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# Resist Improvements needed for EUVL Extension

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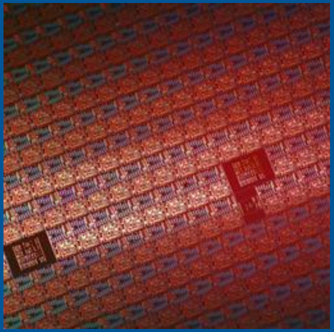

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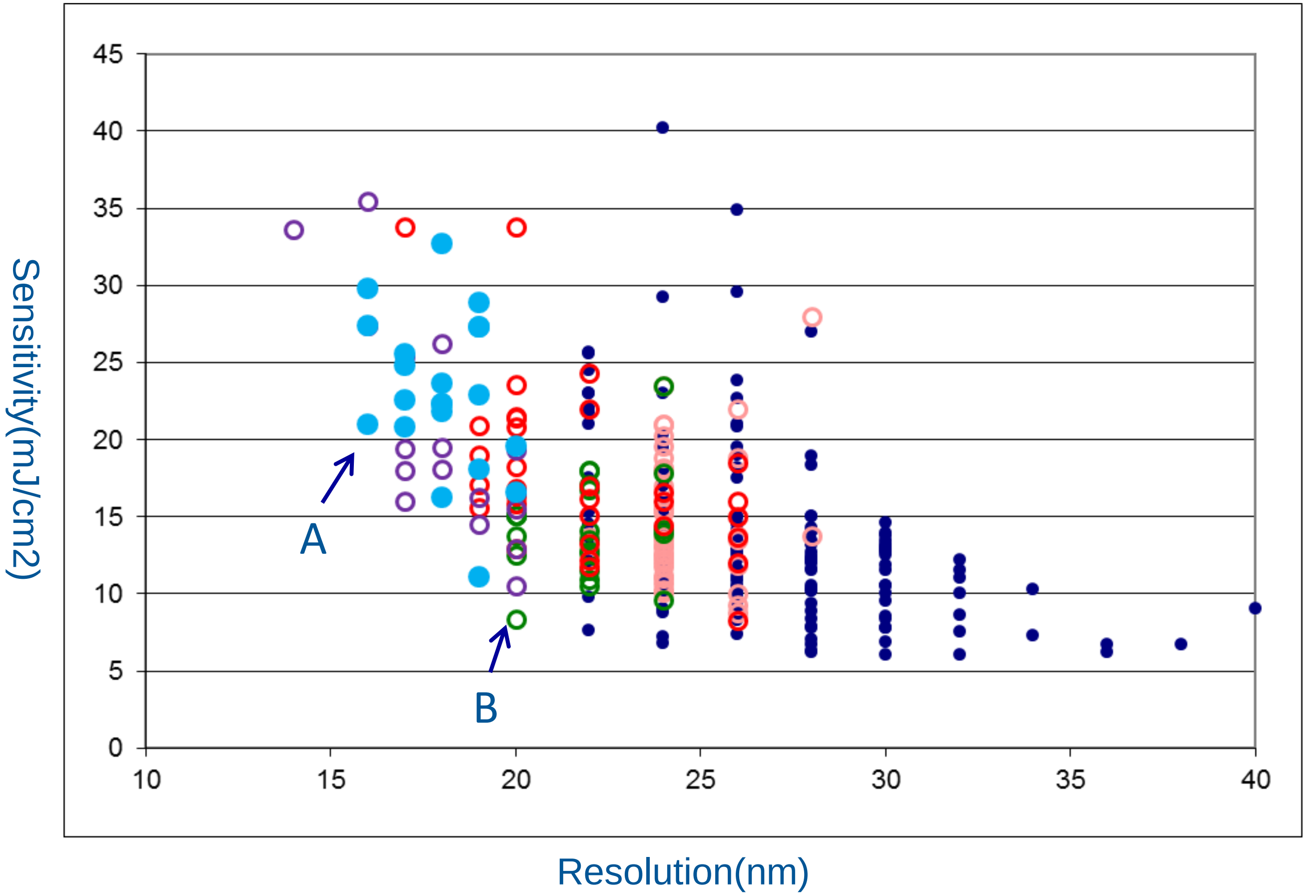
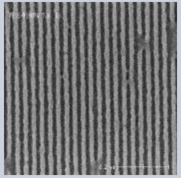
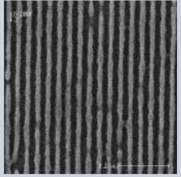
# Outline

- Current Status of Resist
  - Line and Space
  - Contact Holes
- Fundamental physical factors and approaches to improve resist
- Key Questions
- Summary

# EUV Resist Performance Status

## *Sensitivity vs. Resolution*

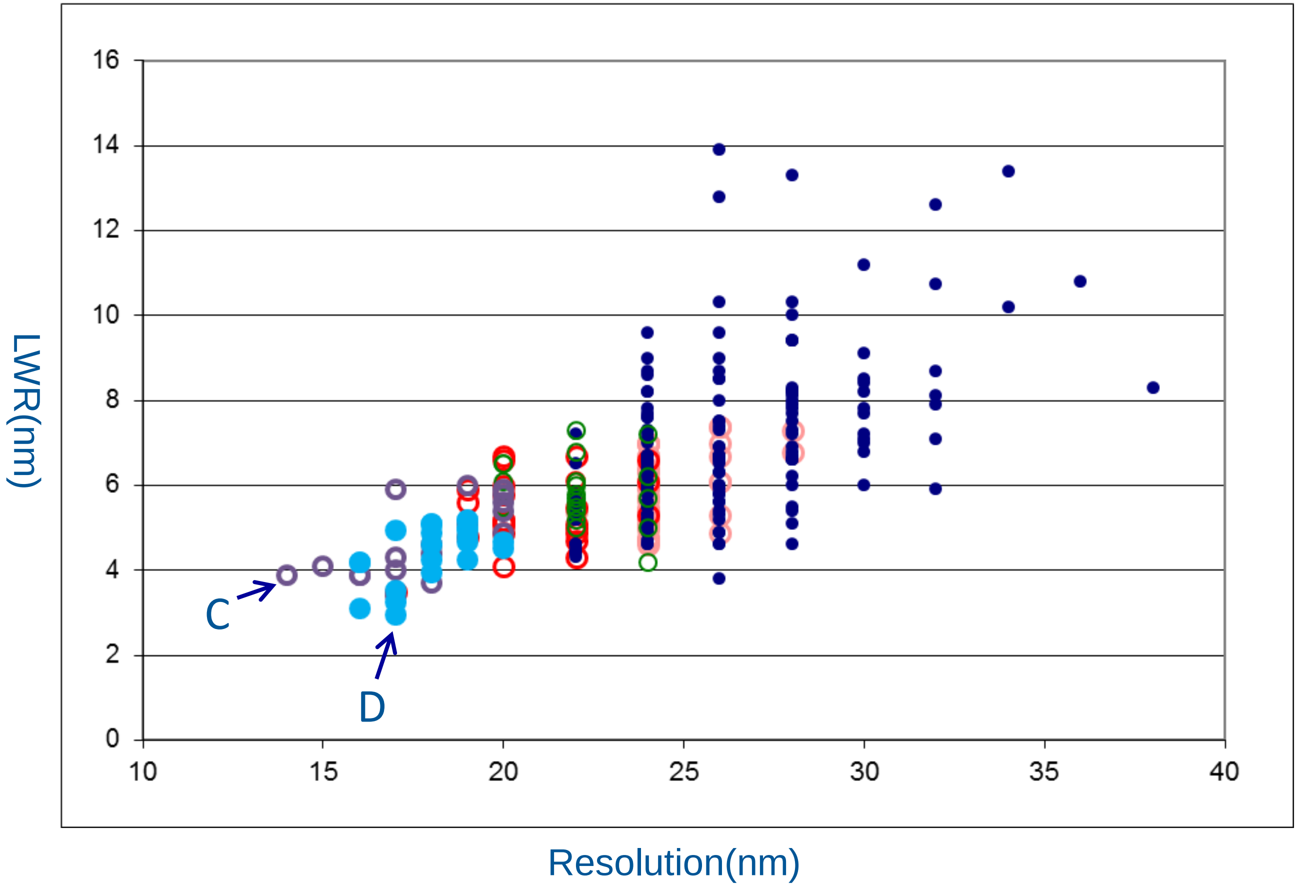


| | A | B |
|---|---|---|
| Image |  |  |
| Size | 16nm HP | 20nm HP |
| LWR | 3.7nm | 5.6nm |
| Speed | 21.0mJ/cm2 | 8.8mJc/m2 |

- Resolution down to 15 nm has been demonstrated by using optimized illumination conditions
- Better resolution has a cost in photospeed

# EUV Resist Performance Status

## *LWR vs. Resolution*



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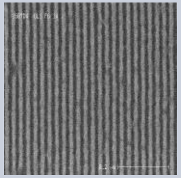
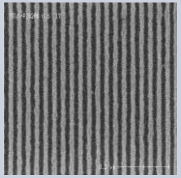
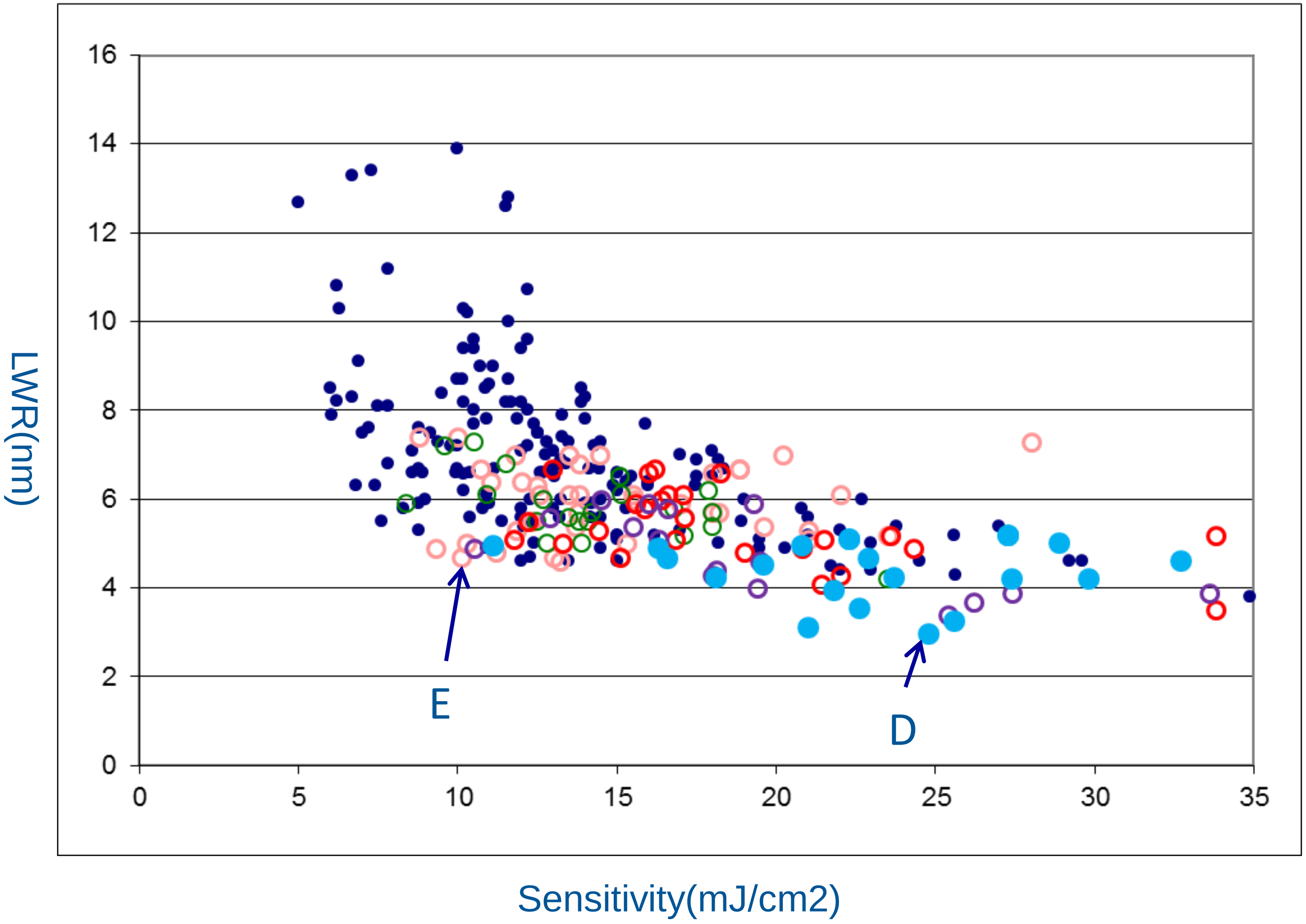
| Image |  |  |
| Size | 14nm HP | 17nm HP |
| LWR | 3.8nm | 2.9nm |
| Speed | 33.6mJ/cm2 | 26.5mJc/m2 |

- There has been some improvement in best LWR recently.  Best LWR is between 3nm and 4nm

# EUV Resist Performance Status

## *LWR vs. Sensitivity*



| | E | D |
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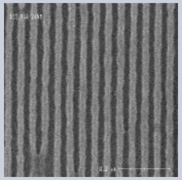
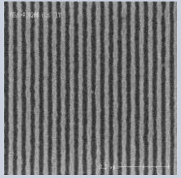
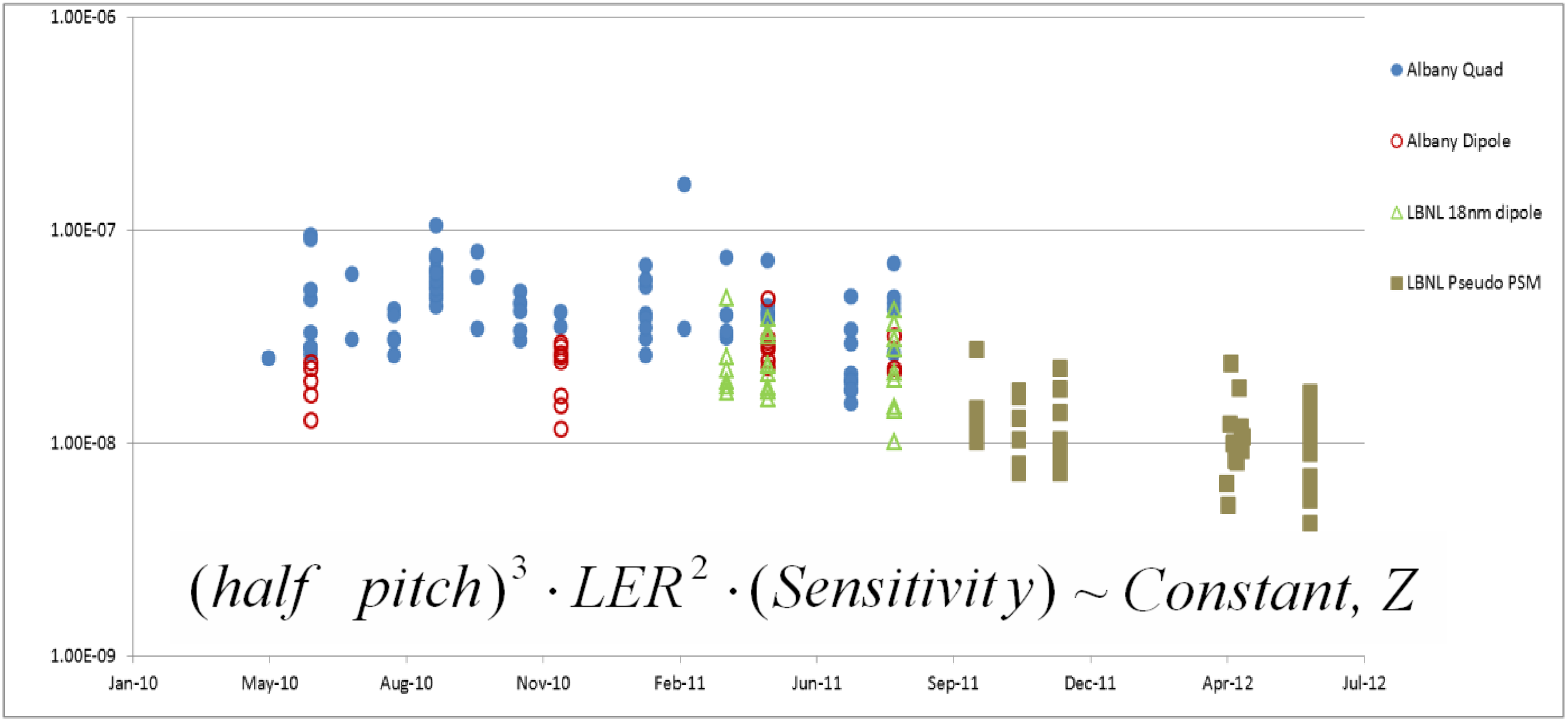
| Image |  |  |
| Size | 24nm HP | 17nm HP |
| LWR | 4.7nm | 2.9nm |
| Speed | 10.1mJ/cm2 | 26.5mJc/m2 |

- LER photospeed trade off may have improved a little
- Recent high performing resists need 20mJ/cm$^2$ or more in dose for lines and spaces

# Z Value of EUV resists over time

## (for lines and spaces)



$$(half\ \ pitch)^3 \cdot LER^2 \cdot (Sensitivity) \sim Constant,\ Z$$

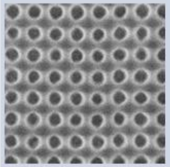
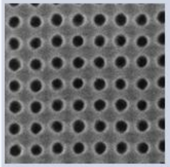
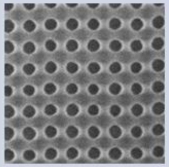
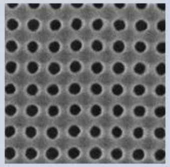
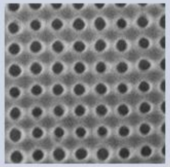
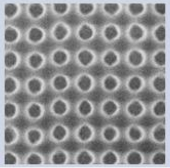
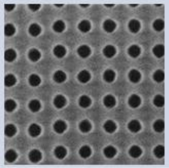
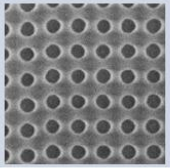
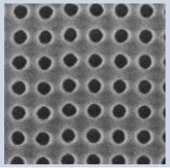
- Data represents materials from six suppliers
- Mostly improvement in Z value comes from improving the aerial image
- Some progress in Z value due to the resist improvements is evident
- Data here is not exactly comparable to ITRS roadmap values due to differences in half pitch and LER measurement details

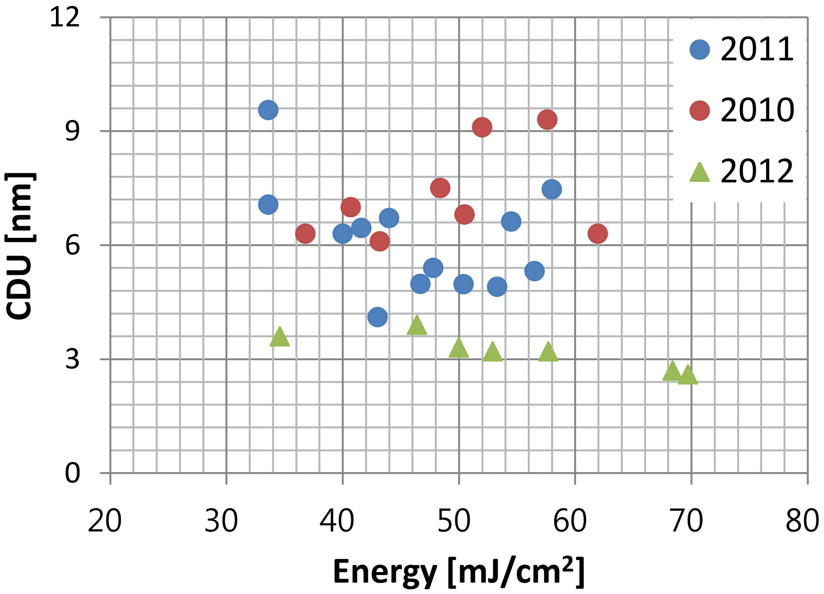
# ITRS Roadmap compared to Current LWR Results

| | 2009 Targets (per 2009 roadmap) | 2011 Targets (per 2011 roadmap) | 2012 Targets (per 2011 roadmap) | 2012 Actual (smoothed EUV resist) | 2012 Actual (best as printed result) |
|---|---|---|---|---|---|
| ½ Pitch | | | | 32 | 18 |
| DRAM ½ pitch | 52 | 36 | 32 | | |
| Flash ½ pitch | 38 | 22 | 20 | | |
| MPU Gate in resist | 47 | 35 | 31 | | |
| 3σ low freq. LWR | 3.7nm | 2.8nm | 2.5nm | 4.66nm smoothed to 3.58nm in resist | 3.0 to 3.5nm with pseudo PSM illumination |

# Contact Hole Resist Status

SEMATECH 2012 data (annular illumination)

| | B3 | A4 | C3 | D2 | F3 |
|---|---|---|---|---|---|
| 30nm |  |  |  |  |  |
| | 52.9mJ<br>31.1nm<br>CDU 3.2nm | 68.4mJ<br>30.3nm<br>CDU 2.7nm | 46.4mJ<br>30.6nm<br>CDU 3.9nm | 69.7mJ<br>31.3nm<br>CDU 2.6nm | 46.5mJ<br>29.9nm<br>CDU 3.3nm |
| 35nm |  |  |  |  | |
| | 43.0mJ<br>35.6nm<br>CDU 3.4nm | 59.2mJ<br>34.1nm<br>CDU 2.1nm | 40.1mJ<br>37.0nm<br>CDU 2.8nm | 60.6mJ<br>35.5nm<br>CDU 2.0nm | |



- CDU is improving with some resists showing sub 3 nm CDU
- Contact hole resists remain much slower than L/S resists
- CER data can be measured but there is not much data yet

# EUV Resist Status Summary

- Resists are showing gradual improvement in LWR
- Photospeed is still an issue
  - Resists with improved LWR are all above 20mJ/cm$^2$
  - Contact hole resist are all 35mJ/cm$^2$ or higher in dose to size
- Resolution is making progress as improved exposure conditions become available

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# Lithographic Improvements needed

- Improvements that probably can be met with evolutionary resist improvement
  - Resolution
  - Line collapse
  - Pattern transfer with thinner films

- Improvement are already evident in literature and in SEMATECH testing

# Lithographic Improvements needed

- Improvements that probably require a design breakthrough
  - Photospeed
    - Ability to get much faster photospeed would give more flexibility to address other issues
    - Increased photoresist absorbance would give potential for faster photospeed
  - LWR
    - New resist mechanisms that are not chemically amplified but have good photospeed have potential to help
    - Higher absorbance has been hypothesized to help but not shown to in practice
    - Shot noise gets worse with smaller features and wavelengths, but in not the only factor and may not be the major one contributing to LWR
    - Post processing has proven effective for significant LWR improvement

# Appropriate Absorbance for Maximum Photospeed Depends on Film Thickness

| Film Thickness | A+B |
|---|---|
| 20.00nm | 41.7 |
| 30.00nm | 27.8 |
| 50.00nm | 16.7 |
| 100.00nm | 8.3 |
| 200.00nm | 4.2 |
| 500.00nm | 1.7 |

- Numbers are absorption for maximum absorption of light at the bottom of the film. A+B is the total absorbance per micron
- Typical actual absorbances for resist are somewhat less than this; e.g. Prolith sample resist models are A+B of 1.5 for 120nm FT of ArF resist and 6.5 for 70nm EUV resist.
- See similar numbers reported in R. Gronheid et al., Proc. SPIE, 7273 (2009). The paper recommends A+B such that 20 to 25% of the light is absorbed in one pass of the film to maintain acceptable side wall slopes

# How different materials absorb at EUV

| Film Thickness | A+B | Material | A+B |
|---|---|---|---|
| 20.00nm | 41.7 | Poly Styrene | 2.8 |
| 30.00nm | 27.8 | PMMA | 5.2 |
| 50.00nm | 16.7 | PF PMMA | 17.7 |
| 100.00nm | 8.3 | Pure $HfO_2$ | 31.3 |
| 200.00nm | 4.2 | Pure $ZrO_2$ | 13.8 |
| 500.00nm | 1.7 | FEVS P1101 | 3.9 |

- FEVS P1101 was IMEC POR EUV resist in 2008. See Gronheid et al.
- HfO2 nanoparticle films for ArF use are 30 to 200nm with absorbance of 0.5 to 5. (M. Trikeritos et al., Proc. SPIE, **7639** (2010)

# Absorbance Improvements Needed

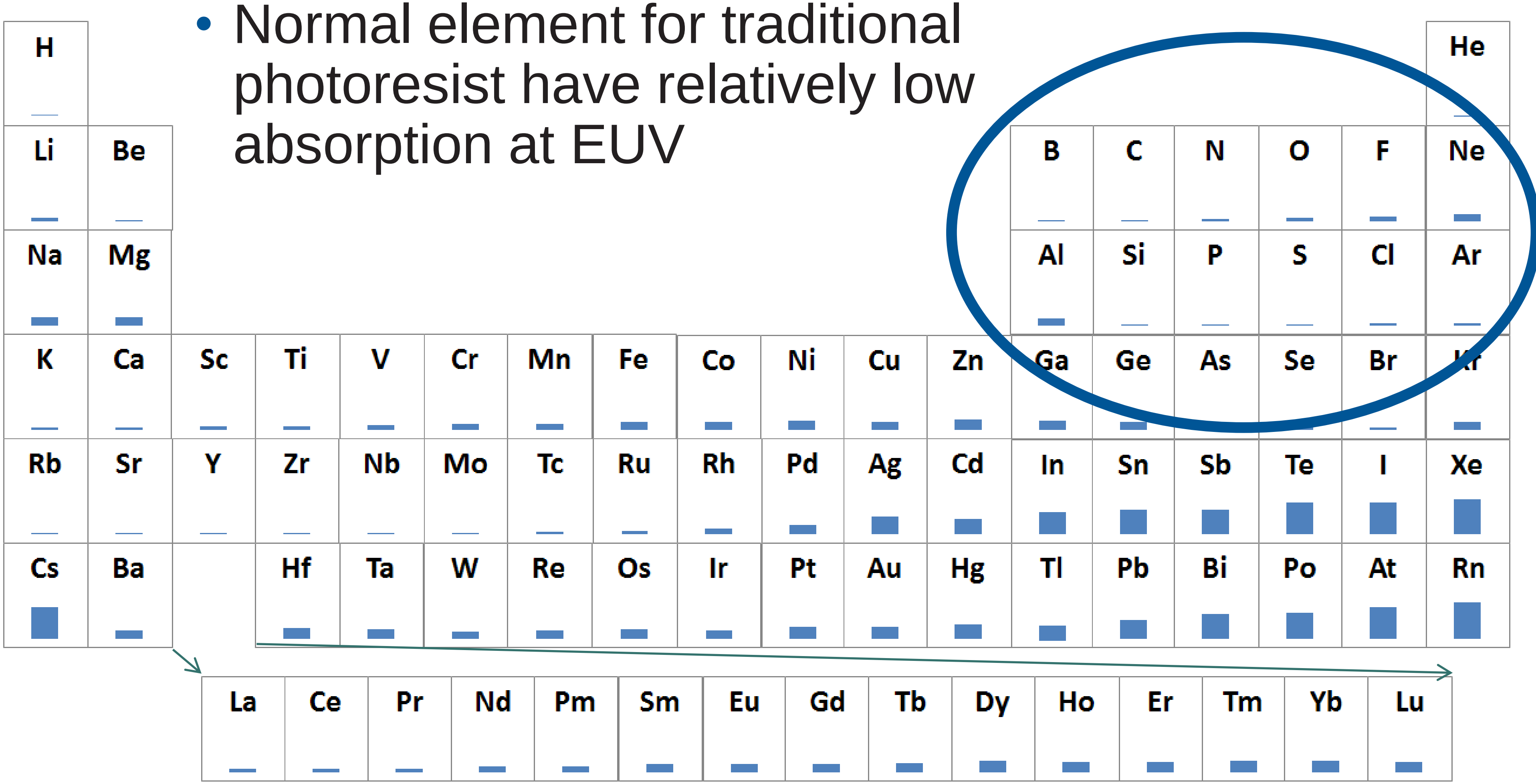
- Two fold or more absorbance for current thickness of resist

- Four fold absorbance increase for future resist thickness

- This should enable doubling of current chemical efficiency
  - Photon counts will reduce with feature size but not with film thickness

# Periodic Table of Absorption at 13.5nm

- Normal element for traditional photoresist have relatively low absorption at EUV



# Implications of EUV Absorbance

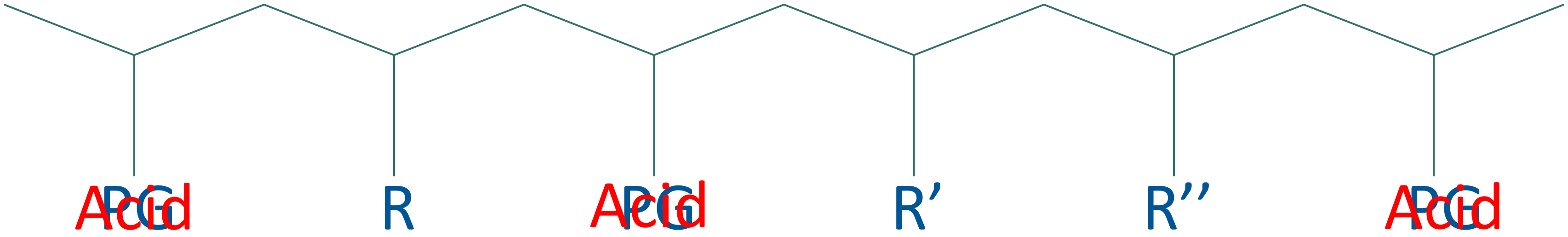
- Unusual elements should be considered for EUV photoresists
  - Periodic table shows clear capability for much higher EUV absorbance

- Need to find resist chemistries that use all the absorbed energy efficiently
  - Polymers that require one chemical event to change solubility completely
  - Many electrons generated from one photon should all be effective in generating catalytic agents for solubility switching chemical reactions.

- This will increase maximum possible photospeed
  - Possible 2X improvement in absorption of resist film
  - Then can reduce photospeed chemically in ways that improve LWR and other resist attributes

# Acid catalyzed solubility change

- Current chemically amplified resists need multiple deprotection reactions needed to completely change solubility



- Can we find systems that need one reaction to completely change polymer solubility? for example:

- A key question is will a novel chemical switching mechanisms for resists improve the photospeed, LWR, resolution tradeoff?

# Photon numbers by wavelength

|  |  |  |  | Photons/10mJ |  |  |
|---|---|---|---|---|---|---|
|  | Wavelength | Energy | Energy increase | Per 1µm squared | Per 100nm squared | Per 10nm squared |
| G Line | 435nm | 2.9eV |  | 215,172,410 | 2,151,720 | 21,520 |
| I Line | 365nm | 3.4eV | 1.2 | 183,529,410 | 1,835,290 | 18,350 |
| KrF | 248nm | 5.0eV | 1.5 | 12,480,000 | 1,248,000 | 12,480 |
| ArF | 193nm | 6.4eV | 1.3 | 97,500,000 | 975,000 | 9,750 |
| EUV | 13.5nm | 92eV | 14.4 | 6,782,610 | 67,830 | 680 |

- Key area for photon statistics defined as an “ambit” with lateral dimension of half the critical dimension in M. Preil, Proc. SPIE, 8325 (2012).
- Numbers in red roughly show order of magnitude of number of photons per an area similar to an “ambit” in size, assuming 10mJ/cm$^2$ photoresist

# EUV Photon Counting and CD Variation

- Noise will go up a photon count goes down
  - For 1000 photons the formula implies about 3% one sigma in noise
- In actual resists, random variations in the conversion of photons into chemical deprotection make stochastic variation larger.

Std. Dev. (no. of photons) = (no. of photons)$^{1/2}$

$$\sigma_{n_p} = \sqrt{\langle n_p \rangle}$$

# The cause of LWR

- LWR has been more and more of an issue as features sizes have gotten smaller and smaller
  - ArF resists have significant LWR issues
  - EUV resist continues the trend
- Shot noise is not the fundamental cause of LWR
  - G. Gallatin, Resist Blur and Line Edge Roughness, Invited Paper, *Proceedings of the SPIE*, **5754**, 38-52 (2005).

    "... it is clear [shot noise effects] are not the driver of LER. Rather it is the random spatial distribution of released acids consistent with image intensity that appears to be the fundamental driver of LER in chemically amplified resist."
- Shot noise makes LWR worse than without shot noise
  - Research on this needs to be done
  - Even EUV 30nm contact holes still have enough photons that CD variations should be manageable. These CD contact holes have 4,800 photons even at a dose of 10mJ/cm$^2$
  - Smaller features will show more LWR in chemically amplified systems, with or without shot noise effects
  - The key issue is at what size how much LWR will be contributed by shot noise

# Ways to address LWR

- Slower photospeed
  - Increase in source power over time should enable some improvement
- Different resist chemistries that aren't chemically amplified.
  - Challenge is to do this and maintain photospeed
  - Research is starting on some approaches to this.
- Increase usage of photons through higher light absorption or more efficient energy transfer and then add quencher to slow the resist back down for better LWR
  - This approach needs to be simulated and verified experimentally
- Post Processing of resist
  - Current published improvements are 25 to 30% (K. Petrillo et al., "*Line Width Roughness Control for EUV Patterning*", Proc. of SPIE., **Vol. 8322**
- Better averaging of LWR during etch should be achievable
- Overall improvements in LWR for a given dose could total to approximately 2X.

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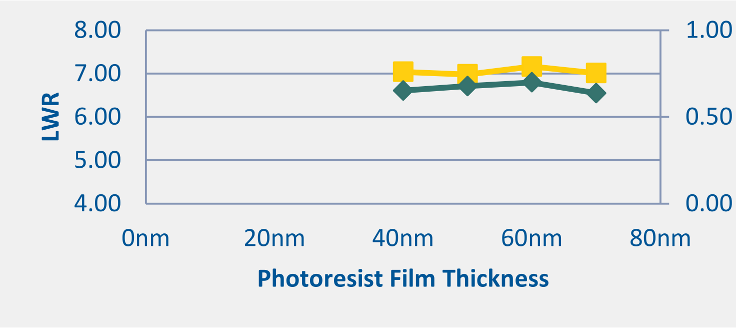
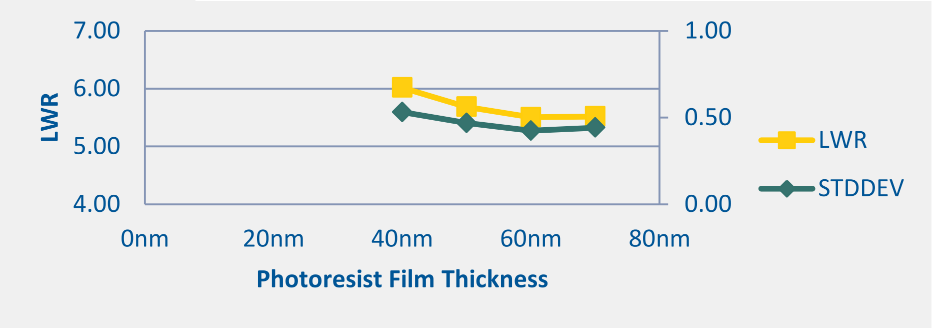
# How will LWR transfer from thin resist films during etch?

- Aspect ratio from line collapse is limited to 2 to 2.5
  - A CD of 10nm would be limited to roughly 20nm film thickness
- LWR is worse in thinner lines
  - Probably due to less vertical averaging
  - This averaging can transfer during etch, or not
- Etch process adjustment can make significant changes in LWR of etch features

# LWR versus Photoresist Film Thickness



No Averaging



With Vertical Averaging

- Results are from stochastic simulations of resist
- LWR at 20nm below the top of the film is large and independent of film thickness
- LWR measured with some vertical averaging is smaller and gets worse as film thickness gets thinner

# How much can post processing improve LWR and LER?

- Many different smoothing technologies exist
  - Techniques often are resist specific or need to be adjusted for different resists
  - There is room for invention
- Current best improvement demonstrated by TEL/SEMATECH is 25.7% (4.66nm to 3.58nm) before etch and 33.8% (4.66nm to 3.19nm) after etch
  - Developer process optimization
  - FIRM rinse
  - Smoothing module
- TEL expects further optimization is possible, particularly in etch and in the smoothing module
- Behavior with better resists and with metallic resists needs to be tested
- Need to test effectiveness as a function of resist thickness

# Can improvements in EUV absorbance be translated into better resists?

- Theory suggests higher absorbance should give formulators more flexibility
- Recent experimental results in the literature are mixed
  - Cardineau et al., *“LER Limitations of Resist Thin Films”*, J. Photopolymer Sci. & Techn., 2012 **(25)**, p.633 reported worse LWR with higher absorbance
  - Inpria shows good LWR but slow photospeed with hafnium based resists
- Both simulation and experimental work is needed

# Will novel chemical switching mechanisms for resists improve the photospeed, LWR, resolution tradeoff?

- Chemically amplified resists were developed to solve sensitivity issues with original KrF exposure tools
  - I line was on photon absorbed meant at most one molecular change in the resist
  - Chemical amplification meant one acid generated per photon and many chemical reactions per acid
- EUV already has more amplification  because of secondary electrons
- Can we get more chemistry per photon (resists with a better chemical solubility switch)?
- If new solubility switching mechanisms are introduced how much chemical noise will remain in the developed image?
- Can new resist materials provide more internal order inside resists thus lowering LWR

# How much does requiring low outgassing resists hamper resist formulators?

- More efficient use of photons implies more chemistry per photon
- More chemistry per photons could mean more molecular fragments
- More fragments could mean more contamination
- SEMATECH is tracking both out gassing and resist performance and will correlate the two when enough data is available.

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# Summary

- EUV Resist performance has a potential for substantial improvement over baseline
  - 2X improvement in etched LWR due to resist and process improvement
  - Some part of process improvements is already realized
  - 2X improvement in sensitivity to EUV Photons
- Much research needs to be done
  - Understanding and making efficient use of secondary electrons
  - Finding heteroatoms that enhance EUV absorption and make good resist
  - Developing new chemical switching mechanisms to make efficient use of resist
  - Understanding how LWR behaves during pattern transfer.


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