Evaluation of Particle Removing Efficiency using Air Jet

Dongbin Kwak, Handol Lee, Seungkoo Kang, Seong Chan Kim, and David Y. H. Pui

Center for Filtration Research, Mechanical Engineering, University of Minnesota, Minneapolis, MN 55455

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Overview

1. **Introduction**

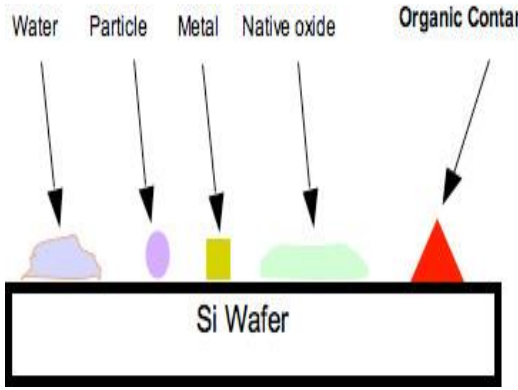
2. **Numerical and Theoretical Study**
   - 2-1. Particle Removal Mechanism
   - 2-2. Air Jet Flow Field near the Wall
   - 2-3. Future Modeling Plan

3. **Experimental Study**
   - 3-1. Particle Deposition Experiment
   - 3-2. Air Jet Cleaning Experiment

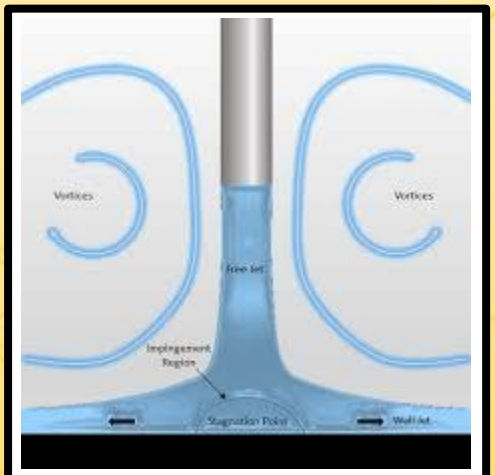
4. **Conclusion & Future Plan**

Reference

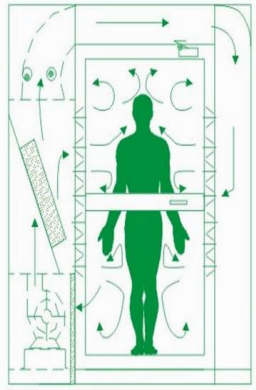
Motivation



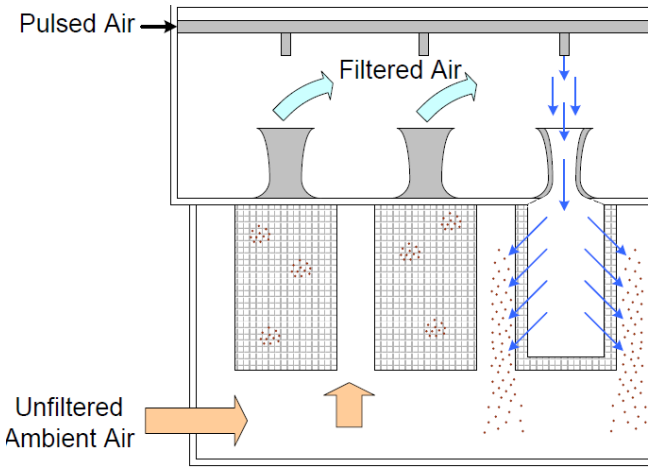
Surface Cleaning



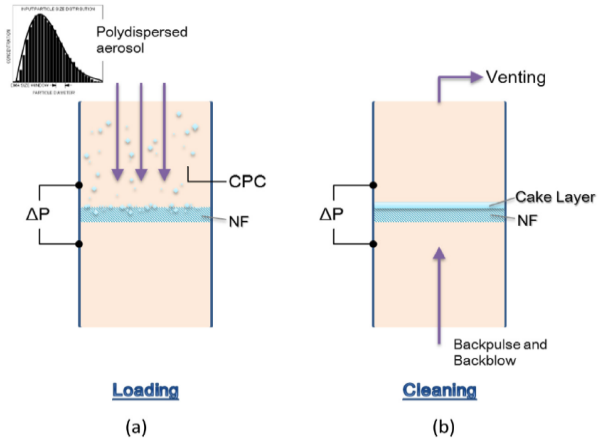
Air Jet Cleaning



Cleanroom Air Shower



Reversed Pulse Clean



Nanofiber Dislodgement

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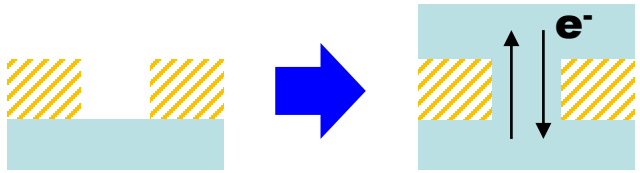
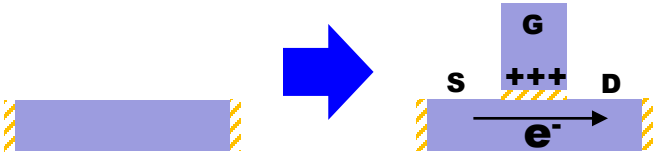
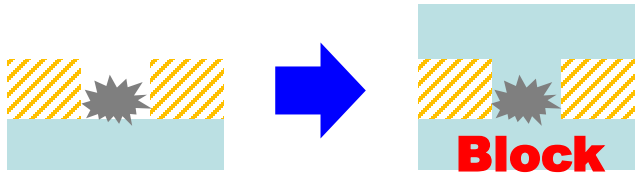
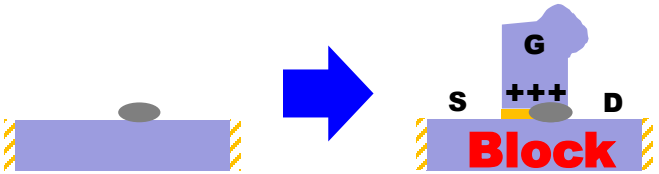
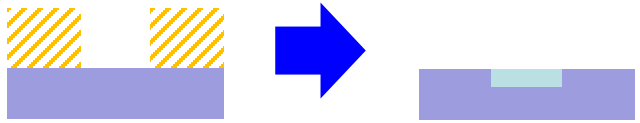
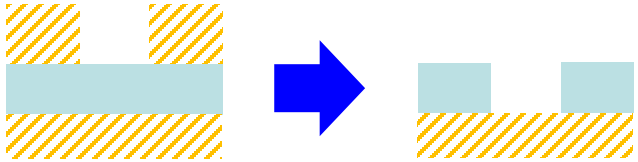
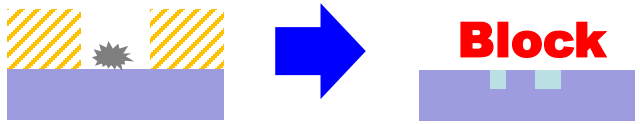
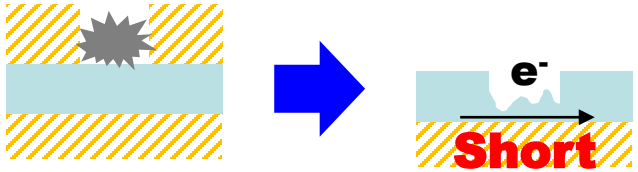
Impact of Particles in IC*

	(a) Particles in trench	(b) In-film particles
Clean		
Dirty		
	(c) Particles as mask	**(d) Patterning deviations**
Clean		
Dirty		

- **The manufacturing of microprocessors consists of hundreds of process steps, many of which are sensitive to particle contamination.**

	Insulator		Particle
	Conductor		Semiconductor

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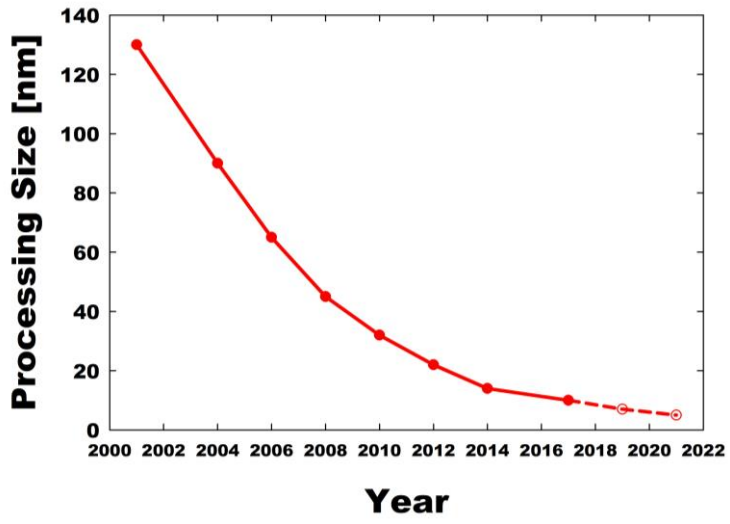
*IC: Integrated Circuit

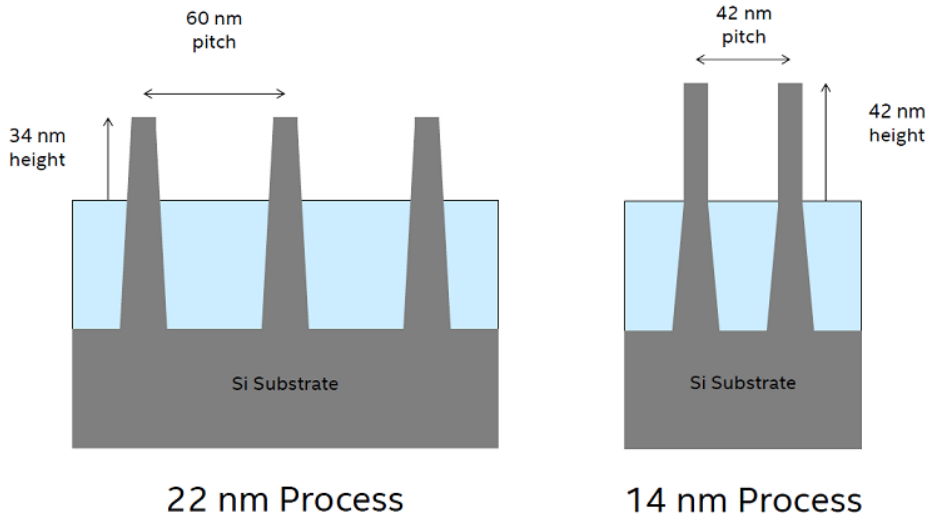
Progress in Semiconductor

Decreasing Process Size



Decreasing pitch size
→ Smaller chip area
→ Particle size to be removed is decreasing

Increasing Aspect Ratio



Increasing fin height
→ Weaker fin strength
→Increasing possibility of destroying structure during cleaning

- **To remove smaller size particle, the strong force is needed.**
- **Not to destroy the 3D structure, the weak force is needed.**
- **It is important to find optimized force to remove particles.**

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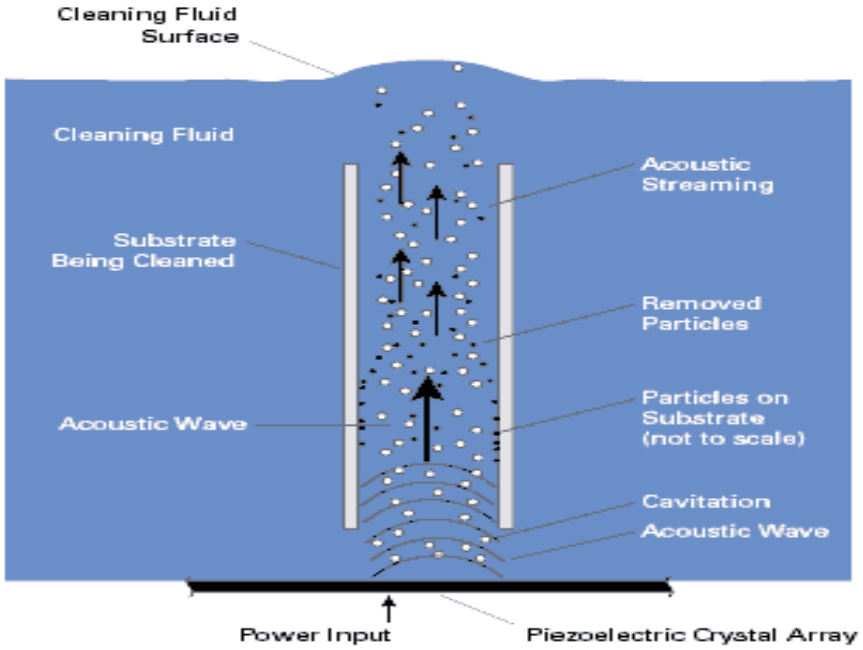
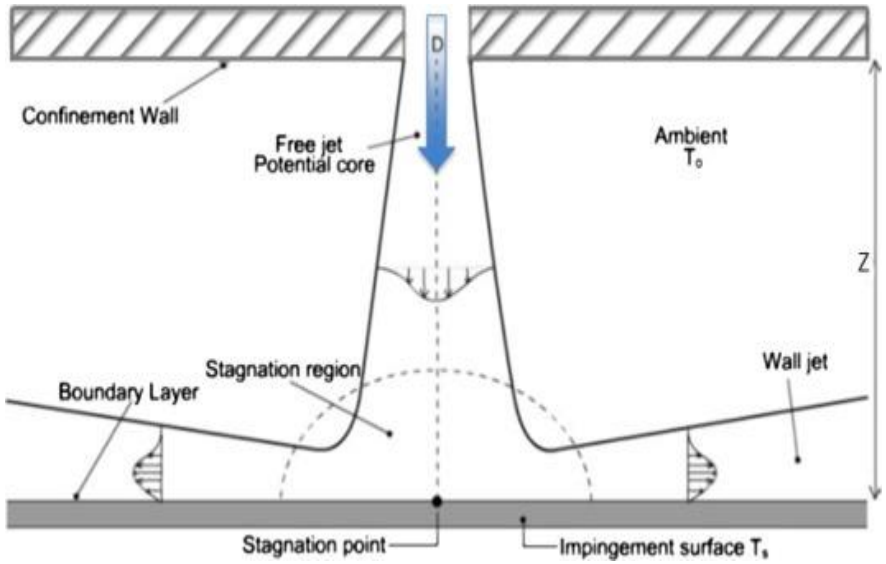
Physical Cleaning Method

Megasonic Cleaning



Air Jet Cleaning



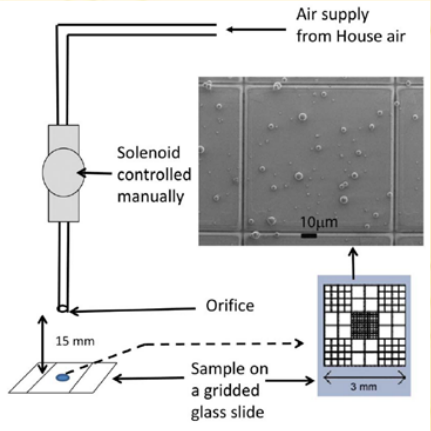
Cavitation & Streaming Effect

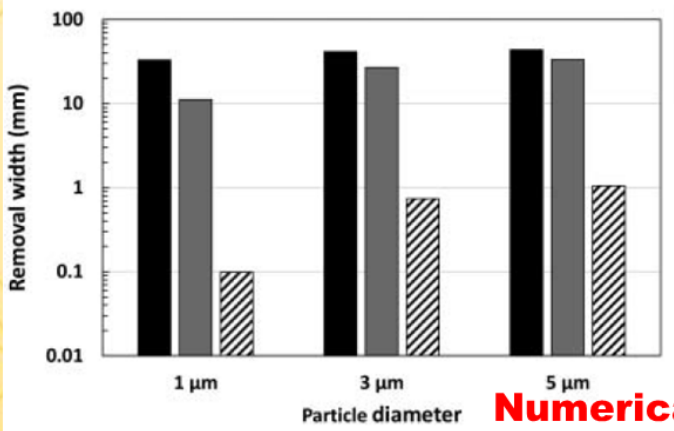
Applicable to remove submicron-sized particles

Aerodynamic Drag Force

Applicable to remove micron-sized particles

Literature Survey of Air Jet





Kesavan et al. (2017)
AST 51.3 : 377-387.

Particle Size	Removal Width [mm]		Error (%)
	Num.	Exp.	
1 μm	~10	~0.1	~9900
3 μm	~20	~0.8	~2400
5 μm	~30	~1	~2900

Numerical results extremely overestimated.

$$e = \frac{|\text{Exp.} - \text{Num.}|}{\text{Exp.}} \times 100\ (\%)$$

Previous Studies Limitation and Problem.

- **Most of papers did not show PRE calculation method.**

  ➡ **Present a quantitative PRE calculation method that ensures repeatability.**

- **No previous studies success with calculating PRE or cleaning area by numerical or theoretical method with small error.**

  ➡ **Present a new numerical and theoretical model calculating PRE and cleaning area.**

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*PRE: Particle Removal Efficiency

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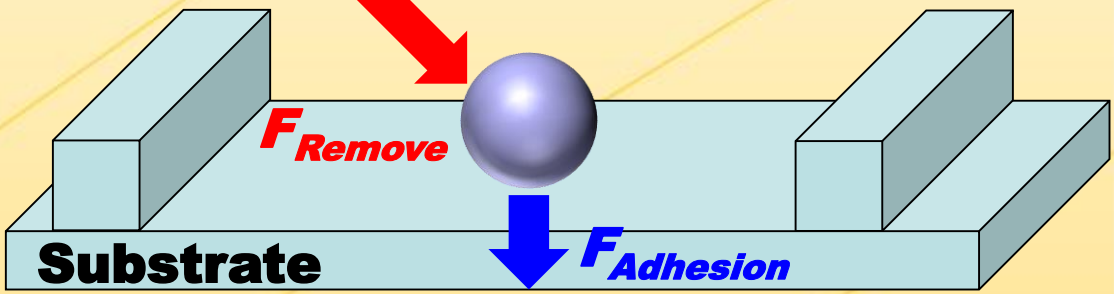
Overview

Particle Removal Mechanism

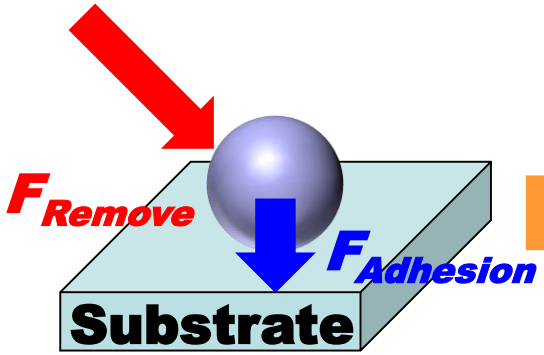
Physical Method
(Momentum Transfer)

Dry Cleaning Method
- Air Jet Cleaning

Wet Cleaning Method
- Megasonic

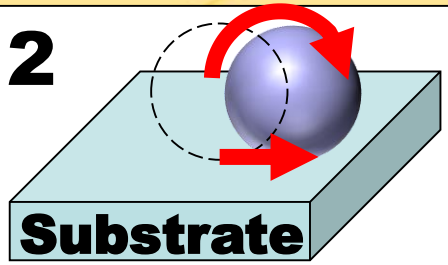


1

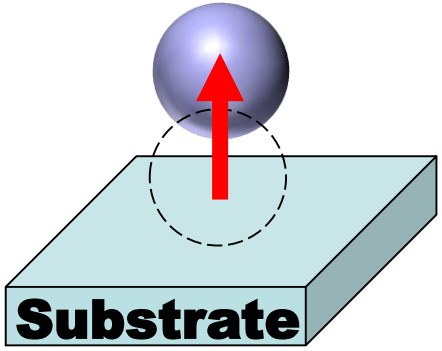


Overcoming Adhesion Force

2

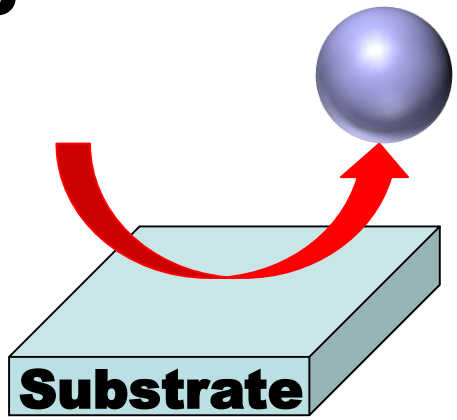


Rolling, Sliding



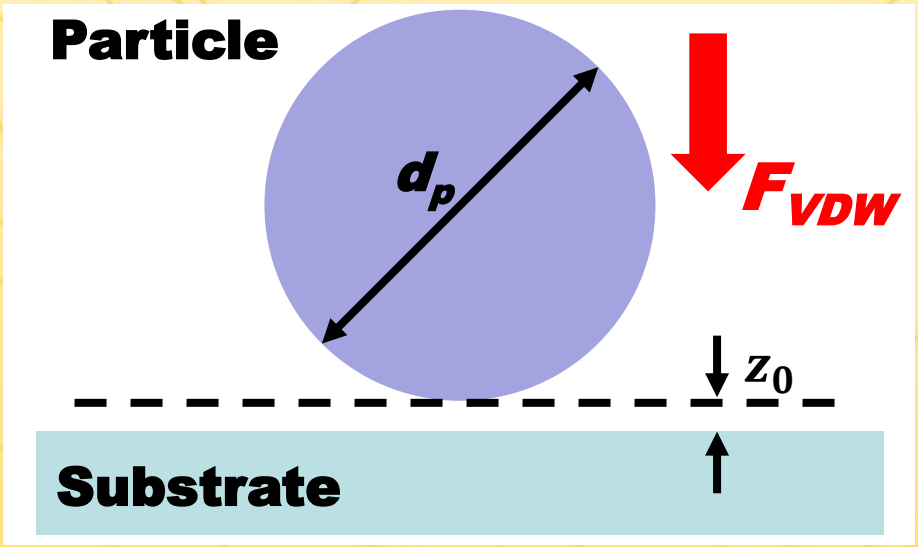
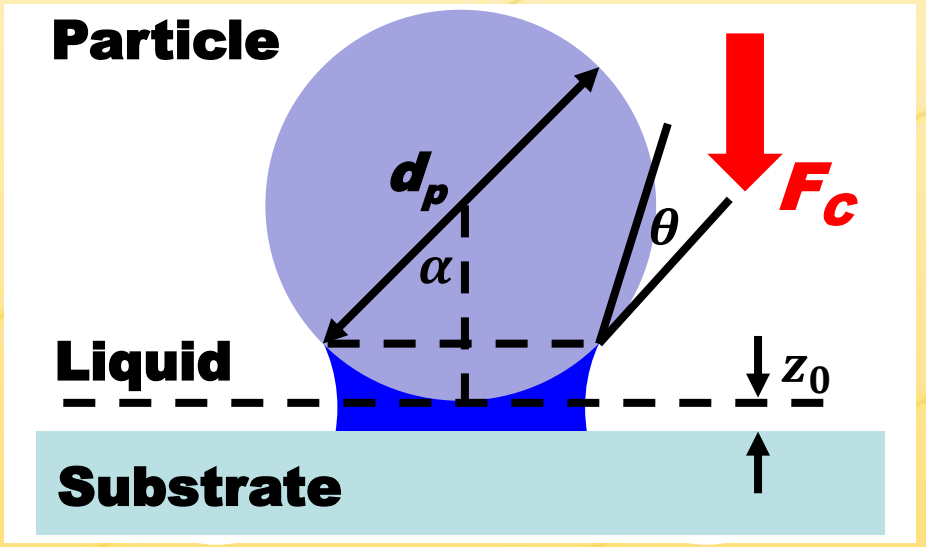
Lifting

3



Transport by Flow

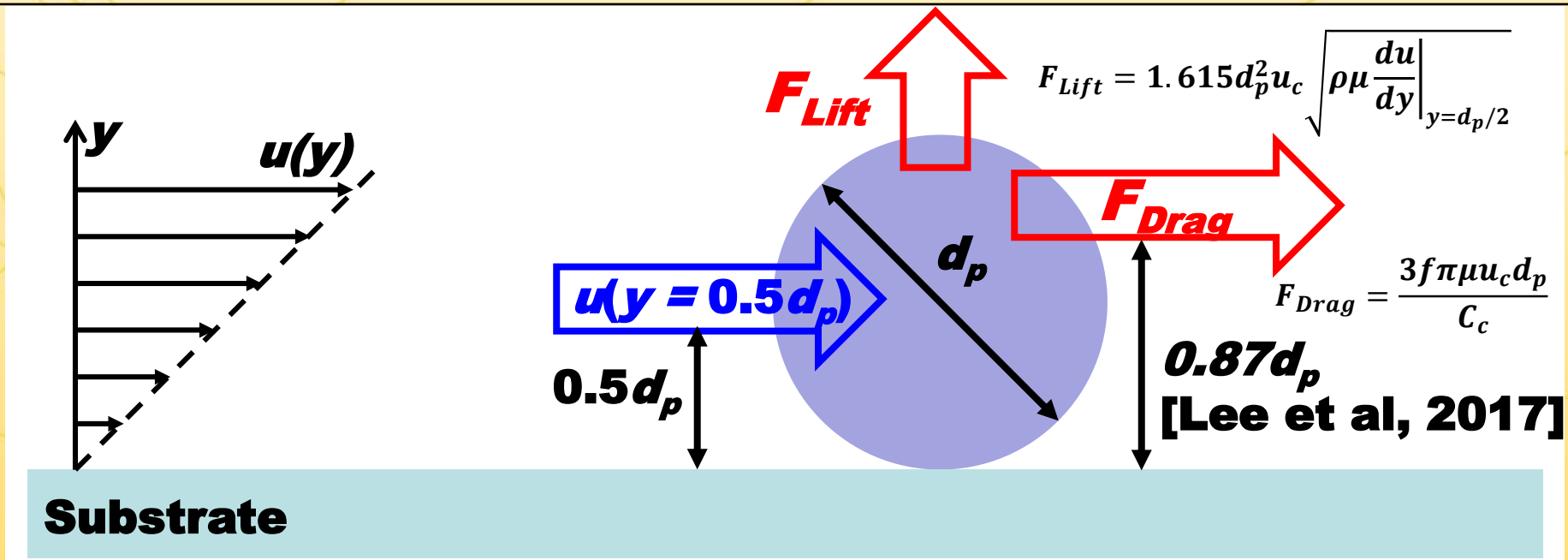
Particle Adhesion Force

Van der Waals Force, F_{VDW}	Capillary Force, F_C
	
$F_{VDW} = \frac{Ad_p}{12z_0^2}$	$F_C = 2\pi\sigma d_p[\sin\alpha\sin(\theta+\alpha)+\cos\theta]$ (G. Ahmadi et al, 2007)

- The major particle adhesion forces are Van der Waals Force and Capillary Force.
- The total adhesion force could be estimated by using these two forces ($F_{Adh} \approx (F_{VDW} + F_c) \propto d_p$)

Removal Force by Air jet

Aerodynamic Drag and Lift Force



- Usually, the drag force is much bigger than the lift force.
- The removal force is proportional to d_p^2 ($F_{Drag} \propto d_p^2$)

d_p	$F_{Drag} \propto d_p^2$	$F_{Adh} \propto d_p$
↓↓	↓↓↓↓	↓↓

This is reason why smaller particles are hard to remove ($F_{Drag} \propto d_p^2$, $F_{Adh} \propto d_p$).

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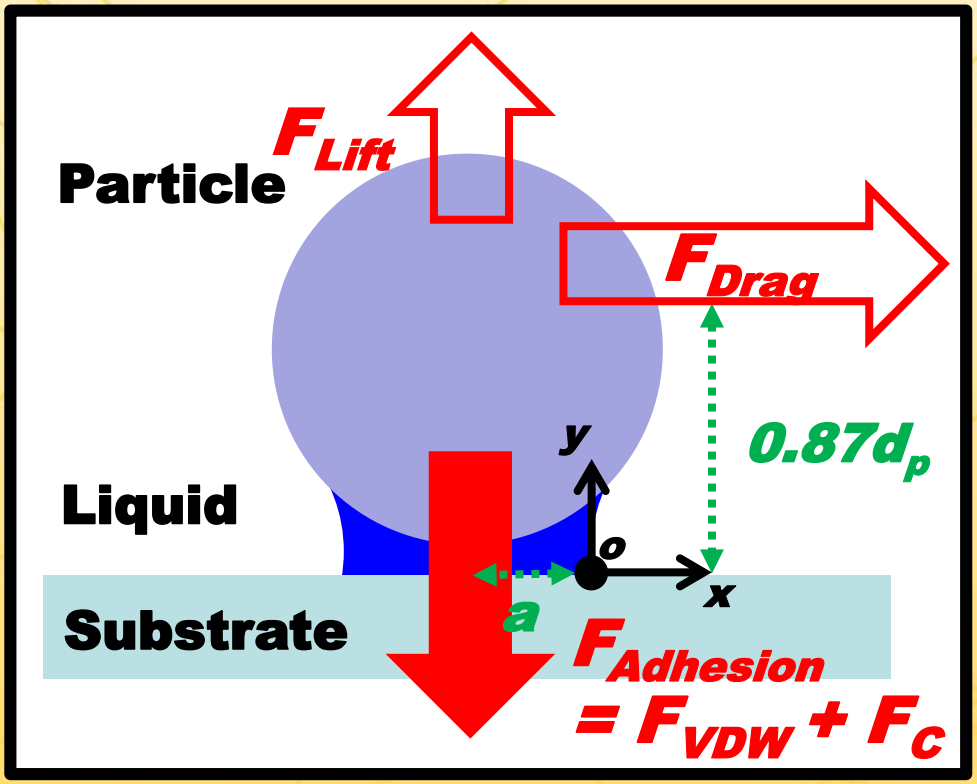
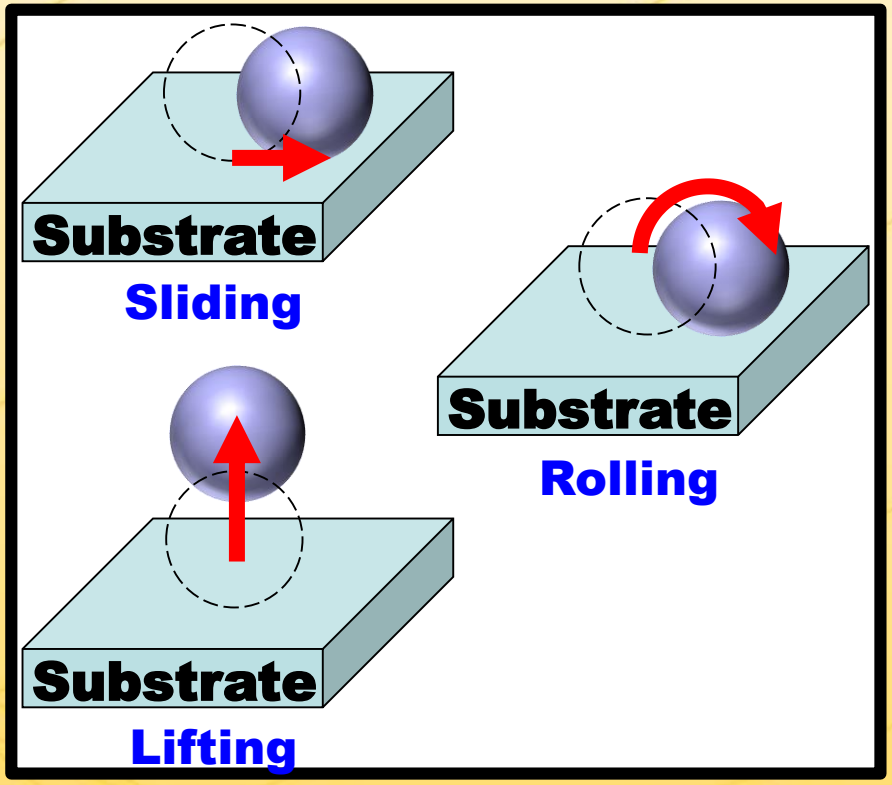
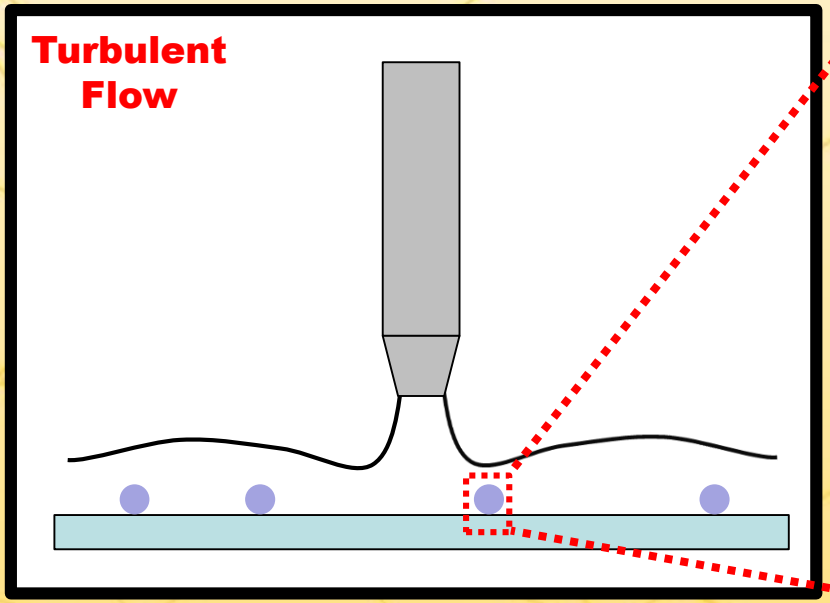
Modeling Particle Detachment

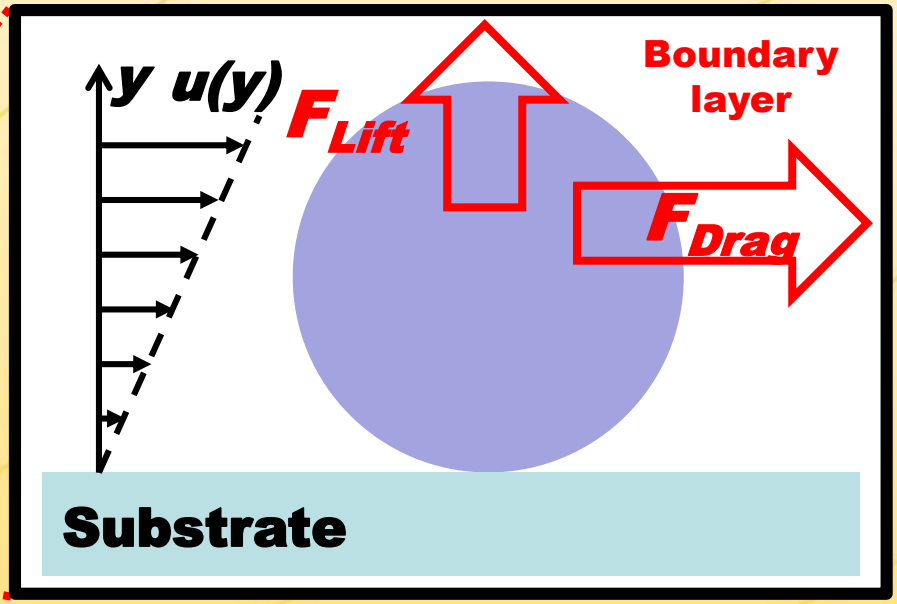




- **Sliding Detachment Mode:** $\sum F_x$: $F_{Drag} > k_s(F_{Adhesion} - F_{Lift})$
- **Lifting Detachment Mode:** $\sum F_y$: $F_{Lift} > F_{Adhesion}$
- **Rolling Detachment Mode:** $\sum M_z (= \vec{F} \times \vec{r})$: $0.87d_p F_{Drag} + aF_{Lift} > aF_{adh}$
- **Rolling Detachment Mode is considered as the initial detachment mechanism.**

Air Jet Flow Field near the Wall





$$F_{Drag} = \frac{3f\pi\mu u_c d_p}{C_c}, \qquad F_{Lift} = 1.615 d_p^2 u_c \sqrt{\rho\mu \left.\frac{du}{dy}\right|_{y=d_p/2}} \quad \Rightarrow \quad F_{Remove} = f(u)$$

- **Velocity profile near the surface resulting from turbulent flow and boundary layer is not simply predicted.**
- **Drag and lift force are function of flow velocity.**
- **Before making the particle detachment model, the velocity profile near the wall should be determined.**

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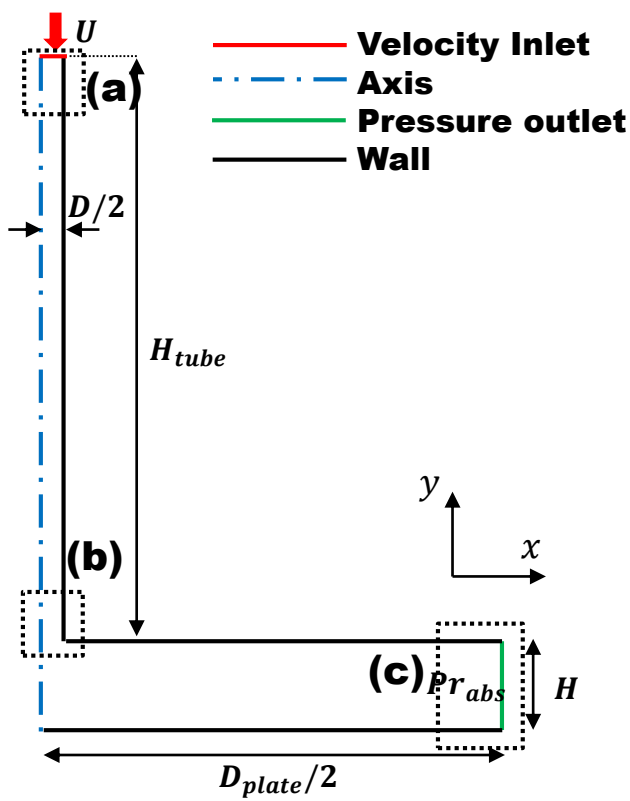
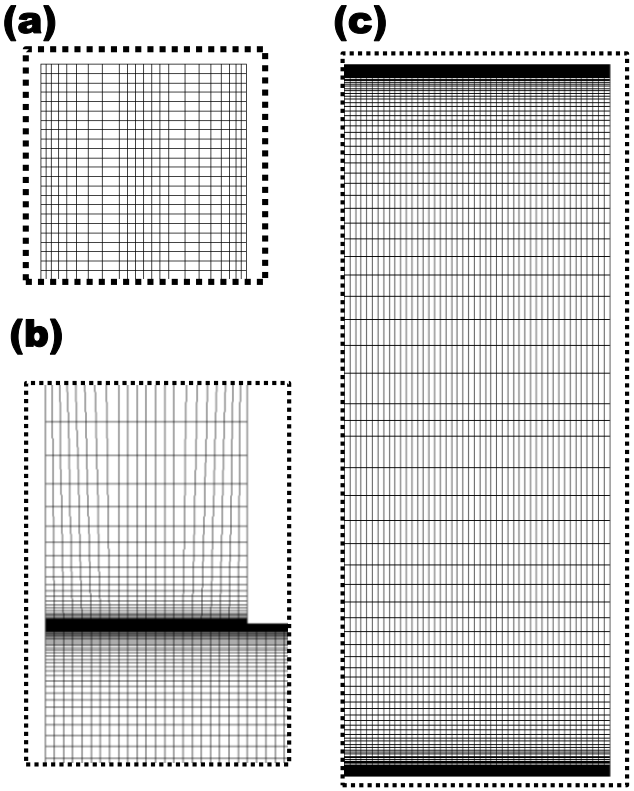
Impinging Air Jet Flow Modeling

Reference Exp.

Present Numerical Model





- **By using CFD software, ANSYS FLUENT, Impinging Air jet Flow is modeled.**
- **Geometric information and boundary conditions were attained from other publication.**

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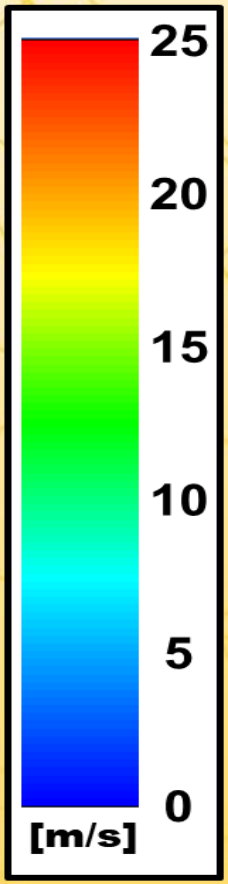
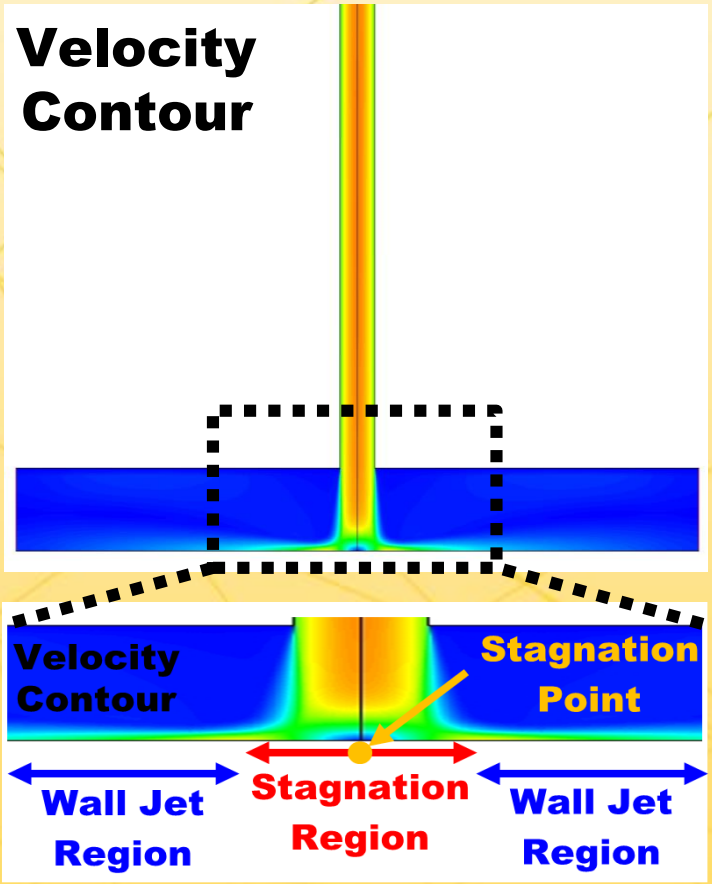
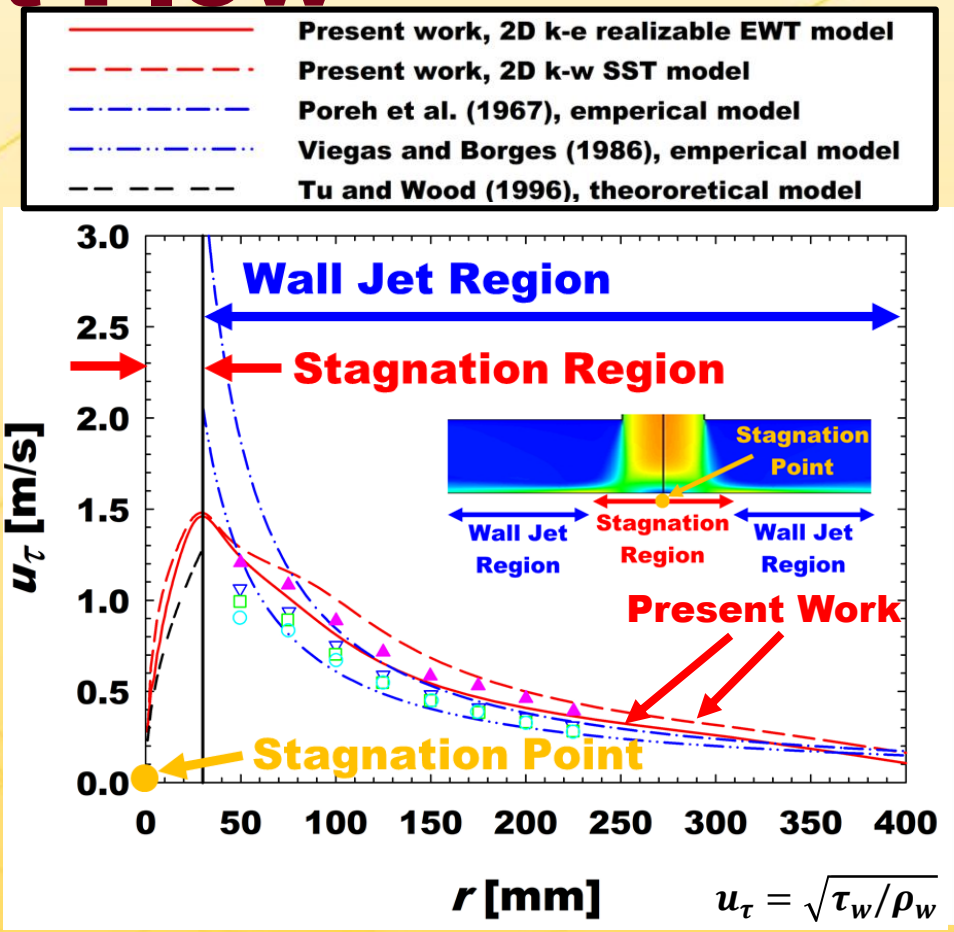
***Detailed geometric info and BCs are available in the appendix section.**

Air Jet Flow

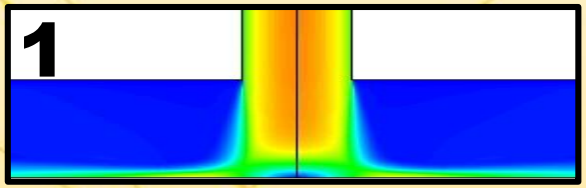






- Two region : Stagnation and Wall Jet
- Numerical results show that velocity profile both regions is successfully validated.

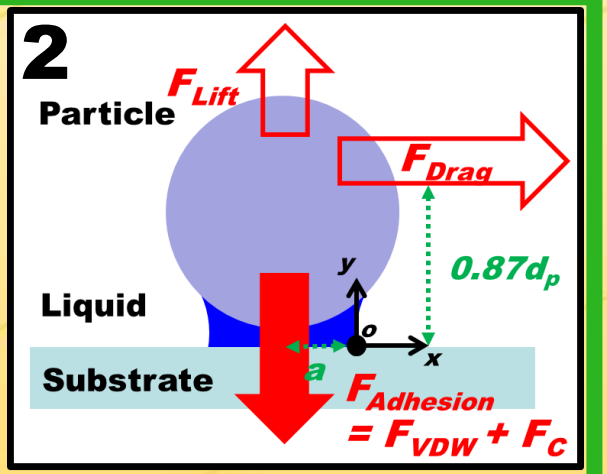
Future Modeling Plan

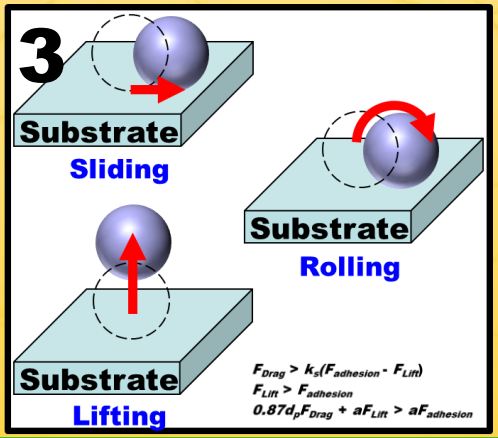


- The flow field is calculated by CFD software, ANSYS FLUENT.

Complete

- With attained flow field, particle removal force including drag and lift forces would be calculated.
- By using particle and substrate material properties, the adhesion force including Van der Waals and capillary forces would be calculated.





- UDF* code would be generated by considering each detach mode (Sliding, Lifting, and Rolling).
- After particles are detached, DPM* code would happen immediately (Transport).
- Finally, PRE* would be estimated.

Plan

*UDF: User-Defined Function
*DPM: Discrete Phase Model
*PRE: Particle Removal Efficiency

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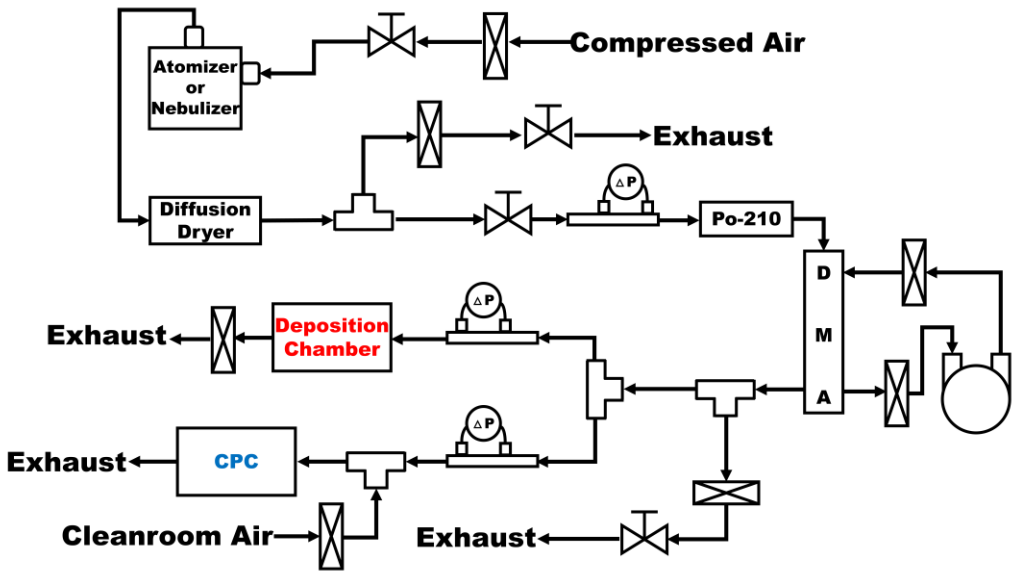
   - **3-2. Air Jet Cleaning Experiment**

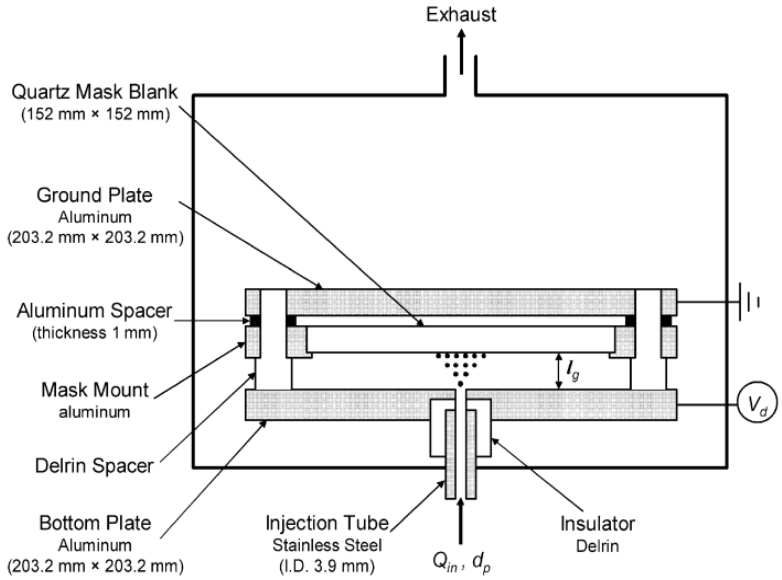
4. Conclusion & Future Plan

Reference

Particle Deposition Experiment



Particle Deposition Experiment Set-up Schematic



Deposition Chamber Schematic

- **PSL Particle was generated by using atomizer or nebulizer.**
- **To remove unintended particles (ex. residue), DMA was utilized.**
- **By using electrophoresis, deposition spot size was controlled.**
- **Measuring particle concentration by using CPC, the number of deposited particle was approximately calculated.**

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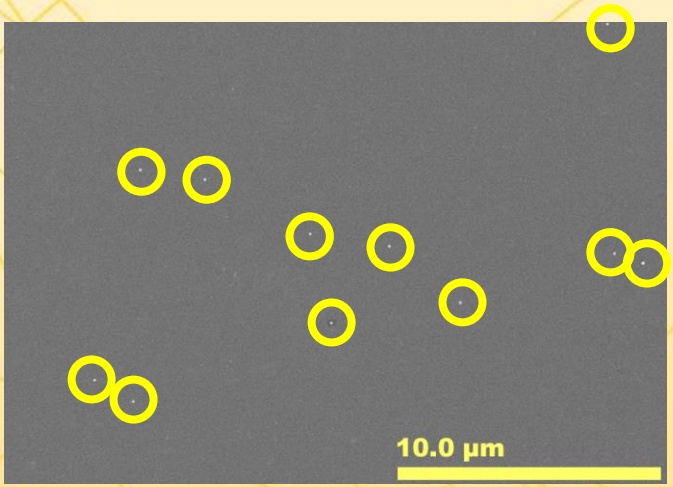
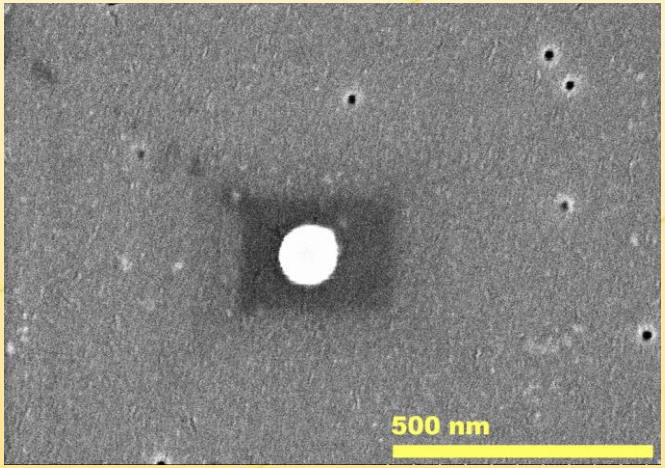
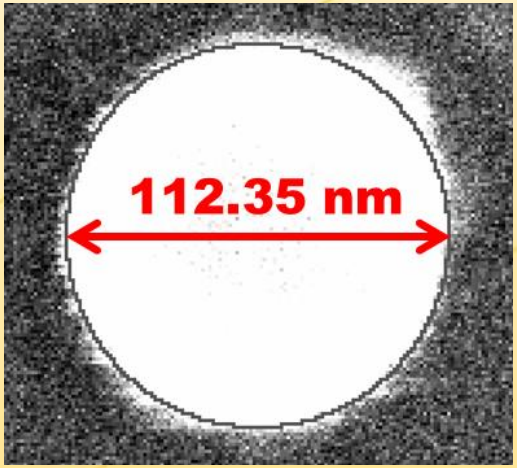
Particle Deposition SEM Result







Particle	PSL 3100 A 102 nm ± 3 nm
DMA Particle size setting	102 nm
DMA Aerosol inlet flow rate	0.3 L/min
DMA Sheath air flow rate	6 L/min
Iridium Sputtering (Coating)	Setting 5 nm (Actual 5.1 nm)
SEM Image Particle Size	112.35 nm

- By using the particle deposition experiment set-up, particle successfully deposited with the intended particle size, 102 nm. (102 nm + 5.1 nm x 2 = 112.2 nm ≈ 112.35 nm).

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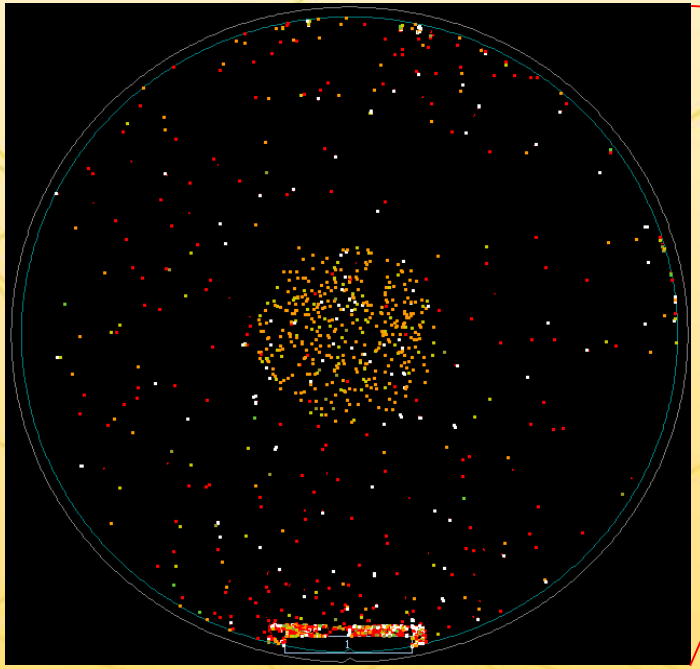
Particle Deposition WSS Analysis



KLARF from WSS

Data analysis
MATLAB Program

1. Particle counting
2. Particle size
3. Spot size
4. Size Distribution

- To estimate PRE and cleaning area, deposited particle information (location, size, number) should be known.
- However, WSS result has a limitation to estimate PRE.
- MATLAB program has developed to overcome this limitation.
- By using this program, we can get several information as shown in next slides.

*KLARF: KLA Raw File
*PRE: Particle Removal Efficiency
*WSS: Wafer Surface Scanner (SP1 Model @ Entegris)

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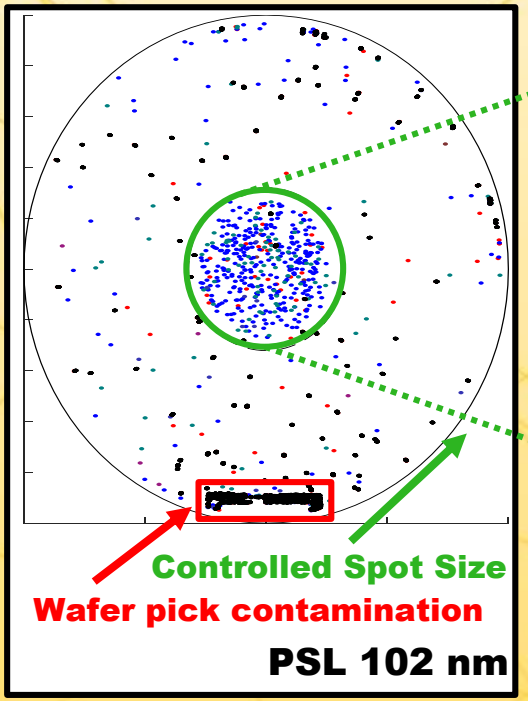
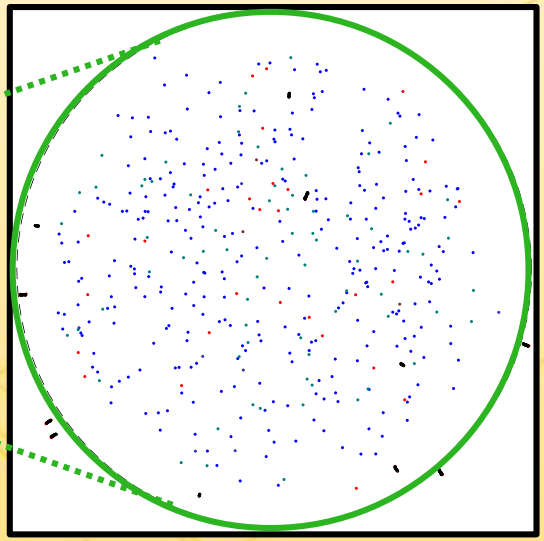
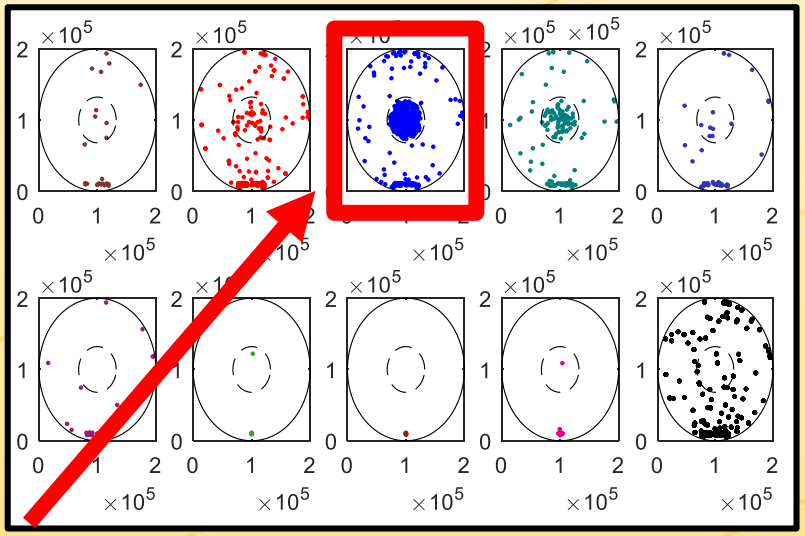
Particle Deposition Spot Size







Size bin Channel	1	2	3	4	5	6	7	8	9	10
Lower limit [μm]	0	0.065	0.090	0.12	0.15	0.2	0.4	0.8	1	2
Upper limit [μm]	0.065	0.090	0.12	0.15	0.2	0.4	0.8	1	2	298

- **PSL 102 nm was deposited on the 200 mm wafer.**
- **By considering the electrostatic and drag forces for the particle motion, deposition spot size can be calculated.**
- **Calculated deposition spot size is very similar to the actual deposited spot size.**

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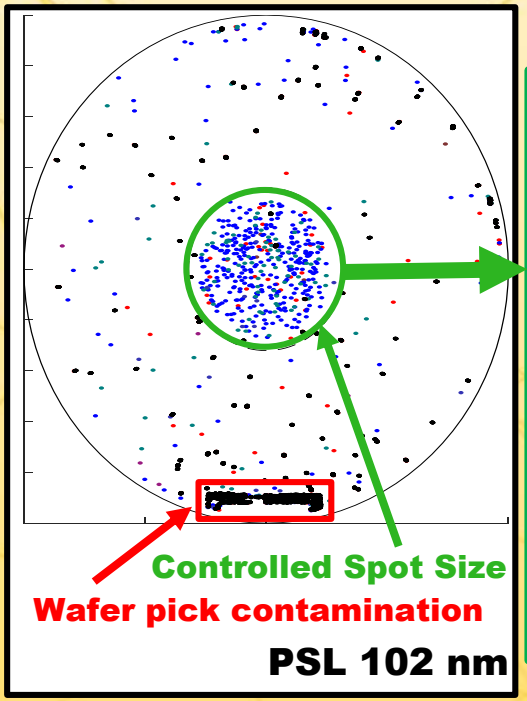
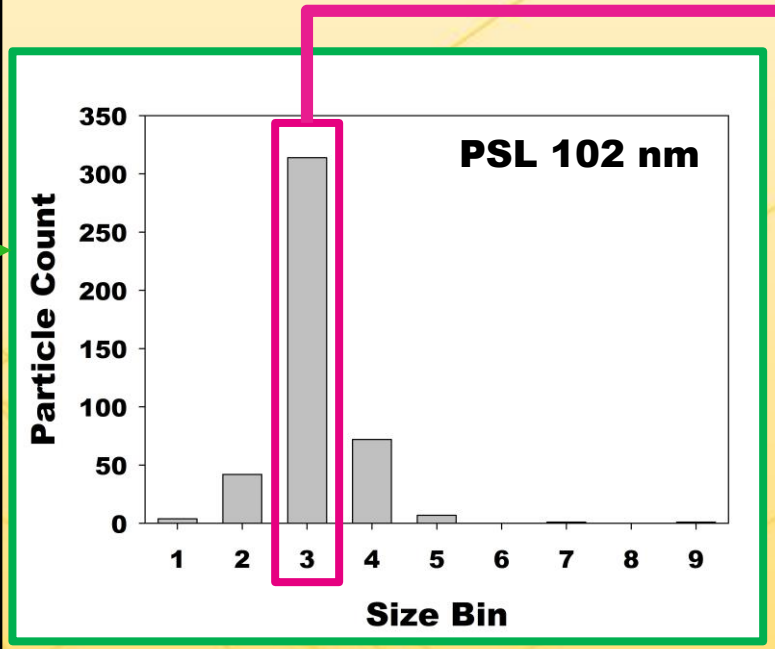
*WSS: Wafer Surface Scanner (SP1 Model @ Entegris)

Particle Deposition Size Bin





Size bin Channel	1	2	3
Lower limit [μm]	0	0.065	0.090
Upper limit [μm]	0.065	0.090	0.12
Size bin Channel	4	5	6
Lower limit [μm]	0.12	0.15	0.2
Upper limit [μm]	0.15	0.2	0.4
Size bin Channel	7	8	9
Lower limit [μm]	0.4	0.8	1
Upper limit [μm]	0.8	1	2

- By using program, upper limit and lower limit easily could be converted easily.
- From the result, WSS could give reasonable result of PSL 102 nm.
- This program would be very helpful to determine PRE with respect to particle location change and cleaning area

*PRE: Particle Removal Efficiency
*WSS: Wafer Surface Scanner (SP1 Model @ Entegris)

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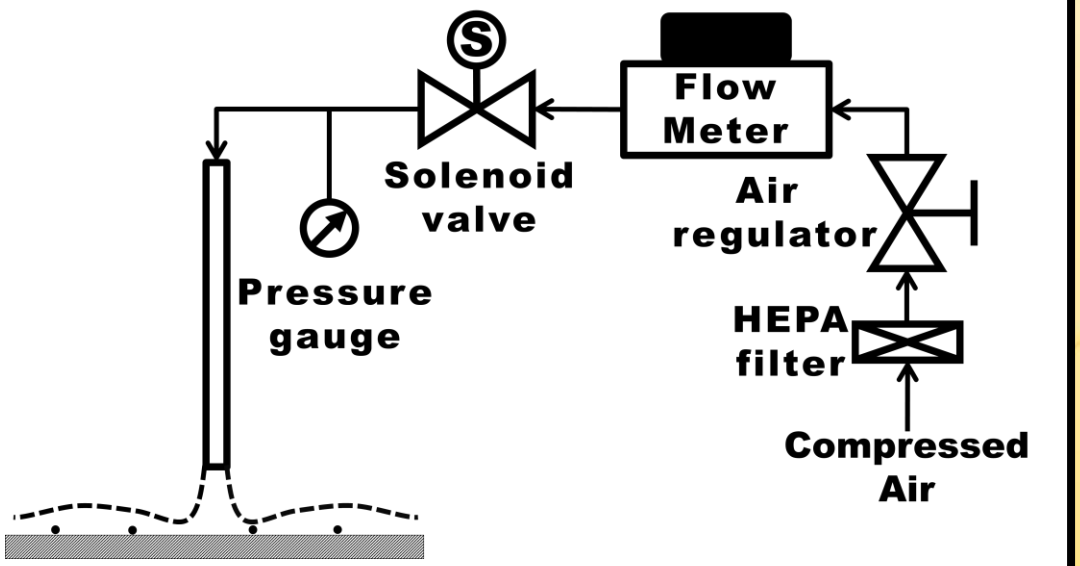
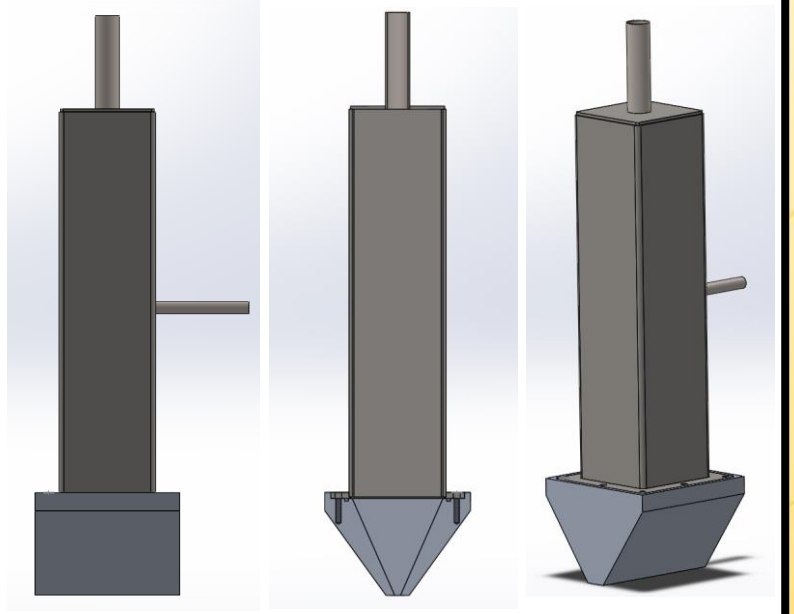
Air Jet Cleaning Experiment



Air Jet Cleaning Experiment Set-up Schematic



Air Jet Nozzle Schematic

- **PRE** would be calculated by checking the position and number of particles using **WSS** before and after the experiment.
- **Solenoid valve** would be employed to generate a **pulsed air jet** by opening and closing the valve over time.
- Measured flow rate and pressure would be used as input value of CFD software.

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*PRE: Particle Removal Efficiency
*WSS: Wafer Surface Scanner (SP1 Model @ Entegris)

University of Minnesota

Overview

1. Introduction

2. Numerical and Theoretical Study
   - 2-1. Particle Removal Mechanism
   - 2-2. Air Jet Flow Field near the Wall
   - 2-3. Future Modeling Plan

3. Experimental Study
   - 3-1. Particle Deposition Experiment
   - 3-2. Air Jet Cleaning Experiment

4. **Conclusion & Future Plan**

Reference

Future Plan

Numerical and Theoretical Study

Present a new numerical and theoretical model calculating PRE and cleaning area.

- **Develop the UDF code which can determine if the particles detached or not.**
- **Using DPM code, PRE and cleaning area would be estimated.**

Experimental Study

Present a quantitative PRE calculation method that ensures repeatability.

- **Complete the air jet surface cleaning set-up.**
- **Perform the parametric study of each variable (nozzle distance, air jet flow rate, pulsed time, angle between nozzle and surface).**

*UDF: User-Defined Function
*DPM: Discrete Phase Model
*PRE: Particle Removal Efficiency

Conclusion

Numerical and Theoretical Study

- By using each particle detachment mode and removal and adhesion force, modeling algorithm is developed.
- Flow field is calculated by CFD software, ANSYS FLUENT and the results show a good agreement with the previous several data.

Experimental Study

- By controlling electrophoresis, deposition spot size is easily controlled and the experiment result show that the calculated size and actual size are almost same.
- Particle deposition WSS analysis program is successfully developed.

*PRE: Particle Removal Efficiency
*WSS: Wafer Surface Scanner (SP1 Model @ Entegris)

Thank You
Q&A

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Reference

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