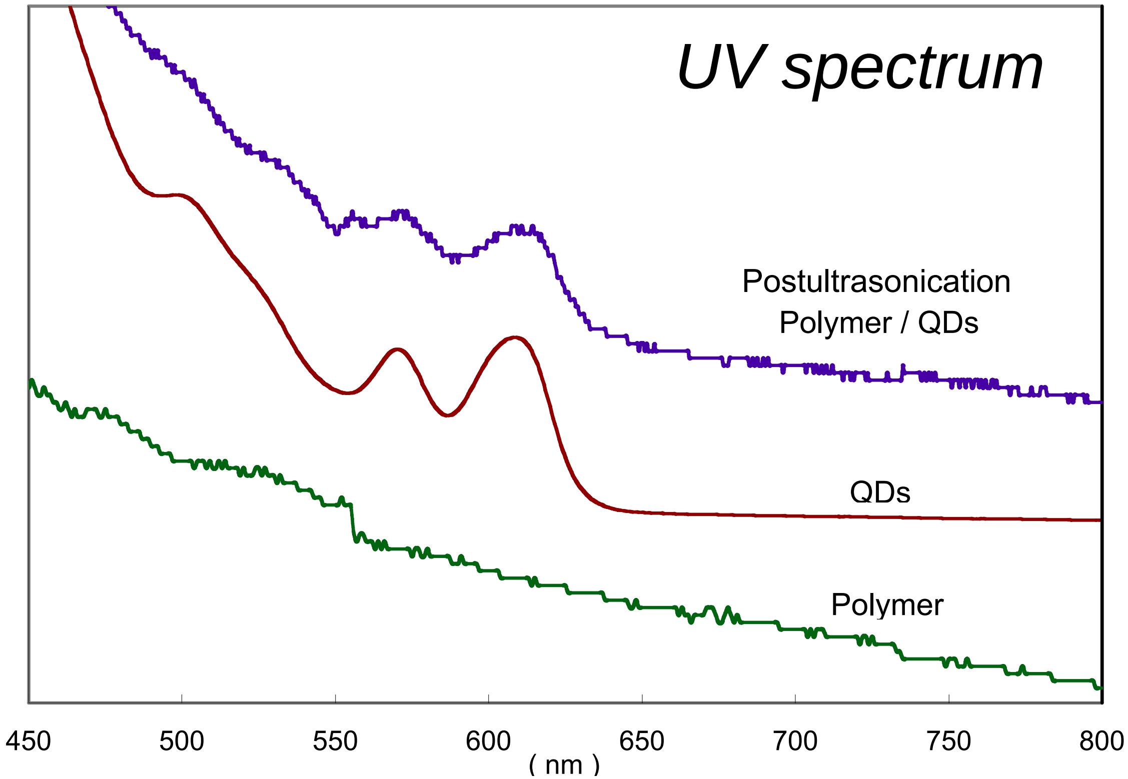
ESH:

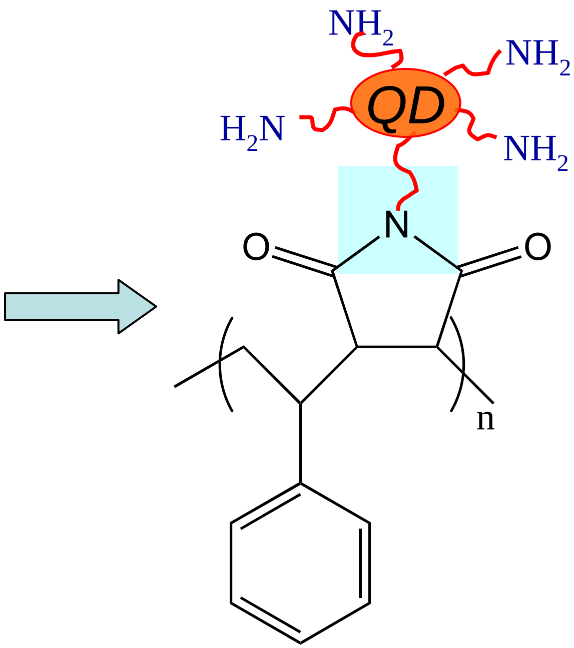
Bulk PSMA is widely used for products such as cooking utensils and coatings on ingestible drugs

W.E. Tenhaeff and K.K. Gleason Langmuir 23, 6624 (2007).

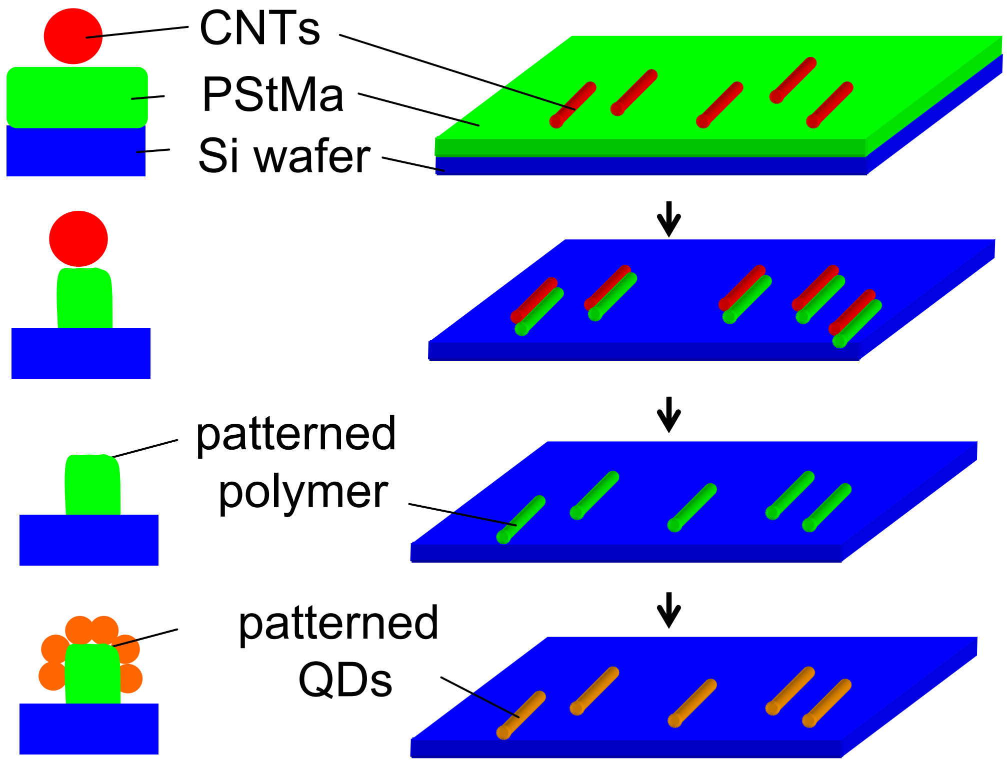
QD Attachment to iCVD PSMa

QD Size ~ 5 nm





CNT masks for patterning iCVD PSMa



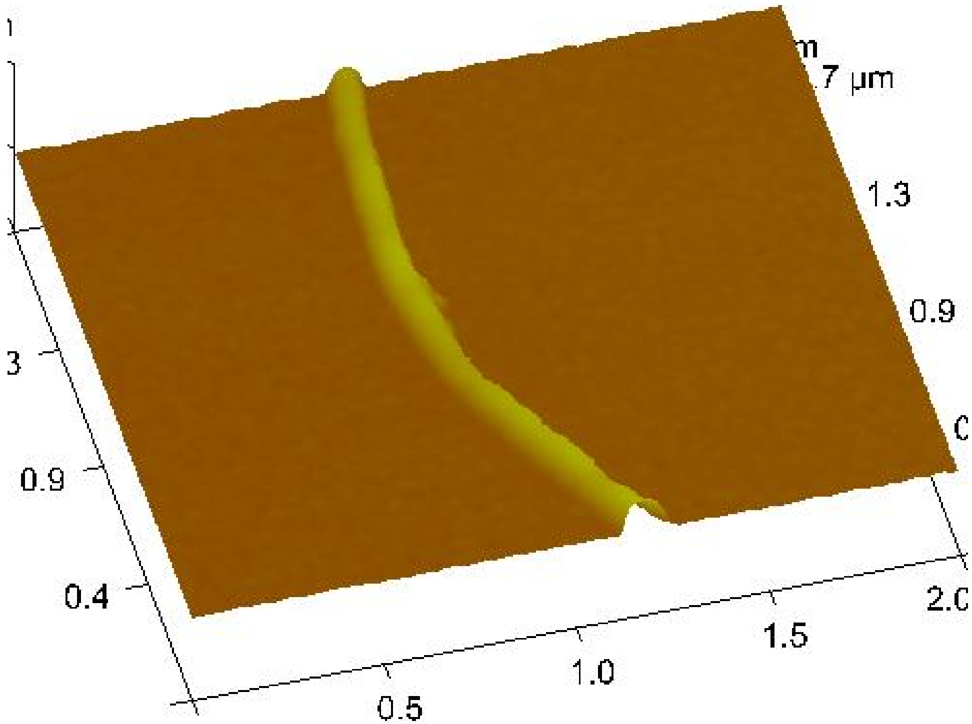
Spin casting of CNT masks on the iCVD PSMa polymer thin film

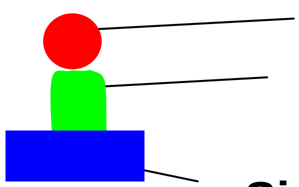
Oxygen plasma etching

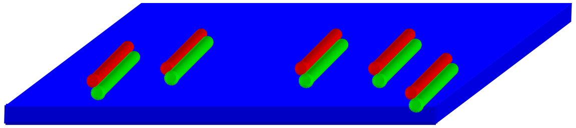
Removal of CNT masks

Quantum dots tethered to surface

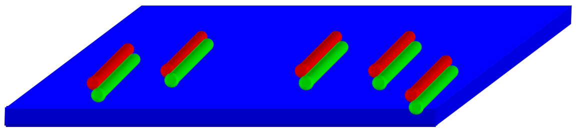
AFM Height Image





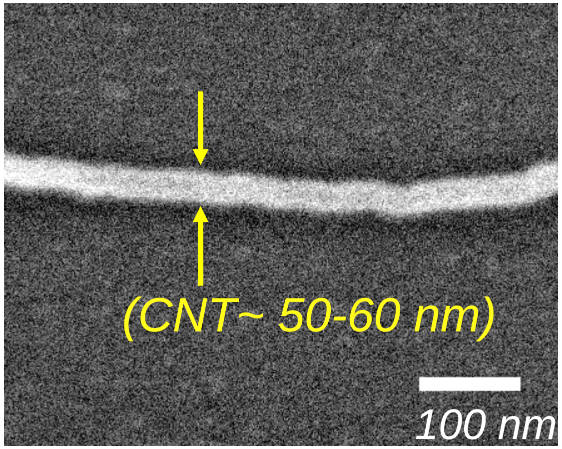


Carbon Nanotube (CNT) masking results

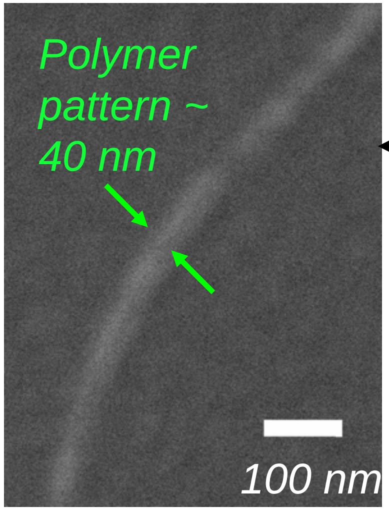


After spin-casting of CNTs

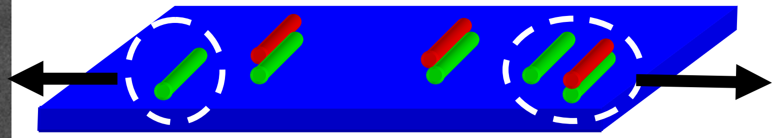
(1)



(2)



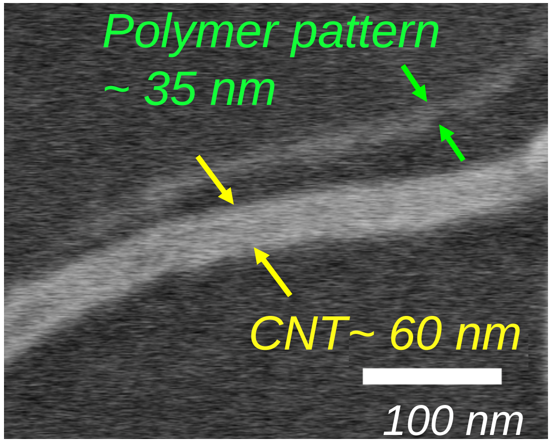
(Etching time: 35 s)



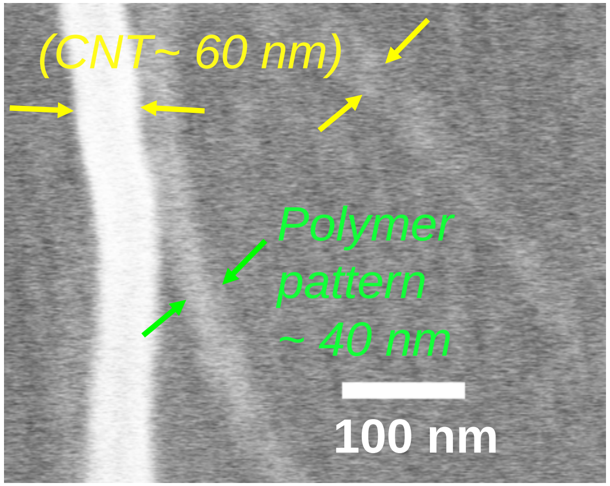
After etching and partial removal of the CNTs

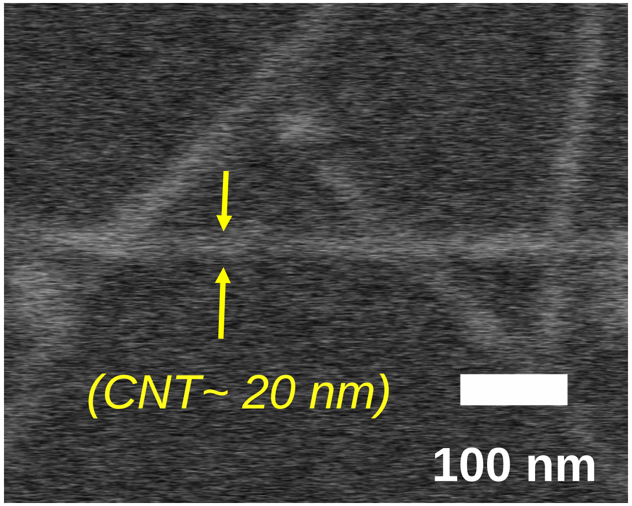
Pattern in polymer is smaller than CNT diameter

(3)



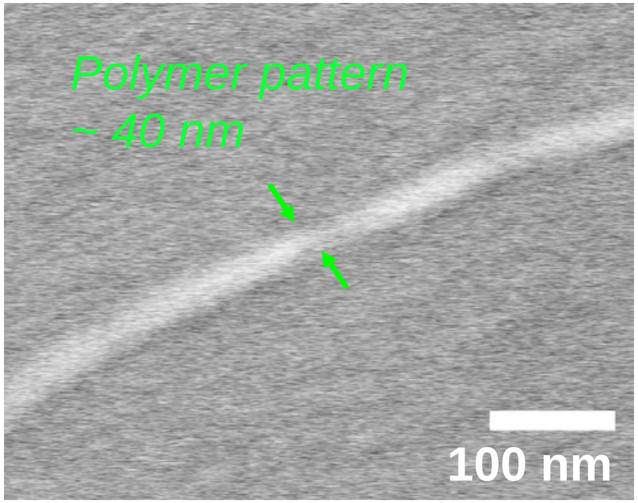
(Etching time: 40 s)



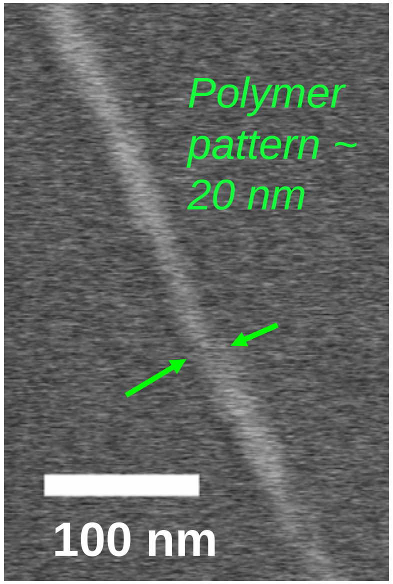


(Etching time: 30 s)

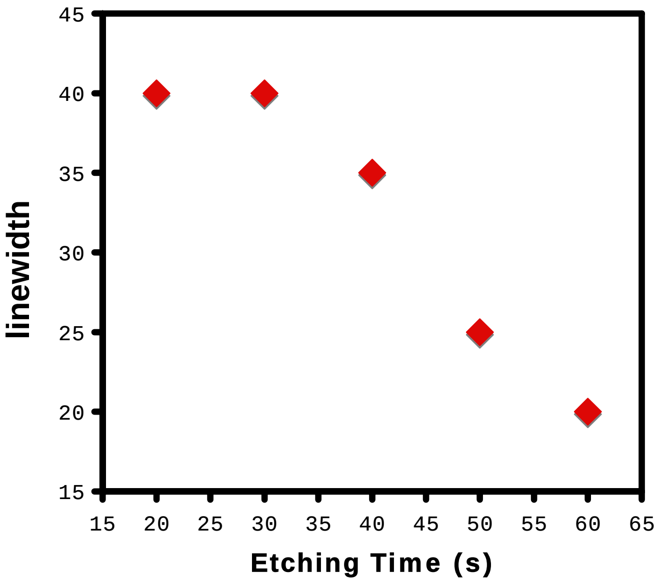
Pattern sizes depend on the CNT diameters and the etching time



(Etching time: 40 s)

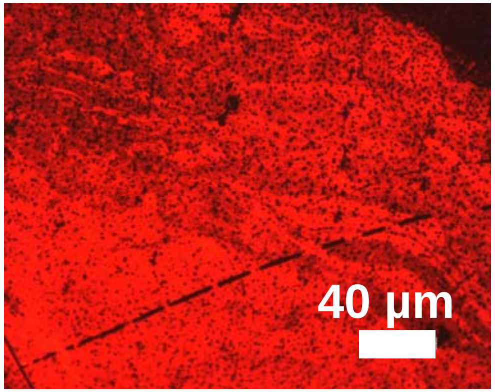


(Etching time: 60 s)

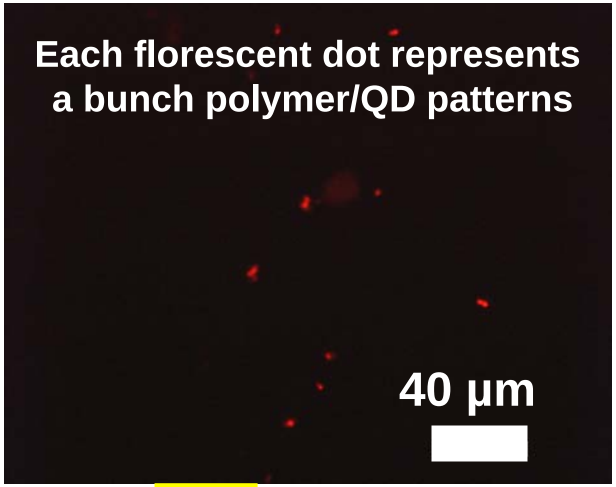


Fluorescence Microscope

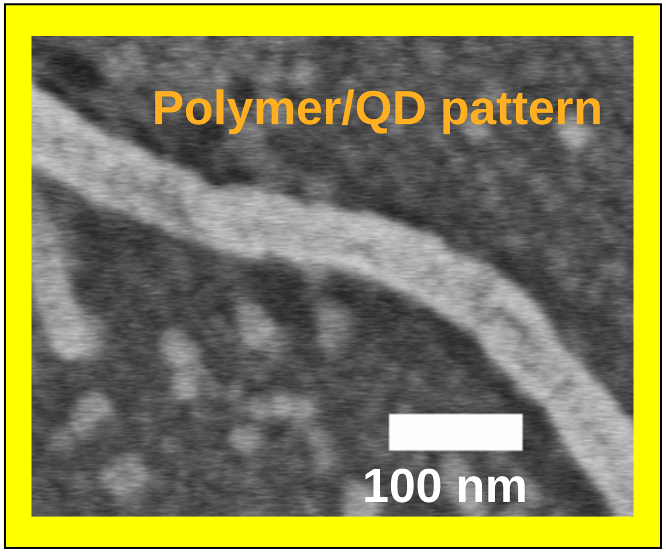
P(StMa) ICVD polymer film



P(StMa) /QD blanket film

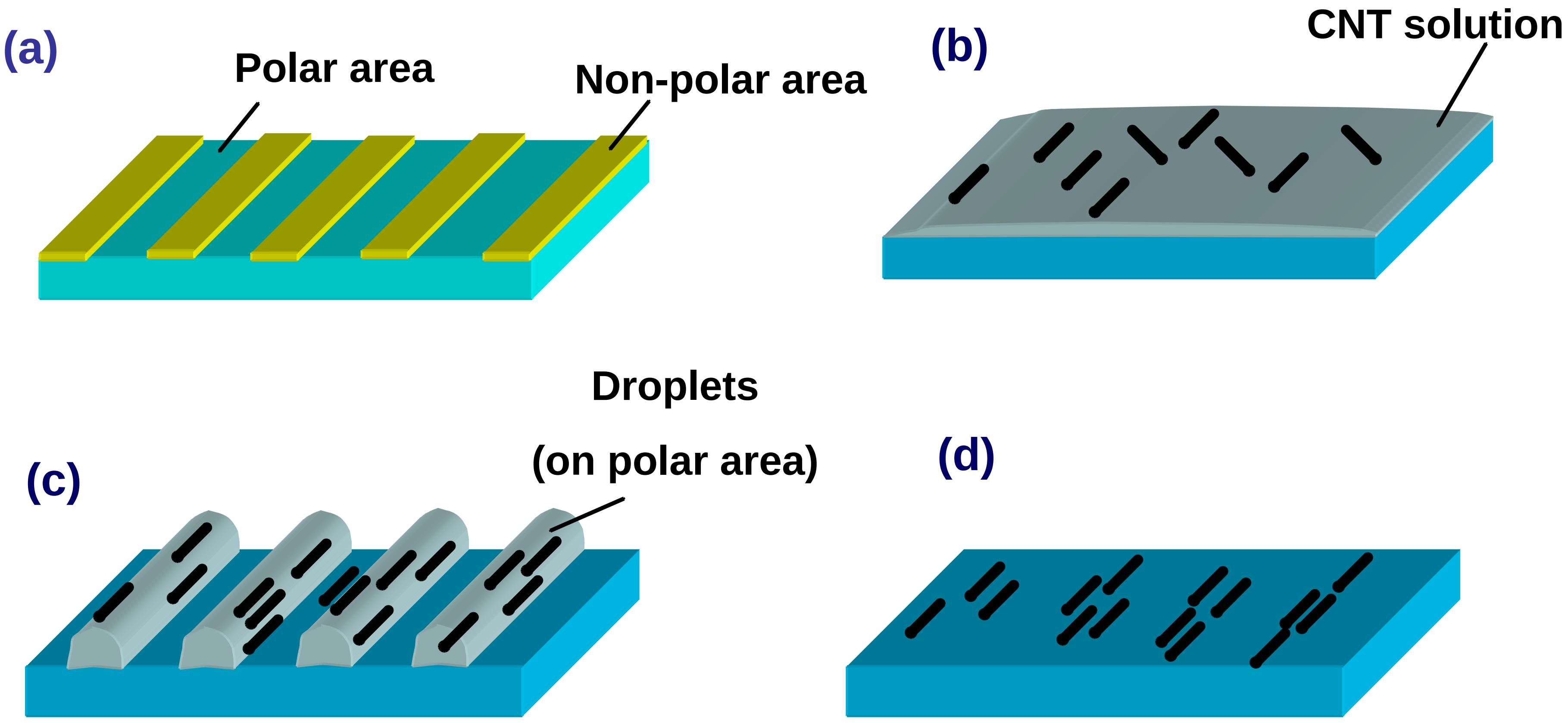


P(StMa) /QD patterned film

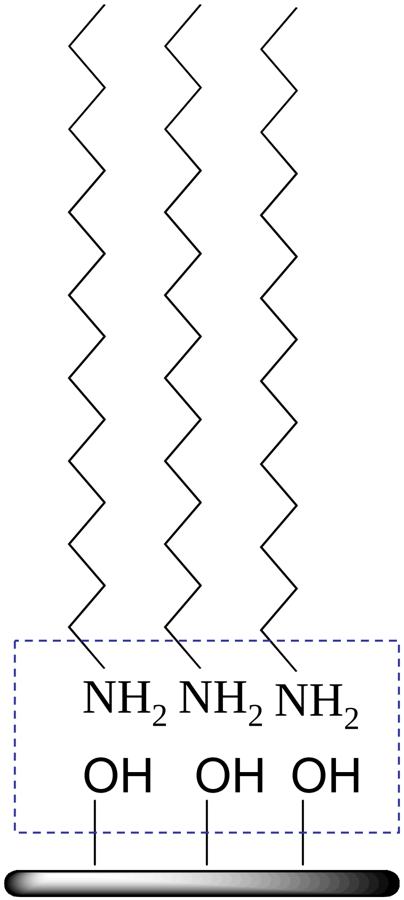


SEM images of polymer/QD pattern

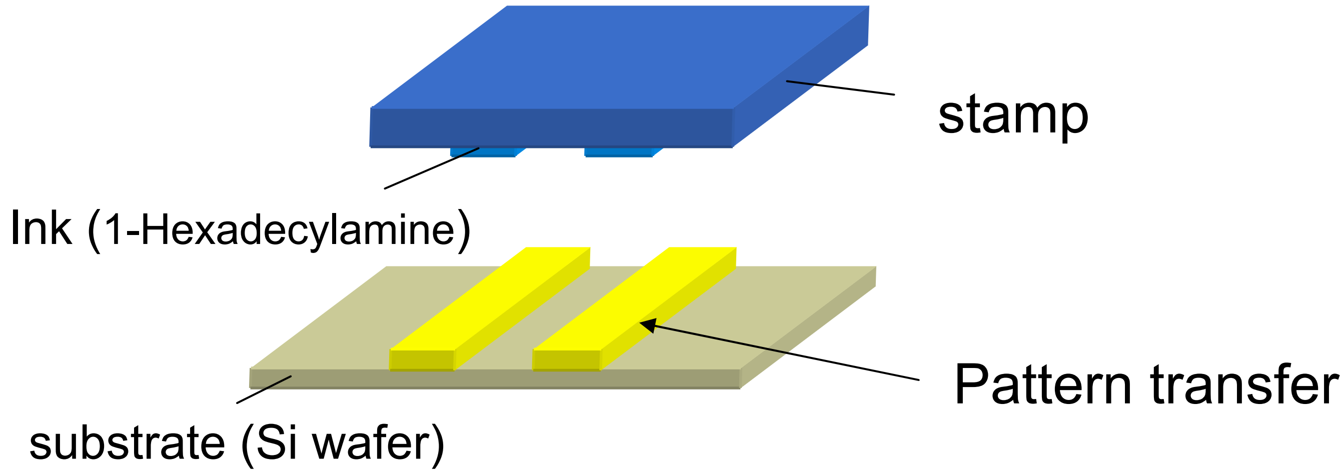
CNT Alignment Strategy



Carbon Nanotube (CNT) Alignment



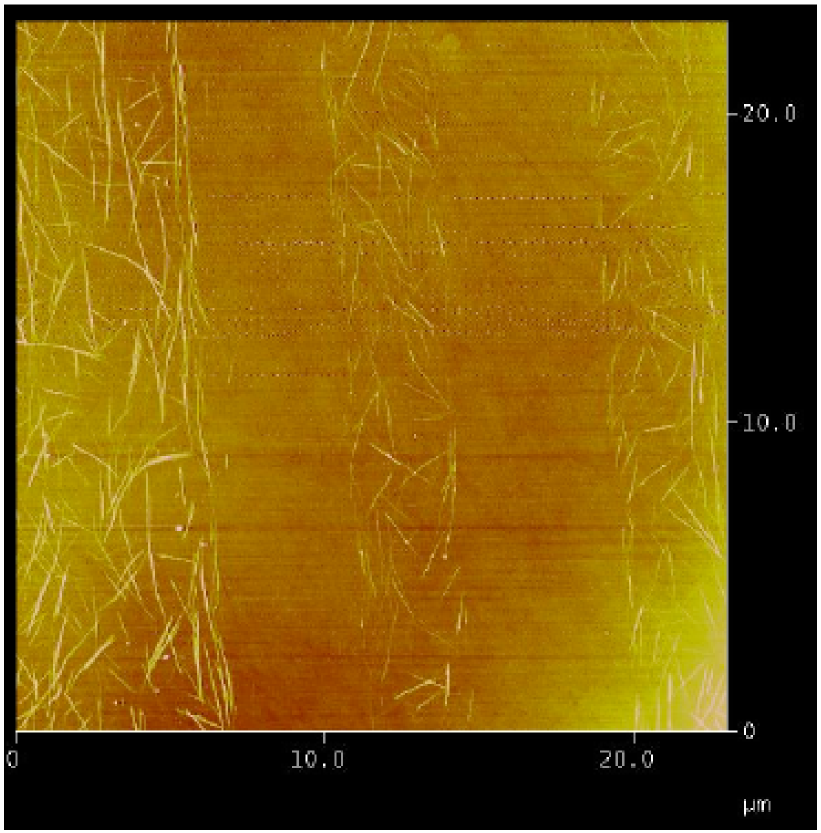
Microcontact stamping



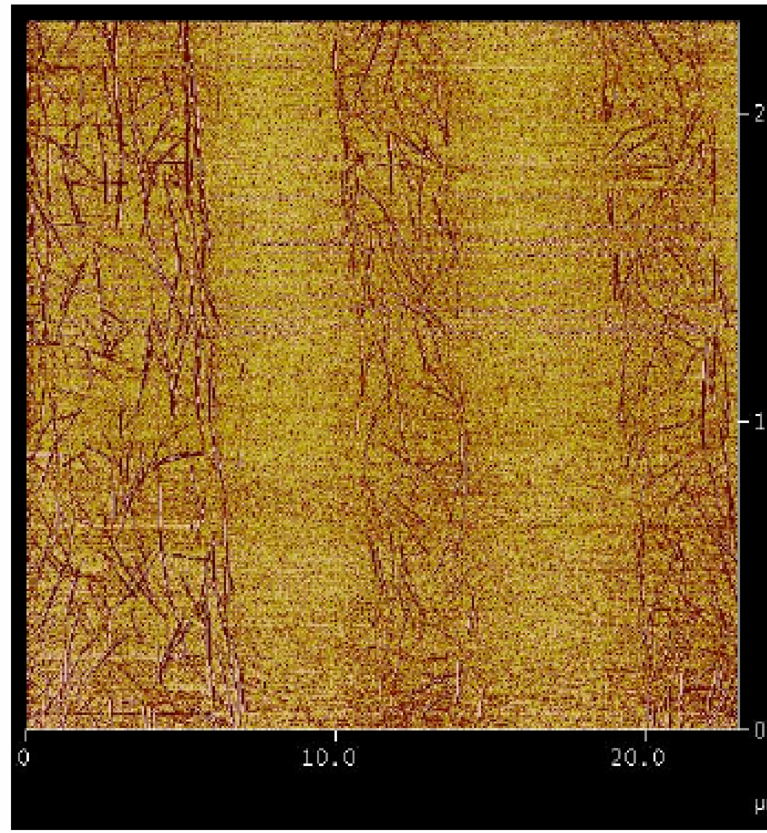
The pattern transfer is based on the formation of "**Hydrogen Bonds**" between the **amine groups** 1-Hexadecylamine and the **hydroxyl groups** of the substrate.

AFM Images

Height image



Phase image



Future Plans

- Use functional iCVD polymers to align the carbon nanotubes
- Fabricate simple quantum dot devices using the novel patterning strategies
- Demonstrate the performance of high resolution devices on flexible, low cost, light weight substrates.