The Tenth U.S.-Korea Forum on Nanotechnology

Atomic Layer Etching : Application to Nanoelectronic Device Processing

15 Oct. 2013

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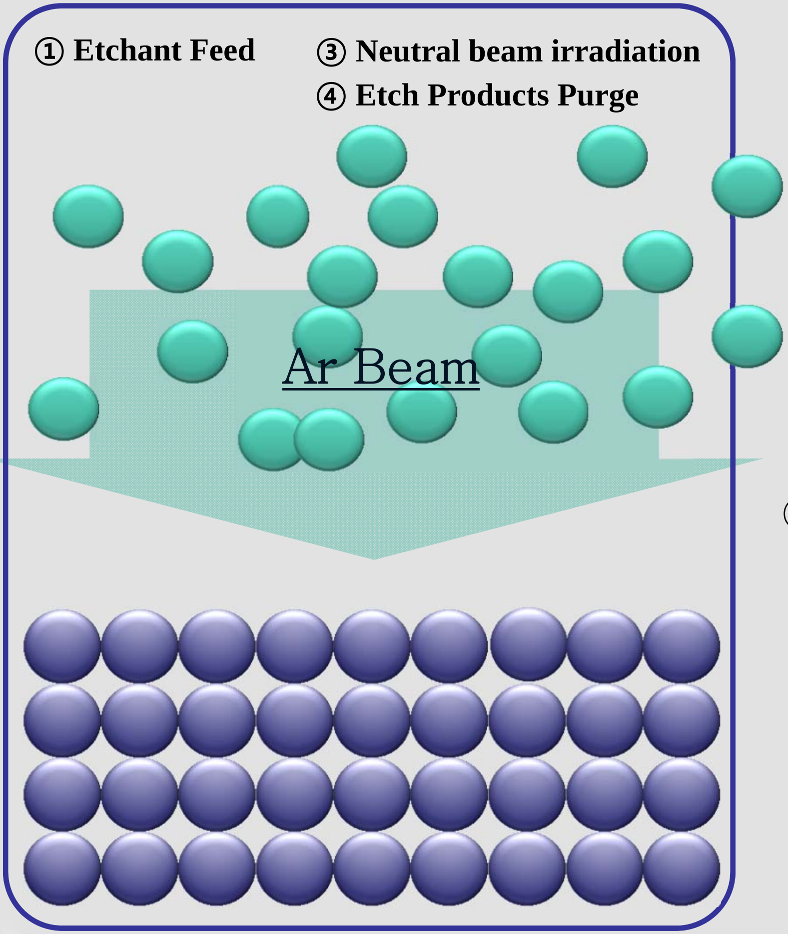
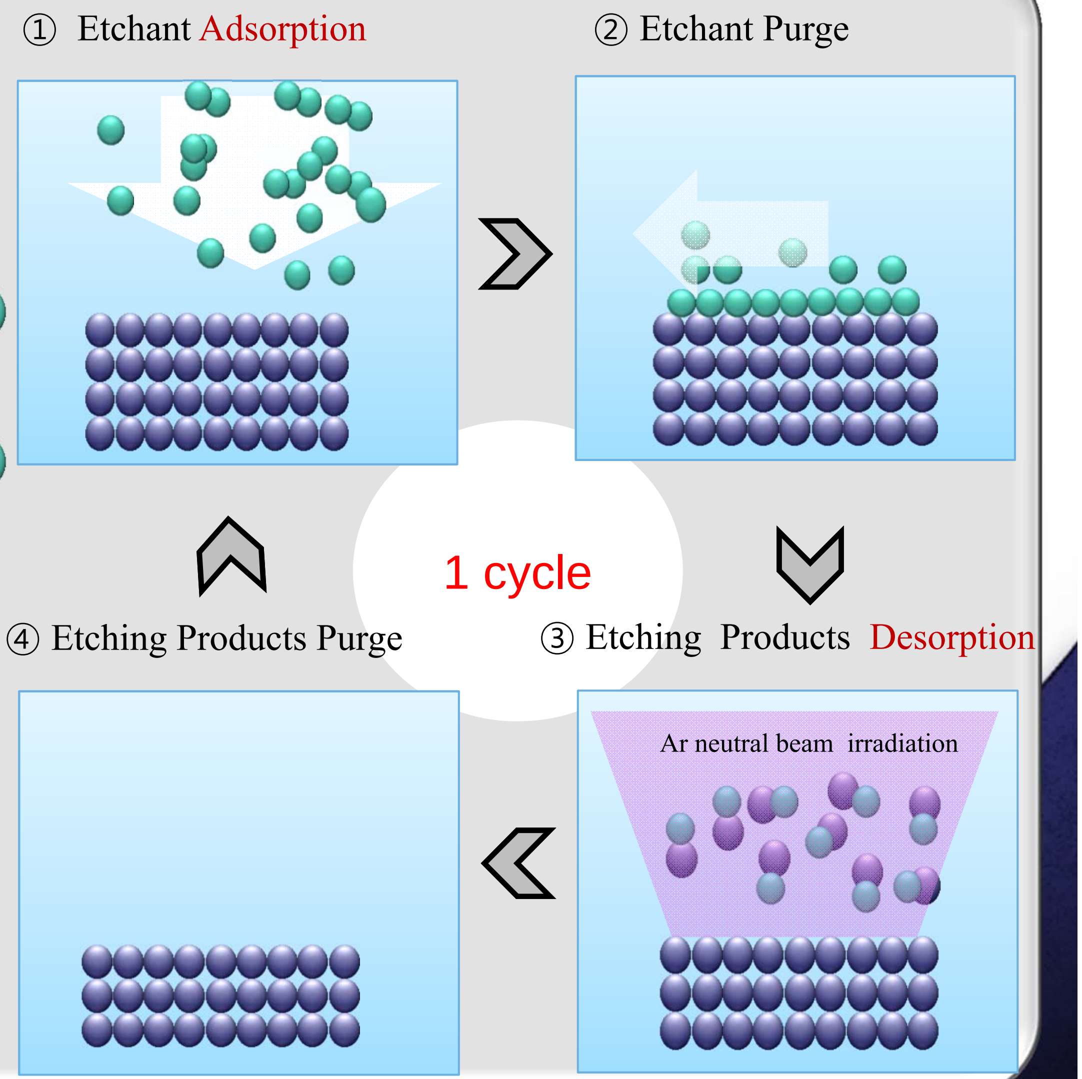
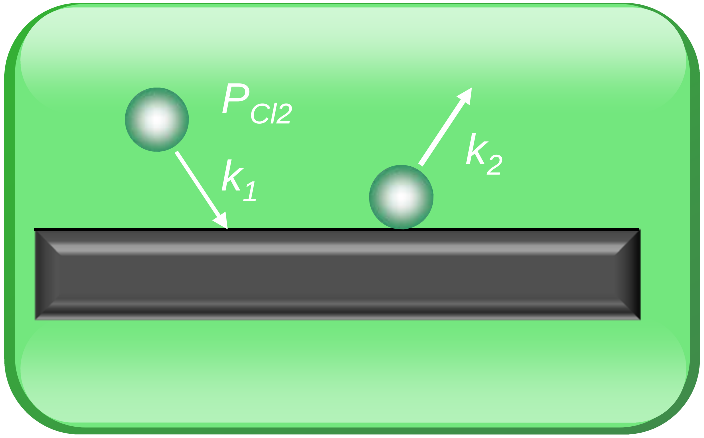
❖ Concept of ALET





Etch mechanism of atomic layer etching

◆ *Chemisorption of Cl_2 on Material*



Dissociative Langmuir isotherm chemisorption :

$$\boxed{Cl_{2(g)} + 2M_{(ad)} \xrightarrow{k_1} 2MCl_{(ad)}}$$

Coverage of the MCl precursor :

$$\boxed{k_1 = \frac{{\theta_{MCl}}^2}{(1-\theta_{MCl})^2 P_{Cl_2}}} \Rightarrow \boxed{\theta_{MCl} = \frac{\sqrt{k_1 P_{Cl_2}}}{1+\sqrt{k_1 P_{Cl_2}}}}$$

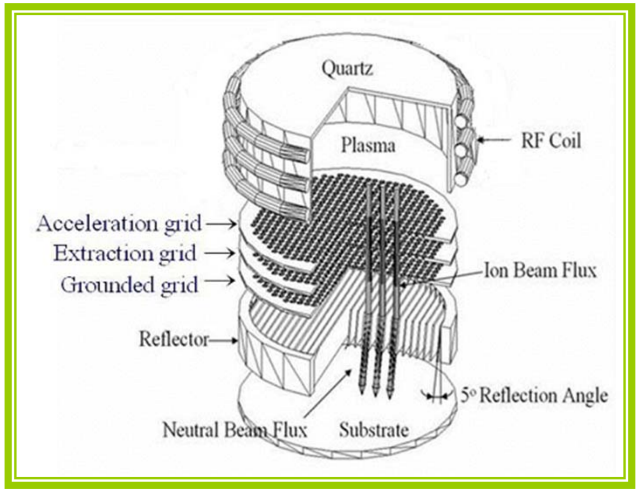
Sputtering of MCl by Ar neutral impact : $\boxed{MCl_{(ad)} \xrightarrow{k_2, Ar_{neu}} MCl_{(g)}}$

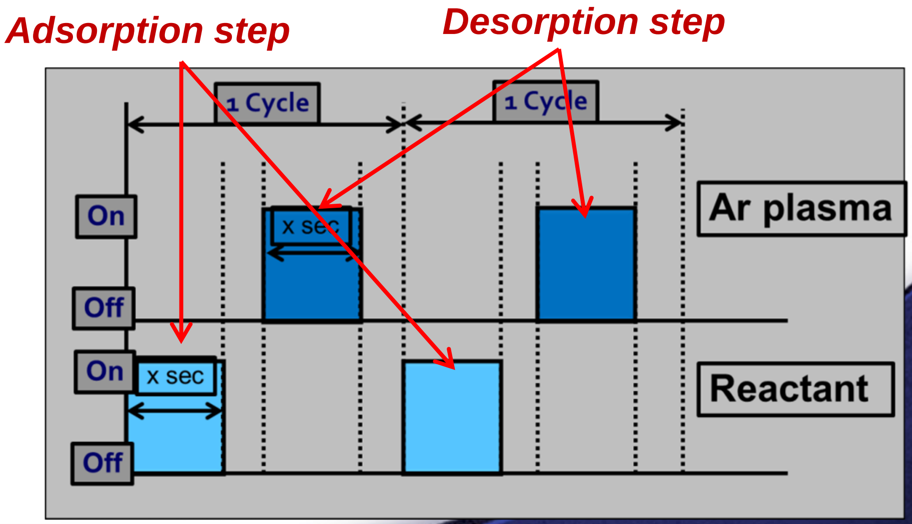
where,
k_1 : adsorption rate constant (Pa·s)$^{-1}$
k_2 : desorption rate constant (s)$^{-1}$
P_{Cl2} : Cl_2 pressure (Pa)

Sputtering rate of Cl-adsorbed Material (MCl) :

$$\boxed{f_{MCl} \propto k_2 \theta_{MCl} f_{Ar_{neu}}}$$

Experimental Equipment



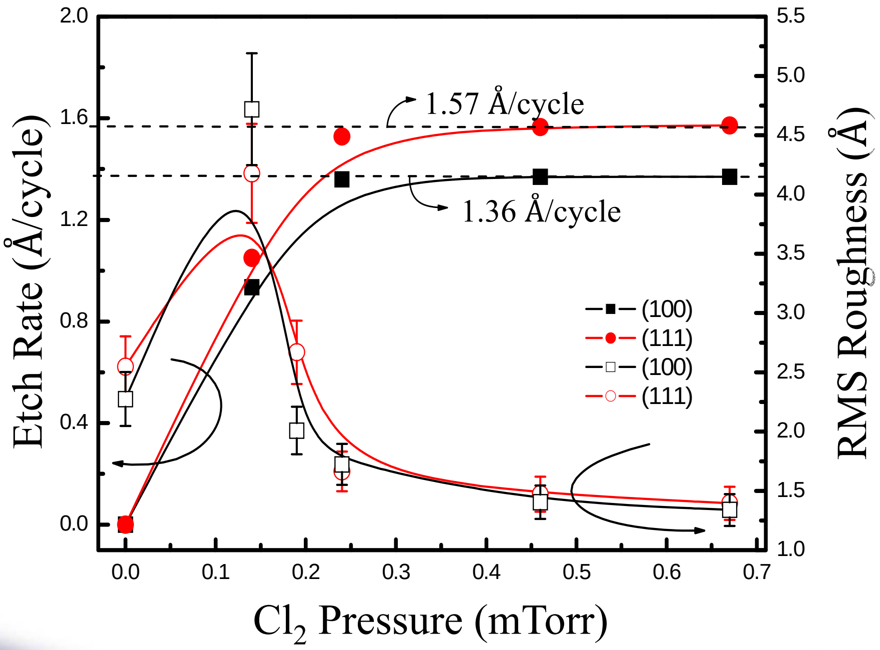


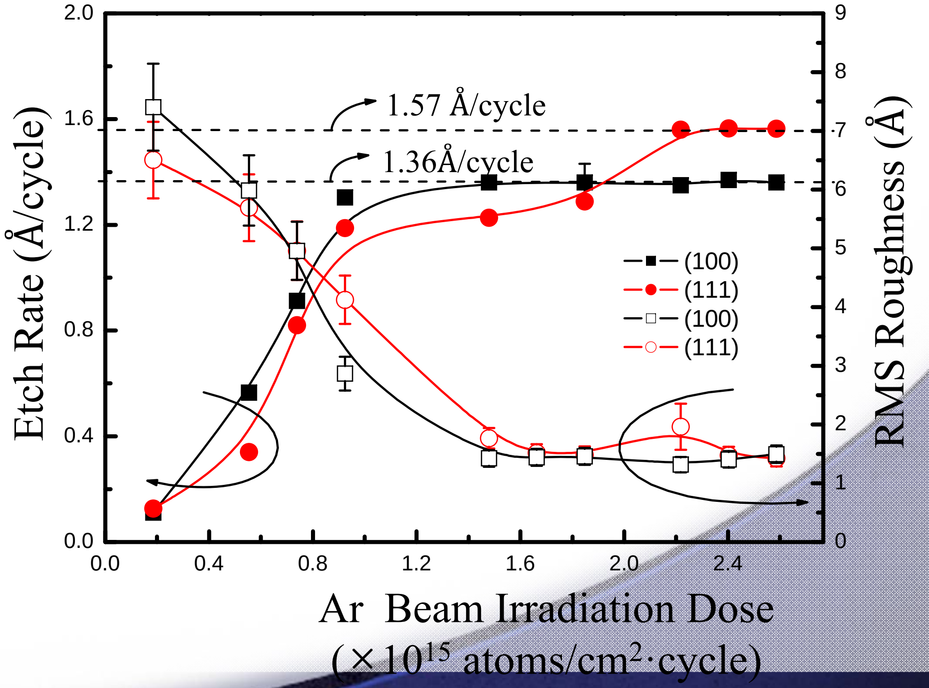
Various Application Study of ALET

Si ALET as a function of etch parameters

- *Conditions :*

Base pressure	**2.0×10^{-6} Torr**	**Chamber pressure**	**2.5×10^{-4} Torr**	**Inductive power**	**800 Watts**
Acceleration voltage	**50 Volts**	**Ar flow rate**	**10 sccm**	**Ar neutral beam irradiation dose**	**0~2.587×10^{15} atoms/cm^2·cycle**
Cl_2 pressure	**0~0.67 mTorr**	**Cl_2 supply time (t_{Cl2})**	**20 sec**	**Cycle**	**75 cycle**

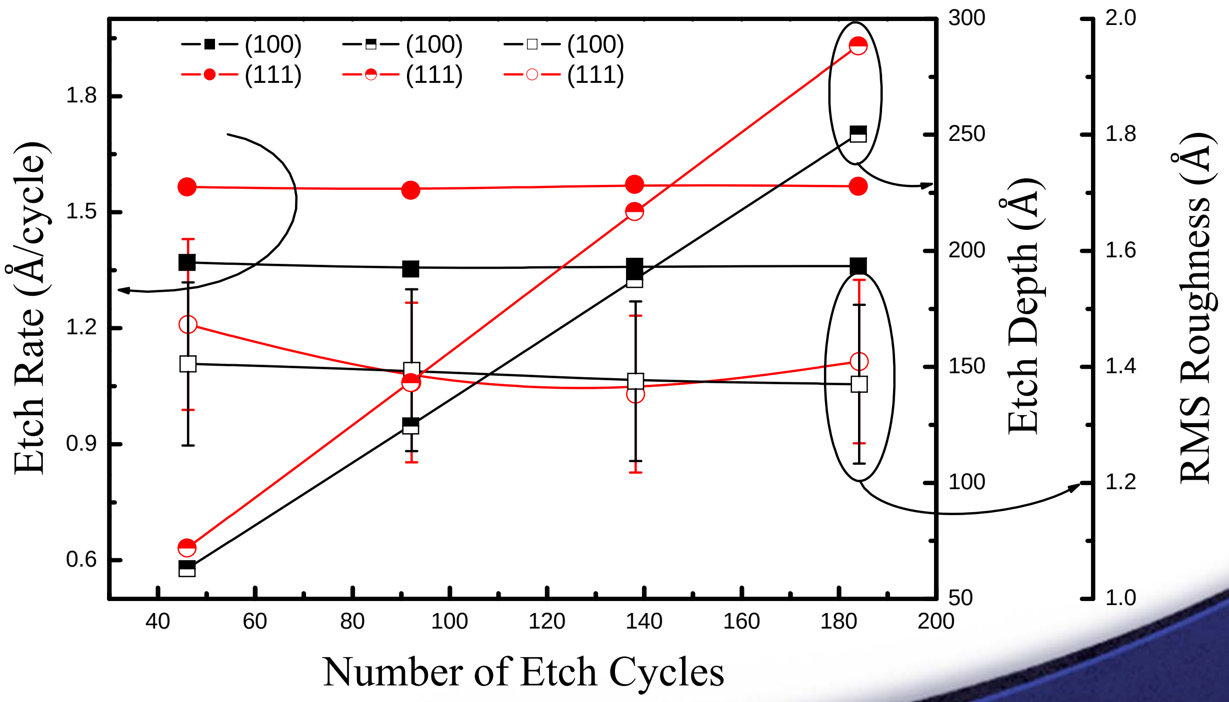




Si ALET as a function of etch cycles

- *Conditions :*

Base pressure	**2.0×10^{-6} Torr**	**Chamber pressure**	**2.5×10^{-4} Torr**	**Inductive power**	**800 Watts**
Acceleration voltage	**50 Volts**	**Ar flow rate**	**10 sccm**	**Ar beam dose**	**2.402×10^{15} atoms/cm^2·cycle**
Cl_2 pressure	**0.46 mTorr**	**Cl_2 supply time (t_{Cl2})**	**20 sec**	**Substrate temp.**	**R.T.**

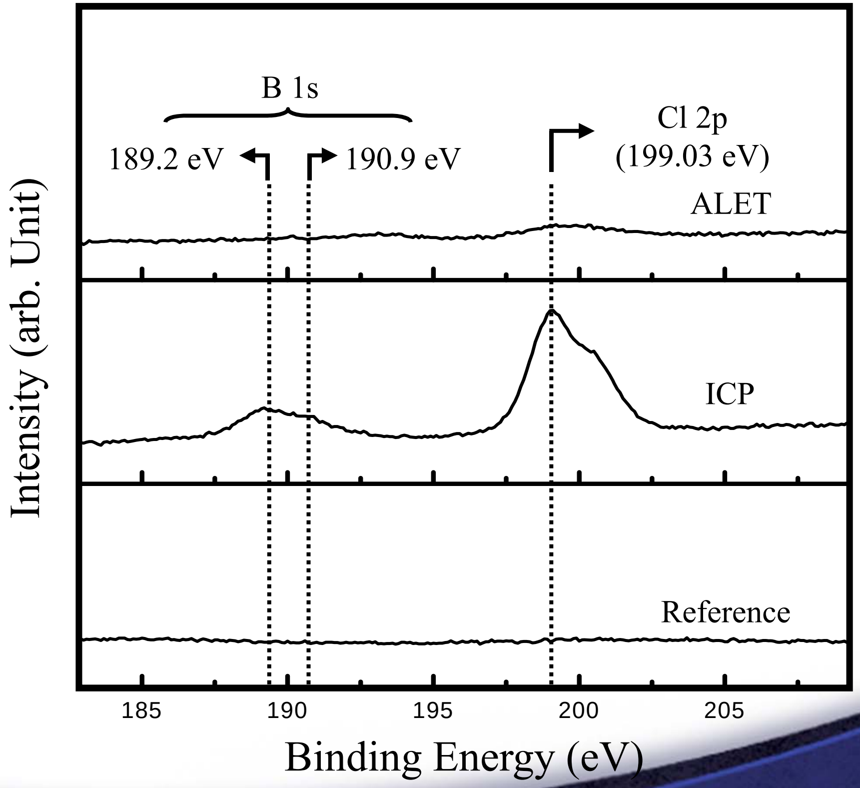


Etch residue remaining on the etched surface

- *Conditions :*

- ICP Etching : BCl_3 (50 sccm)/Ar (50 sccm), 300 W, -60 V, 12 mTorr, 149 sec

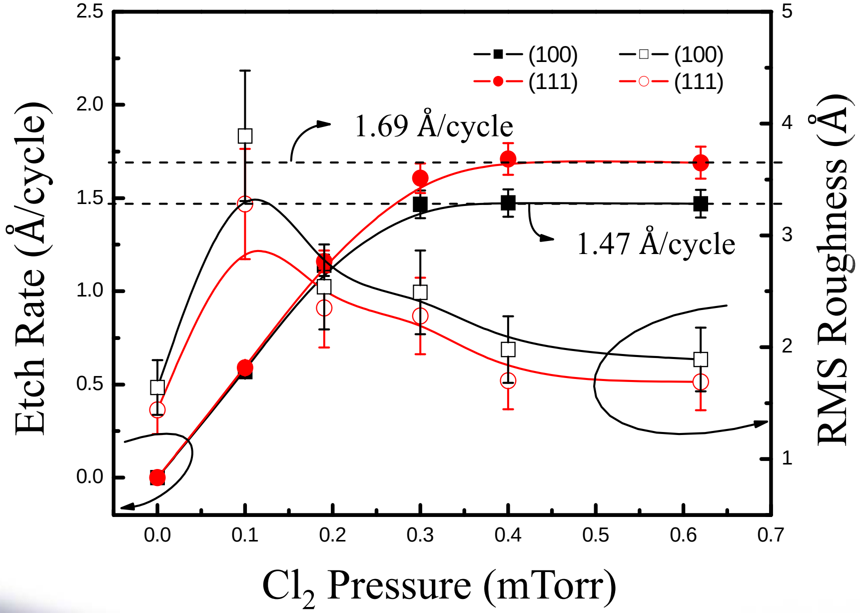
- Atomic Layer Etching : Neutral beam irradiation dose (1.485×10^{17} atoms/cm^2·cycle), BCl_3 pressure (0.33 mTorr), Etch cycle (217 cycle)

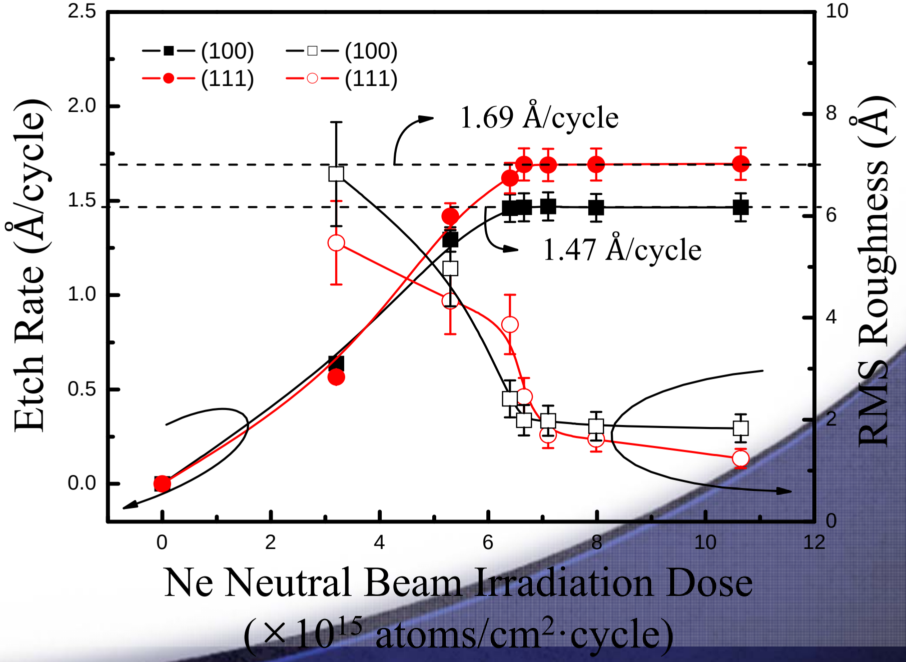


InP ALET as a function of etch parameters

- *Conditions :*

Base pressure	**3.0×10^{-7} Torr**	**Chamber pressure**	**8.9×10^{-5} Torr**	**Inductive power**	**300 Watts**
1st grid voltage	**5 Volts**	**2nd grid voltage**	**-250 Volts**	**Ne flow rate**	**70 sccm**
Ne neutral beam irradiation dose	**0~10.6×10^{15} atoms/cm^2·cycle**	**Cl_2 pressure**	**0~0.62 mTorr**	**Cl_2 supply time (t_{Cl2})**	**10 sec**



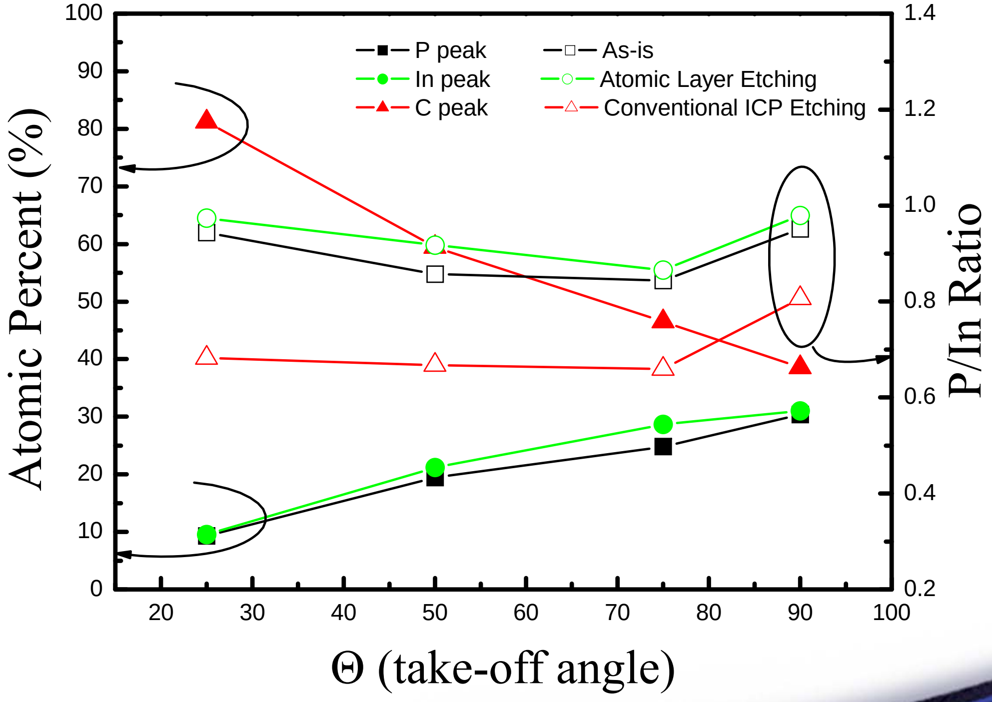


Stoichiometry modification of InP surface

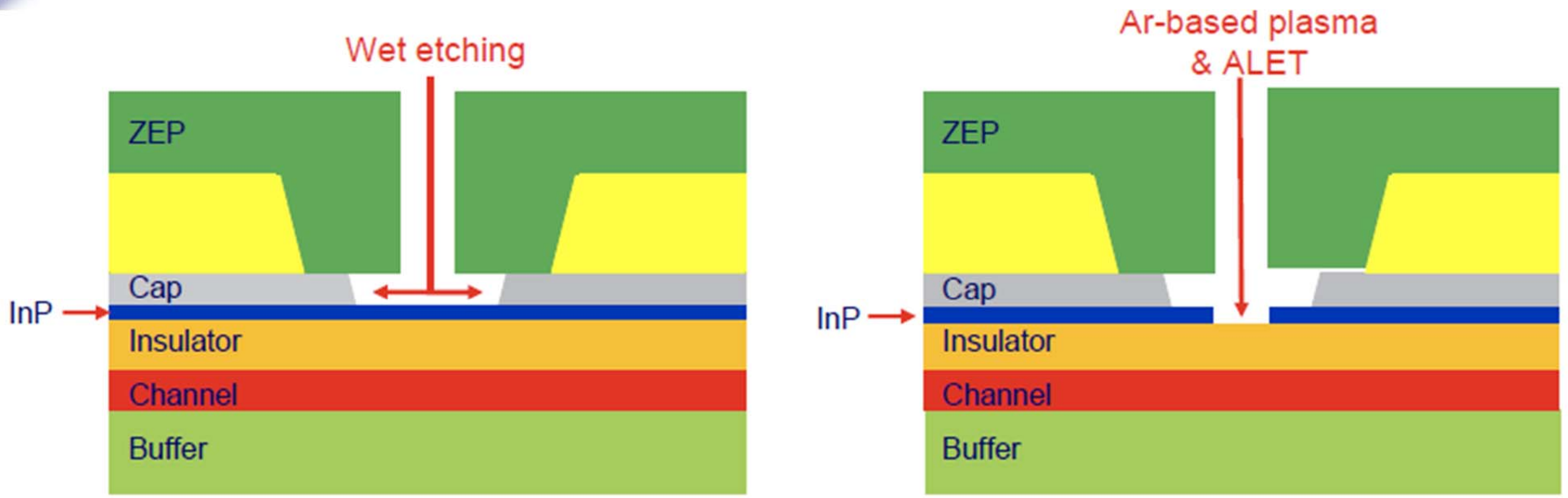
➢ *Conditions :*

- ICP Etching : Cl_2 (70 sccm)/Ar (30 sccm), 700 W, -100 V, 12 sec

- Atomic Layer Etching : Neutral beam irradiation dose (7.2×10^{15} atoms/cm^2·cycle), Cl_2 pressure (0.4 mTorr), Etch cycle (100 cycle)



Application – InP HEMTs (Gate Recess Process)



<Ref: Suemitsu et al. (IEDM 98)>

◆ Conventional gate recess process : Combination of wet & dry recess etching

- Wet recess : InGaAs cap layer; Citric Acid + H_2O_2 = 7:1
- Dry recess : InP etch stop layer; Ar RIE (Ar (50 sccm), 7 W, -65 V, 20 mTorr)

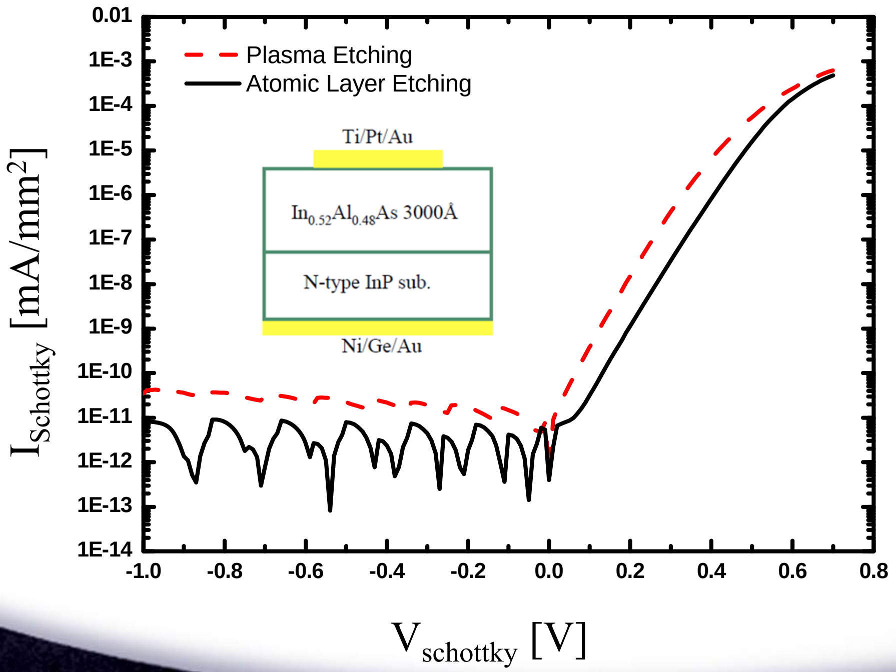
InP HEMTs (Gate Recess Process)

Schottky Diode Characteristics

- *Conditions :*

- Plasma Etching : Ar (50 sccm), 7 W, -65 V, 20 mTorr, 20 min

- Atomic Layer Etching : Neutral beam irradiation dose (7.2×10^{15} atoms/cm^2·cycle), Cl_2 pressure (0.4 mTorr), Etch cycle (62 cycle)



	Ideality factor (η)	Schottky barrier height (Φ_B)
Plasma Etching	1.25	0.56 eV
Atomic Layer Etching	1.17	0.64 eV

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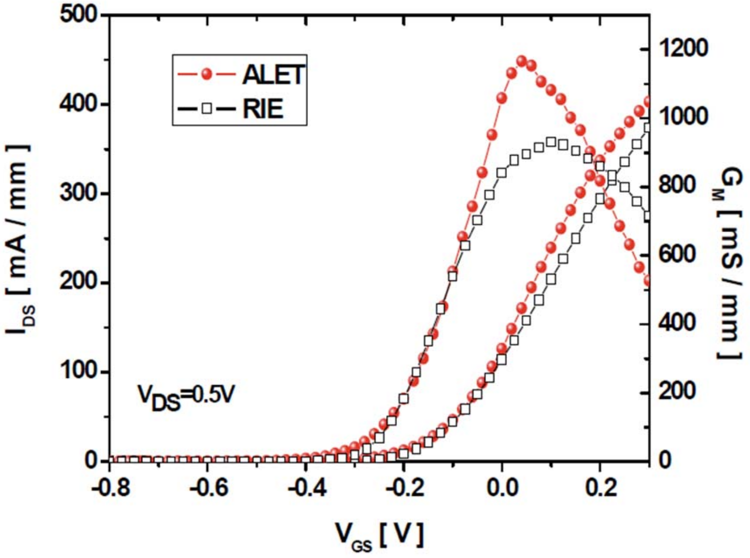
60-nm depletion mode InP HEMT

- *Conditions :*

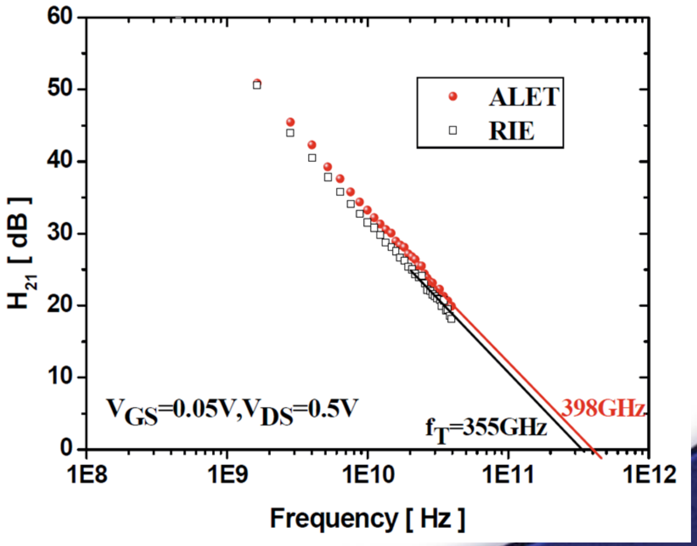
- Plasma Etching : Ar (50 sccm), 7 W, -65 V, 20 mTorr, 15 min

- Atomic Layer Etching : Neutral beam irradiation dose (7.2×10^{15} atoms/cm^2·cycle), Cl_2 pressure (0.4 mTorr), Etch cycle (41 cycle)

DC Characteristics



RF characteristics

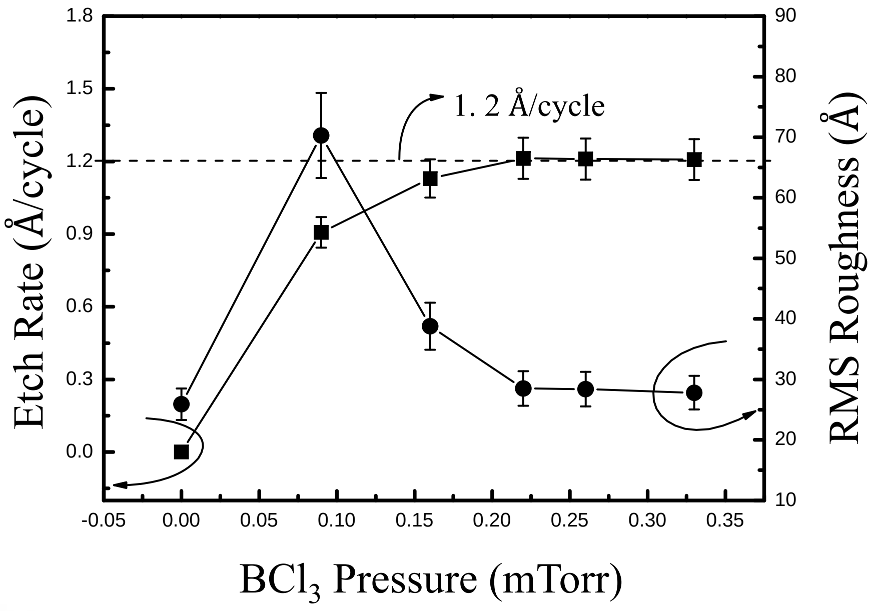


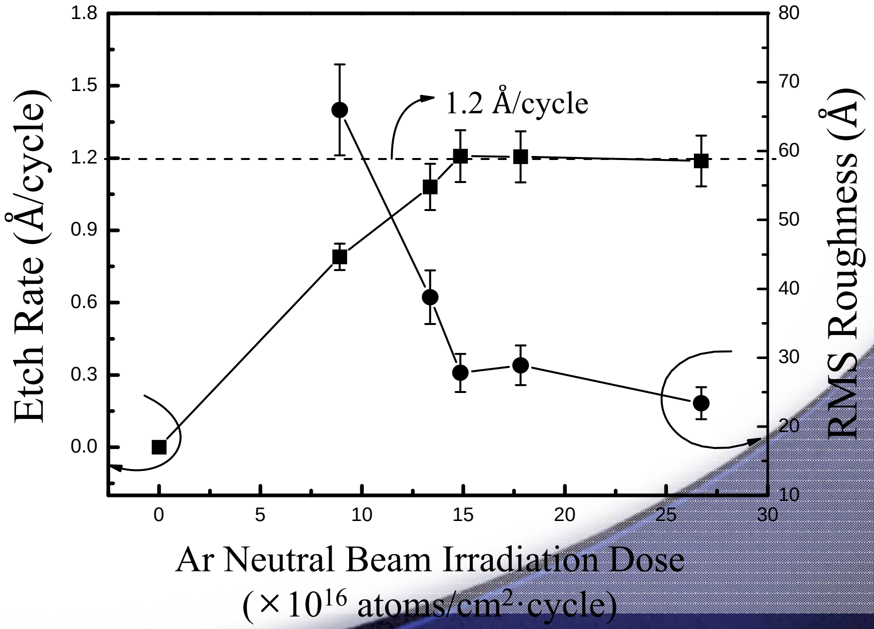
$G_{M,Max}$ of the p-HEMTs fabricated by the ALET process was larger than that using Ar-based RIE by 21%

HfO_2 ALET

- *Conditions :*

Base pressure	**3.0×10^{-7} Torr**	**Chamber pressure**	**2.0×10^{-4} Torr**	**Inductive power**	**300 Watts**
1st grid voltage	**60 Volts**	**2nd grid voltage**	**-250 Volts**	**Ar flow rate**	**30 sccm**
Ar neutral beam Irradiation dose	**$0\sim2.67\times10^{17}$ atoms/cm$^2\cdot$cycle**	**BCl_3 pressure**	**0~0.33 mTorr**	**BCl_3 supply time (t_{Cl2})**	**20 sec**

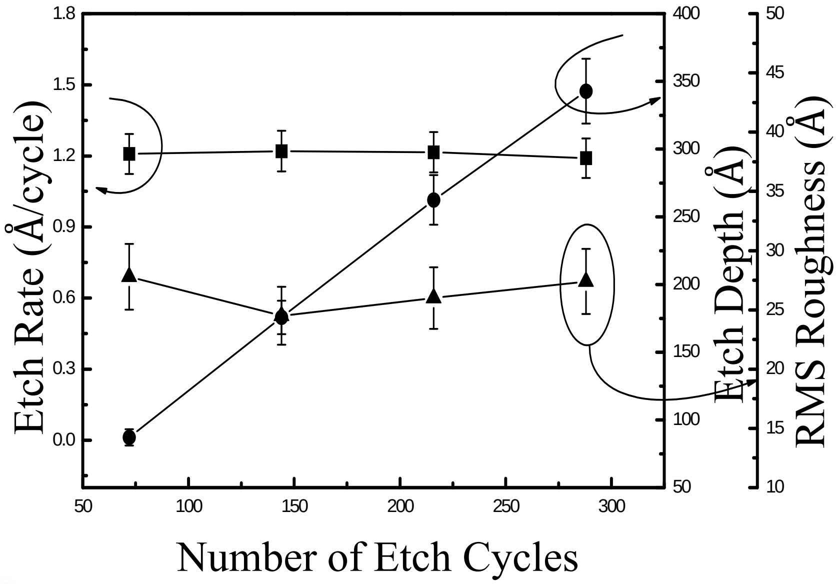


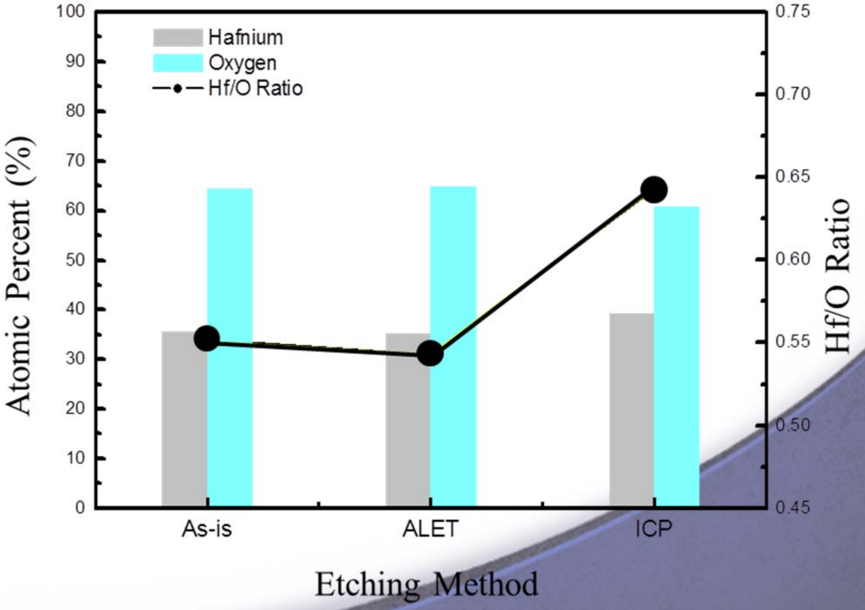


HfO_2 ALET

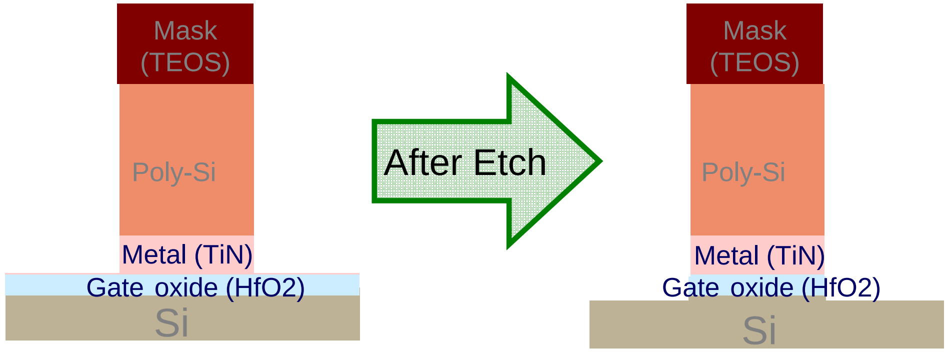
- *Conditions :*

Base pressure	**3.0×10^{-7} Torr**	**Chamber pressure**	**2.0×10^{-4} Torr**	**Inductive power**	**300 Watts**
1^{st} grid voltage	**60 Volts**	**2^{nd} grid voltage**	**-250 Volts**	**Ar flow rate**	**30 sccm**
Ar neutral beam Irradiation dose	**1.485×10^{17} atoms/cm^2·cycle**	**BCl_3 pressure**	**0.33 mTorr**	**BCl_3 supply time (t_{Cl2})**	**20 sec**





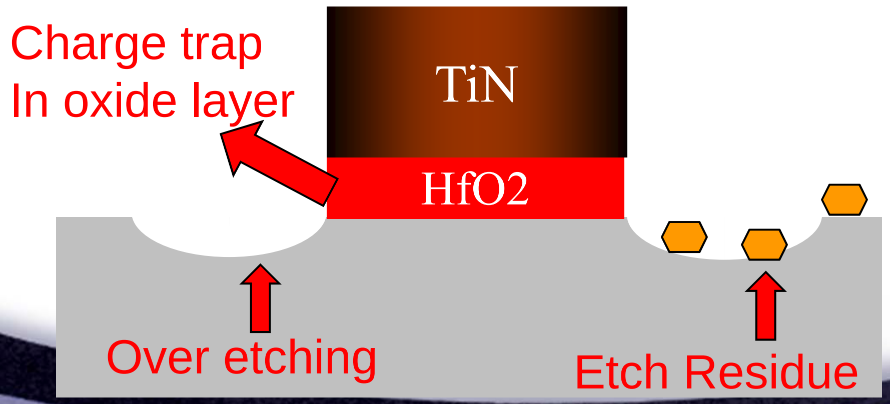
MOSFET fabrication with HfO_2 ALET



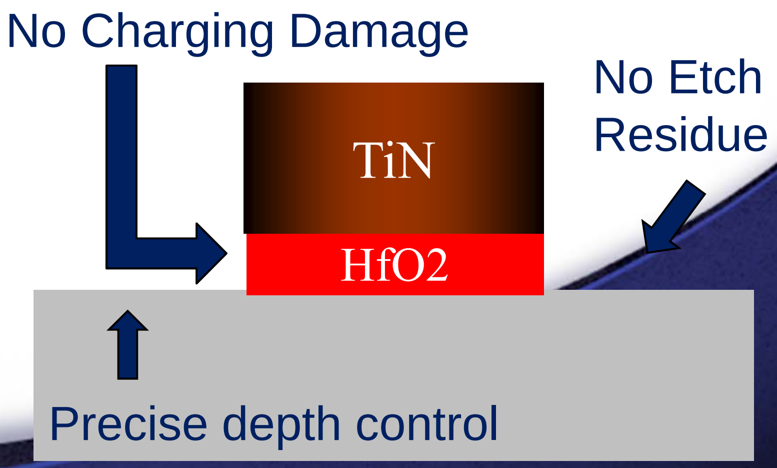
<Main etch challenges>

- Gate dimensions down to less than 30 nm
- CD control better than 2 nm required
- Low silicon recess (~ 1 nm)

<Convention RIE etcher>

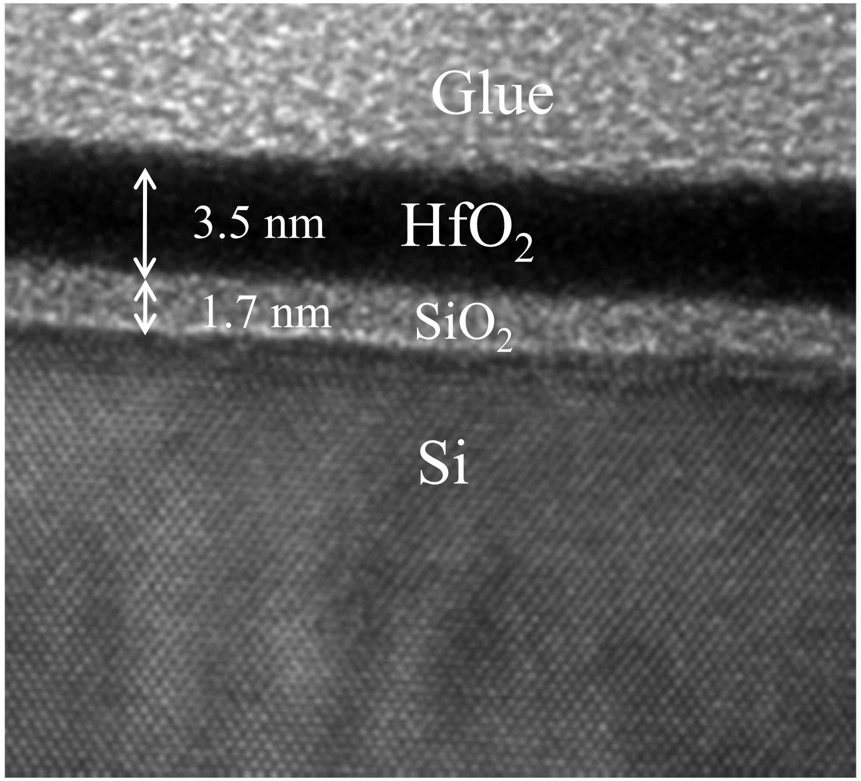


<Atomic layer etcher>

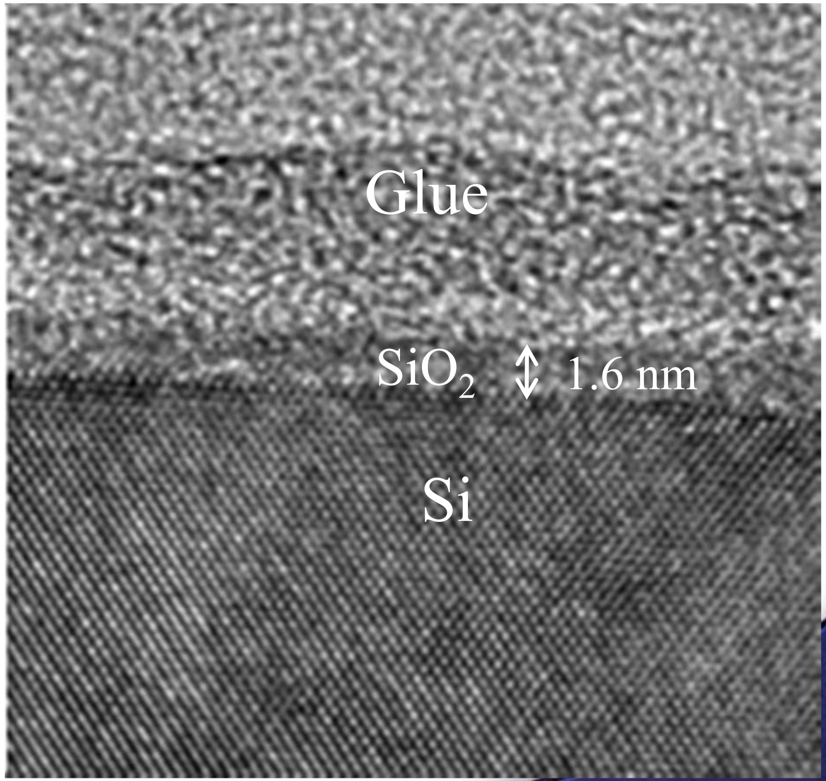


TEM Image of HfO_2 etched by ALET

✓ **Precise Etching of HfO_2 on SiO_2 using ALET**
: Blank wafer (HfO_2 on SiO_2] etching

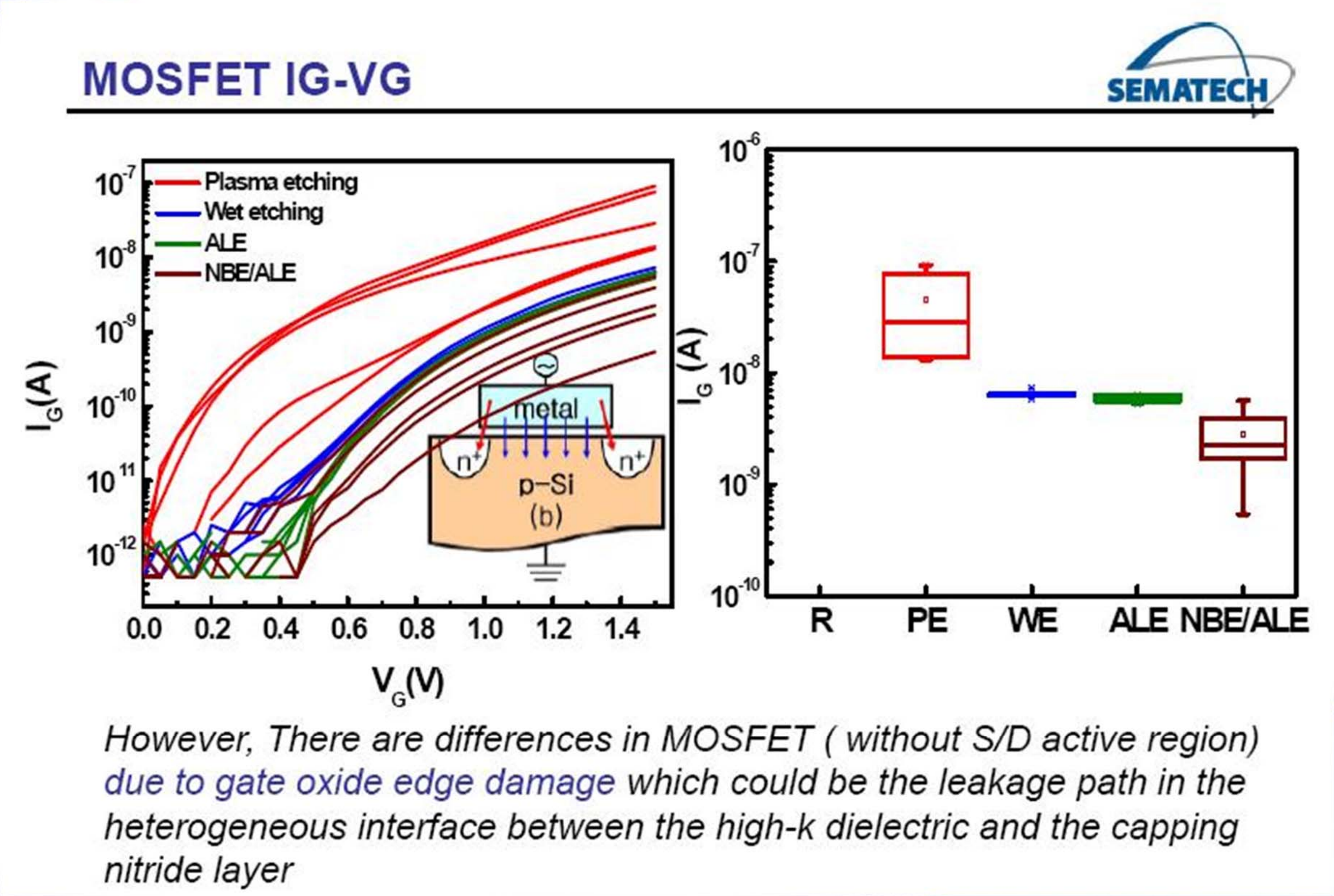


Before ALET Process



After 30 Cycle of ALET

MOSFET device results



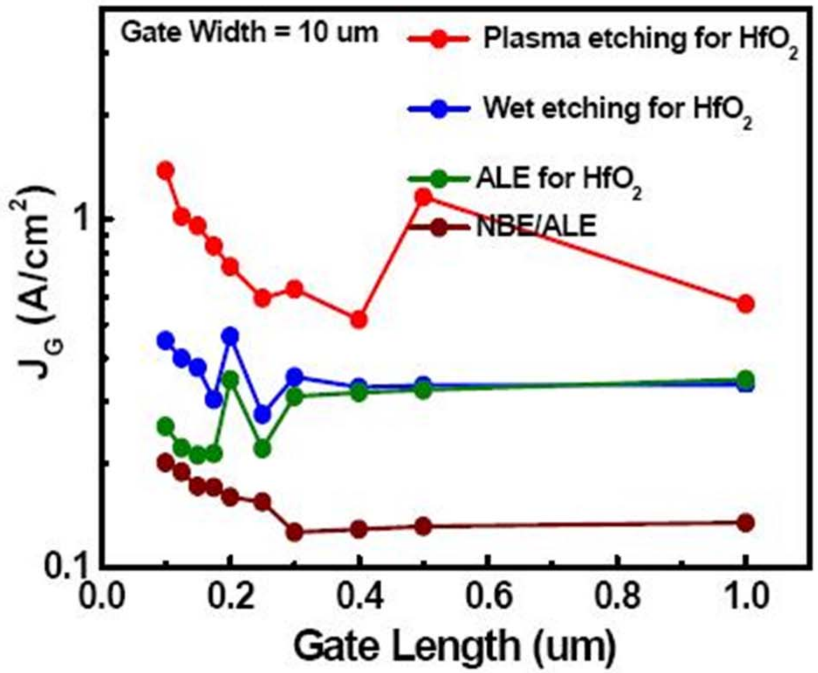
MOSFET IG-VG

However, There are differences in MOSFET (without S/D active region) due to gate oxide edge damage which could be the leakage path in the heterogeneous interface between the high-k dielectric and the capping nitride layer

MOSFET device as a function of gate length

MOS Parameter – IG

SEMATECH



As gate length decrease from 1um to 100nm, the gate leakage current is as low as wet etching compared that of plasma etching.

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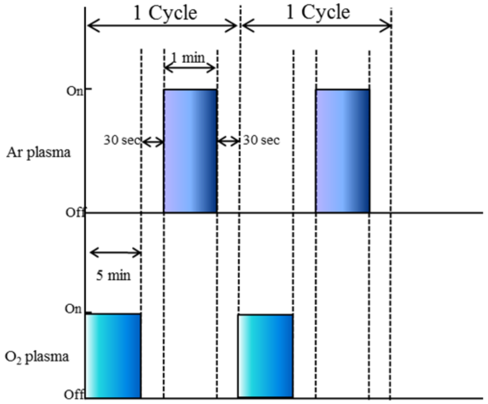
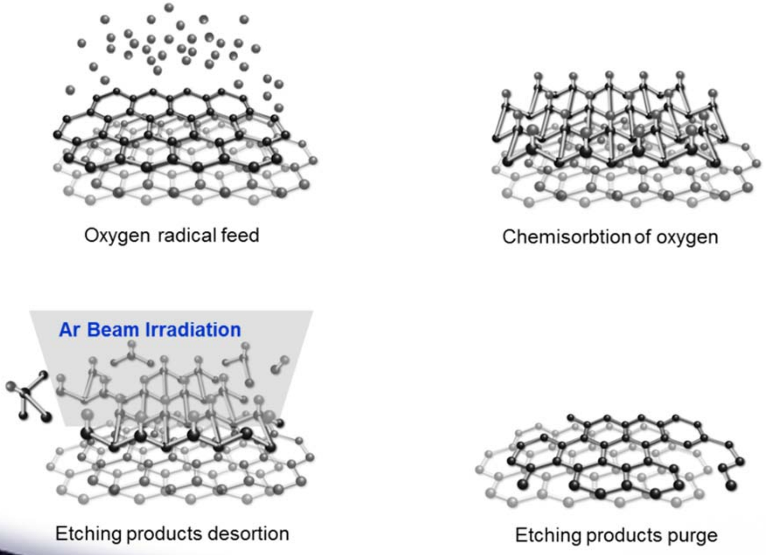
Condition for atomic layer etching of graphene



Concept of graphene ALET



1. O_2 Plasma Condition

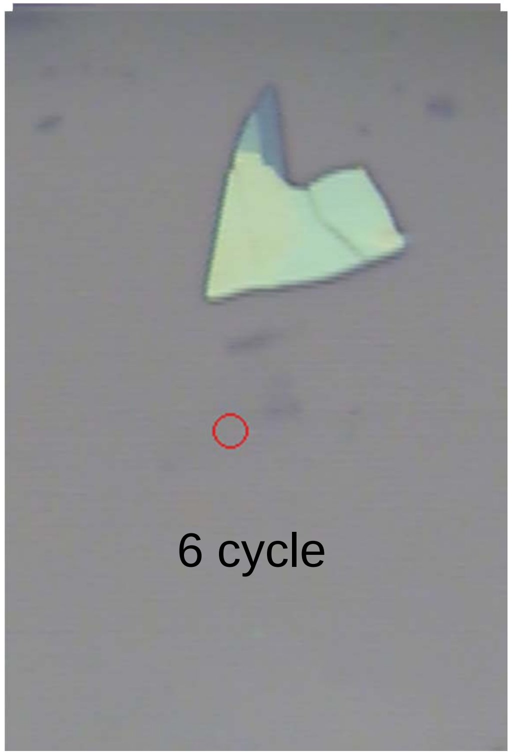
Base Pressure	3.0×10^{-7} Torr
Working Pressure	8.9×10^{-5} Torr
Inductive Power	300 Watts
1st Grid Voltage	**No Bias**
2nd Grid Voltage	**No Bias**
O_2 Gas Flow Rate	20 sccm
O_2 radical exposure time	5 min

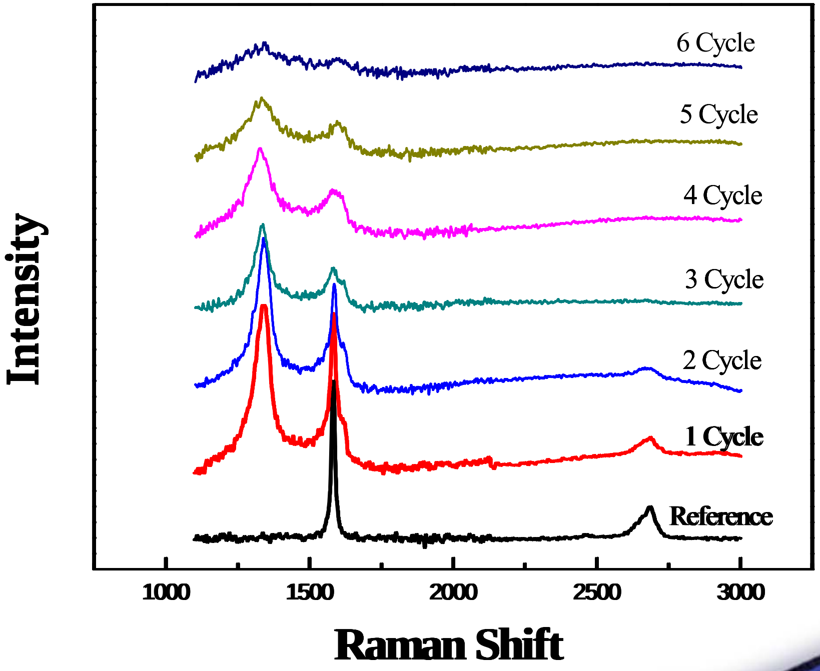
2. Ar Plasma Condition

Base Pressure	3.0×10^{-7} Torr
Working Pressure	4.2×10^{-5} Torr
Inductive Power	300 Watts
1st Grid Voltage	**30 V**
2nd Grid Voltage	**-150 V**
Ar Gas Flow Rate	30 sccm
Ar neutral beam Irradiation time	1 min

Atomic layer etching of HOPG (highly oriented pyrolytic graphite) graphene

1. HOPG graphene





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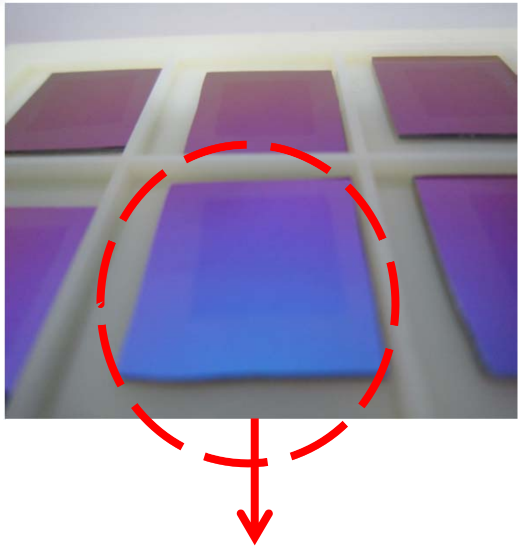
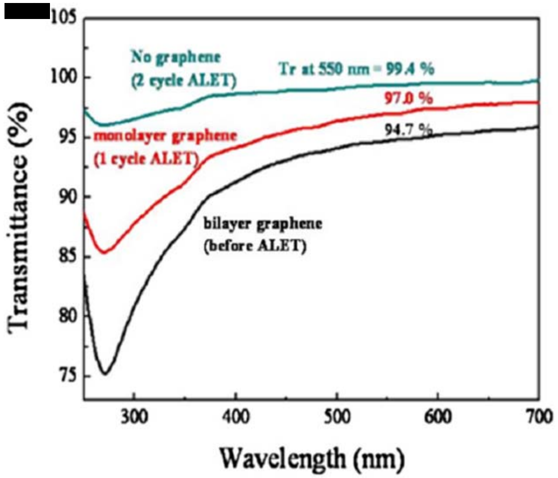
Atomic layer etching of CVD graphene

CVD graphene



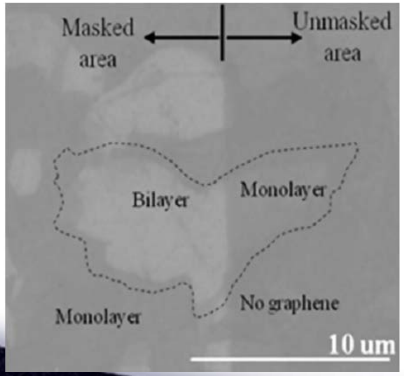
CVD graphene on SiO_2 wafer

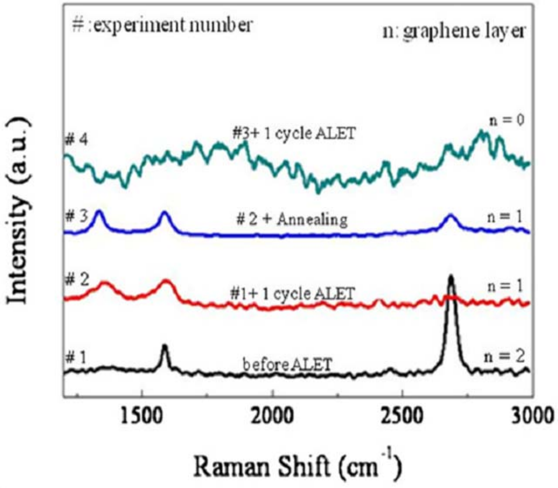


Transmittance (%)	
Bilayer graphene	**94.7 %**
Monolayer graphene (1 cycle ALET)	**97.0 %**
No graphene (2 cycle ALET)	**99.4 %**

2.3 %

2.4 %

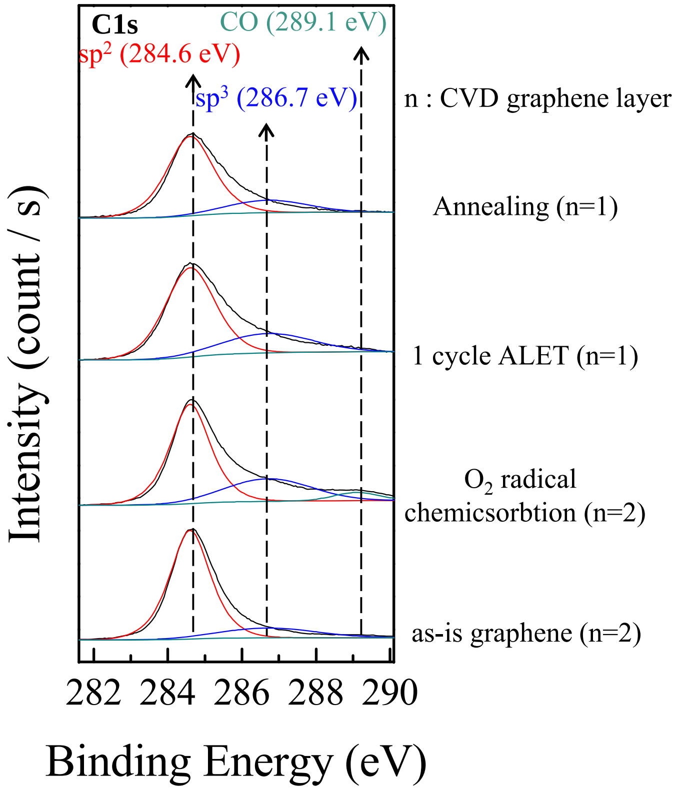


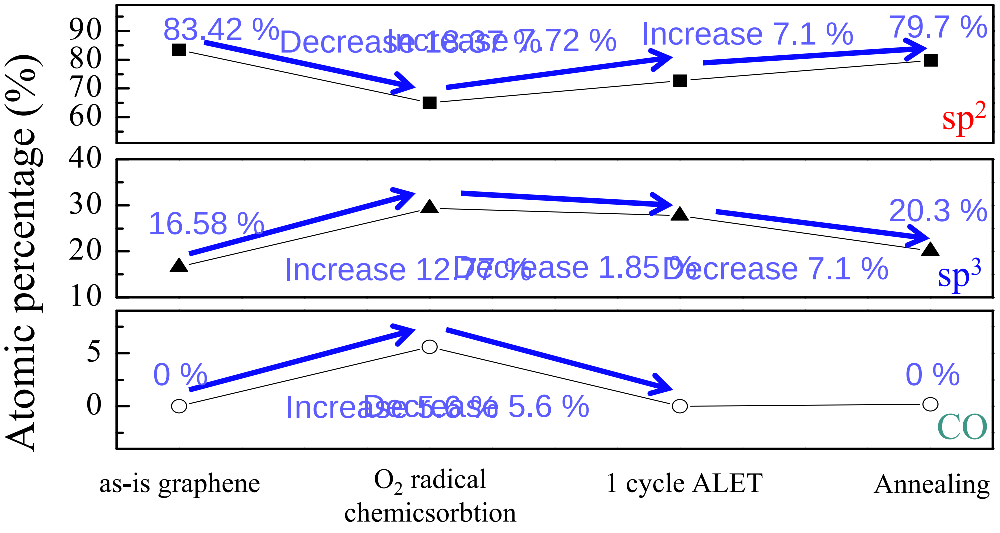


1. Transmittance differences: **2.3-2.4%**
   ➔ Layer by Layer etching
2. 2D peak is recovered with annealing process
3. D peak is generated because of high energy of Ar beam (48 eV)

Carbon binding E change : Atomic layer etching of graphene

2. CVD graphene

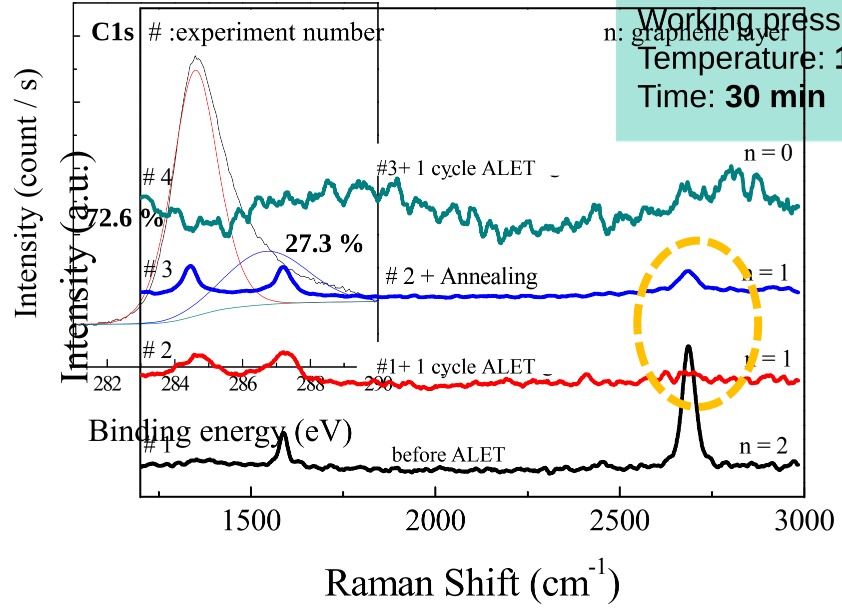


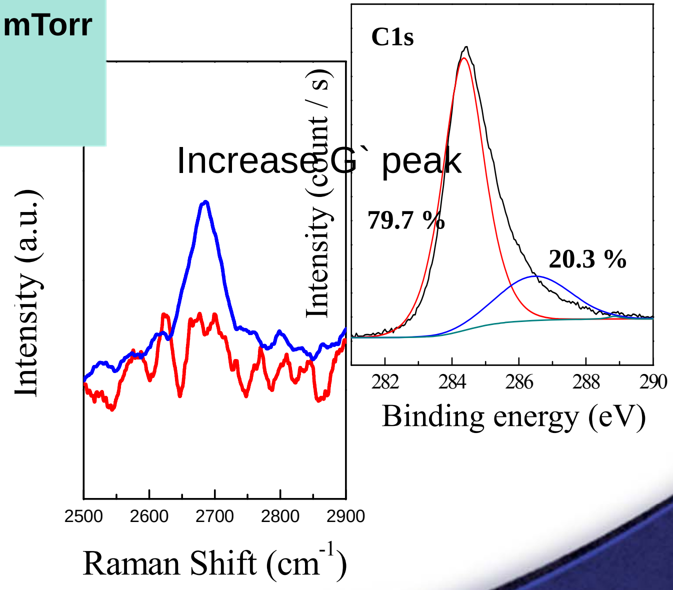


Restructure of graphene surface damage

Annealing

H_2:He Gas ratio: **42:1**
Working pressure: **130 mTorr**
Temperature: **1000 °C**
Time: **30 min**



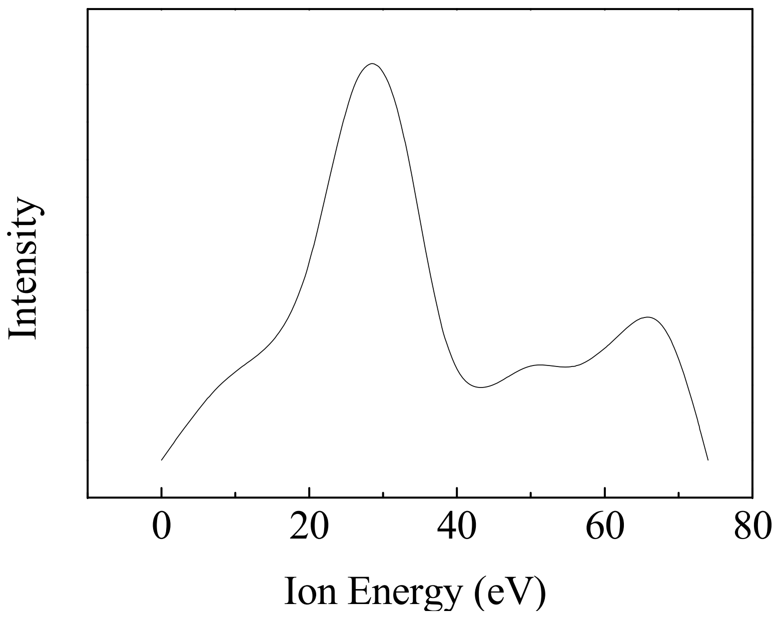


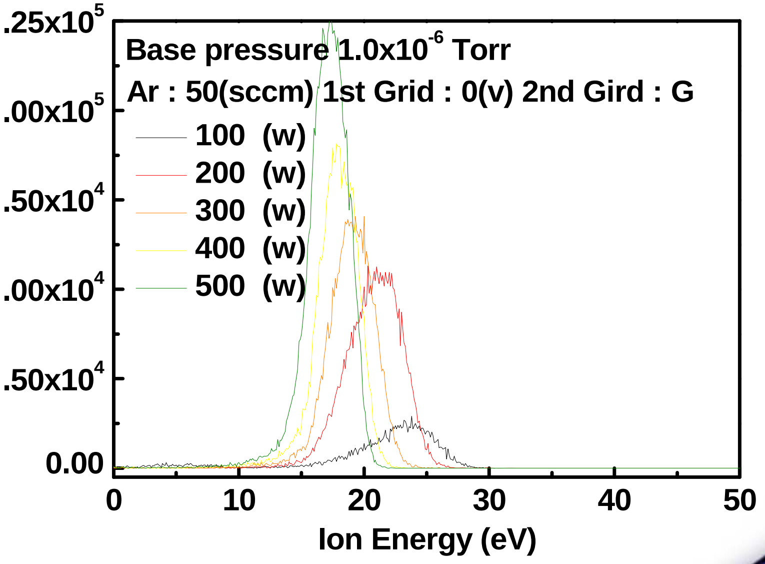
Ar beam energy modification

Inductively coupled plasma (ICP) source - 13.56 Mhz

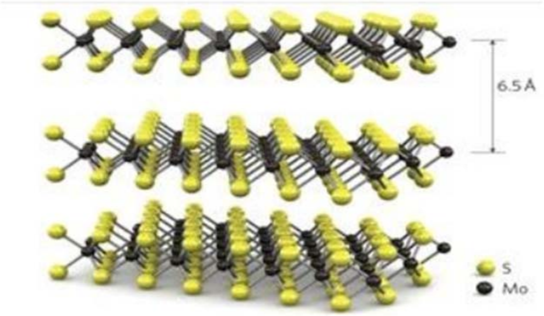
Gas : Ar 25 - 125 sccm Power : 100 – 500 w 1st Grid voltage : 0 v 2nd Grid voltage : G

- **Mass spectroscopy**

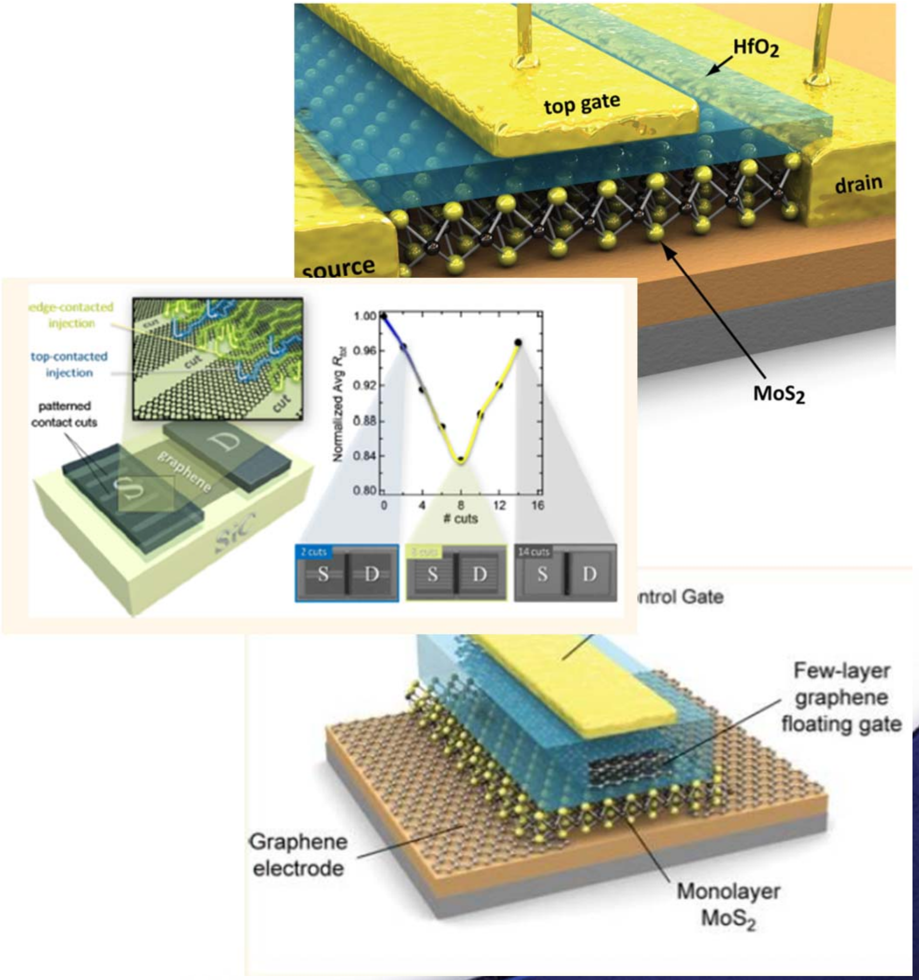


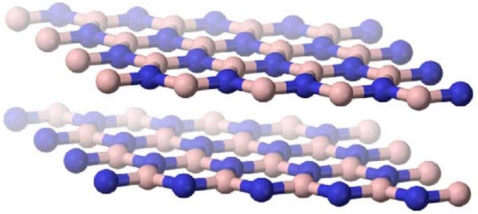


Materials for future 2-D devices



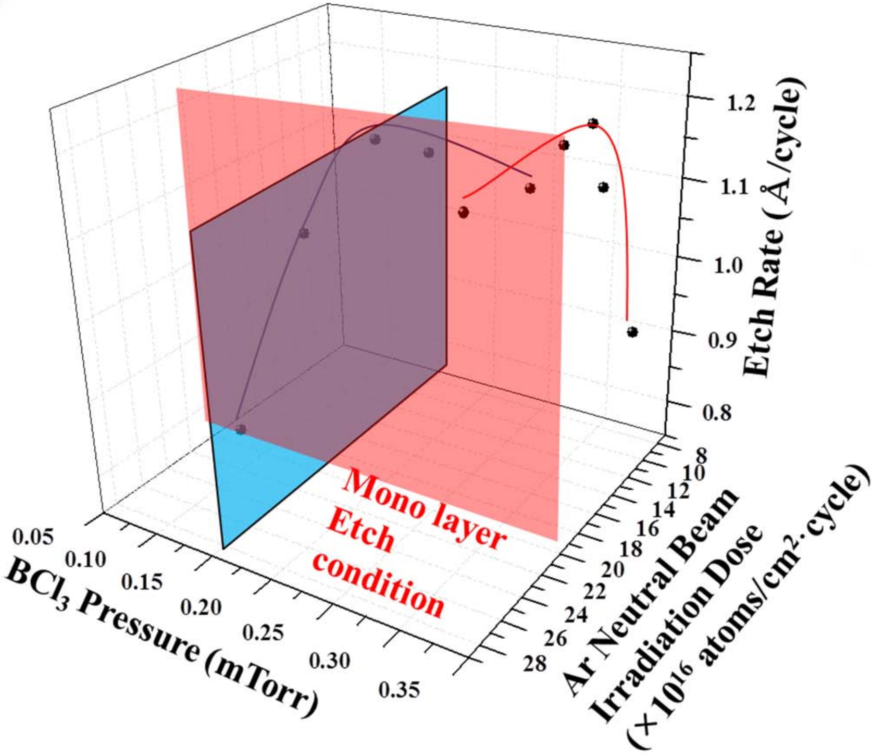
MoS2, WS2, etc - semicondutor

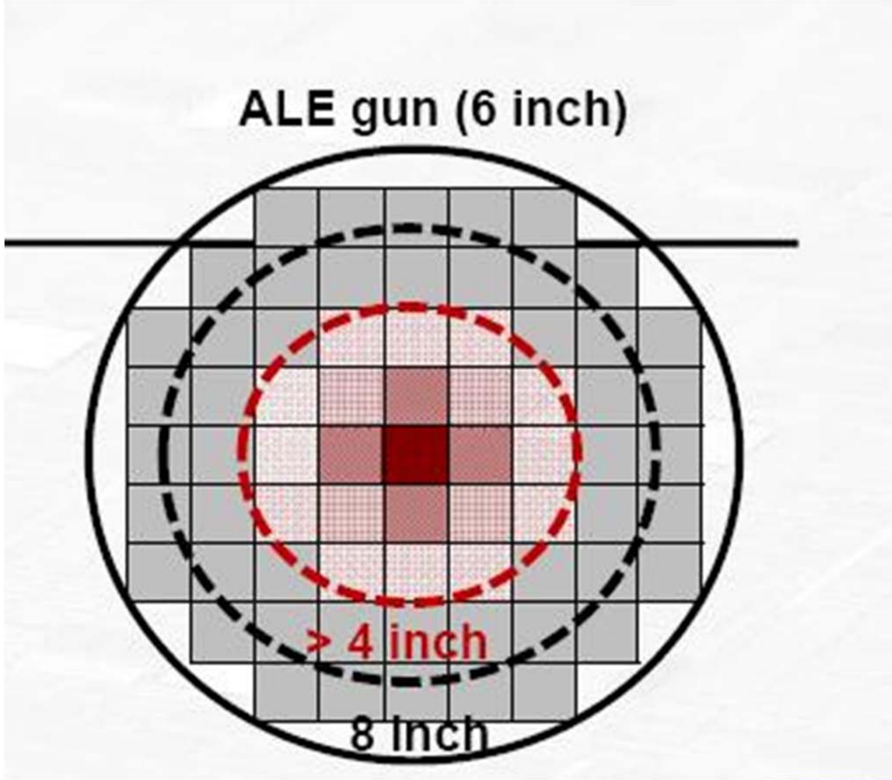




BN - insulator

Properties of ALET





Wide process window

The max-min non-uniformity : 2.56 %

Summary

- Atomic layer etching has been successfully applied to the fabrication of various nanoscale devices to nanoscale Si and III-V devices.

- Using the ALET, not only the precise etching depth control but also the decrease of etch damage could be observed.

- It is believed that ALET could be more successfully applied to future 2-D device applications.

Thank you for your attention!