ALE 2017 Tutorial

Atomic Layer Etching with Ion/Neutral Beams

2017. 07. 15.

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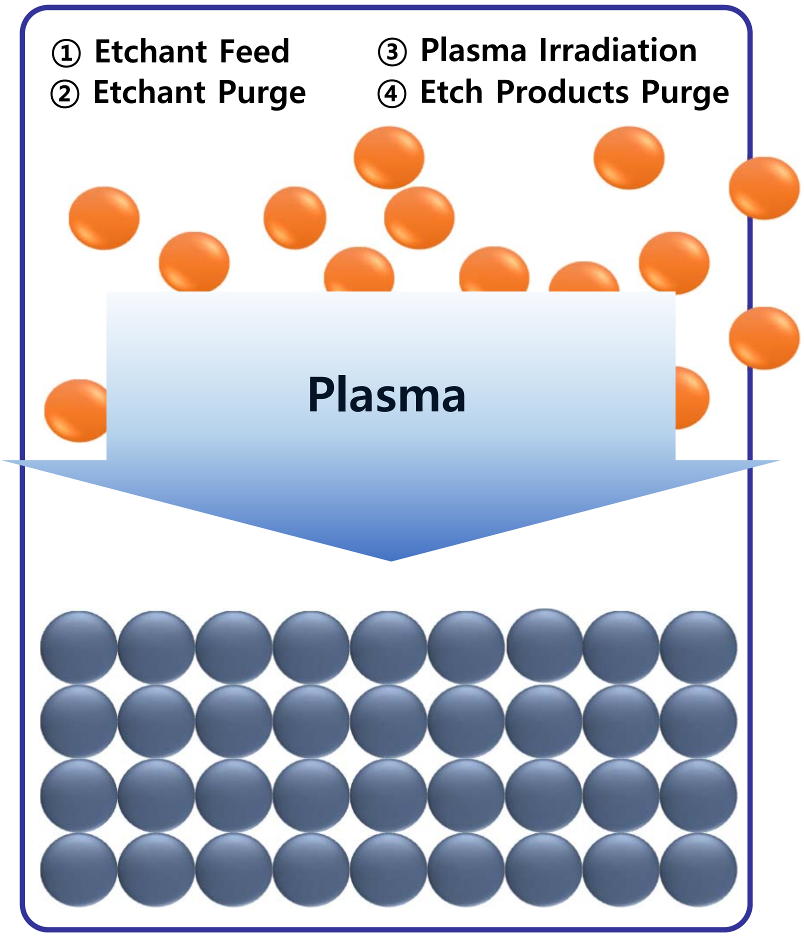
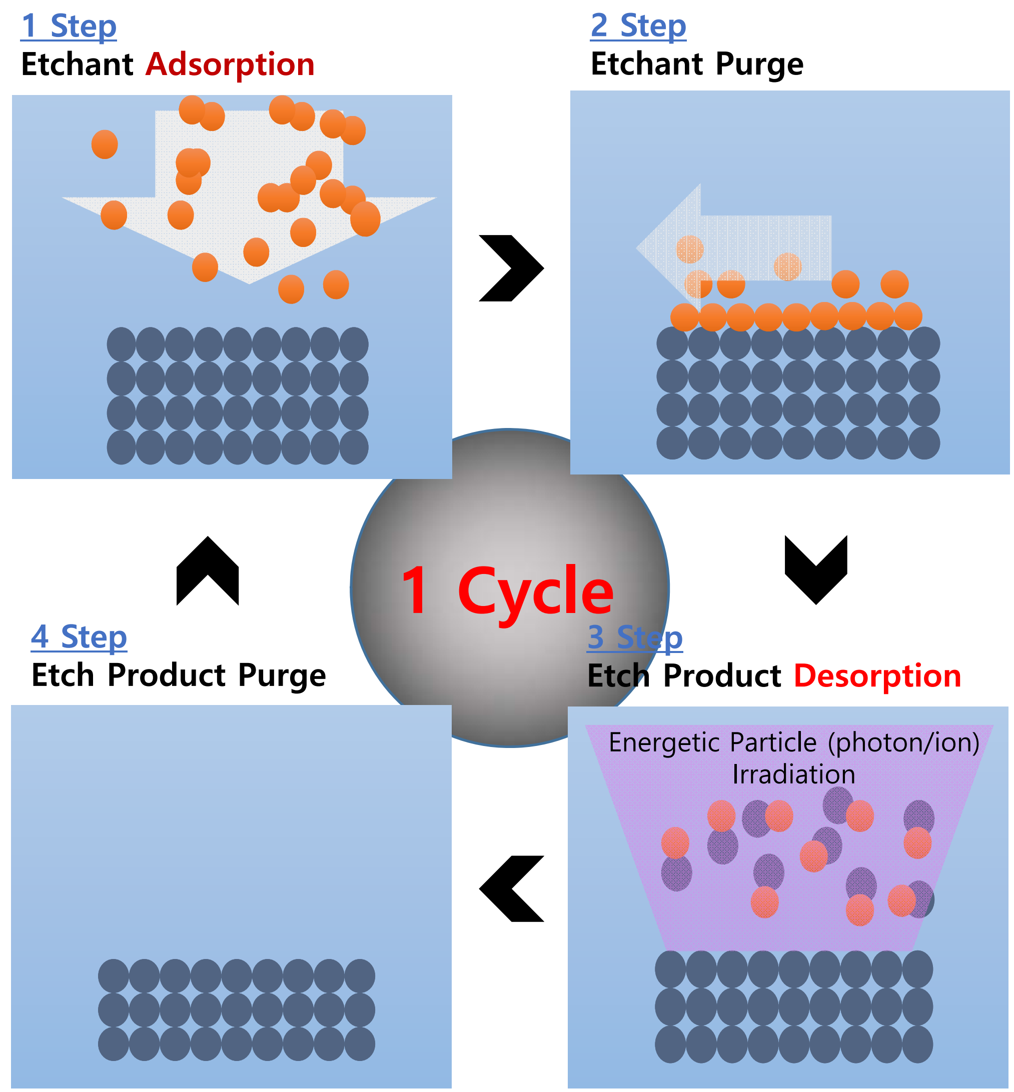
Contents

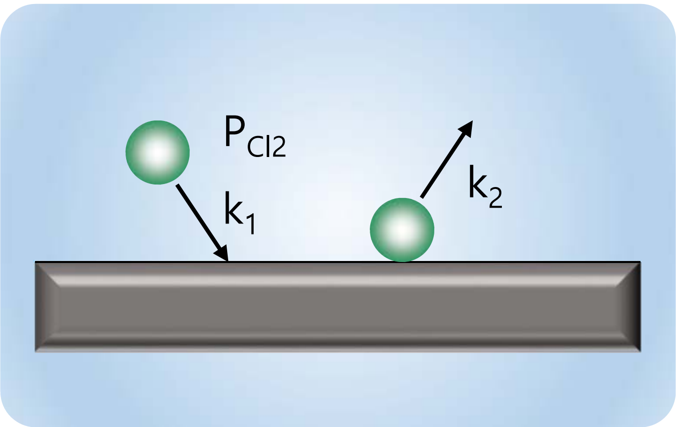
◆ Concept of ALET





Mechanism of ALE

Chemisorption of Cl_2 on materials



Dissociative Langmuir isotherm chemisorption :

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

Coverage of the MCl precursor :

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

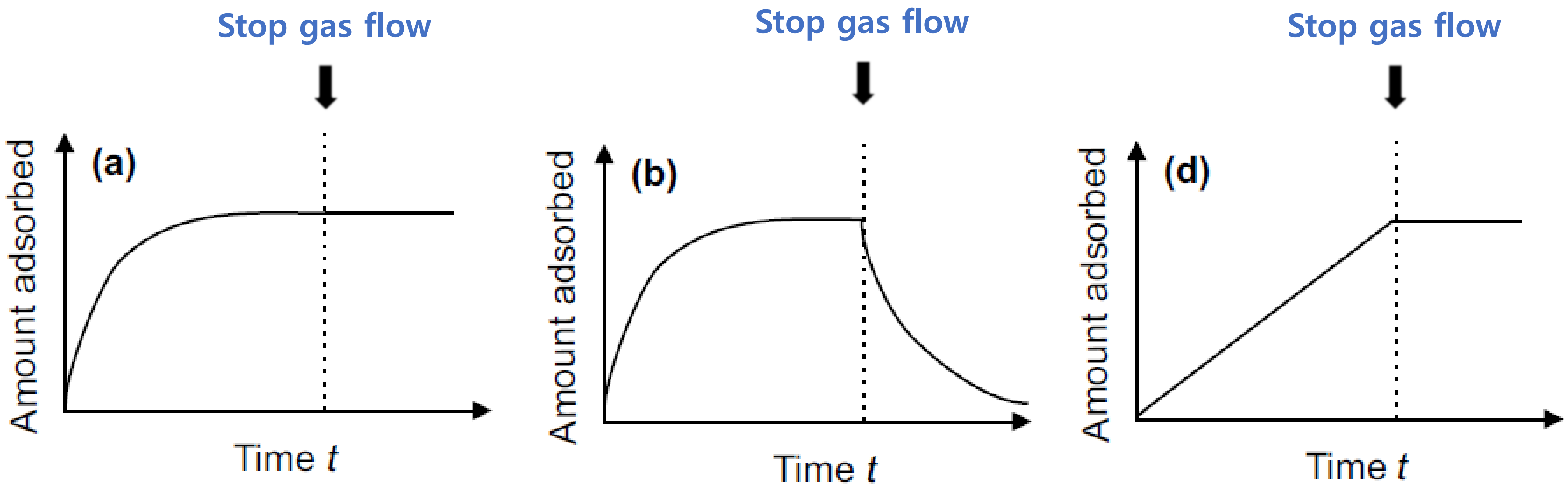
Desorption of chemisorbed materials by Ar^+ bombardment

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

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

Sputtering rate of Cl-adsorbed Material (MCl) : $f_{MCl} \propto k_2 \theta_{MCl} f_{Ar_{neu}}$

Adsorption Condition for ALE



- **Irreversible saturation:**
  - Required for ALE

Surface saturates with a m onolayer of precursor, stron g chemisorption (=chemical bonds formed)

- **Reversible saturation:**

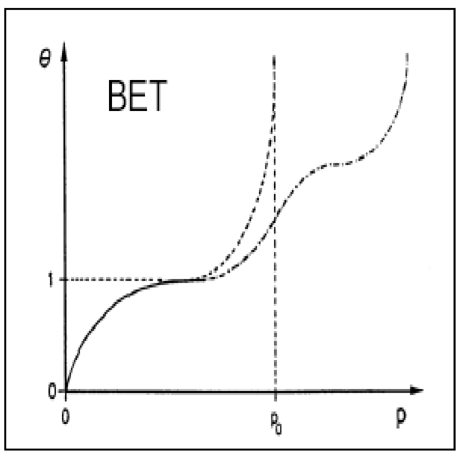
Physisorption only (weak bon ds like van der Waals): once precursor flux is stopped, surf ace specie will desorb.

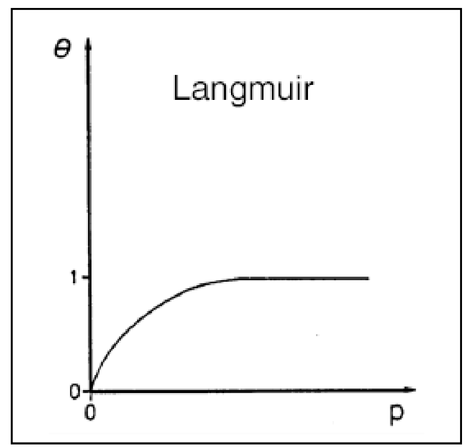
- **Irreversible non-saturation:**

Physisorption multila yers and continuous deposition

Adsorption and Reaction at Surfaces

Physisorption	Chemisorption
weak, long range bonding Van der Waals interactions	**strong, short range bonding** Chemical bonding involving orbital overlap and Charge transfer
Not surface specific	**Surface specific**
ΔH_{ads} = 5~50 kJ/mol	**ΔH_{ads} = 50~500 kJ/mol**
No surface reaction	**Surface reactions may take place** Dissociation, reconstruction, catalysis
Multilayer adsorption BET Isotherm used to model adsorption equilibrium	**Monolayer adsorption** Langmuir Isotherm used to model adsorption equilibrium



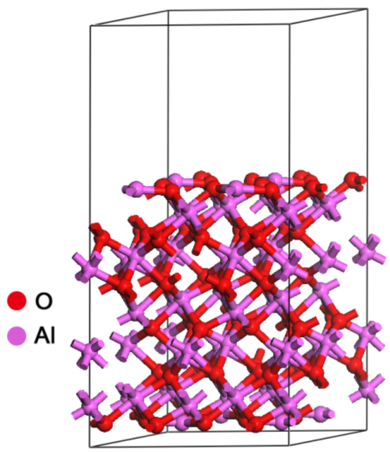


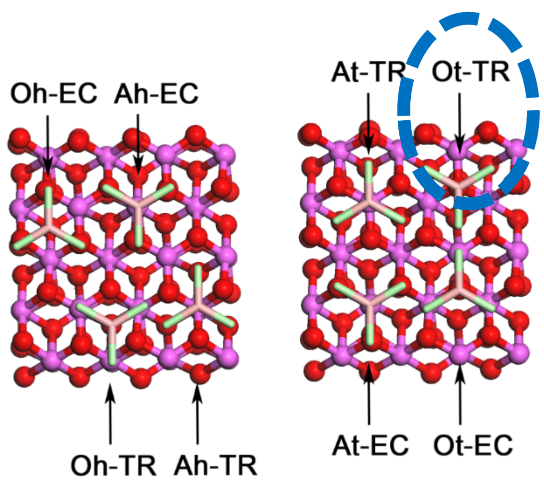
First Principle Study of Al_2O_3 ALE

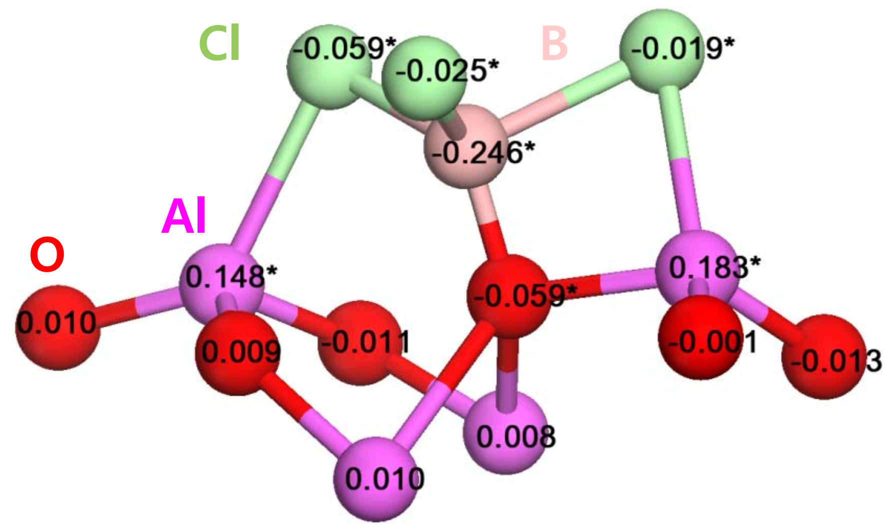
◆ Adsorption

Configuration	Ah-EC	Ah-TR	At-EC	AT-TR
Energy (Kcal/mol)	-32.293	-32.142	-15.347	-17.574
Configuration	Oh-EC	Oh-TR	Ot-EC	Ot-TR
Energy (Kcal/mol)	-32.633	-31.707	-45.617	-58.986

Ot-TR configuration led to the most stable BCl_3 adsorption with an adsorption energy of 58.99 Kcal/mol



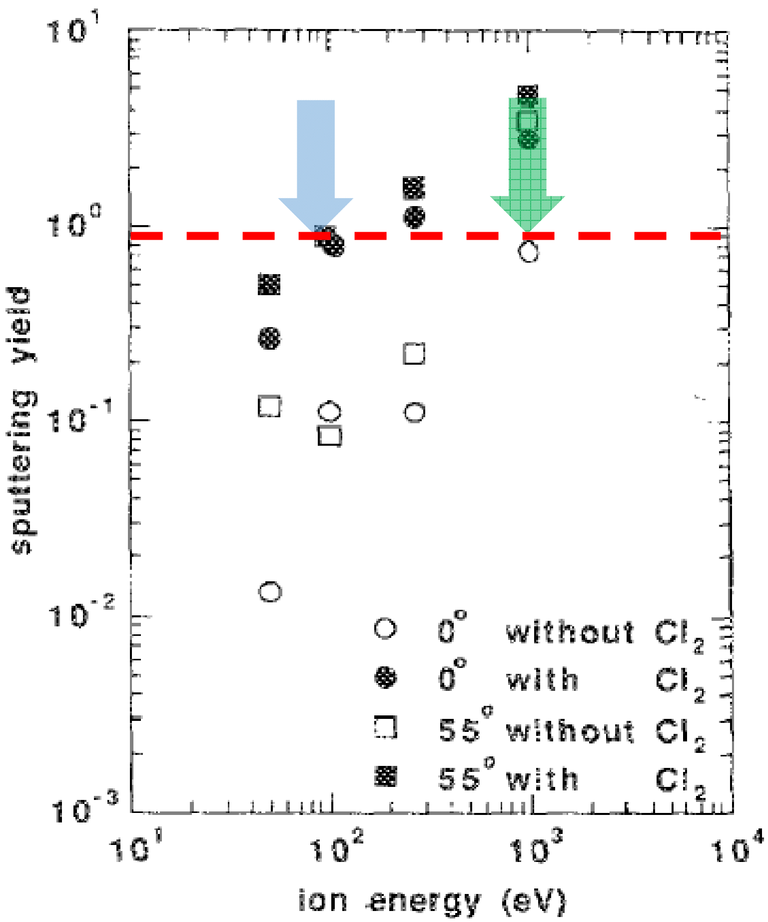




*: significant electron population change upon the BCl_3 adsorption

"Understanding time-resolved processes in atomic-layer etching of ultra-thin Al_2O_3 film using BCl_3 and Ar neutral beam"
Young I. Jhon, Kyung S. Min, G. Y. Yeom, and Young Min Jhon
Appl. Phys. Lett. 105, 093104 (2014)

Sputter Rate of Silicon in a Cl_2 Environment



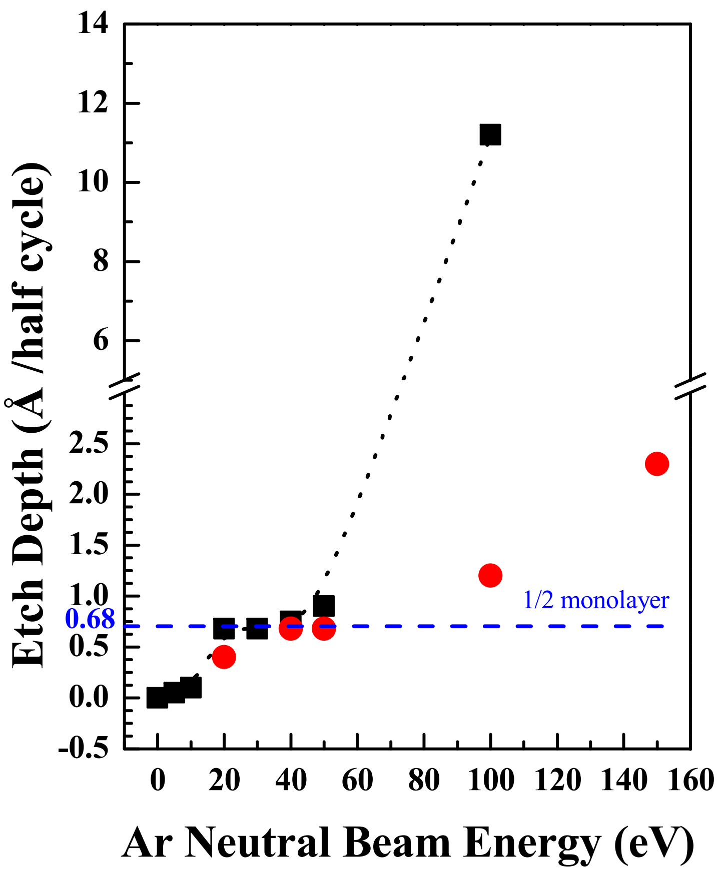
“Near threshold sputtering of Si and SiO_2 in a Cl_2 environment”
D. J. Oostra, R. P. van Ingen, A. Haring, and A. E. de VriesG. N. A. van Veen
Appl. Phys. Lett. 50, 1506 (1987)

◆ Average product yield

Yield	Average value ± (95% confidence intervals)	
Si	0.013±0.002	(8%)
Cl	0.040±0.003	
Ar	0.803±0.078	
Ar thermalization	0.192±0.062	
Ar trapped permanently	<0.01	
SiCl	0.145±0.035	(84%)
$SiCl_2$	0.014±0.003	(8%)

“Molecular dynamics simulation of atomic layer etching of silicon”
Satish D. Athavale and Demetre J. Economou
J. Vac. Sci. Technol. A 13 (2) (1995)

Si ALE as a function of Ar Beam Energy

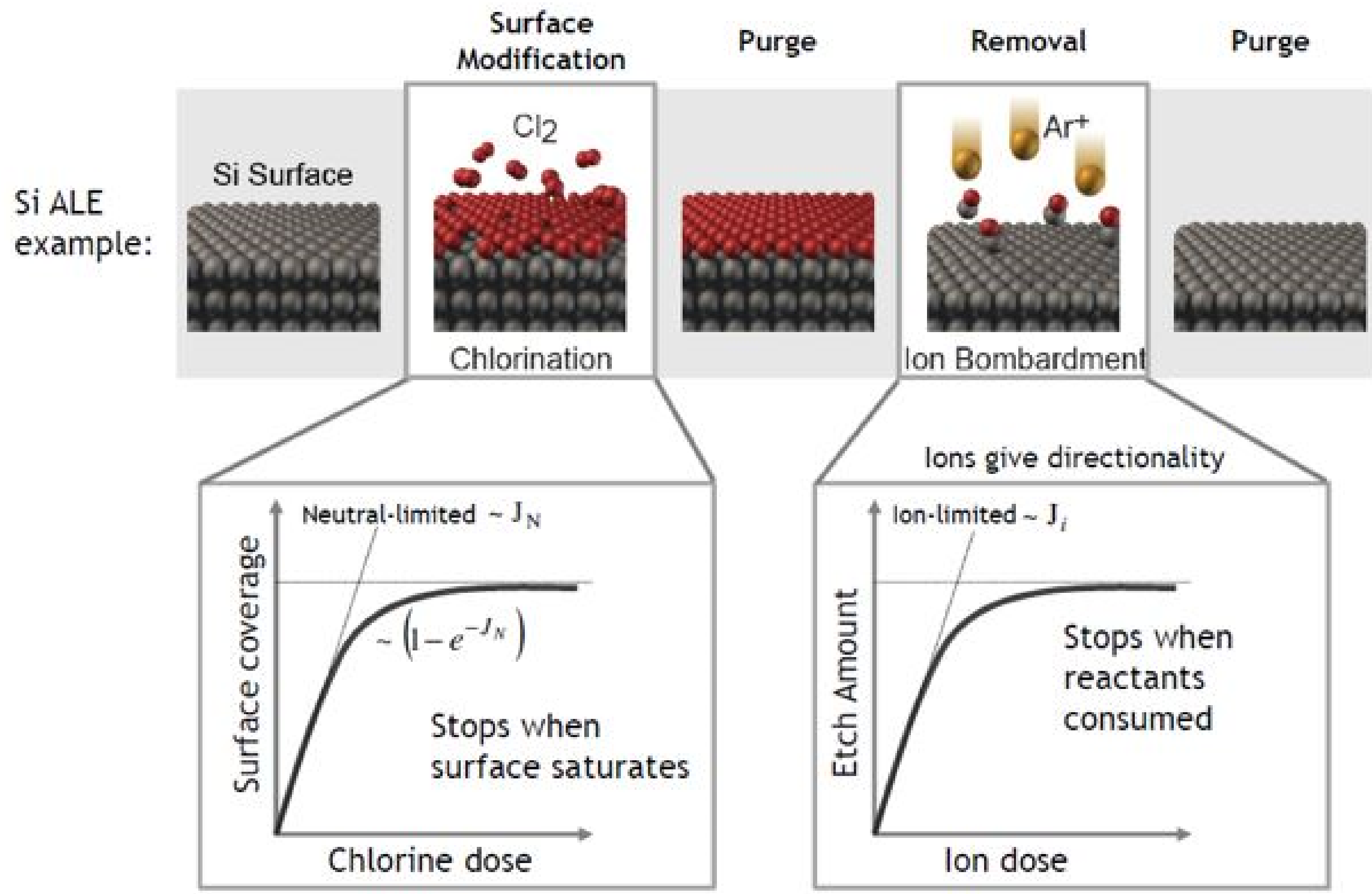


Base pressure	2.0×10^{-6} Torr
Operating pressure	4.0×10^{-4} Torr
Cl_2 partial pressure	10 mPa
t_{Cl2}	20 sec
t_{Ar+}	5 sec
Ar flow rate	40 sccm
RF power	50 W
Ion acceleration voltage	40 ~ 150 V

Below about 50 eV of energy, the chemical etching is found to be more dominant than the physical sputtering. Etch rate increase by Ar energy (Threshold E < 50 eV)

Si ALE as a function of Etch Parameters

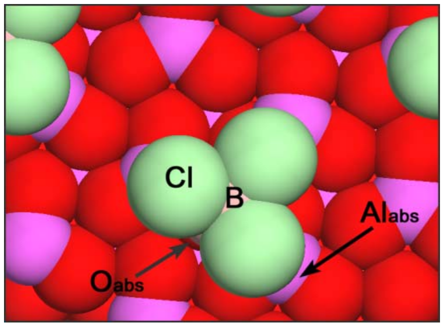
- ◆ **Use time domain to simplify**

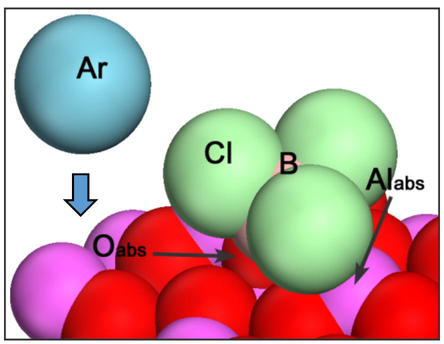


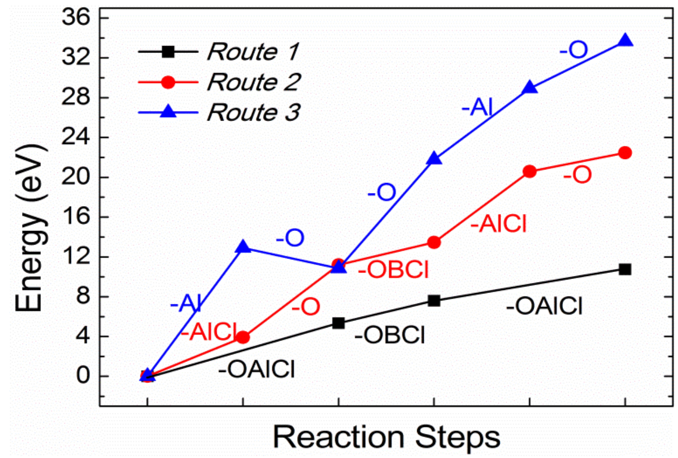
"Overview of atomic layer etching in the semiconductor industry"
Keren J. Kanarik, Thorsten Lill, Eric A. Hudson, Saravanapriyan Sriraman, Samantha Tan, Jeffrey Marks, Vahid Vahedi, and Richard A. Gottscho
J. Vac. Sci. Technol. A 33 (020802) (2015)

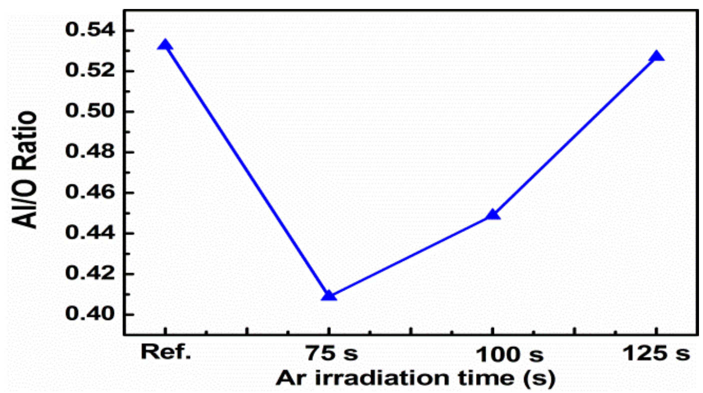
First Principle Study of Al_2O_3 ALE

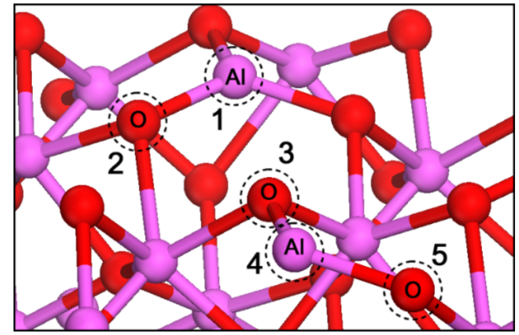
◆ Desorption

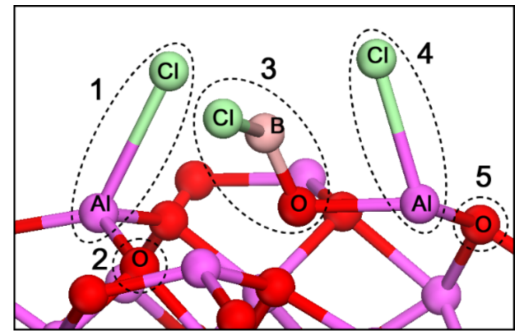


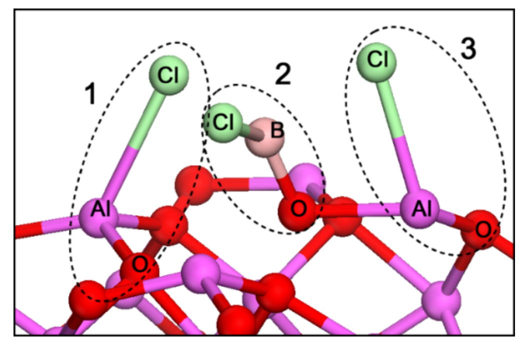






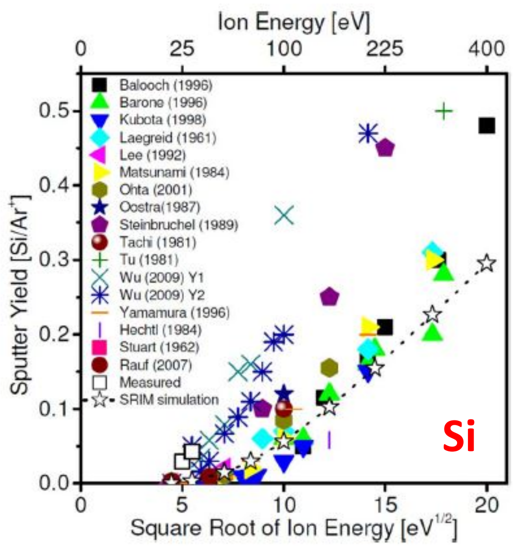


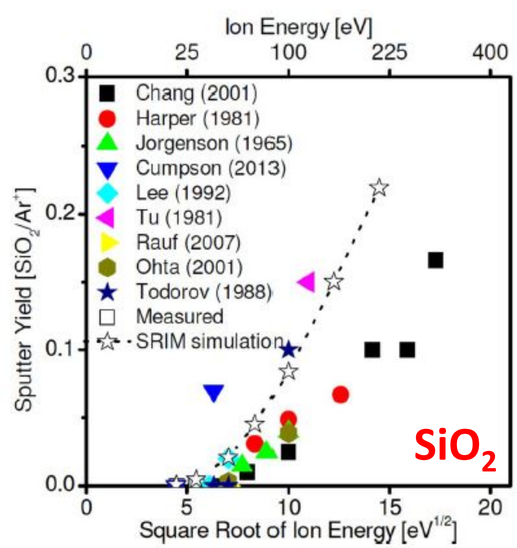




"Understanding time-resolved processes in atomic-layer etching of ultra-thin Al_2O_3 film using BCl_3 and Ar neutral beam"
Young I. Jhon, Kyung S. Min, G. Y. Yeom, and Young Min Jhon
Appl. Phys. Lett. 105, 093104 (2014)

Threshold Energy for Sputtering





"Atomic Layer Etching at the Tipping Point: An Overview"
G. S. Oehrlein, D. Metzler, and C. Li
ECS Journal of Solid State Science and Technology, 4 (6) N5041-N5053 (2015)

- **Ion energy control is essential to enable atomic scale precision**
  - Energy threshold chosen specifically to enable reactant activation and removal of one material selective to all others

TABLE 1 Threshold Energies

	Ne	Ar	Kr	Xe	Hg		Ne	Ar	Kr	Xe	Hg
Be.....	**12**	15	15	15		Mo....	24	24	**28**	**27**	32
Al.....	**13**	**13**	15	18	18	Rh....	25	24	**25**	**25**	
Ti.....	**22**	**20**	**17**	18	25	Pd....	20	20	**20**	**15**	20
V......	21	**23**	**25**	28	25	Ag....	12	15	**15**	**17**	
Cr.....	22	**22**	**18**	20	23	Ta....	25	26	30	**30**	30
Fe.....	22	**20**	**25**	23	25	W.....	35	33	30	**30**	30
Co.....	20	**25**	**22**	22		Re....	35	35	25	**30**	35
Ni.....	23	**21**	**25**	20		Pt....	27	25	22	**22**	25
Cu.....	17	**17**	**16**	15	20	Au....	20	20	20	**18**	
Ge.....	23	**25**	**22**	**18**	25	Th....	20	24	25	**25**	
Zr.....	23	22	**18**	**25**	30	U.....	20	23	25	**22**	27
Nb.....	27	25	**26**	**32**							

Boldface values are those for which the energy-transfer factor $4m_1m_2/(m_1+m_2)^2$ is 0.9 or higher.

"Sputtering Yields at Very Low Bombarding Ion Energies"
R. V. Stuart and G. K. Wehner
Journal of Applied Physics, 7 (33) (1962)

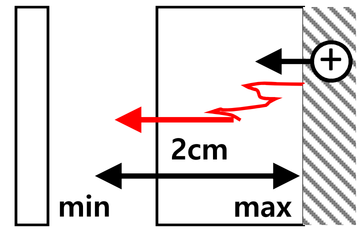
Energy Control of Energetic Particles for Desorption

◆ **Energy distribution of the ions incident to the electrode by the above oscillation**

500 eV Ar^{+} : velocity = 5×10^{6} cm/sec

⬇

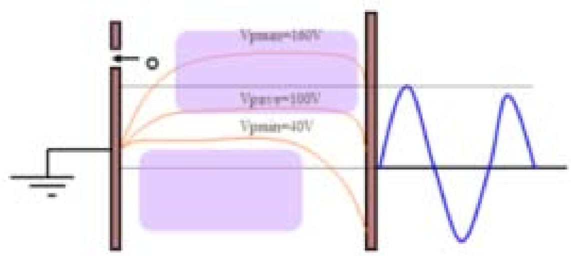
It takes 400 ns for the movement of 2 cm

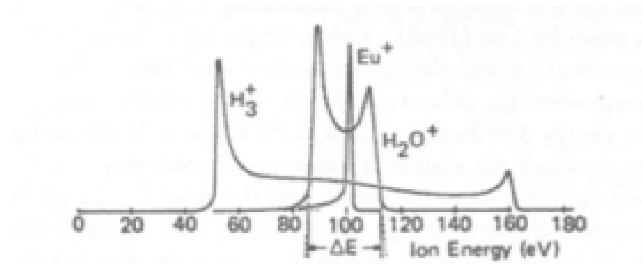


Oscillation period at 13.56MHz $t = \dfrac{1}{13.56 \times 10^{6}} \approx 74\, ns$

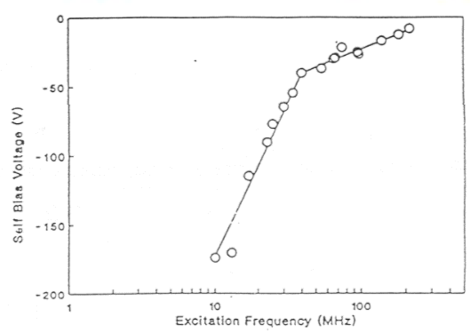
∴ During the pass of sheath, the incident ions oscillate for a few times

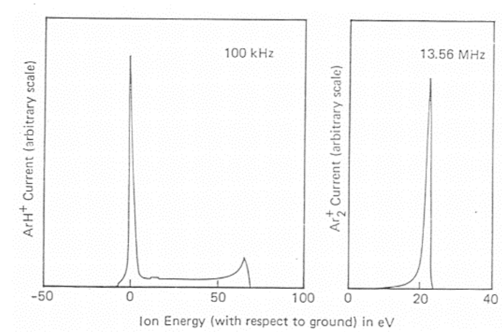
1) Ion mass





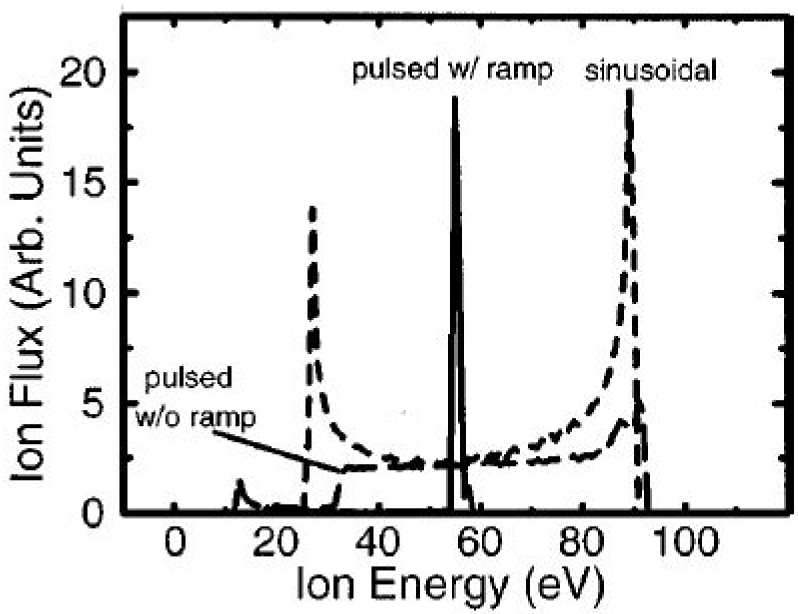
2) Frequency



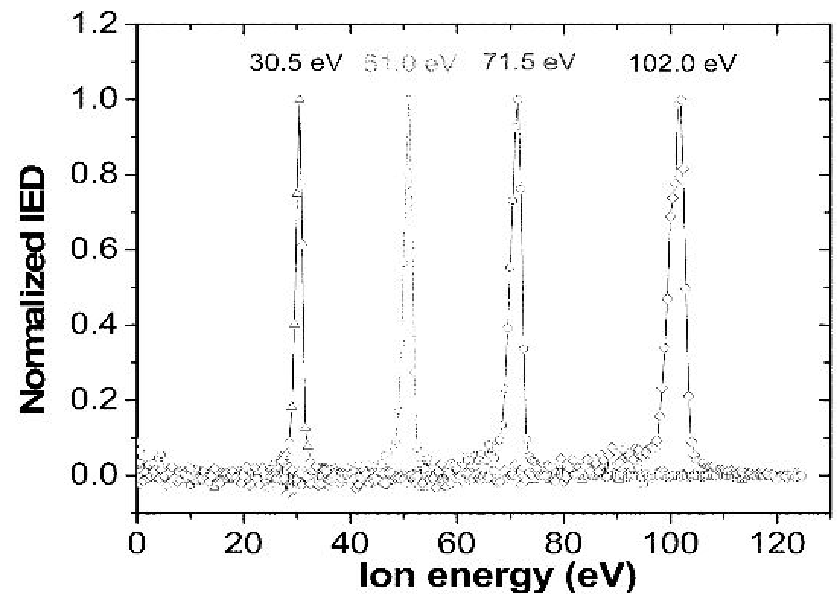


Energy Control of Energetic Particles for Desorption

- **Novel plasma pulsing methods (waveforms) can be used to tailor ion energy distribution function**



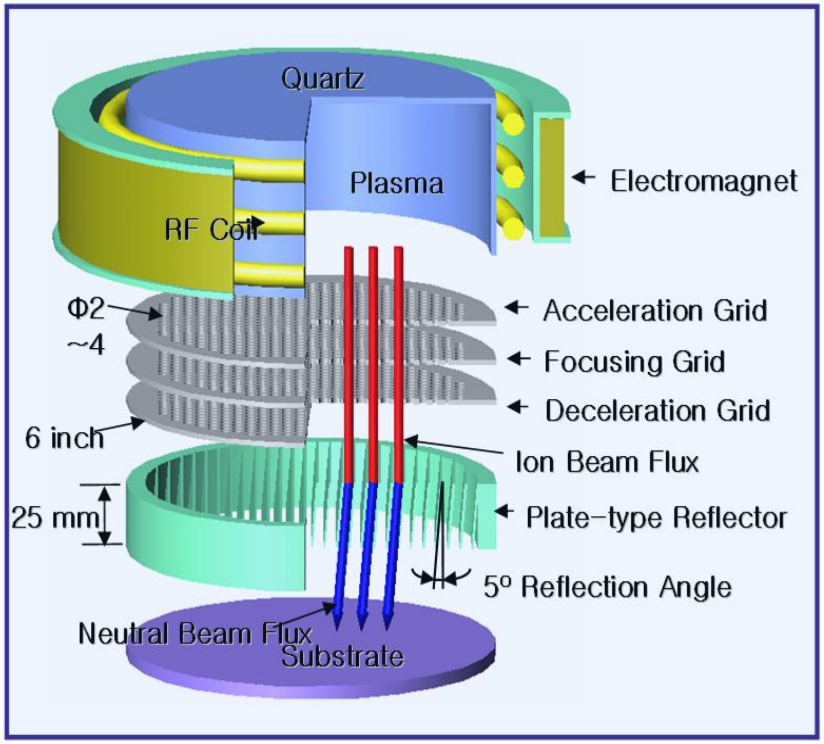
"Control of ion energy distribution at substrates during plasma processing"
S.-B. Wang and A. E. Wendt
Journal of Applied Physics 88, 643 (2000)

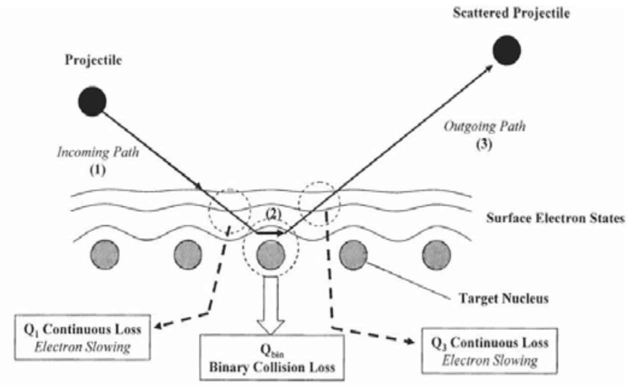


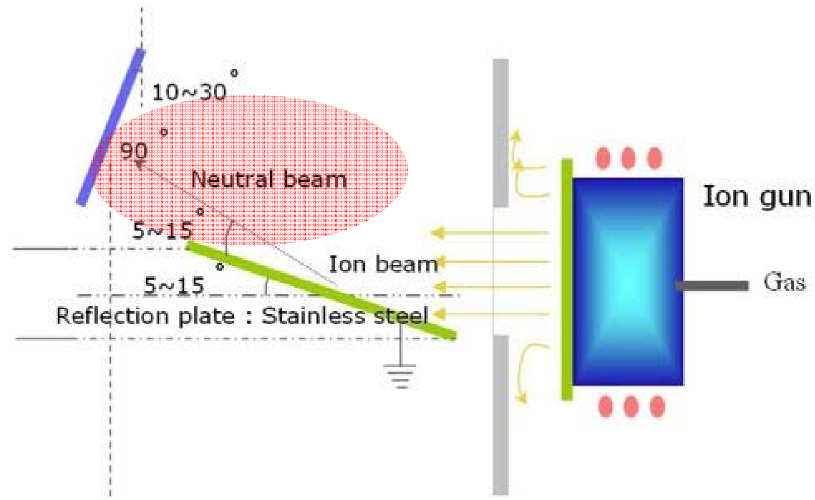
"Atomic layer etching with pulsed plasmas"
Vincent M. DONNELLY, Demetre J, and ECONOMOU
US 20110139748A1, 2011

Formation of Energetic Neutral Beam

◆ Ion-surface neutralization







When the ion beam was reflected by a reflector at the angles lower than 15º, most of the ions reflected were neutralized and the lower reflector angle showed the higher degree of neutralization.

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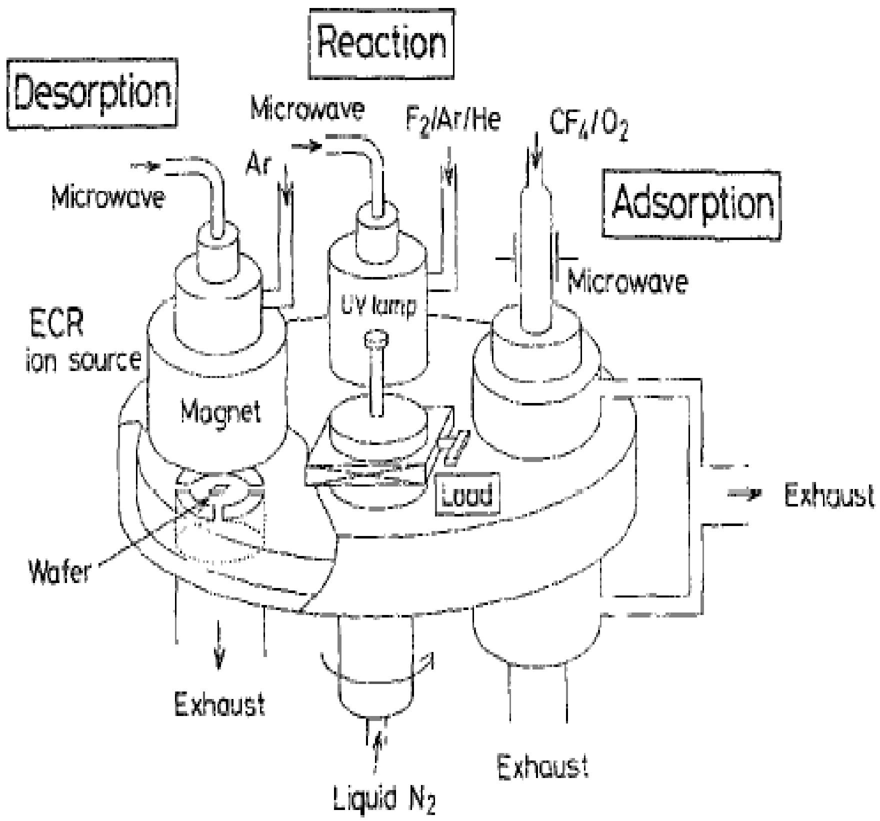
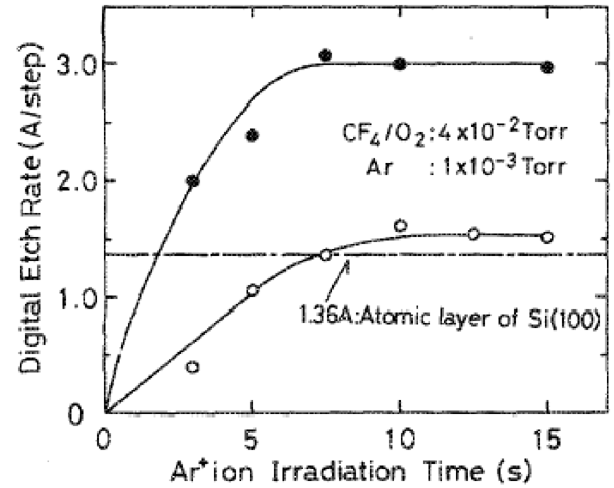
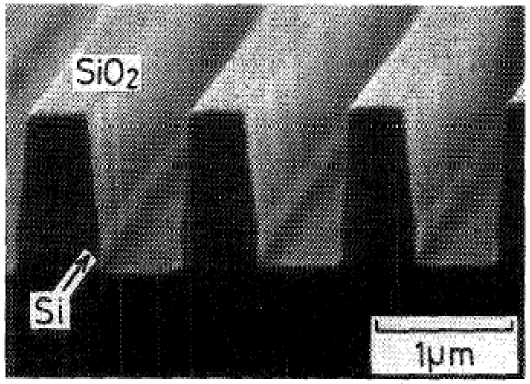
ALE using ECR Ion Source



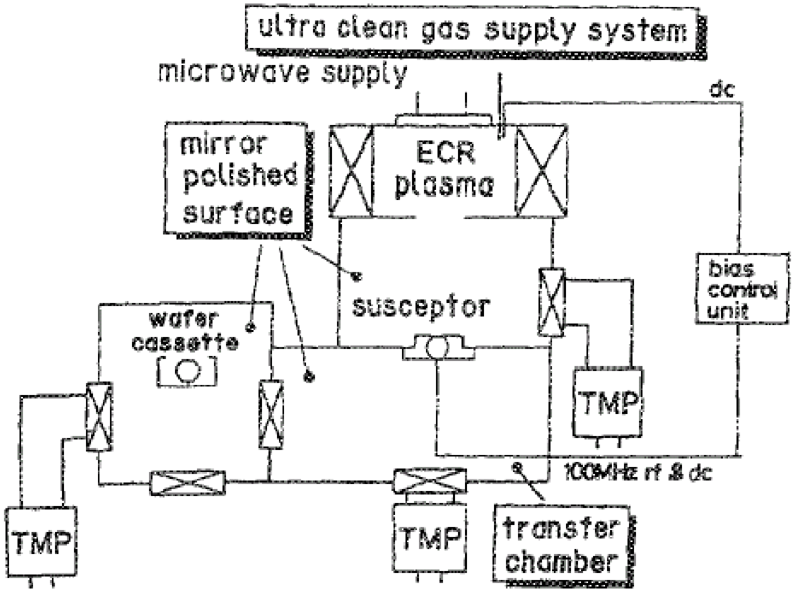


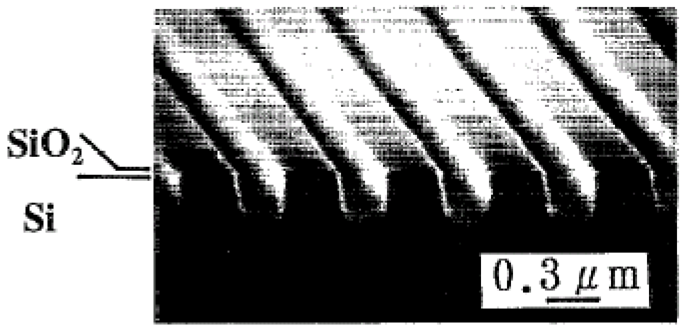


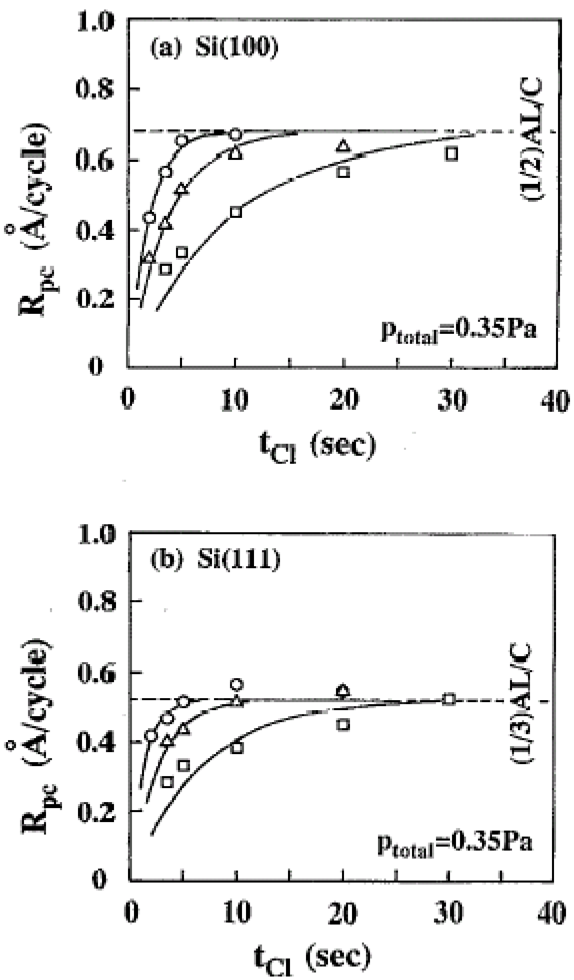
CF_4/O_2

"Digital chemical vapor deposition and etching technologies for semiconductor processing"
Y. Horiike, T. Tanaka, M. Nakano, S. Iseda, H. Sakaue, A. Nagata, H. Shindo, S. Miyazaki, and M. Hirose
J. Vac. Sci. Techno!. A 8 (3) (1990)

ALE of Si using Low Energy Ion (ECR)

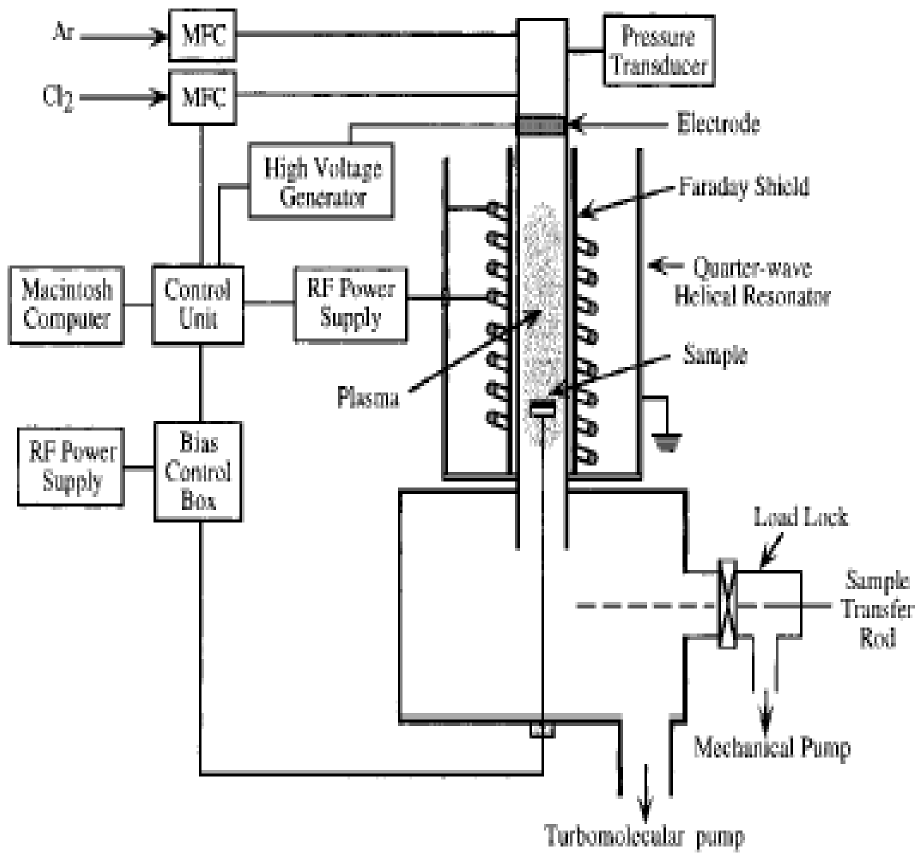


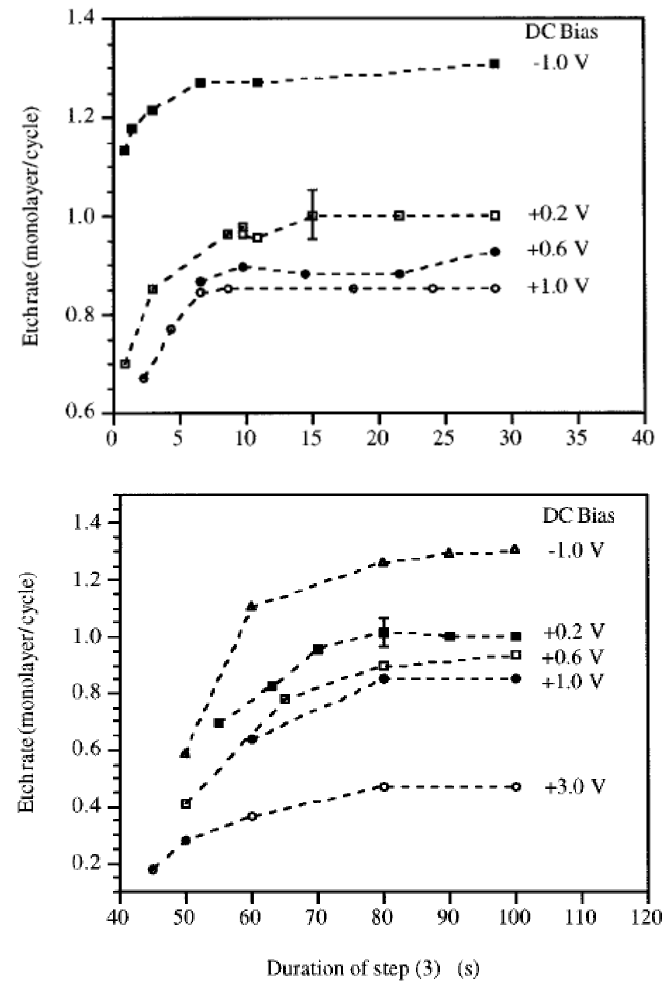




"Selflimited layerbylayer etching of Si by alternated chlorine adsorption and Ar^{+} ion irradiation"
Takashi Matsuura, Junichi Murota, Yasuji Sawada, and Tadahiro Ohmi
Appl. Phys. Lett. 63 (20) (1993)

ALE using Helical Plasma Source



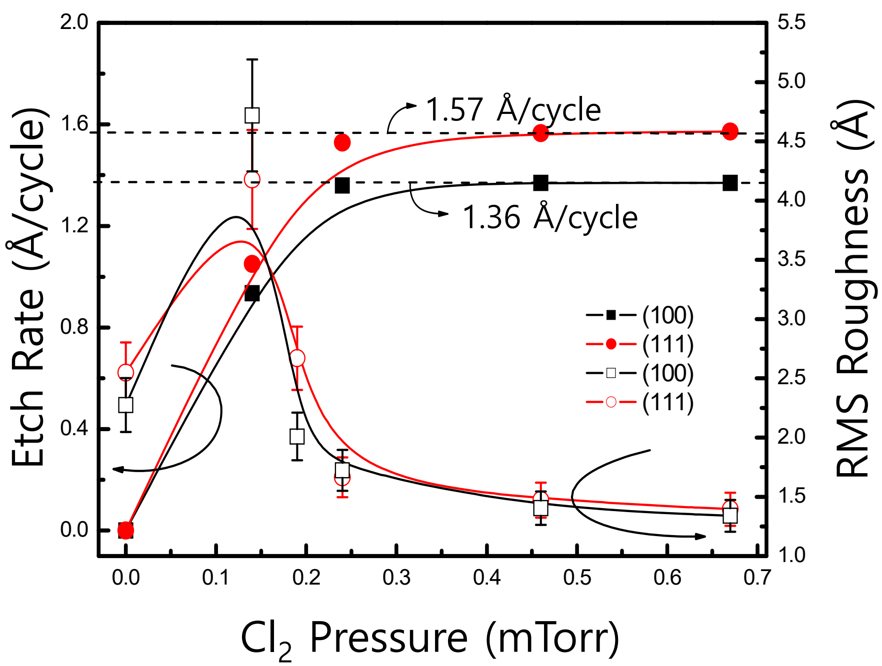


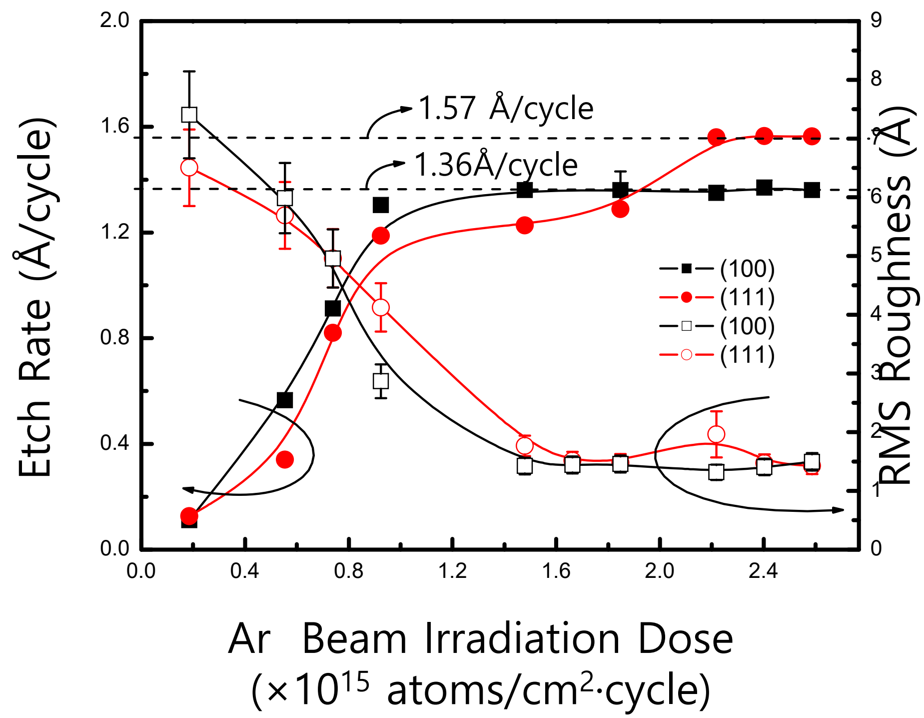
"Realization of atomic layer etching of silicon"
Satish D. Athavale and Demetre J. Economou
J. Vac. Sci. Technol. B 14(6) (1996)

Si ALE

◆ 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 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





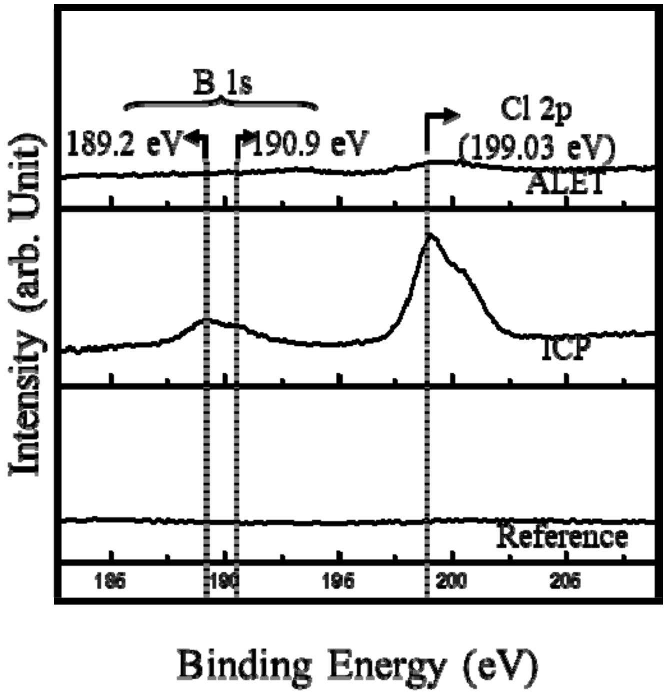
"Surface Roughness Variation during Si Atomic Layer Etching by Chlorine Adsorption Followed by an Ar Neutral Beam Irradiation"
S. D. Park, C. K. Oh, D. H. Lee, and G. Y. Yeom
Electrochemical and Solid-State Letters, 8 11 C177-C179 (2005)

Etch Residue

◆ Conditions :

- ICP Etching : BCl_3 (50 sccm)/Ar (50 sccm), 300 W, -60 V, 12 mTorr, 149 sec
- Atomic Layer Etching : Ne beam irradiation dose (1.485×10^{17} atoms/cm^2·cycle), BCl_3 pressure (0.33 mTorr), Etch cycle (217 cycle)

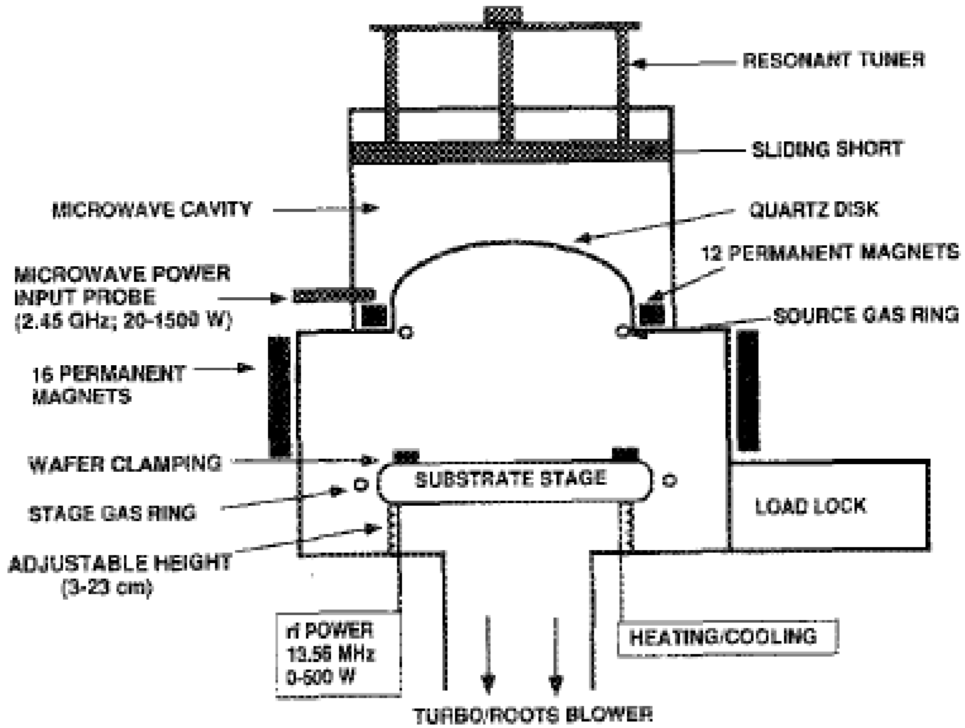
Etched surface by XPS

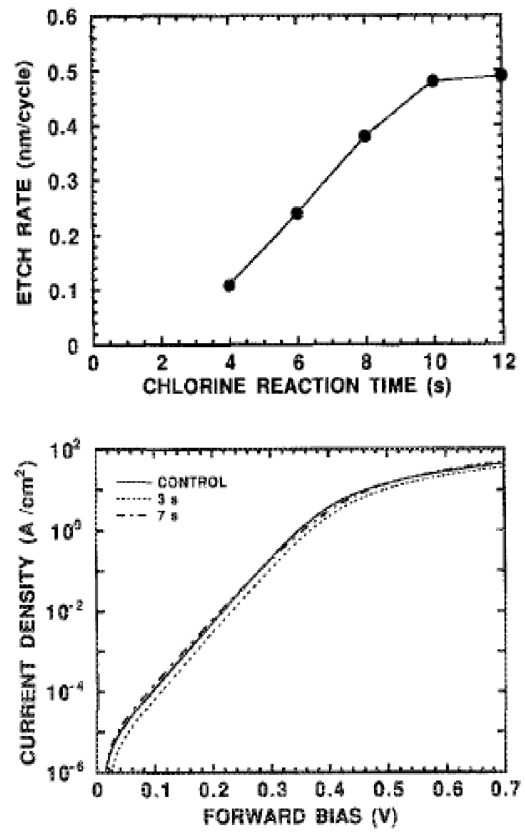


"Precise Depth Control and Low-Damage Atomic-Layer Etching of HfO_2 using BCl_3 and Ar Neutral Beam"
S. D. Park, W. S. Lim, B. J. Park, H. C. Lee, J. W. Bae, and G. Y. Yeom
Electrochemical and Solid-State Letters, 11 4 H71-H73 (2008)

Contents

GaAs ALE using ECR Source





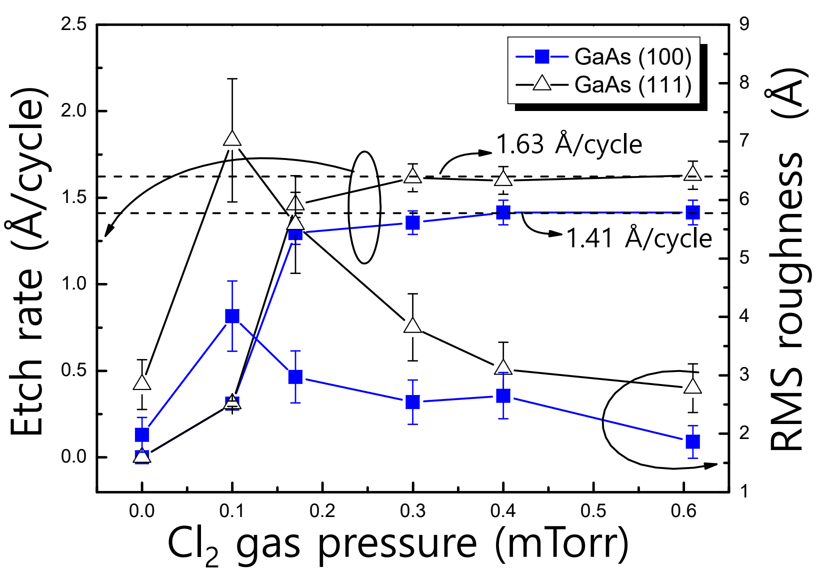
Layer by layer etching with the etch rate in the range of 0.5 nm/cycle has been achieved on GaAs.

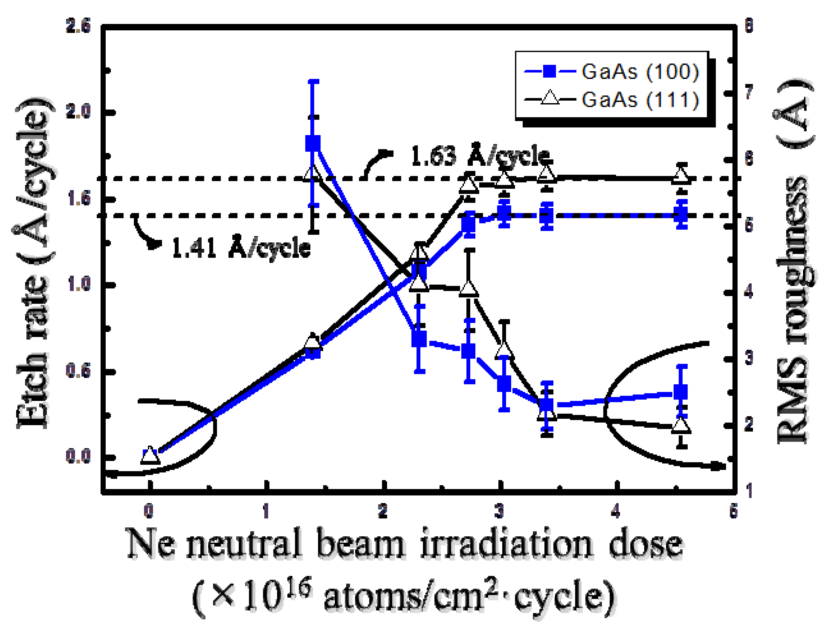
"Controllable layerbylayer etching of III–V compound semiconductors with an electron cyclotron resonance source"
K. K. Ko and S. W. Pang
J. Vac. Sci. Techno!. B 11(6) (1993)

GaAs ALE

◆ Conditions :

Base pressure	3.0×10^{-7} Torr	1^{st} grid voltage	10 Volts	Cl_2 pressure	0~0.62 mTorr
Chamber pressure	2.0×10^{-4} Torr	2^{nd} grid voltage	-250 Volts	Ne beam Irradiation dose	0 ~ 4.55×10^{16} atoms/cm2·cycle
Inductive power	300 Watts	Ne flow rate	70 sccm	Cl_2 supply time (t_{Cl2})	10 sec





"Atomic layer etching of (100)/(111) GaAs with chlorine and low angle forward reflected Ne neutral beam"
Woong Sun Lim, Sang Duk Park, Byoung Jae Park, Geun Young Yeom
Surface & Coatings Technology 202, 5701–5704 (2008)

Stoichiometry Modification of GaAs Surface

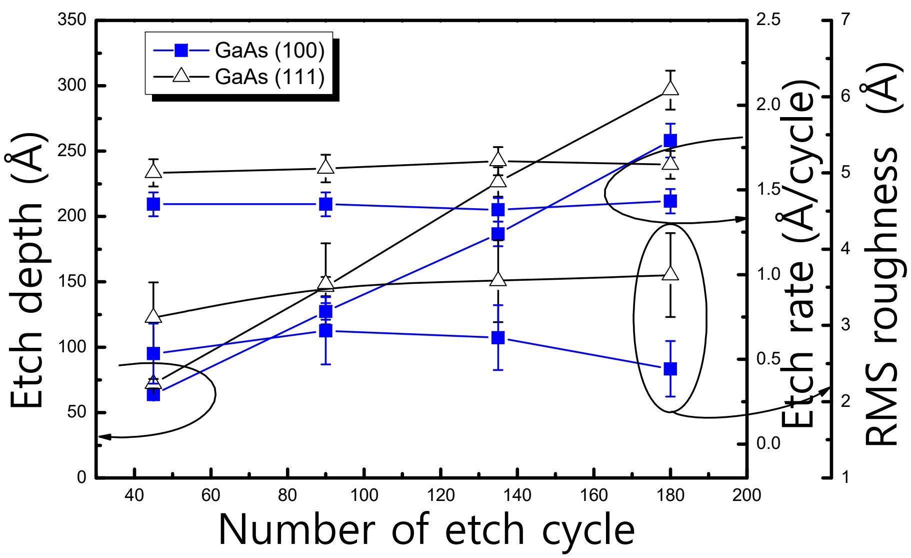
◆ Conditions :

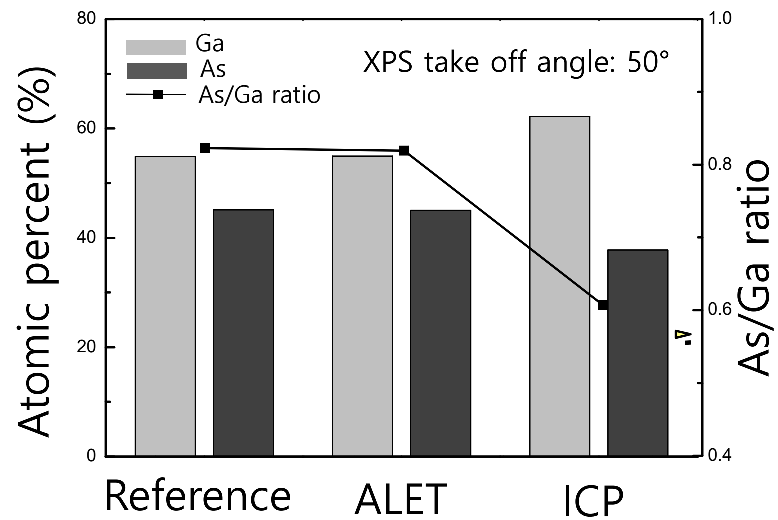
ALET

Base pressure	3.0×10^{-7} Torr	1st grid voltage	10 Volts	Cl_2 pressure	0.4 mTorr
Chamber pressure	2.0×10^{-4} Torr	2nd grid voltage	-250 Volts	Ne neutral beam Irradiation dose	3.03×10^{16} atoms/cm2·cycle
Inductive power	300 Watts	Ne flow rate	70 sccm	Cl_2 supply time (t_{Cl2})	10 sec

ICP

Inductive power	700 Watts	Etch time	12sec
D.C bias voltage	-100 Volts	Gas pressure	12 mTorr [Cl_2(70sccm)/Ar(30sccm)]



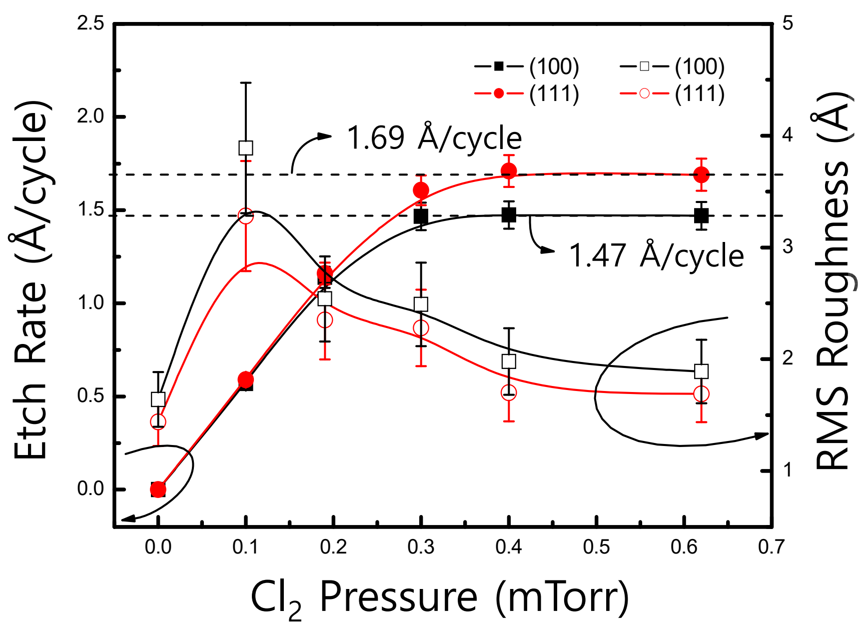


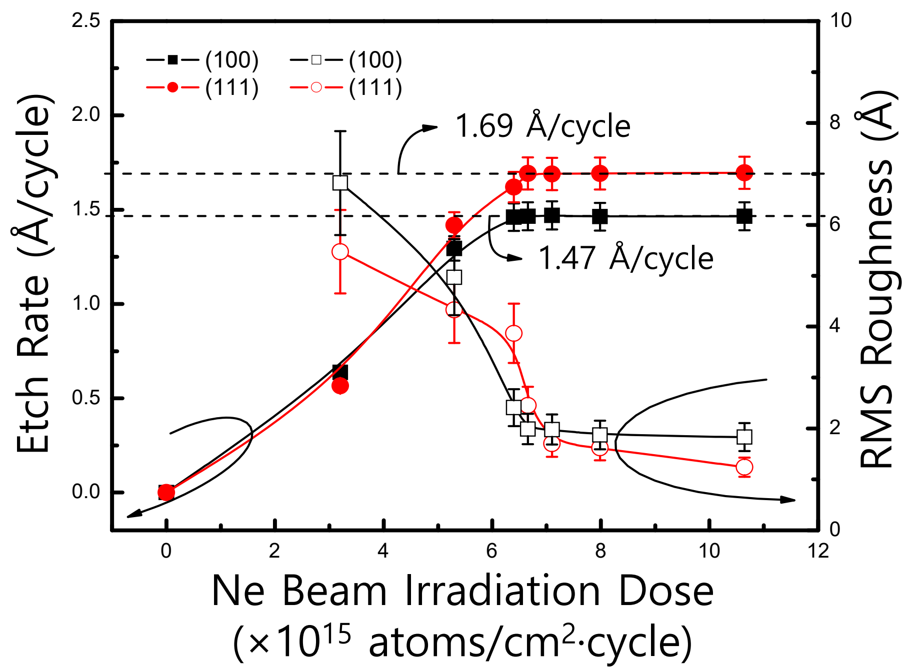
"Atomic layer etching of (100)/(111) GaAs with chlorine and low angle forward reflected Ne neutral beam"
Woong Sun Lim, Sang Duk Park, Byoung Jae Park, Geun Young Yeom
Surface & Coatings Technology 202, 5701–5704 (2008)

InP ALE

◆ 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	$0\sim10.6\times10^{15}$ atoms/cm²·cycle	Cl_2 pressure	0~0.62 mTorr	Cl_2 supply time (t_{Cl2})	10 sec



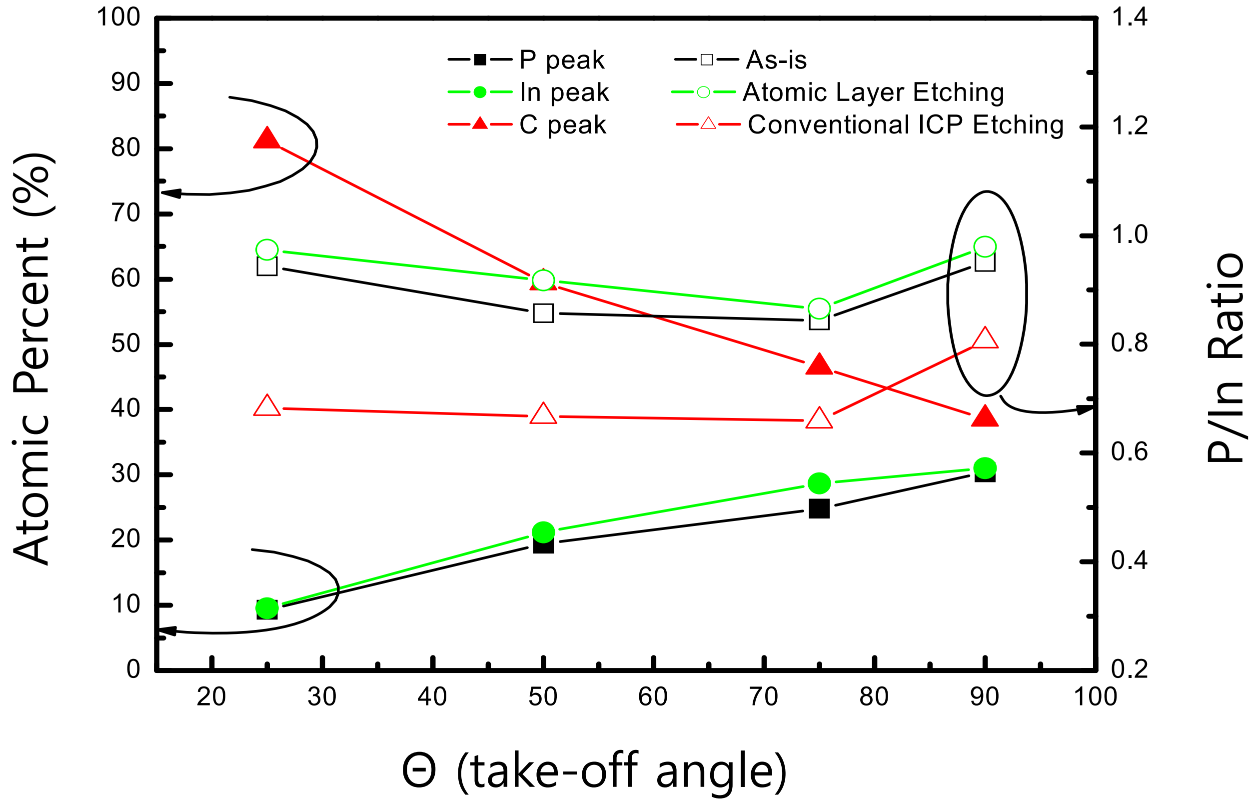


"Atomic layer etching of InP using a low angle forward reflected Ne neutral beam"
S. D. Park, C. K. Oh, J. W. Bae, G. Y. Yeom, T. W. Kim
Appl. Phys. Lett. 89, 043109 (2006)

Stoichiometry Modification of InP Surface

◆ Conditions :

- ICP Etching : Cl_2 (70 sccm)/Ar (30 sccm), 700 W, -100 V, 12 sec
- Atomic Layer Etching : Ne beam irradiation dose (7.2×10^{15} atoms/cm^2·cycle), Cl_2 pressure (0.4 mTorr), Etch cycle (100 cycle)

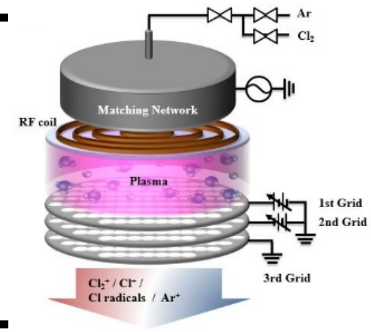


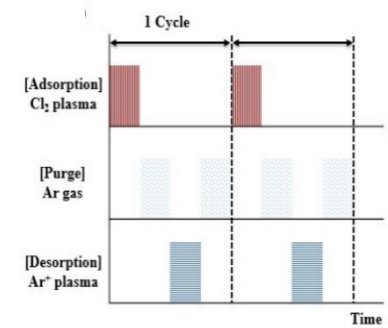
"Atomic layer etching of InP using a low angle forward reflected Ne neutral beam"
S. D. Park, C. K. Oh, J. W. Bae, G. Y. Yeom, T. W. Kim
Appl. Phys. Lett. 89, 043109 (2006)

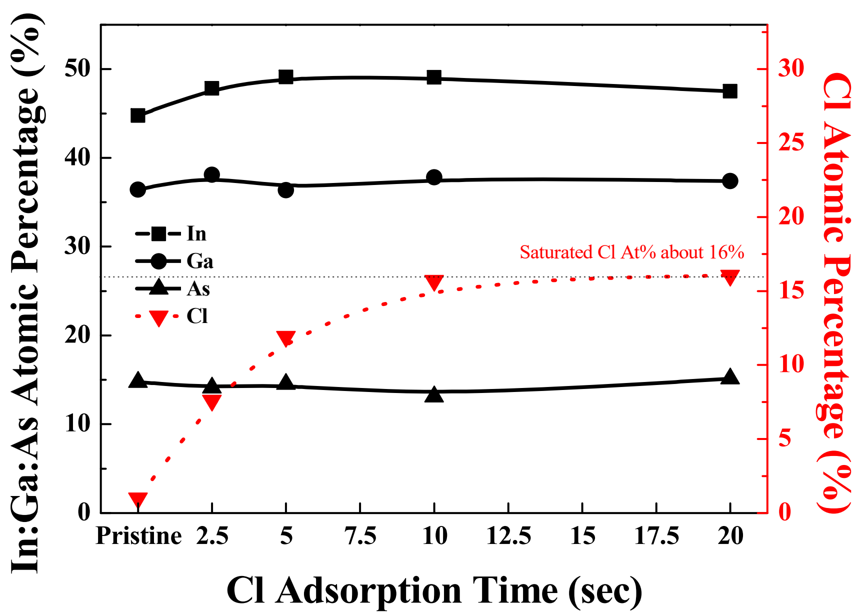
InGaAs ALE

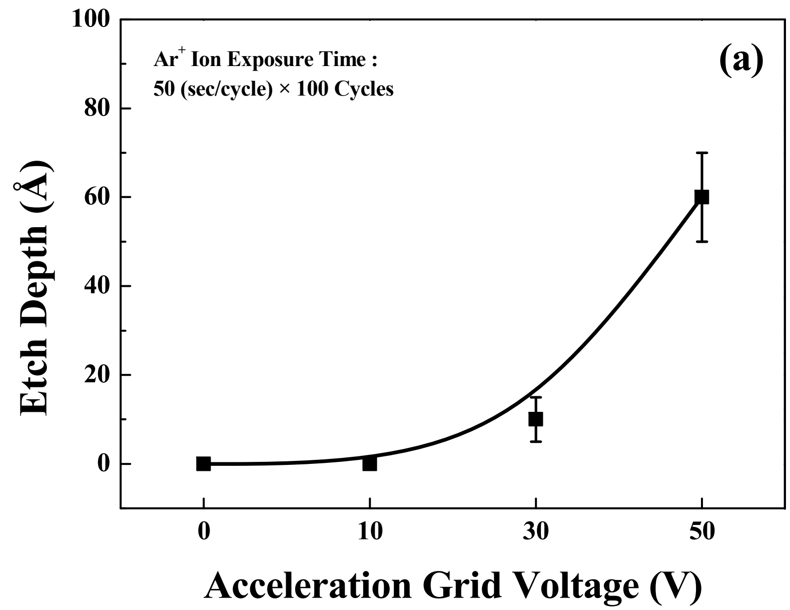
◆ Conditions :

Base pressure	2.0×10^{-6} Torr	Chamber pressure	2.0×10^{-4} Torr
Inductive power	200 Watts		
1st grid voltage	10 Volts	2nd grid voltage	-100 Volts
Cl_2 pressure	1.0 mTorr	Ar pressure	3.0 mTorr
Cl supply time	10 sec	Ar Irradiation time	50 sccm







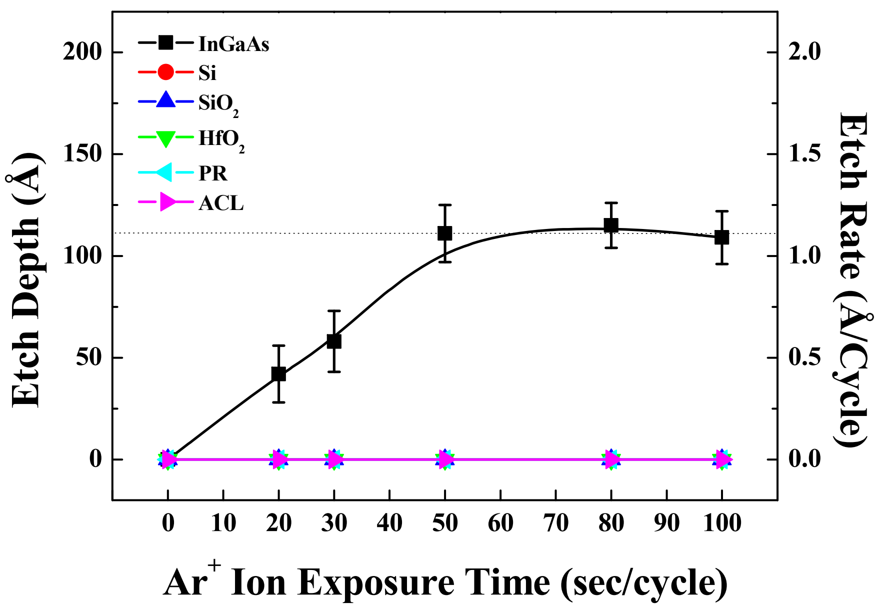


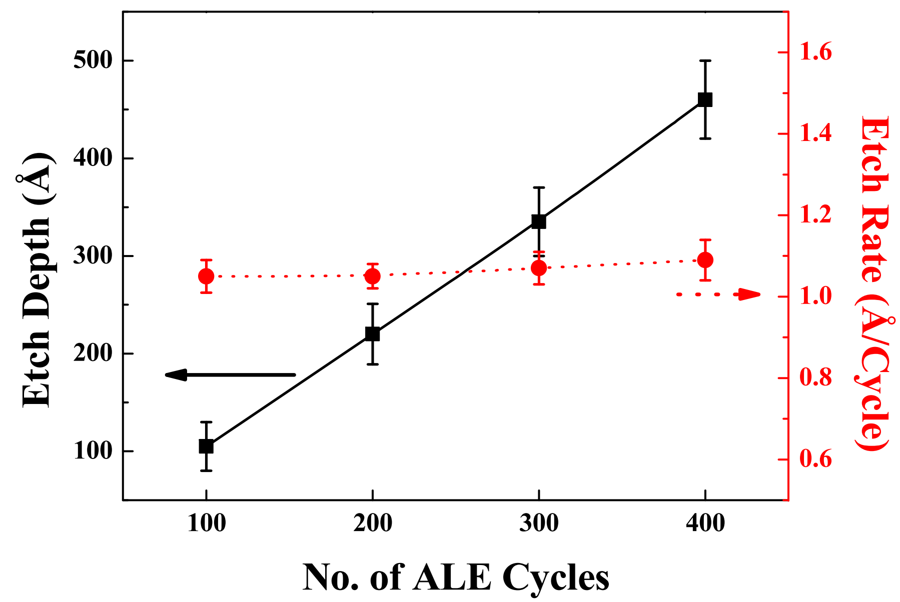
"Atomic layer etching of InGaAs by controlled ion beam"
Jin Woo Park, Doo San Kim, Mu Kyeom Mun, Won Oh Lee, Ki Seok Kim amd Geun Young Yeom
Accepted by Journal of Physics D: Applied Physics

InGaAs ALE

◆ Conditions :

Base pressure	2.0×10^{-6} Torr	Chamber pressure	2.0×10^{-4} Torr	Inductive power	200 Watts
1st grid voltage	10 Volts	2nd grid voltage	-100 Volts	Ar pressure	3.0 mTorr
Ar Irradiation time	50 sccm	Cl_2 pressure	1.0 mTorr	Cl supply time	10 sec

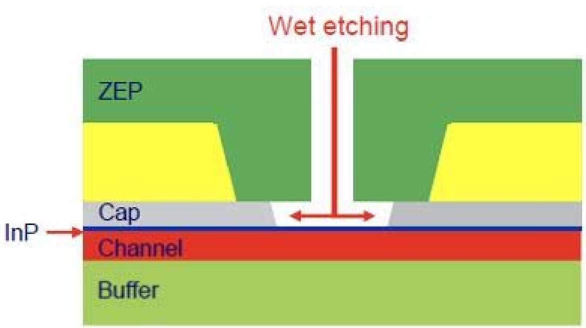


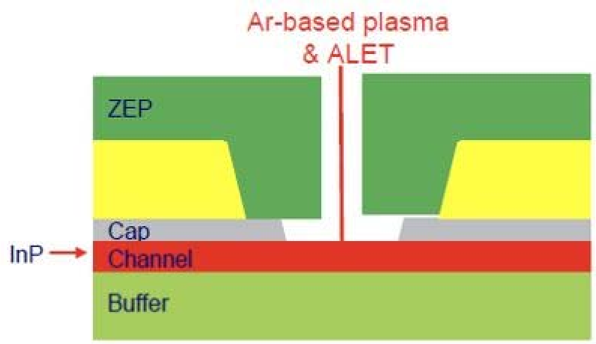


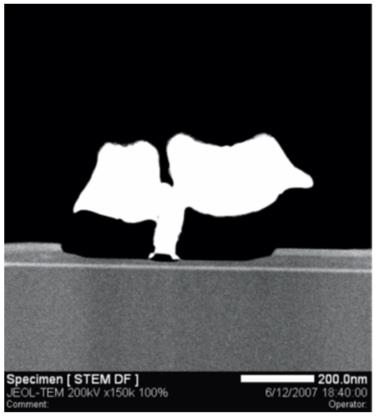
"Atomic layer etching of InGaAs by controlled ion beam"
Jin Woo Park, Doo San Kim, Mu Kyeom Mun, Won Oh Lee, Ki Seok Kim amd Geun Young Yeom
Accepted by Journal of Physics D: Applied Physics

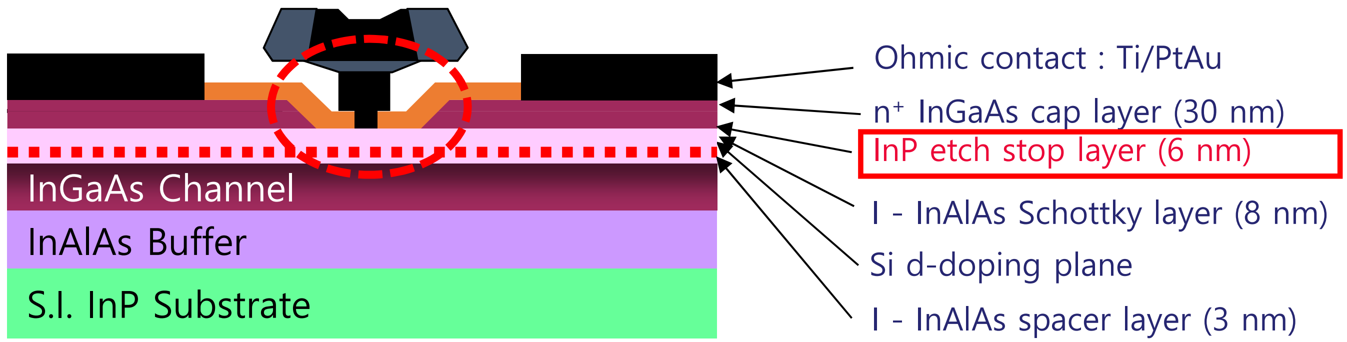
Application – InP HEMTs (Gate Recess Process)

- **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]







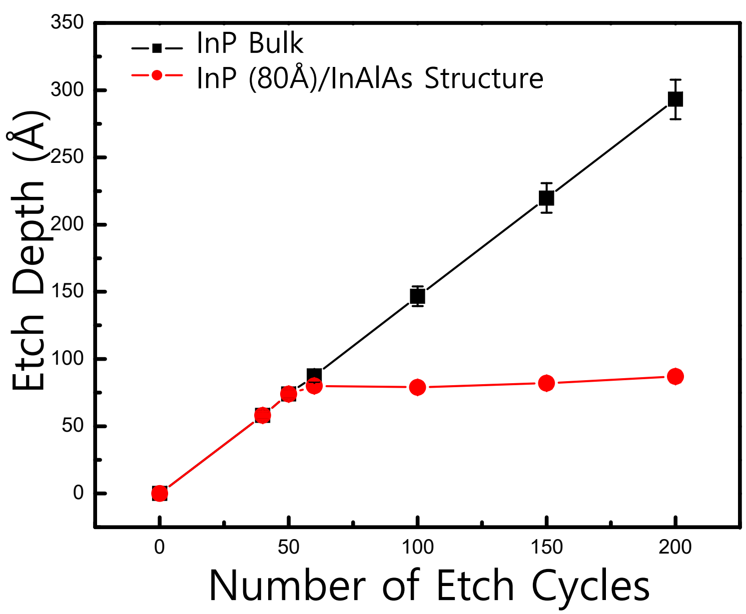


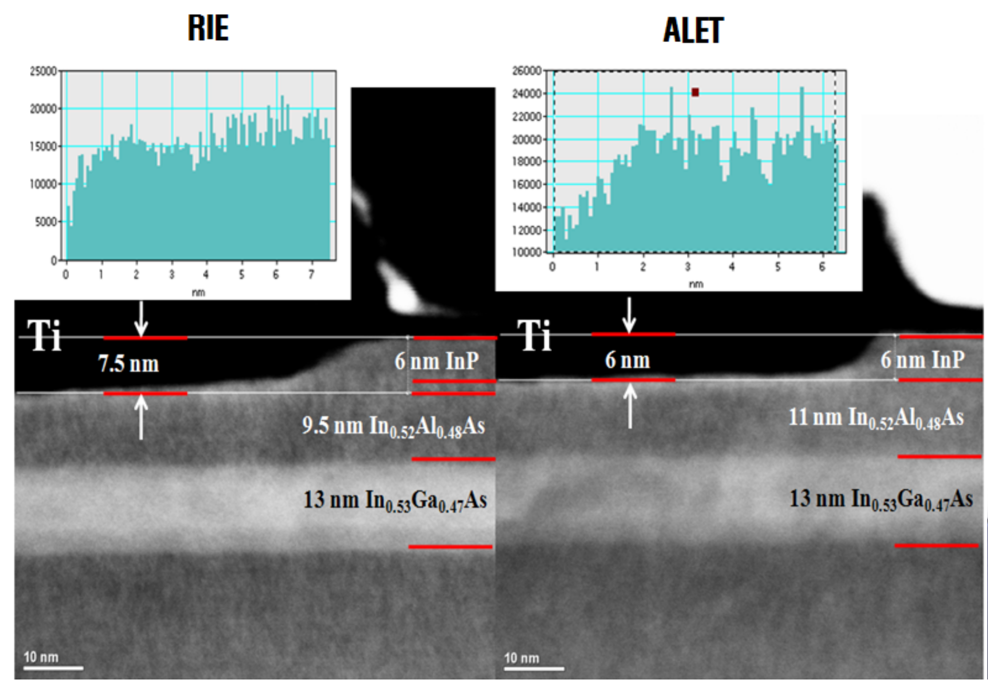
"30 nm gate InAlAs/InGaAs HEMTs lattice-matched to InP substrates"
Tetsuya Suemitsu, Tetsuyoshi Ishii, Haruki Yokoyama, Yohatro Umeda, Takatomo Enoki, Yasunobu Ishii, Toshiaki Tamamura
Electron Devices Meeting, (1998). IEDM'98

InP HEMTs (Gate Recess Process)

◆ Conditions :

Base pressure	3.0×10^{-7} Torr	Chamber pressure	2.0×10^{-4} 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	7.2×10^{15} atoms/cm²·cycle	Cl_2 pressure	0.4 mTorr	Cl_2 supply time (t_{Cl2})	10 sec





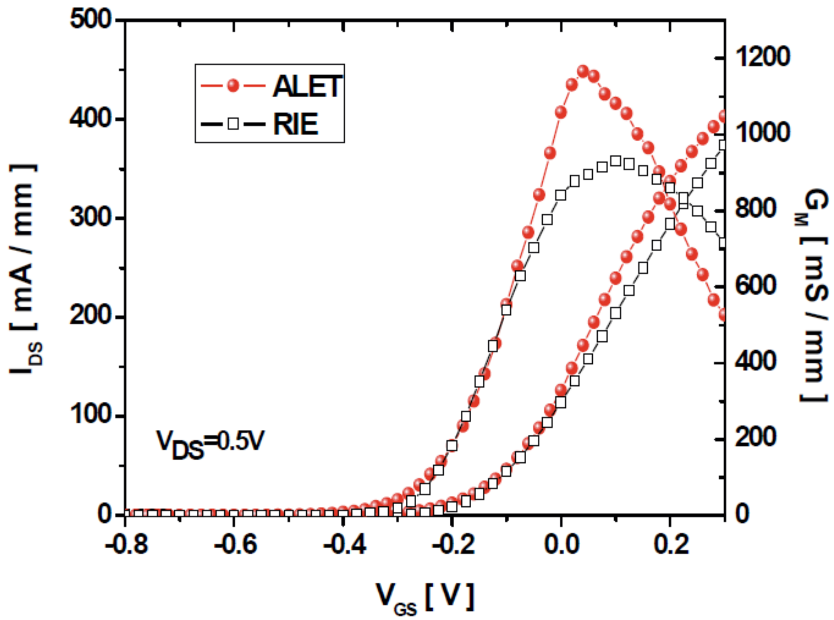
"A Two-Step-Recess Process Based on Atomic-Layer Etching for High-Performance $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ p-HEMTs"
Tae-Woo Kim, Geun-Young Yeom, Jae-Hyung Jang, Jong-In Song
IEEE TRANSACTIONS ON ELECTRON DEVICES, 55, 7, (2008)

60 nm Depletion Mode InP HEMT

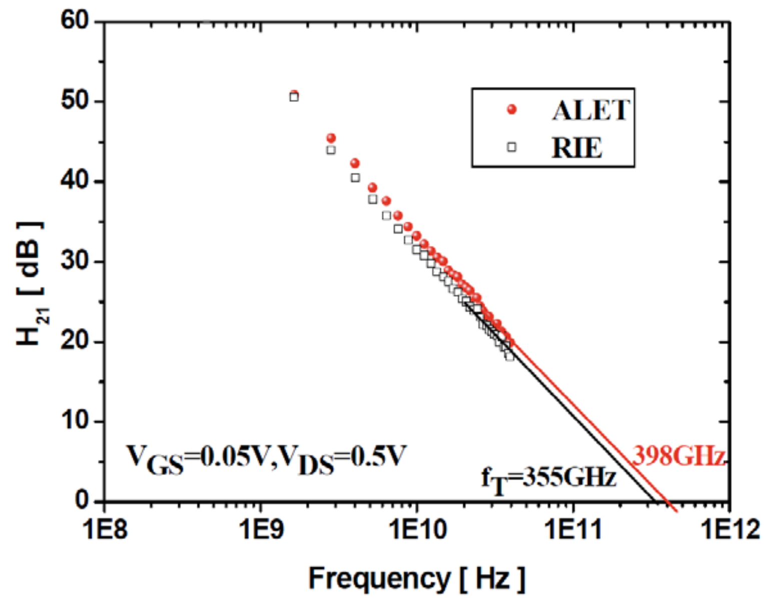
Conditions :

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

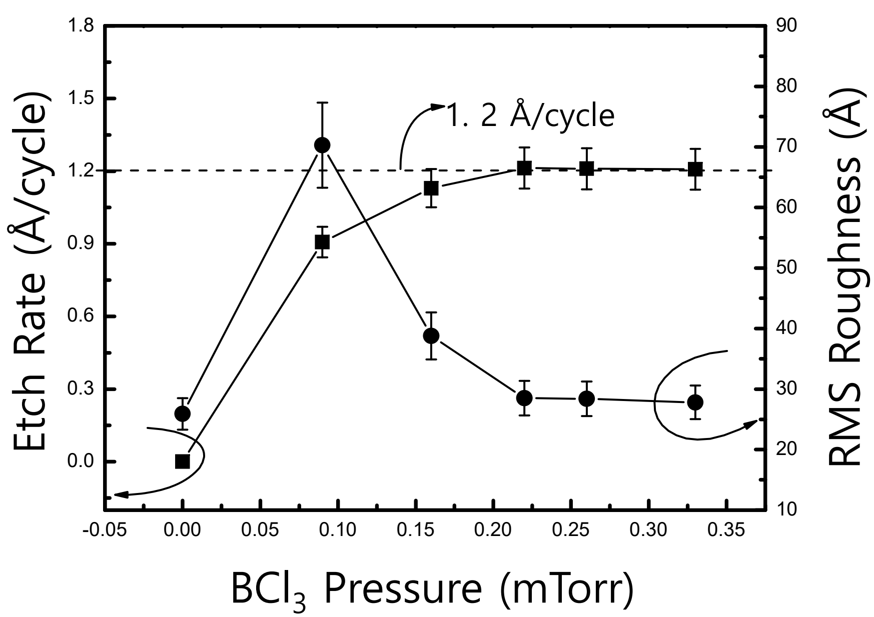
"A Two-Step-Recess Process Based on Atomic-Layer Etching for High-Performance $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ p-HEMTs"
Tae-Woo Kim, Geun-Young Yeom, Jae-Hyung Jang, Jong-In Song
IEEE TRANSACTIONS ON ELECTRON DEVICES, 55, 7, (2008)

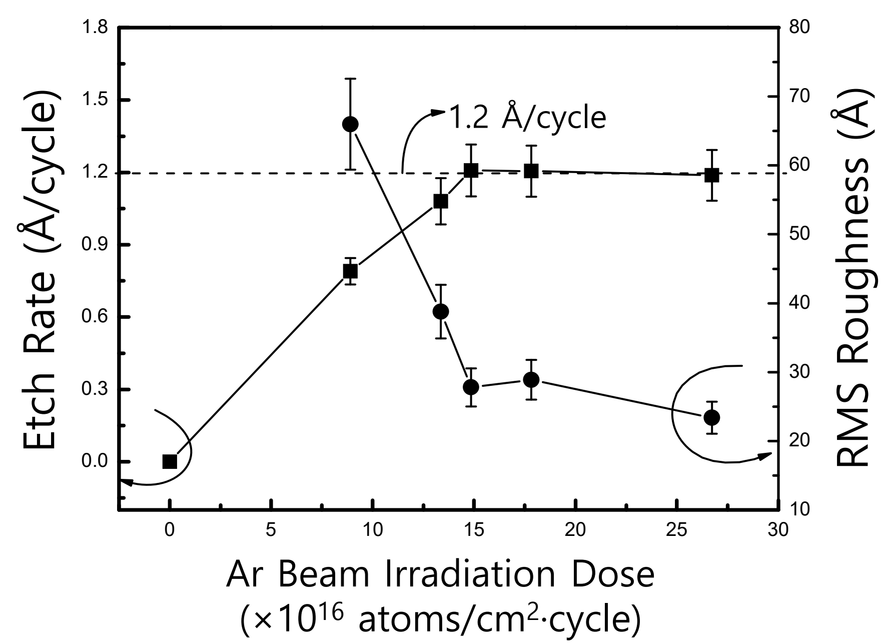
Contents

HfO_2 ALE

◆ 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 beam Irradiation dose	$0\sim2.67\times10^{17}$ atoms/cm^2·cycle	BCl_3 pressure	0~0.33 mTorr	BCl_3 supply time (t_{Cl2})	20 sec



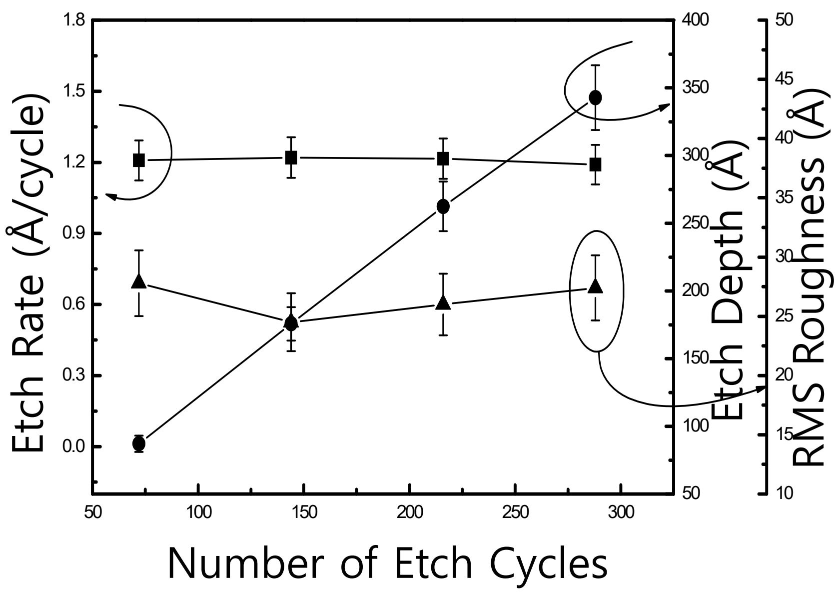


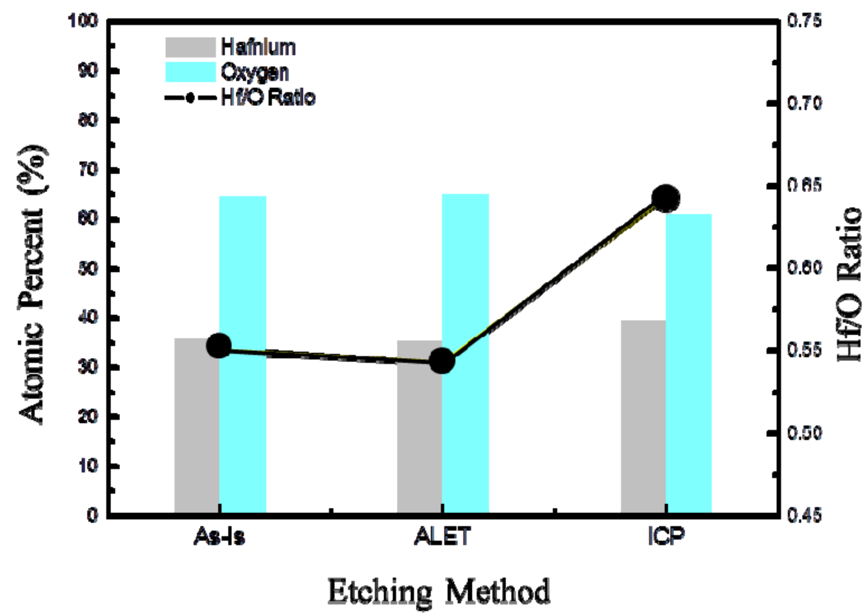
"Precise Depth Control and Low-Damage Atomic-Layer Etching of HfO_2 using BCl_3 and Ar Neutral Beam"
S. D. Park, W. S. Lim, B. J. Park, H. C. Lee, J. W. Bae, and G. Y. Yeom
Electrochemical and Solid-State Letters, 11 4 H71-H73 (2008)

HfO_2 ALE

◆ 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	1.485×10^{17} atoms/cm^2·cycle	BCl_3 pressure	0.33 mTorr	BCl_3 supply time (t_{Cl2})	20 sec





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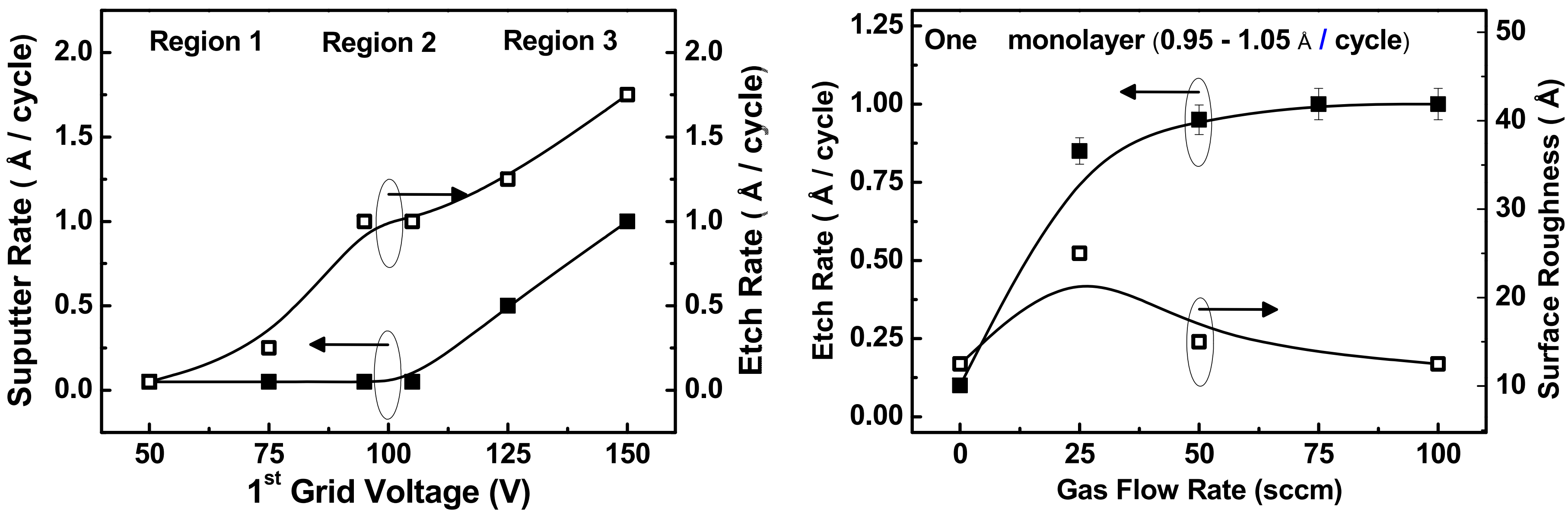
S. D. Park, W. S. Lim, B. J. Park, H. C. Lee, J. W. Bae, and G. Y. Yeom
Electrochemical and Solid-State Letters, 11 4 H71-H73 (2008)

Al_2O_3 ALE

◆ Conditions :

Base pressure	5.0×10^{-7} Torr	Chamber pressure	2.5×10^{-4} Torr	Inductive power	300 Watts
1st grid voltage	100 Volts	2nd grid voltage	-250 Volts	Ar flow rate	50 sccm
BCl_3 gas flow rate	0~100 scmm	BCl_3 supply time (t_{Cl2})	30 s	Ar neutral beam Irradiation time	125 sec

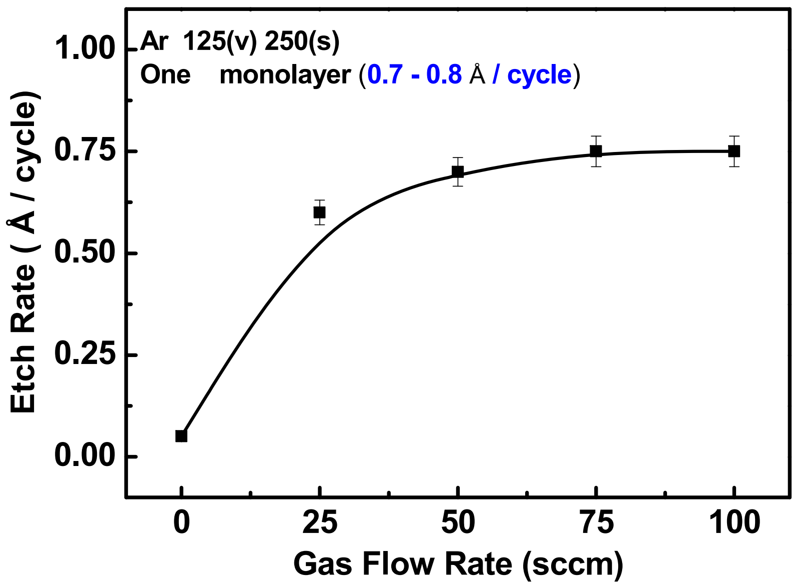


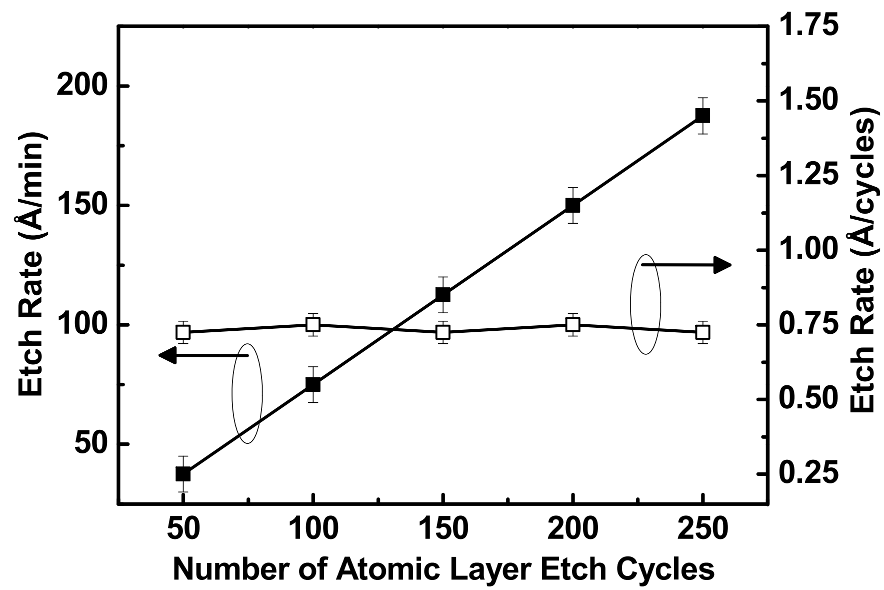
"Atomic layer etching of Al_2O_3 using BCl_3/Ar for the interface passivation layer of III–V MOS devices"
K.S. Min a, S.H. Kang a, J.K. Kim a,c, Y.I. Jhon b, M.S. Jhon b, G.Y. Yeom
Microelectronic Engineering 110, 457–460 (2013)

BeO ALE

◆ Conditions :

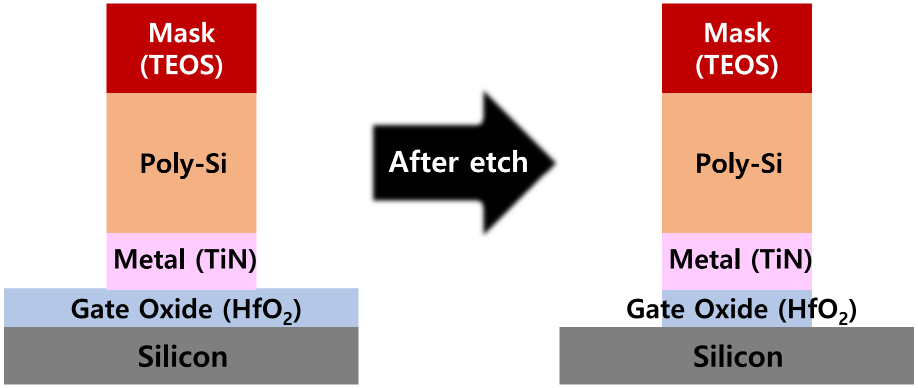
Base pressure	5.0×10^{-7} Torr	Chamber pressure	2.5×10^{-4} Torr	Inductive power	300 Watts
1st grid voltage	125 Volts	2nd grid voltage	-250 Volts	Ar flow rate	50 sccm
BCl_3 gas flow rate	0~100 scmm	BCl_3 supply time (t_{Cl2})	30 s	Ar neutral beam Irradiation time	125 sec





"Atomic layer etching of BeO using BCl_3/Ar for the interface passivation layer of III–V MOS devices"
K.S. Min, S.H. Kang, J.K. Kim, J.H. Yumg, Y.I. Jhon, Todd W. Hudnall, C.W. Bielawski, S.K. Banerjee, G. Bersuker, M.S. Jhon, G.Y. Yeom
Microelectronic Engineering 114, 121–125 (2014)

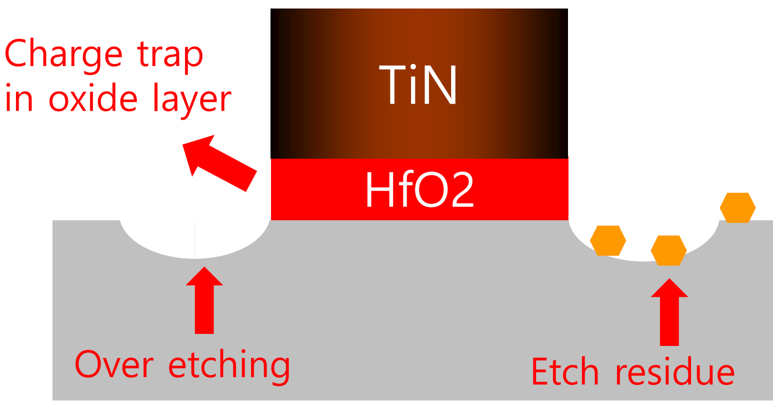
MOSFET Fabrication with HfO_2 ALE



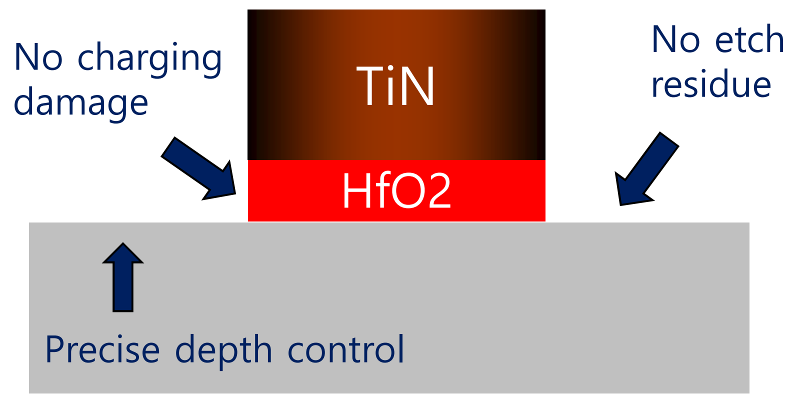
◆ Main etch challenges

- 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

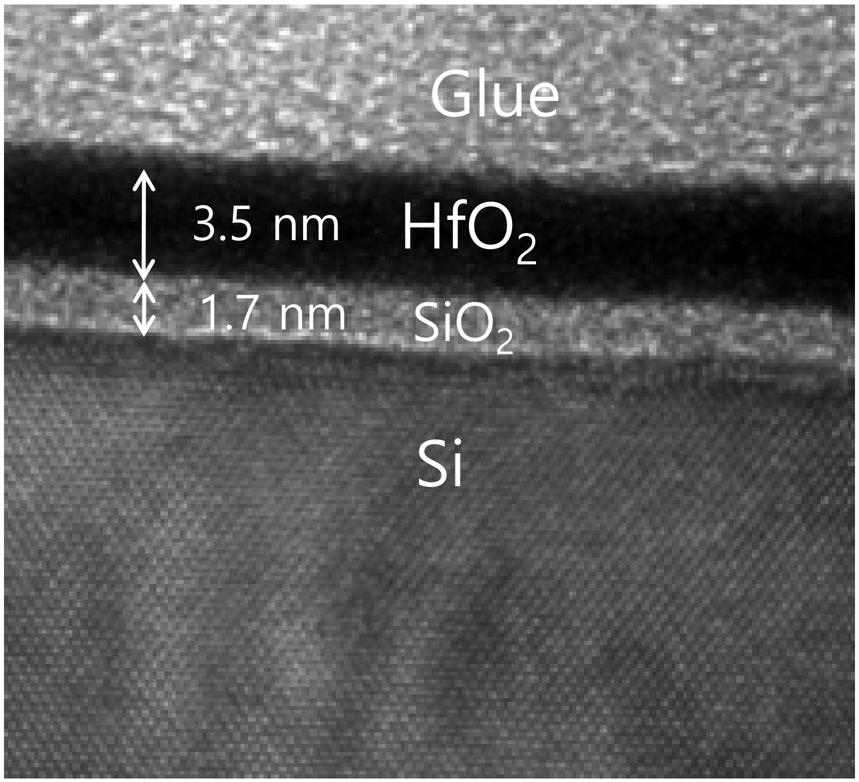


“Atomic layer etching of ultra-thin HfO_2 film for gate oxide in MOSFET devices”
Jae Beom Park, Woong Sun Lim, Byoung Jae Park, Ih Ho Park, Young Woon Kim and Geun Young Yeom
J. Phys. D: Appl. Phys. 42, 055202 (2009)

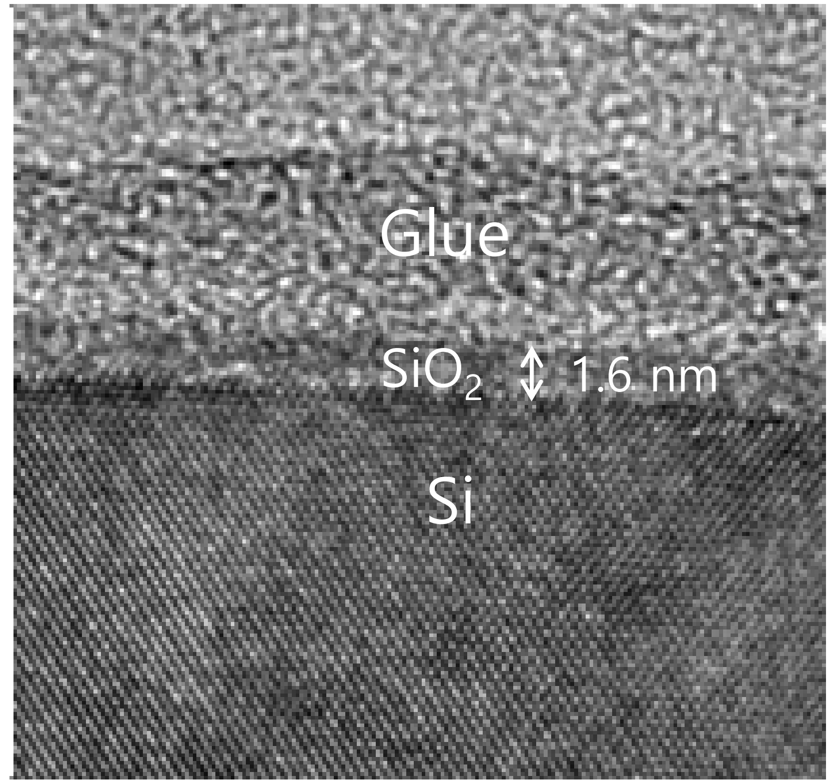
TEM Image of HfO_2 Etched by ALE

- **Precise etching of HfO_2 on SiO_2 using ALE**

: Blank wafer (HfO_2 on SiO_2) etching



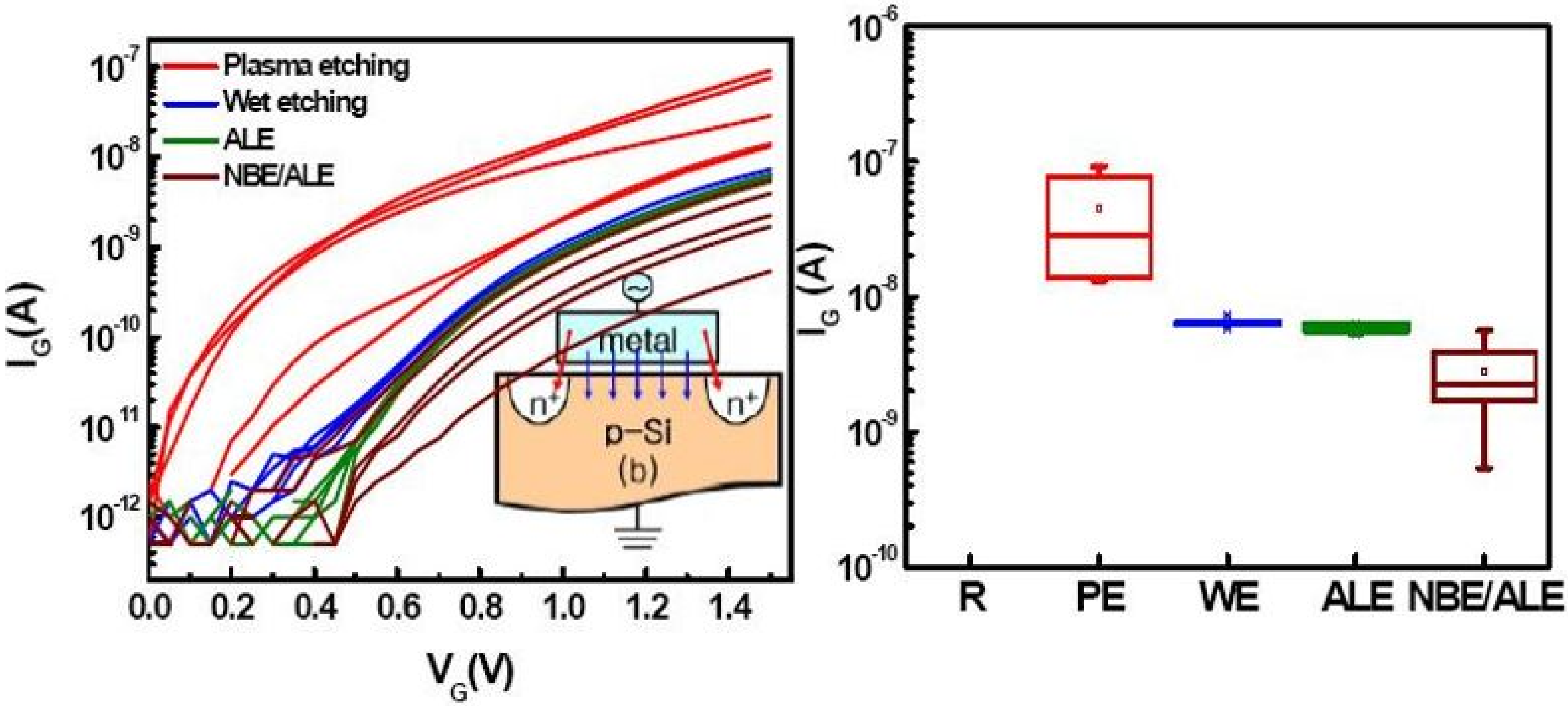
Before ALE process



After 30 cycles of ALE

"Atomic layer etching of ultra-thin HfO_2 film for gate oxide in MOSFET devices"
Jae Beom Park, Woong Sun Lim, Byoung Jae Park, Ih Ho Park, Young Woon Kim and Geun Young Yeom
J. Phys. D: Appl. Phys. 42, 055202 (2009)

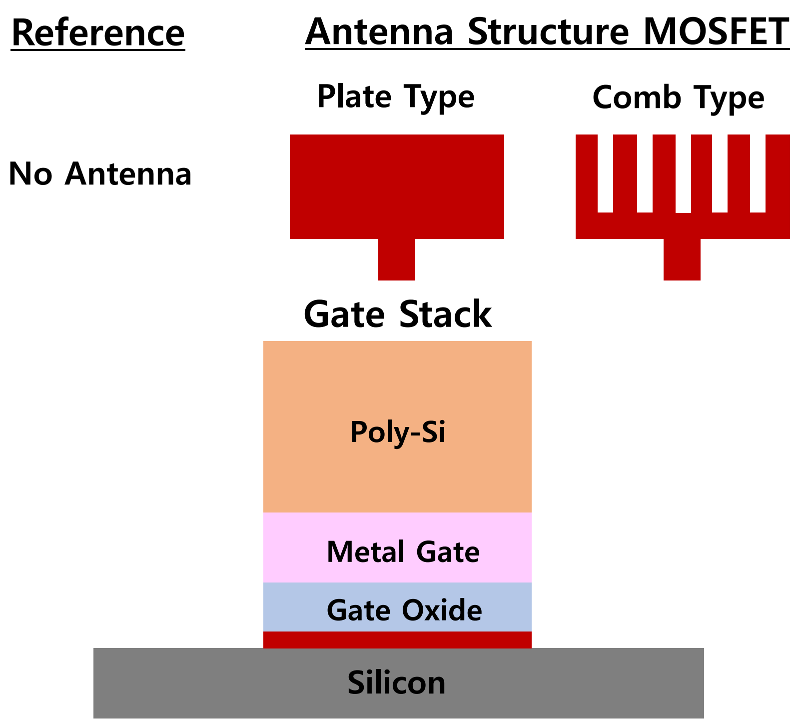
MOSFET IG-VG



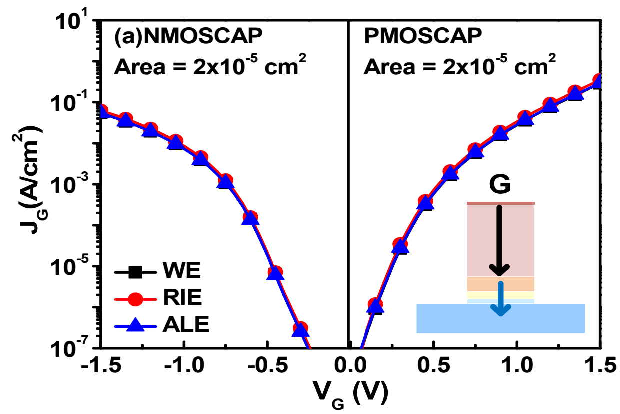
However, there are differences in MOSFET (without S/D active region) due to gate oxide edge damage which could be the leakage path in the heterogeneous interface between the high-k dielectric and the capping nitride layer

"Atomic layer etching of ultra-thin HfO_2 film for gate oxide in MOSFET devices"
Jae Beom Park, Woong Sun Lim, Byoung Jae Park, Ih Ho Park, Young Woon Kim and Geun Young Yeom
J. Phys. D: Appl. Phys. 42, 055202 (2009)

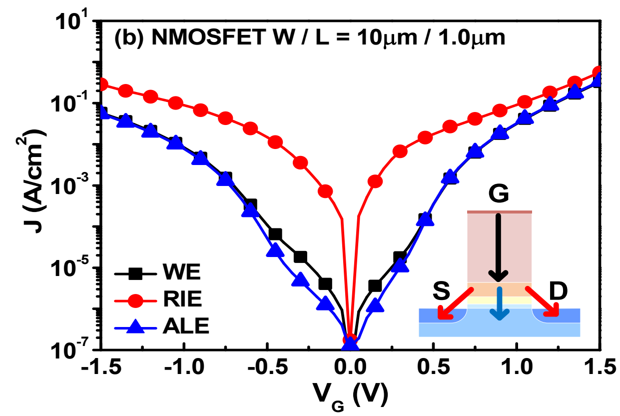
MOSFET IG-VG



I_G-V_G characteristics of STI edge transistor



I_G-V_G characteristics of S/D edge transistor

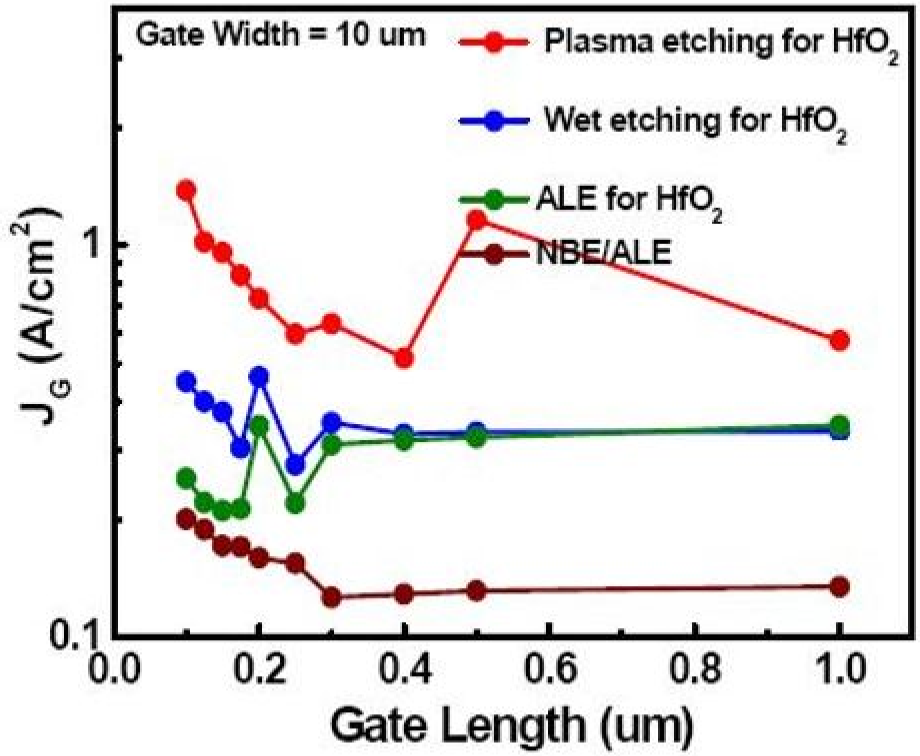


The ALET can minimize the plasma etching damage at the edge of gate oxide.

"Atomic layer etching of ultra-thin HfO_2 film for gate oxide in MOSFET devices"
Jae Beom Park, Woong Sun Lim, Byoung Jae Park, Ih Ho Park, Young Woon Kim and Geun Young Yeom
J. Phys. D: Appl. Phys. 42, 055202 (2009)

MOSFET Device as a function of Gate Length

◆ MOS Parameter - IG

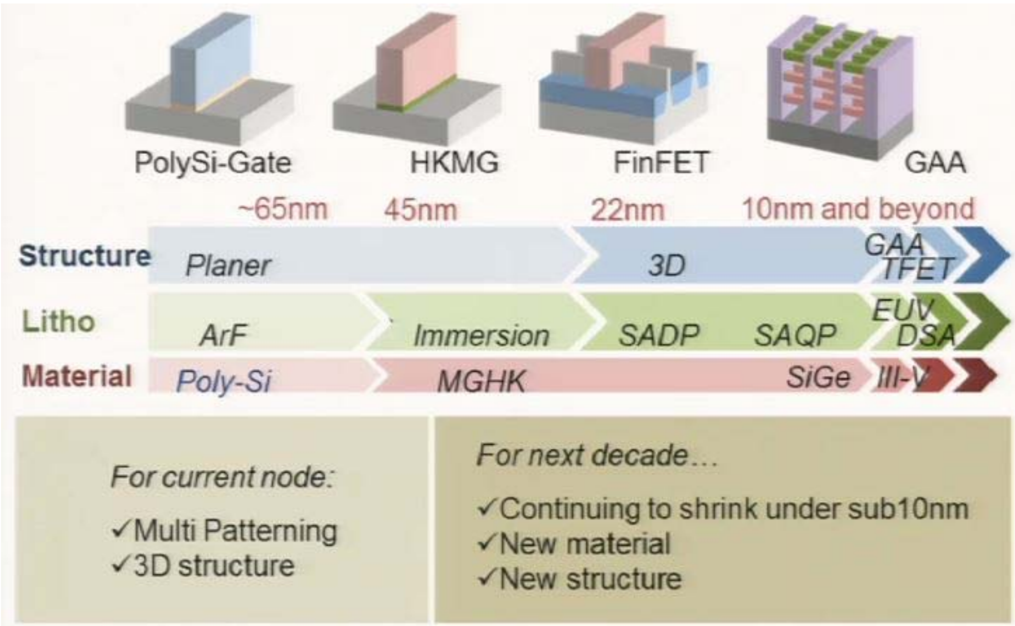


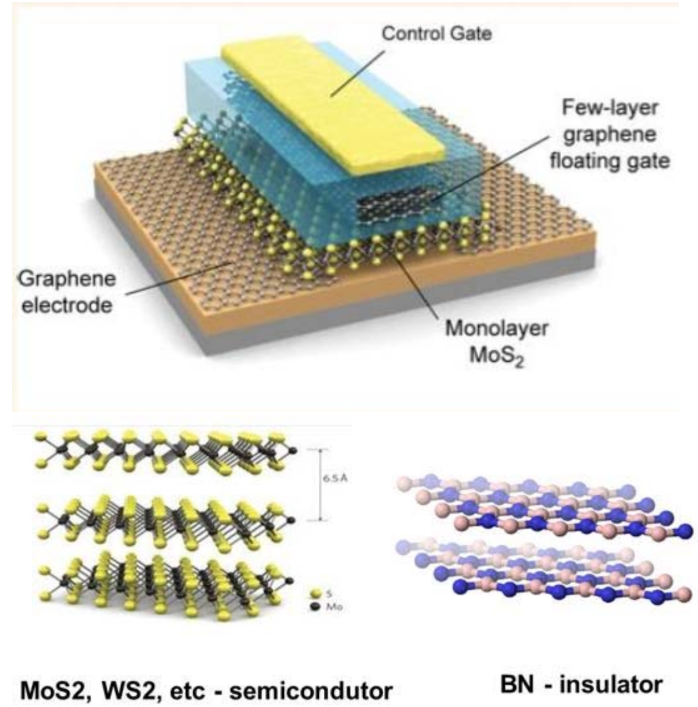
As gate length decrease from 1 um to 100 nm, the gate leakage current is as low as wet etching compared that of plasma etching

"Atomic layer etching of ultra-thin HfO_2 film for gate oxide in MOSFET devices"
Jae Beom Park, Woong Sun Lim, Byoung Jae Park, Ih Ho Park, Young Woon Kim and Geun Young Yeom
J. Phys. D: Appl. Phys. 42, 055202 (2009)

Contents

Need for ALE



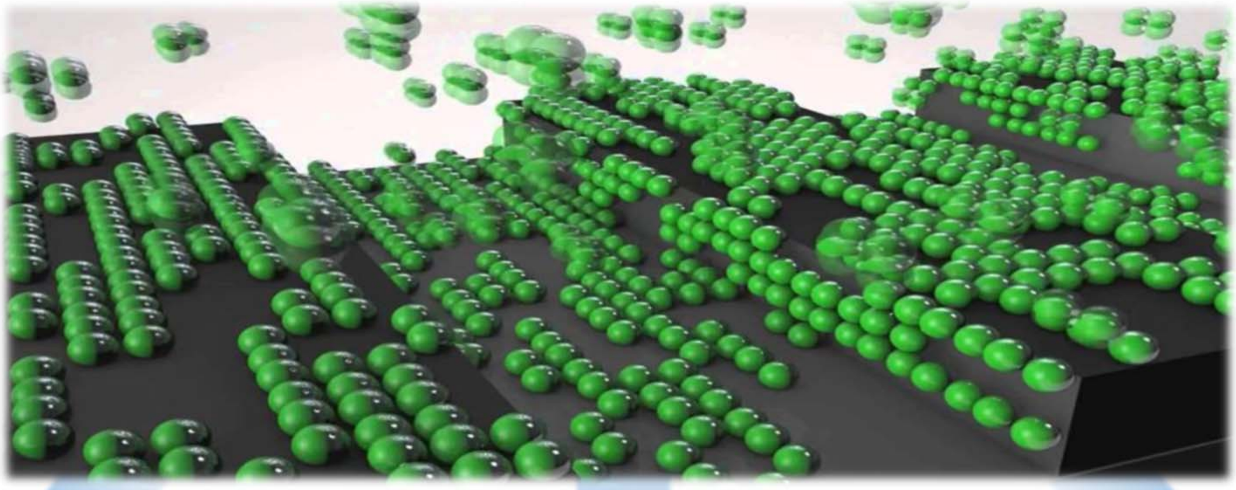


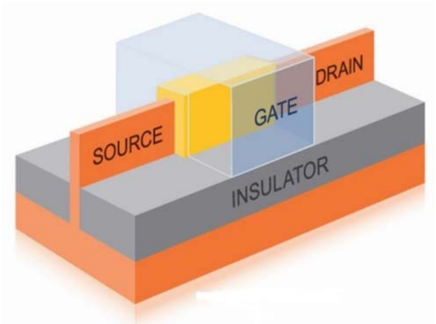
"Atomic Level Etching of Poly-Si in a Microwave Electron Cyclotron Resonance Plasma Etcher"
Yasushi Sonoda (HITACHI)

◆ Films getting thinner: slow etch rate is not a problem

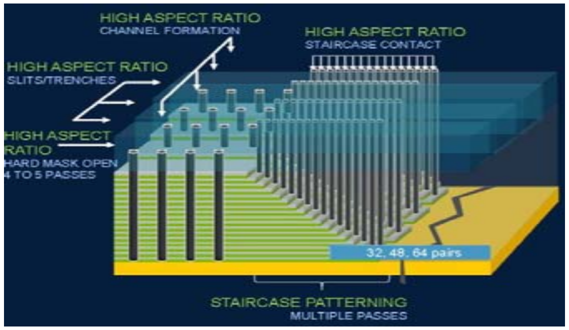
- High etch selectivity
  - Negligible etching into underlayer
- Low etch damage and contamination
- Precise control of etch depth in atomic scale

Possible Application of Anistropic ALE



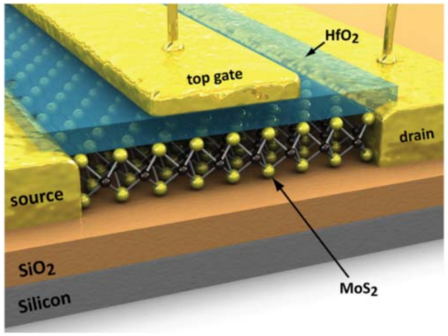


Gate etch



Contact etch

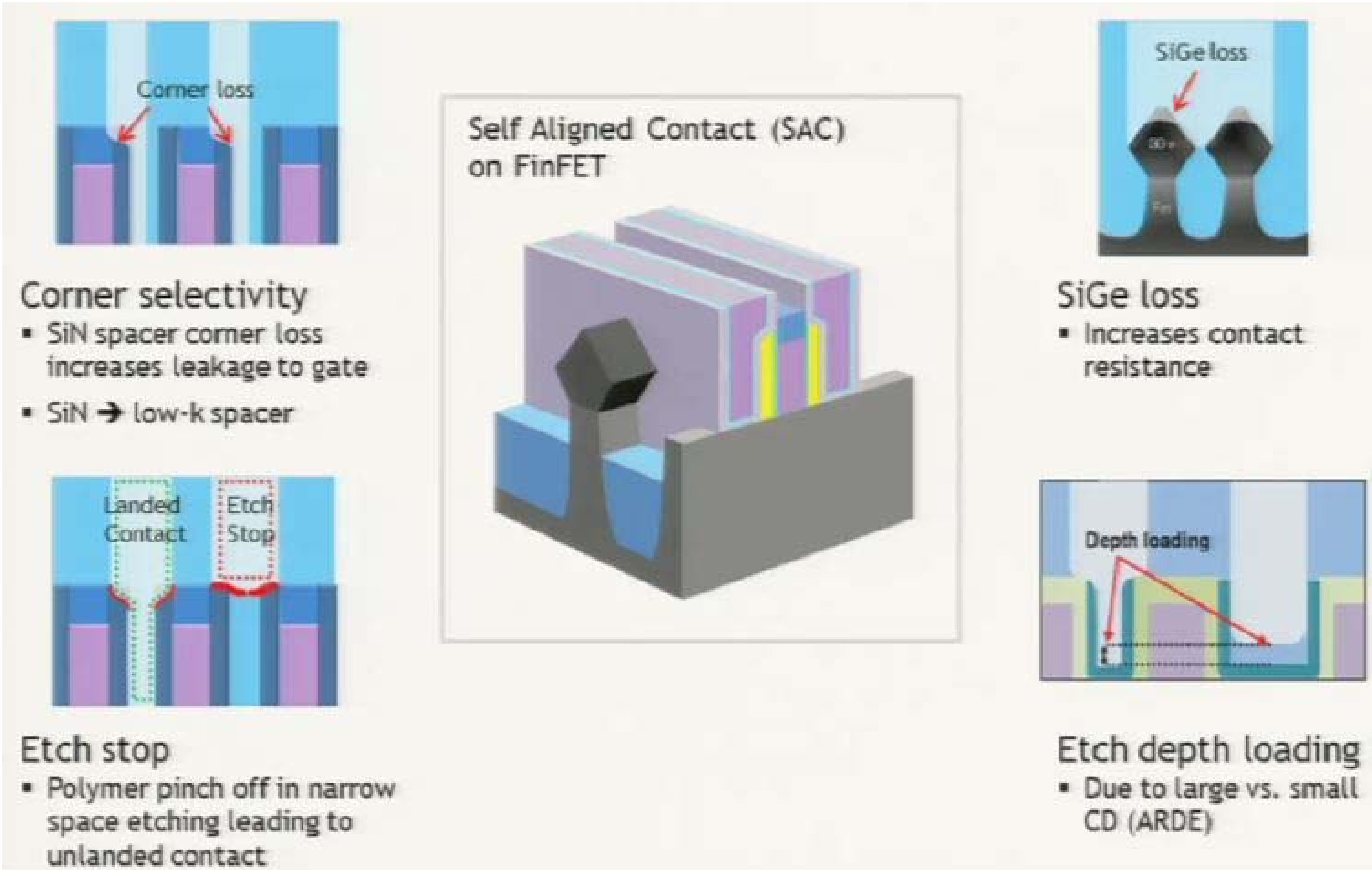
Dummy/Sacrificial layer removal



2D-materials

Logic Challenges for 10 nm Node and Beyond

◆ Self-aligned contact



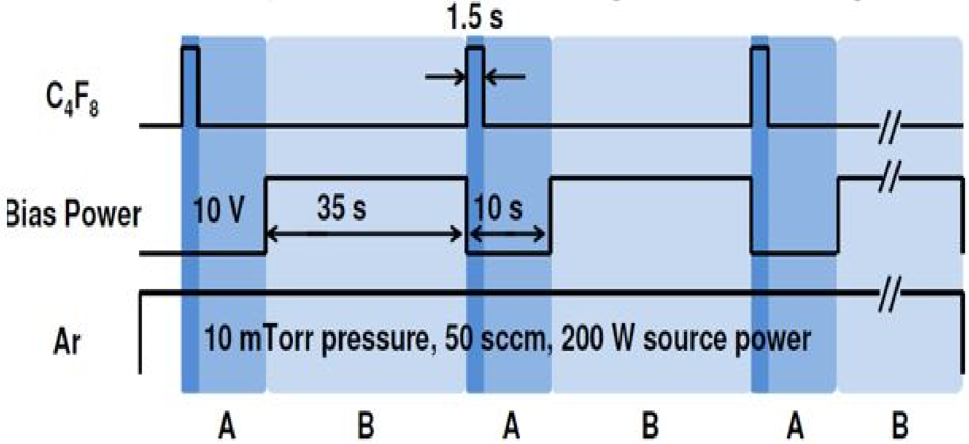
"Fluorocarbon-based Atomic Layer Etching of Silicon Dioxide for Self-aligned Contact"
Eric Hudson (Lam Reserach)

ALE of SiO_2 using ICP with Pulsing Gases

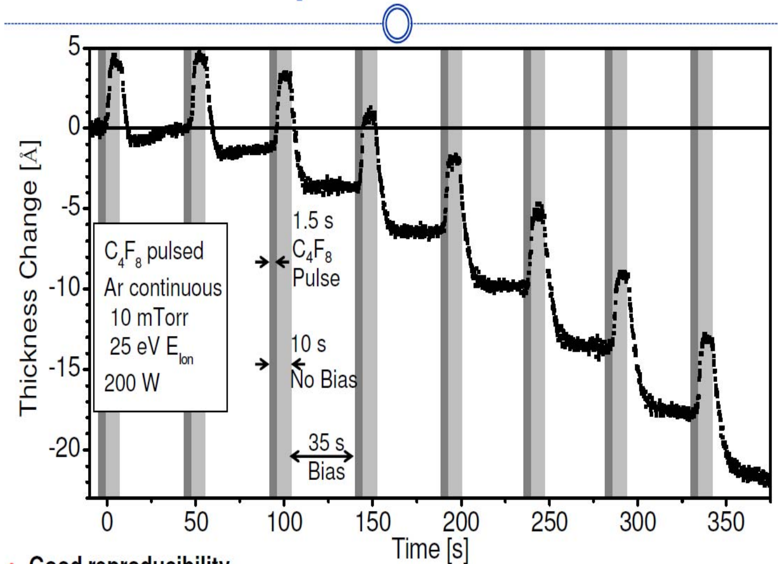
A. Deposition Step → Short precursor pulse

B. Etch Step → Removal of modified surface layer

– In-situ ellipsometry allows real-time monitoring of thickness changes



Time-Dependent Etch Rates



- Good reproducibility

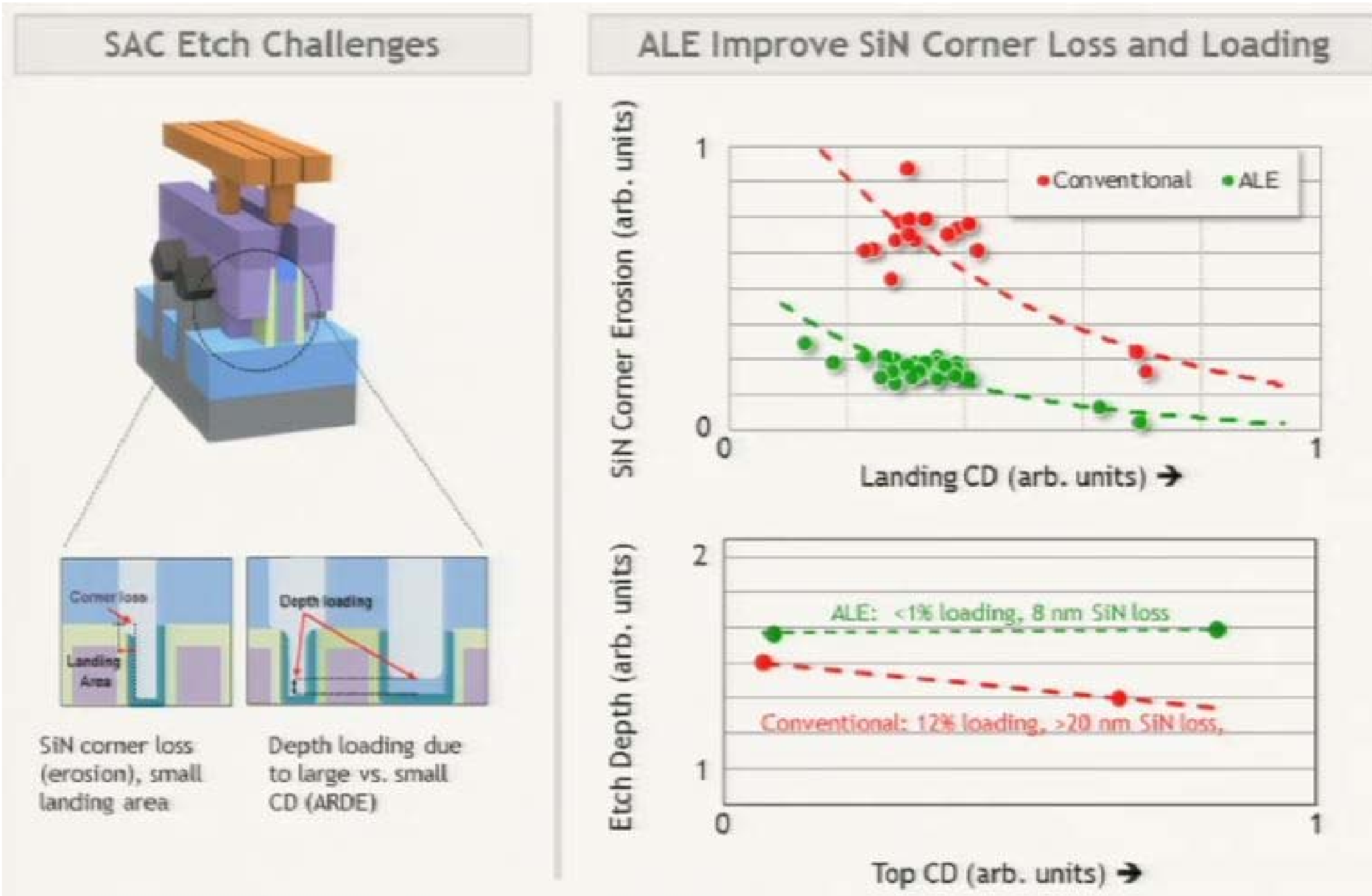
SEMATECH ALET Workshop
April 21, 2014

"Fluorocarbon assisted atomic layer etching of SiO_2 using cyclic Ar/C_4F_8 plasma"
Dominik MetzlerRobert L. Bruce, Sebastian Engelmann, and Eric A. Joseph **Gottlieb S. Oehrlein**
J. Vac. Sci. Technol. A 32, 020603 (2014)

ALE Tool by Lam Research Inc.

◆ Oxide ALE for SAC etch

: Better selectivity and loading

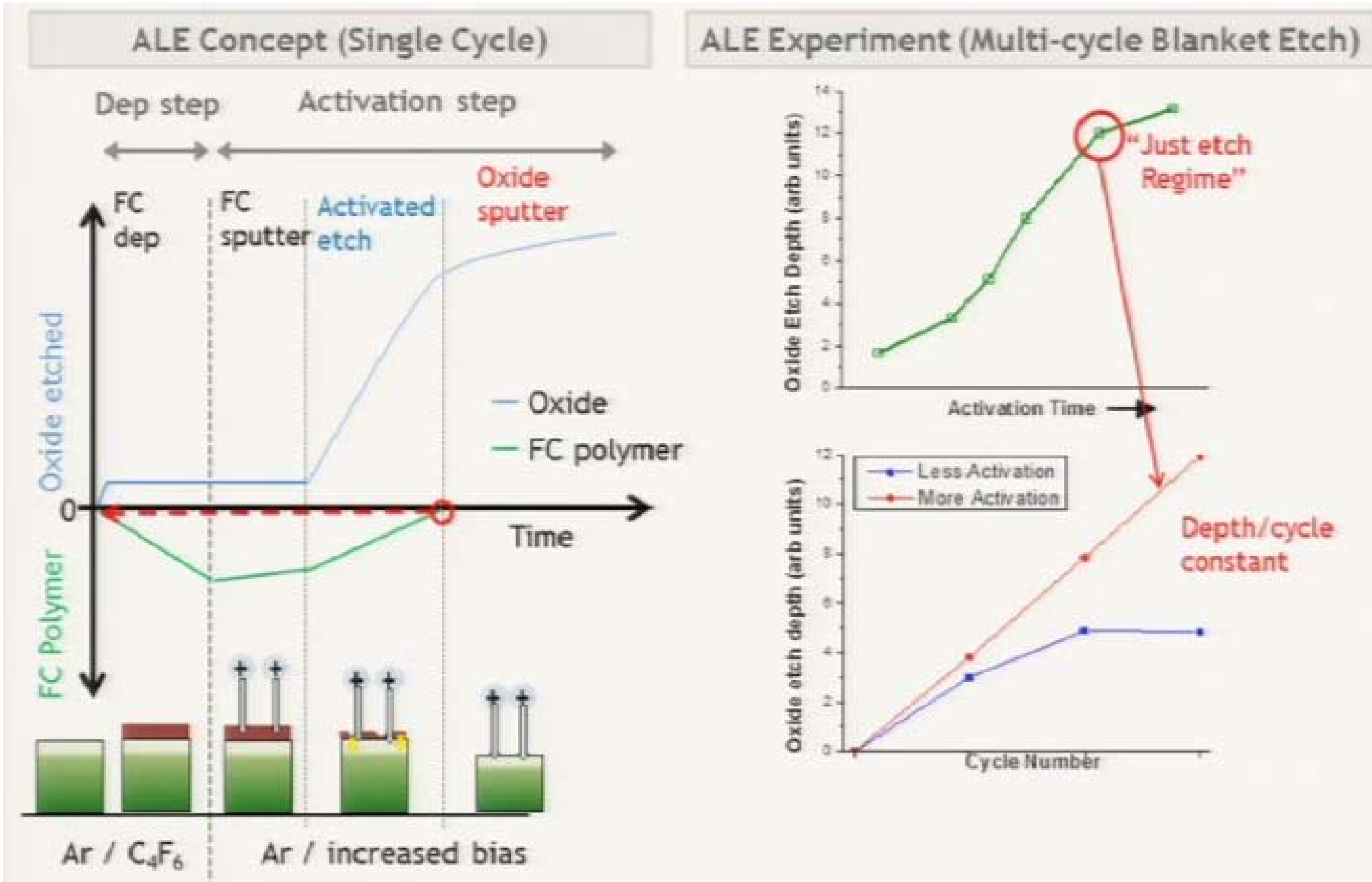


"Fluorocarbon-based Atomic Layer Etching of Silicon Dioxide for Self-aligned Contact"
Eric Hudson (Lam Research)

ALE Tool by Lam Research Inc.

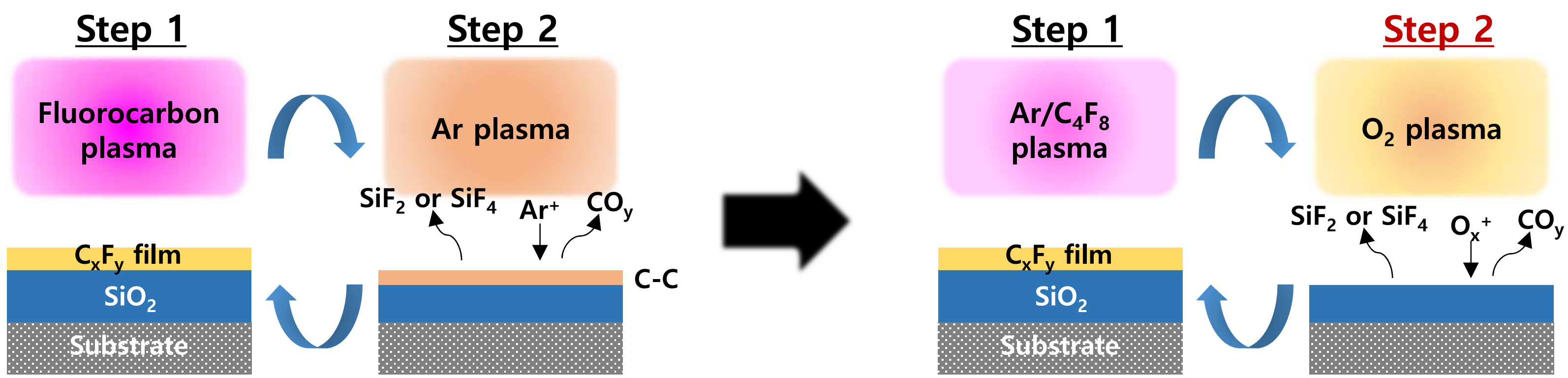
◆ Deposition + Activation cyclic process

: Concept vs. Experiment



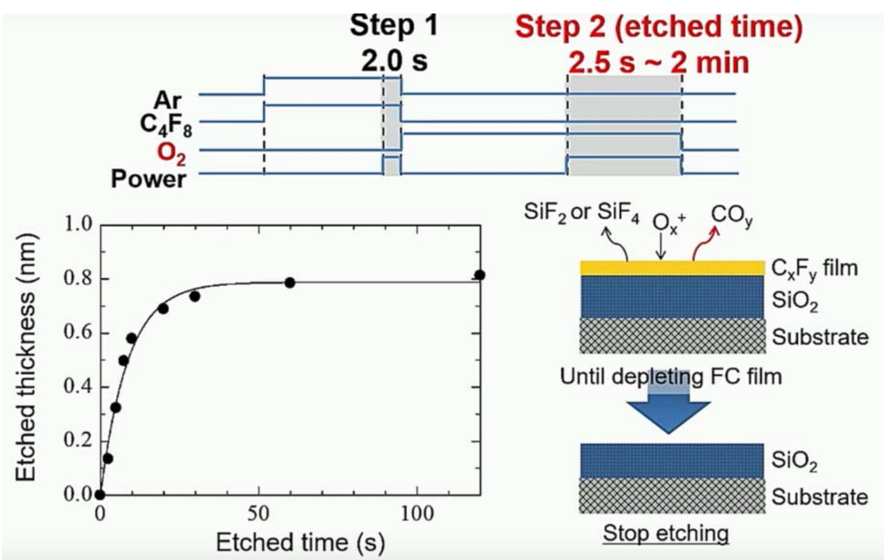
"Fluorocarbon-based Atomic Layer Etching of Silicon Dioxide for Self-aligned Contact"
Eric Hudson (Lam Research)

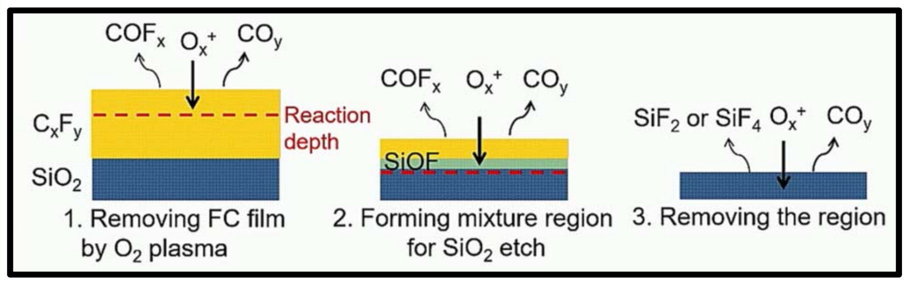
SiO_2 ALE using O_2 as Desorption Gas



◆ **Advantage**

- To remove extra carbon such as CO or CO_2, COF_x during ALE
- To maintain clean chamber by O_2 plasma process

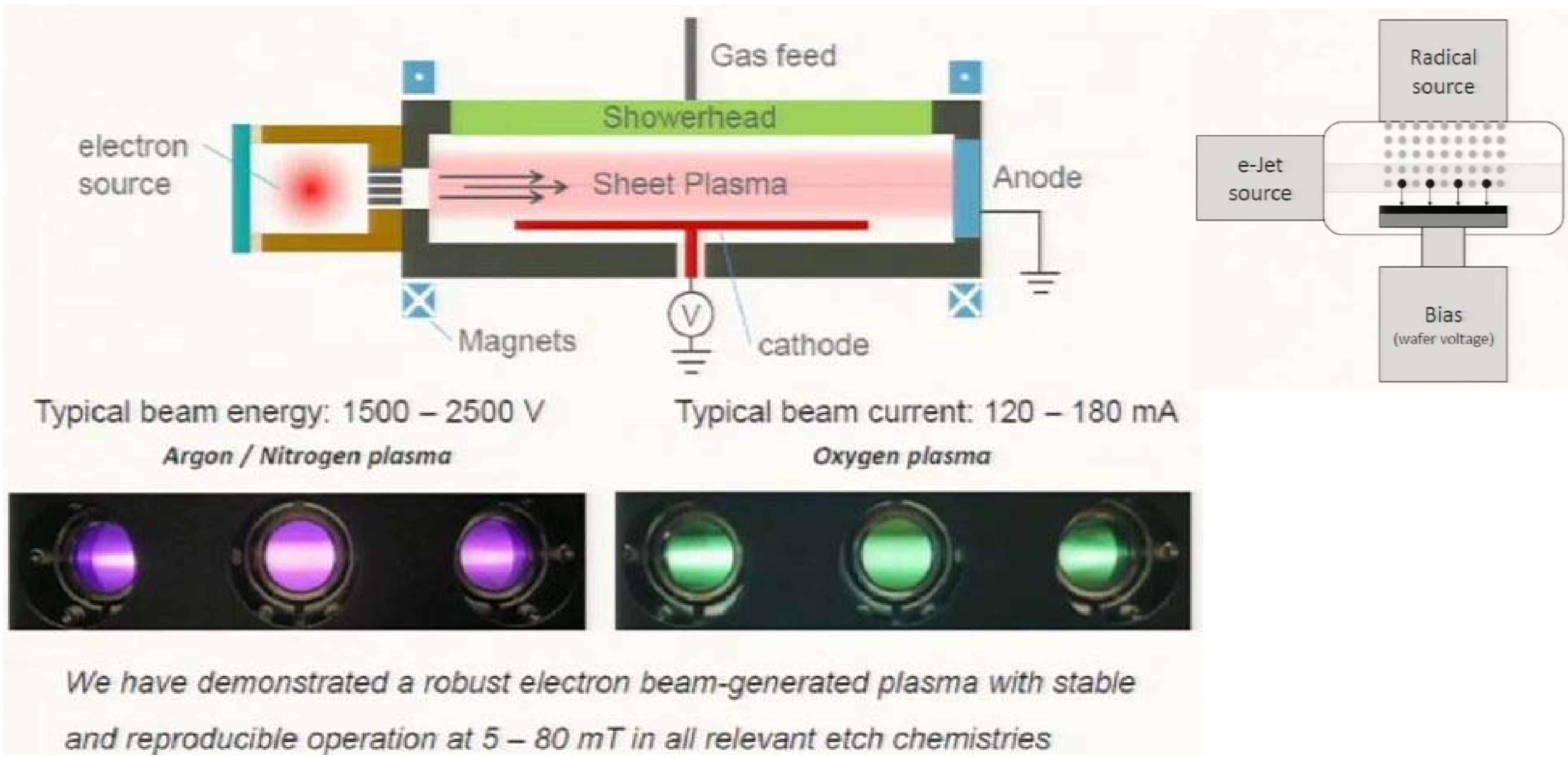




"A novel atomic layer etching of SiO_2 with alternating O_2 plasma with fluorocarbon film deposition"
Takayoshi Tsutsumi (Nagoya Uni.), Masaru Zaitsu, Akiko Kobayashi, Hiroki Kondo, Toshihisa Nozawa, Nobuyoshi Kobayashi, Masaru Hori

Low Energy E-beam Etch Tool of Applied Materials for ALE

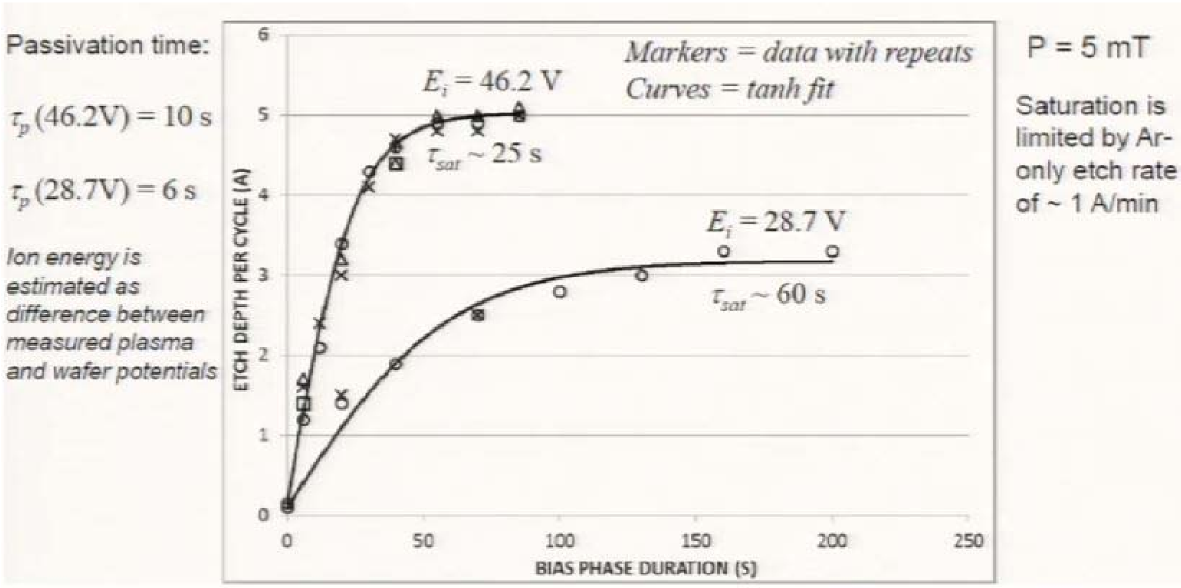
◆ Electron beam-generated plasma etch tool

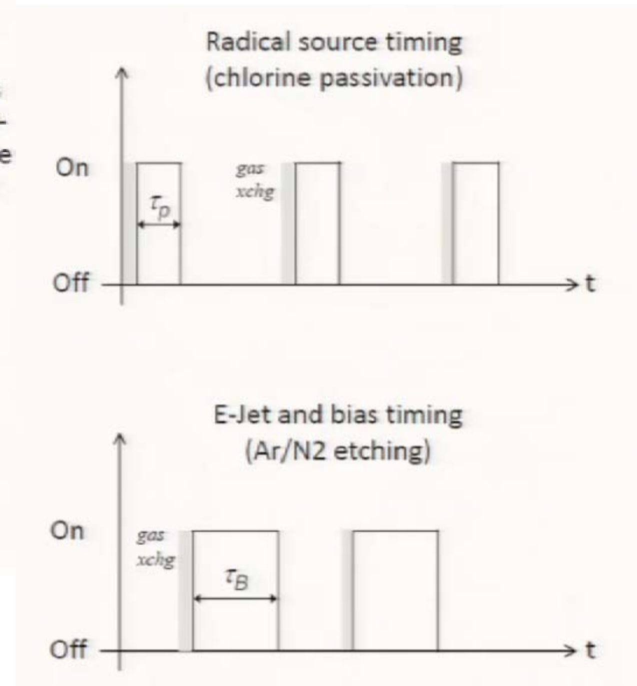


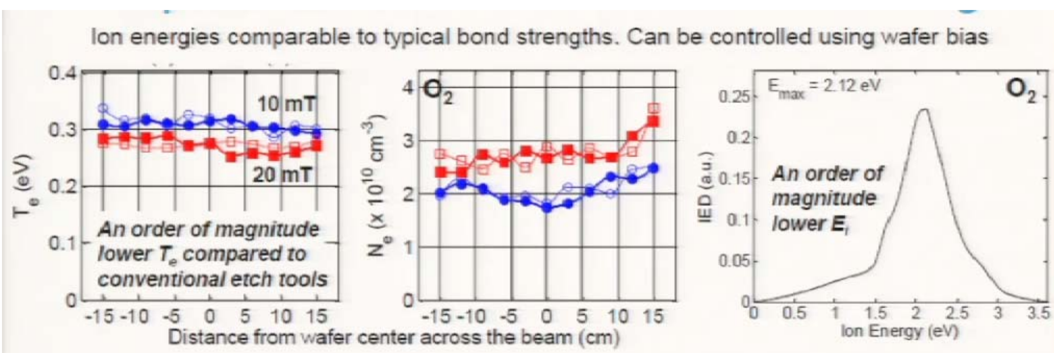
"Low Damage Etch Chamber for Atomic Precision Etching"
L. Dorf, S. Rauf, A. Agarwal, G. Monroy, K. Ramaswamy, K. Collins (Applied Materials)

Low Energy E-beam Etch Tool of Applied Materials for ALE

◆ Si ALE in chlorine at different ion energies







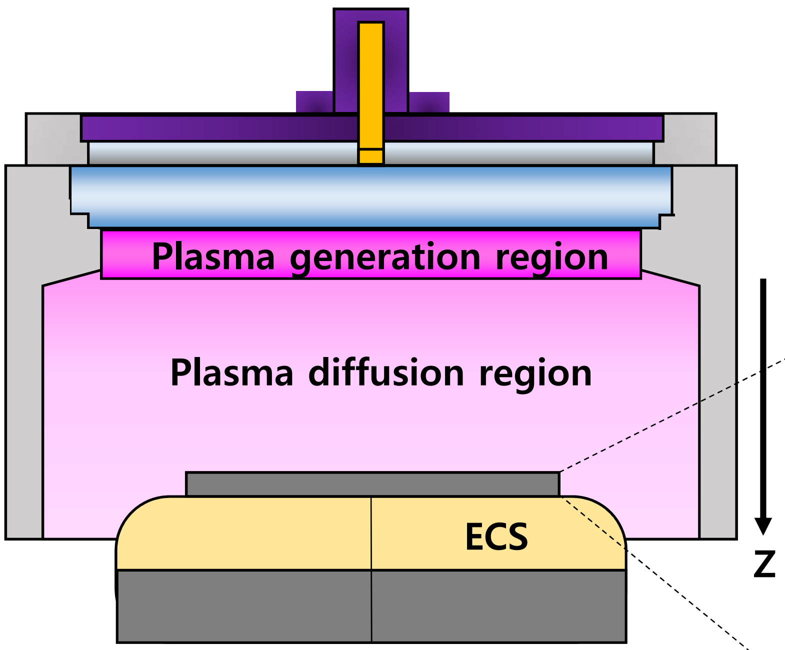
ATOMIC LAYER ETCHING July 1-2, 2015 Portland, Oregon USA Portland Hilton Atomic Layer Etching Workshop

"Low Damage Etch Chamber for Atomic Precision Etching"
L. Dorf, S. Rauf, A. Agarwal, G. Monroy, K. Ramaswamy, K. Collins (Applied Materials)

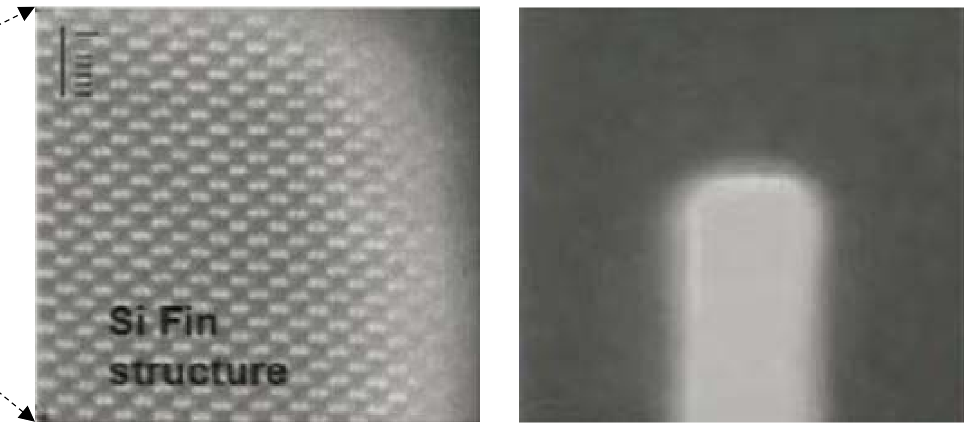
Cyclic Etch Tool by TEL

◆ One way

: Spatial pulsing with microwave plasma processes



- Allows access to an energy range where chemistry can be done on a surface and the sub-surface left pristine



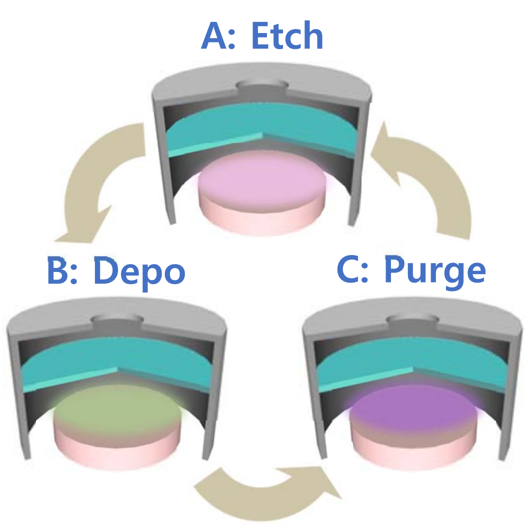
"Modeling and simulation for rapid advanced cyclic etch processes"
Peter Ventzek (TEL)

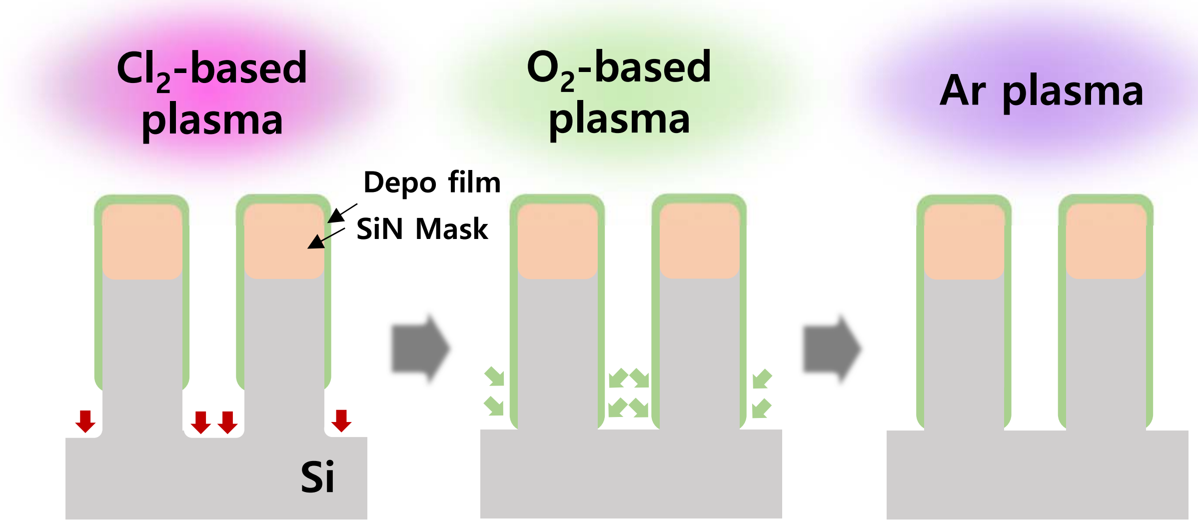
ALE Tool by Hitachi

◆ Gas pulsing process

: Tri-time modulation

- Tri-TM is triadic combination of pulsing techniques, bias plasma and gas pulsing
- Tri-TM process is demonstrated for Fin etching of Si





A: Etch

- Cl_2-based Si etch step
- Bias & Plasma pulsing

B: Depo

- O_2-based passivation step

C: Purge

- Ar purge step

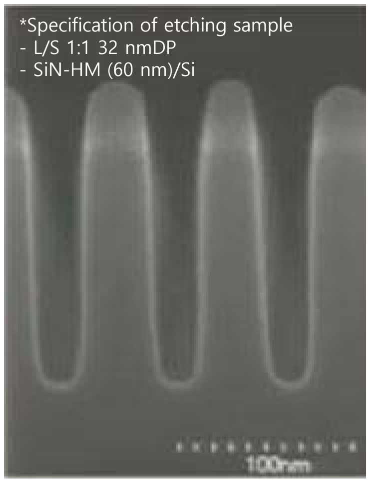
"Atomic Level Etching of Poly-Si in a Microwave Electron Cyclotron Resonance Plasma Etcher"
Yasushi Sonoda (HITACHI)

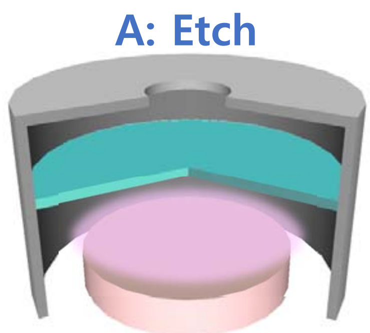
ALE Tool by Hitachi

◆ Results: Gas pulsing process

: Gas pulsing enables to realize the vertical profile and higher selectivity

Single step process

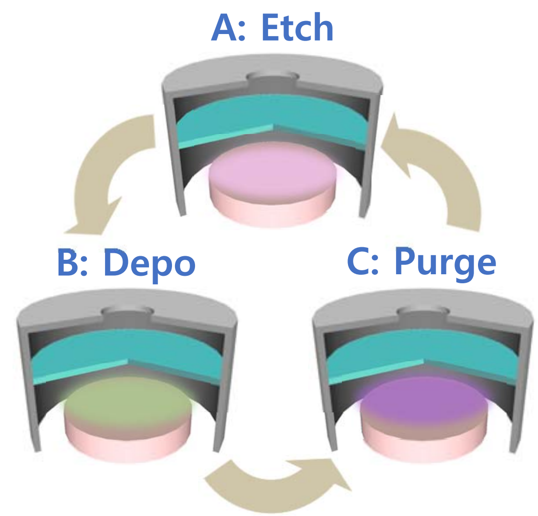




Continuous process:

- Tapered profile
- Lower selectivity
- Rounding etch front

Gas pulsing process



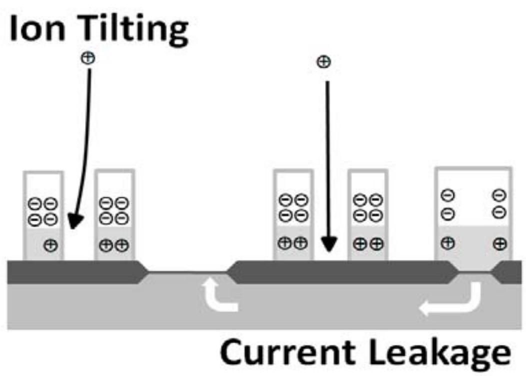
Gas pulsing process achieves:

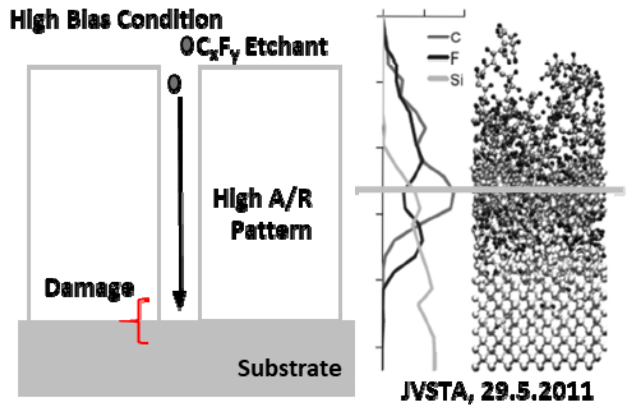
- Vertical profile
- Higher selectivity
- Flat etch front

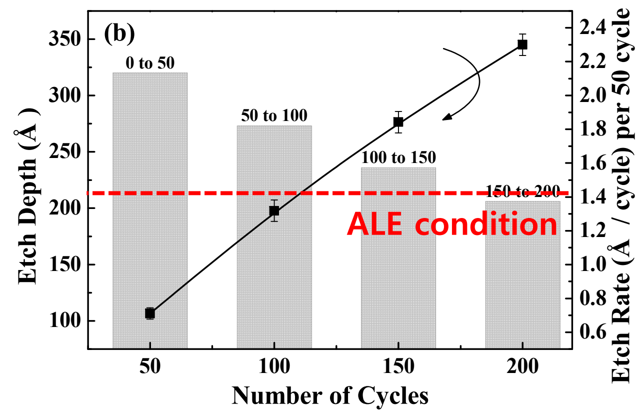
ATOMIC LAYER ETCHING
July 1-2, 2015
Portland, Oregon USA
Portland Hilton
Atomic Layer Etching Workshop

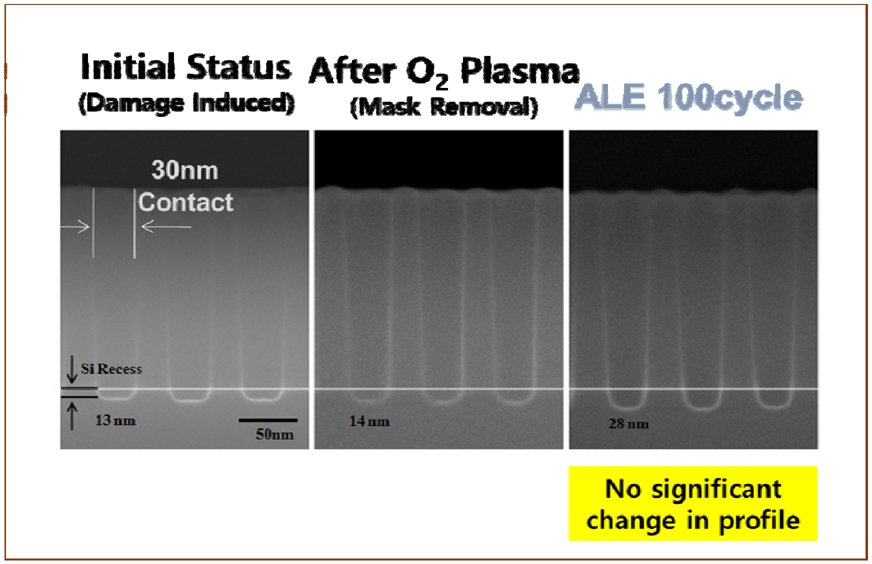
"Atomic Level Etching of Poly-Si in a Microwave Electron Cyclotron Resonance Plasma Etcher"
Yasushi Sonoda (HITACHI)

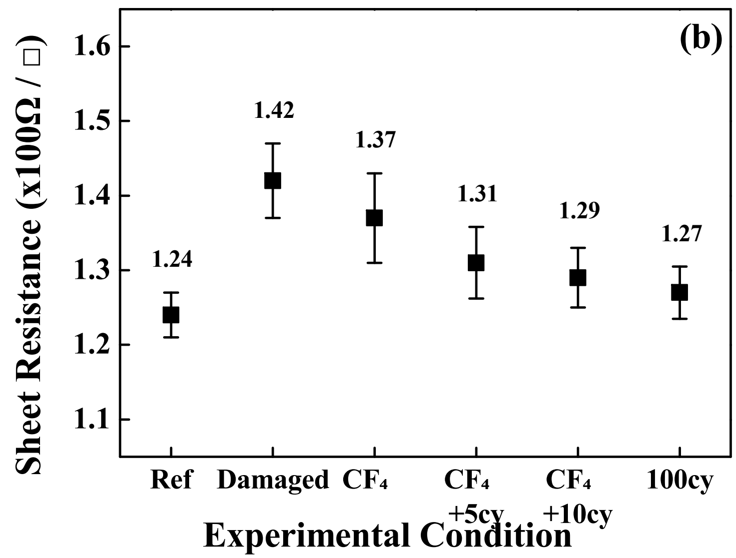
Possible Advantage of Neutral Beam instead of Ar Ion Beam?







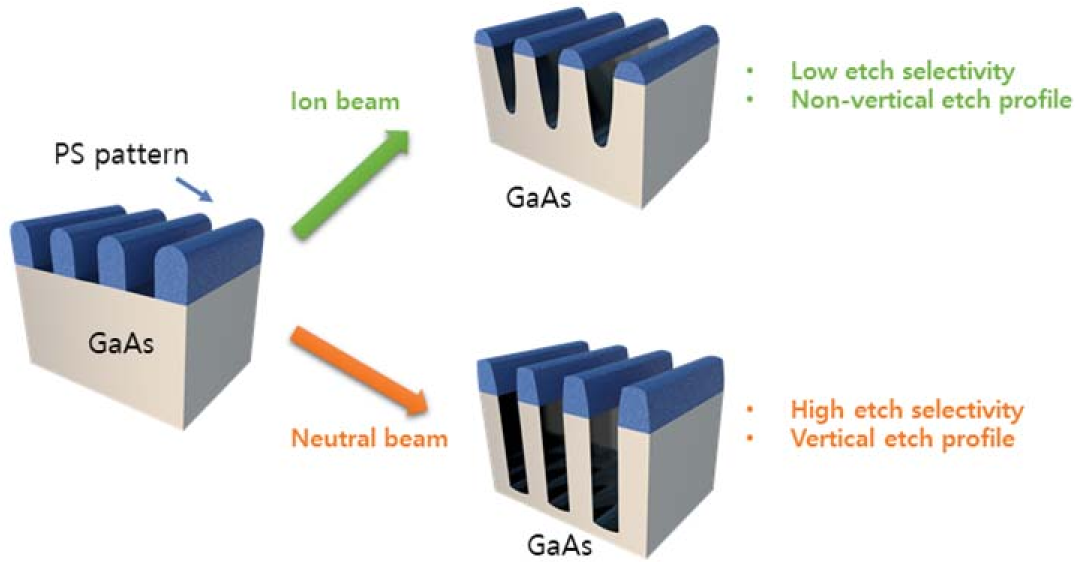


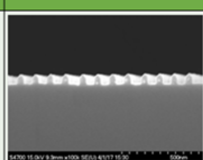
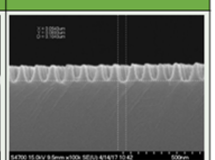


"Damaged silicon contact layer removal using atomic layer etching for deep-nanoscale semiconductor devices"
Jong Kyu Kim, Sung Il Cho, Sung Ho Lee, Chan Kyu Kim, Kyung Suk Min, Seung Hyun Kang, and Geun Young Yeom
Journal of Vacuum Science & Technology A 31, 061310 (2013)

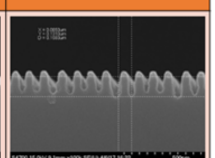
"Atomic layer etching removal of damaged layers in a contact hole for low sheet resistance"
Jong Kyu Kim, Sung Il Cho, Sung Ho Lee, Chan Kyu Kim, Kyung Suk Min, and Geun Young Yeom
Journal of Vacuum Science & Technology A 31, 061302 (2013)

Possible Advantage of Neutral Beam instead of Ar Ion Beam?

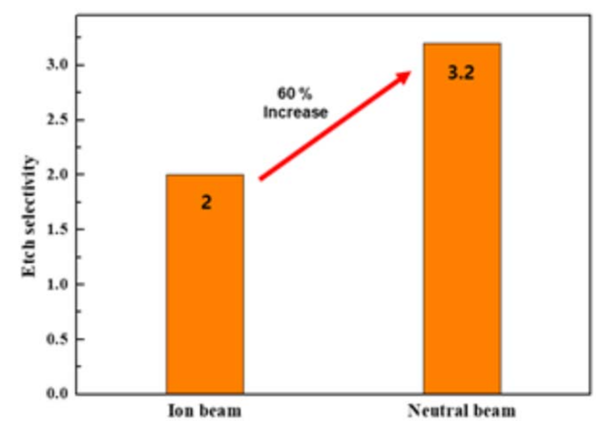


Ion Beam	Ref.	흡착
Etch profile		
Etch depth		110~126 nm

Power	200W
Cl_2	1.5mTorr
Ar	2mTorr
Cycle(time)	500cycle(10-10-10-10)
Grid	10V, -250 V

Neutral Beam	Ref.	흡착
SEM		
Etch depth		190~210 nm

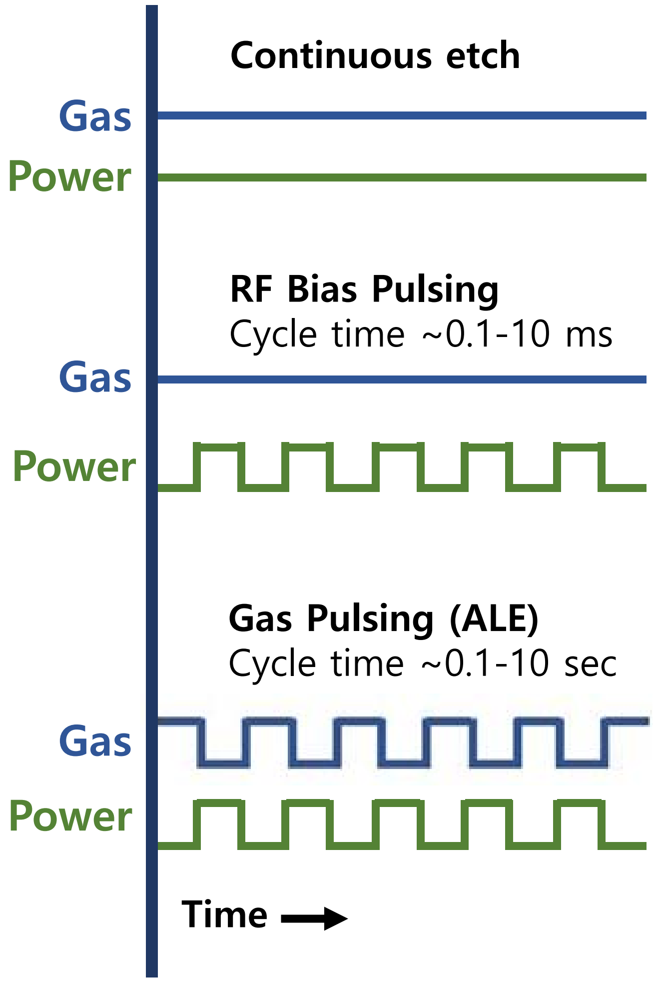
Power	200W
Cl_2	1.5mTorr
Ar	2mTorr
Cycle(time)	500cycle(10-10-35-10)
Grid	10V, -250 V



Etch selectivity improved by over 60 % with low-damage plasma source

Contents

Summary



Continuous Etch

- Maintain constant gas and RF power
- Recipe steps typically >10 sec

RF Pulsing

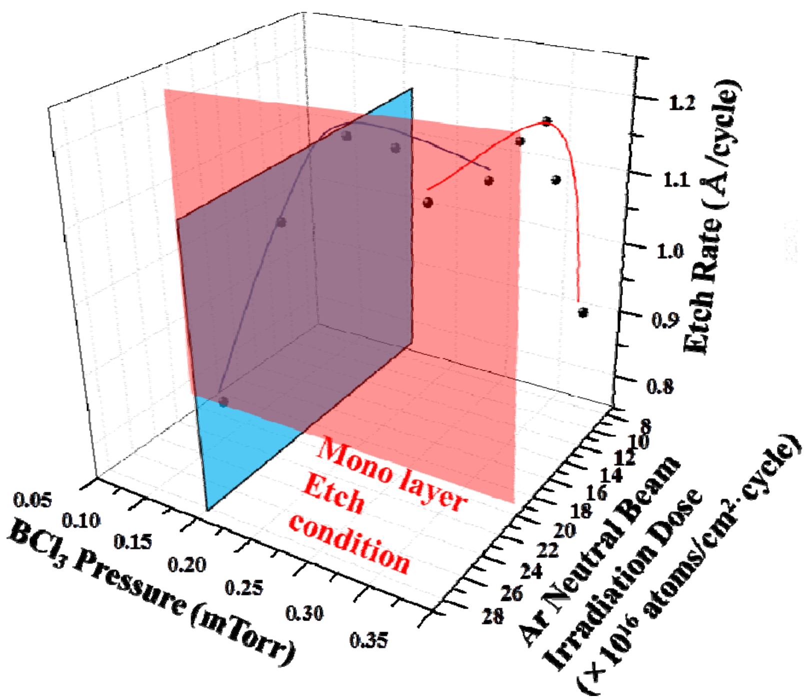
- Rapid variation in RF power to plasma
- Many different process benefits
- Bias pulsing modulates ion energy, effectively decouples ion energy control from gas neutral chemistry

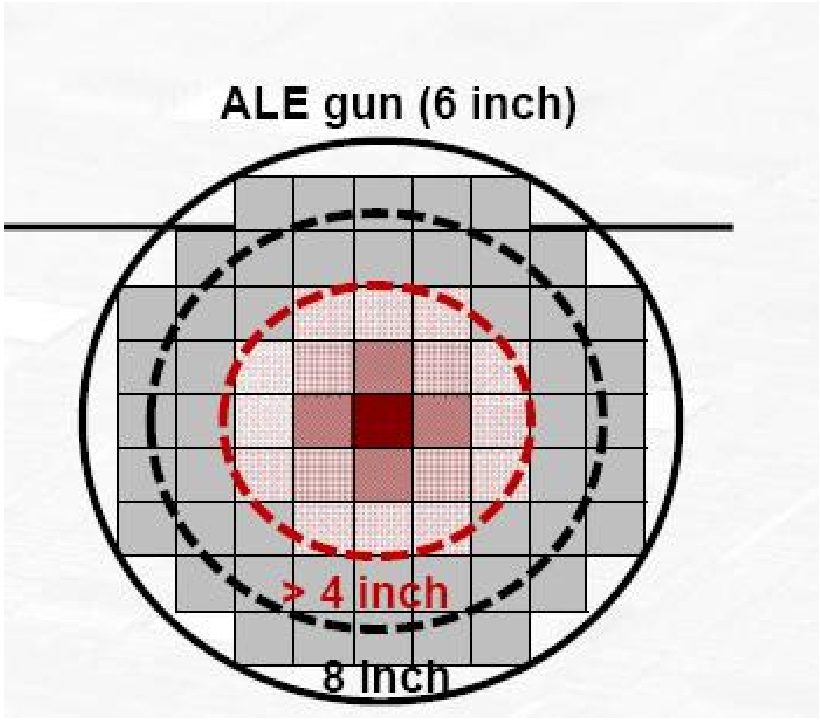
Gas Pulsing

- Rapid variation of gas mixture delivered to reactor
- Generally slower than RF pulsing
- Synchronize gases to RF power (bias) to enable processes of atomic layer etching

Neutral Beam ? What else ?

Properties of ALE





Wide process window

Theoretical Uniformity : 0.0 %