Technological trends for Etch patterning in the aspect of energy and environment

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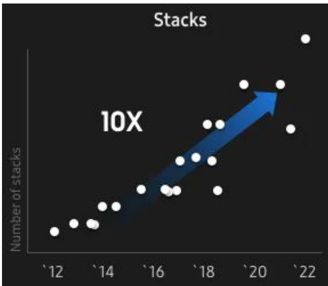
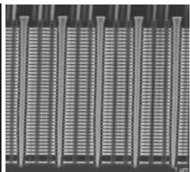
SAMSUNG

Stack-up History and Roadmap in 3D NAND

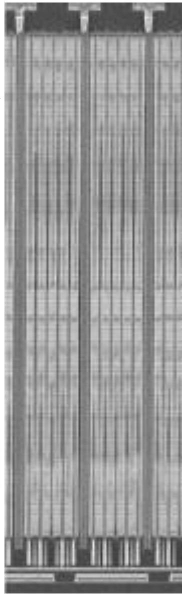
- The number of 3D NAND stacks have been jumping up 10 times from its first introduction.
- Most of chip makers revealed the roadmap over 500 layer 3D NAND as a eco-memory in next 10 years



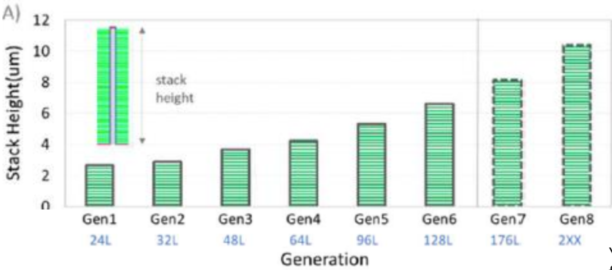


Samsung 32L NAND
from TechInsight at 2013

X3.5

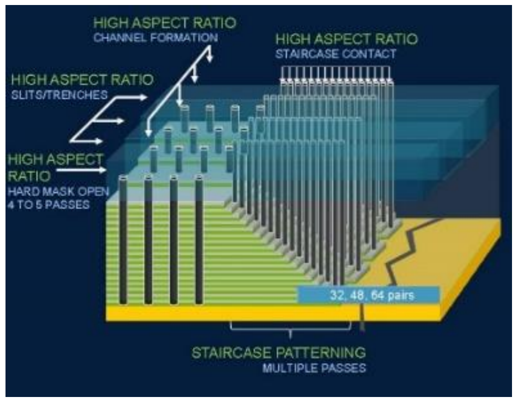


YMTC 232L NAND
from Techinsights at 2022



Ref.) L. Jiang, *et al.*, 2021 IEEE International Memory Workshop, "Integration scheme for 3D NAND with non-replacement word line and its cell characteristics investigation"

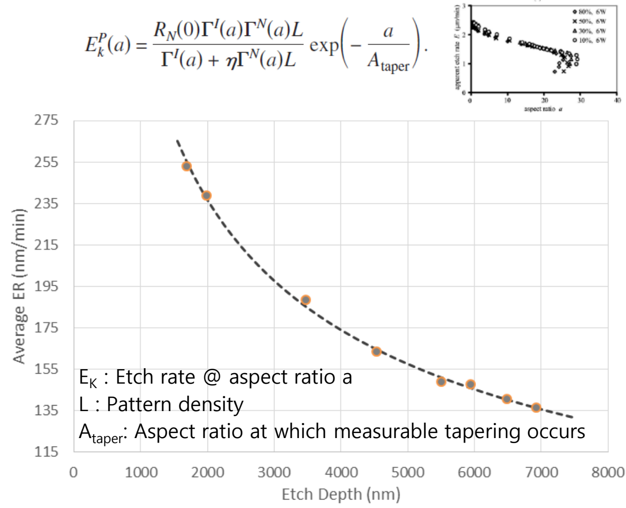
- In 2021, SK Hynix former CEO, Seok-Hee Lee, said "NAND flash will be able to stack more than **600 layers**" at IRPS of IEEE
- In 2022, Micron reveals NAND roadmap out of **500-Plus level** at an Investor Day.
- In 2022, Jung-bae Lee, head of Samsung Electronics' memory business division(president), presented "Samsung will develop a **1000 layer** NAND by 2030" at Samsung Tech Day

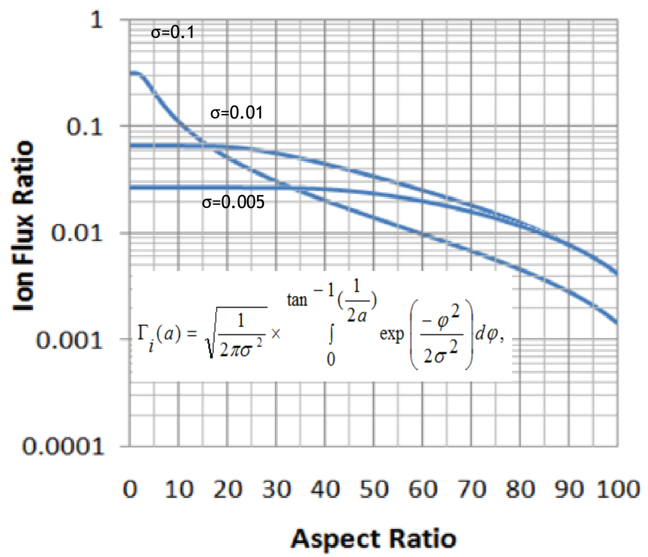


Sited from Applied Materials

Aspect Ratio Dependent Etching

- Most of issues in etching HARC, such as lack of mask selectivity and throughput, are coming from loading, so called **ARDE**
- Some researchers predicted **"Depth Limitation"** due to lack of neutrals and ions transfer
  - Maximum achievable aspect ratio was confined by flux of neutral and ion
  - Even rollover behavior was observed



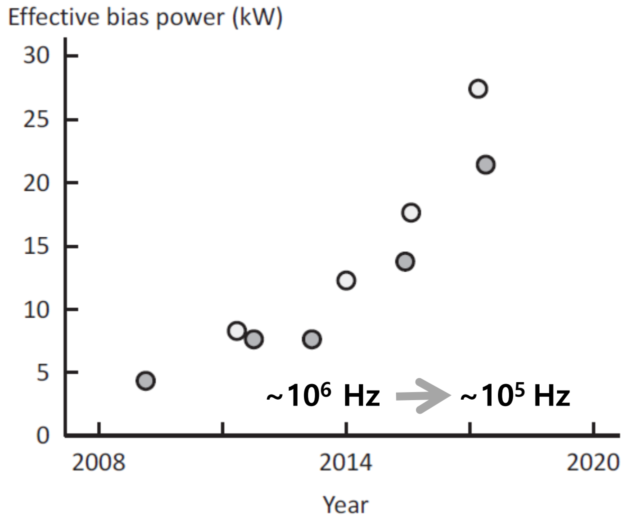


Ref.) J. Yeom, *et al.*, J. Vac. Sci. Technol., B **23**(6), 2319 (2005)

Technology to Increase Ion Energy

- **To secure directionality of ion**, it has been tried to increase ion energy by applying high LF power.
- Lowering RF frequency enhances power efficiency

Increase RF Power



Ref.) K. Ishikawa, *et. al.*, Jpn. J. Appl. Phys., **57**, 06JA01 (2018)

Decrease frequency of RF Power

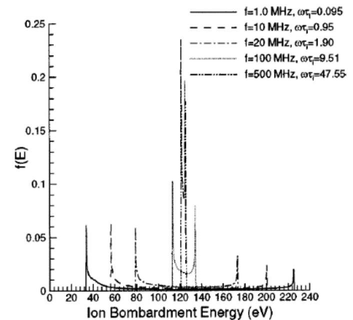
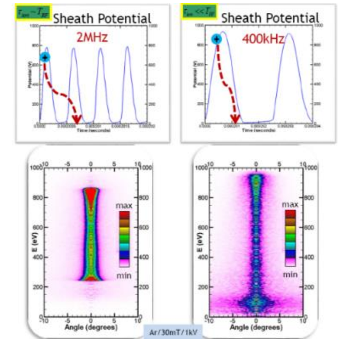
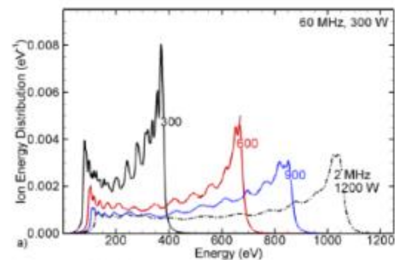


FIG. 7. Ion energy distribution as a function of $\omega\tau_i$. As the value of $\omega\tau_i$ is increased, the energy dispersion is decreased and the IED changes from bimodal to a single peak distribution at very high frequencies. Applied potential is shown as solid line in Fig. 2.



Ref.) Simulation from LAM research

Ref.) T. Panagopoulos and D. J. Economou, J. Appl. Phys., **85(7)**, 3435 (1999)



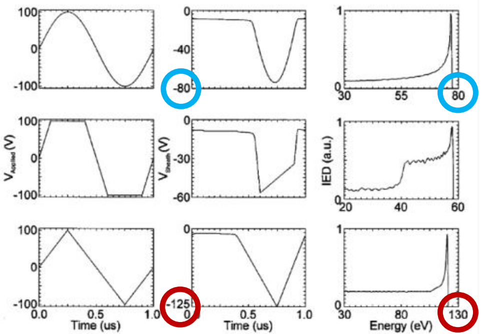
Ref.) Y. Zhang, *et. al.*, J. Vav. Sci. Technol., **A33** 031302-1 (2015)

Alternative Technology to enhance power efficiency

❖ Tailored RF forms to increase ion energy have been suggested since the early 2000s

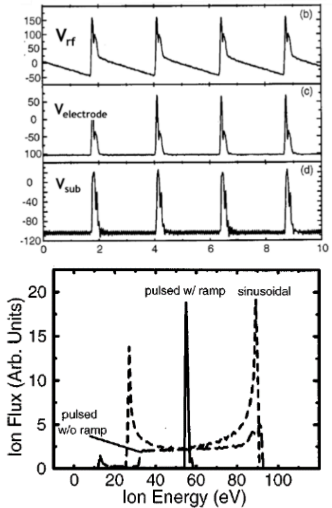
Saw tooth type

ICP, 20mT Ar, 500Ws / 100Vb, 1MHz rf bias voltage.



Ref) S. Rauf, J. Appl. Phys., **87**(11) 7647 (2000)

Short spike



Ref) S.B. Wand and A.E. Wendt,
J. Appl. Phys., **88**(2) 643 (2000)

RF Modulation

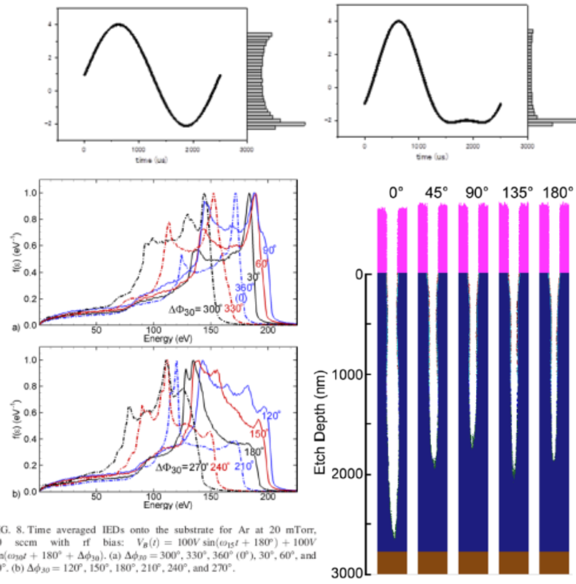
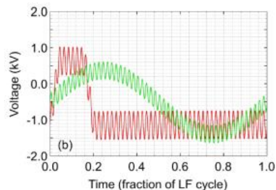


FIG. 8. Time averaged IEDs onto the substrate for Ar at 20 mTorr, 50 sccm with rf bias: $V_B(t) = 100V \sin(\omega_{15}t + 180°) + 100V \sin(\omega_{30}t + 180° + \Delta\phi_{30})$. (a) $\Delta\phi_{30} = 300°, 330°, 360° (0°), 30°, 60°$, and $90°$. (b) $\Delta\phi_{30} = 120°, 150°, 180°, 210°, 240°$, and $270°$.

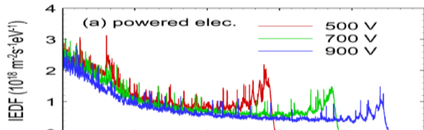
Ref) Y. Zhang, *et. al.*, J. Appl. Phys., **117**, 233302 (2015)
F. Kruger, *et. al.*, J. Vac. Sci. Technol., A **41**, 013006 (2022)

Plasma Uniformity Degradation in Non-Sinusoidal Power

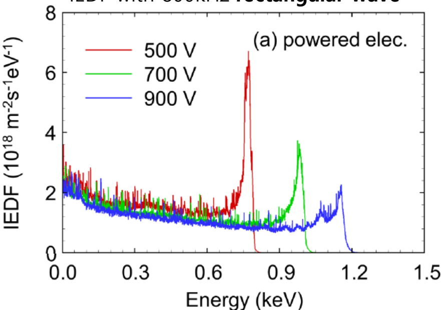
- ❖ Rectangular power shows high efficiency to generate high energy ion with same electrical power.
- ❖ However, plasma uniformity becomes worse in rectangular power, because of strong oscillation of sheath.



IEDF with 800kHz **Sinusoidal wave**

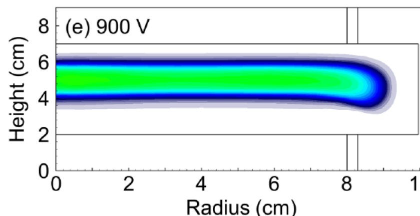


IEDF with 800kHz **rectangular wave**

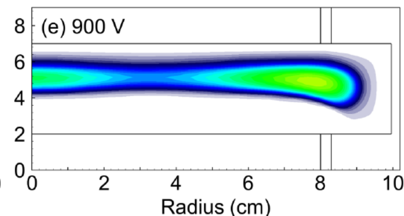


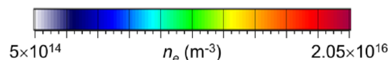
Large population of high energy ion in rectangular wave, is calculated at even same low frequency voltage

Electron density for 800kHz **Sinusoidal wave** voltage of 900V



Electron density for 800kHz **rectangular wave** voltage of 900V





At high voltage, plasma in rectangular wave splits into two regions, center of chamber and near the electrode edge, because plasma is produced efficiently when LF bias is applied with positive.

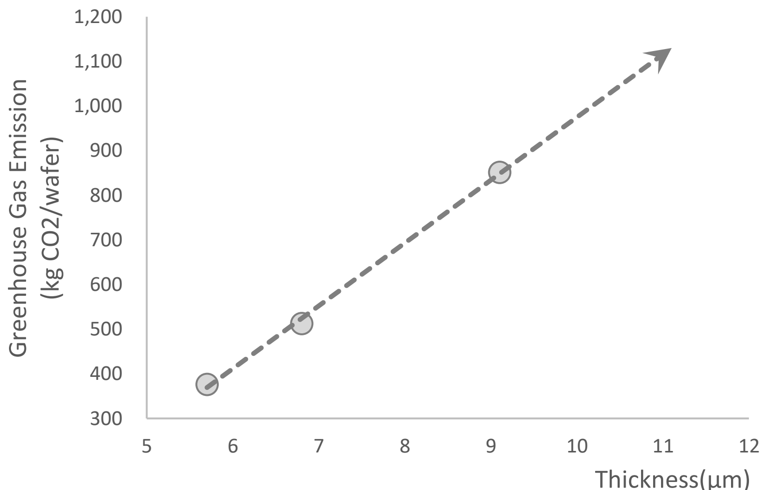
Ref) S. Rauf, *et al.*, J. Vac. Sci. Technol., B **40**, 032202 (2022)

Global Warming : Greenhouse gas emission

❖ Conventionally used etchants, most HFCs(Hydrofluorocarbon) and PFCs(Per-fluorinated Compounds), are known as greenhouse gases with high Global Warming Potential(GWP).

❖ The amount of **greenhouse gas emission** to fabricate a wafer, increases with aspect ratio of the pattern

Gas	GWP*
CO2	1
CF4	6630
CHF3	12400
CH2F2	677
C3F8	8900
c-C4F8	9540
C4F6	9200
SF6	23500
NF3	16100



* GWP values for 100 year time horizon. 5th Assessment Report

Global Warming : Research for Low GWP Etchant

- ❖ Many efforts were made to find a replacement of etchant with low GWPs gases
- ❖ "Because of the technological complexity of semiconductor industry, any substantial change to current processes or materials would **require 5 - 10 years of R&D and qualifications**, so there is a long lag between a scientific breakthrough in green chemistry and its potential implementation"

Ref) F. Iacopi and M. McIntosh, Green Chem., **21**, 3250 (2019)

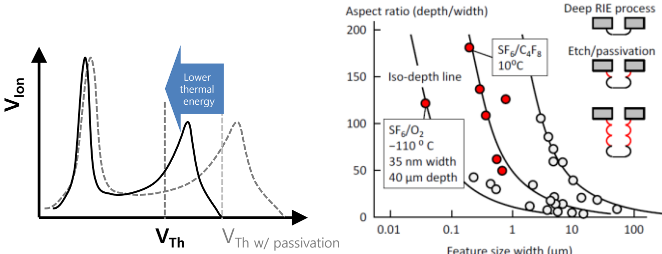
Gas	GWP*	대체 Gas	GWP	Papers
CO2	1			
CF4	6630	C2F4	0.24	D. Lino, *et. al.*, Jpn. J. Appl. Phys. **60**, 050904 (2021)
CHF3	12400	C3F7OCH3	530	Y. Kim, *et. al.*, J. Vac. Sci. Technol. A **38**, 022606 (2020)
CH2F2	677			
C3F8	8900			
c-C4F8	9540	C5F10O C3H2F6O C3H2F6 C3F6O	3 190 1330 <100	S. You, *et. al.*, Korean J. Chem. Eng., **39(1)**, 63 (2022) S. You, *et. al.*, Coatings, **12**, 679 (2022) H. W. Tak, *et. al.*, Appl. Surf. Sci., **600**, 154050 (2022) H. S. Lee, *et al.*, J. Vac. Sci. Technol. A **36**, 061306 (2018)
C4F6	9200			
SF6	23500			
NF3	16100			

* GWP values for 100 year time horizon. 5th Assessment Report

New Technology : Cryogenic Etching

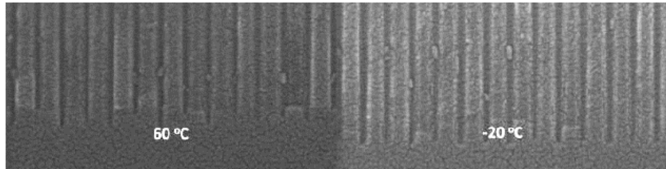
❖ Recently, etching at low temperature is introduced to mitigate ARDE problem.

❖ Prof. Dussart and coworkers were disclose the conformal SiOFx physisorbed layer working as passivation.

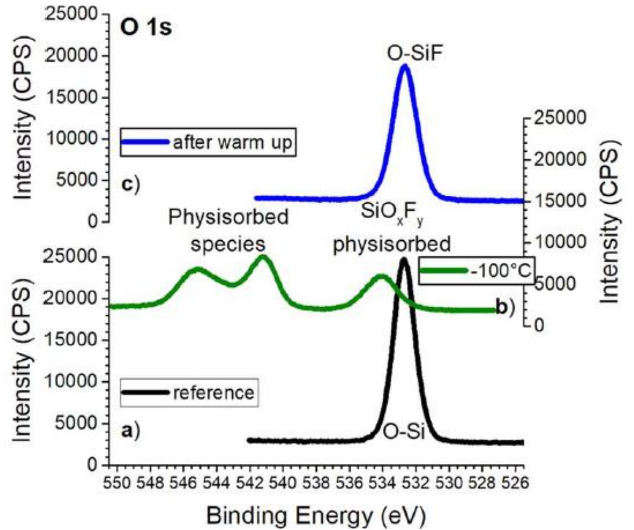


By lowering thermal energy, lateral enlargement can be improved without polymer passivation

Ref) J. Parasuraman, *et. al.*, Microelectron. Eng. **113**, 35 (2014).



Depth variation is improved at temperatures below -20C



F-rich SiOFx layer is observed at cryogenic temperatures

Ref) J. Hou, *et al.*, 2022 China Semiconductor Technology International Conference (2022)

Ref) G. Antoun, *et al.*, ECS J. Solid State Sci. Technol., **11**, 013013 (2022)

New Chemistry for Cryogenic Etching

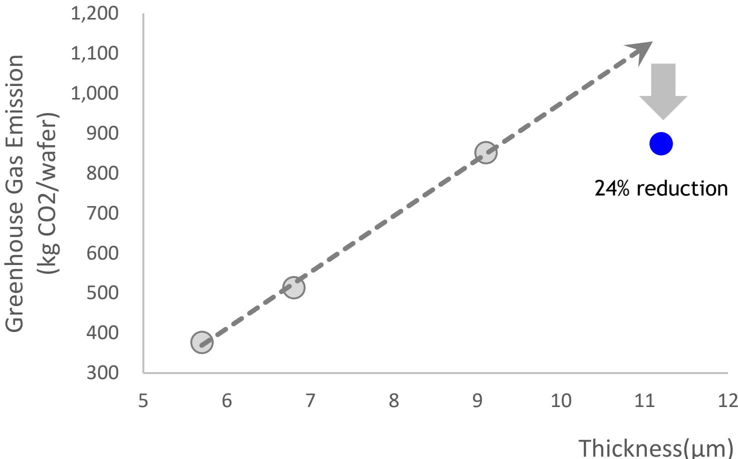
❖ There have been lots of efforts to find **appropriate chemistry for cryogenic etching**

Etchant	Material	References	
SF6	Si	T. D. Bestwick, *et. al.*, Appl. Phys. Lett. **57**, 431 (1990)	IBM Research Division
SiF4, O2	Si	US 8012365 B2 (2008)	STMicroelectronics, Orleans University-CNRS
SF6, O2, C4F8	Si	US 9005548 B2 (2010)	California Institute of Technology
H2, CH4, CH3F, CH2F2,	SiO2	JP 6449141 B2 (2015)	Tokyo Electron Limited
H2, CF4, NF3	Si3N4, SiO2	US 9659789 B2 (2016)	Tokyo Electron Limited
H2, CF4, CHF3, HBr	Si3N4, SiO2	US 9966273 B2 (2016)	Tokyo Electron Limited
Cl2, O2	Cr	D. Staaks, *et al.*, Nanotechnology, **27(41)** 415302 (2016)	Lawrence Berkeley National Laboratory Ilmenau University of Technology, Seagate
CH4, CxHy, CH2F2, CH3F, CHF3, CxFy, SF6, H2, HF, NH3	Si3N4, SiO2	US 10692729 B2 (2017)	Tokyo Electron Limited
H2, NF3, CF3I, CH3F, CH2F2, C4F8, C3F6, SF6, O2, CF4, CH4, CHF3	Si3N4, SiO2	US 10847374 B2 (2017)	LAM Research Corporation
C2F6, CF4, C2F6, C3F8, C4F10, CHF3, C2HF5, SF6, HI, HBr, IBr, CF3I, C2IF5, C2I2F4, C2F5I, CF3I, SO2, CS2, COS, (IF, IF3, IF5, IF7)	Si3N4, SiO2	US 2018/0286707 A1 (2017)	LAM Research Corporation
CH3OH, NH3, CO, Ar	MTJ	US 20190115528 A1 (2018)	IBM
NF3, XeF2, WF6, SiF4, TaF5, IF7, HF, ClF5, BrF5, AsF5, NF5, PF5, NbF5, BiF5, UF5, SiCl2, CrO2Cl2, SiCl4, TaCl4, HfCl4, TiCl3, TiCl4, CoCl2, TiCl3, TiCl2	Si3N4, SiO2	US 2021/0005472 A1 (2019)	LAM Research Corporation
Fluorocarbon, Hydrofluorocarbon, SF6	SiO2	KR 20220117945 A (2021)	대전대학교, 성균관대학교
HF, CF based and CHF based gas, Phosphorus containing gas, Sulfur containing gas, Boron containing gas	Si3N4, SiO2, Si	US 2022/0367202 A1 (2022)	Tokyo Electron Limited
SF6, NF3, F2 with Xe, Kr,	Si	US 11515166 B2 (2022)	Applied Materials Inc
CHF3, Ar	SiO2	K. Sun, *et. al.*, 1st International Workshop on Plasma Cryogenic Etching Processes	Nagoya University, Kioxia Corporation
SiF4/O2 and Ar	Si3N4, Si	G. Antoun, *et. al.*, J. Vac. Sci. Technol. A **40**, 052601 (2022)	Orleans University-CNRS

For green etching technology, it is inevitable to find a new chemistry and to understand its mechanism.

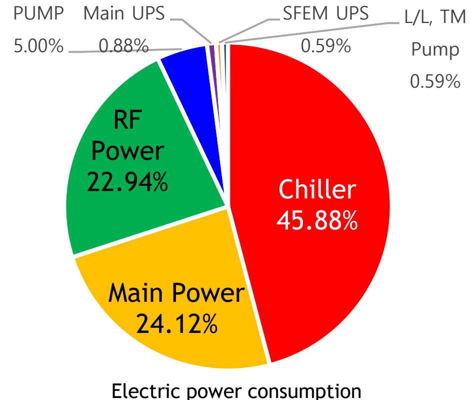
Environmental Remaining Issues in Cryogenic Etching

❖ Greenhouse gas emission can be reduced ~24% by introducing cryogenic etching into 40% processes only.



❖ Chiller becomes the largest energy consuming facility.

Energy saving chiller is required in future.



Summary of Presentation

- ❖ To extend NAND technology over 500 layers, HARC etching technology will be developed by **increasing RF power and etchant consumption**. That means, ironically, more electricity consumption and greenhouse gas emission to make eco-memory.
- ❖ It is strongly required to develop the **environmentally friend etching technology**, with low GWP and energy saving technology. However, it takes 5-10 years of R&D and qualification to introduce new chemistry and technology. Therefore, the industry-academic cooperation with government support, is strongly required.
- ❖ **The cryogenic etching** has been introduced as an alternative technology, but to optimize the process, we should find the **appropriate chemistry** and **energy saving facilities**.
- ❖ Current semiconductor fabrication technology requires huge electricity consumption, so that, there is an activity to increase voltage, to lessen the power loss. Global **standards for 440V** should be established and enough s**upply for green electricity should be** prepared also.

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