Shot noise effect analysis in E-beam and EUV lithography

Sang Hee Lee[1], Jin Choi[1], Sung-Ho Park[1], Hee Bom Kim[1], Byung Gook Kim[1], Sang-Gyun Woo[1], and Han-Ku Cho[1]

[1] Semiconductor R&D Center, Samsung Electronics Co., Ltd.

*sanghee27.lee@samsung.com

Contents

- Introduction
- Shot noise effect of e-beam lithography
- Shot noise effect of EUV lithography
- LER transfer function
- Discussion & Summary

Introduction

- **Shot noise effect**
  - **Statistical effect of photons or particles in the photo-resist**
    - **Exposure dose → number of quanta**
    - **CD variation due to statistical fluctuation**
  - **Photon energy and dose**
    - **Small number of quanta for shorter wavelength → Large shot noise effect**

$$E = h\nu = \frac{hc}{\lambda} \Rightarrow Dose = N_{Photon} E = N_{Photon} \frac{hc}{\lambda}$$

Resist dose and number of quanta

Lithography	Energy (eV)	Wavelength	Resist dose (mJ/cm2)	No. quanta (50nm pixel)
ArF	6.4	193nm	40	1,000,000
EUV	92	13.5nm	20	34,000
E beam	50,000	5.5pm	600 (12uC/cm2)	1,880

Ref.: JVST B Vol. 21, 2632 (2003)
SPIE Vol. 7520, 752004 (2009)

Introduction

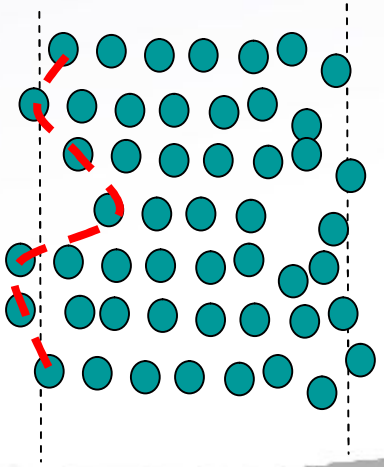
- **Shot noise effect for LER**
  - **Dose and energy should be considered**

$$LER \propto \frac{1}{\sqrt{N}} \dashrightarrow LER \propto \frac{1}{\sqrt{Dose}}$$ **@ same wavelength / energy**

$$LER \propto \frac{1}{\sqrt{\lambda}}$$ **For photo**

$$LER \propto \sqrt{E}$$ **For E-beam**

@ same dose



Small statistics
→ Large variation of edge

High energy photon
→ Small number of quanta @ same dose

SAMSUNG ELECTRONICS

Shot noise effect of e-beam lithography

- **Monte Carlo simulation**
  - **GEANT S/W: Monte Carlo (MC) simulation tool developed for high-energy physics at CERN**
  - **Quantum efficiency estimation**

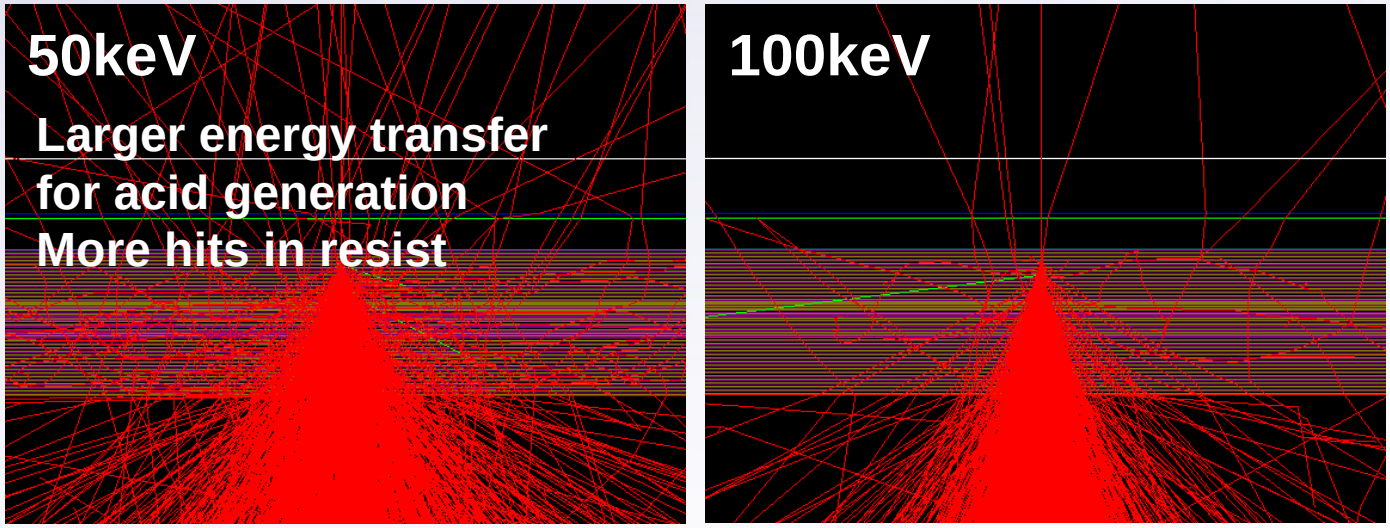
$$\text{Quantum Efficiency(QE)} = \frac{\text{Number of hits for acid generation}}{\text{Number of electrons}}$$

  - **LER from shot noise → affected by QE / QE is a function of energy**

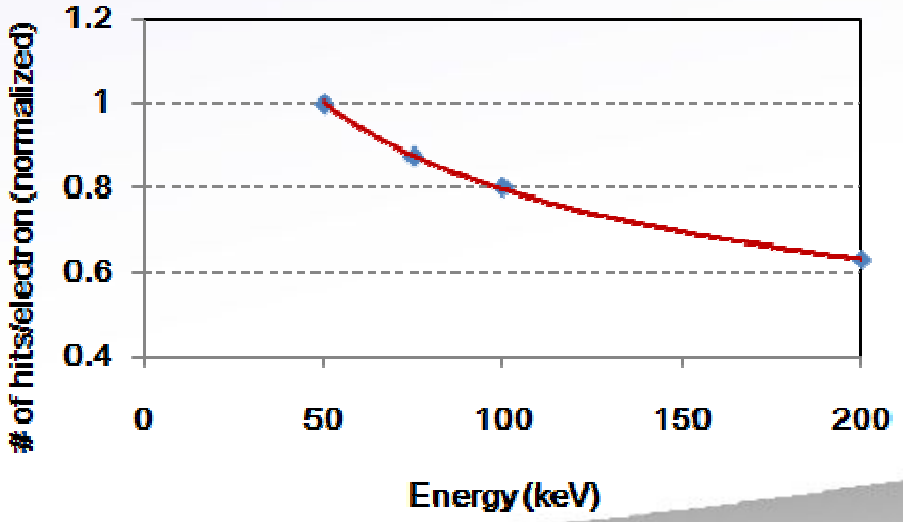
$$LER \propto \sqrt{E}$$ → **Modification is need due to QE**

Shot noise effect of e-beam lithography

Simulation → 10000 electrons are generated



Large QE in low energy e-beam

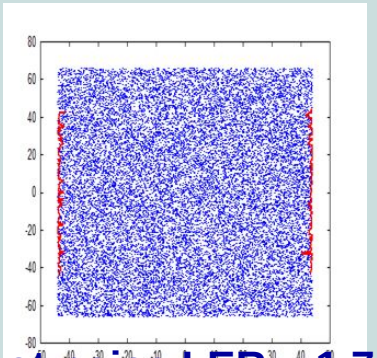
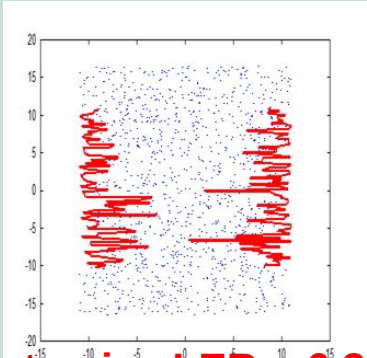


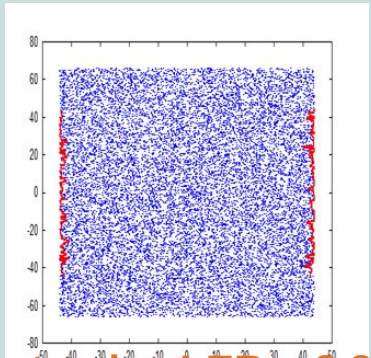
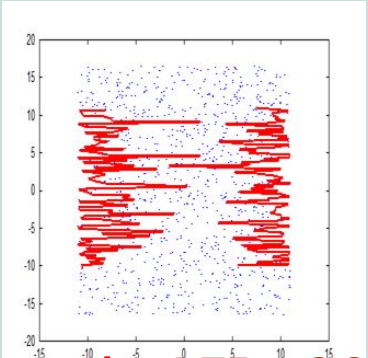
$$LER \propto E^{0.33}$$

High energy e-beam ~ LER is larger

SAMSUNG ELECTRONICS

Shot noise effect of e-beam lithography

E-beam (50keV)	22nm node (4X)	22nm node (1X)
30uC/cm^2	 Shot noise LER = 1.7nm	 Shot noise LER = 6.3nm

E-beam (100keV)	22nm node (4X)	22nm node (1X)
30uC/cm^2	 Shot noise LER = 2.3nm	 Shot noise LER = 8.2nm

Shot noise effect for mask patterning of 22nm node and beyond

→ Below 22nm node, shot noise effect reduction will be needed

SAMSUNG ELECTRONICS

Shot noise effect of EUV lithography

- **Monte Carlo simulation**
  - **GEANT S/W: Monte Carlo (MC) simulation tool developed for high-energy physics at CERN**
  - **Quantum efficiency estimation**

$$\text{Quantum Efficiency(QE)} = \frac{\text{Number of hits for acid generation}}{\text{Number of electrons}}$$

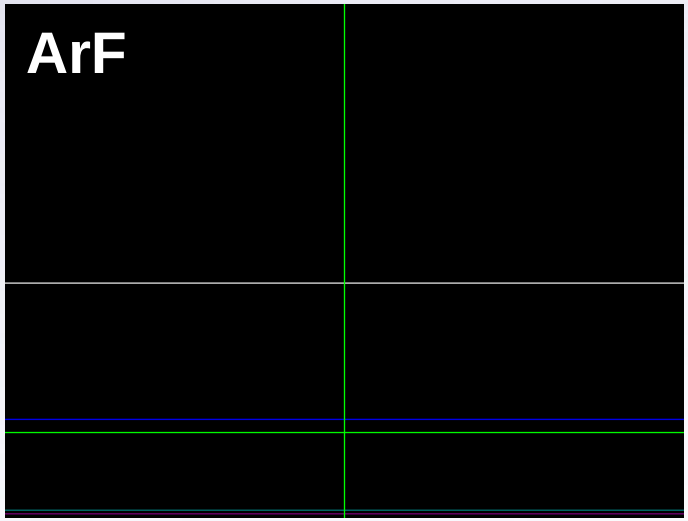
  - **LER from shot noise → affected by QE / QE is a function of energy**

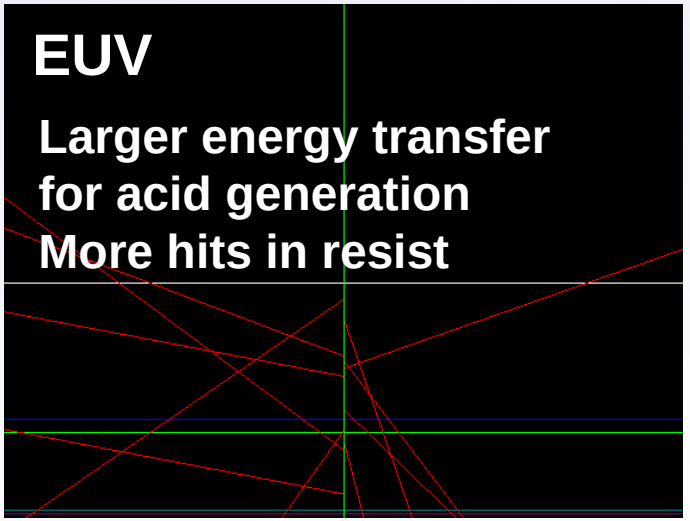
$$LER \propto \frac{1}{\sqrt{\lambda}}$$

Modification is need due to QE

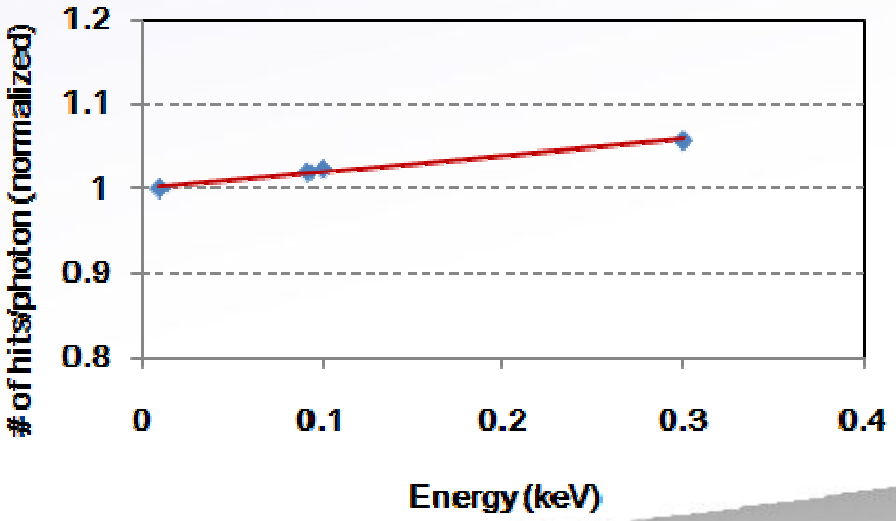
Shot noise effect of EUV lithography

Simulation → 10000 photons are generated





Large QE in high energy photon, shot wavelength

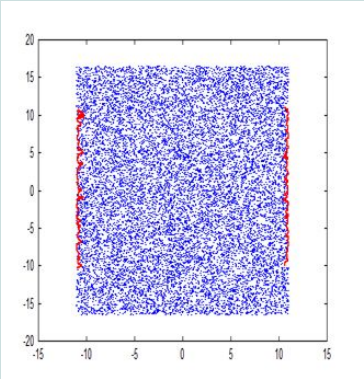
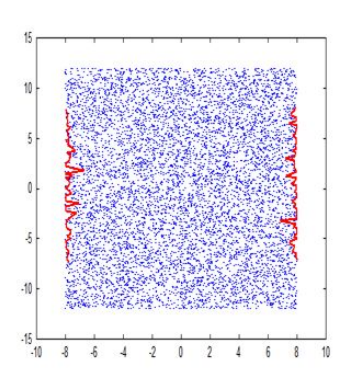
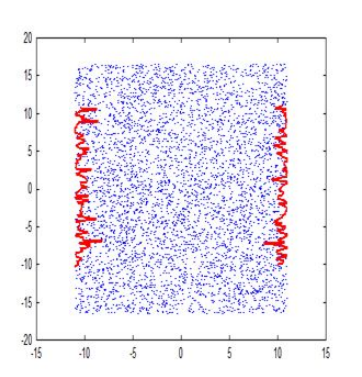
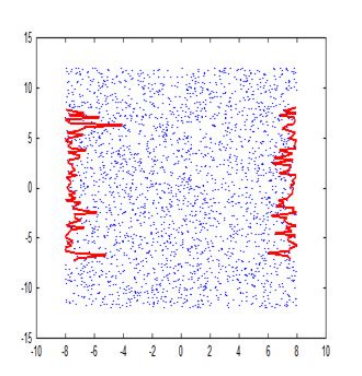


$$LER \propto \frac{1}{\sqrt{1.02\lambda}}$$

Shot noise effect is slightly compensated in EUV due to large QE

SAMSUNG ELECTRONICS

Shot noise effect of EUV lithography

EUV	22nm node	16nm node
30mJ/cm^2 **Shot noise** **LER = 0.6nm**		
10mJ/cm^2 **Shot noise** **LER = 1.7nm**		

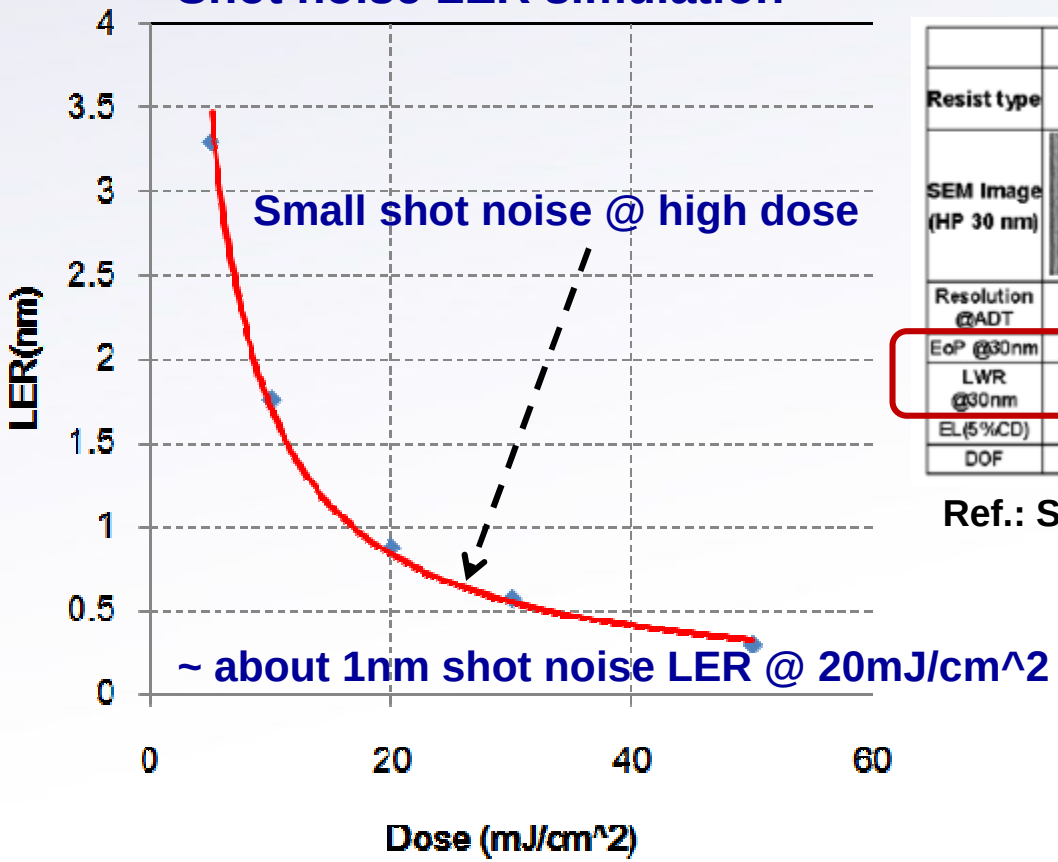
Shot noise effect for EUV patterning of 22nm node and beyond

→ Shot noise effect reduction will be needed for EUV lithography

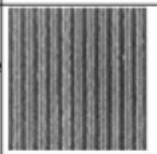
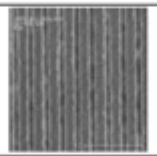
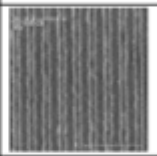
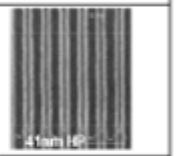
Shot noise effect of EUV lithography

- **Shot noise reduction & LER improvement using high dose**

Shot noise LER simulation



EUV resist performance

	Resist-A	Resist-B	Resist-C	ArF Immersion
Resist type	Acrylate PAG bound	Acrylate Blend PAG	Hybrid Blend PAG	Acrylate Blend PAG
SEM Image (HP 30 nm)				
Resolution @ADT	27 nm	27 nm	28 nm	-
EoP @30nm	20.2 mJ	18.4 mJ	17.5 mJ	30 mJ
LWR @30nm	4.4 nm	5.3 nm	6.7 nm	3.7 nm
EL(5%CD)	-	8.6 %	5.3%	10.0%
DOF	~150 nm	~150 nm	~150 nm	~100 nm

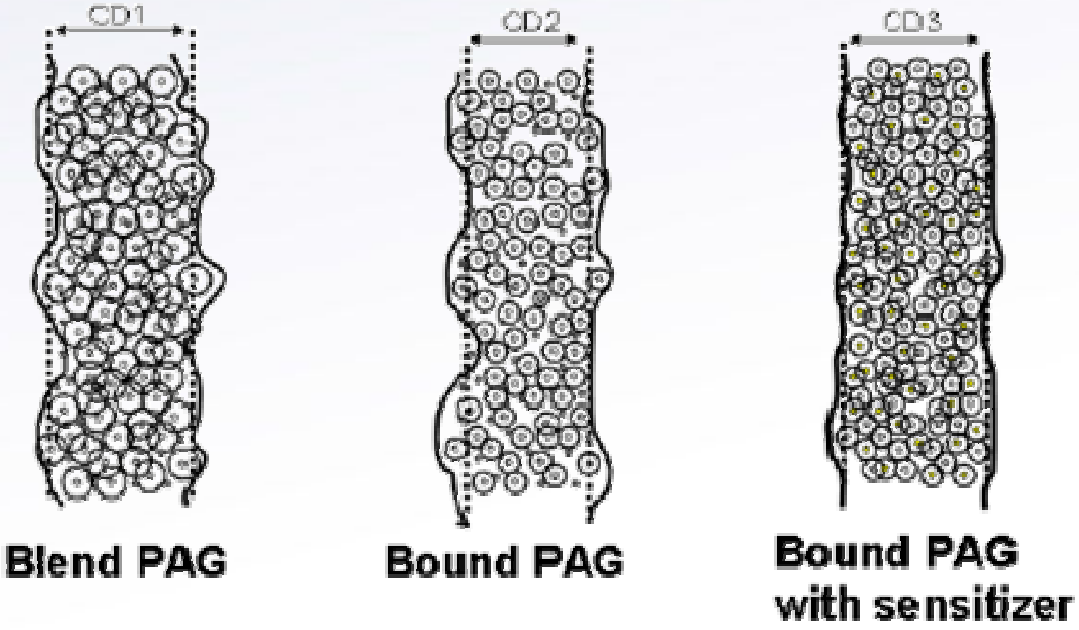
Ref.: SPIE Vol. 7636, 76360Q (2010)

SAMSUNG ELECTRONICS

Shot noise effect of EUV lithography

- **Shot noise reduction & EUV resist**
  - **Polymer bound PAG looks promising for EUV resist → smaller diffusion length, higher exposure energy**

Ref.: SPIE Vol. 7636, 76360Q (2010)



SAMSUNG ELECTRONICS

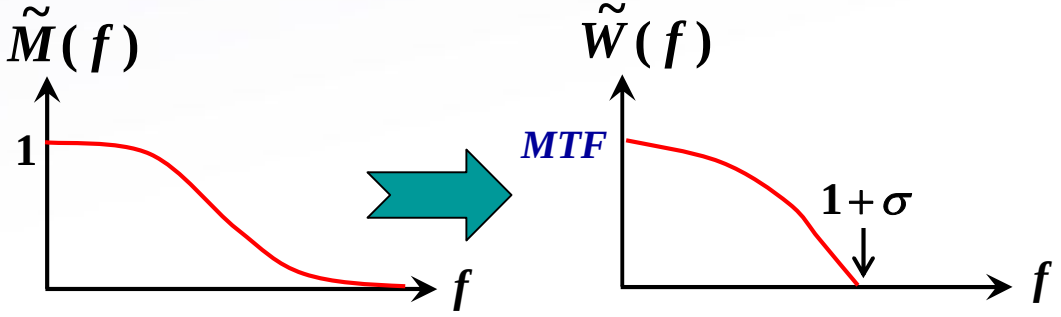
LER transfer function

- **LER transfer function**
  - **Cutoff spatial frequency of LER@mask can be defined by LER transfer func.**
  - **LTF depends on NA, σ, Pattern design, Pattern pitch, etc.**

$$M(y) \xrightarrow{\text{F.T.}} \tilde{M}(f) \xrightarrow[LTF(f)]{\text{Transfer function}} \tilde{W}(f) \xrightarrow{\text{F.T.}} W(y)$$

$$W(y) = \int dg S(g) \left| \int df \exp(-2\pi i g \cdot f) \sigma(g+f) \tilde{M}(f) \right|^2$$

source pupil

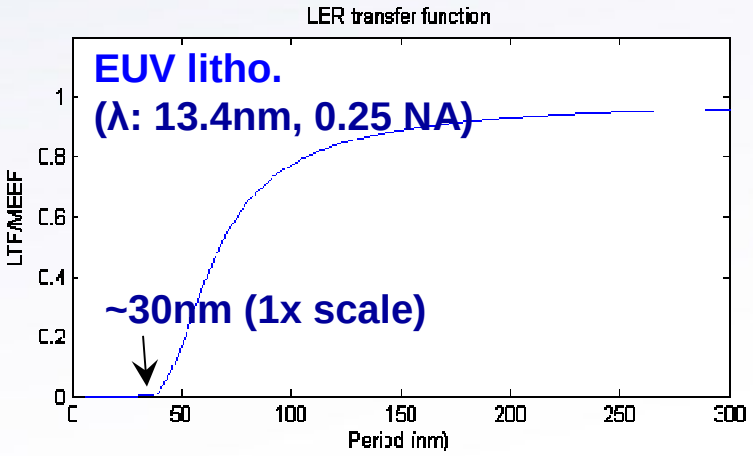


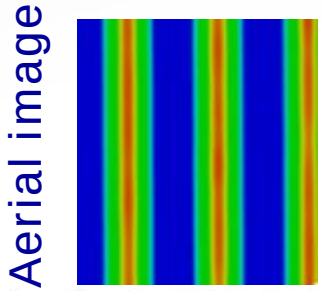
Ref: H. Tanabe, SPIE Vol. 6607 (2007)
P.P. Naulleau, Applied Optics Vol. 42, 3390 (2003)

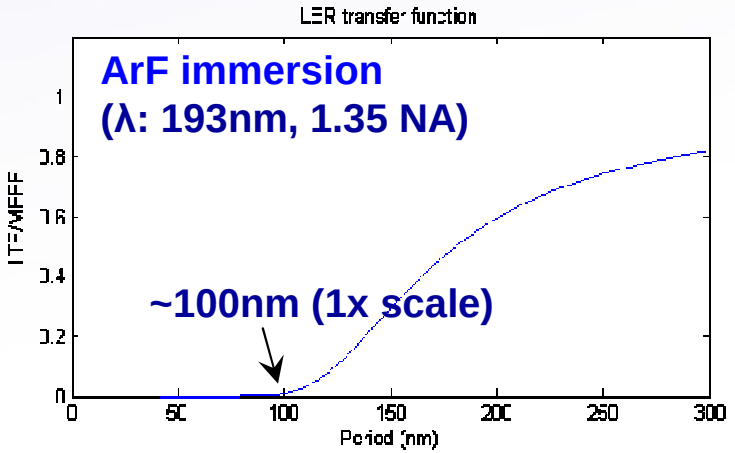
SAMSUNG ELECTRONICS

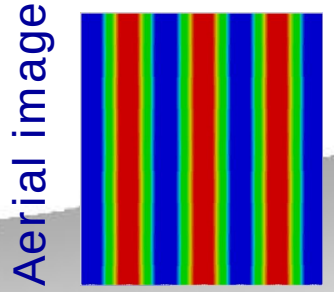
LER transfer function

- **LTF simulation**
  - **Cut-off frequency → 30nm(1X) period**
  - **No significant effect due to e-beam shot noise for EUV mask patterning**
  - **At higher NA, cut-off frequency will be higher → Mask LER including e-beam shot noise will be important**









Discussion & Summary

- **Shot noise effect is statistical error due to the number of photons or electrons**
- **High energy photon or e-beam makes large shot noise effect**

- **For e-beam lithography, QE is large at low energy**
- **For photo lithography, QE is large at high energy → EUV has larger QE than ArF**

- **For e-beam lithography, shot noise LER is 1.7nm for 22nm node with 50keV e-beam for mask patterning**
- **For EUV lithography, shot noise LER is 1.7nm for 22nm node with 10mJ/cm^2**

- **High dose can reduce shot noise and improve LER**
- **Although e-beam lithography has large shot noise, it is not significant yet. It will be important in future with high NA**