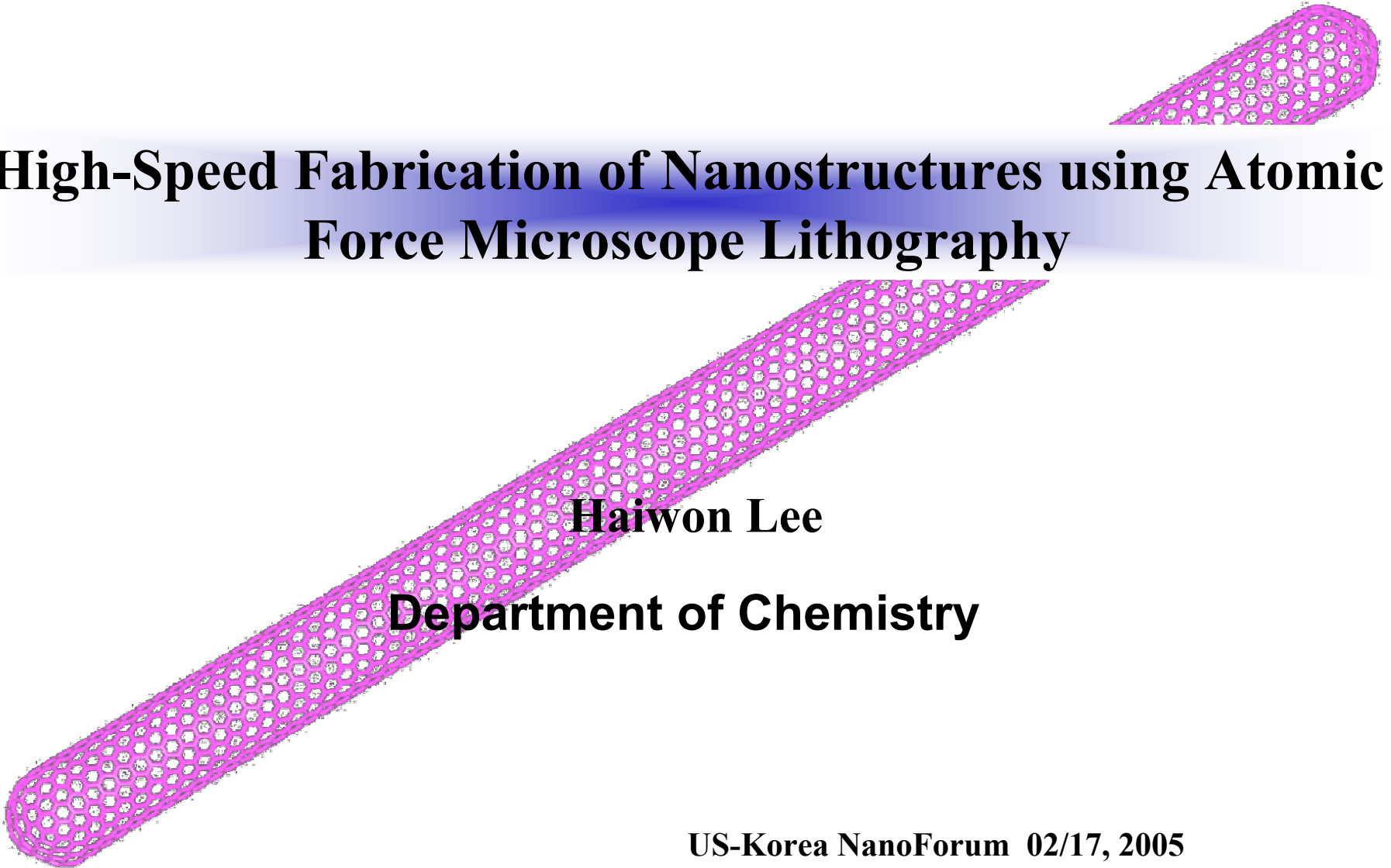


# High-Speed Fabrication of Nanostructures using Atomic Force Microscope Lithography

Haiwon Lee

Department of Chemistry



# Acknowledgements

OTFL

January, 2004  
Jeju Island



National Research Lab.



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**Atomic force microscope lithography**

## **II. Molecular resists**

**Self-assembled monolayers (SAMs), Spin-cast films**

## **III. AFM lithography**

**Anodization process**

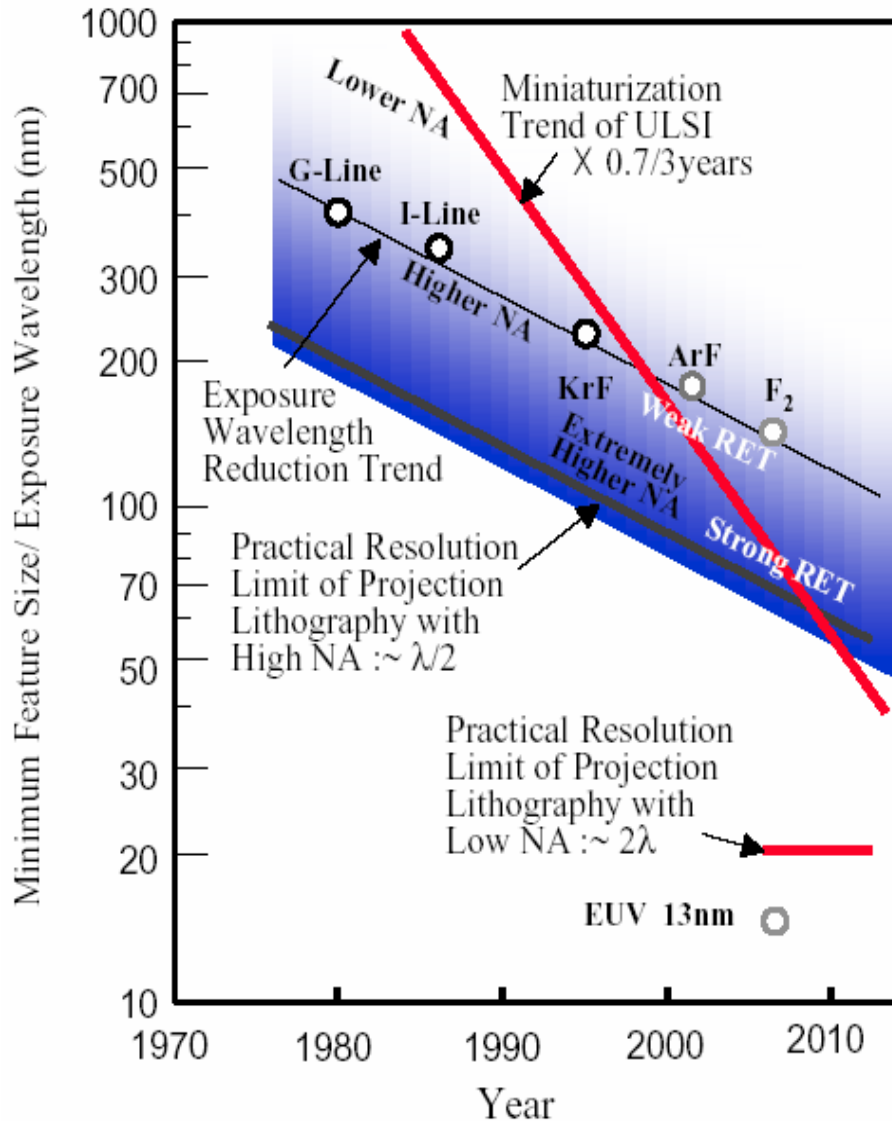
**Nanopatterning with organic resists on Si and metal films**

**CNT tip fabrication**

## **IV. Application**

**Photo mask fabrication, High-speed lithography system**

# Scaling Trend of Semiconductor Devices



## Next Generation Lithography Technologies

-Proximity X-ray Lithography (PXL):

1X system @ 1.3nm

-Extreme Ultra-Violet Lithography (EUVL):

4X system @ 13.5nm

-E-beam projection (SCALPEL, PREVAIL) :

4X electrons

-Proximity E-beam Lithography (LEEPL) :

1X electrons

-Multiple E-beam Lithography:

1X multi electron-beam

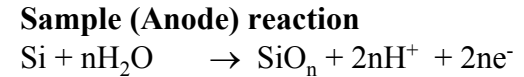
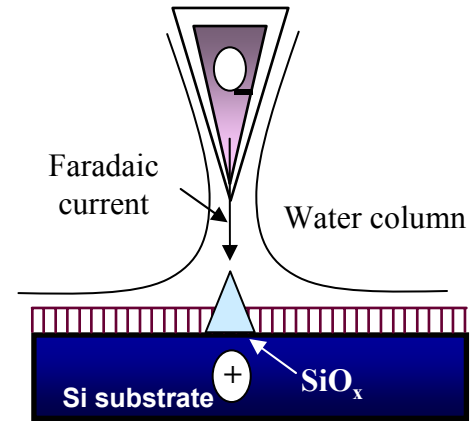
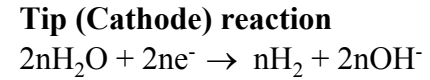
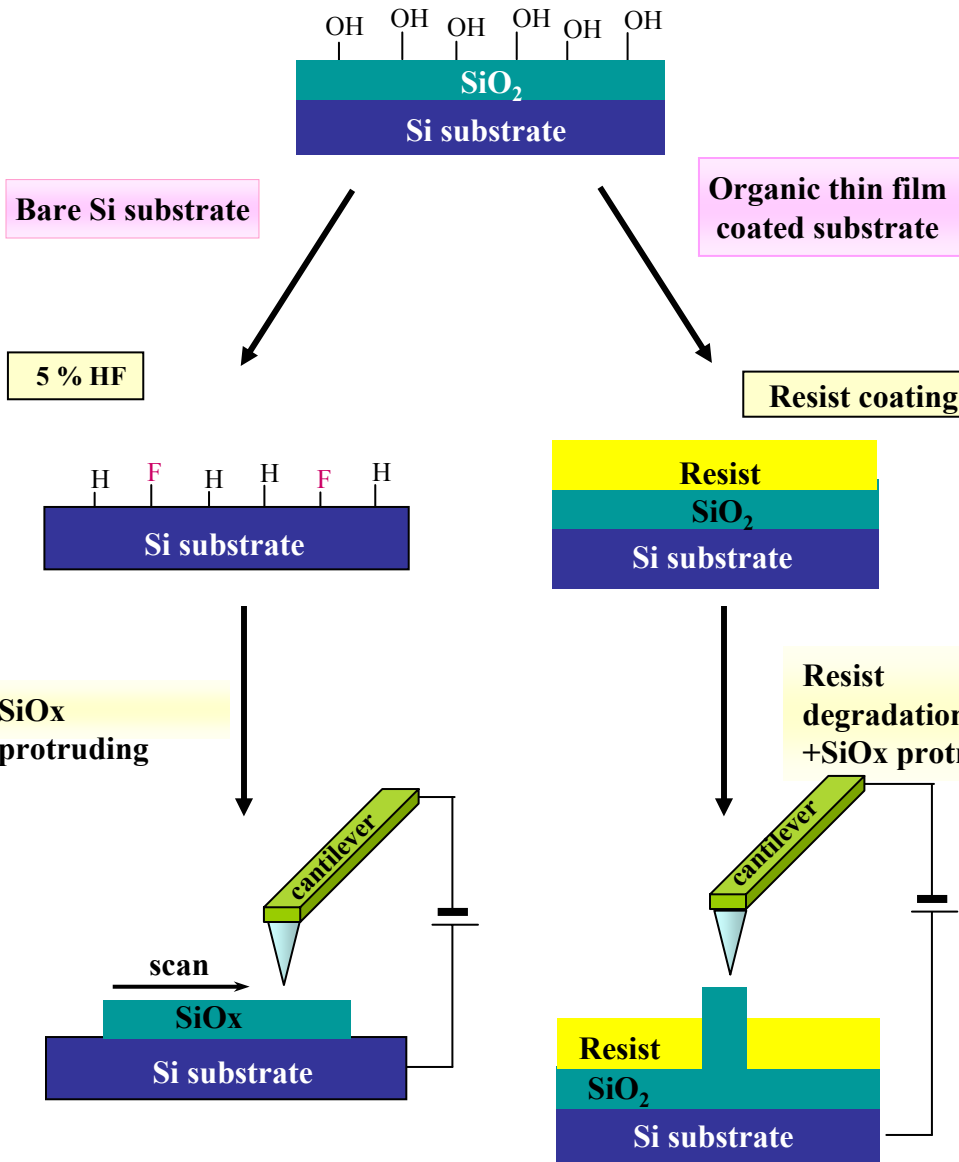
-Ion Projection Lithography (IPL):

4-5X system

-Non-optical lithography

SPM, Nanoimprint, Stamping

# Pattern Formation by Anodization Process

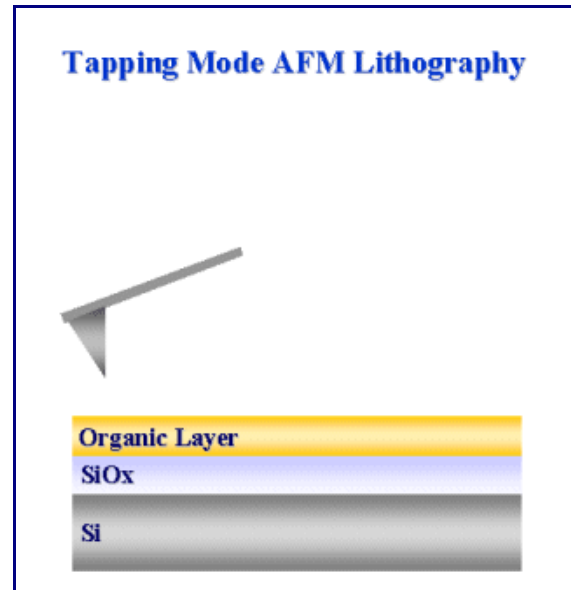
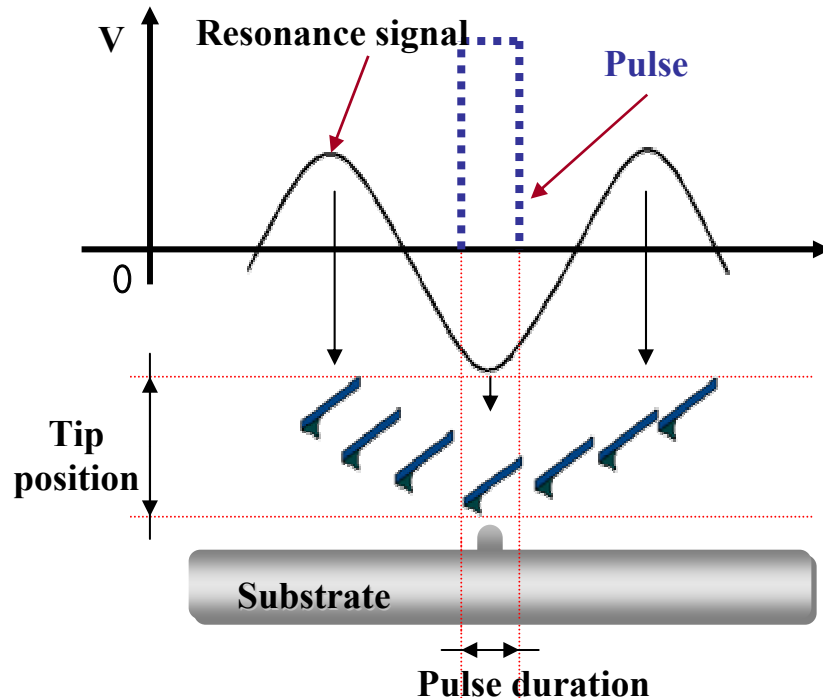
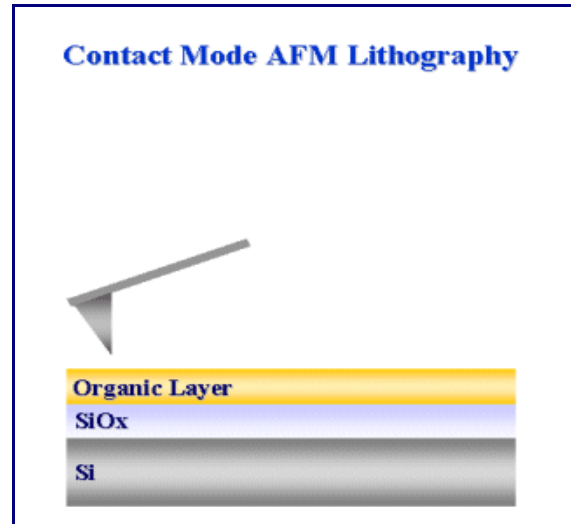
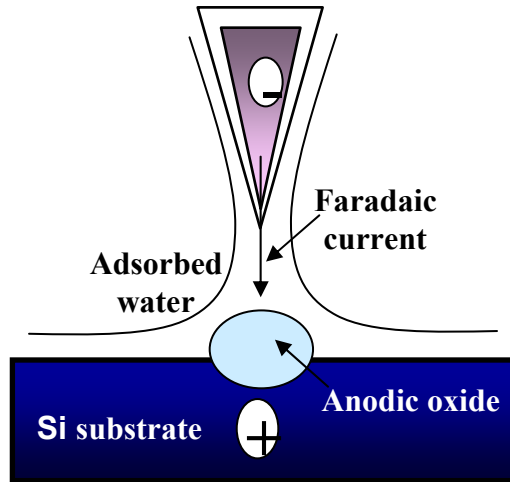


## Lithographic parameters

- Applied voltage & current
- Scanning speed
- Relative humidity
- Resist property
- Substrate property
- Cantilever tip
- Energy level

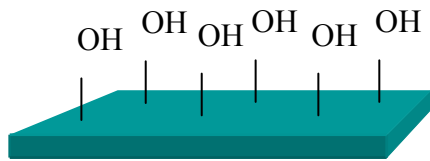
# Pattern Formation by Anodization Process

OTFL

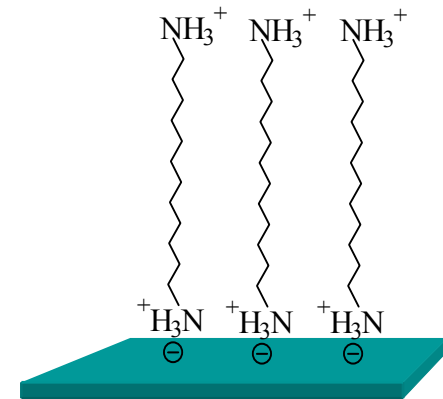
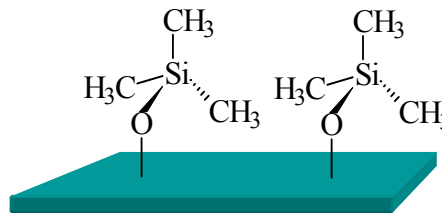
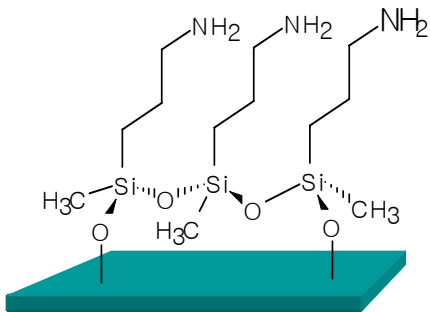
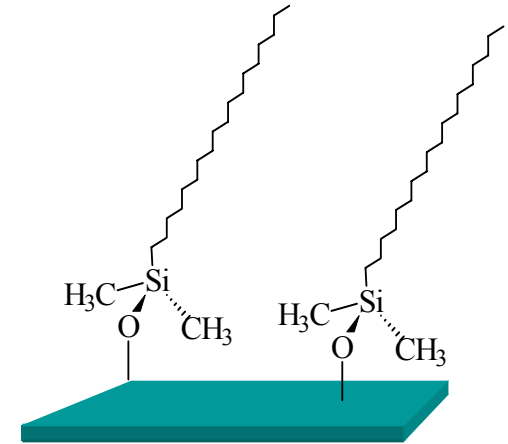
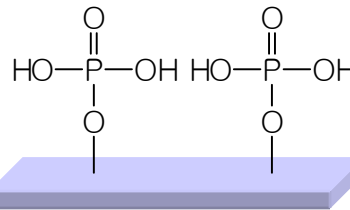
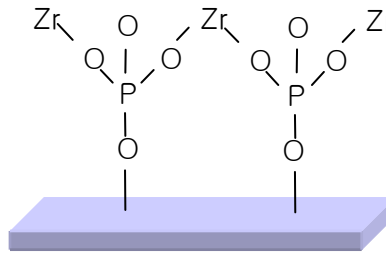


# Surface Modification with Self-assembled Monolayers (SAMs)

OTFL



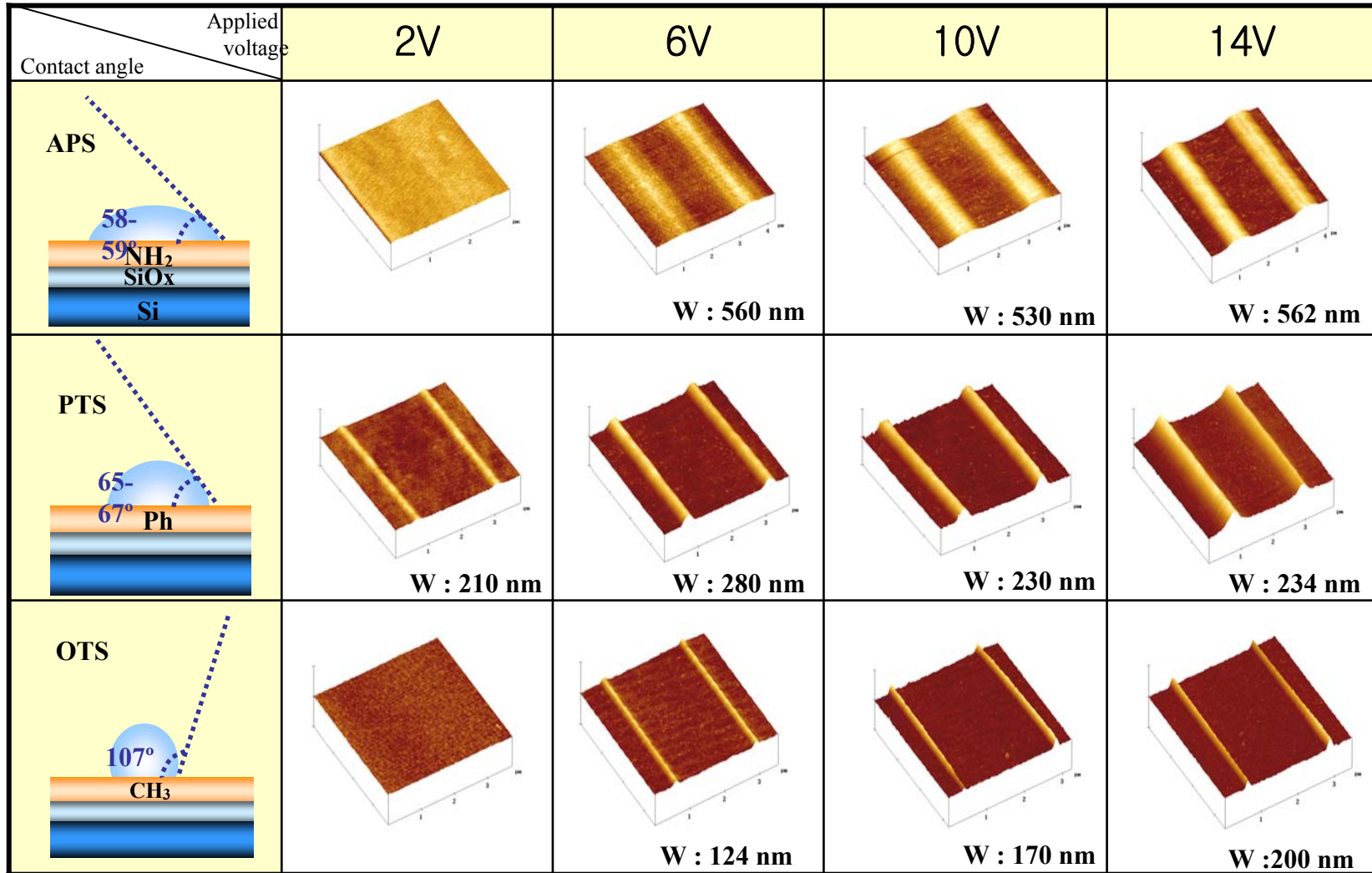
Hydroxylated silicon wafer





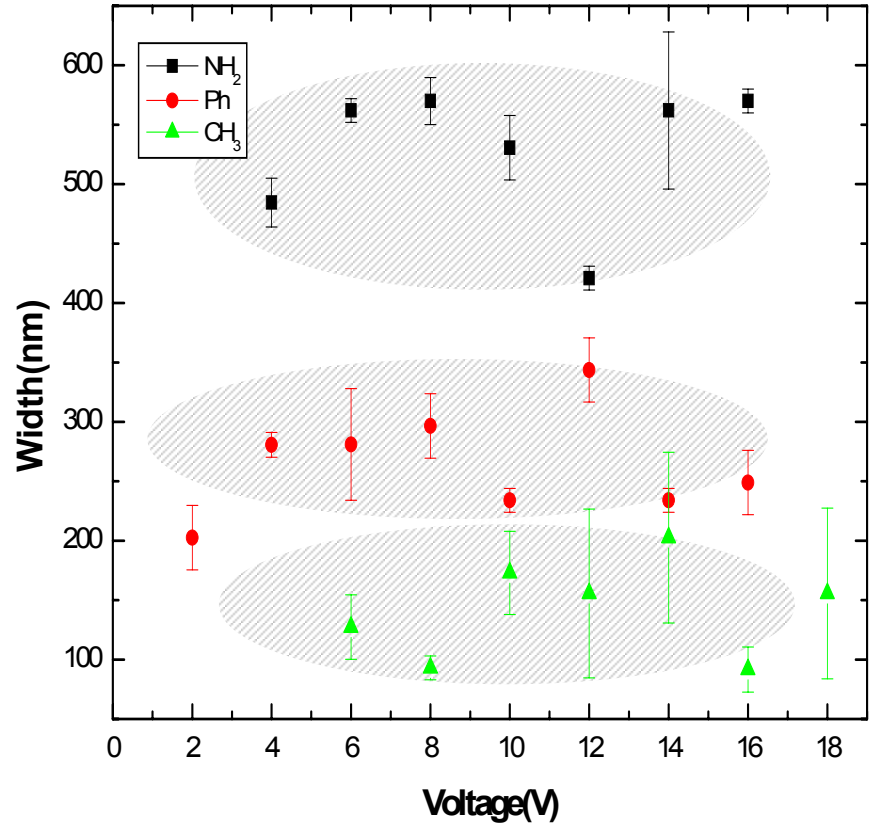
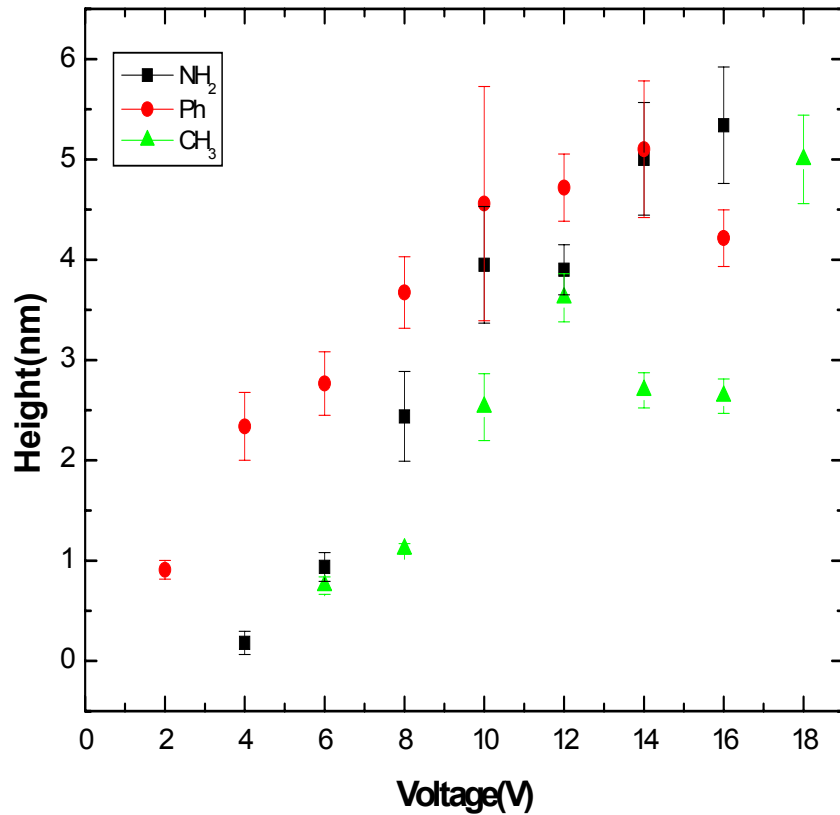
# Dependence of Surface Functional Groups

Temperature : 24°C / Humidity : 60 % / Tip : Pt coated silicon tip / Speed : 1 μm/s

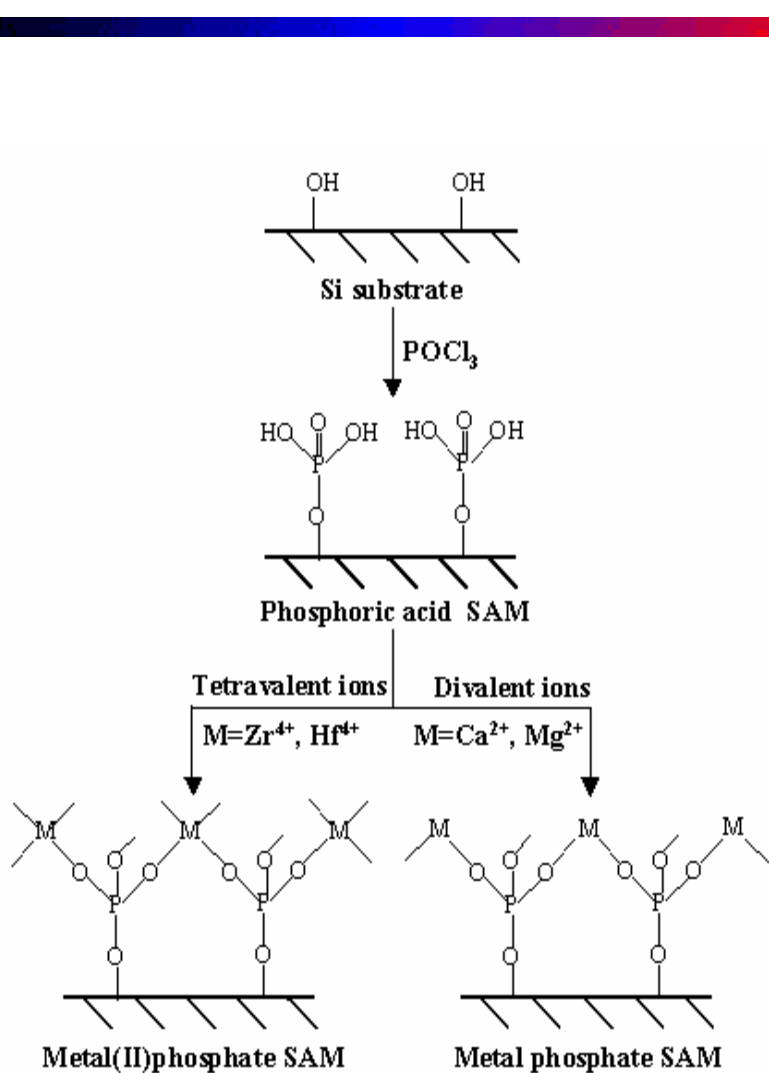




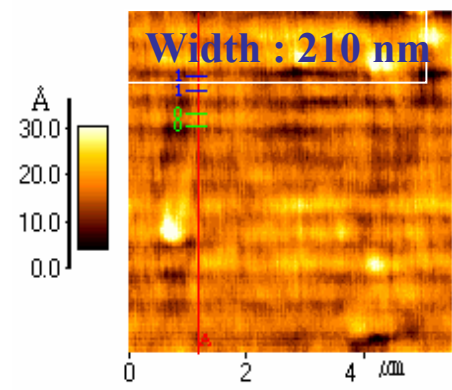
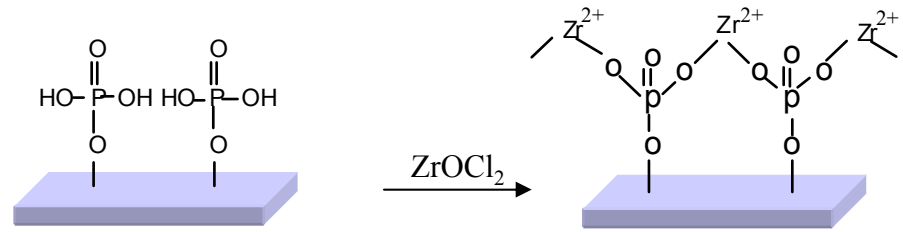
# Dependence of Surface Functional Groups



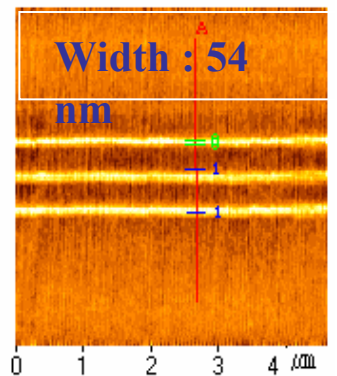
# Schematic Diagram of Metal-phosphate SAM



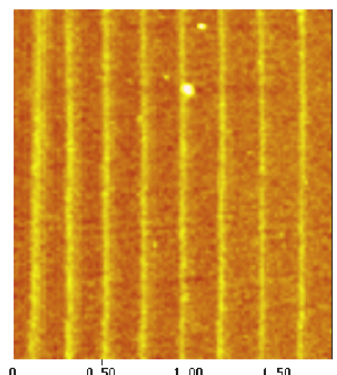
OTFL



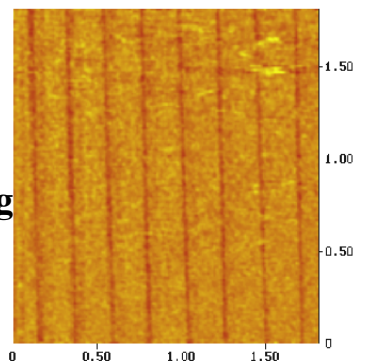
Applied Voltage : 12 V



Scan Speed : 30 μm/s



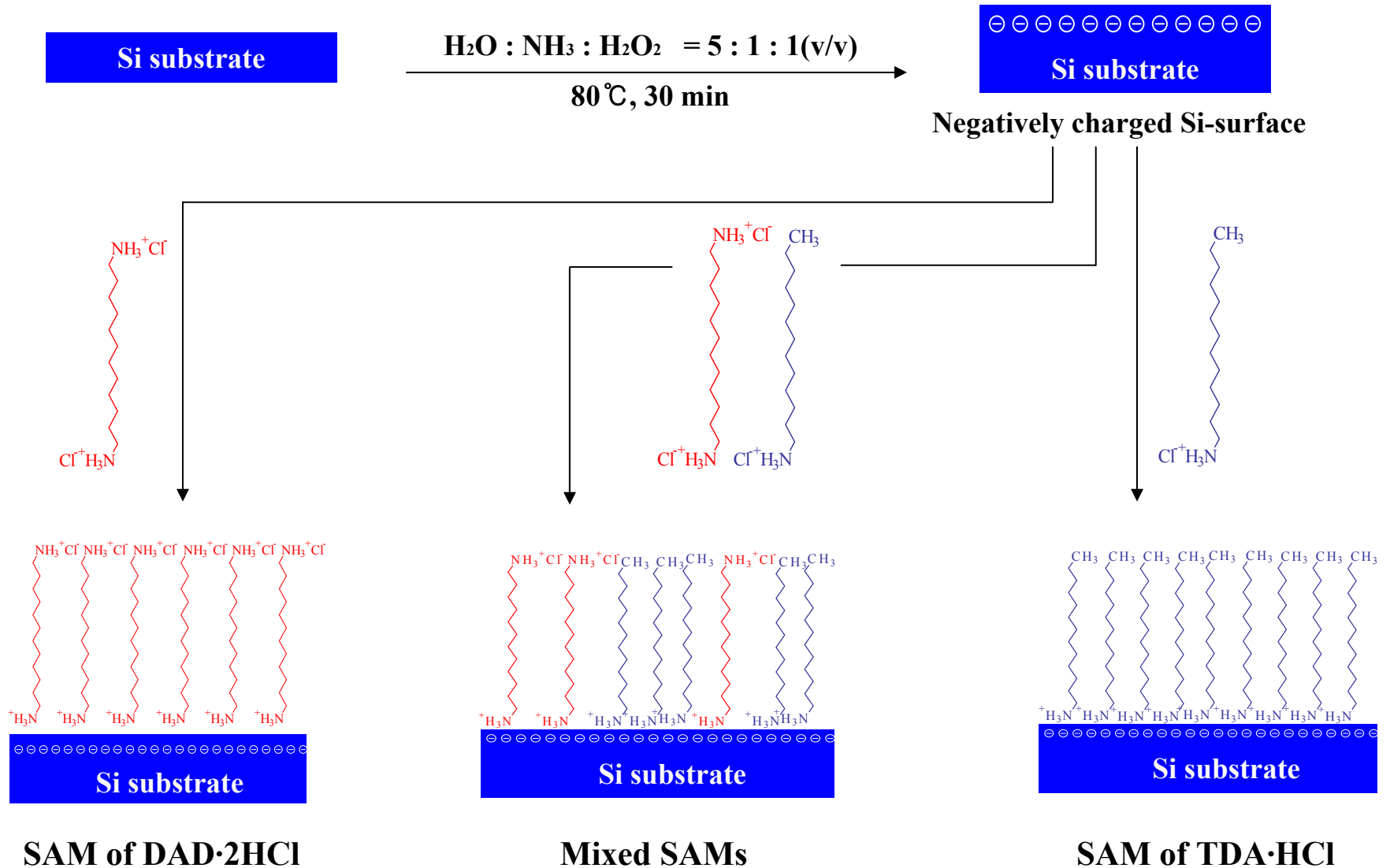
Applied Voltage: 16 V



Etching

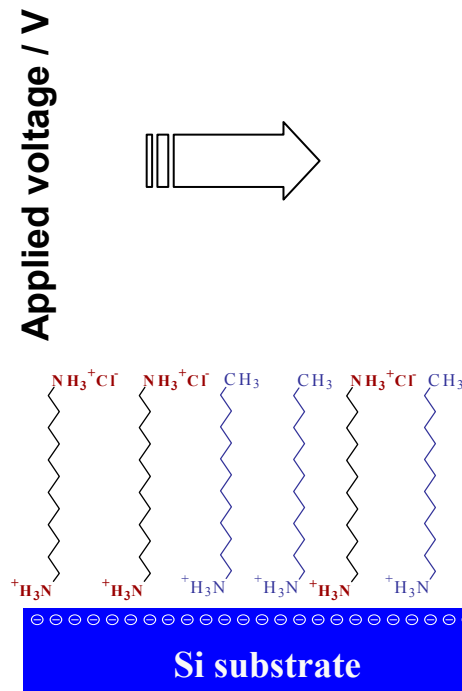
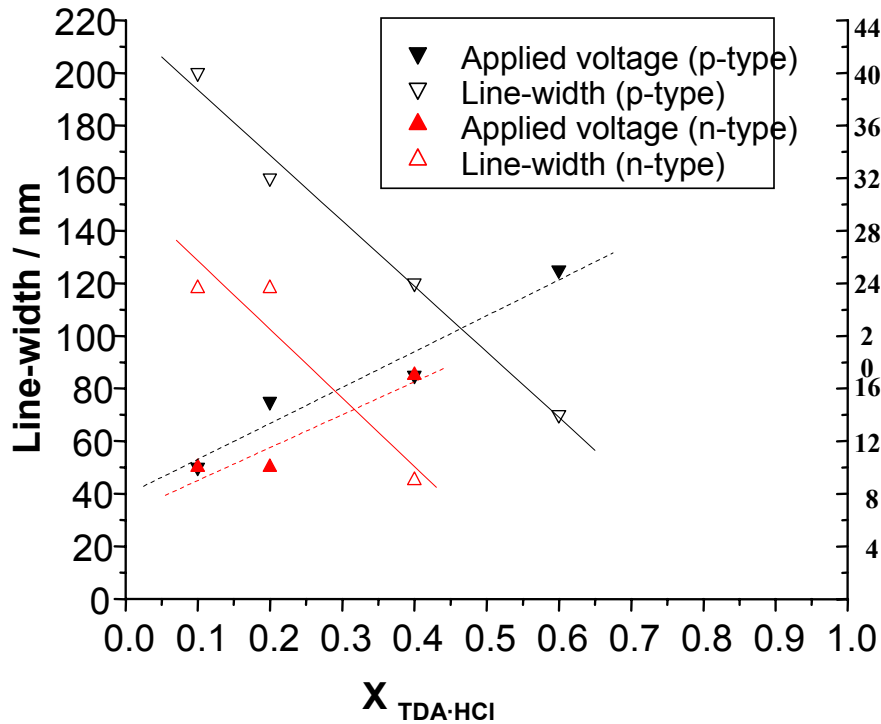
Scan speed: 500 μm/s

# Preparation of Mixed SAMs



# Effects of Surface Groups and Substrate Types

OTFL



## Mixed SAM (6:4)

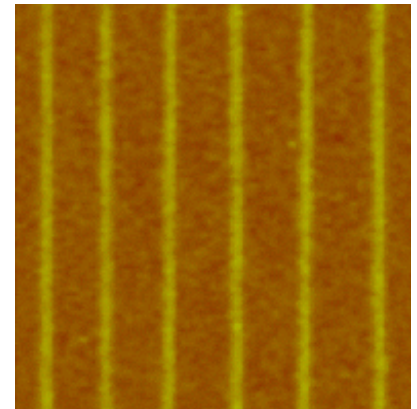
Scan speed : 2 mm/s

Applied voltage : 12 V

Cantilever : Pt-Coated Si

Relative humidity : 60 %

Line width : 45 nm



DAD·2HCl monolayer

Hydrophilic surface, Wide line-width

Uniform protruded line

TDA·HCl monolayer

Hydrophobic surface, Narrow line-width

Rough protruded line

Mixed SAMs

Controlled hydrophilicity

Uniform protruded lines

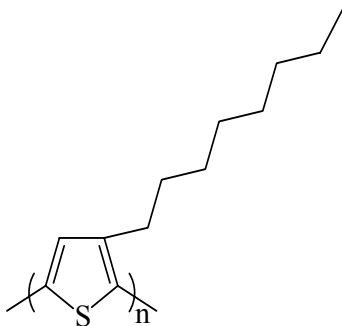
Narrow line-width

# Spin-cast Polythiophene Derivatives Films

OTFL

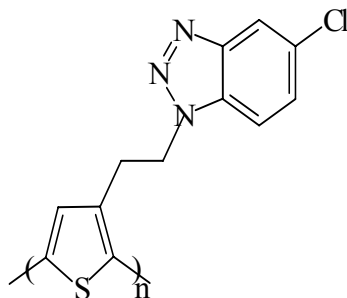
## POT

Poly(3-octylthiophene)



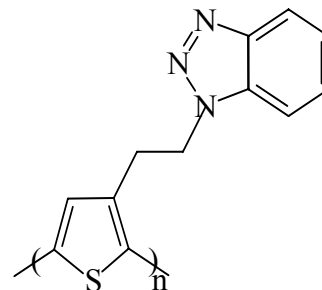
## PCBET

Poly(3-(2-benzotriazoloethyl)thiophene)

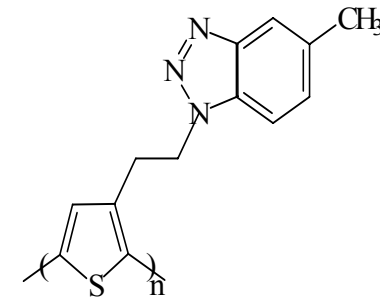


## PBET

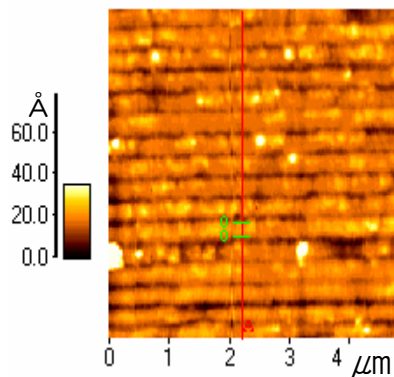
Poly(3-(2-benzotriazoloethyl)thiophene)



## PMBET

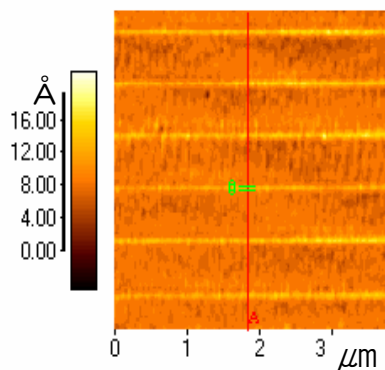


Applied voltage : 10 V, Scan speed : 4  $\mu\text{m/s}$



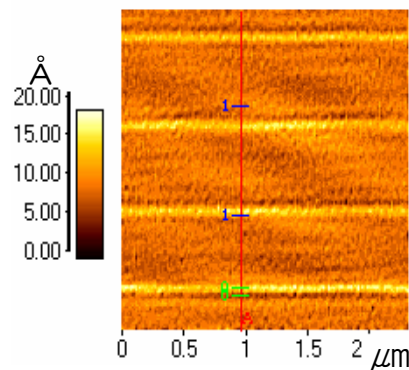
Line Height: 0.6 nm

Line Width: 220 nm



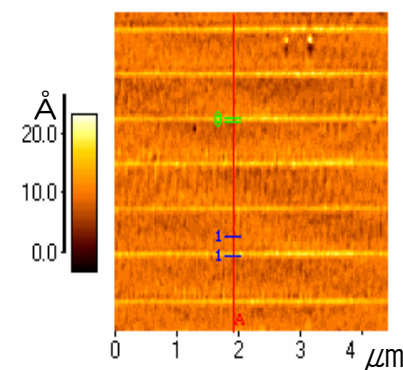
Line Height: 0.7 nm

Line Width: 50 nm



Line height: 0.7nm

Line width: 52 nm

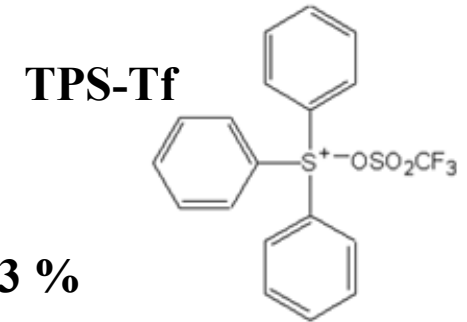
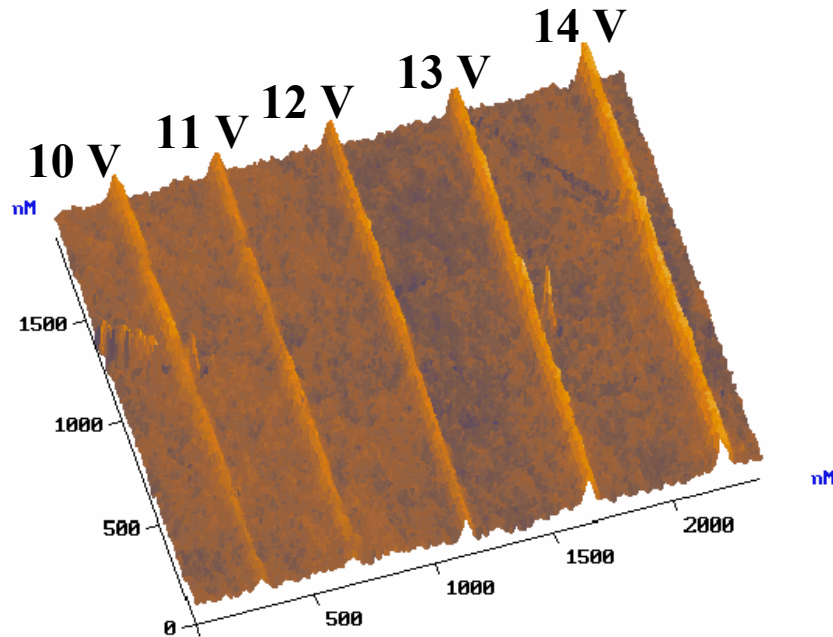


Line height: 0.8 nm

Line width: 50 nm

# Fabrication on Spin-cast triphenyl-sulfonium triflate Film

OTFL



Tip : NSC15

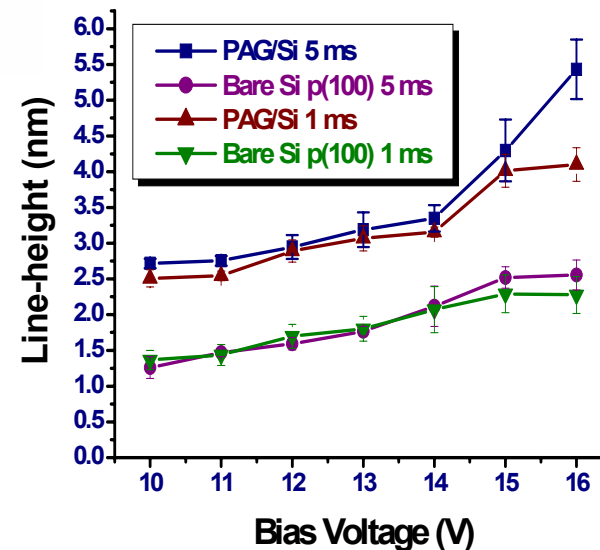
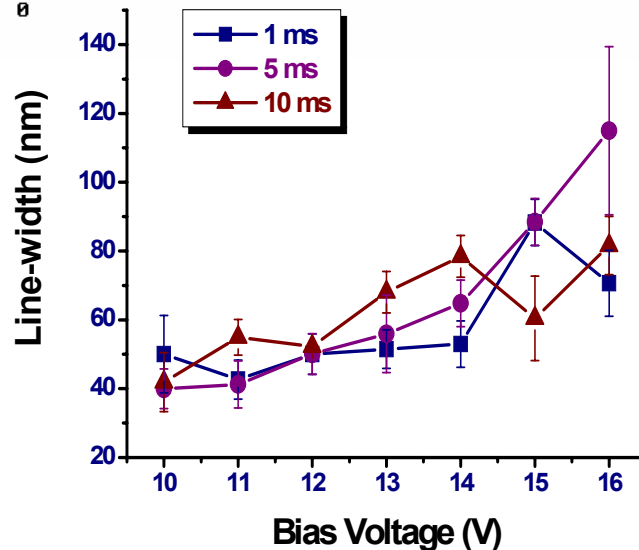
Humidity : 43 %

Temp : 30 °C

Substrate : TPS-Tf/Si

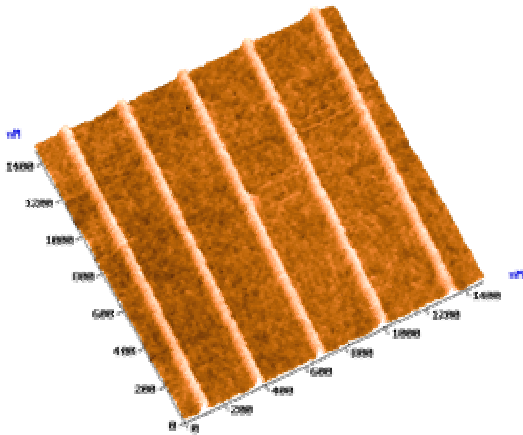
Film thickness : 2.0 nm (RMS : 1.5 Å)

Tip amplitude : 84.3 nm

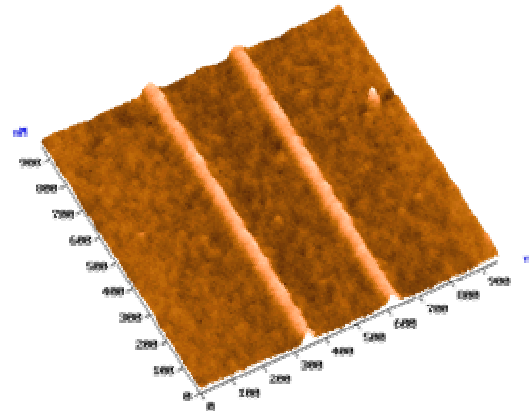


# Fabrication on Spin-cast triphenyl-sulfonium triflate Film

OTFL

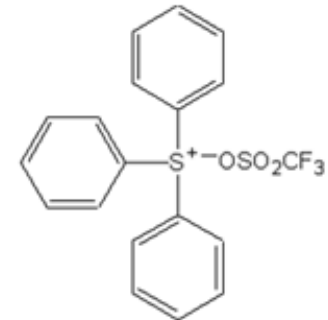


Speed: 10  $\mu\text{m/s}$   
Line Height : 1.37 nm  
Line Width : 35.7 nm

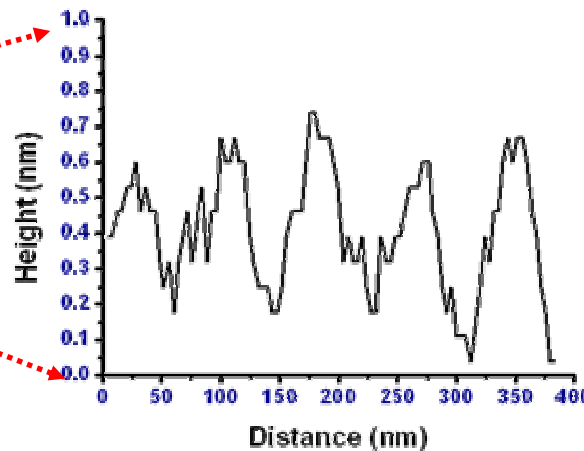
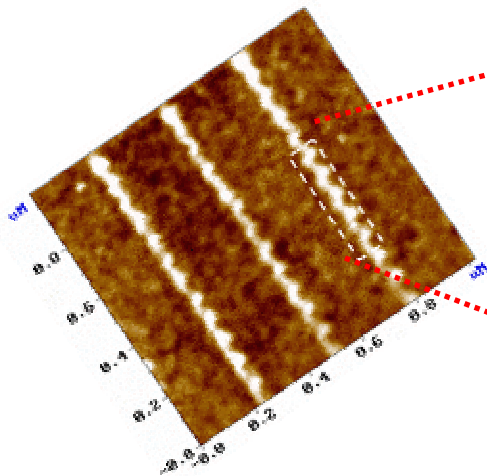


Speed: 50  $\mu\text{m/s}$   
Line Height : 1.19 nm  
Line Width : 29.2 nm

Mode : Tapping mode  
Bias Voltage : 10 V  
Temp : 27 °C  
Humidity : 45 %  
Film Thickness : 2.4 nm



*TPS-Tf*



Speed: 60  $\mu\text{m/s}$   
Line Height : 0.75 nm  
Line Width : 32.9 nm



# Schematic Diagram of Energy Band

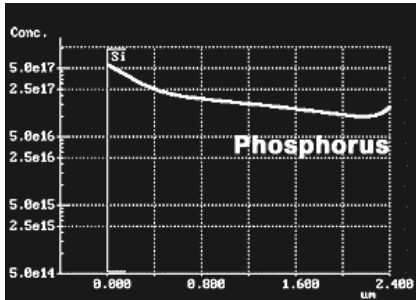
## Si Tip Fermi Level

$$T = 300 \text{ K}, N_D \gg N_A, N_D \gg n_i$$

$$N_D \text{ (Phosphorus) } 5.0e17$$

$$E_F - E_i = kT \ln(N_D/n_i)$$

$$E_F = -4.13 \text{ eV}$$

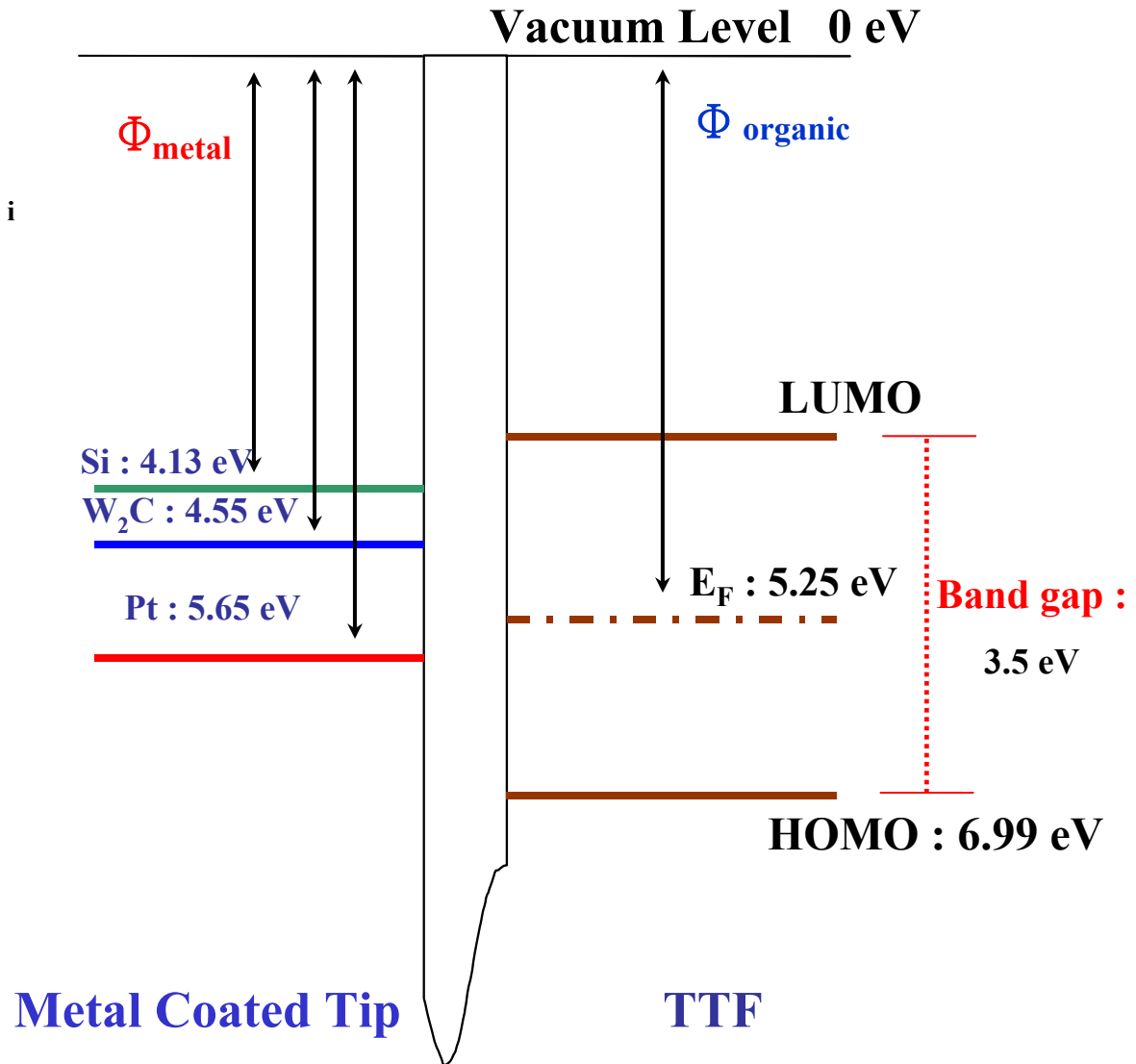


## W<sub>2</sub>C Tip Work function

$$E_F = -4.55 \text{ eV}$$

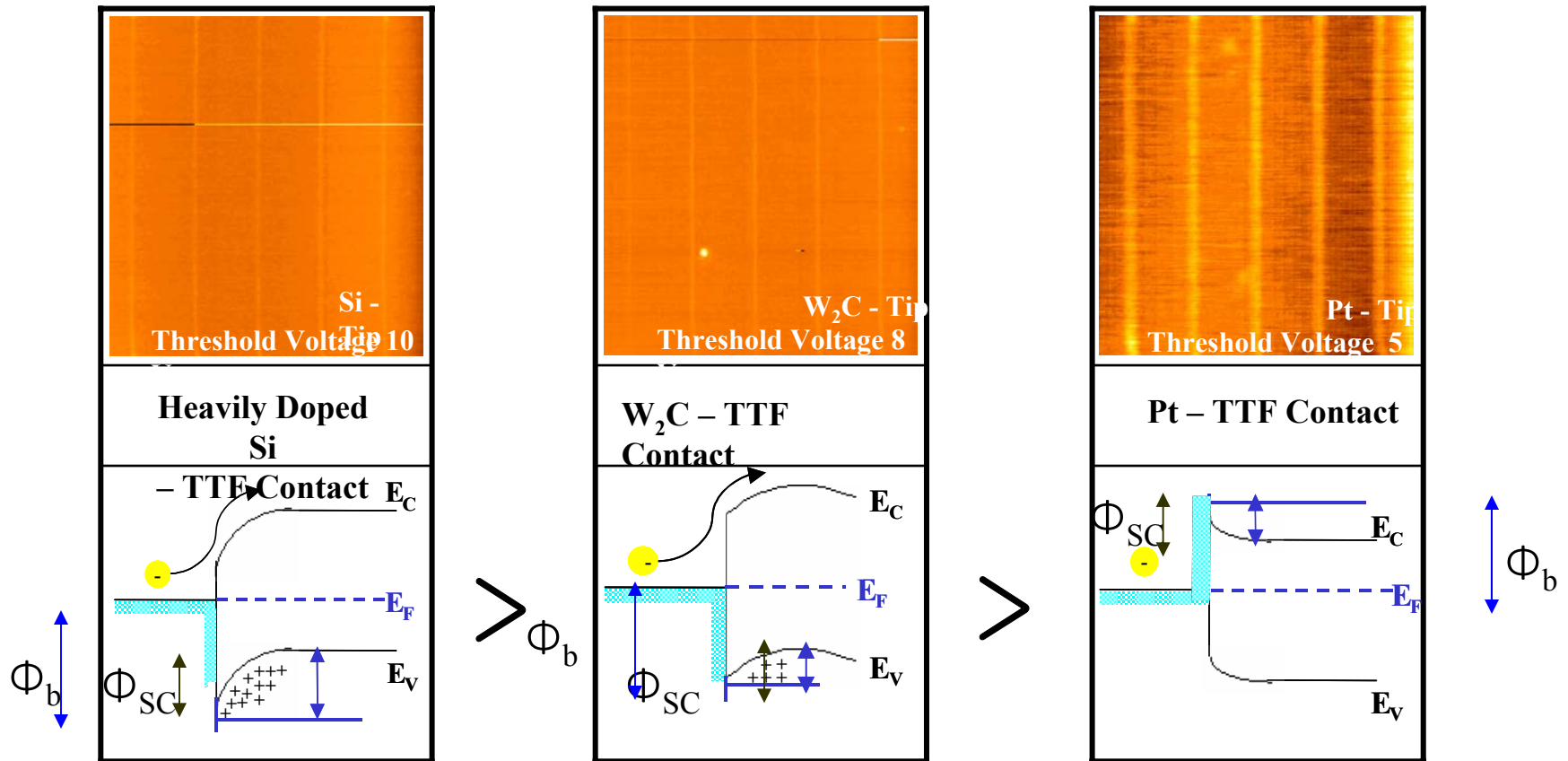
## Pt Tip Work function

$$E_F = -5.65 \text{ eV}$$



# Tip Effect on Threshold Lithographic Voltage

OTFL

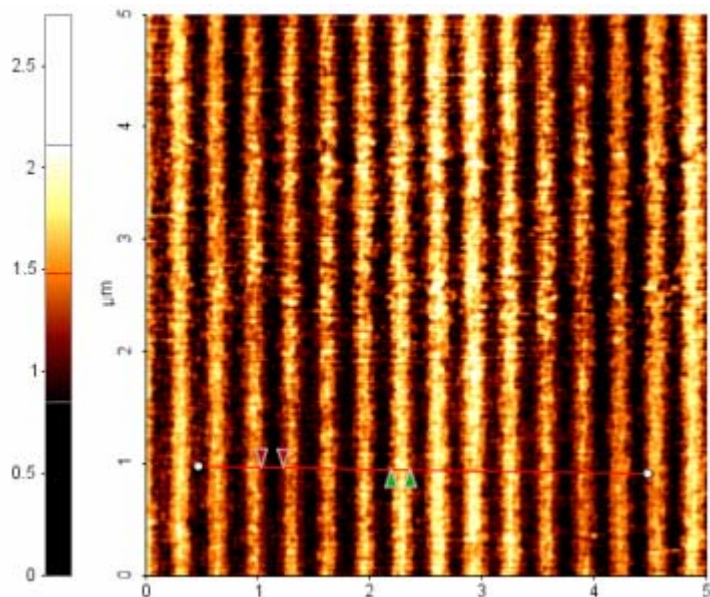


Humidity : 40 ~ 45 %  
Litho. Speed : 10  $\mu\text{m} / \text{s}$

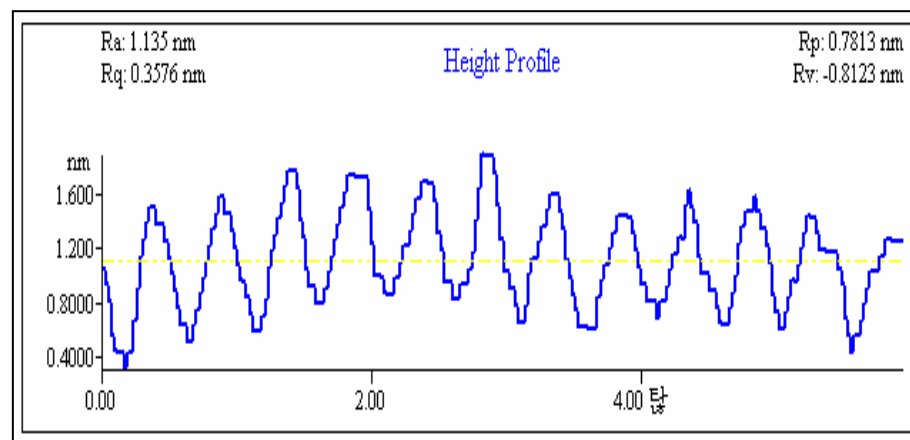
	Si	W <sub>2</sub> C	Pt
Threshold Voltage (V)	10	8	5
Fermi Level (eV)	-4.13	-4.55	-5.65

# Nanostructures on Ta Metal Film

OTFL



**Depth : 1.25 nm, Line width : 100 nm**



**$C_4F_8$  : 11 sccm**  
**Bias power : -120 V**  
**Time : 50 sec**

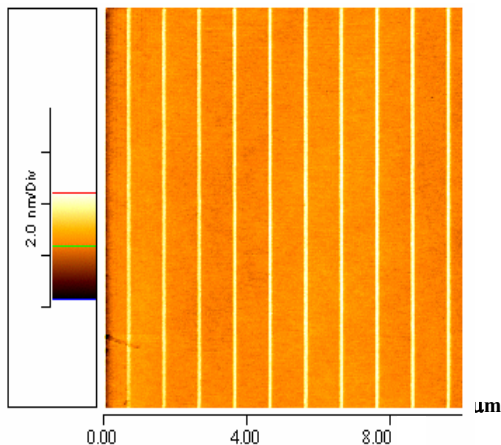
**RF power : 600 W**  
**Working pressure : 10 mtorr**

# Aspect Ratio Improvement by Temperature Control

Humidity: 39-41 %, T: 22-23 °C

Bias voltage : 18 V

Speed : 1 μm/sec

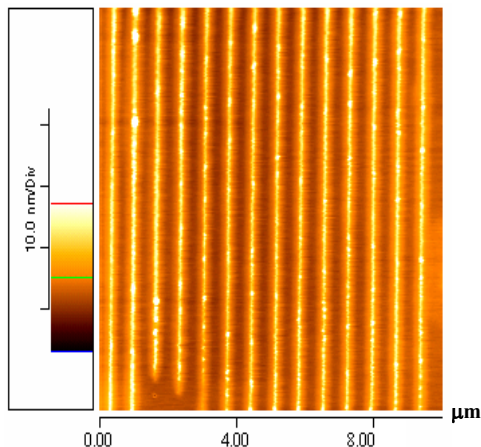


Height: 1-2 nm, Width : 50 nm

Humidity: 30 %, T: 30-31 °C

Bias voltage : 18 V

Speed : 1 μm/sec

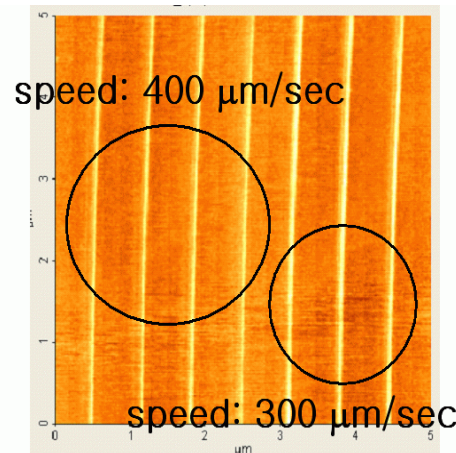


Height: 12-16 nm, Width : 78 nm

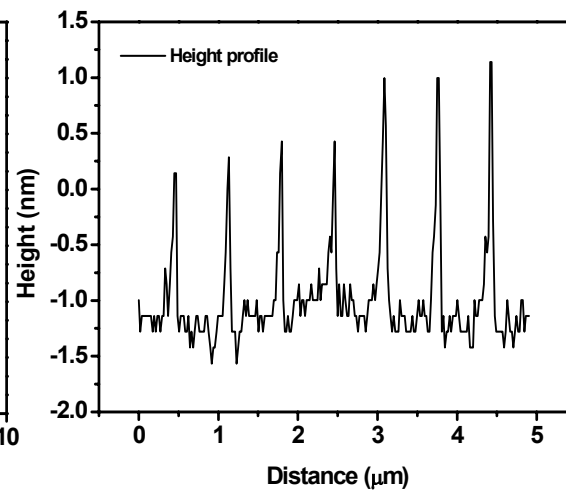
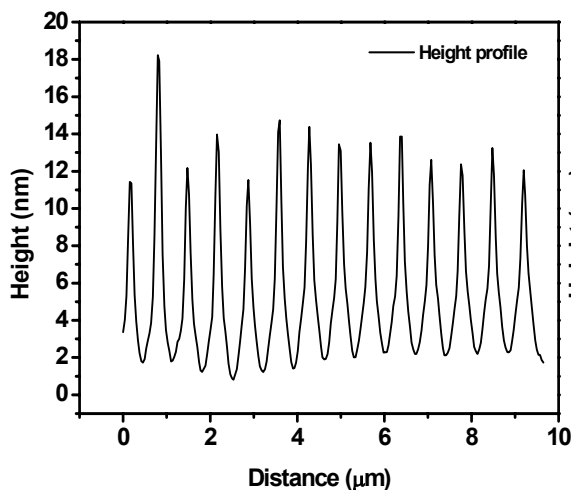
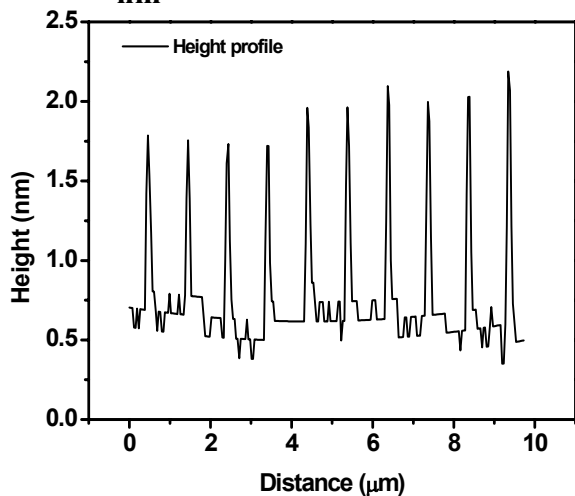
Humidity: 30 %, T: 30-31 °C

Bias voltage : 18 V

Speed : 300-400 μm/sec

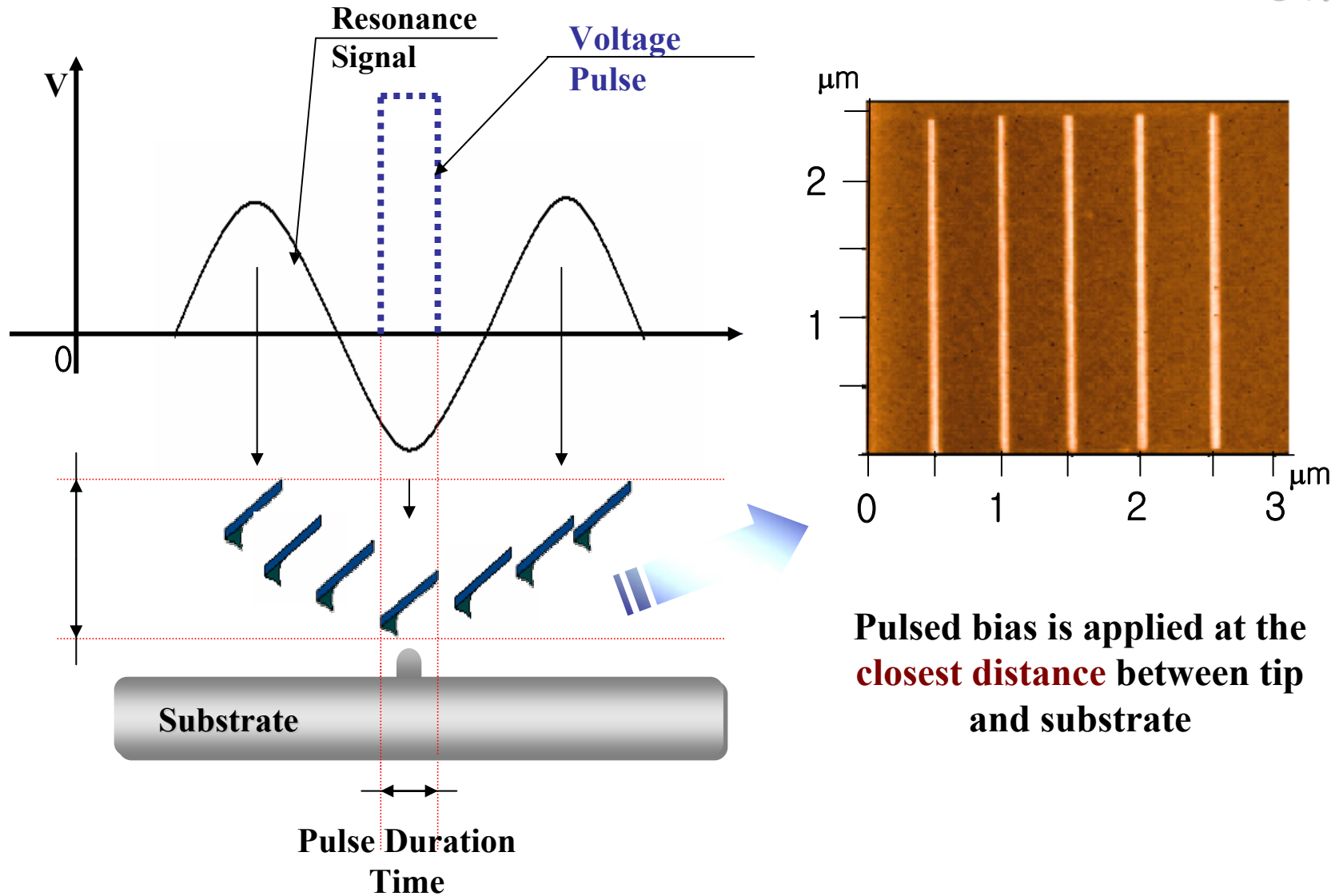


300 μm/sec - Height : 2.5 nm, Width : 60 nm  
400 μm/sec - Height : 1.7 nm, Width : 40 nm



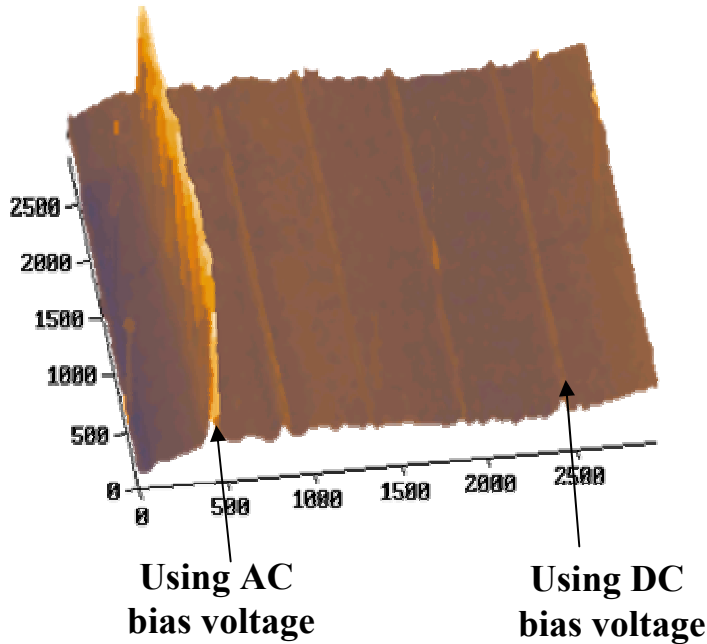
# Fabrication of Oxide Nanostructure using Pulsed Bias Voltage

OTFL

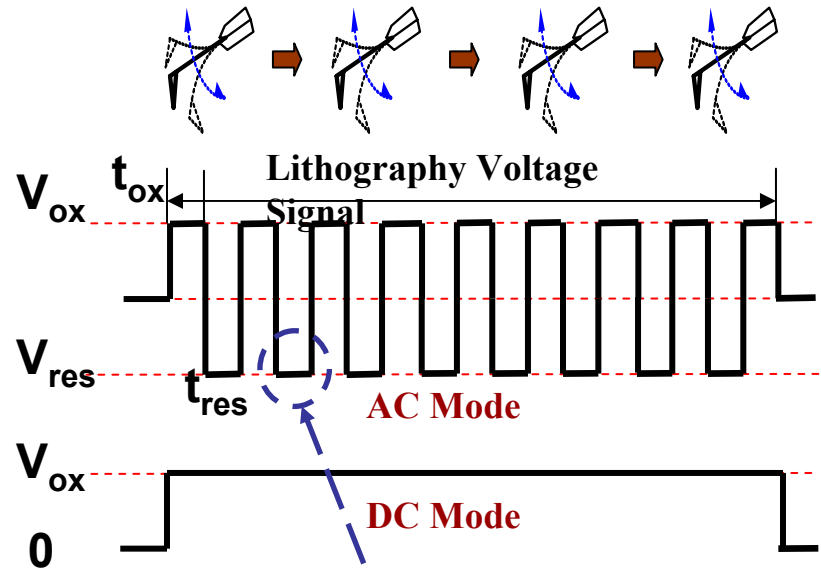


# Aspect Ratio Improvement by Applying AC Bias Voltage

Fabricated Structures at both AC Bias and DC Bias Applied AC Bias Voltage



$t_{ox} = t_{res} = 50 \text{ ms}$   
 $V_{ox} = 10 \text{ V}, V_{res} = -10 \text{ V}$

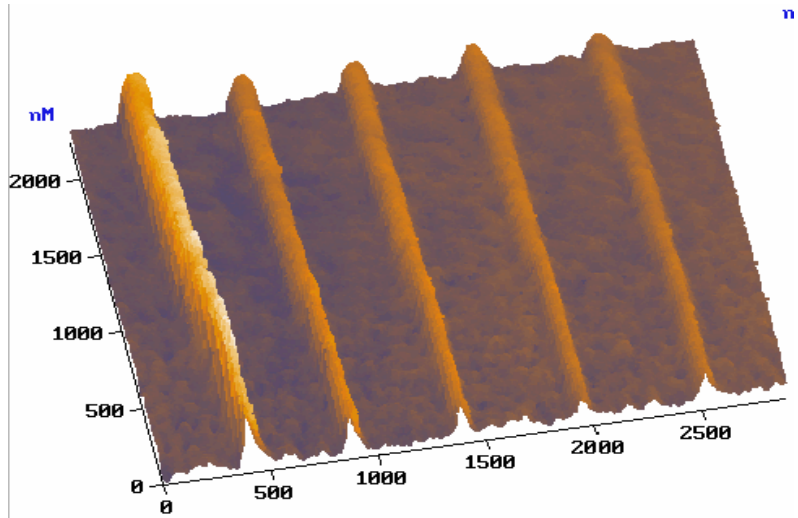


Reducing Space Charge Effect

	AC Bias Voltage		DC Pulsed Bias Voltage	
	Height(nm)	Width(nm)	Height(nm)	Width(nm)
Pt coated Si Tip	<b>7.6</b>	<b>48.7</b>	<b>0.84</b>	<b>34.6</b>

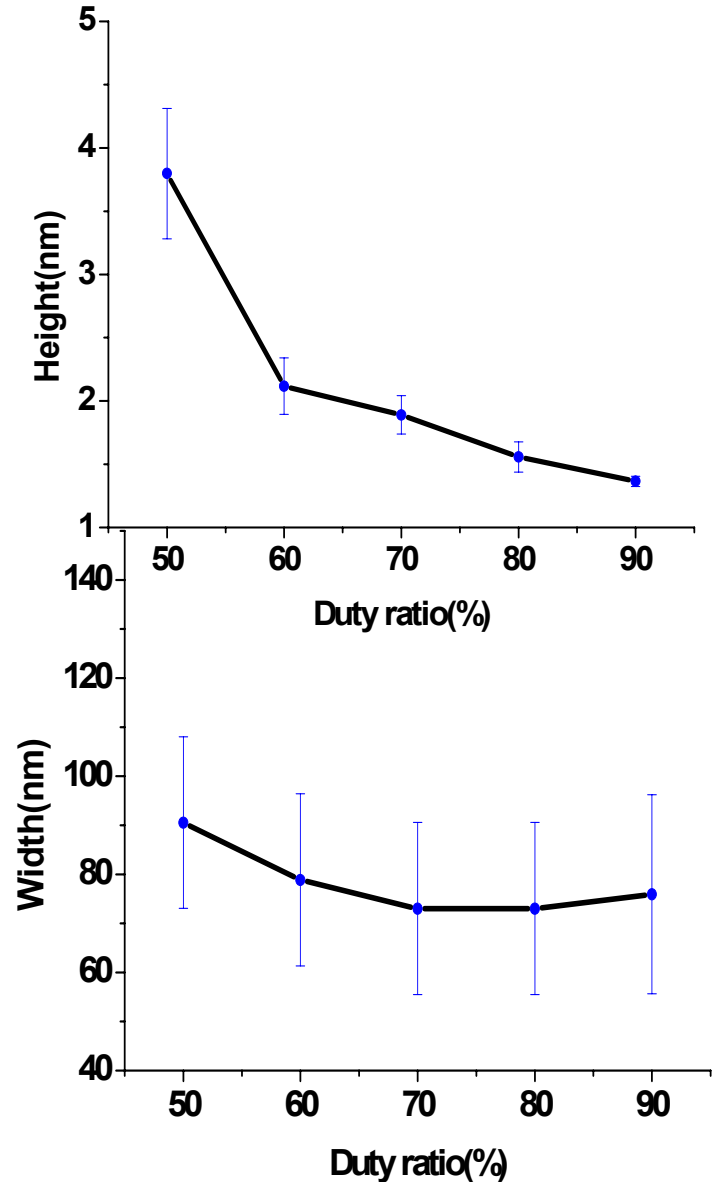
# Lithography Image of Various Duty Ratio

OTFL



T1 = 5 6 7 8 9 ms (+15V)  
T2 = 5 4 3 2 1 ms (-15V)

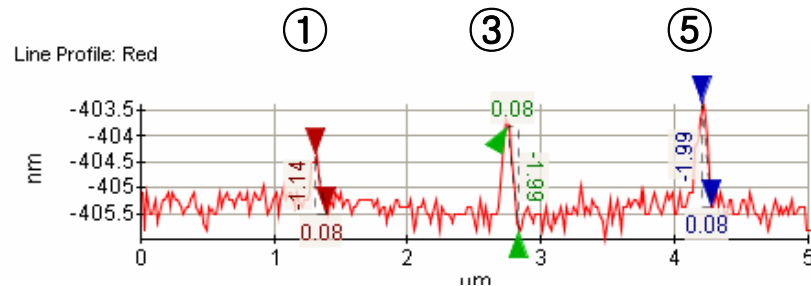
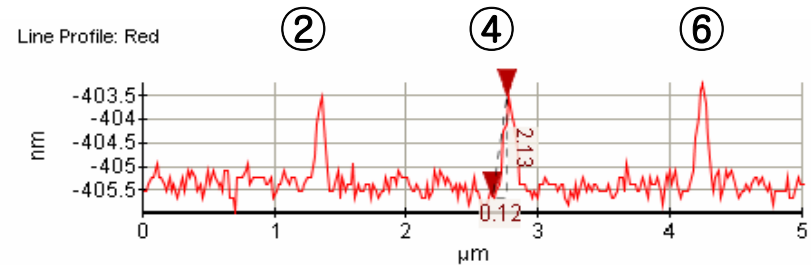
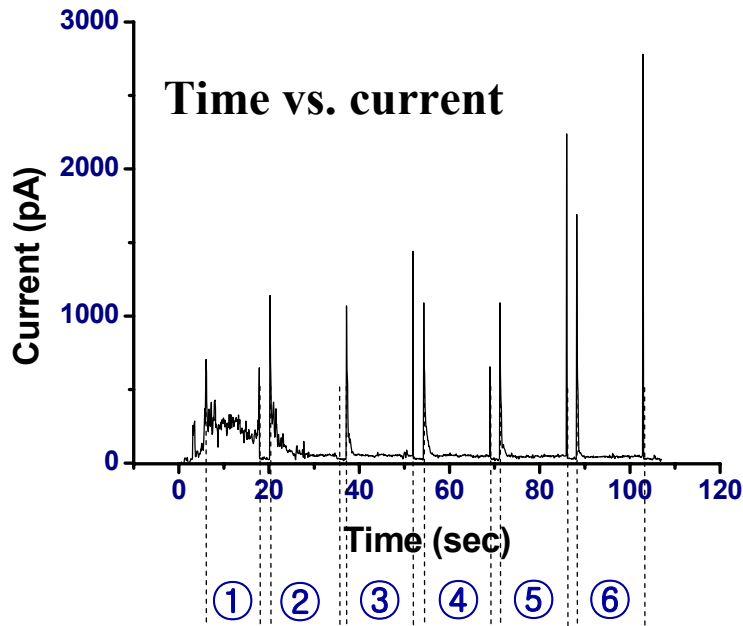
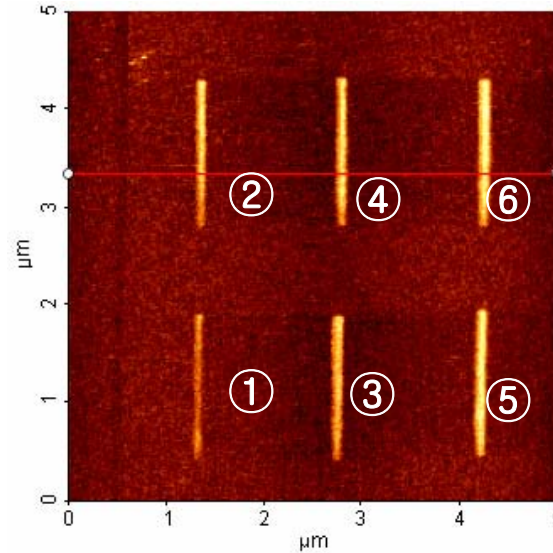
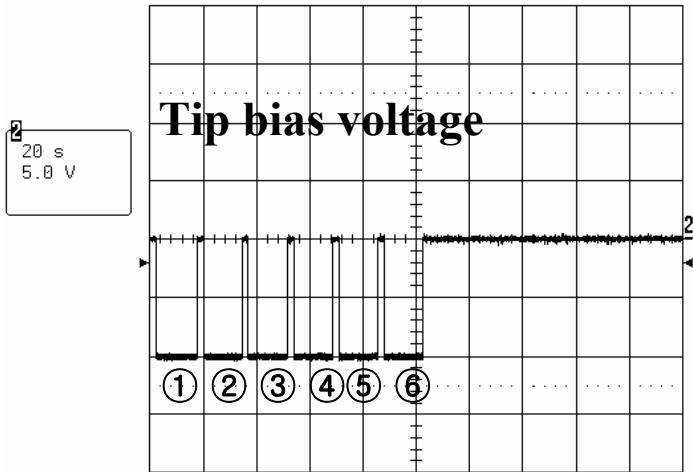
**Voltage = +15V, -15V (AC)**  
**Temperature = 23.5 °C**  
**Humidity = 50%**  
**Velocity = 10mm/s**  
**Duration time: T1+T2= 10ms**





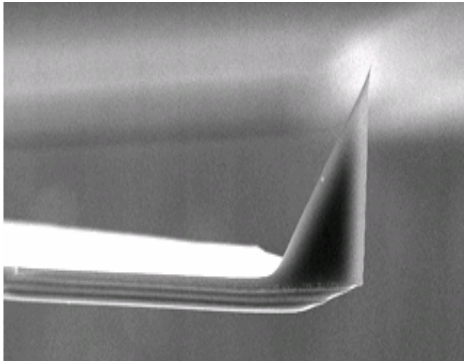
# Real-Time Current Measurement

OTFL

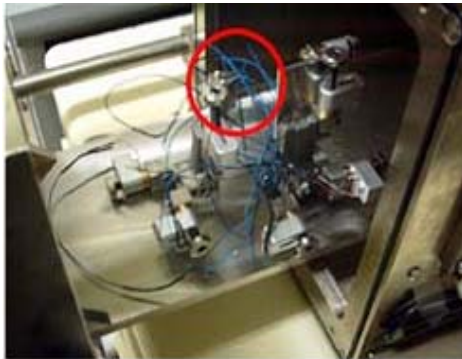
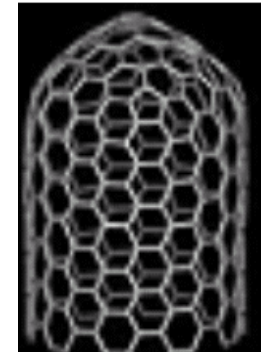
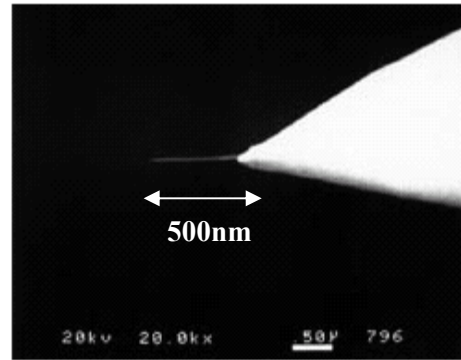


# Carbon Nanotube Tip

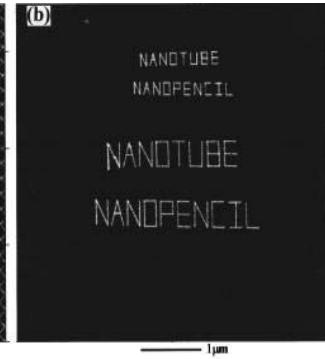
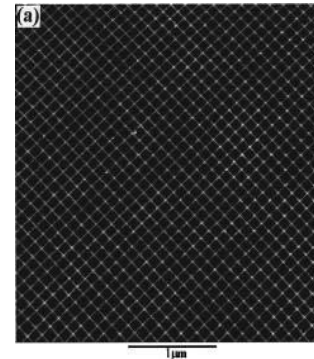
Silicon tip



MWCNT-attached tip



- Nanomanipulator -



**Advantage :** - Proper structure as a SPM tip

- High strength
- High resolution

Hongjie Dai, APL, 73, 1508 (1998)

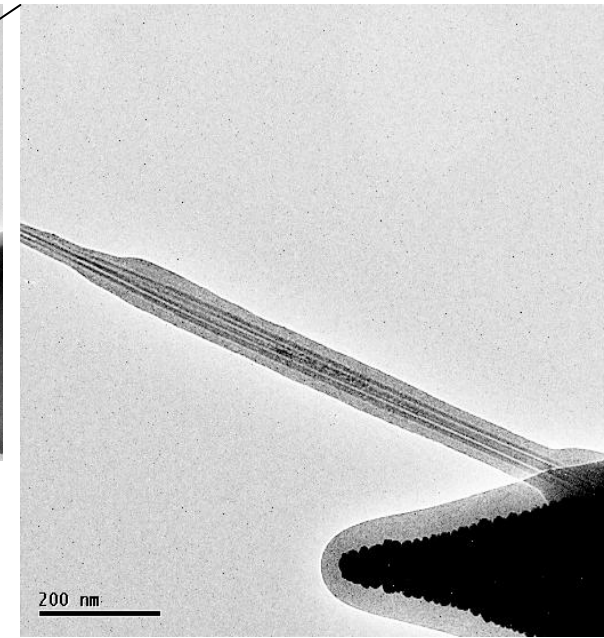
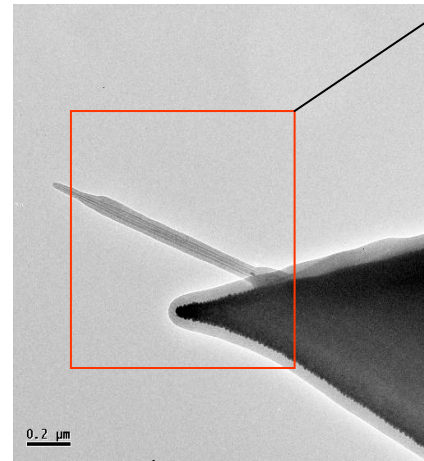
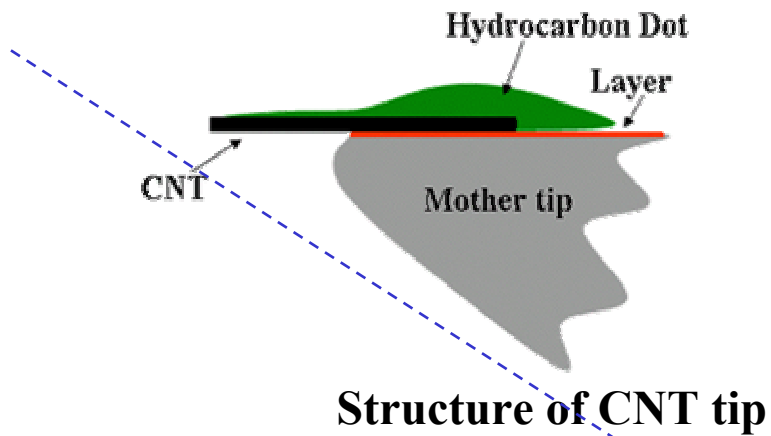
**Disadvantage :** - Long fabrication process time

- Demand of high junction technology (Increase of contact resistance)

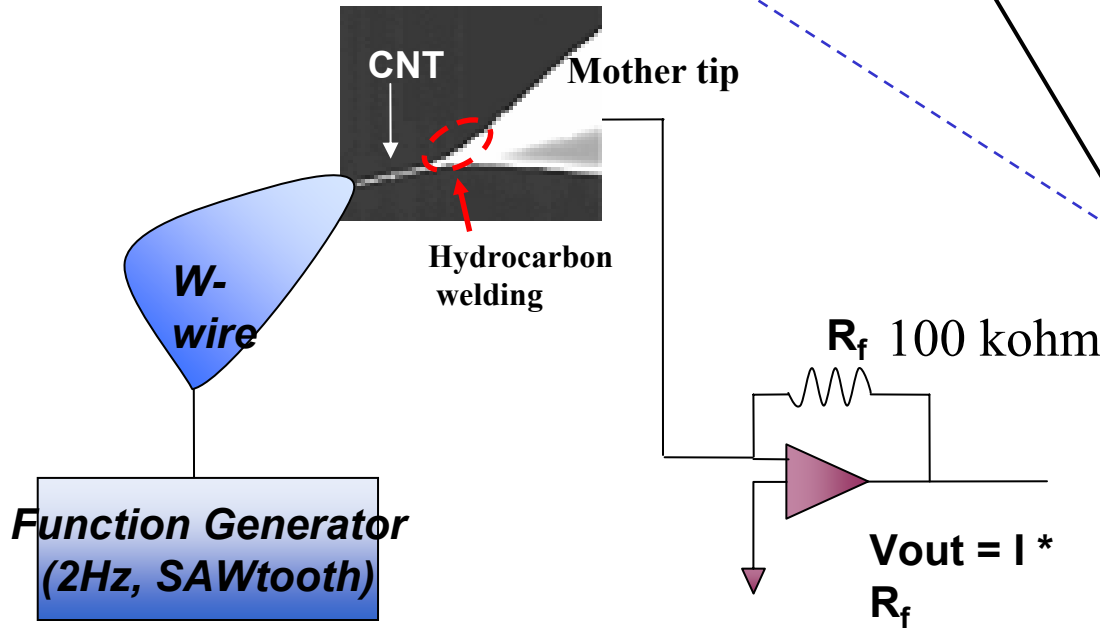
Reasonable application in the tapping mode because of high tensile strength and Young's modulus

# Carbon Nanotube (CNT) Tip

OTFL



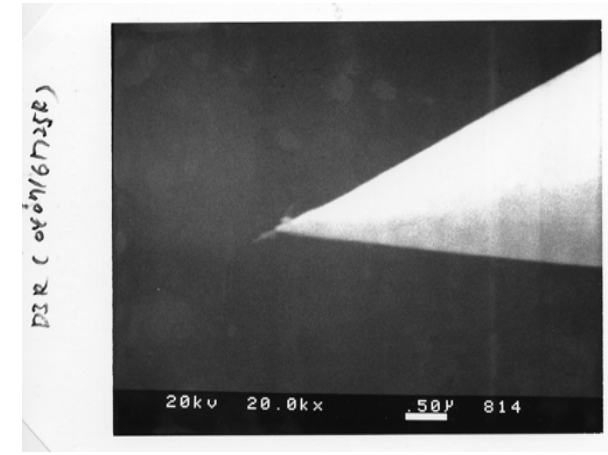
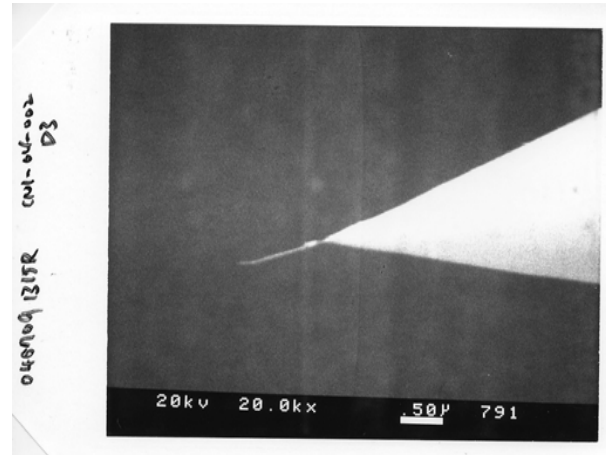
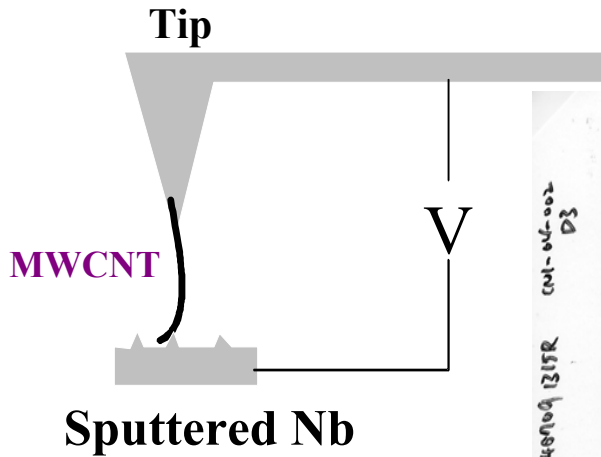
TEM photograph of CNT cut electrically in XEM manipulator.



Schematic for cutting carbon nanotube on CNT tip.

# Cutting and Length Measurement of CNT

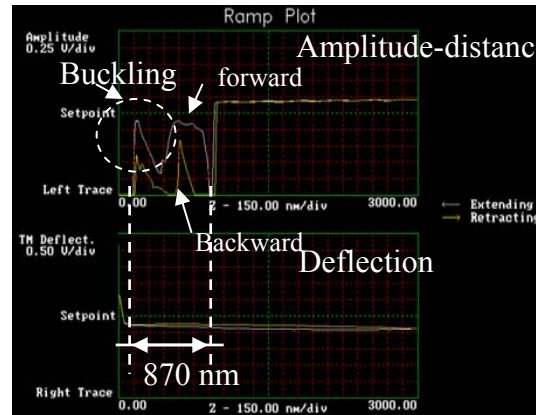
OTFL



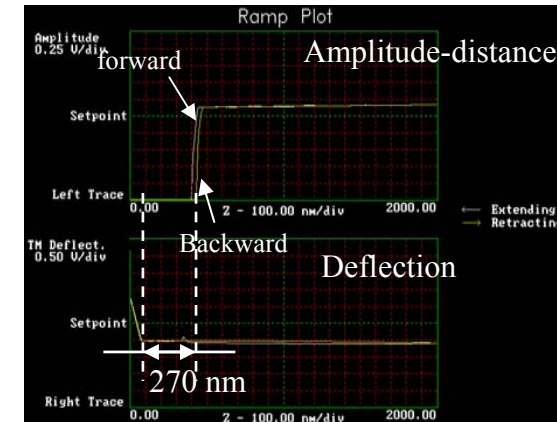
Threshold voltage: 10V

Cutting speed : 0.1~5 nm/s

CNT cutting with current discharge method



5.8div = 870nm before cutting



2.7div = 270nm after cutting

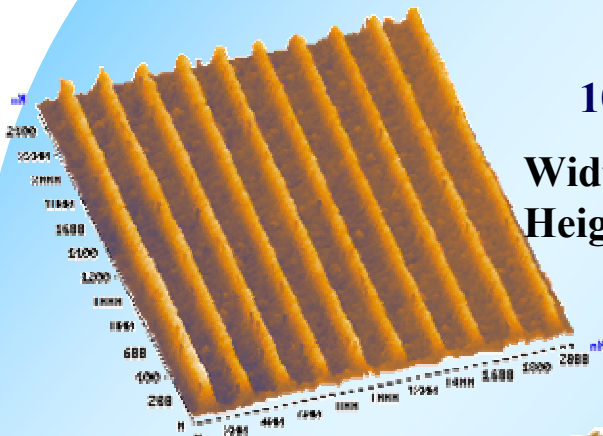
CNT tip before(left) and after(right) cut with electrical method in AFM.



# Nanostructure Fabrication Using CNT Tip

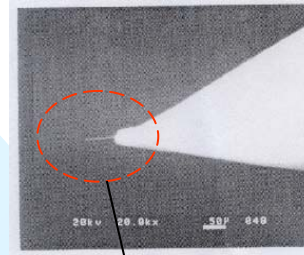
OTFL

**Bare Si**



**24 V**  
**10  $\mu\text{m/s}$**

**Width : 44 nm**  
**Height : 0.7 nm**



**CNT length :**

**Spin-cast  
monomer/Si**

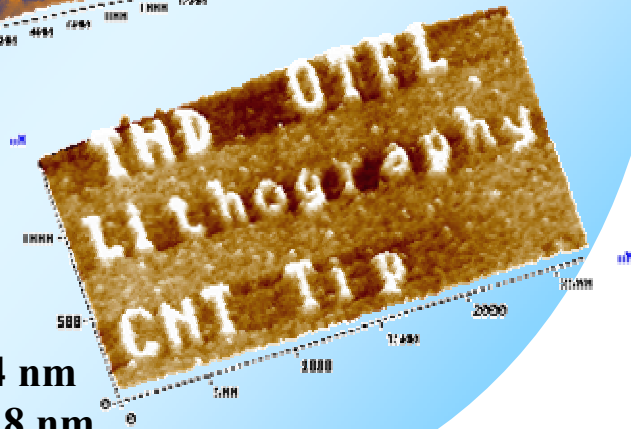


**17 V**  
**10  $\mu\text{m/s}$**

**Width : 29 nm**  
**Height : 1.3 nm**

**24 V**  
**5  $\mu\text{m/s}$**

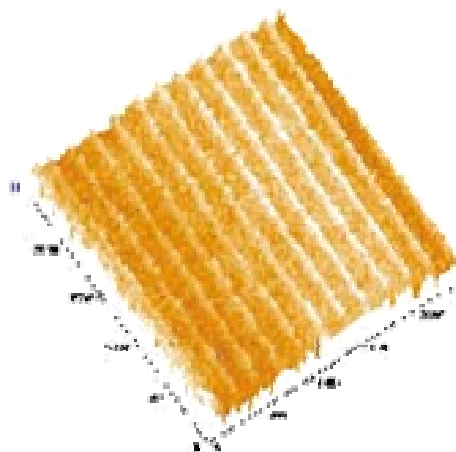
**Width : 44 nm**  
**Height : 0.8 nm**



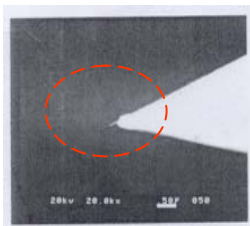
# Nanostructure Fabrication on Metal Substrates Using CNT Tip

OTFL

## Tantalum

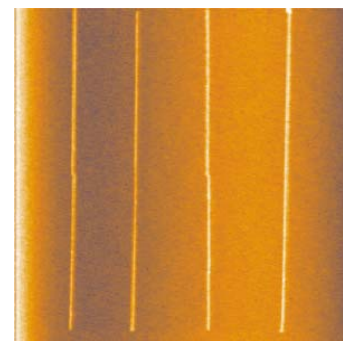


CNT length : 350 nm



Width : 35 nm,  
Height : 0.4 nm  
Voltage : 25.5 V  
Speed : 10  $\mu\text{m/s}$

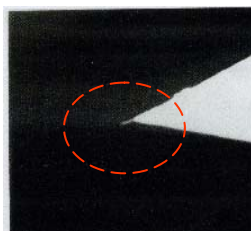
## Titanium



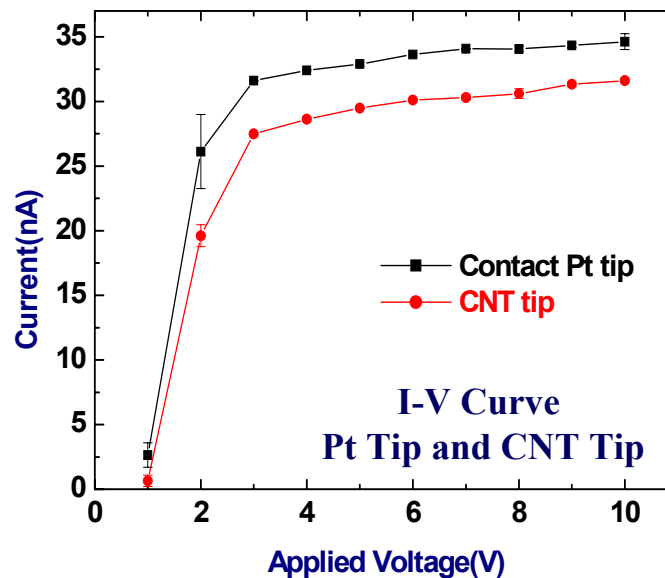
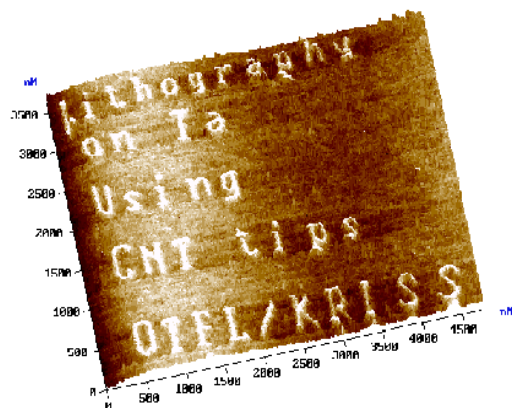
Voltage: 8 V  
10  $\mu\text{m/s}$

Width : 18 nm  
Height : 0.7 nm

CNT length : 200 nm

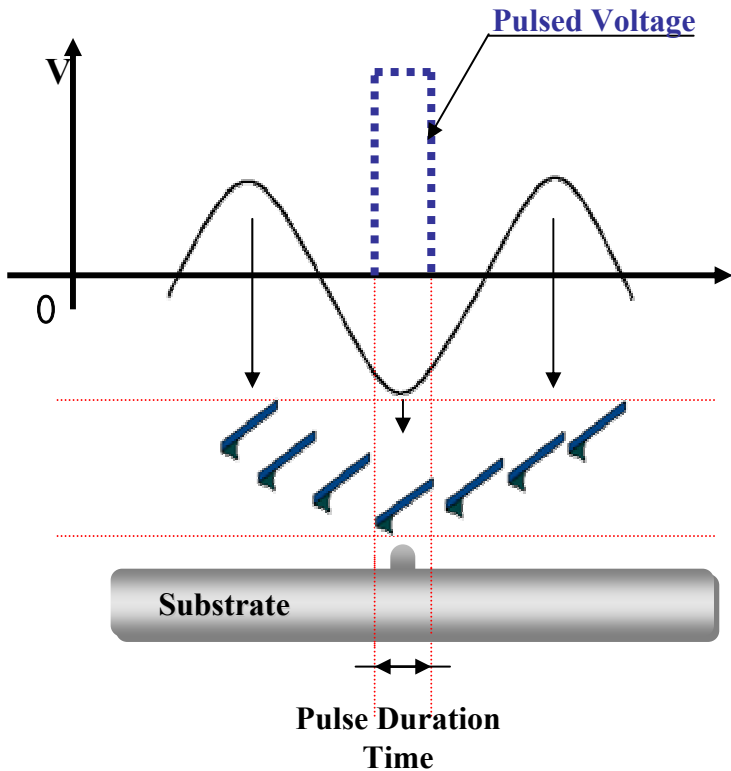
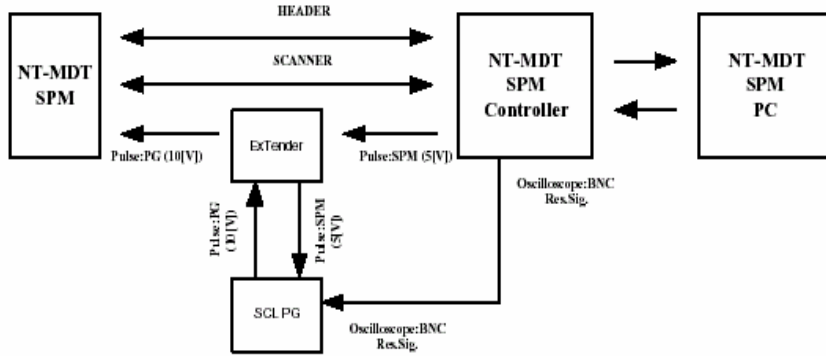


Width : 40 nm,  
Height : 0.6 nm  
Voltage : 10 V  
Speed : 10  $\mu\text{m/s}$



# Enhancement of Aspect Ratio Using Pulse Generator (Si Substrate)

OTFL



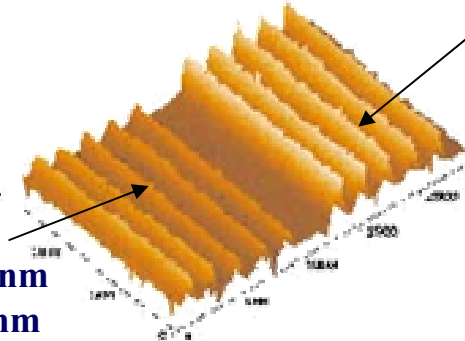
**W<sub>2</sub>C tip**

**Pulsed Bias Patterns**

**Height : 1.1 nm  
Width : 68 nm**

**DC Bias Patterns**

**Height : 0.5 nm  
Width : 64 nm**



**10 V  
10 μm/s 0.5 μs**

**CNT tip**

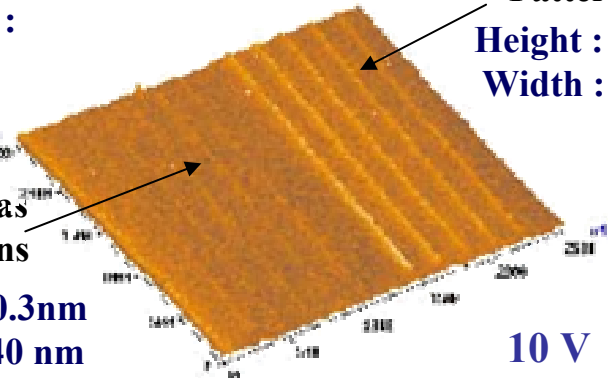
**Pulsed Bias Patterns**

**Height : 0.5 nm  
Width : 39 nm**

**CNT length :  
700nm**

**DC Bias Patterns**

**Height : 0.3nm  
Width : 40 nm**

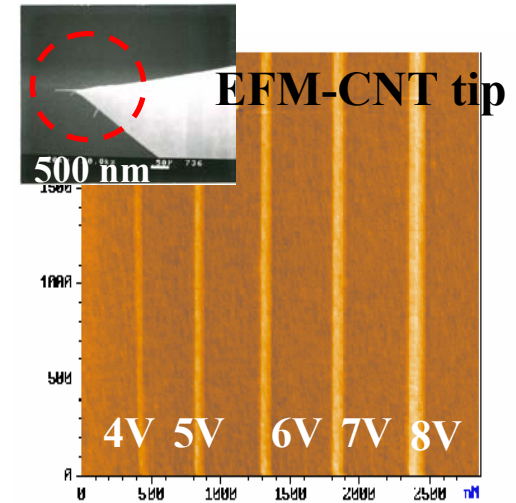
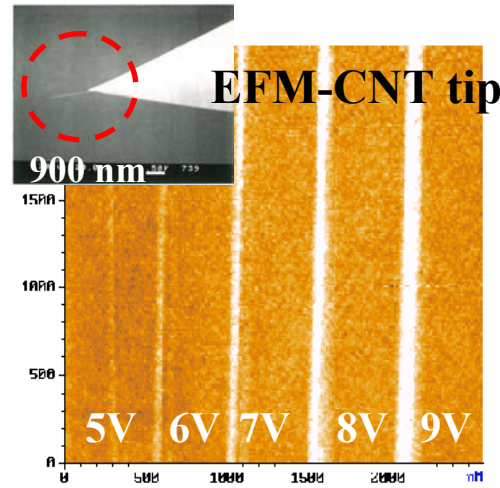
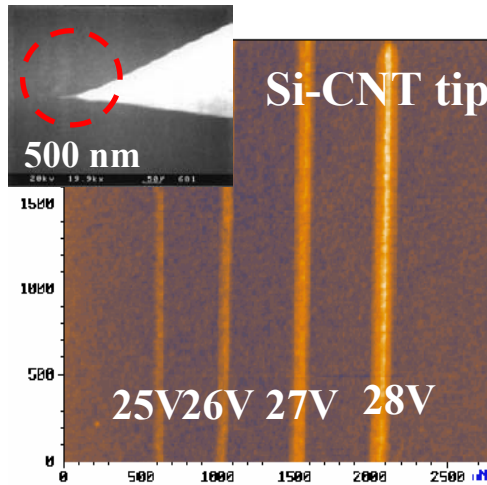


**10 V  
10 μm/s 0.7 μs**

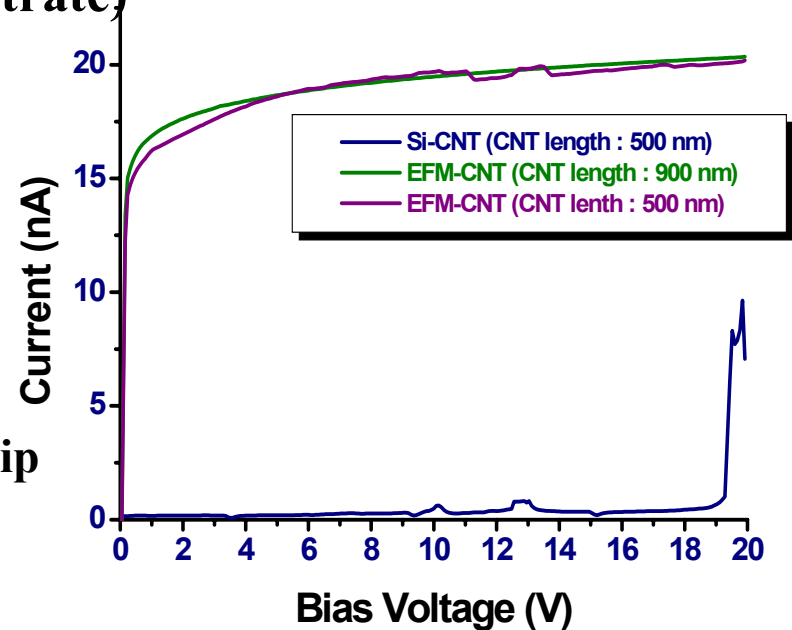
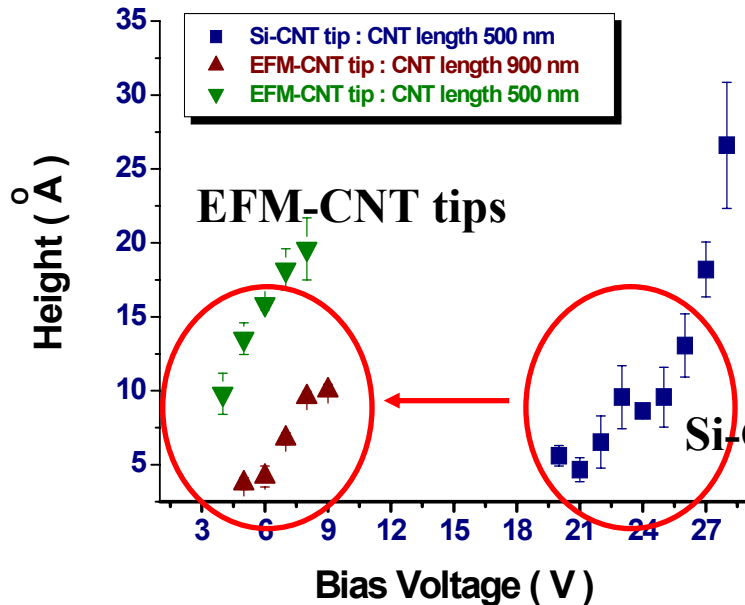


# Depression of Threshold Lithographic Voltage using EFM-CNT tip

OTFL

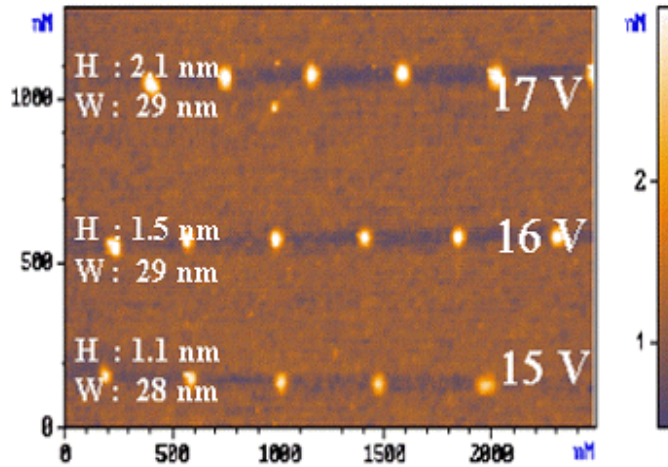


(Ta substrate)

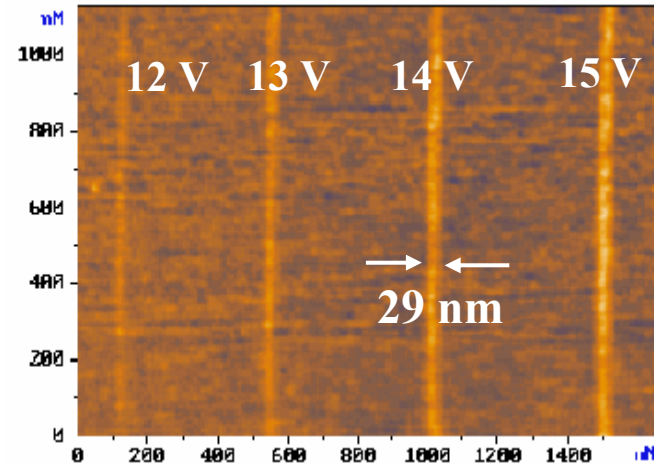


# Fabricated Dots and Line Structures using EFM-CNT Tip

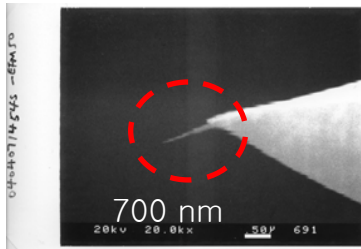
(Ta substrate)



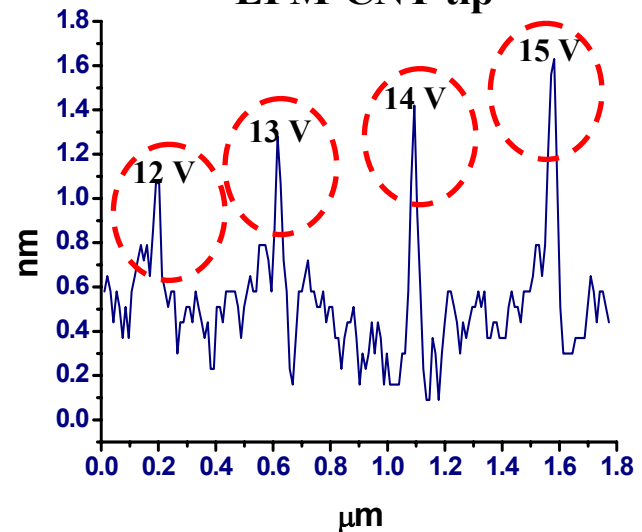
Dot oxide patterns using EFM-CNT tip



Line patterns using EFM-CNT tip

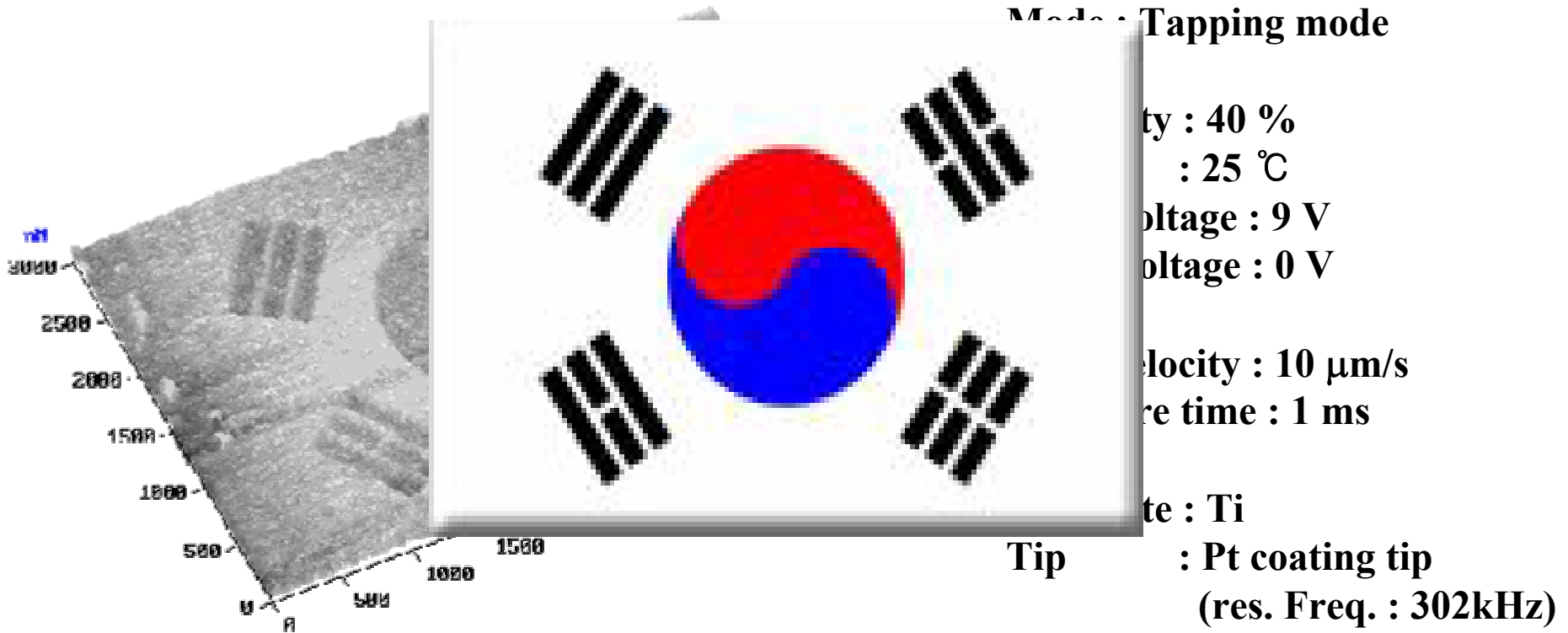


Substrate : Ta/Si  
Velocity : 10  $\mu\text{m/s}$   
Humidity : 35 %  
Temp. : 25 C



# Korean National Flag (Teageukgi)

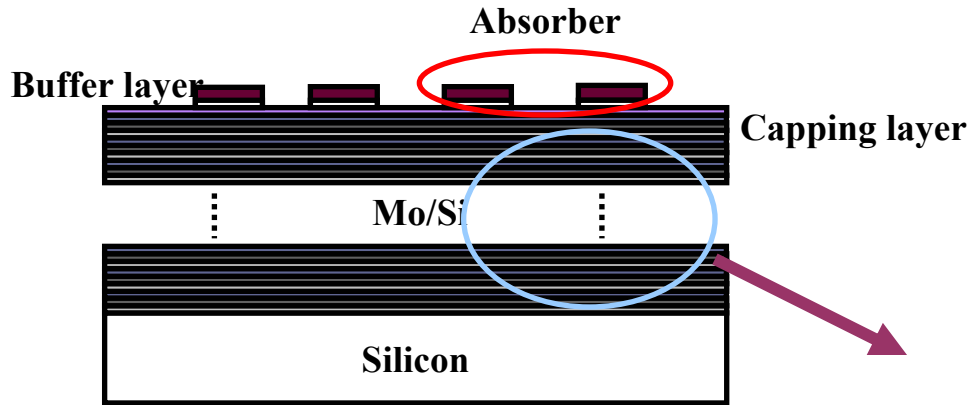
OTFL



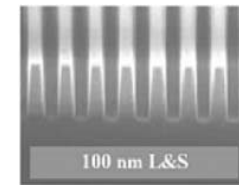
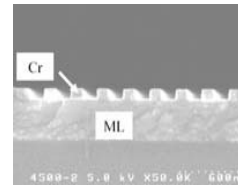
**The smallest Taegyeukgi in the world !!**

# Fabrication of EUV Photomask

## Structure of EUV mask



## Absorber materials : Cr, Ta, W



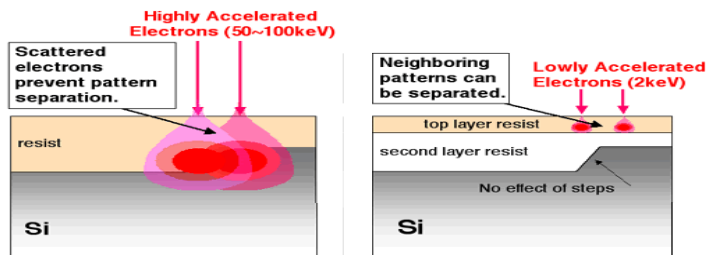
## TEM image of Mo/Si multilayer



## Structure of Photo Mask



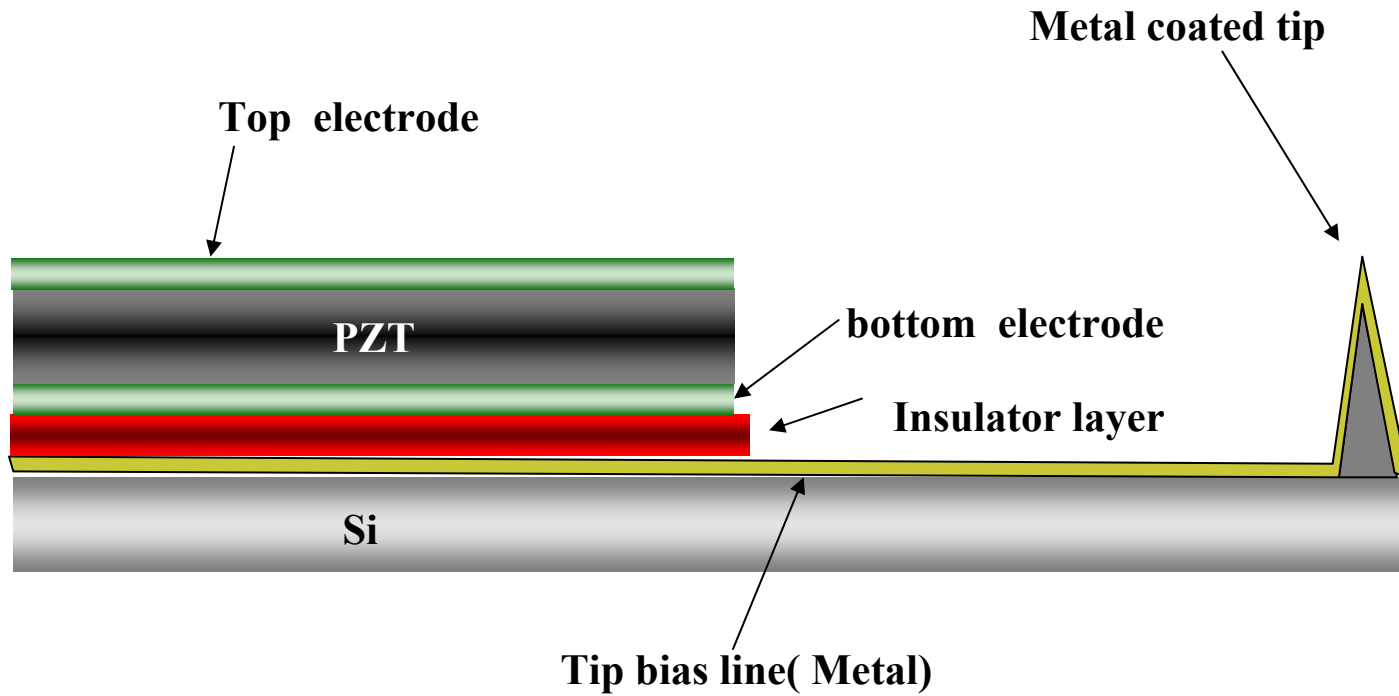
## Damage of ML and limit of pattern size (<30 nm) by electron beam



- 40 period stacking

# Fabrication of New Probe

OTFL

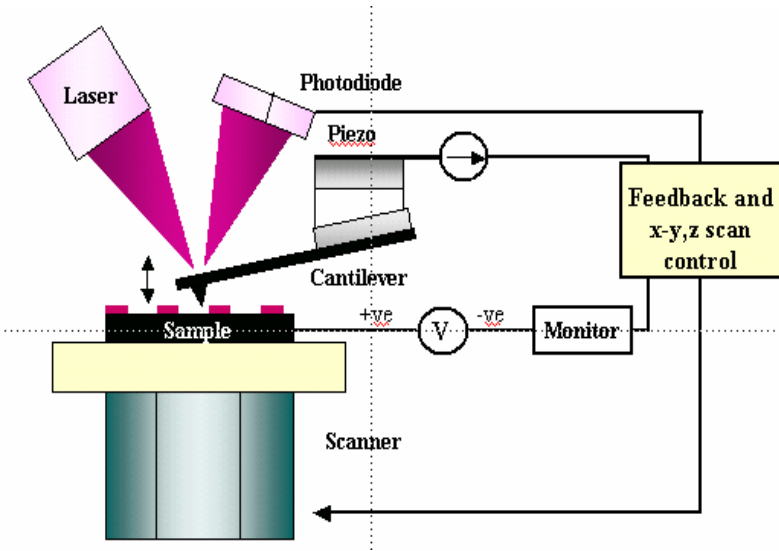


# High-speed AFM Lithography

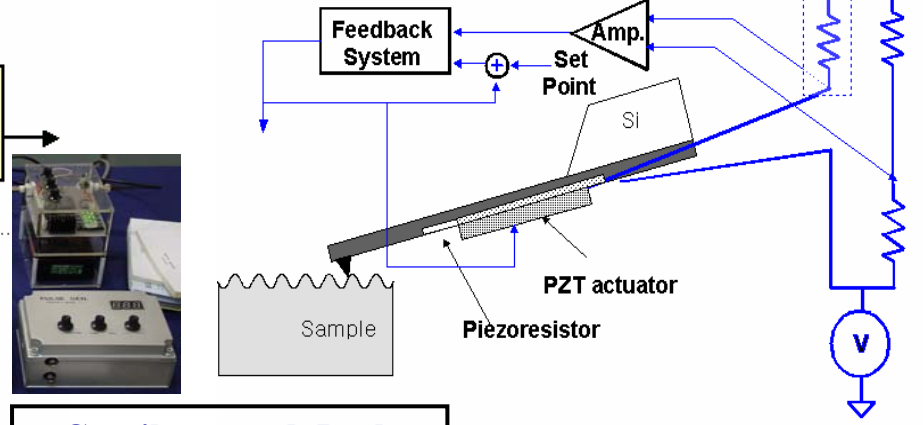
OTFL

Conventional SPM w/ PZT-tube Scanner

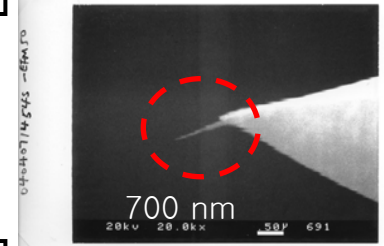
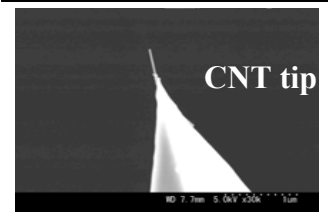
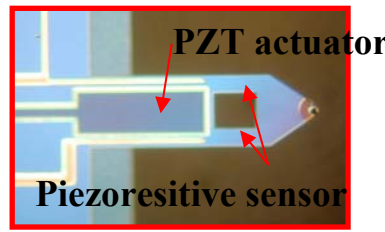
High Speed SPM w/ Self-sensing & Self-actuating Probe



## Lithography System



## Cantilever and Probe



## Resist and Patterning

