# Defectivity Improvements Enabling HVM for EUV Scanners

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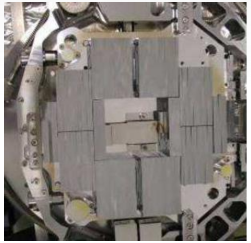
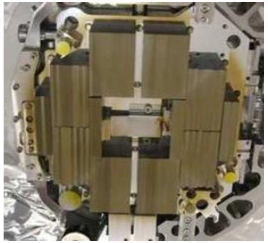
# EUV lithography is key enabler for IC manufacturing Supporting ever-growing data/connectivity needs





**NXE:3400B:**

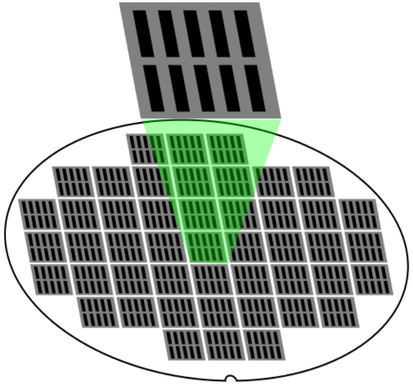
- First EUV scanner for commercial production
- EUV wavelength $\lambda$ = 13.5 nm
- Numerical Aperture NA = 0.33
- Resolution lines/spaces 11 nm

System is <u>not</u> at vacuum: ~5 Pa of $H_2$

- Driven by prevention of oxidation of Ru-coated mirrors and removal of carbon growth
- Drawbacks are transport of particles by gas and chemical activity of hydrogen plasma

# Examples of reticle front side particle contamination

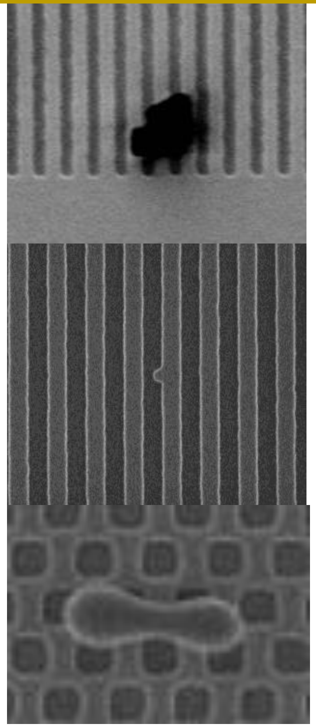
## Reticle front side defectivity is a key business driver



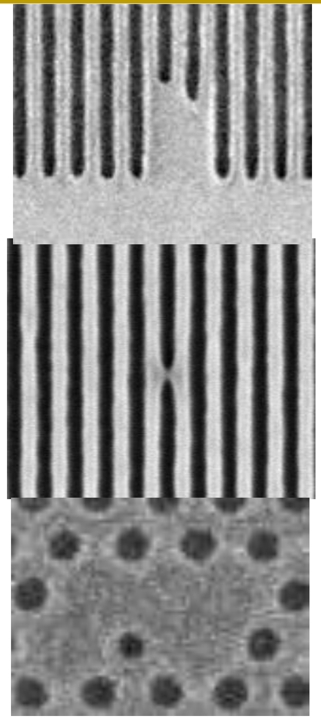
A particle on reticle front side is <u>repeated</u> on every wafer for each die (100% yield loss for full field dies)

Damage threshold for 7nm node is ~52nm

Particle @ reticle level



As printed on wafer

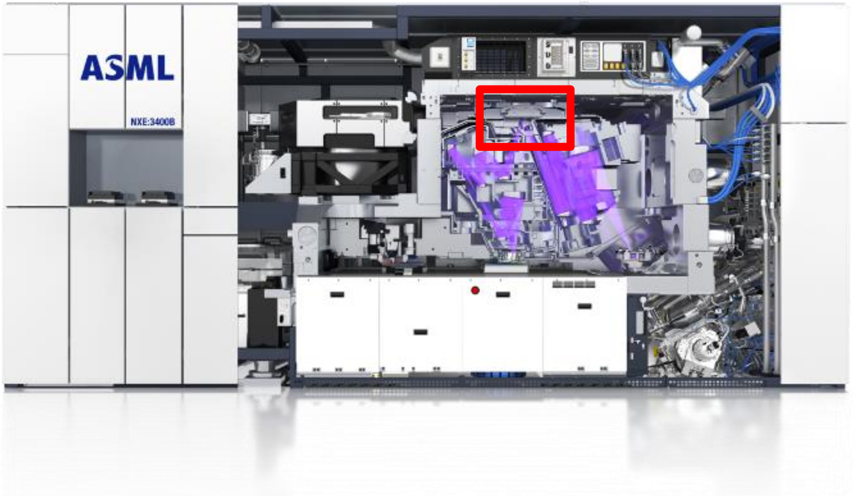


# Two-fold approach to eliminate reticle front-side defects

## Focus of this presentation: 1. Clean system without pellicle



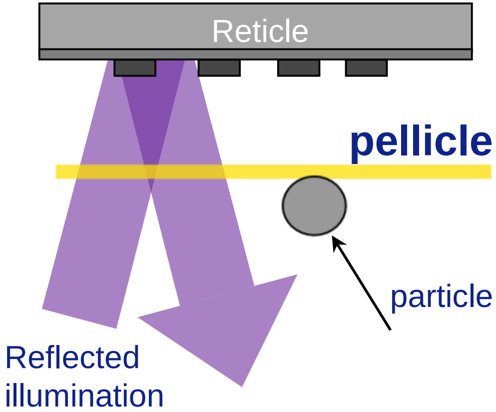
### 1. Clean system
(without pellicle)

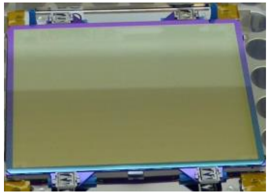



**Reticle**

### 2. EUV pellicle

**EUV Reticle** (13.5nm)



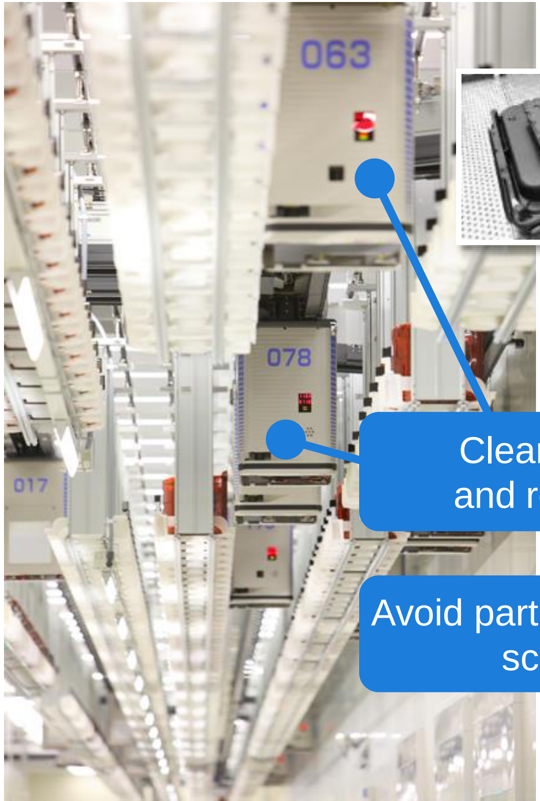



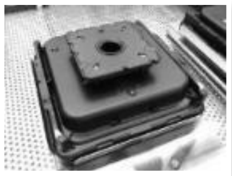
**Reticle with pellicle**

# 1. Clean System (without pellicle) for HVM

## Reticle front-side defectivity improving in all categories





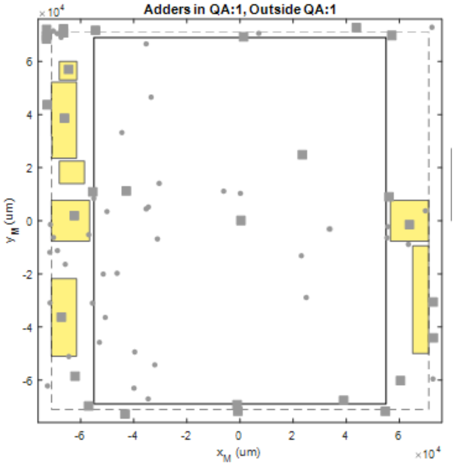

Avoid that particles in scanner reach reticle surface

Clean environment and reticle handling

Avoid particle release in scanner

# Reticle defectivity is defined as: #particles added to reticle after 10,000 wafer exposure

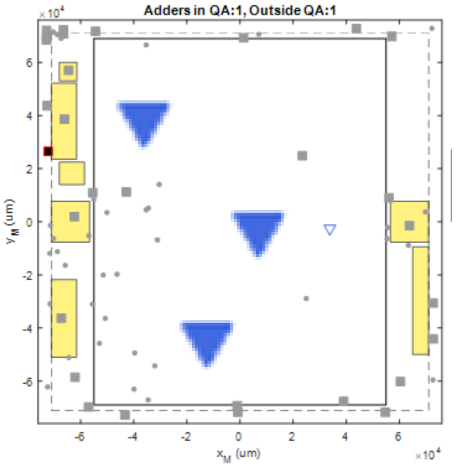





PRE measurement

74 defects

750 wafers exposed




POST measurement

3 **added** defects

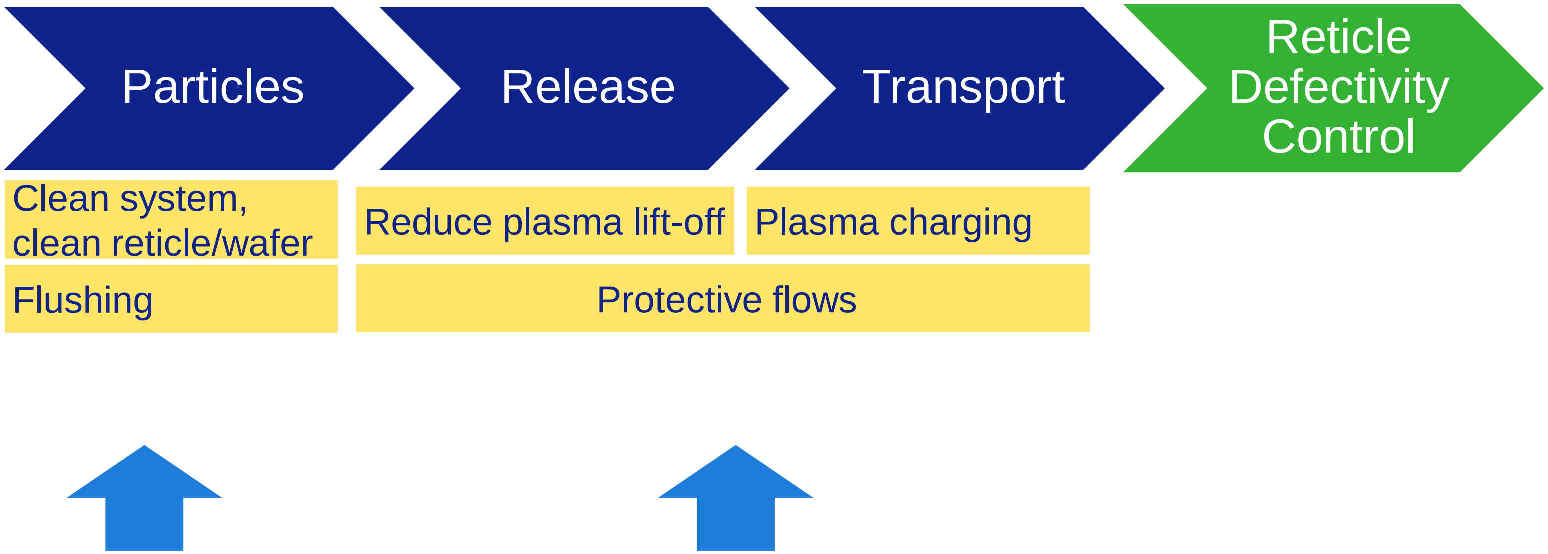
$$\text{Defectivity} = \frac{3\ \text{adders}}{750\ \text{wafers}} = \frac{40\ \text{adders}}{10{,}000\ \text{wafers}}$$

→ **"40/10k"**

# Scanner Particle Contamination Control



To maximize yield, Scanner Contamination Control must aim at breaking the Particle Contamination Chain at all possible links




Minimize particle population

Optimize flow and plasma conditions in critical areas

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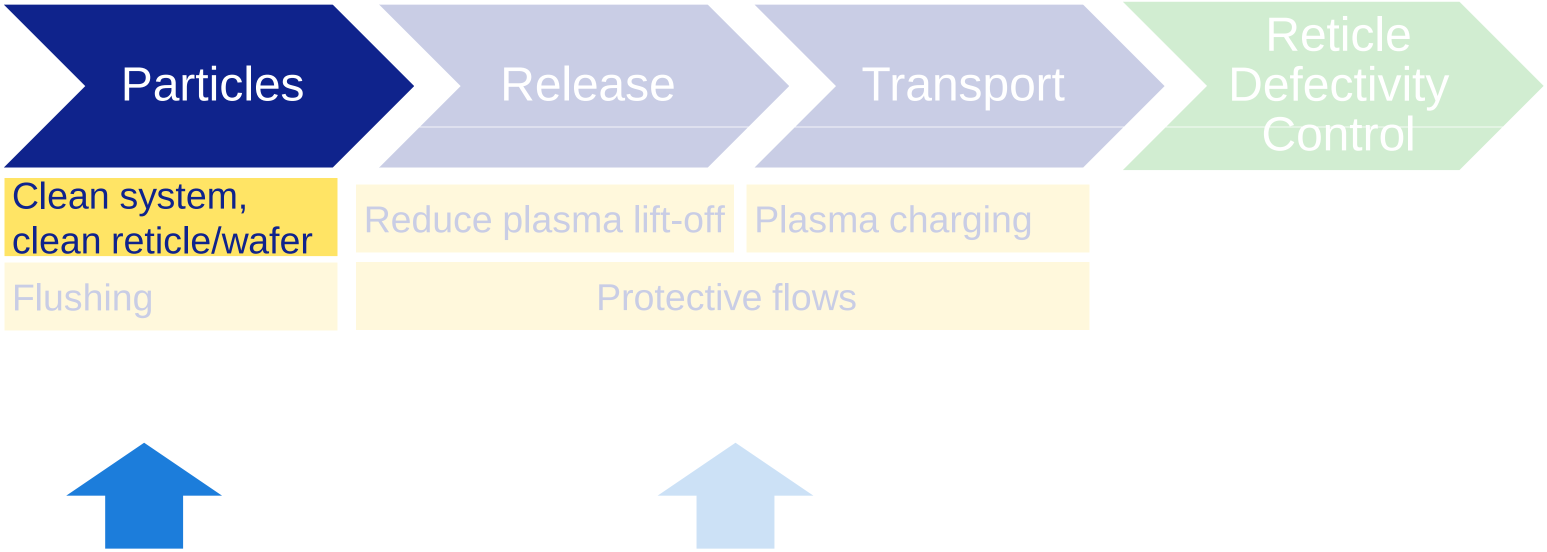



Minimize particle population

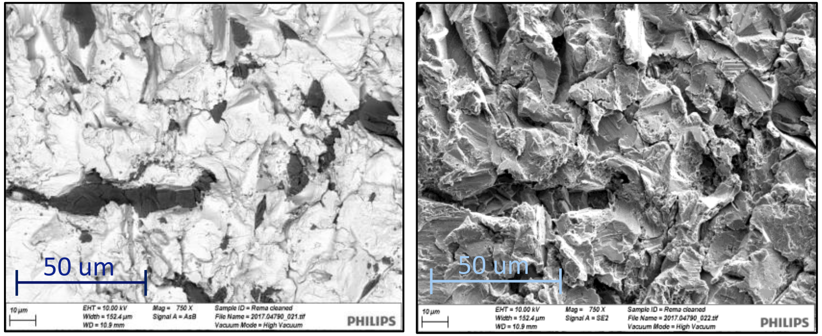
Optimize flow and plasma conditions in critical areas

# RME part cleanliness correlated to PRP performance

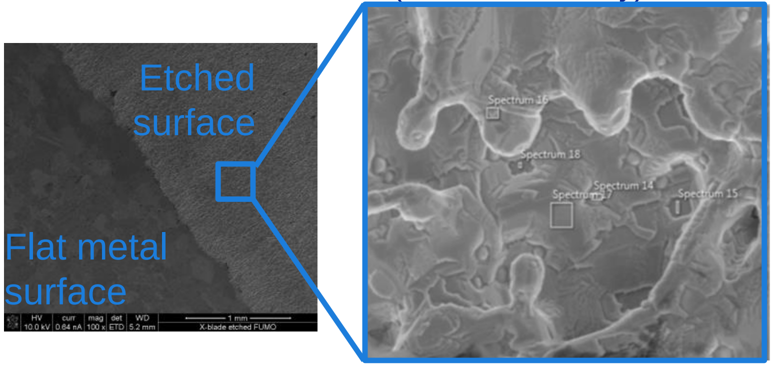
## Novel clean etching process of ReMa blades meets both defectivity and optical requirements

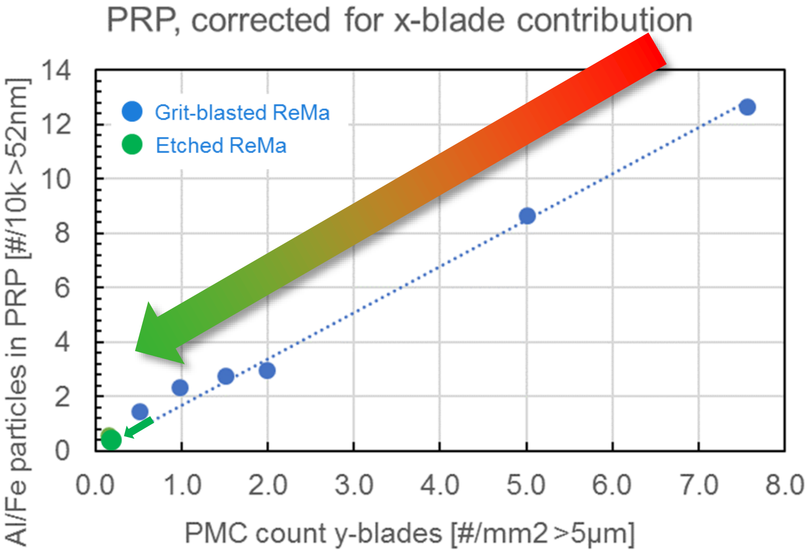


Surface of roughened ReMa blade (top/bottom) after cleaning




Surface of etched ReMa blade (bottom side only) after cleaning



# Scanner Particle Contamination Control



To maximize yield, Scanner Contamination Control must aim at breaking the Particle Contamination Chain at all possible links

Particles → Release → Transport → Reticle Defectivity Control

| Particles | Release | Transport |
|---|---|---|
| Clean system, clean reticle/wafer | Reduce plasma lift-off | Plasma charging |
| Flushing | Protective flows | |

Minimize particle population

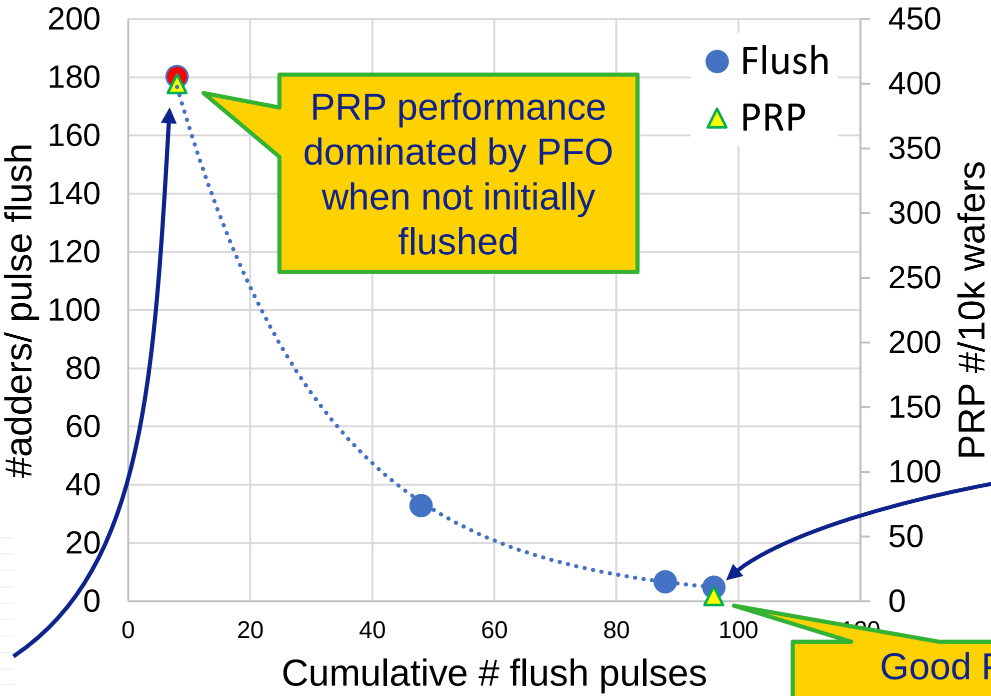
Optimize flow and plasma conditions in critical areas

# Flushing: Assembly/PFO particles are removable



## Loosely bound fall-out particles effectively flushed out prior to first wafer exposures

➔ Initial flushing necessary to meet HVM PRP spec

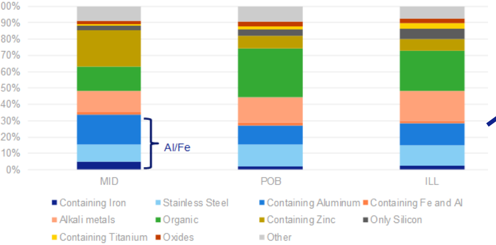



PRP performance dominated by PFO when not initially flushed

Good PRP performance after flushing sequence

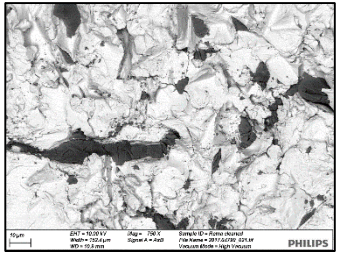
Can be measured by air sampling

Material Pareto for particle fall-out




Not measurable by air sampling, needs contacting sampling

Example of roughened ReMa blade

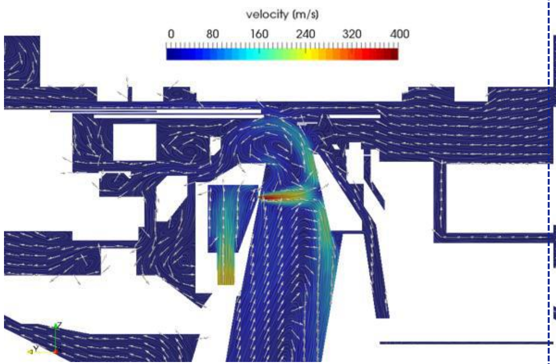


# Y-nozzle Flushing highly effective for critical surfaces

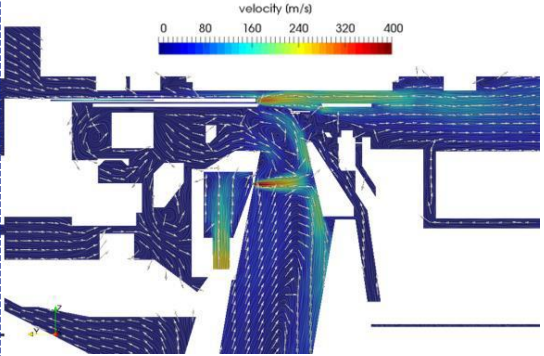


*~100x higher flushing efficiency over critical defectivity area of ReMa-blades is achieved, in combination with moving ReMa blades and Reticle Stage through the turbulent region close to Y-nozzle*

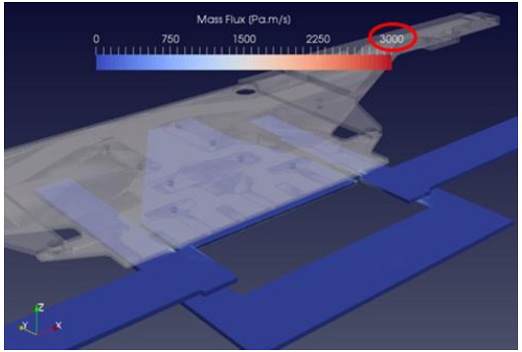
flow field default flush



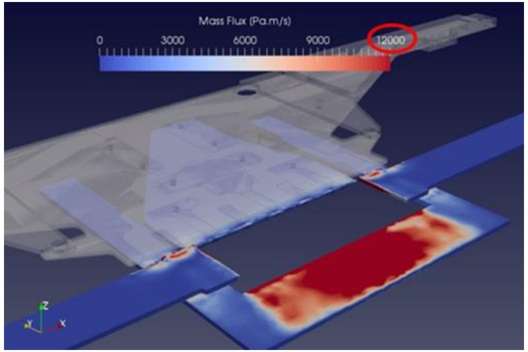

flow field Y-nozzle flush



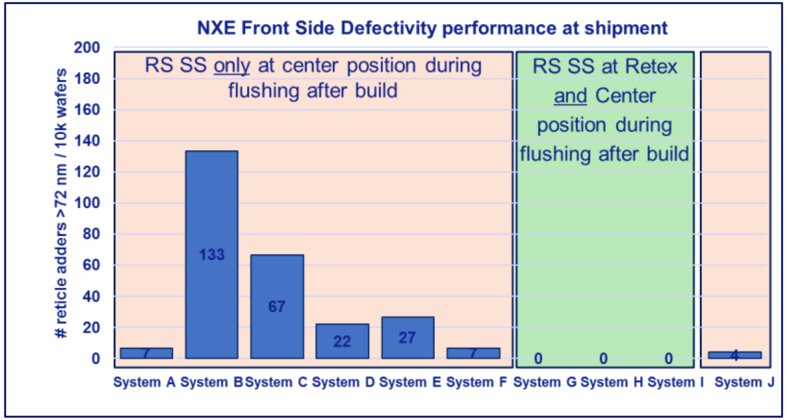

drag force default flush




drag force Y-nozzle flush




Flushing Improvement confirmed by Defectivity: all 3400B champion results were achieved with Y-nozzle flushing



# Scanner Particle Contamination Control



To maximize yield, Scanner Contamination Control must aim at breaking the Particle Contamination Chain at all possible links

Particles → Release → Transport → Reticle Defectivity Control

| Particles | Release | Transport |
| --- | --- | --- |
| Clean system/ reticle/ pods | Reduce plasma lift-off | Plasma charging |
| Flushing | Protective flows | |

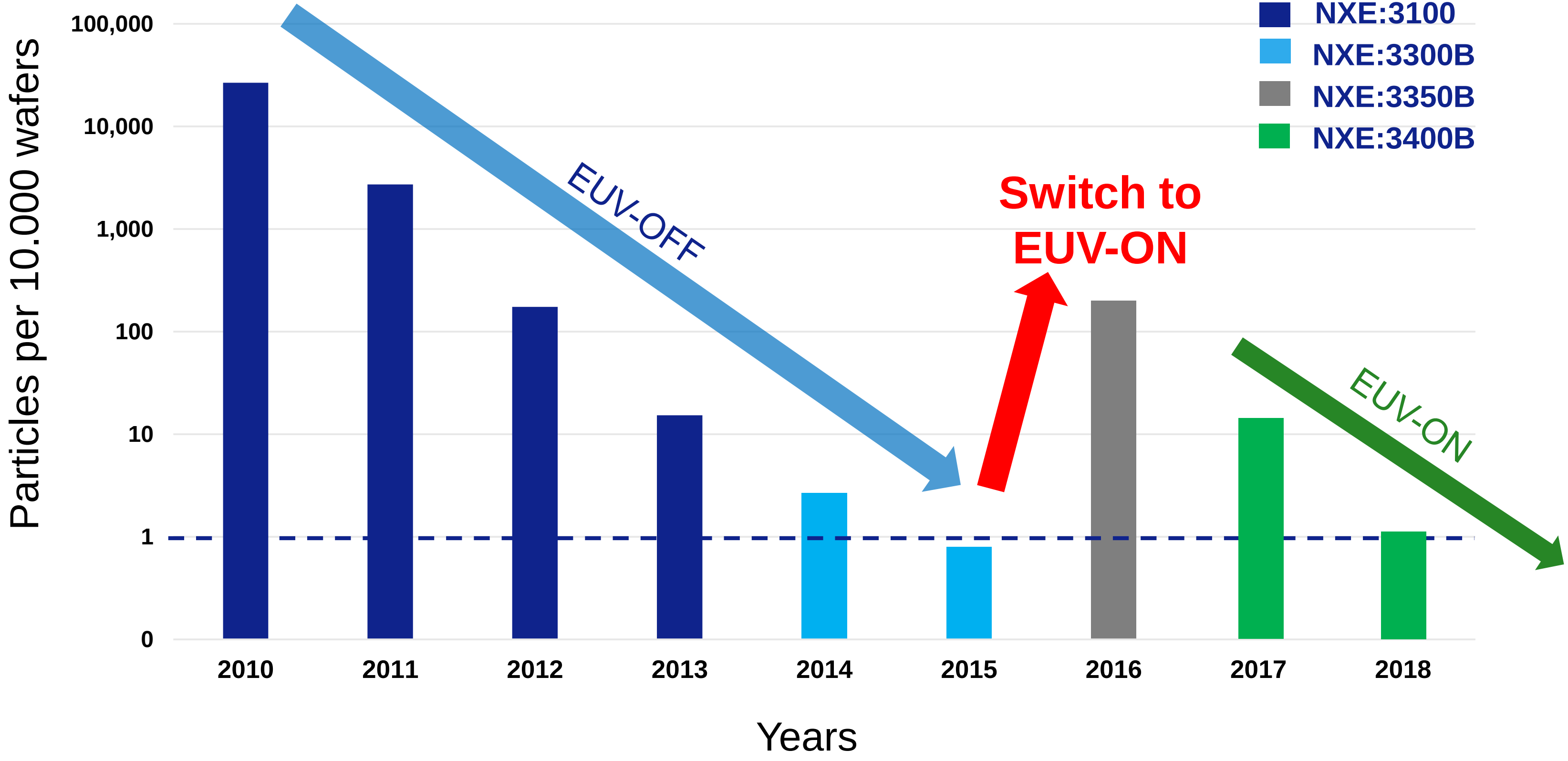
Minimize particle population

Optimize flow and plasma conditions in critical areas

# Switch to EUV-ON in 2016 showed >100x more particles

*EUV-induced plasma results in new release forces and reduced adhesion;*
*Solutions for this have been developed in past years for NXE:3400*



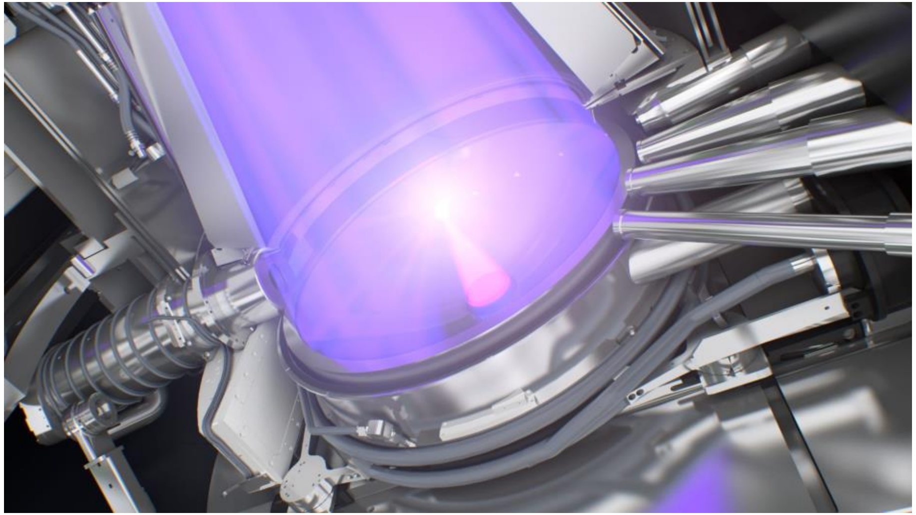


# EUV scanner plasma is different from source plasma

## In scanner, plasma is created by EUV photons



### Inside the EUV source



- Intense $CO_2$ laser pulse strikes tin droplets
- High plasma density & temperature

### Inside the EUV scanner


- EUV photons hit $H_2$ molecules
- Primary electrons create secondaries
- Low plasma density & temperature

# Plasma creates electrical release force on particles

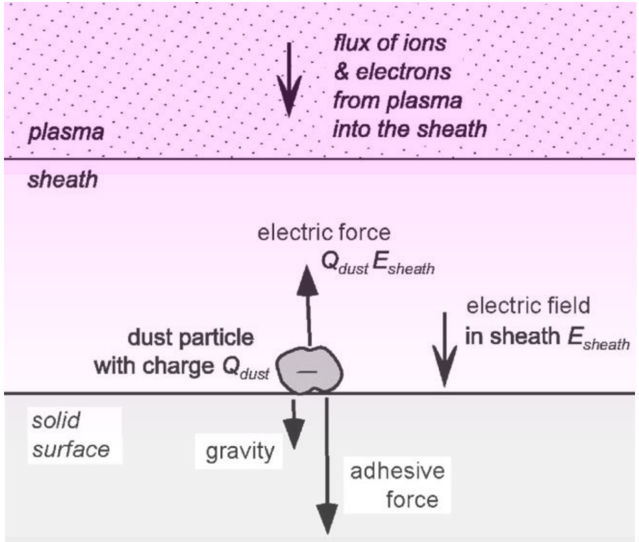
*For plasma lift-off: particle should be charged and feel E-field*

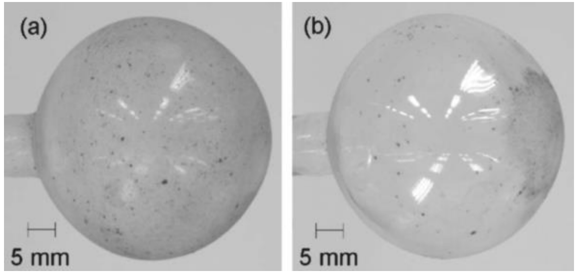
Electrical release force is product of particle charge and electrical field close to the surface.

$$\mathbf{F} = Q_{\text{dust}} \cdot \mathbf{E}_{\text{sheath}}$$

**So we need:**

- Charged particle
  - By photoelectric effect (EUV photons)
  - Plasma species (electrons, ions)
  - From (conductive) surface
- E-field
  - Sheath E-field (up to MV/m)
  - External fields (unshielded ears)



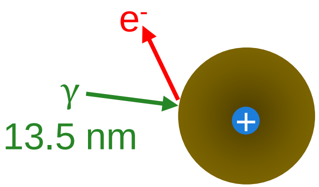




Flanagan et al, "Dust release from surfaces exposed to plasma", 2006

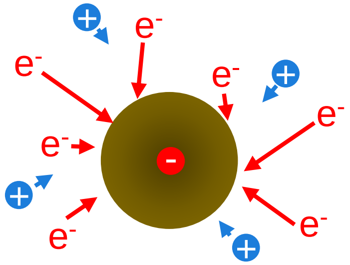
# Particle charging in EUV-induced plasma

## EUV, plasma and surface charge particle → particle can be positive or negative

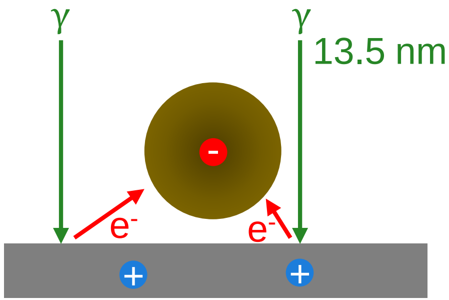




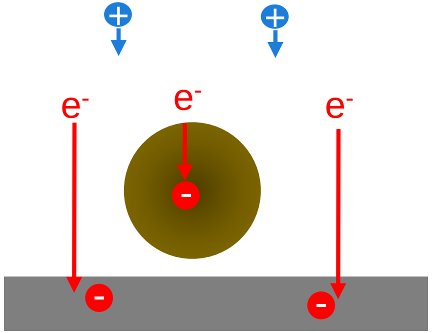

Photoelectric effect
(dominant in EUV beam)



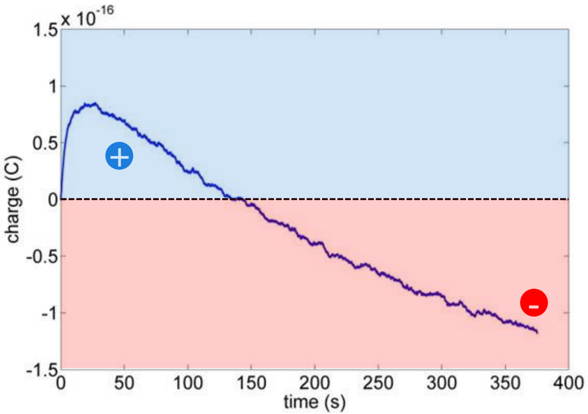

Plasma charging
(outside of EUV beam
and in aftermath of pulse)



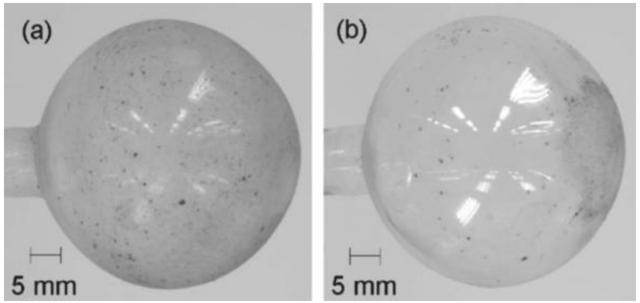

Near surface in beam




Near surface out of beam
(or after beam)




S. Frazier et al, “Charging behavior of Dust Aggregates in a Cosmic Plasma Environment”, 2013



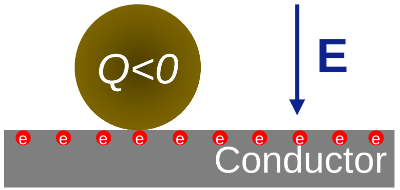

T. Flanagan et al, “Dust release from surfaces exposed to plasma”, Physics of Plasma 13(12), 2006

# Nanoparticle charging is highly stochastic

*Release driven by 'black swan' charge excursions – not by classical average*



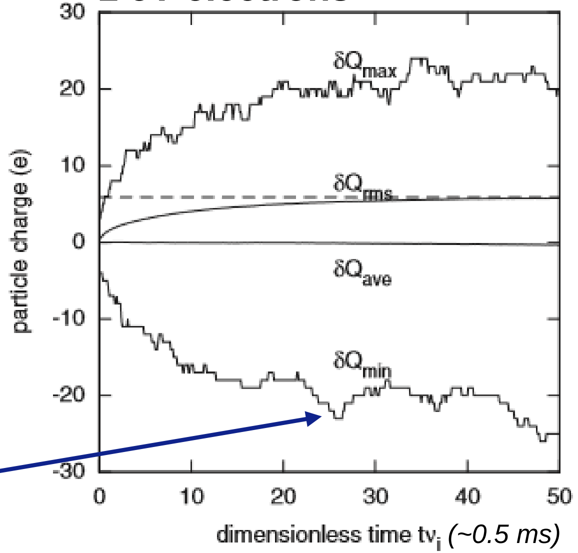
Nanoparticle charging is a stochastic process:
discrete arrival of ions and electrons




For E-fields of ~MV/m:
Charge average approx. $-0.1|e|$

Charge stochastics: $\pm 25|e|$

**Example: 40 nm particle, 1 eV electrons**




Sheridan, Appl.Phys.Letters, 2011

Stochastic release force $\mathbf{F} = Q\mathbf{E}$
up to 2 orders of magnitude higher!

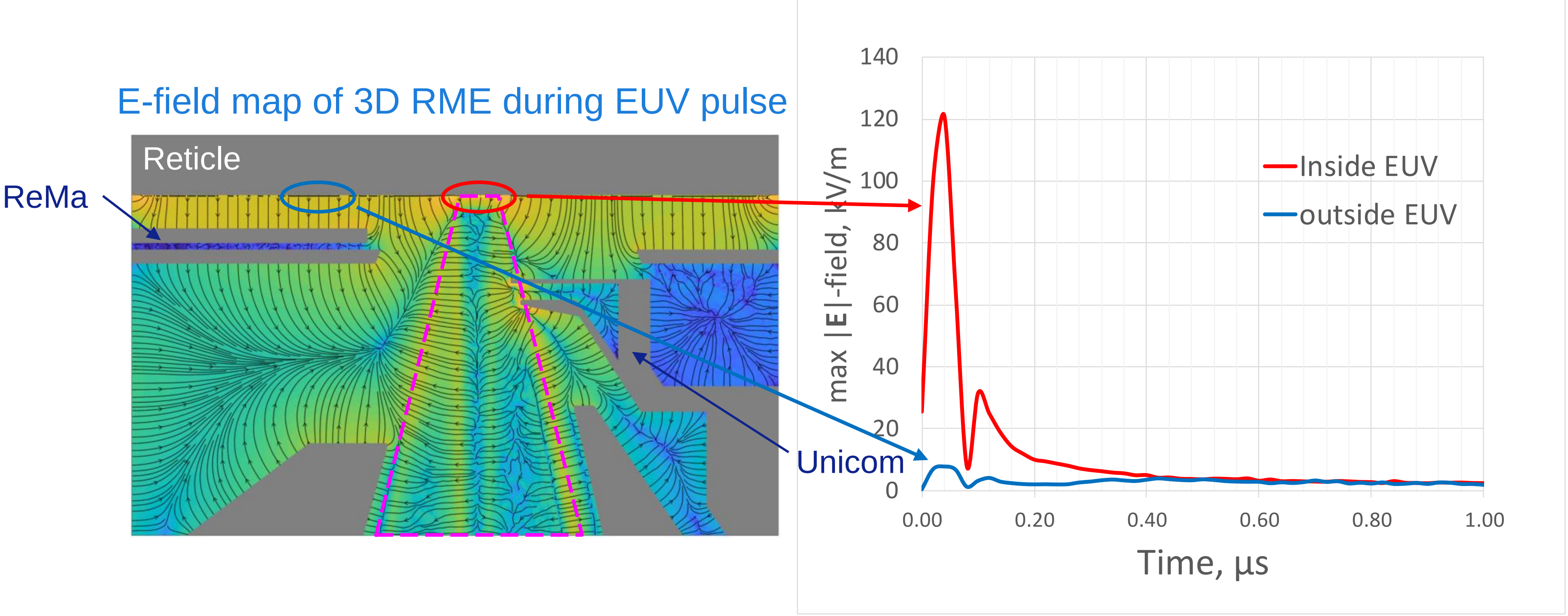
# Strong transient plasma fields on irradiated surfaces



## E-field can reach >100 kV/m on reticle, and adjacent parts

## Away from EUV-beam, E-fields fall off quickly

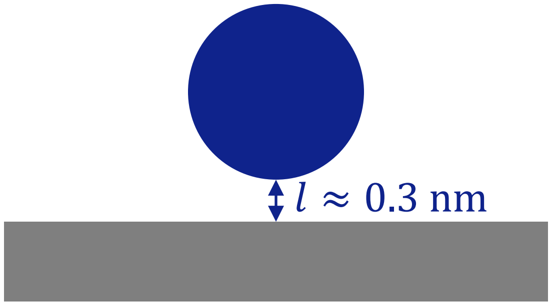
E-field map of 3D RME during EUV pulse



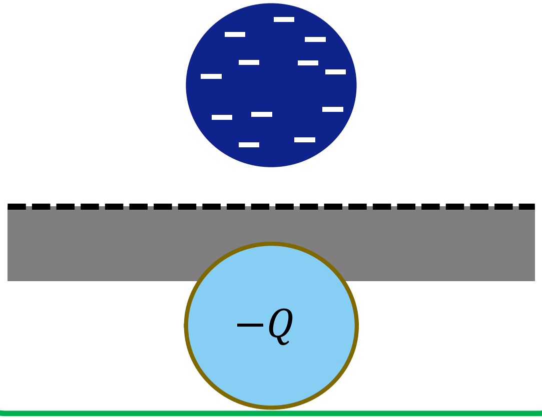
# EUV and plasma can reduce particle adhesion

## Besides release force from EUV-plasma, also adhesion can be reduced

### Van der Waals

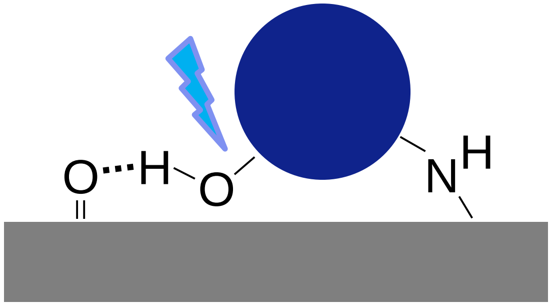



### Electrostatic / mirror charge

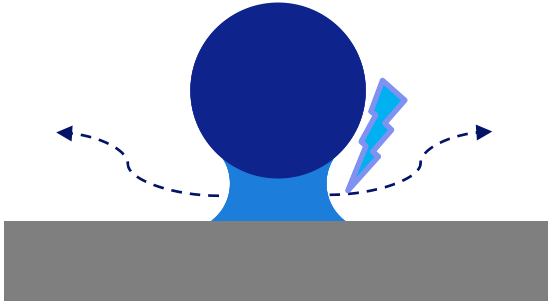



These adhesion forces are not affected by EUV photons & EUV induced H-plasma

### Chemisorption bonds broken




### Capillary force evaporates



These adhesion forces will be reduced by EUV photons and EUV induced H-plasma

# Release of particles in plasma: dielectric vs metallic

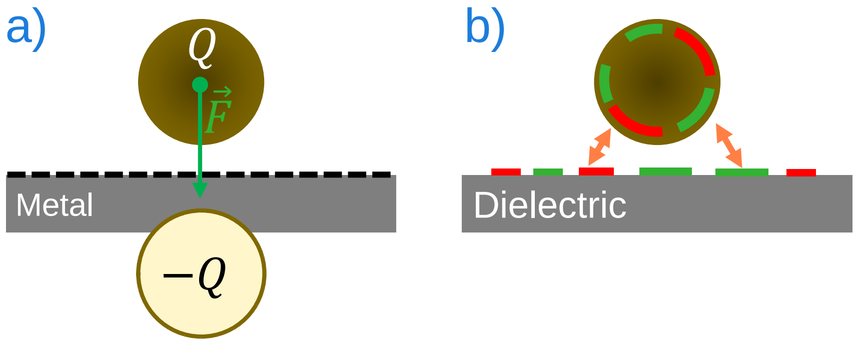
Release efficiency dependent on material properties of BOTH particle AND substrate



**Relevant factors:**

a) Mirror charge force
➔ Adds attractive force component
➔ Efficient for metallic substrates:

b) Local (patch) charging
➔ Can locally result in high repulsion
➔ Efficient for dielectrics



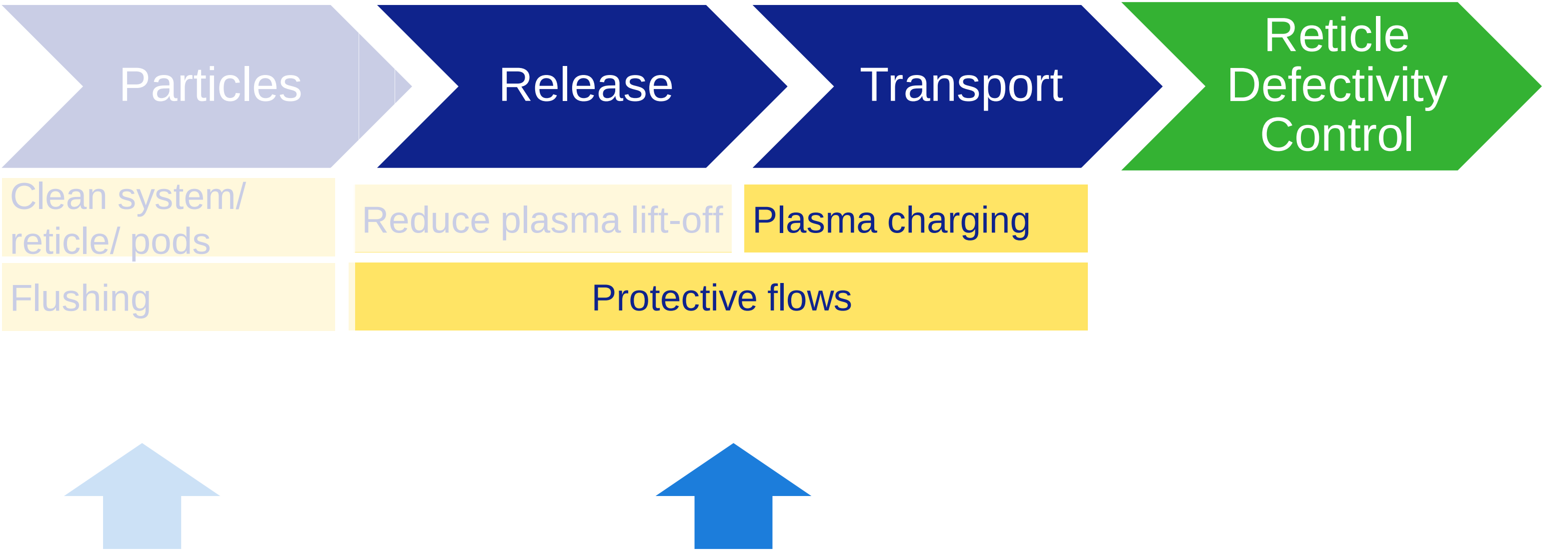

**Release efficiency**

| Particle / Substrate | Dielectric | Metallic |
|---|---|---|
| Dielectric | Highest | High |
| Metallic | Low | Lowest |

# Scanner Particle Contamination Control



To maximize yield, Scanner Contamination Control must aim at breaking the Particle Contamination Chain at all possible links



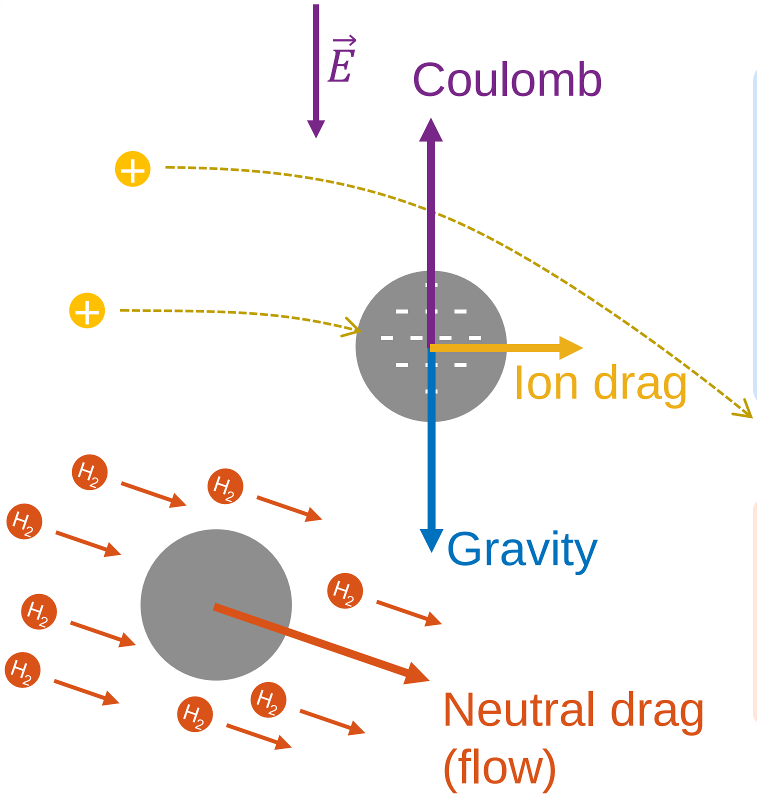

Minimize particle population

Optimize flow and plasma conditions in critical areas

# Forces in volume

## Sophisticated modeling allows us to calculate relevant forces on particles






Self-consistent kinetic modeling of EUV-induced plasma:

- Ion & electron densities
- Ion & electron energies
- Electric field

Sophisticated CFD models:

- $H_2$ pressure maps
- $H_2$ flow speed

Calculation of forces on particles:

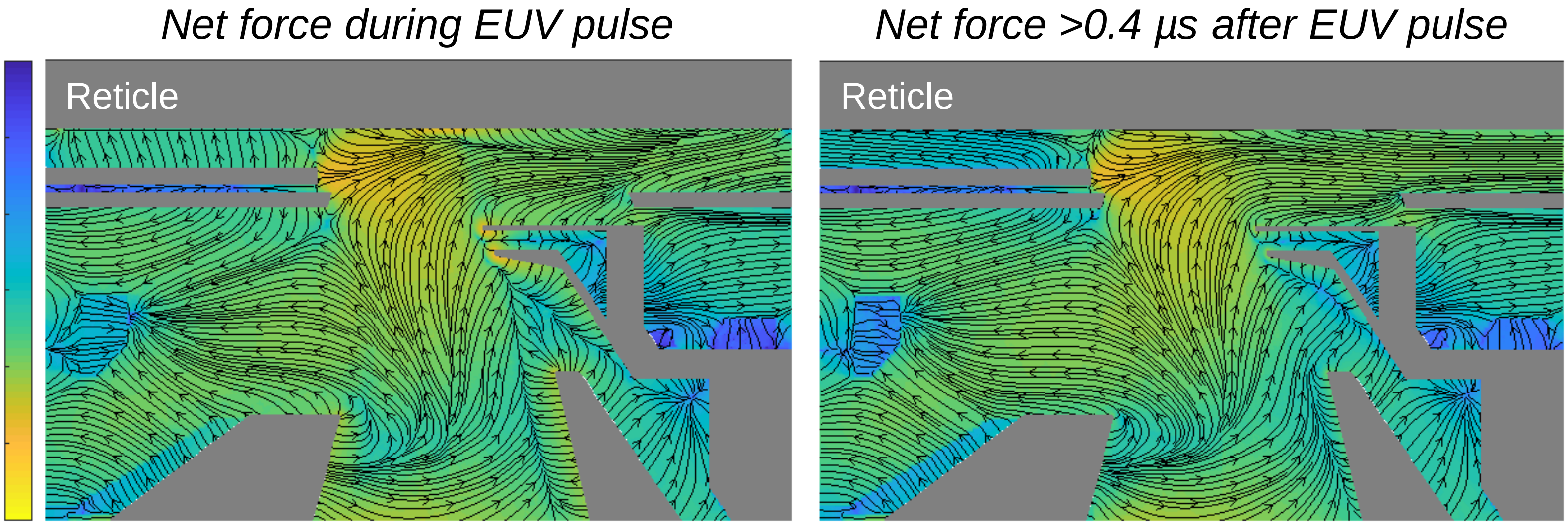
- Coulomb force
- Ion drag force
- Neutral drag force

# Plasma E-fields around reticle create Coulomb forces



Strong cross-flow is designed to minimize residence time of particles to prevent strong charging → minimal transport to reticle frontside

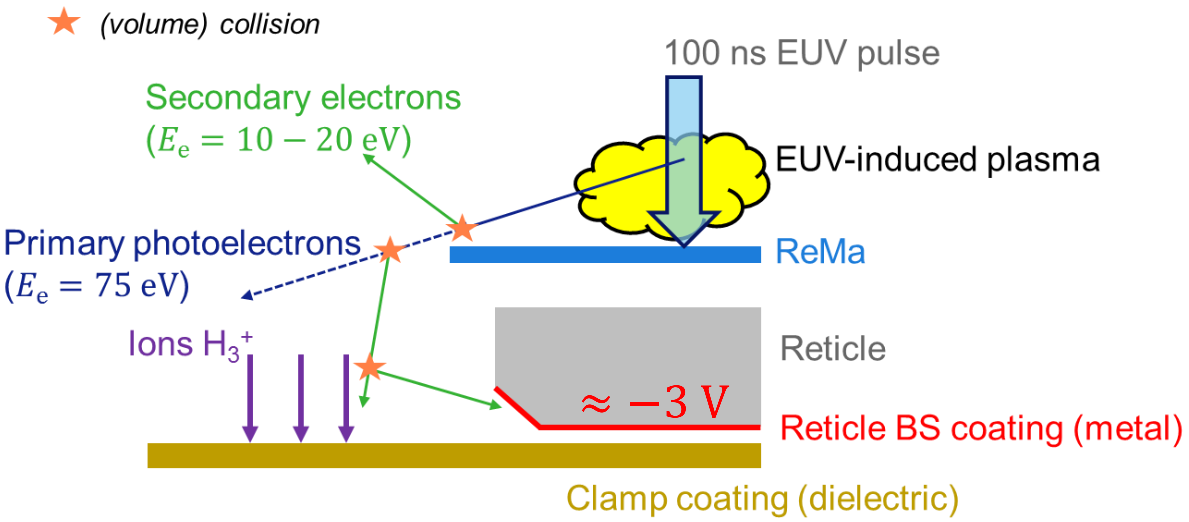
Coulomb and neutral drag force dominant forces for negatively charged particles (100-1000 nm) in RME:



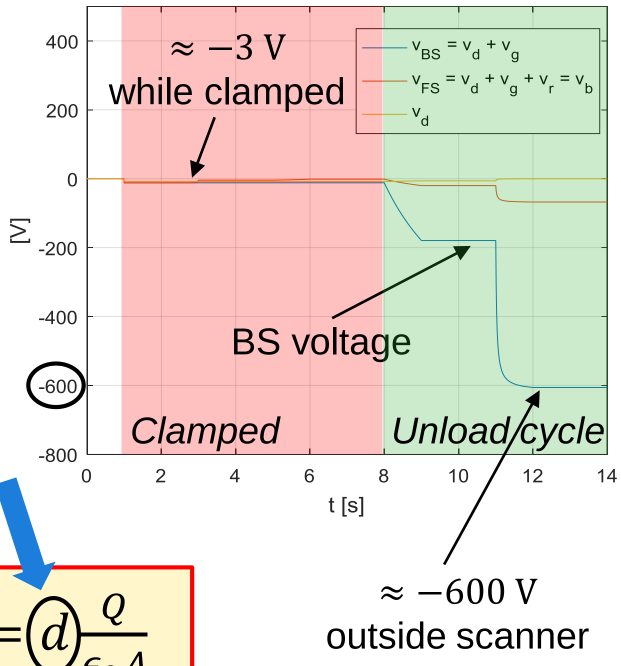
# Charging of reticle backside by fast electrons

## Electrons can reach reticle BS after multiple collisions, while ions are accelerated towards clamp "ears"






Reticle BS & FS voltage during unload




While clamped: couple of volts
➔ blows up during reticle unload

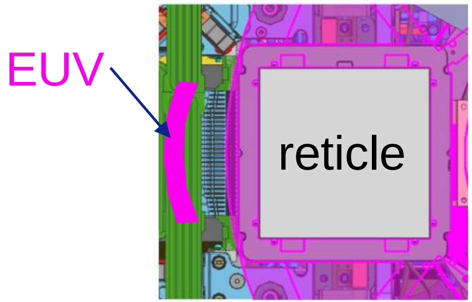
$$V \sim \frac{Q}{C} \sim \frac{Q}{\epsilon_0 A/d} = d\,\frac{Q}{\epsilon_0 A}$$

# Solution: EUV ON during unload

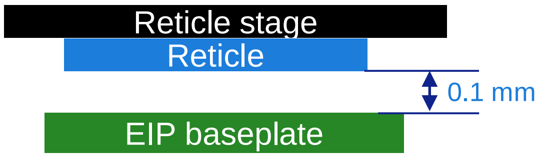
## Reticle leaves scanner uncharged with EUV ON during unload



EUV ON during reticle unload has proven that the EUV-induced plasma can neutralize the reticle backside by supplying charges (ions) to it, effectively working as electrical grounding.




*EUV ON during MUC*

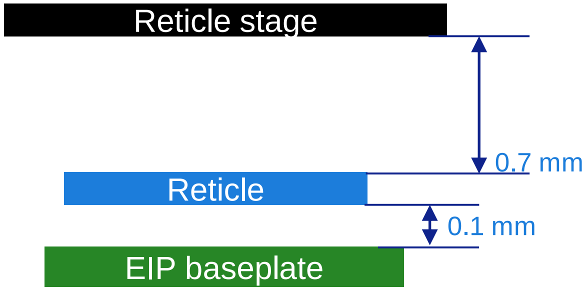



**Outside scanner:**

BS: -650 V

FS: -60 V

*EUV ON during unload*




**Outside scanner:**

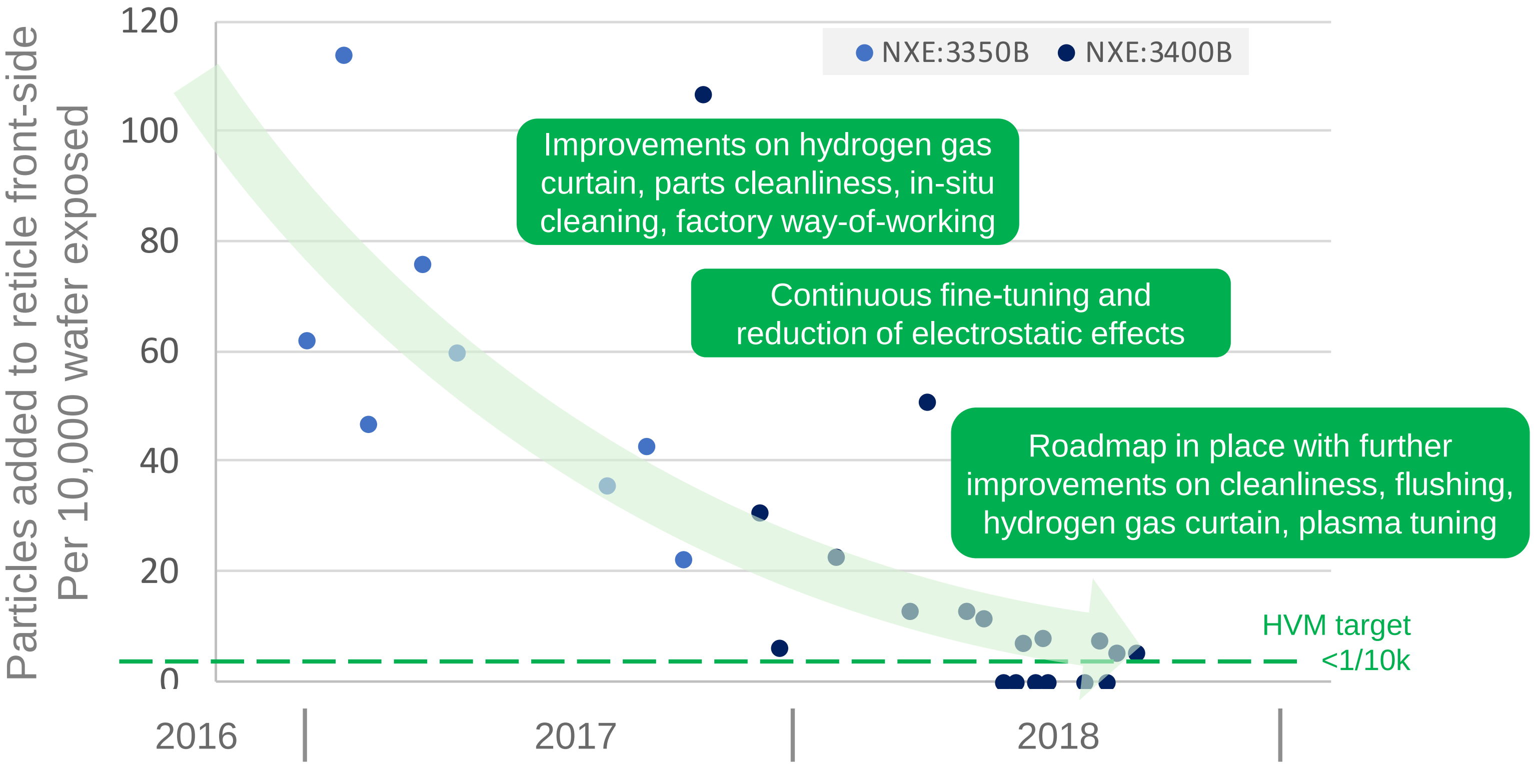
BS: -35 V

FS: -5 V

# Conclusions

# Reticle front-side defectivity performance approaching <1/10k wafers HVM target



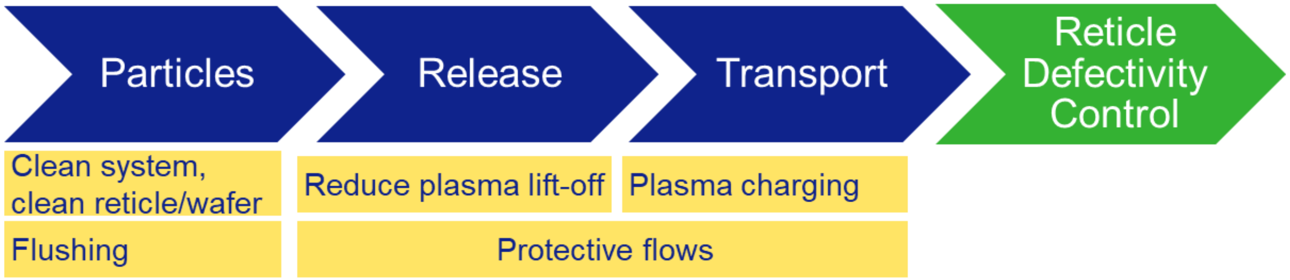



Each data point represents between 1,000 and 10,000 wafer exposures in ASML factory or at a customer

# Summary



- Reticle frontside most critical as yield impact is largest
  ultimate requirement: ~1 particle (>32nm) per month
- We are continuously and aggressively improving defectivity performance through breaking the defect generation chain
  - Improved cleanliness of system
  - Improved flushing
  - Protective (cross-)flows
  - Tune the EUV-induced plasma (gas pressure, gas composition, dynamics)



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