Investigation of Reticle Defect Formation at DUV Lithography

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Outline

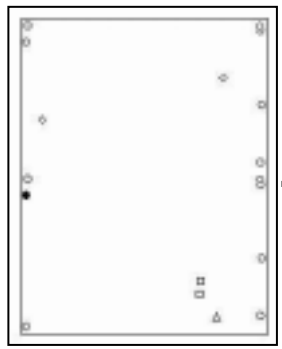
- Introduction
- Background
- Experiment and Results
- Defect Composition Analysis
- Defect Formation Mechanism
- Conclusions

Introduction

- DUV lithography has introduced new defect challenges for photomasks at low k_1 processes.
  - Common industry issue
  - Returns based on soft defects are the second largest category (K. Kimmel reported, BACUS 9/30)
- A reticle used in a 300-mm wafer fab receives about double the scanner exposure compared to reticles at a 200-mm fab.
- Some new reticles meeting IQC specification can degrade over the course of only few hundred wafer exposures in the fab.

Background

- For **I-line scanner exposure**, an interesting defect cluster was found during routine mask QC.

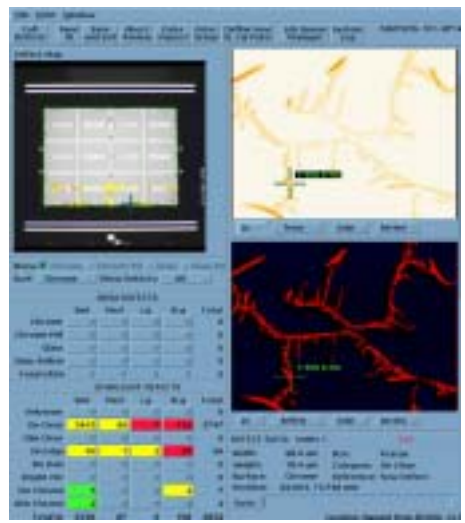


After one month of production exposure at I-line scanner

Incoming Reticle Inspection (total defect = 18)

Routine Re-Inspection after one month (total defect > 5000)

- We have seen a similar **DUV 248-nm scanner exposure** growth problem was found and was traced back to the ammonia out-gassing from the pellicle frame adhesive.
  - Published on Solid State Technology, June 2000



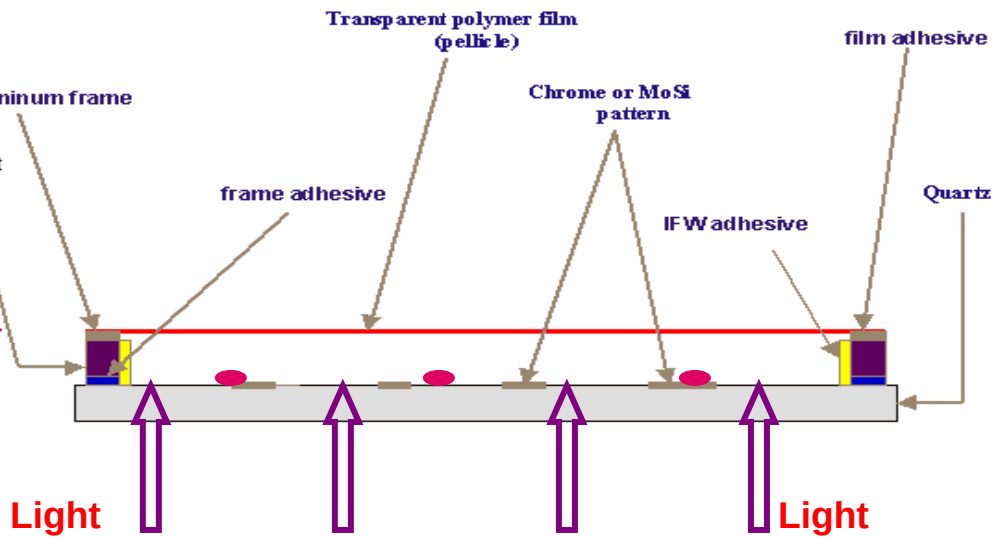
Defect Growth at DUV 248-nm scanner exposure

Background (contd.)

Reticle container

Stepper Environment

Storage



Components of a photomask

- A pellicle protects the pattern surface of the mask from outside contaminants
- With the advent of low k_1 and shorter wavelength lithography, the materials and environment trapped between the pellicle film and the mask surface can create a highly reactive environment. This environment can trigger photo-chemical reaction providing the opportunity for formation of "killer" (printable) defects on the mask.

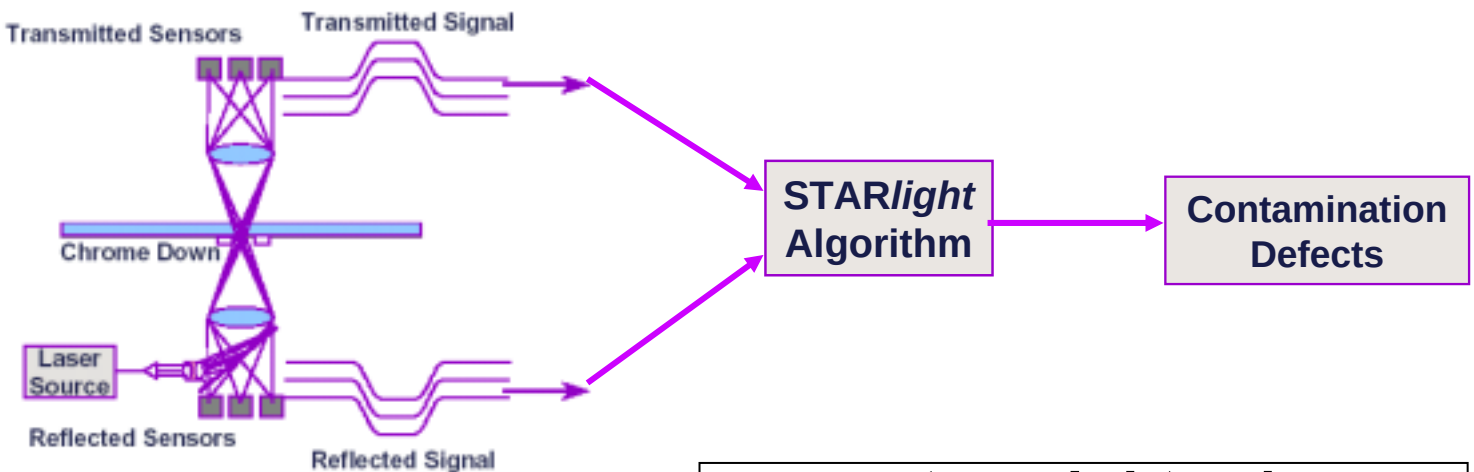
Defect Formation Mechanism

- Possible Sources

- Reticles from many leading IC manufactures have shown many sources of defect residue formation. (Source: Grenon Consulting):
  - Wafer Fab Environment
    - Stepper storage
    - Reticle container(s) out-gassing
      - **Longevity of 193-nm/ArF excimer pellicle (influences of organic vapors),** T. Kozeki, S. Shigematsu, H. Nakagawa, Mitsui Chemicals, Inc. (Japan) : PMJ Apr., 2000
  - Pellicle manufacturing residue
  - Mask materials and processes

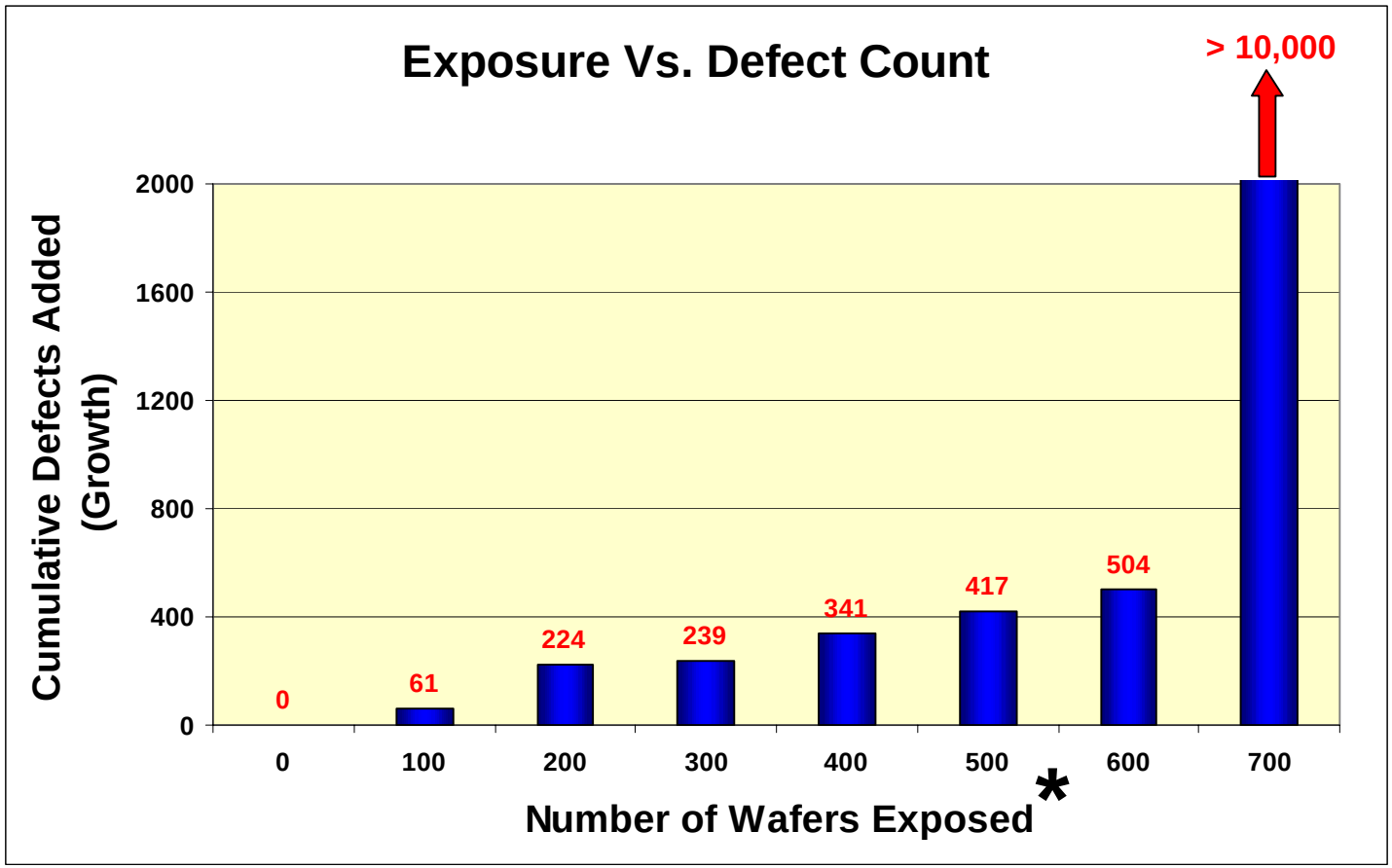
Experiment

- Attenuated phase shift mask
- Exposed on a 193-nm scanner using 200mm wafers
- A reticle defect inspection using a TeraStar (STARlight) tool after every hundredth wafers exposure
- KLA-Tencor's TeraStar (STARlight) inspection system used in this study utilizes simultaneous transmitted and reflected UV illumination and a special contamination detection algorithm



TeraStar (STARlight) architecture

Results - Modeled Exposure versus Defect Count

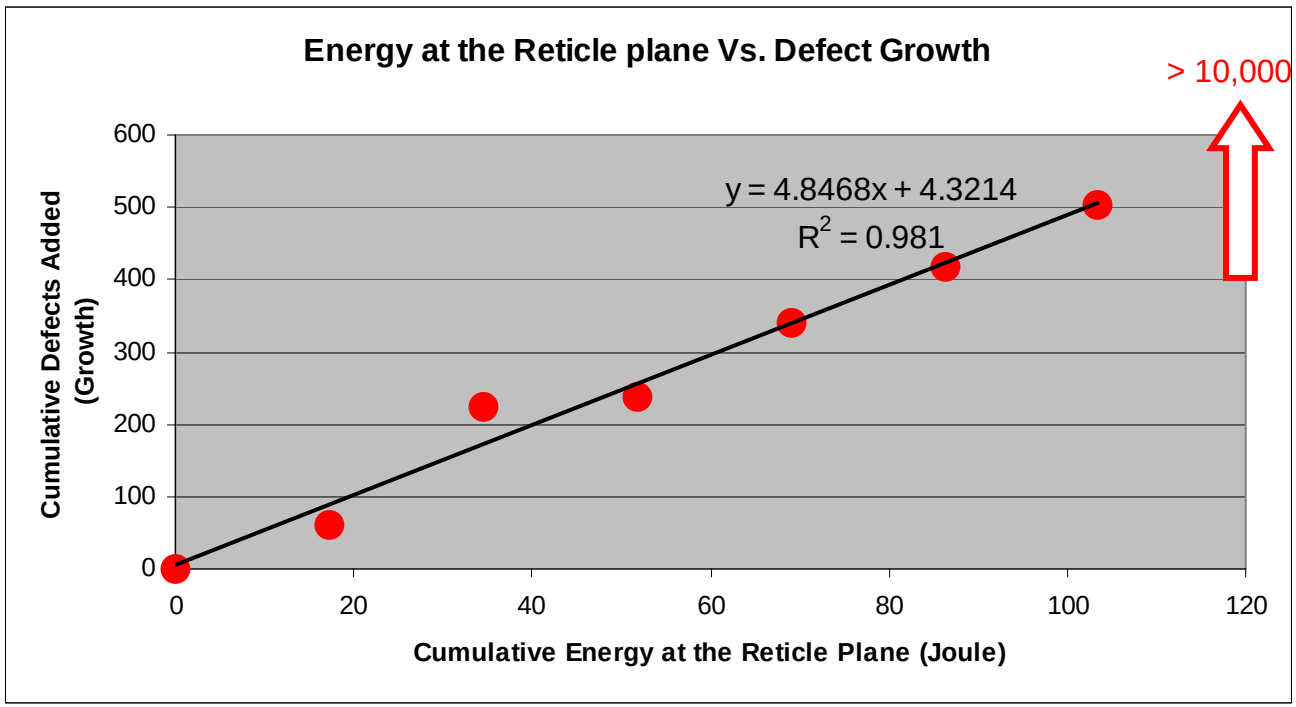


* Equivalent number at nominal dose; e.g., 100 wafers in the chart mean that actually 20 wafers were exposed @ five-times nominal dose

Results - Energy at Reticle Plane versus Defect Growth

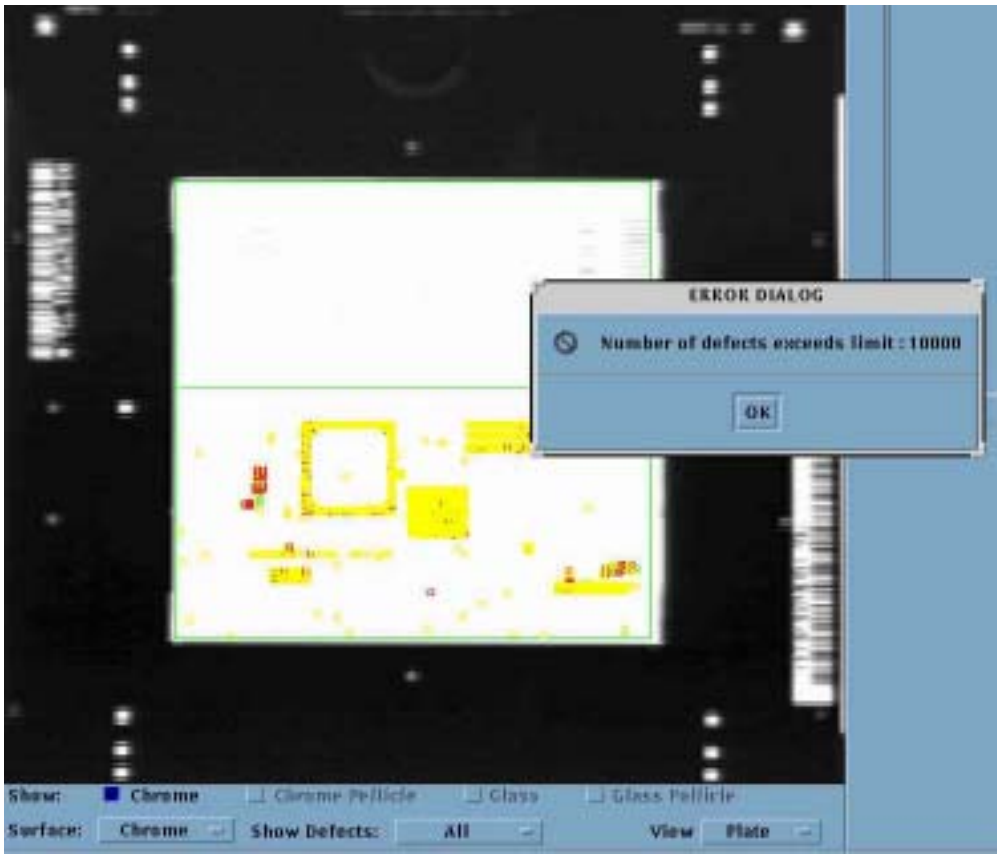
$$Pellicle\_dose = \frac{Wafer\_dose \cdot Fields/wafer}{Mag^2 \cdot Lens\_transmission} \cdot number\_of\_wafers$$

(Where, Wafer Dose = 20 mJ; Fields/Wafer = 69; Mag = 4; Lens_transmission = 0.5)



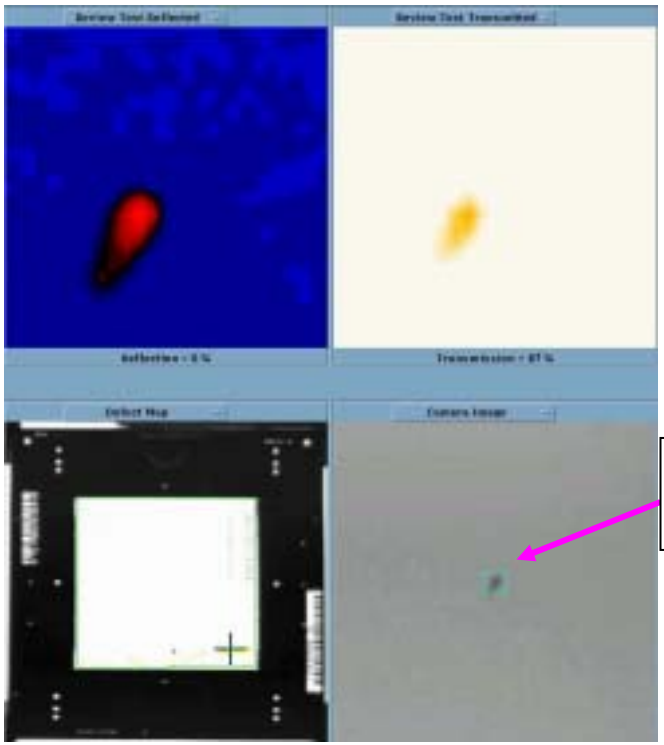
Results - Defect map

- The following pictures show the defects captured by the STARlight tool. The reticle inspection after the 700th exposed wafer showed a drastic increase of defects on the reticle.



Results - Defect images

- Most of the defects are located in the clear area or at clear / attenuator interface. The majority of all the defects consist of two distinct kinds: one that looks like a large contamination and the other resembles a comet with a long narrow tail and a prominent nucleus.



1 micron box

A defect (0.5 x 1micron) showing 13% transmission loss

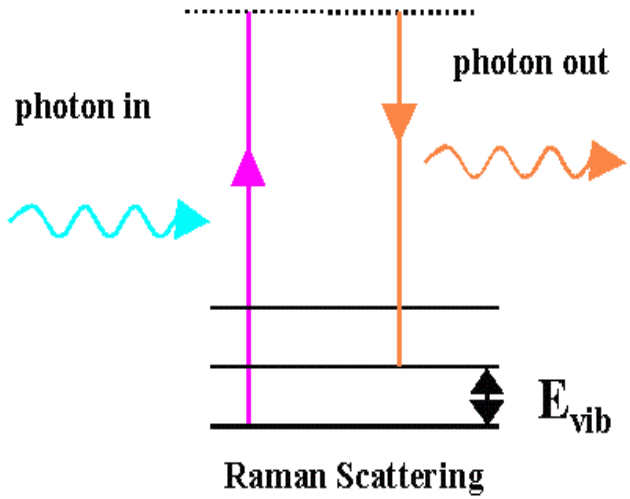
A very narrow comet defect with 5% transmission loss

Defect Composition Analysis Method

- Raman Spectroscopy

- Raman spectroscopy is a light scattering technique often referred to as the sister of complementary technique to infrared spectroscopy.

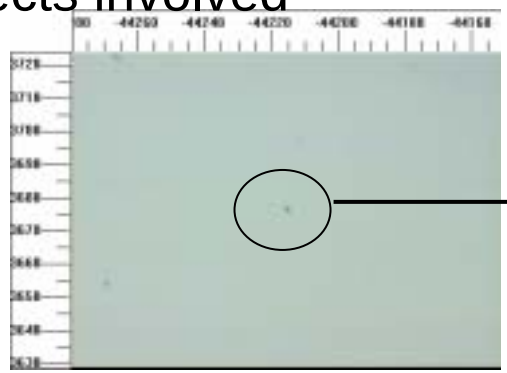
- The Raman spectra were collected using a Renishaw Model 2000 Raman spectrometer equipped with a 633-nm laser. All measurements were made without removing the pellicle. The beam size was approximately 1 micron in diameter.



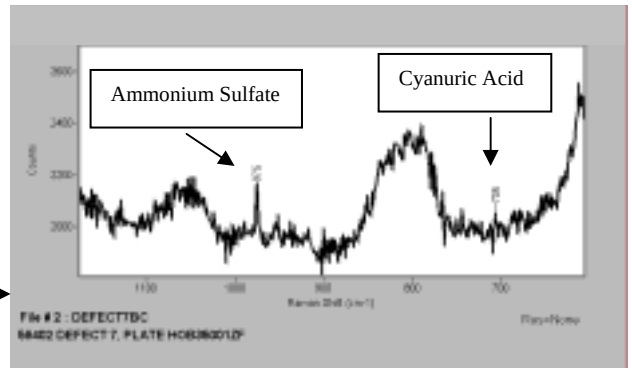
Defect Composition Analysis Result

- Raman spectroscopy on these mask defects shows that there are three different kinds of defects involved –

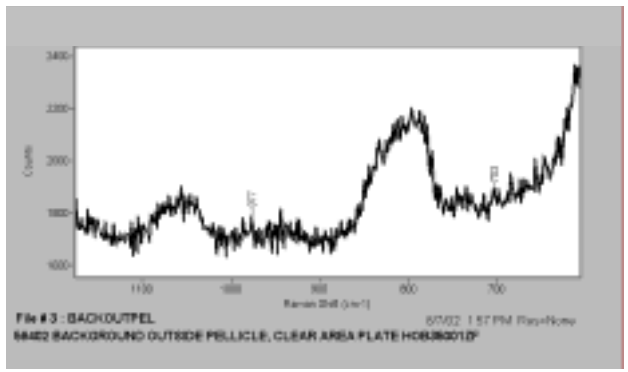
- **Ammonium sulfate** (Raman peak at 975 cm^{-1})
- **Cyanuric acid** (Raman peak at 703 cm^{-1} or 705 cm^{-1})
- Some **unknown** compound(s) (with two peaks at 1064 cm^{-1} and 790 cm^{-1}).



A defect used to collect Raman Spectra



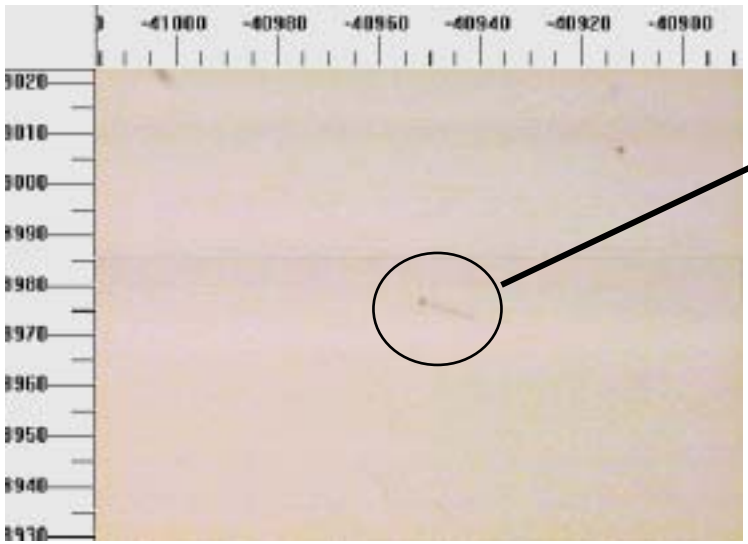
Raman Spectra on the defect



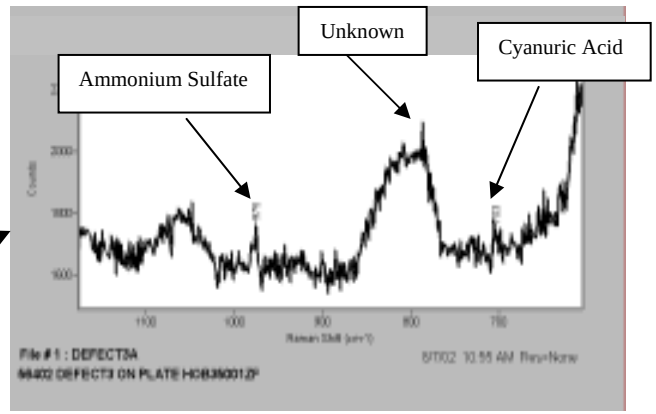
Background Spectra

Defect Composition Analysis Result

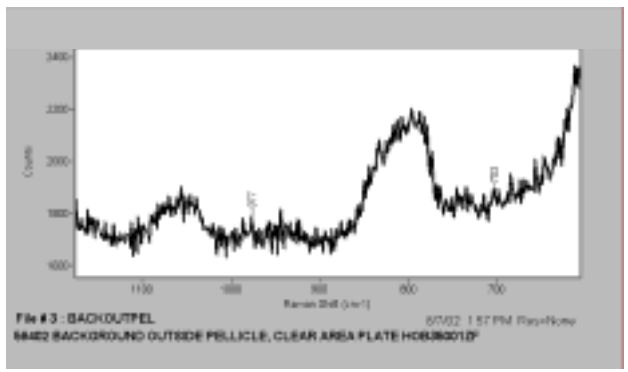
- Raman spectroscopy result on the comet type defect also showed the presence of ammonium sulfate and cyanuric acid. An unknown peak was also observed at 790 cm^{-1}.



The comet type defect used to collect Raman Spectra



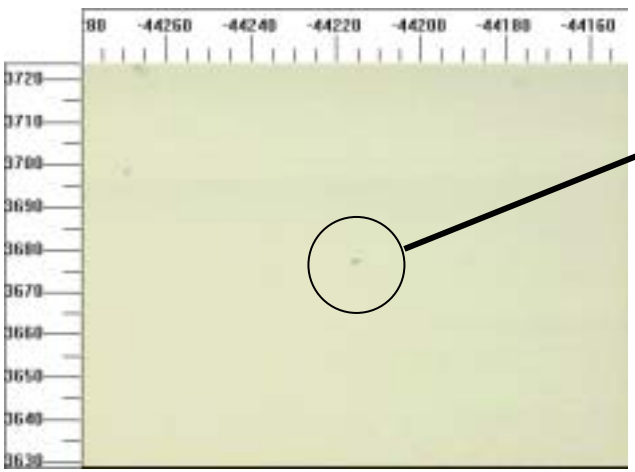
Raman Spectra on the nucleus of this comet type defect



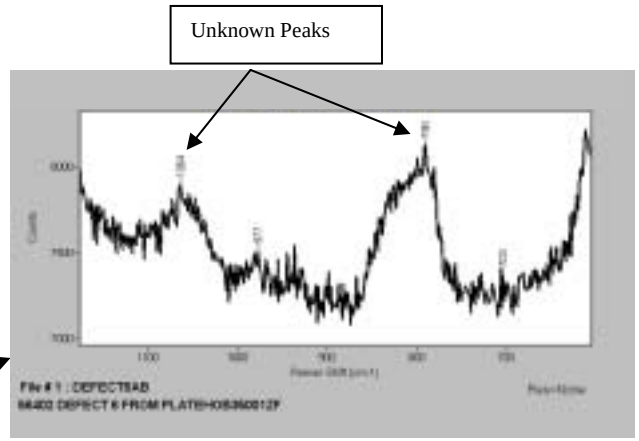
Background Spectra

Defect Composition Analysis Result

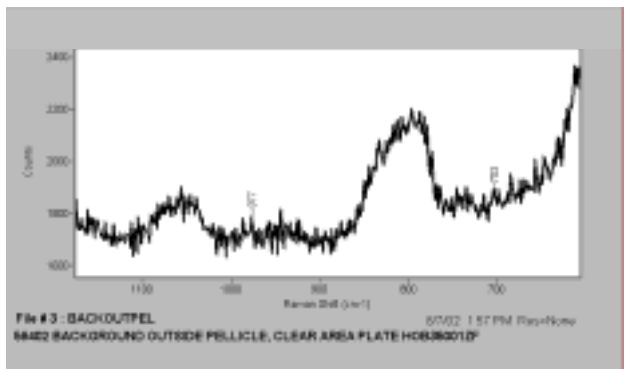
- Raman spectroscopy result on an another defect showed two unknown peaks at 1064 cm^{-1} and 790 cm^{-1}. These could be from some organic compound and an investigation is ongoing.



Another defect used to collect Raman Spectra



Unknown Raman Spectra found on this defect at 1064 cm^{-1} and 790 cm^{-1}

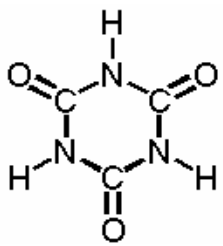


Background Spectra

Defect Composition Analysis Result

- result summary

- As found from the defect composition analysis, the majority of the defects are:
  - Ammonium sulfate [$(NH_4)_2SO_4$]
  - Cyanuric acid [$C_3O_3N_3H_3$]

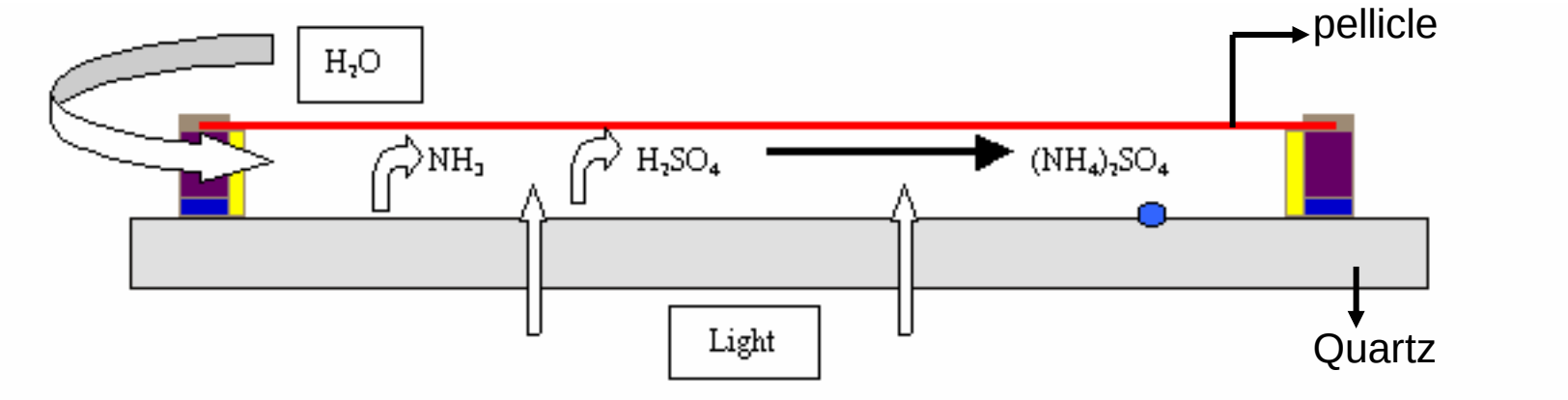


Defect Formation Mechanism

- Ammonium sulfate formation

- Residual ammonium ions left on the mask surface from rinse reacts with the residual sulfuric acid or sulfate ions from strip process in a high energy environment is a possible explanation for ammonium sulfate [$(NH_4)_2SO_4$] formation indicated below:

$$H_2O + H_2SO_4 + 2NH_4OH \longrightarrow (NH_4)_2SO_4 + H_2O$$



Defect Formation Mechanism

- Cyanuric acid formation (scenario 1 of 2)

- **<u>Cyanuric acid formation scenario# 1</u>: ammonia or ammonium ions, carbon dioxide, water:** A possible source for ammonia could be the residual ammonium ions remaining on the mask surface after the rinse.

Here is a direct mechanism for Cyanuric Acid formation:

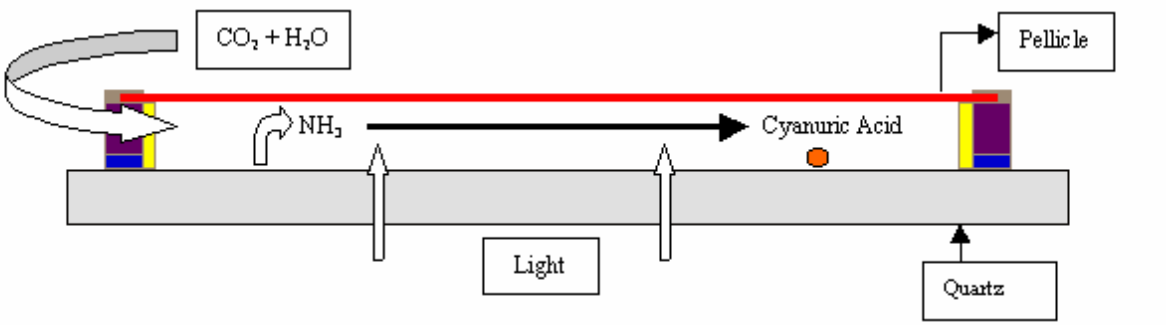
$3\ NH_3 + 3\ CO_2 \xrightarrow{\text{High energy}} C_3O_3N_3H_3\ (\text{Cyanuric Acid}) + H_2O$

And a possible secondary mechanism:

$2\ NH_3 + 3\ CO_2 \xrightarrow{\text{High energy}} CH_4N_2O\ (\text{urea}) + H_2O$

$CH_4N_2O\ (\text{Urea}) + NH_3 + CO_2 \longrightarrow C_2H_5N_3O_2\ (\text{biuret}) + H_2O$

$C_2H_5N_3O_2\ (\text{biuret}) + H_2CO_3 \longrightarrow C_3O_3N_3H_3\ (\text{Cyanuric Acid}) + H_2O$

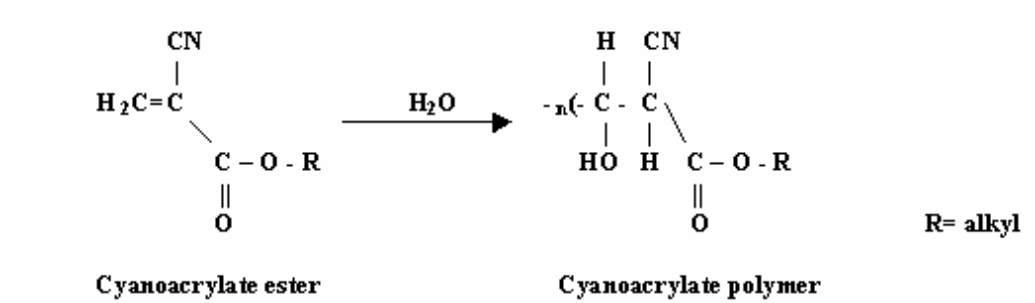


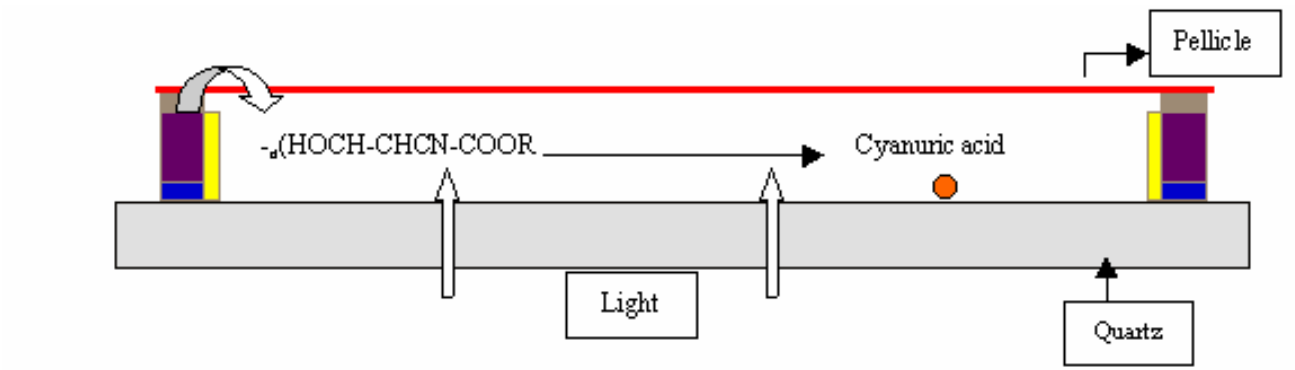
Defect Formation Mechanism

- Cyanuric acid formation (scenario 2 of 2)

- **Cyanuric acid formation scenario# 2: possible photo-degradation of cyanoacrylate pellicle film adhesive:**

  While it may not be clearly obvious that the degradation of these compounds could result in the formation of cyanuric acid, it should be noted that their degradation could result in the elimination of a labile nitrile group. Cyanoacrylate adhesives are monomeric cyanoacrylates that polymerize spontaneously in the presence of moist air.



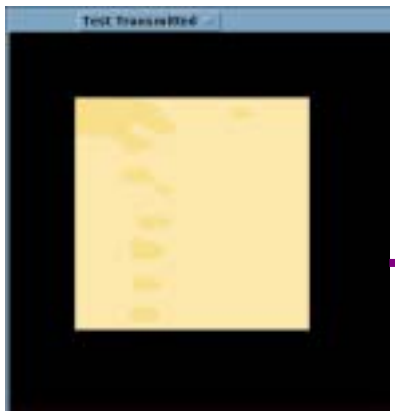


Factors involved in Defect Growth

- This defect growth can be accelerated of the following factors:
  - Fab / stepper environment
  - Mask cleaning process residuals
  - Cumulative energy through the mask
  - Wavelength of exposure
  - Mask level pattern density (clear field/dark field)
  - Time

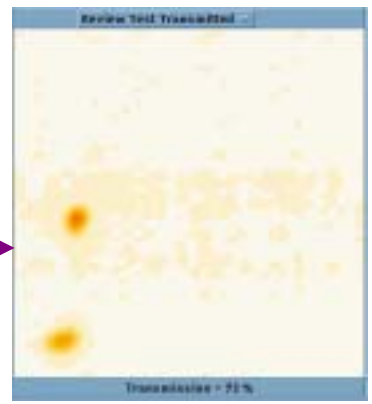
Defect Formation is a Dynamic Process

- a chrome on glass mask showing similar progressive defect growth with repetitive 193-nm scanner exposure



More prominent defects are forming with the increase in reticle exposures

Exposed on 193-nm scanner



Reticle defect image after modeled 160 wafers were exposed

(300-mm wafers)

Defect image after modeled 236 wafers were exposed

(300-mm wafers)

Conclusions

- Crystal defect mechanism sources are under investigation, possibilities are:
  - mask making materials and process residues
  - reticle containers, fab or stepper environment.

- IC industry still at the early phase of learning curve for 193nm lithography.
  - 193nm stepper processes are untested territory for mask behavior
  - Cumulative effects of prolonged exposures with 300mm wafers at this wavelength.

- The preceding experiments at 193-nm scanner illumination can create a highly reactive environment under the pellicle, which trigger photochemical reaction, forming critical defects on the mask.

- Ideal reticle quality control goal should be to detect the defect growth as the defects are just starting to form and are not yield limiting.
  - it is recommended that a carefully developed reticle inspection strategy is implemented to minimizing mean-time to detect (MTTD) any defect growth resulting from prolonged reticle use.