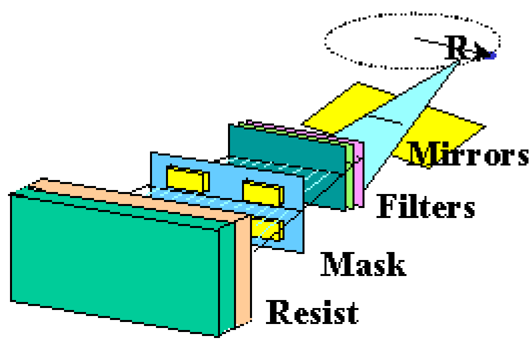
Jefferson Lab Technical Note 03-016

X-Ray Lithography towards 15 nm



The report of a meeting held January 24, 2003
Thomas Jefferson National Accelerator Facility (JLab)
Newport News, Virginia.

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Executive Summary

A consortium of key technical executives representing a broad range of advanced lithography disciplines concluded that it is essential that a modest program be developed as soon as possible to re-define a road-map for x-ray processes to assure the maintenance of US competitiveness. The group further concluded that there are no show-stoppers. As the semiconductor lithography industry continues to follow Moore's Law, device "design rules" shrink, and present optical lithography cannot provide the continually dimishing critical dimensions. With the technology changes that are currently proposed, there is a real danger of a reversal in the reducing cost-per-component trend. Unless mitigated, the adverse situation is likely to arise after the generation of lithography based on excimer lasers, the last of which is the F2 laser at 157nm (printing down close to 50 nm). Systems introduced around 2008 will thus have to adopt new or next-generation-lithography (NGL) tools. There are many such tools available, all of which can print well below 50nm but x-ray lithography (XRL) is already showing substantial cost reductions compared to competing techniques in the framework of present design rules and can be extended to smaller dimensions and higher throughput. Near-field x-ray lithography (NFXrL) is a variation of XRL in which printing is done in the near rather than far field, with demagnification of the mask features. We believe that it will be one of the leading candidates for semiconductor manufacturing at the sub 30nm level in terms of performance, cost and throughput.

Introduction

X-ray lithography has been explored for over 20 years. In the USA major programs exist or existed at MIT, IBM, BNL, UW-Madison, BAES, JSAL and among collaborating institutions. The technology has an excellent track record for sources, optics, masks, resists and steppers. A wide variety of functional, complex integrated circuits have been fabricated including 64 Mb DRAMs, with over 6M transistors, and logic circuits with over 6M transistors at design rules between 250 and 100 nm. Since the wavelength of the light is only 1nm, it is capable of printing well below the 30nm level. It is possible that it may be the system of choice for the future when all cost and throughput factors are included.

The main point of this initial workshop was to assemble a group, representing all aspects of both X-ray Lithography (XRL)), both traditional 1× and Near Field (NFXrL), to discuss collectively the issues involved in taking X-ray techniques to 15nm, and to make recommendations, which are summarized in the Executive Summary. Near Field X-ray Lithography is a reduction printing technique. Wafers are exposed in the near-field taking advantage of interference to reduce mask feature sizes, see page 16.

In the narrative that follows, we focus on key issues in several topic areas. The agenda and talks are presented at the back.

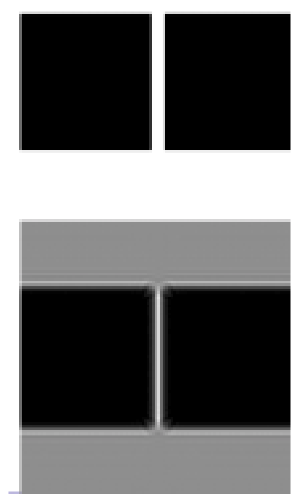
Key Issues in NFXrL towards 15nm

(a). Resists.

There are no fundamental changes required in resist technology to go to 15nm, and in fact the field is mature both for positive and negative resists. Issues such as exposure dose, process latitude are well known from XRL and can readily be scaled.

(b). Masks.

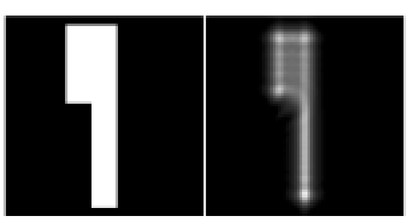
Masks are generally agreed to be the most difficult and critical element of an XRL system, but there are programs in place at IBM and NTT-AT to attack this challenge. NFXrL, with its image reduction, places a relaxed burden on mask feature size. In Fresnel diffraction, the gap increases with the square of the demagnification factor, so that finer prints can now be made with larger gaps than previously used in 1× XRL.



NFXrL printing of a bridge from mask (top) with width 100 nm, and resulting print (bottom) with width 33 nm. Gap 5 μm, λ=0.62-1.24 nm.

(c). Arbitrary 2-D patterns and Magnification Correction.

NFXrL uses near-field interference effects to reduce the printed feature size compared to that of the mask, but much discussion focused on the ability of the technique to print arbitrary 2-D patterns. Theoretical work is needed to establish the limitations of the technique, and in particular to determine how sensitive the diffraction patterns are to the spatial coherence of the source.



NFXrL print simulations of a “flag”. Mask (left) width 150 nm at bottom and 300 nm at top to print (right) 50 nm at bottom and 250 nm at top. Gap 11.2 μm, λ=0.62-1.24 nm.

Here we present simulations of the printing of a flag and a bridge using NFXrL, which were done in response to questions and concerns about arbitrary patterning capability. They were done by Antony Bourdillon in collaboration with Chris. B. Boothroyd, IMRE, Singapore. Notice that the technique is used for printing dense lines by rapid multiple exposures with high contrast and single development. The field is kept compact as in traditional XRL for 50mm x 30mm exposures.

(d). Source Issues.

(i) Resolution: There are 2 main sources available for NFXrL, namely "point" sources and synchrotron radiation. The point sources are of 2 types, namely laser plasma and dense focused (Z-pinch) plasma. In an analysis done by Antony Bourdillon, it was found that for uncollimated beams, penumbral blur was 1 nm for the synchrotron sources and 0.1, and 10 nm respectively for the point sources. Run-out (or magnification error) was found to be 25 nm for the synchrotron, and 250 nm for point sources without collimation, essentially zero with collimation. The magnification errors are correctible by various means. Bourdillon's conclusion was that laser plasma point sources offer advantages over dense focused plasma sources for testing purposes.

(ii) Power and throughput: We note that synchrotron radiation sources produce **hundreds of milliwatts /** cm^2 of power for wafer exposure compared with **milliwatts** / cm^2 for plasma based sources due primarily to the natural collimation of the x-ray beams generated by relativistic electrons. This is due to the fundamental physics given in Larmor's formula, see Nature **420** 153-156 (2002) or S.L. Hulbert and G.P., Williams, "Synchrotron radiation sources." In Handbook of Optics: Classical, Vision, and X-Ray Optics, 2nd ed., vol. III, chap. 32. Michael Bass, Jay M. Enoch, Eric W. Van Stryland, and William L. Wolfe (eds.). New York: McGraw-Hill, pp. 32.1--32.20 (2001). For x-ray point sources see C.J. Gaeta et al. "High Power Compact Laser-Plasma Source for X-ray Lithography" Jpn. J. Appl. Phys. **41** 4111 (2002). The throughput ultimately depends on a combination of source power and resist sensitivity, and stepper overhead, so exact scaling .

(e). Costs of Ownership / Throughput.

NFXrL is expected to cost the same as XRL and therefore to be very competitive. In a report by Yoshio Gomei to ASET, the Japanese Association for Super Advanced Electronic Technologies to XEL 98 (November 9-10), Yokohama, ion projection was compared with SCALPEL (electrons), XRL and EUV and the following table was given:

NGL	Synchrotron XRL	IPL*	EUVL* (estimated)	EUVL (Ref. 1)	SCALPEL
Raw throughput (8"wafers/hr)	47	32 44 54	42 54	3	13 33
System cost $M	10	15 11 9	15 12	60	33 14

Table 1. Throughput and system costs for various next generation lithography tools.

* These are older estimates and over-optimistic based on present knowledge. We note that for IPL, EUV and SCALPEL the multiple entries indicate that an evolutionary path was defined. For XRL it was assumed that 10 steppers share the cost of one synchrotron storage ring. Reference 1 is a press release in the San Jose Mercury News, March 2002.

A detailed comparison of the costs of a specific e-beam system and a specific point-source XRL system is offered in Table 2 on the following page, prepared by John Heaton. This assumes the same throughput for the 2 systems, namely the JMAR/SAL X-ray stepper (with SRL point source) and the e-beam system, which are compared. But note that Table 2 is for a point source of a few milliwatts compared to the few hundred milliwatts available for the synchrotron source of Table 1, see previous section.

Tool	Purchase Cost	Yearly Depreciation	Yearly Maintenance Cost	Yearly Operational Cost	Facility Floor Space Cost	Total Yearly Cost
Lieca EBMF 10.5 E-Beam Heritage Tool	$2M	$400K	$80K	$450K	$50K	$980K
Leica EBPG5000 E-Beam	$5M	$1000K	$200K	$325K	$50K	$1574K
JMAR/SAL SRL Point Source X-Ray Stepper	$8M	$1200K	$200K	$325K	$15K	$2140K

Table 2. Costs of Operation of e-beam and point-source x-ray lithography tools.

Notes: 1.) Depreciation of lithography tools over 5 years
2.) 2 shift operation for EBMF10.5 E-Beam, 1 shift for others
3.) Staff = 1 tec/shift plus 1 senior engineer: Senior Engineer @ $100/hr, tec @ $63/hr
5.) Facility cost @ $1000/sq ft for class 100 for E-Beams; $300/sq ft for class 1000 for X-Ray with 10 year depreciation; each tool at 500 sq ft

Finally Table 3 illustrates the striking cost advantages in using XRL for a specific application.

Tool	0.10 micron MMIC cost of litho per die	Savings compared to EBMF5000 (for 2M MMIC chip/year)	% of single shift capacity of litho tool for 2M MMICs/year
Lieca EBMF 10.5 E-Beam Heritage Tool	$7.72	NA	1575%
Leica EBPG5000 E-Beam	$3.54	$0M	450%
SAL/SRL Point Source X-Ray System	$0.86	$5.3M	80%

Table 3. Reduction in cost of x-ray lithography for MMIC manufacture - compiled by John Heaton, BAE Systems.

Assumptions: 1.) 6” Dia. wafers
2.) EBMF10.5 @ 0.13 levels/hr, EBPG5000 @ 0.9 levels/hr, X-Ray system @ 5 levels/hr

3.) 50 week year
4.) 0.14 x 0.14 inch chip, yield of 500 MMICs/wafer
5.) Two chip levels printed with selected tool, other levels with optical stepper

(f). Alignment.

Alignment issues are identical for x-ray and optical, therefore not special.

(g). Gap.

Gaps are required to be not less that 5 μm and preferably, not less than 7 μm. The appropriate magnification will be achieved by an appropriate bias. Additionally, an acceptable gap variation ("depth of focus") has to > 1-2 μm without serious image degradation.

Future Gate Length Requirements for MMICs in Military Applications

Military requirements continue to push the state of the art in microwave and millimeter wave MMICs because MMICs set the performance level of radar and communications systems where they are used as low noise receiving amplifiers or transmit amplifiers. Improved receive noise figure or increased transmit power and efficiency translate into increased range, longer battery life or smaller satellite solar panels and lower cost launch to orbit. Also, military applications increasingly require higher frequency of operation, above 100 GHz, for smart seeker target differentiation or improved quality imaging systems for concealed weapons detecting imaging radars. In FET based MMICs this push for performance translates into a requirement to reduce gate length. Currently, 120 nm gate devices are used at frequencies up to 100GHz. Next year (2004) requirements for noise figure improvements in current satellite communications and missile seeker systems will require 100 nm. In 2005, further reduction in noise figure and power output will drive the industry to 70 nm, and volume requirements for new applications such as the millimeter imaging radar will moving into production. Next generation systems moving to 140 GHz for improved resolution will require 50 nm devices in quantity in 2007. The trend is expected to continue, toward 35 nm in 2010. Although prototype devices with gate lengths as small as 35 nm can be produced with direct write e-beam lithography, volume applications cannot be supported by available e-beam tools because of e-beam's long write times, particularly at the sub-100nm dimensions. DUV lithography also has not been applied successfully to high performance MMIC fabrication because current processes and available flatness of gallium arsenide wafers require depth of field approaching 1 micron. X-ray lithography has potential to support the needs of the military MMIC market for affordable highest performance MMICs, where other currently available technologies fall short.

Road-map for NFXrL

In principle an R&D program could begin in October 2004 aimed at market entry in 2010 at the 45 nm level. The JMAR/SAL x-ray stepper is an important instrument for developing the key components. For the synchrotron source required for ultimate throughput, 2.5 years would be required to install the Helios-1 storage ring in a building, another 6 months to re-commission the beamlines and install the SVGL stepper. Thus synchrotron R&D could begin in 2007.

Appendix A – Agenda

X-Ray Lithography, towards 15nm

Jefferson Lab, Newport News, VA
CEBAF Center, Room L102/104

8:00	Continental Breakfast	
9:00	Welcome	Swapan Chattopadhyay, Assoc. Dir. JLab
9:05	Welcome	Fred Dylla, Chief Technology Officer, JLab
9:10	Welcome	Rex Pelto, Center for Innovative Technology, VA
9:15	Welcome	David Patterson, DARPA
9:20	Introduction and charge	Gwyn Williams, JLab
9.30	Near Field concepts and capability	Antony Bourdillon, UhrlMasc.Inc.
10.00	Near Field demonstrations, X-ray developments and limits	Yuli Vladimirsky, ASML
10:30	Break	
11:00	Facility requirements Virginia Commonwealth University	Hadis Morkoç,
11:20	Need for small imaging systems	Om Nolamasu, Rensselaer Polytechnic Institute
11:40	Application of X-Ray Lithography to MMIC Fabrication for Military Applications	John Heaton, BAE Systems
12:15	Lunch	
1:30	Steppers	Bob Selzer, JMAR/SAL
2:00	Presentation of “straw-person” roadmap, followed by discussion moderated by	Dennis Manos, College of William & Mary
3:30	Break	
4:00	Resume Discussions	

Topics for discussion will include but not be limited to:

Sources:	granularity, reliability, beamlines, throughput, exposure, field size, depth of focus, uniformity, wavelength of operation
Masks:	stability, extensibility, magnification correction
Aligners:	overlay accuracy, proximity gap stepping
Resists:	resolution, speed
Facilities:	clean rooms and equipment, beam writers, inspection and repair
Timescale:	entry point for pxrl
General:	printing versatility

5:00	Adjourn	
6:00	Dinner	

Appendix B – Participants

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Appendix C – Talk 1

Antony Bourdillon
UhrlMasc, Inc.

Lithography to 15 nm
- Using Near Field* X-rays

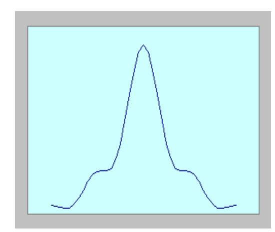
Antony J Bourdillon

and

Yuli Vladimirsky

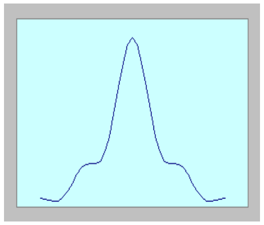
UhrlMasc Inc

*Ultra High Resolution Lithography, US Patent 6383697

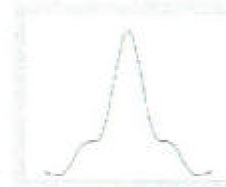


Principal Features in Near Field

- High Resolution
  - Intentionally Demagnify PXL using bias
- Half Pitch
  - with multiple exposures of sharp peaks,
  - Short exposure times
- Build on demonstrated PXL with high throughput
  - Company solution possible
- Other advantages of the Sweet Spot



Technology



Needs

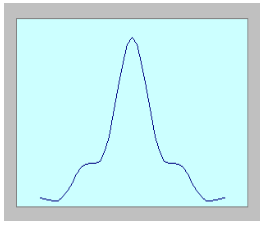
- Low equipment cost
  - EUVL ~60M
- High throughput
  - (EUVL 2-4 WPH)
- Demonstrated
- Extensible
- Available

Near Field PXL

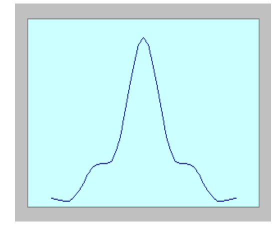
- One synchrotron line $2m
- Stepper 5m
- 30-60 WPH
- Circuits at 0.1 nm, lines at 25 nm
- To 15 nm
- Several equipment suppliers, sufficient development that industry wide solution not required

Sweet Spot

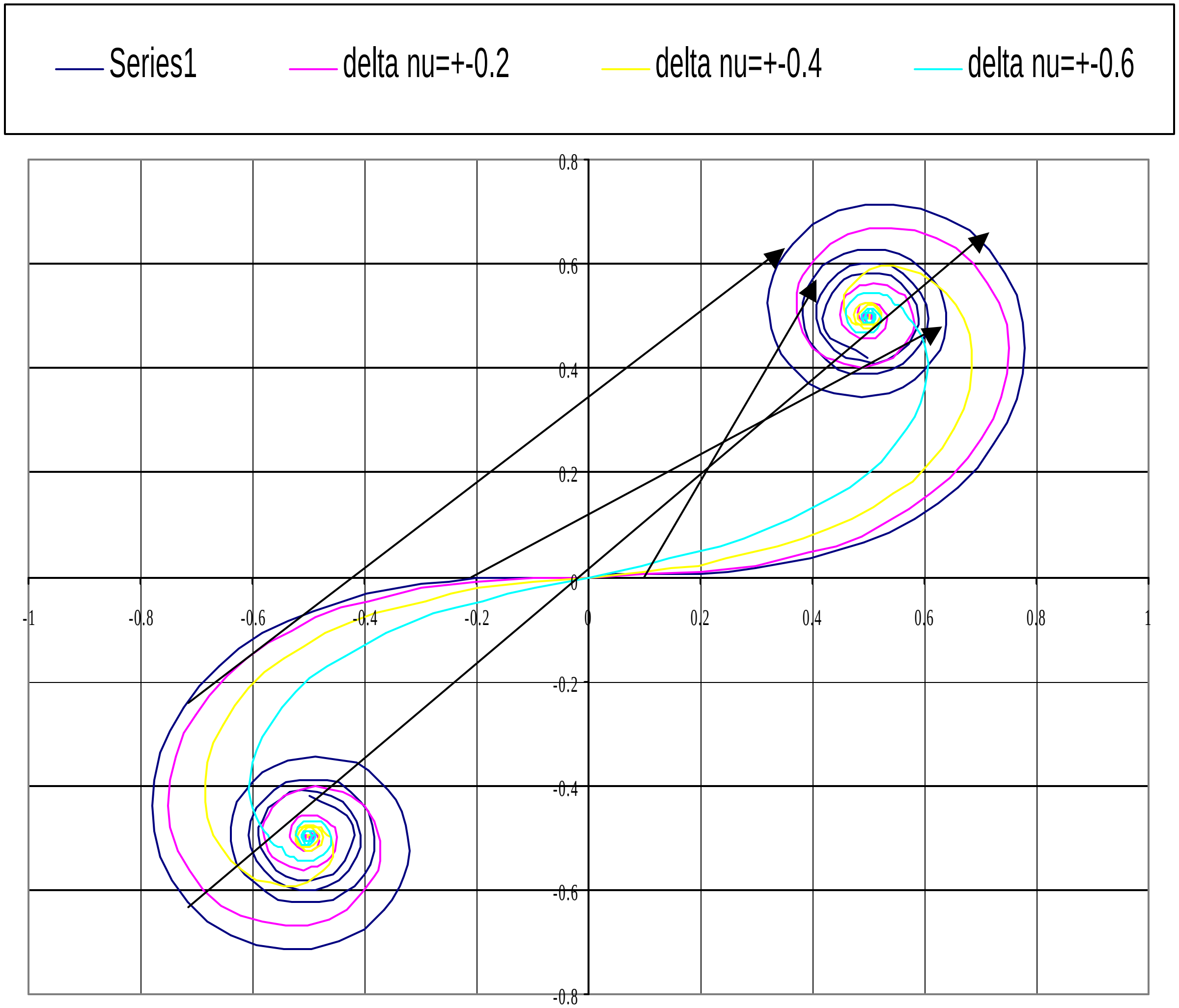
- Demagnification by bias – of mask features; field kept compact
- Highest resolution at Critical Condition
- Rapid exposure at peak (not tail)
- Small pitch with rapid multiple exposures, single development
- Demonstrated to 25 nm
- Broadband for high throughput
  - Using relativity condenser and clean source
- Ideal 2D features by temporal and spatial incoherence
- High contrast for robustness
  - No sidebands, esp. with periodic structures



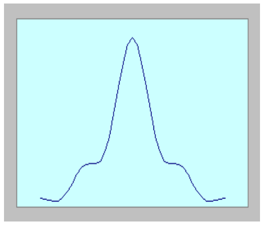
- Further extensible with enhancements with shorter wavelengths
- Standard technique
  - All equipment, resists etc available from multiple suppliers
- Other advantages (large gaps, large mask features, large depth of focus, no ARC, high aspect, regular resists, easy topography etc etc)



Simulation of a Fresnel diffraction current with wavelength 0.8 nm passing though a slit of width 150 nm. The critical condition lies at a gap of 10 micrometers. Notice the sharp peak and adjacent shoulders.



Critical Condition



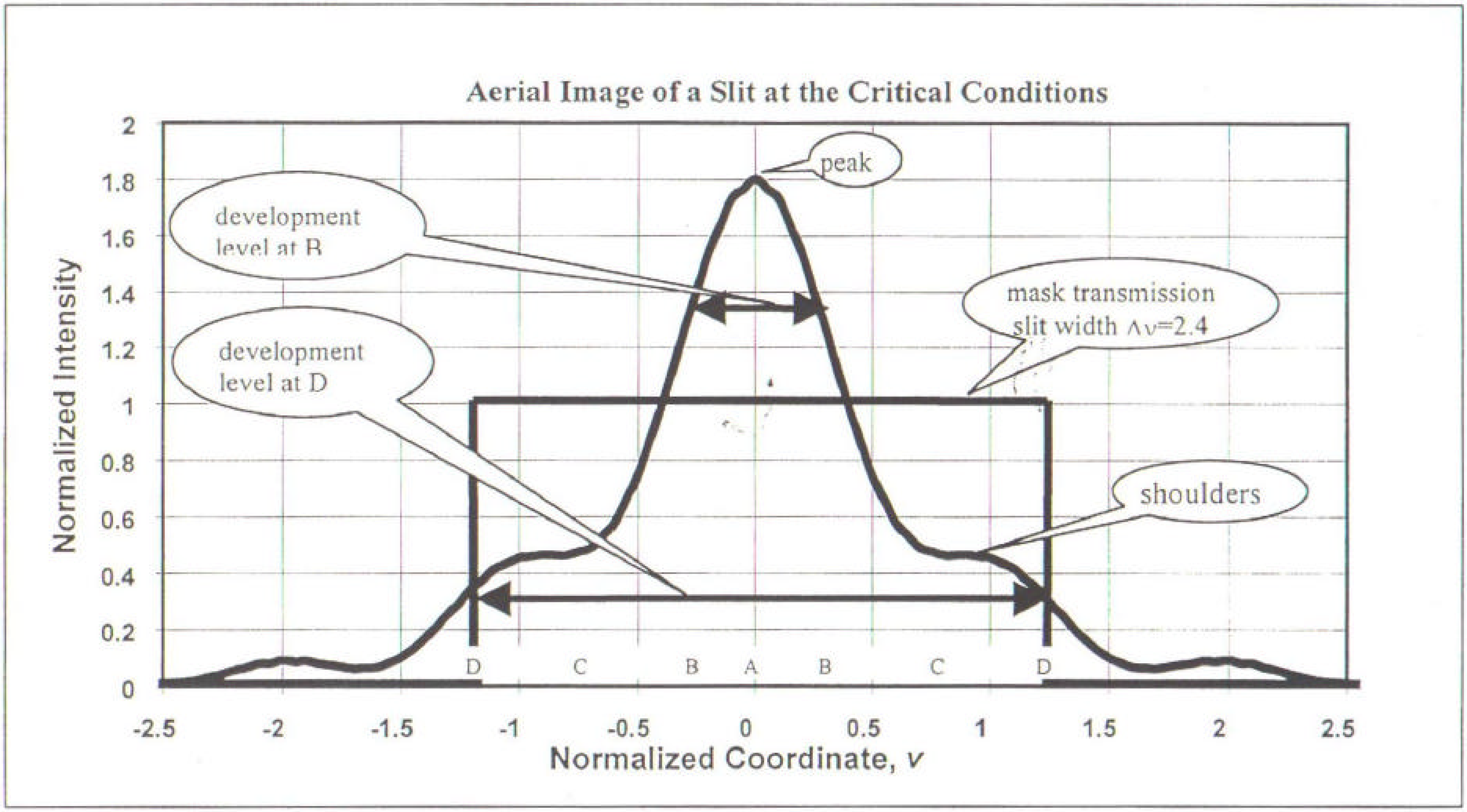
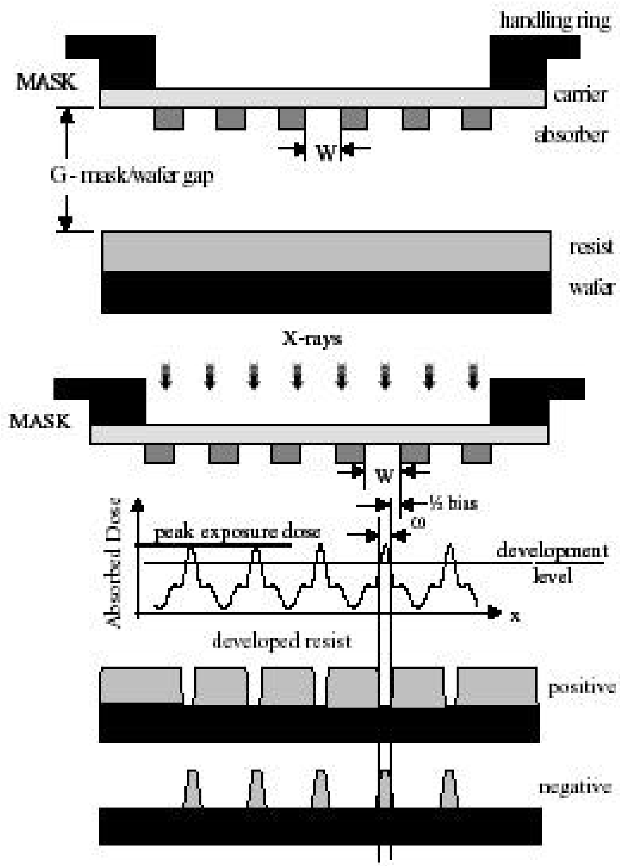


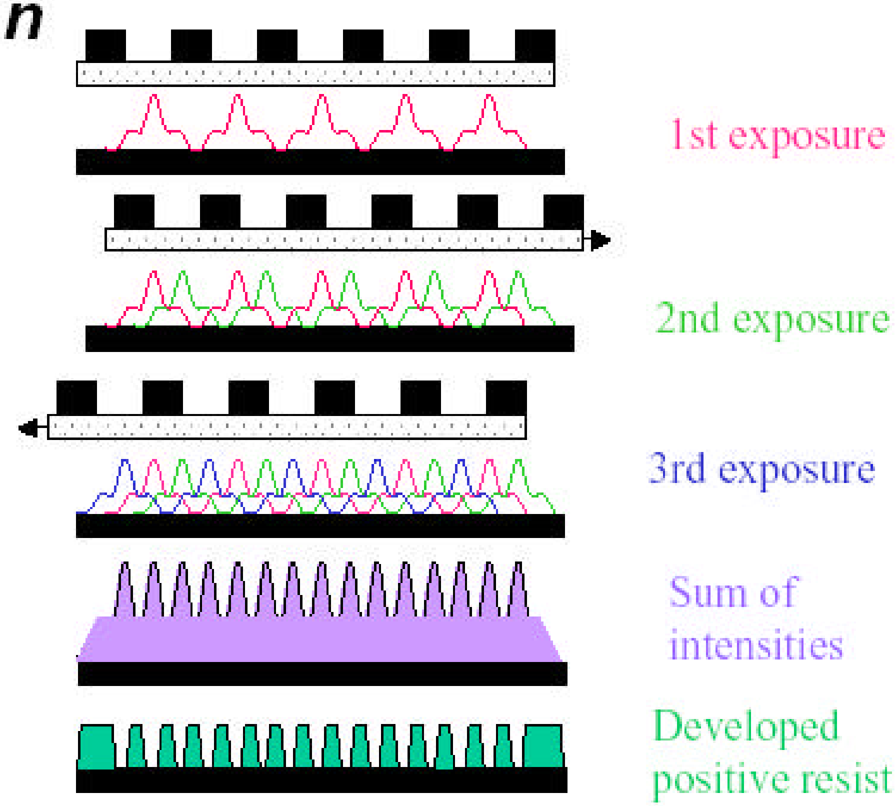
Figure 2b. Aerial image of a slit at the critical condition showing a peak at A. Also shown are a 4x demagnified image of the slit at development level B and a 1:1 image at the development level D. The normalised co-ordinate $\nu = x(2/G\lambda)^{1/2}$ at the wafer and corresponds to $2.4 = \Delta s(2/G\lambda)^{1/2}$ at the mask, where the transmission is shown

Nested lines formation in PXRL

with demagnification



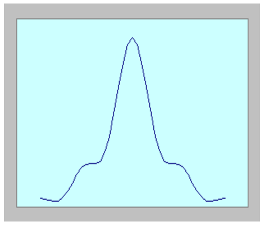
Resist processing

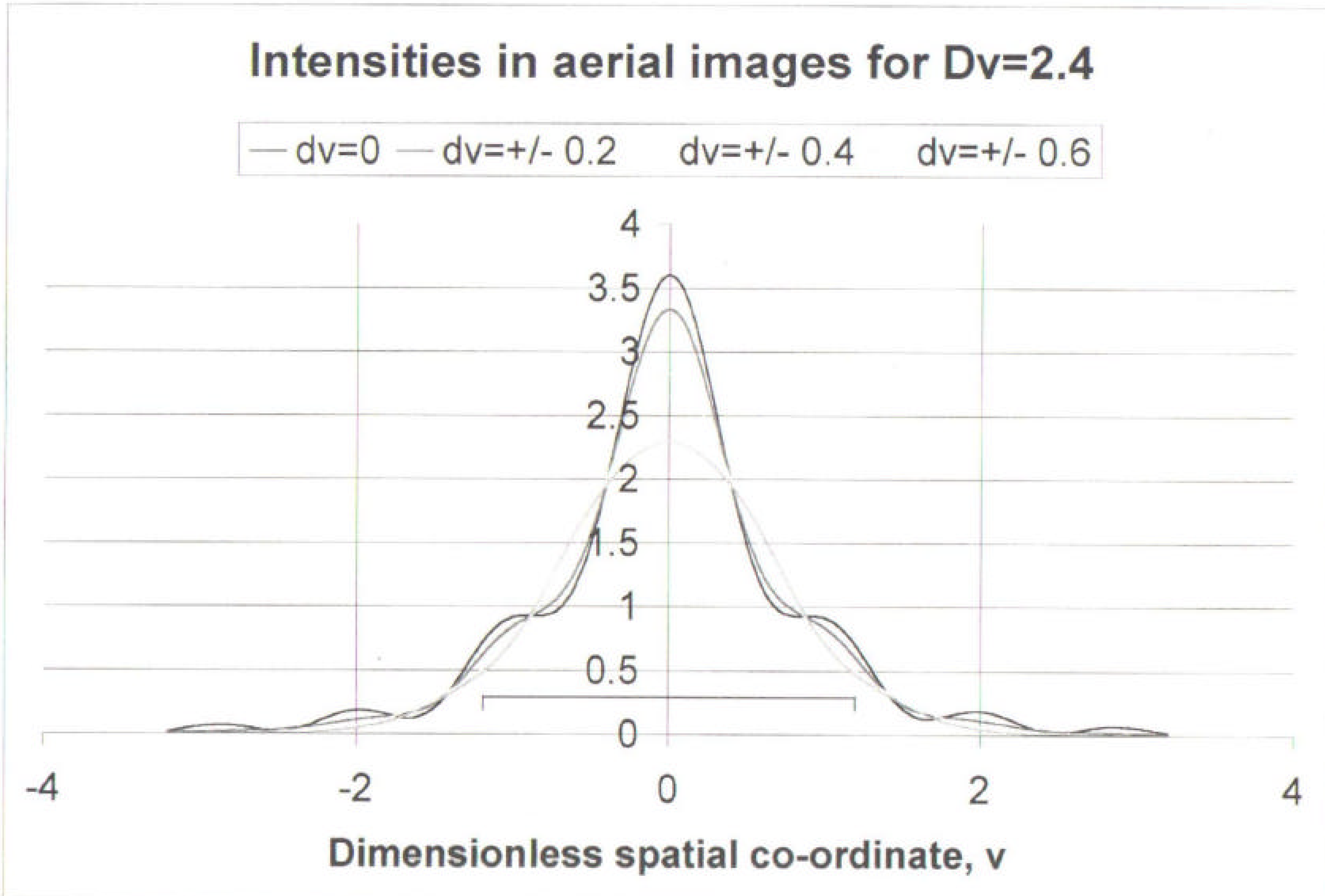


- nested features formation in positive and negative resists by multiple sequential exposure and single development step

Broadband in Near Field PXL

- High throughput
- Cornu spiral for
  - Monochromatic
    - The critical condition
  - Broad band
    - High contrast
- Ripple, Bright Spots eliminated
- Clean source, no contamination

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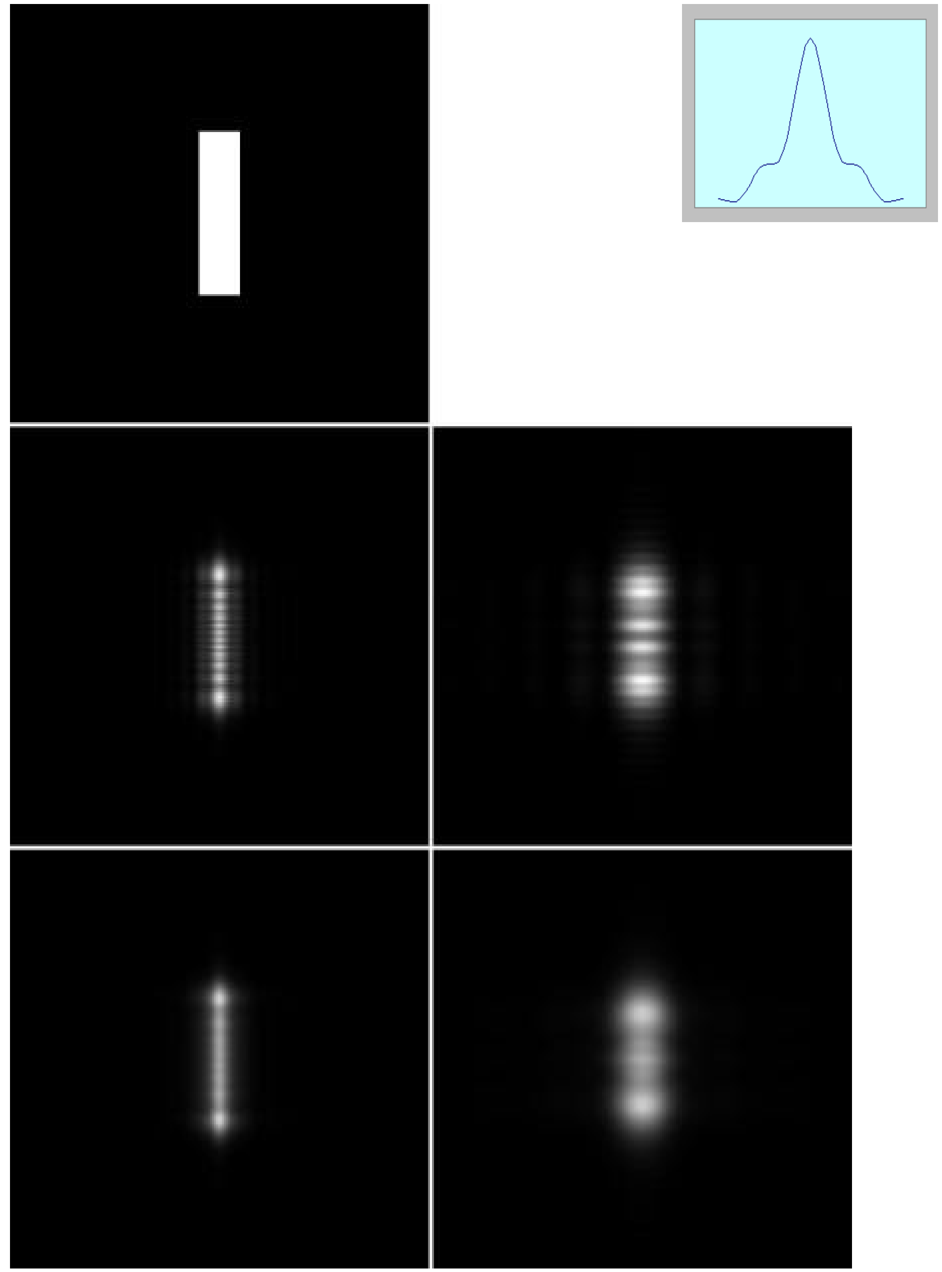
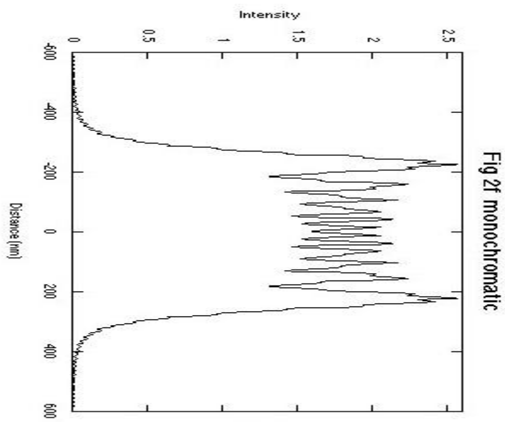
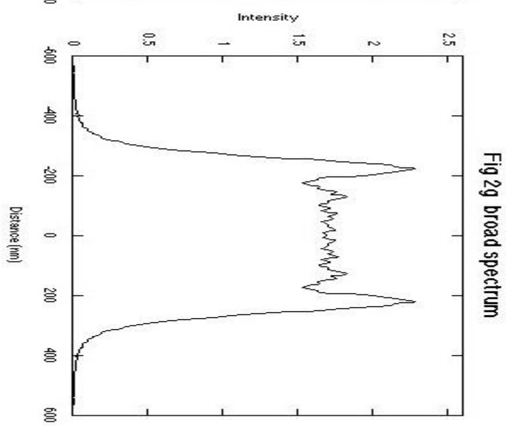
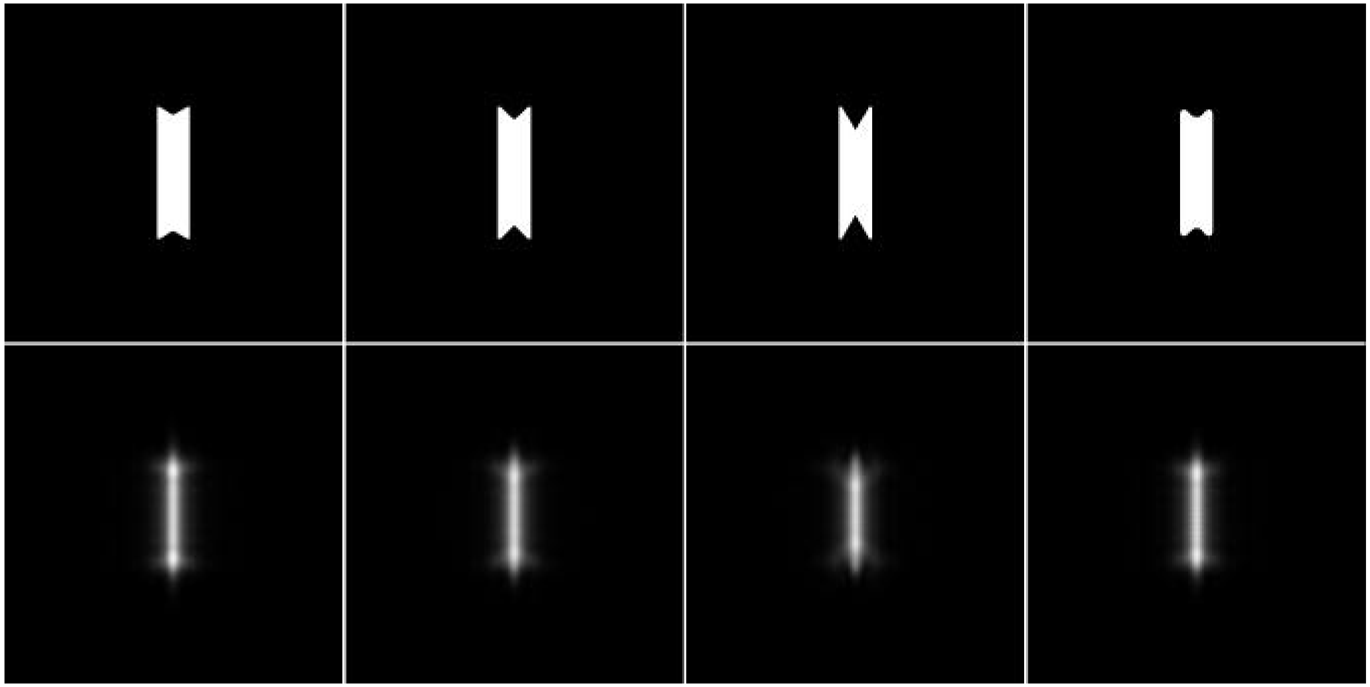
Dimensionless spatial co-ordinate, v

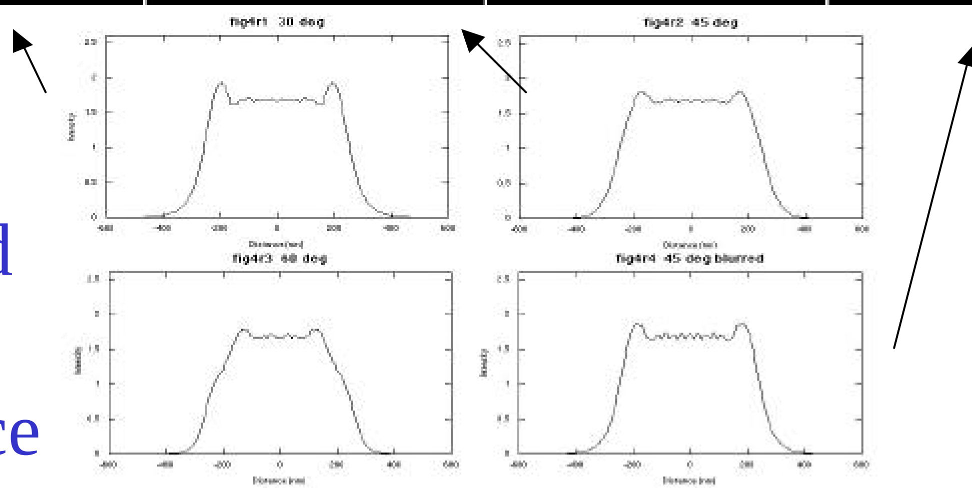
2-D Simulations Monochromatic and Broadband



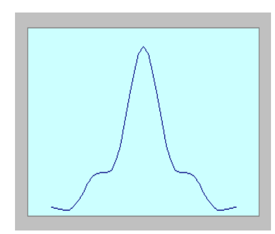




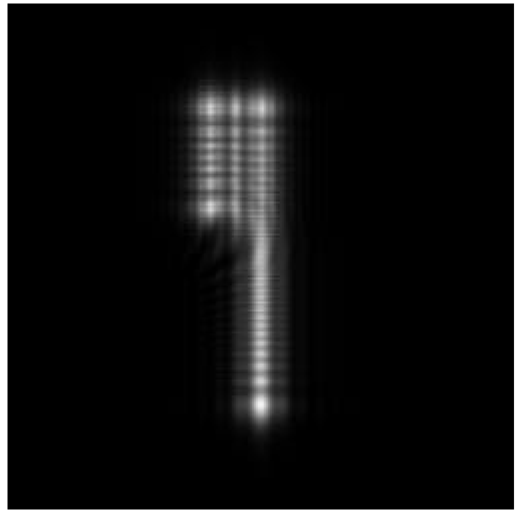




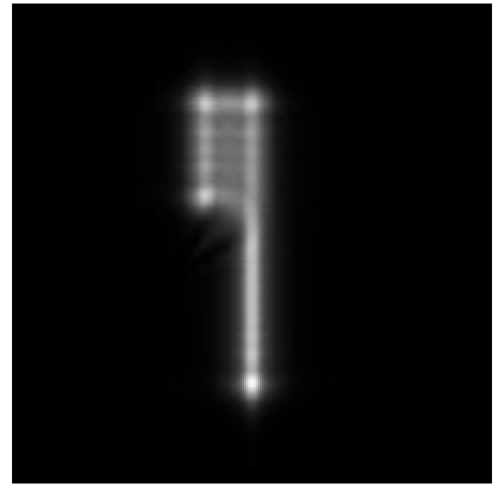
Spatial and temporal incoherence



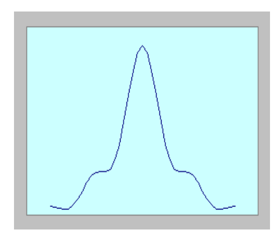
Varied dimensions

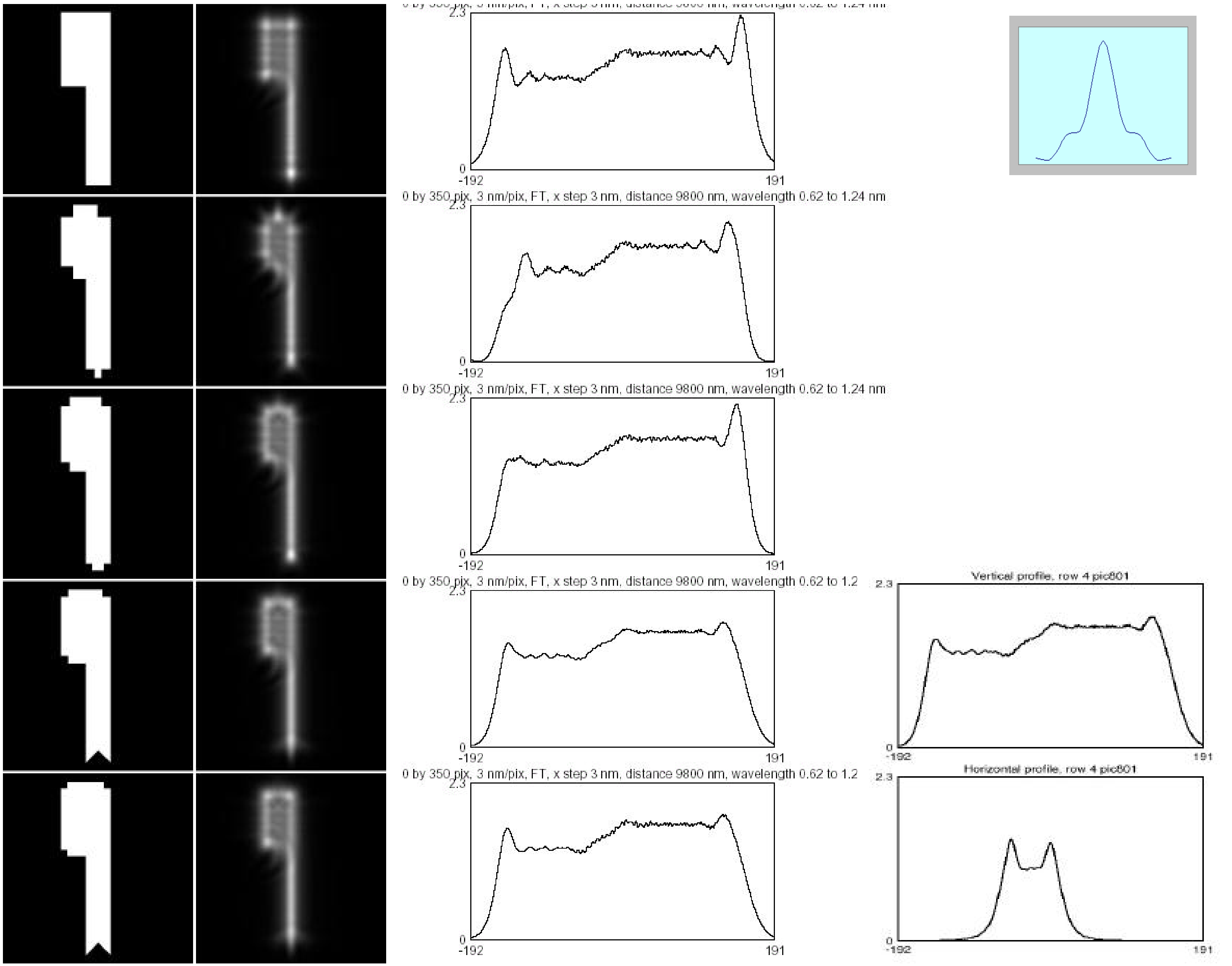


Aerial image, monochromatic



Aerial image with temporal incoherence, but not spatial



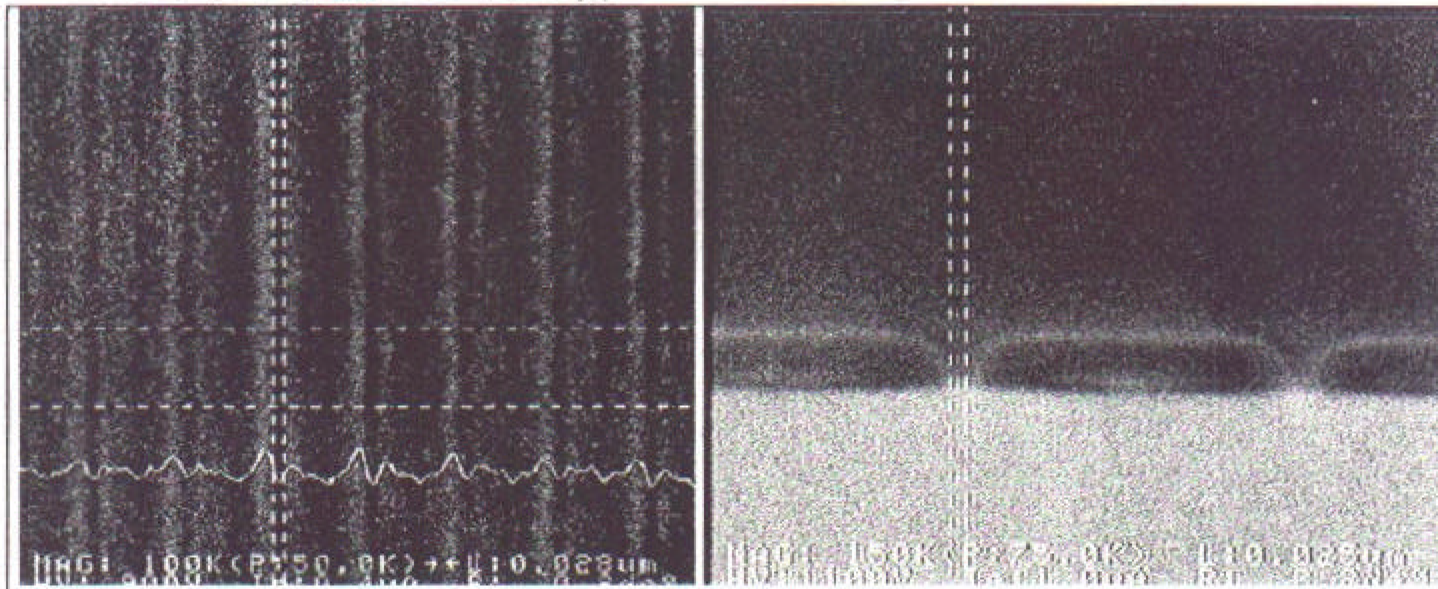

0 by 350 pix, 3 nm/pix, FT, x step 3 nm, distance 9800 nm, wavelength 0.62 to 1.24 nm
0 by 350 pix, 3 nm/pix, FT, x step 3 nm, distance 9800 nm, wavelength 0.62 to 1.24 nm
0 by 350 pix, 3 nm/pix, FT, x step 3 nm, distance 9800 nm, wavelength 0.62 to 1.2
0 by 350 pix, 3 nm/pix, FT, x step 3 nm, distance 9800 nm, wavelength 0.62 to 1.2
2.3
0
-192
191
Vertical profile, row 4 pic801
Horizontal profile, row 4 pic801

NATIONAL UNIVERSITY of SINGAPORE

Experimental Results: Single exposure

Yuli Vladimirsky July 14, 2000

Mask line-width 223 nm, $k_w = 1.62$ Resist trench-width 25 nm, $k_e = 0.18$



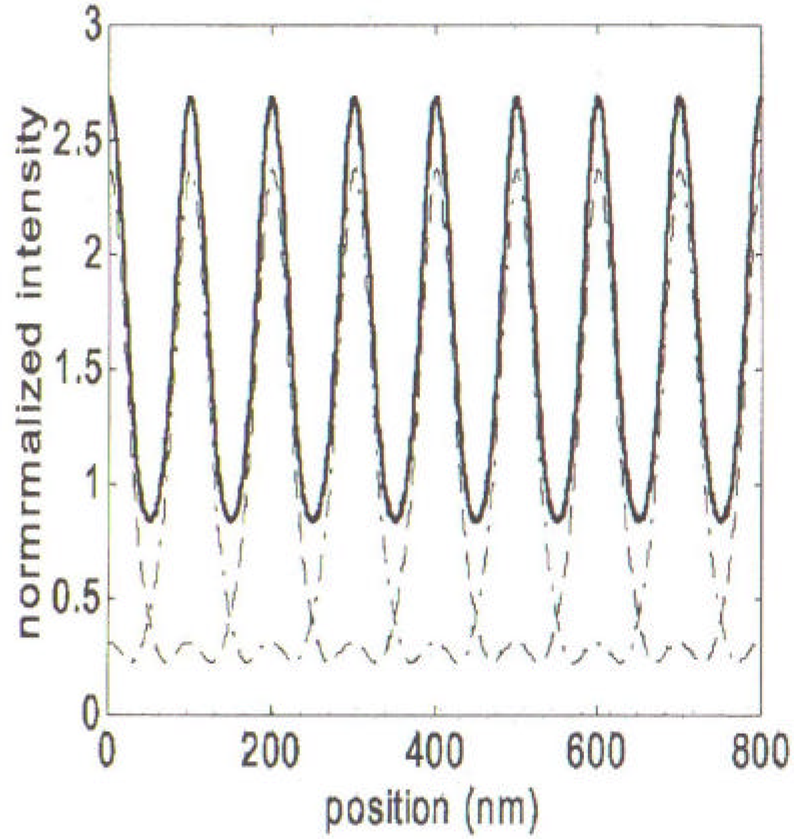
28-25 nm lines

9x demagnification achieved at 20μm mask-wafer gap on 100nm thick PMMA

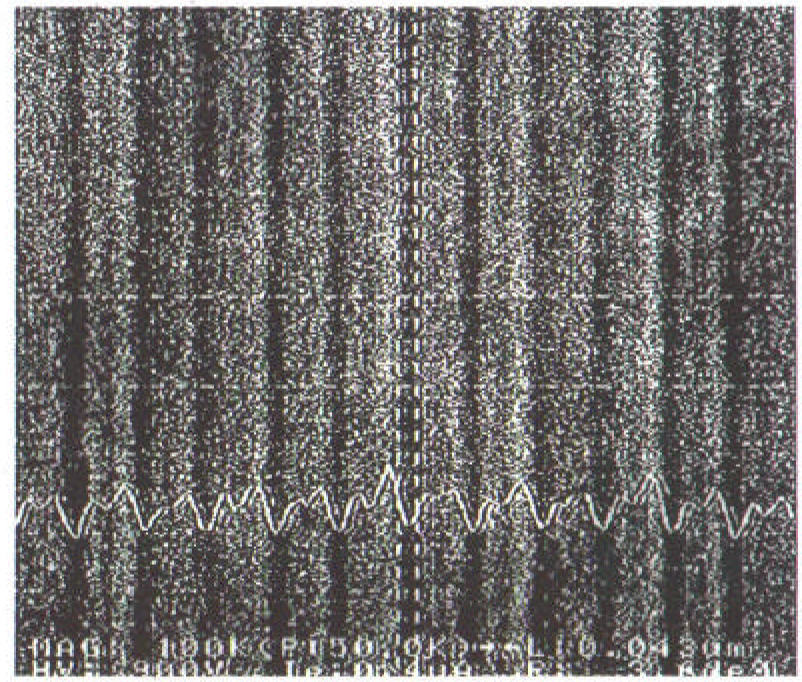
Double Exposure-Single Development

SVG Silicon Valley Group Lithography Systems

NanoTech Wisconsin



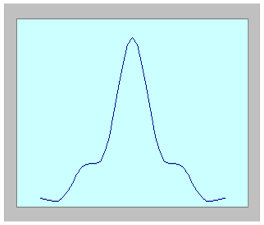
Simulation results showing double exposure



43 nm lines with155 nm pitch obtained by a double exposure-single development technique (mask pattern with 310 nm period and 160 nm features)

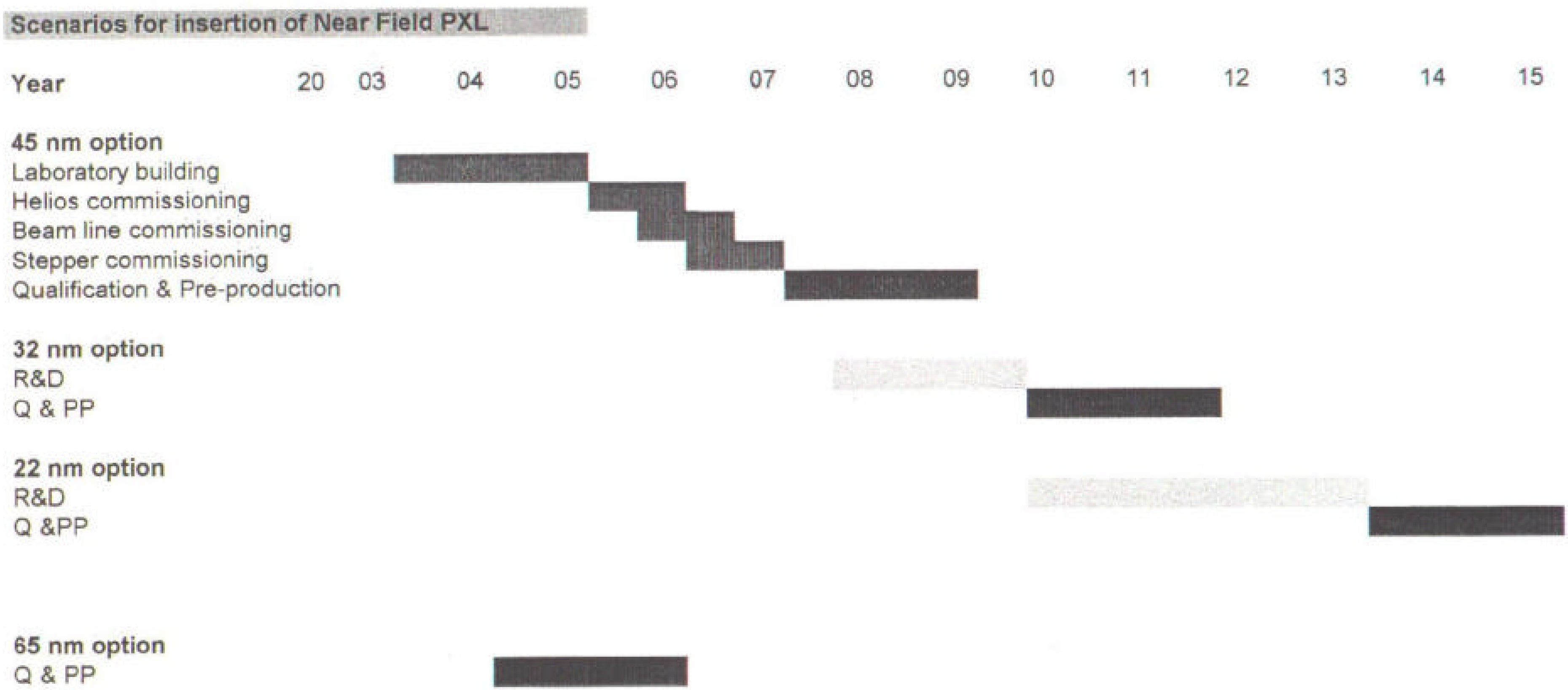
Attractions

• With Small R&D Investment
• Reduce total cost by strategic selection of
  - demonstrated technology with
  - long extensibility
• Given the maturity, implementation possible depending on company needs.



Moving Forward

- Let Jefferson expertise manage the overhead
  - Build a beamline on Helios-1
- Industrial application with 0.8 nm x-rays
  - from immediate needs to 25 nm
  - including manufacturing by exposing in SMIF modules, with low overhead
  - start tests on point sources
- R&D with 0.4 nm x-rays
  - extend to 15 nm
- Technology transfer and license


Scenarios for insertion of Near Field PXL
Year
20 03
04
05
06
07
08
09
10
11
12
13
14
15
45 nm option
Laboratory building
Helios commissioning
Beam line commissioning
Stepper commissioning
Qualification & Pre-production
32 nm option
R&D
Q & PP
22 nm option
R&D
Q &PP
65 nm option
Q & PP

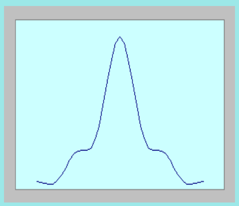
Appendix C - Talk 2

Yuli Vladimirsky, Uhrl Masc, Inc.

Extensibility of Proximity X-Ray Lith nm imaging

Yuli Vladimirsky

Antony J Bourdillon



Contributors:
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(CNTech, Wisconsin)

X-Ray Lithography, towards 15nm

Workshop at

Thomas Jefferson National Laboratory

Newport News, Virginia

January 24, 2003

Outline

- ***Why the X-Ray Lithography was not given the “green light”?***
- ***Demagnification-by-bias or low-k imaging***
- ***<u>Extendibility down to 15 nm</u>***
- ***Short wavelength l : 4-6Å***

Why the PXL was not given the "green light" ?

☺ **Among the sub-100 nm NGL techniques the PXL is still the most advanced and mature.**

😐 **The 1999 and 2001 ITRS Lithography Roadmaps kept open the "back" door for PXL for sub-100 down to 22 nm technology nodes.**

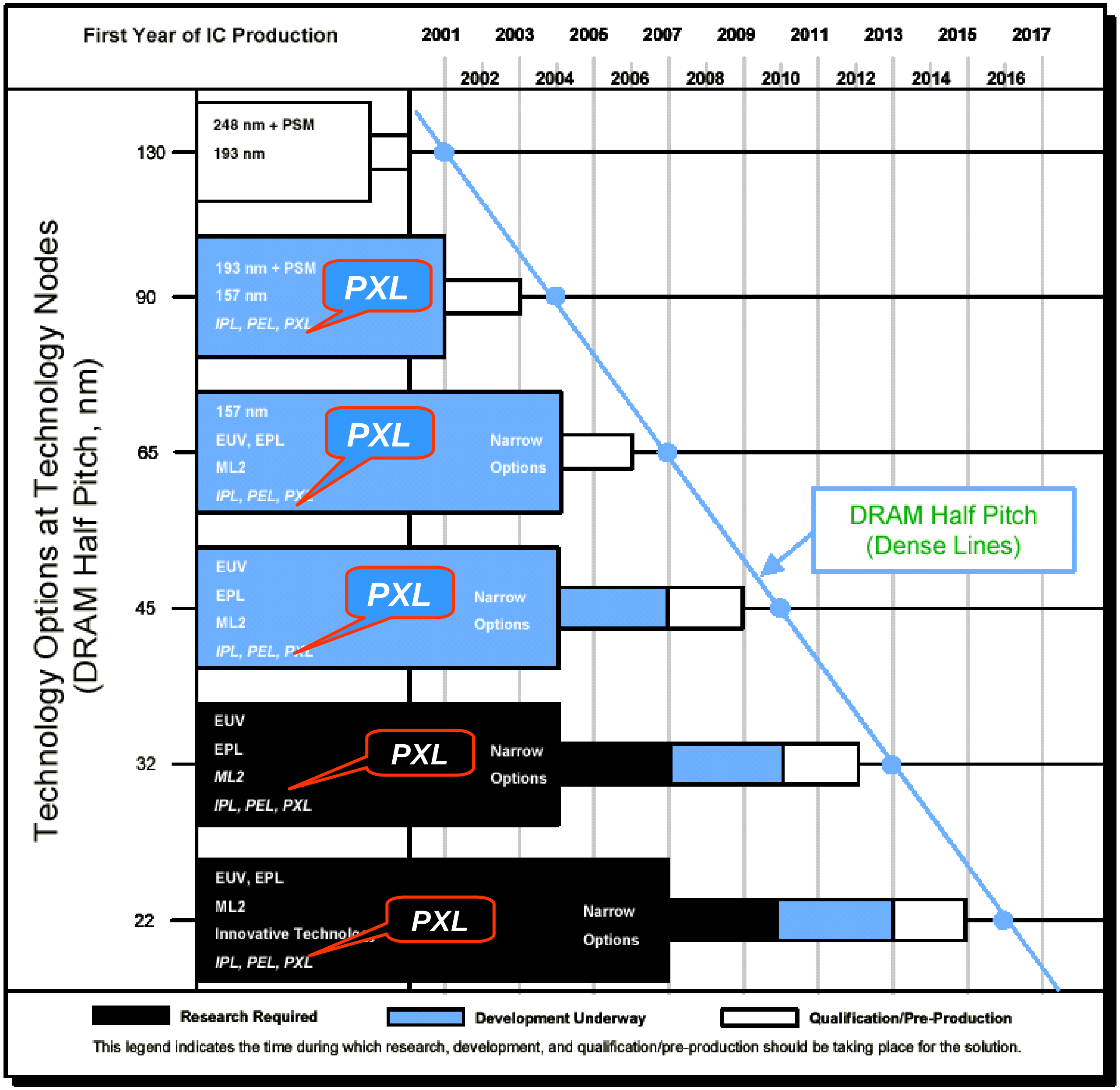
However

☹ **Classical PXL requires the use of a 1´ mask,**

☹ **Small <5-7 mm mask/wafer gap poses an increased risk of mask damage and imposes strict requirements on the mask flatness.**

💣 **The lack of a clear path to 25nm resolution together with the reasons stated above have accounted largely for the hesitation in adoption of PXL as the next generation lithographic technology resulting in the scaling down efforts in this area.**

2001 ITRS Lithography RoadMap



Lithography Exposure Tools Potential Solutions

EUV- extreme ultraviolet

EPL- electron projection lithography

ML2- maskless lithography

IPL- ion projection lithography

PXL- proximity X-ray lithography

PEL- proximity electron lithography

Extendibility of Proximity XRL to 25 nm

Lines patterned at k<0.7

0.50 < k < 0.7

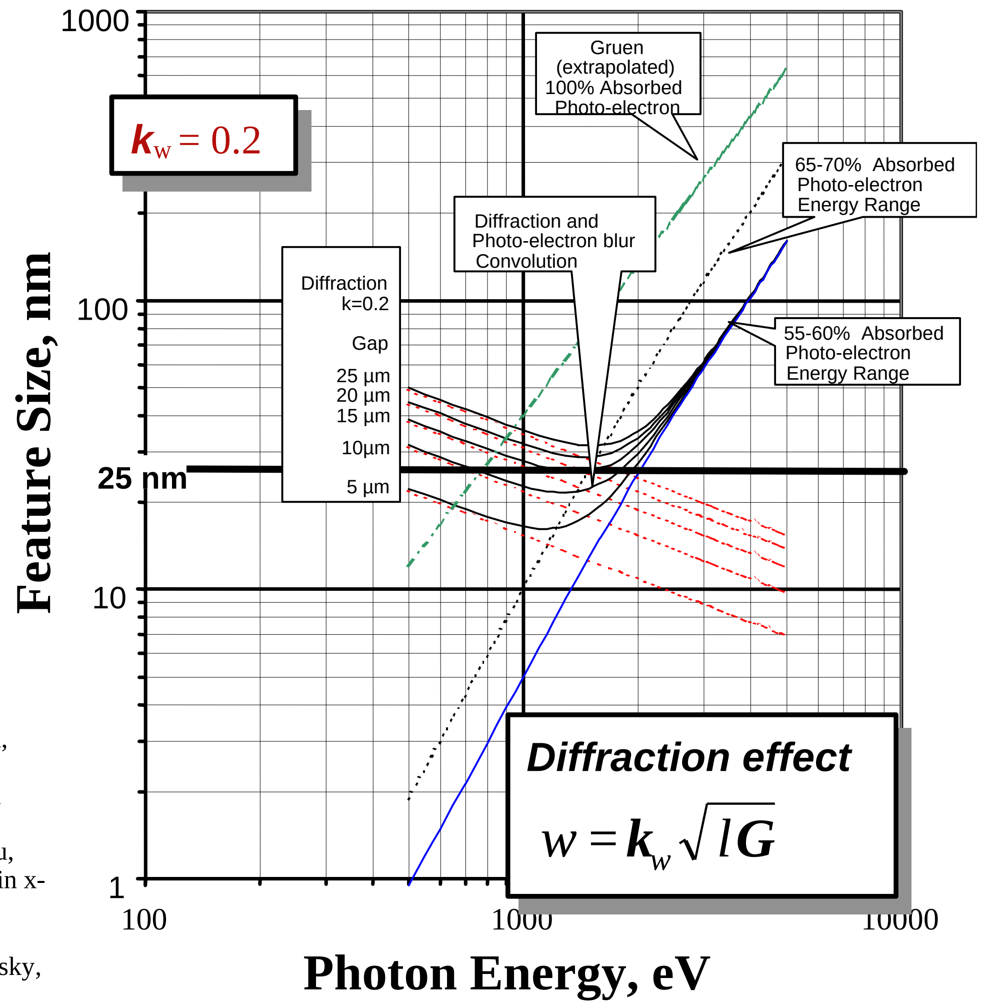
0.24 < k < 0.50

0.18 < k < 0.22

w nm	Gap µm	*k*	λ Å	Ref
100	25	0.67	8.8	1,2
90	15	0.62	14	
80	10	0.68		
50	5	0.67	11	
24	1	0.69	12	
16	0.5	0.65		
93	30	0.54	10	3
85	20	0.60		
52	15	0.45	9	4
60	15	0.49		
65	30	0.37		
40	30	0.24		
32	25	0.22	9	5
28	25	0.19		
25	25	0.18		

1. F. Cerrina, "X-Ray Lithography", Ch.3 in **Handbook of Microlithography, Micromachining, and Microfabrication 1,** ed. P.Rai-Choudhury, pp. 253-319 (SPIE Press, Bellingham, Washington, USA, 1997)
2. L.E.Ocola, "Electron-Matter Interactions in X-ray and Electron Beam Lithography", Ph.D. Thesis, UW-Madison (1996)
3. K.Fujii, Y. Tanaka, T.Taguchi, M.Yamabe, Y. Gomei, and T.Hisatsugu, "Low-dose exposure technique for 100-nm diameter hole replication in x-ray lithography" *J. Vac. Sci. Technolog.*, **B 16(6),** (Nov/Dec 1998)
4. **Sub-100nm Imaging in X-ray Lithography**, O. Vladimirsky, N. Dandekar, W. Jiang, Q. Leonard, K. Simon, S. Bollepalli, Y. Vladimirsky, J.Taylor, *SPIE Proc* Vol. **3676**, (1999)

Imaging 25 nm features at 15 µm mask/wafer gap



Diffraction effect

$$w = k_w \sqrt{\lambda G}$$

Image Formation in PXRL

Diffraction of x-rays l = 8Å from a 150 nm slit

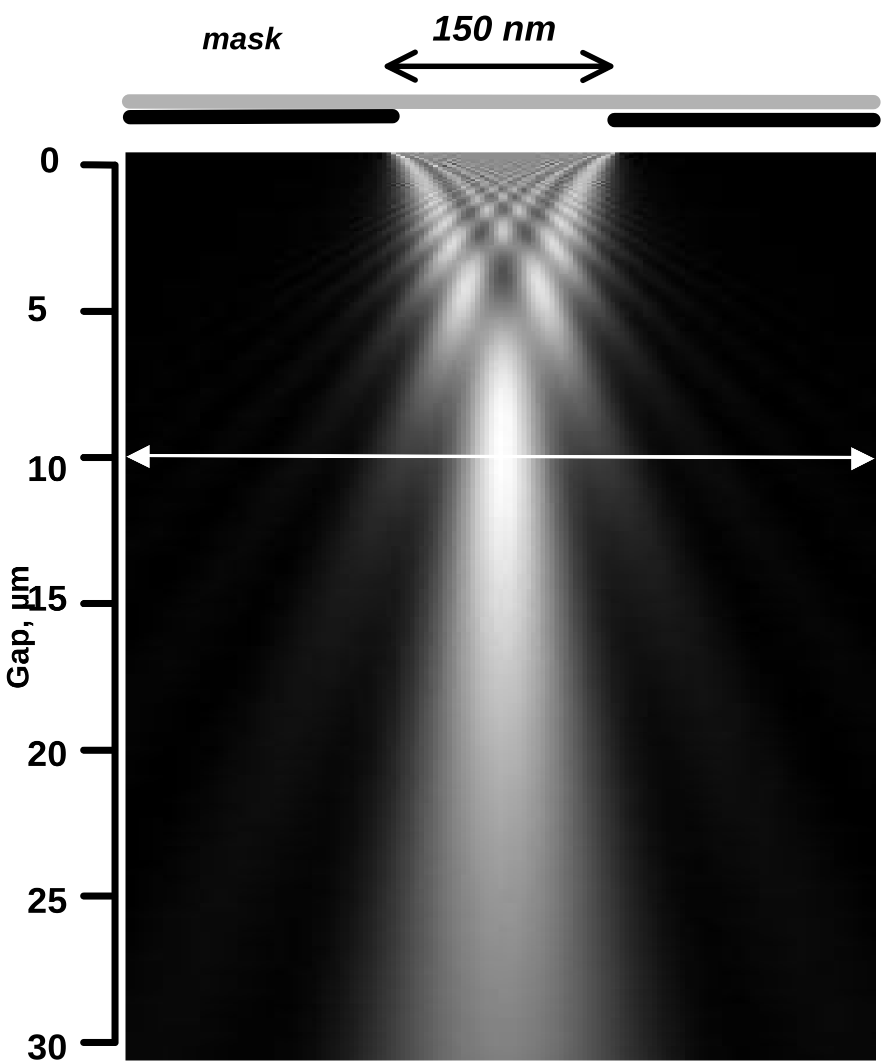


Image formation in proximity is described by Fresnel diffraction
The relation between feature size *w*, wavelength l , and distance *G* from the object to the "image" plane, can be formulated in terms of the number of Fresnel (half-wavelength) zones. Reliable in terms of fidelity imaging requires at least two Fresnel zones.

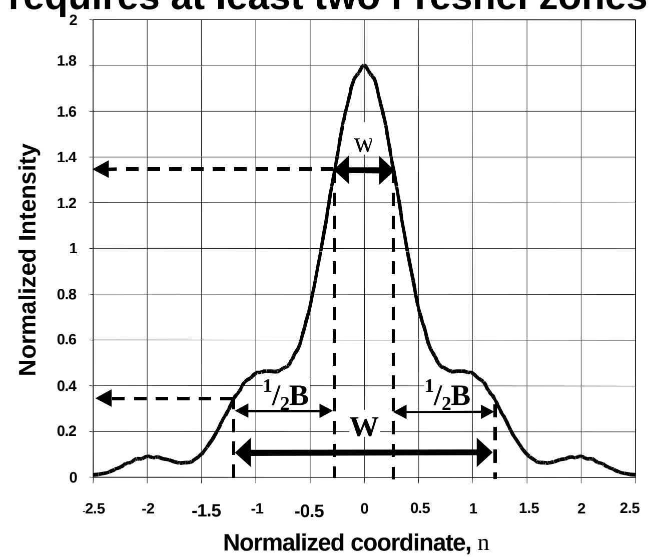
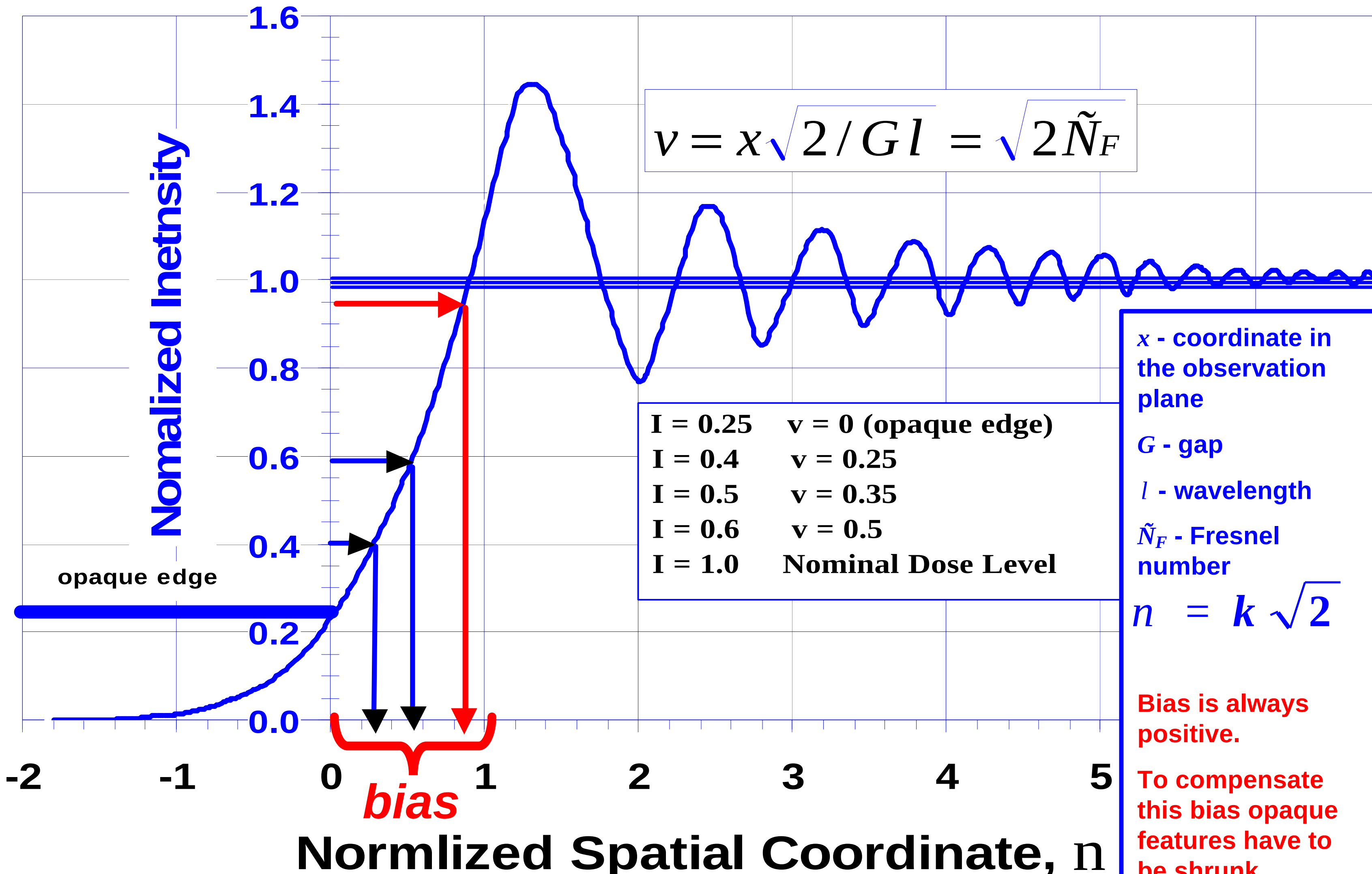


Figure 1. Diffraction profile of a slit

$$w_{prx} = k\sqrt{lG}\ ; \quad k = 1.4,\ 1.0,\ 0.7\ldots\ 0.1\ ?$$

Lithographic Bias Formation



x - coordinate in the observation plane

G - gap

l - wavelength

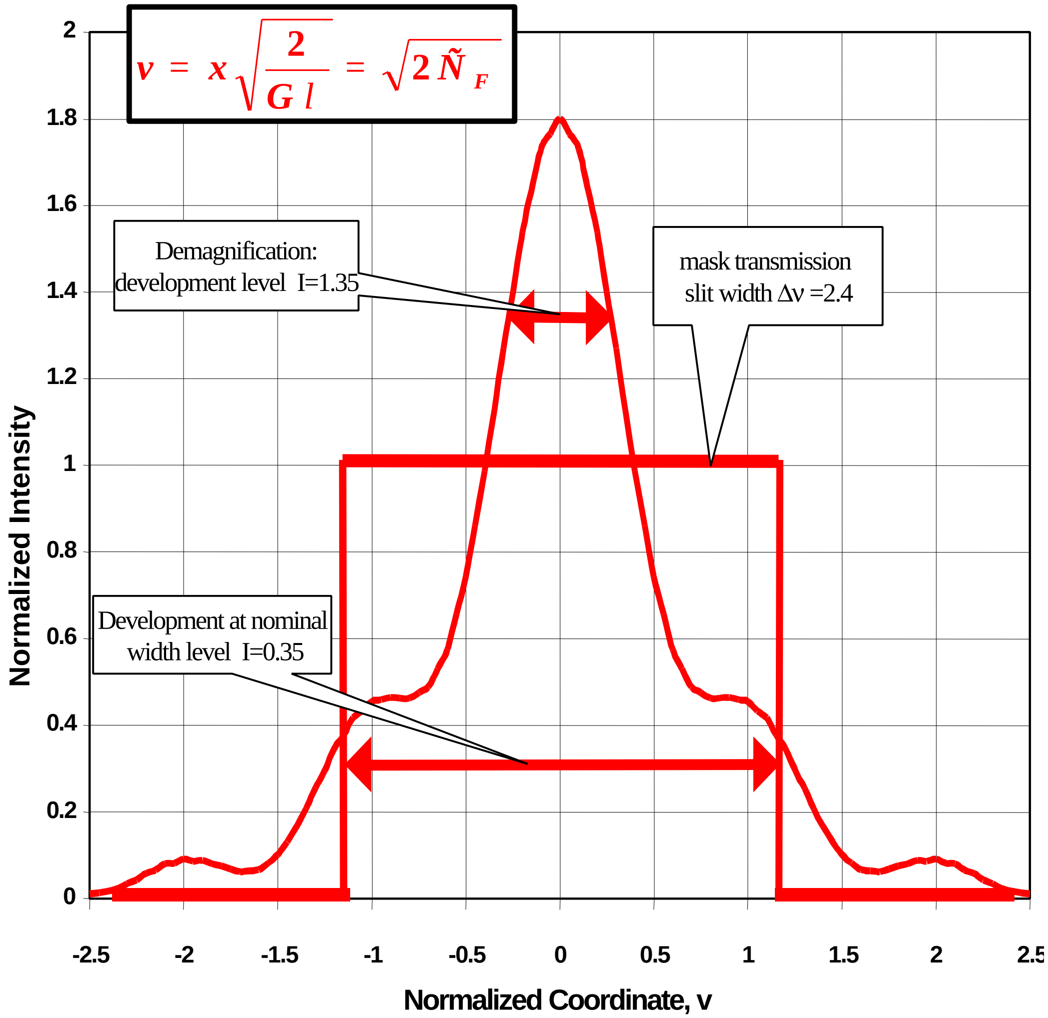
$\tilde{N}_F$ - Fresnel number

$n = k\sqrt{2}$

Bias is always positive.

To compensate this bias opaque features have to be shrunk

Demagnification-by-Bias



Diffraction pattern profile of a slit.

Two-side bias:

$$B \approx (0.3 \div 1)\sqrt{\lambda G}$$

mask feature size

$$W = k_W\sqrt{\lambda G} \approx (1.2 \div 1.7)\sqrt{\lambda G}$$

printed feature size

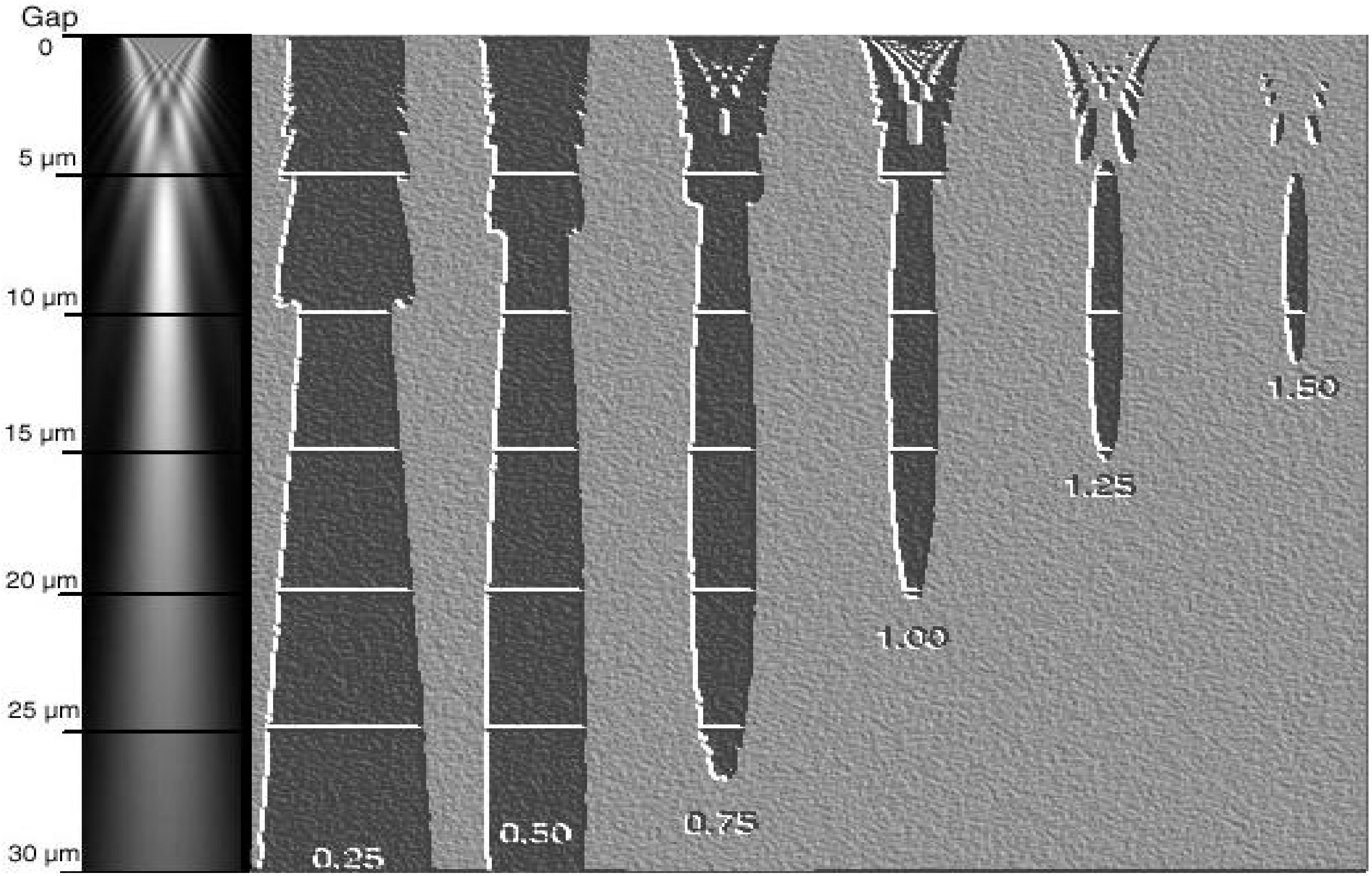
$$w = W - B = k_w\sqrt{\lambda G} \rightarrow 0.2\sqrt{\lambda G}$$

demagnification

$$D_{emag} = W/w = k_W/k_w = \times 2 \div \times 6$$

× 2 to × 6 demagnification by bias can be achieved in PXRL (without lens)

Computer Simulation



A 150 nm line as it would be seen after development at different levels

Region of special interest

The slope of the straight sections of the lines is practically the same as for 1´ line. The shift along the ordinate axis represents bias.

region of interest (90-170 nm):

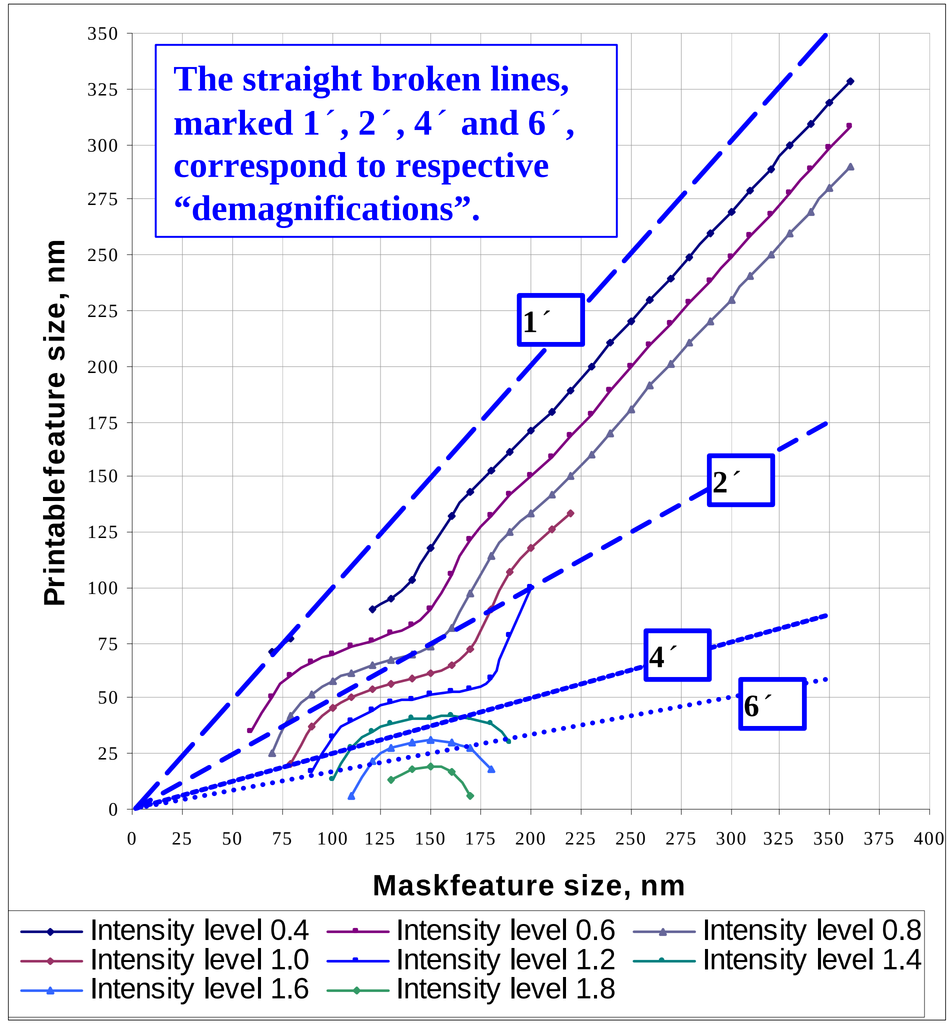
a) high degree of demagnification can be achieved

b) resist feature size only slightly depends on the mask feature size,

c) the curves corresponding to different dose levels are positioned closer to each other compared with other regions.

These aspects can be translated into enhanced linewidth control, relaxed mask CD requirement, and reasonably wide dose latitude.

Levels between 1.6 and 1.8 yield 20-30 nm features from a 150 nm mask ~4´-6´. demagnification



Printable feature size of an isolated slit vs. mask feature size at 10 µm gap and 10nm blur

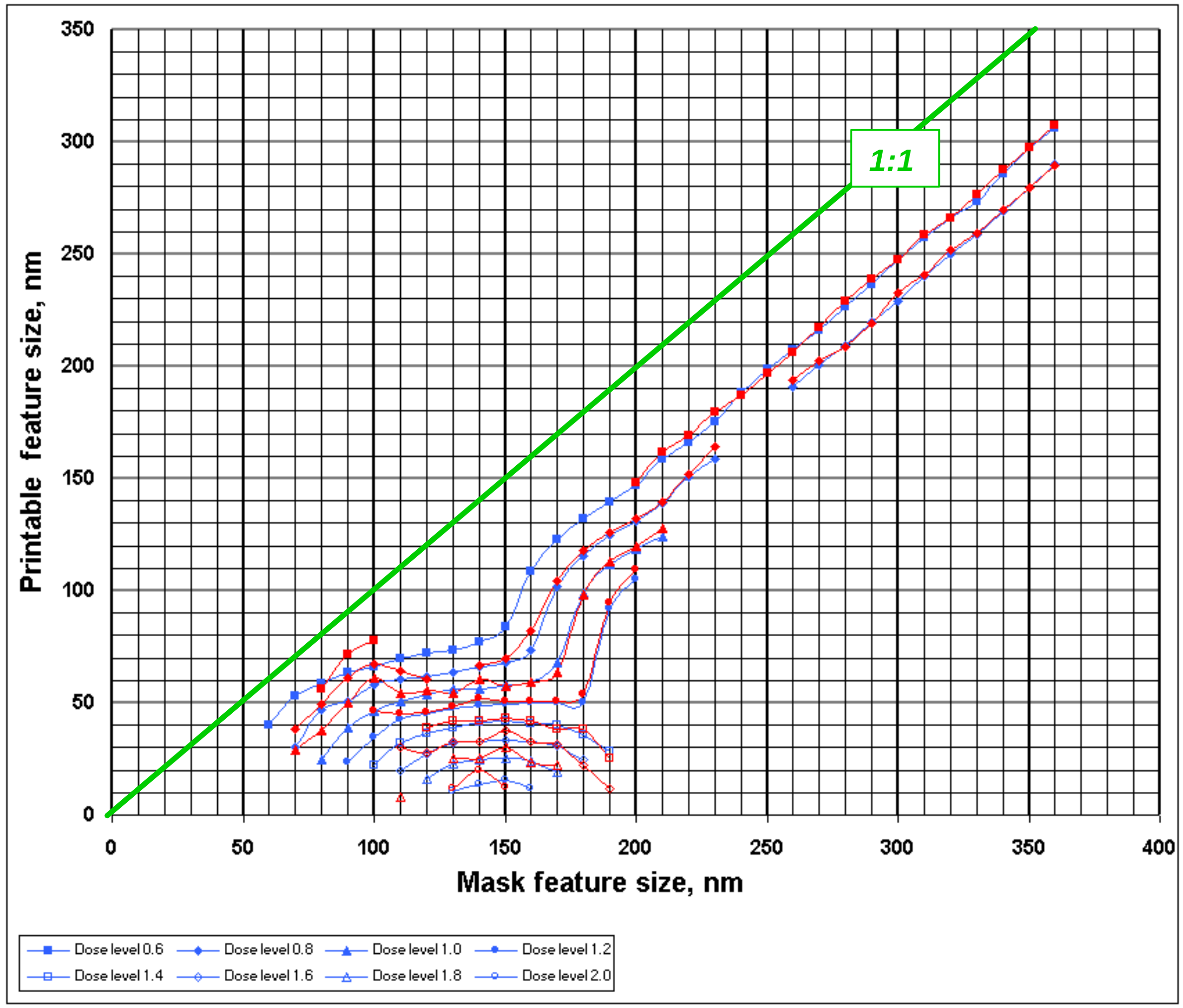
Isolines and Lines&Spaces

Computer simulation for isolated spaces and equal line/space features at a 10-µm gap.

Obtained sets of curves are very similar. This is an indication that at the same conditions both feature types will be printed simultaneously.

Some difference between these sets of curves can be observed for mask features smaller than 90 nm.

The interruptions in the curves are due to strong intensity oscillation in some image profiles.



Printable resist feature size vs. mask feature size at 10-µm gap (no blur) at different "development" levels.
blue - isolated spaces, red– equal lines and spaces

Diffraction Scaling

Three sets of curves for eight "development" levels correspond to 10, 20, and 30 μm mask/wafer gaps. The blur for all three gaps was 10 nm.

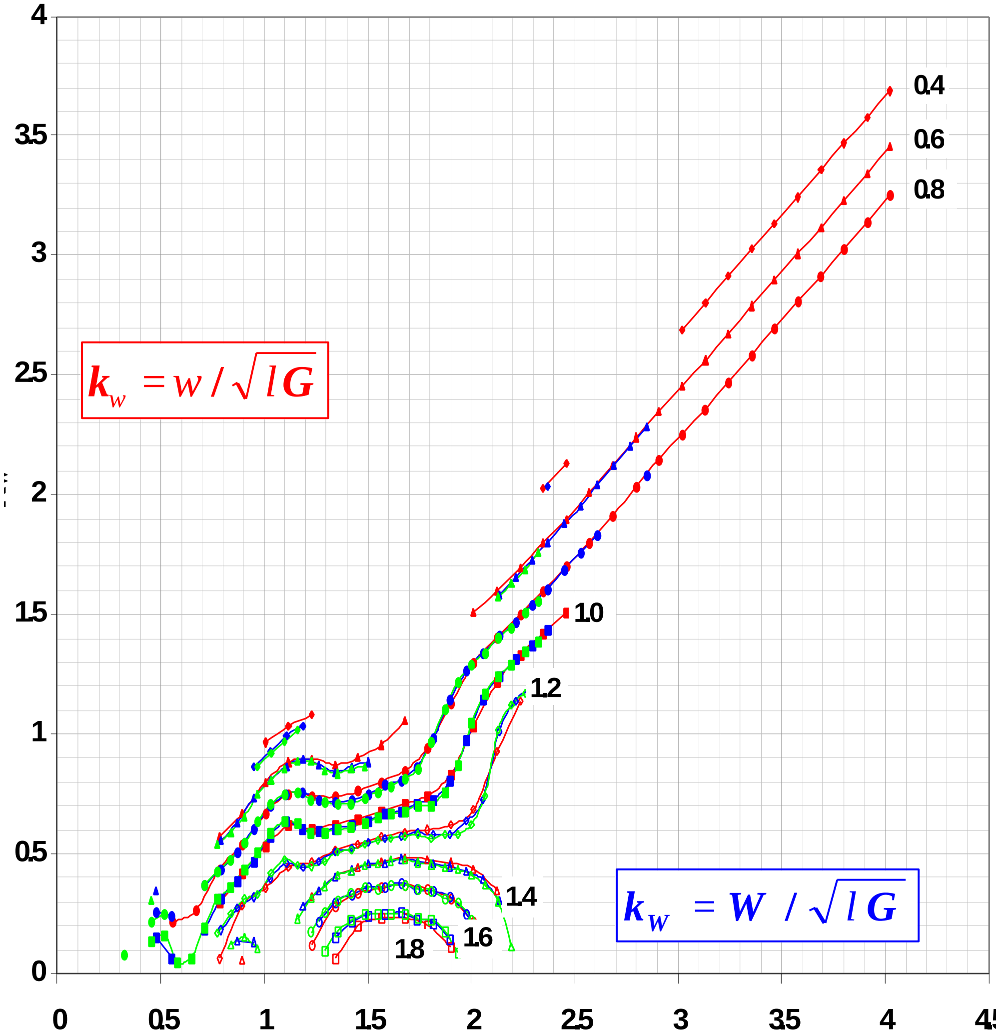
reveals very good overlap of the curves.

A special region in the vicinity of *k*-values of *k* = 1.2 to 1.9 can be very clearly identified.

Only a slight dependence of the printed feature size is observed.

The curves corresponding to different dose levels are positioned close to each indicating wide dose latitude.

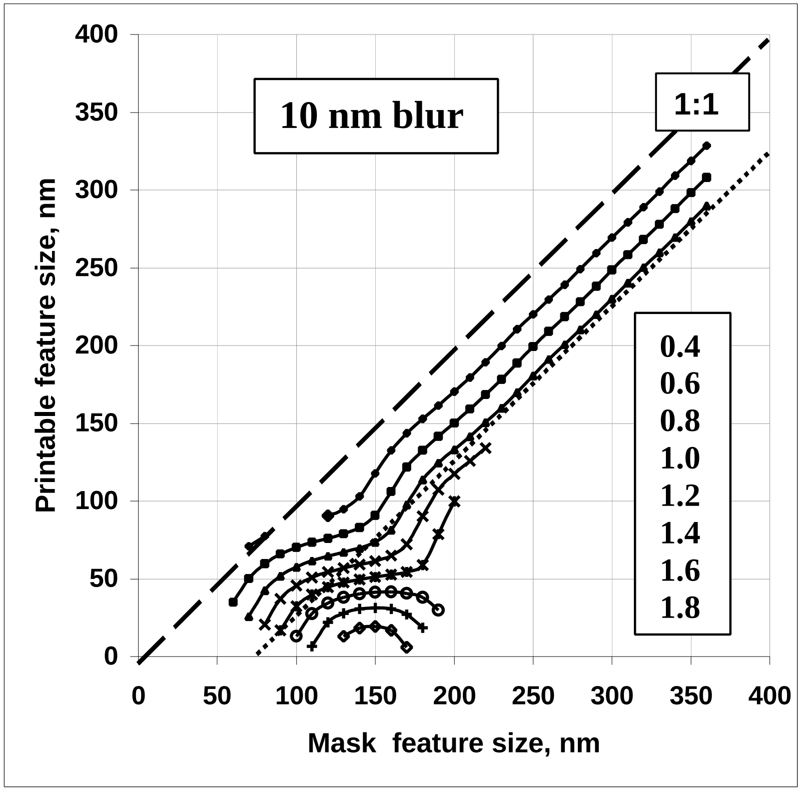
The typical intensity profile in this region (k_W = 1.7) is presented in Fig.1. The steep slopes of the central lobe are the reason for this behavior.

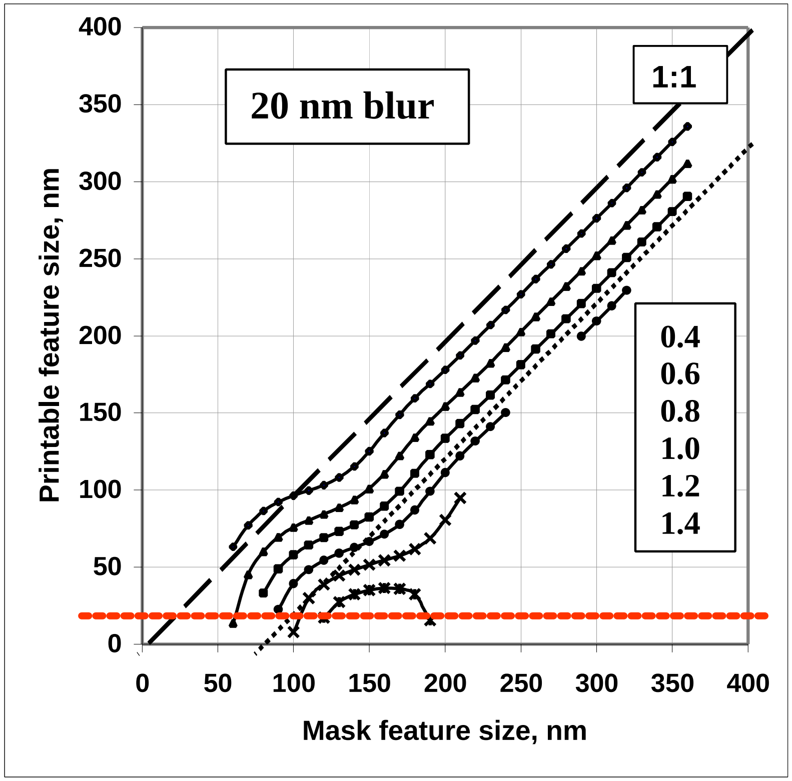


Normalized presentation of equal line/space features printability

Demagnification in PXRL -Blur

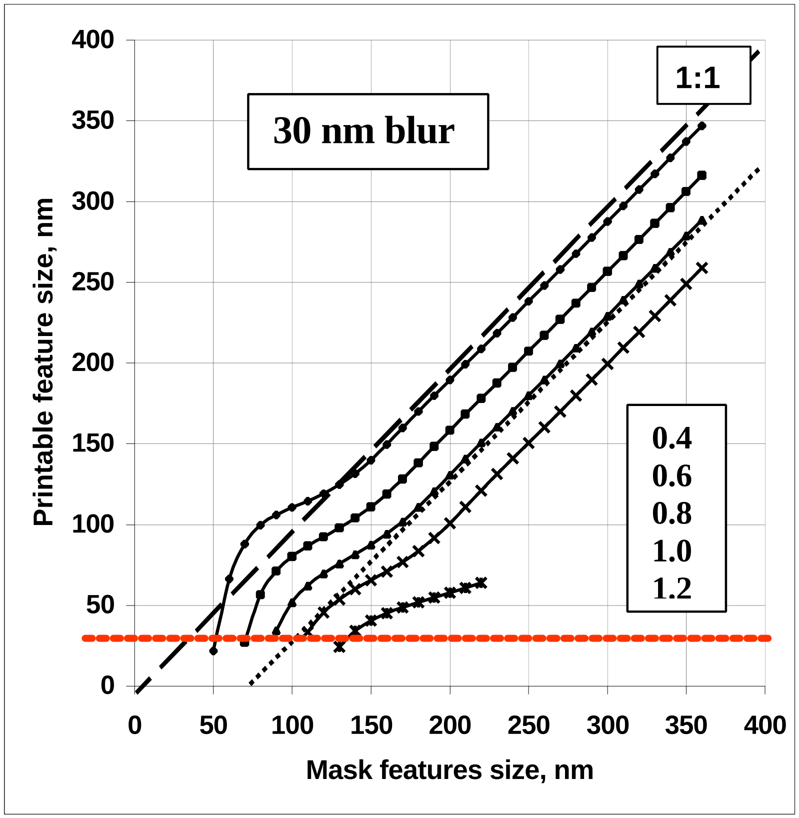
Adding incoherent blur tends to smooth the curves, but does not alter their general slope . The blur increases the printed feature size, but only for the levels less than 0.8. For the 30 nm blur the response curve, corresponding to level 0.4, practically coincides with the 1:1 reproduction line. The blur of 30 nm could be considered as an optimal for 1-to-1 replication at a 10-µm mask/wafer gap. For the 50 nm blur the printed spaces will be larger than on the mask. There is no change for the dose level 0.8. Development" higher than 0.8 produces smaller linewidth with increasing blur

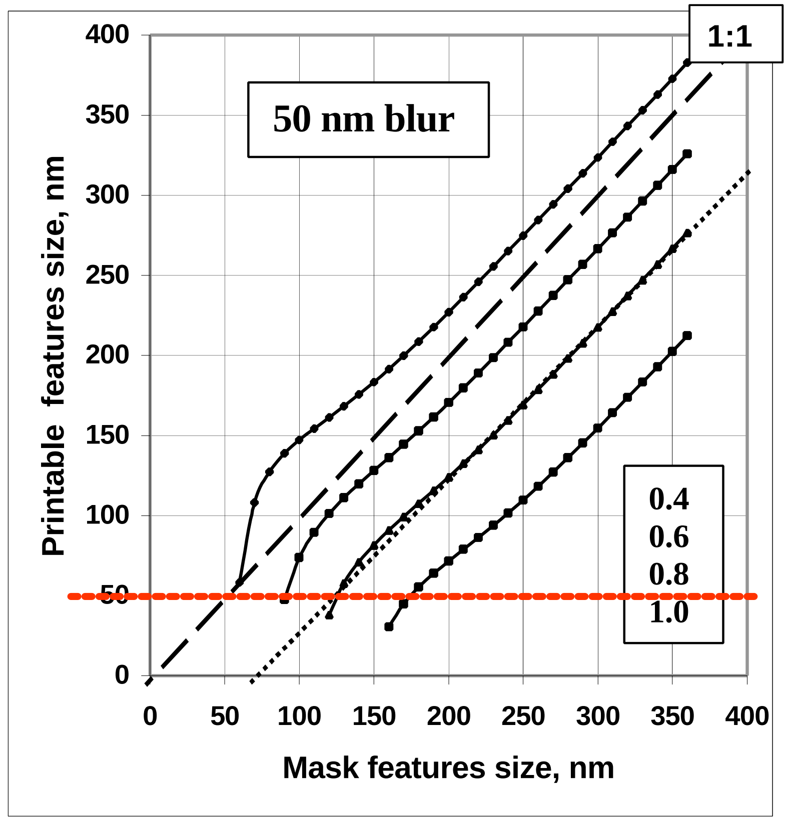




Demagnification in PXRL - Blur

Excessive blur narrows the dose latitude: the distance between neighboring curves along the ordinate is increasing. For the mask feature sizes above 150-160 nm this change small, when the blur is in 10 nm to 30 nm region: with DD/D=10% per ~8-10 nm. 50 nm blur dose variation of DD/D=10% will produce up to 35 nm linewidth changes. In the region of 100 to 160 nm the dose latitude deteriorates for a blur above 10 nm, and demagnification-by-bias could require more stringent control of the blur, compared with conventional proximity imaging.



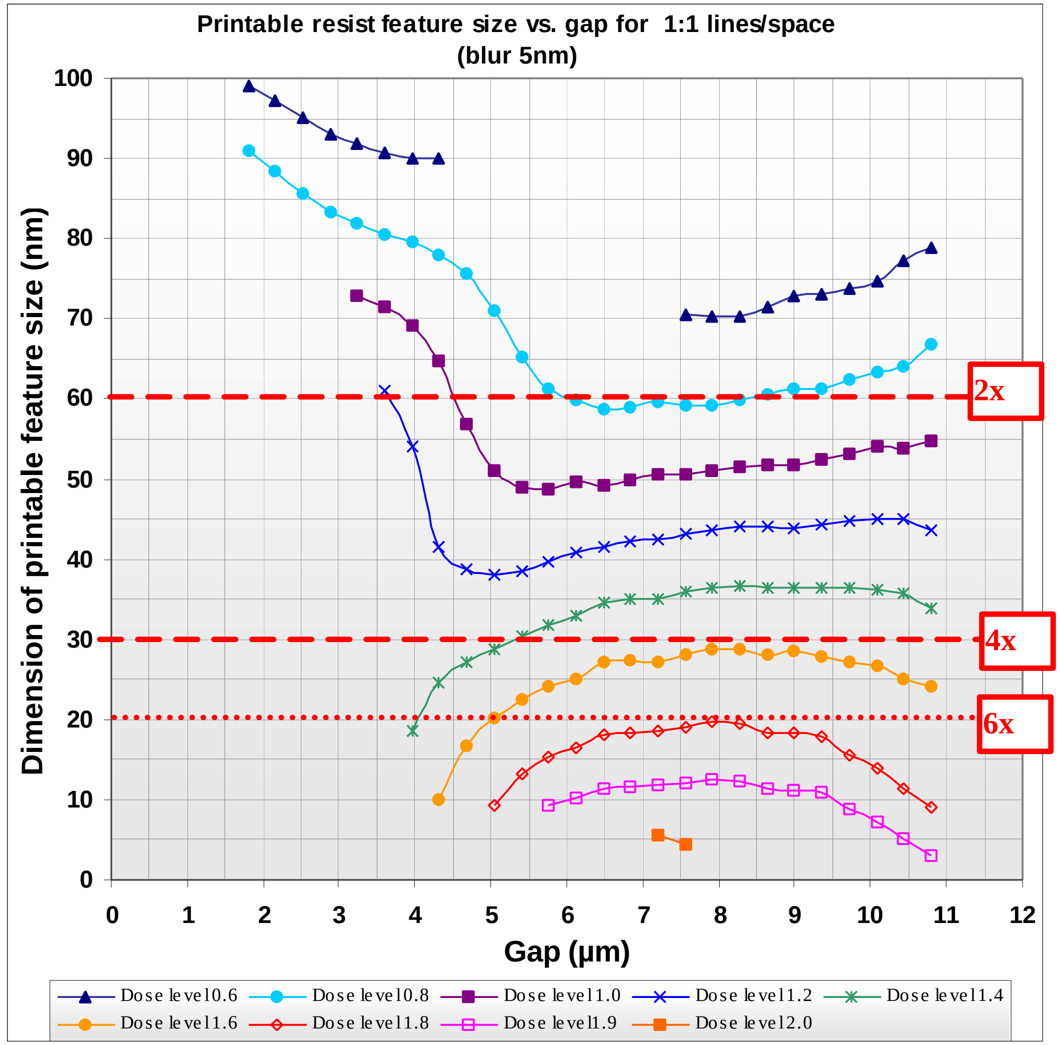


Mask/Wafer Gap

A series of calculations was undertaken to address the sensitivity of demagnification-by-bias approach to the mask/wafer gap variation.

The gap was varied from 1.5 to 11 µm for the 120 nm clear feature of a 1:1 line space pattern and the simulation results are shown.

In this figure the "demagnification lines" are horizontal. Features below 100 nm and as small as 15 nm can be produced at wide range of gaps from 5 to 10 µm, demonstrating large "depth of focus".

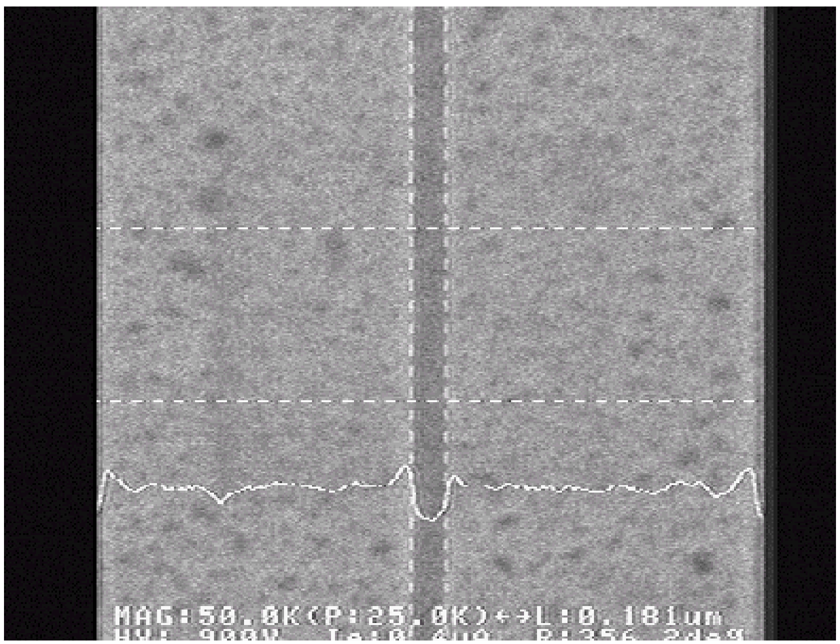


Printable resist feature size vs. gap for 120nm 1:1 lines/space and 6 nm blur

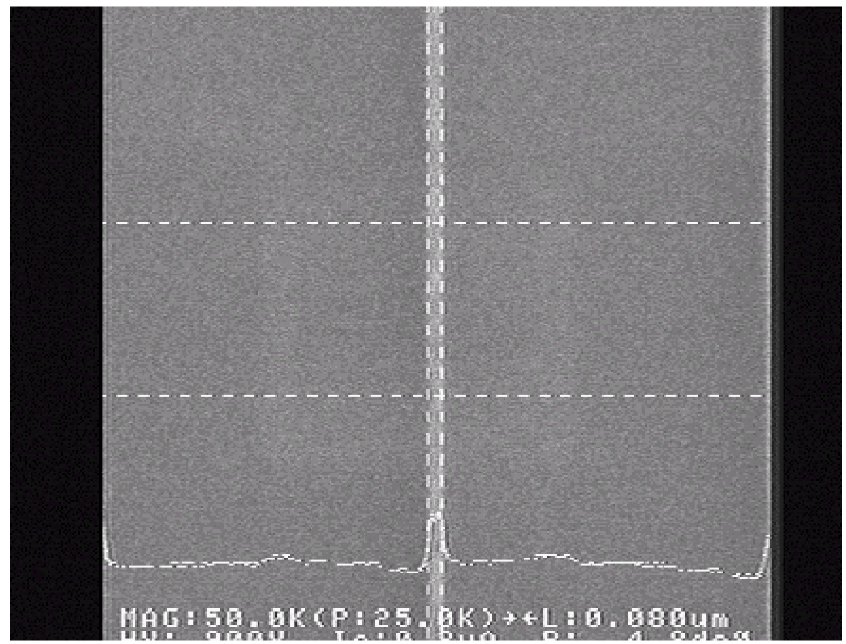
Isolated lines formation

Printing Isolated lines from Isolated lines

mask line width 181 μm



printed line width 80 nm

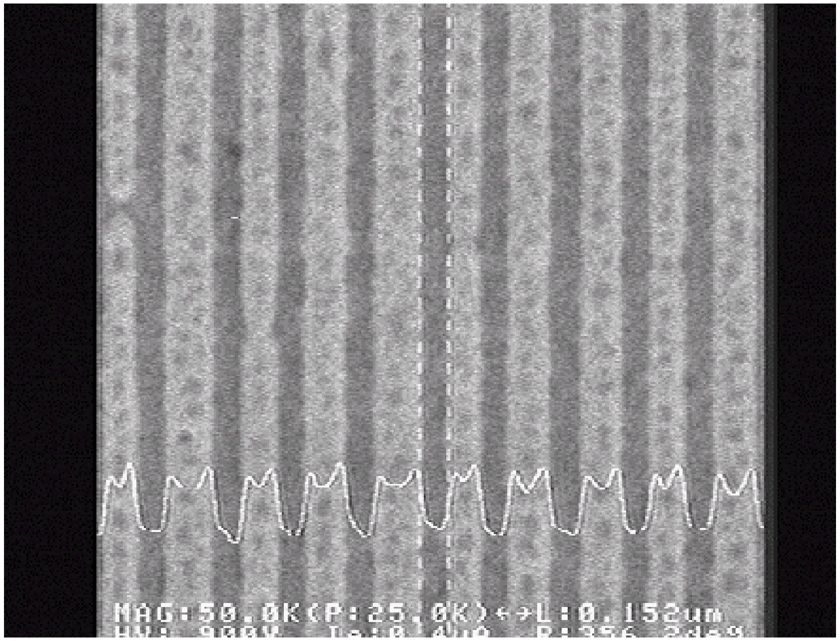


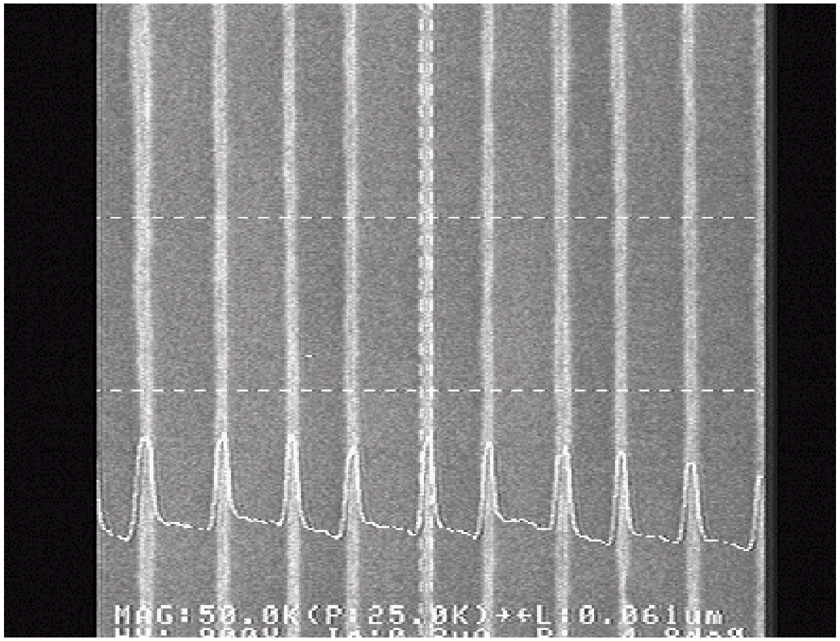
2.3X demagnification achieved at 30 μm mask/wafer gap in 0.5μm thick negative resist using mask with isolated features

Isolated lines formation

Printing Isolated lines from Nested lines

mask line width 152 nm | **printed line width 61 nm**



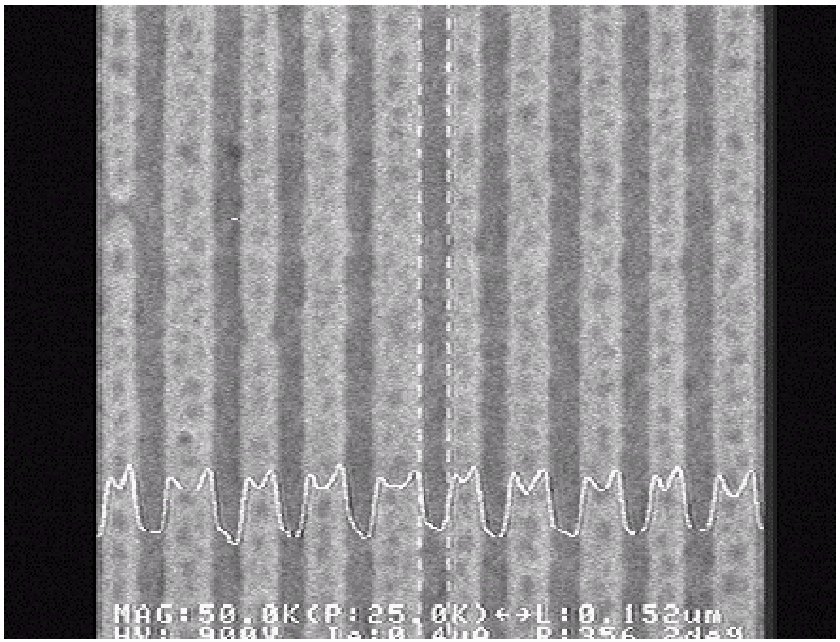


2.5X demagnification achieved at 30 µm mask/wafer gap in 0.5µm thick negative resist using mask with nested features

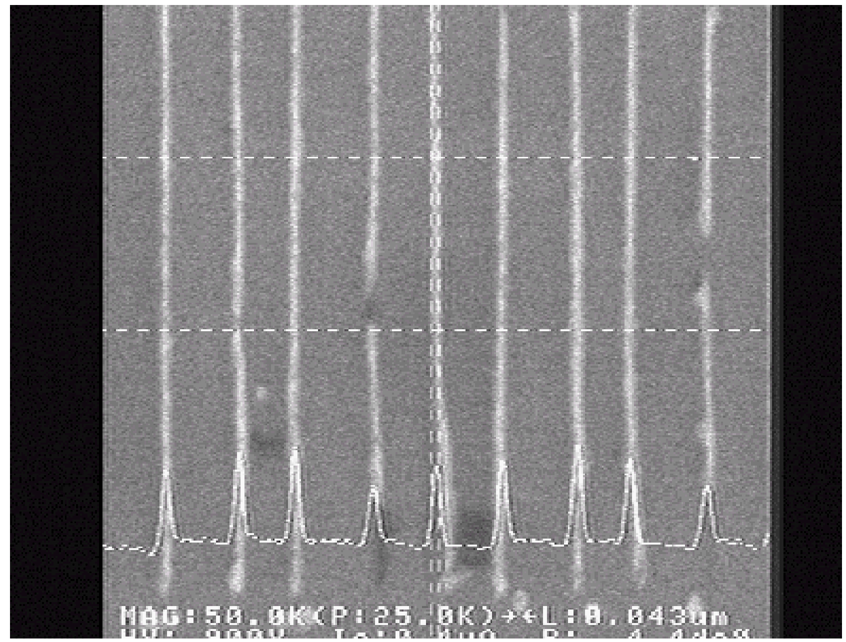
*** formed lines demonstrate smoothing effect during printing**

3.5 X Demagnification

mask line width 152 nm



Line width 43 nm

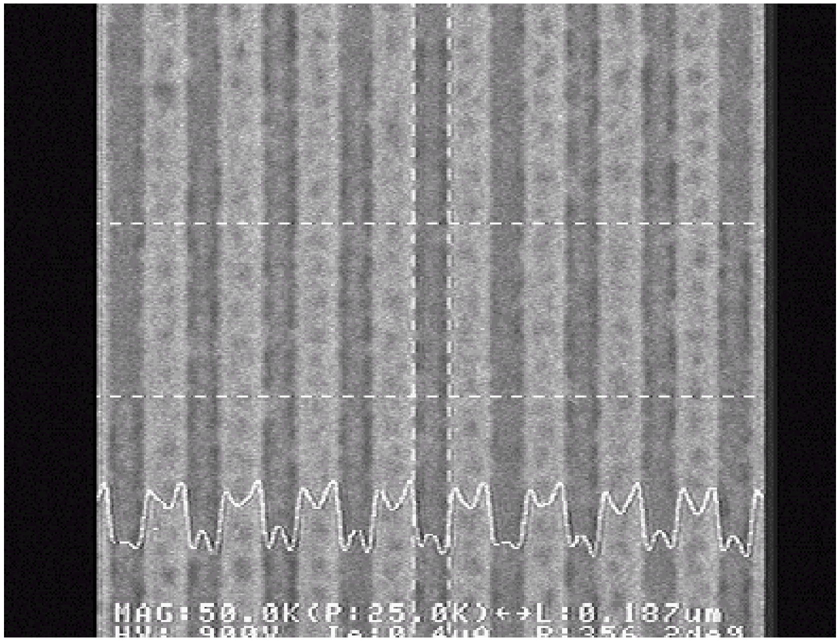


3.5X demagnification achieved at 30 μm mask/wafer gap in 0.5μm thick negative resist using mask with nested features

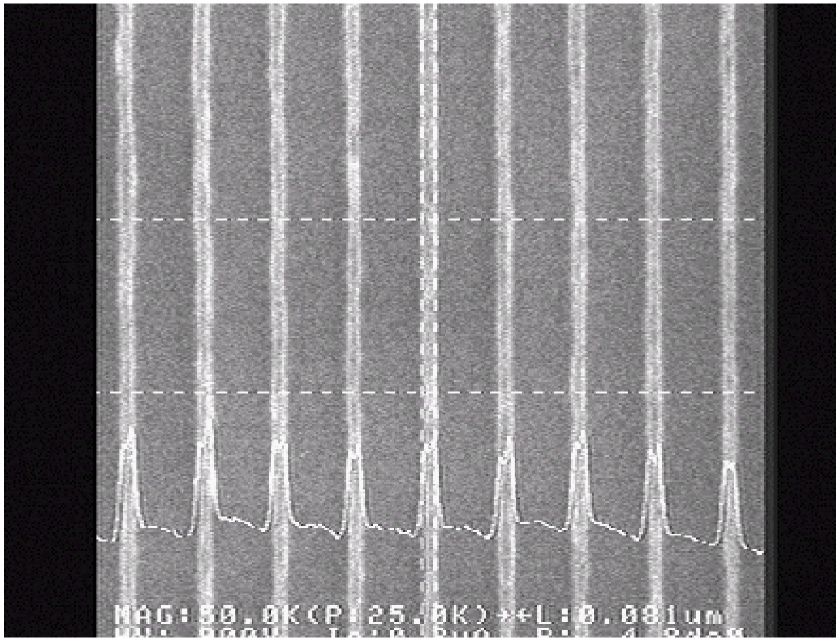
(the lines show signs of collapsing due to very high aspect ratio > 12)

2.3X Demagnification

mask line width 187 nm

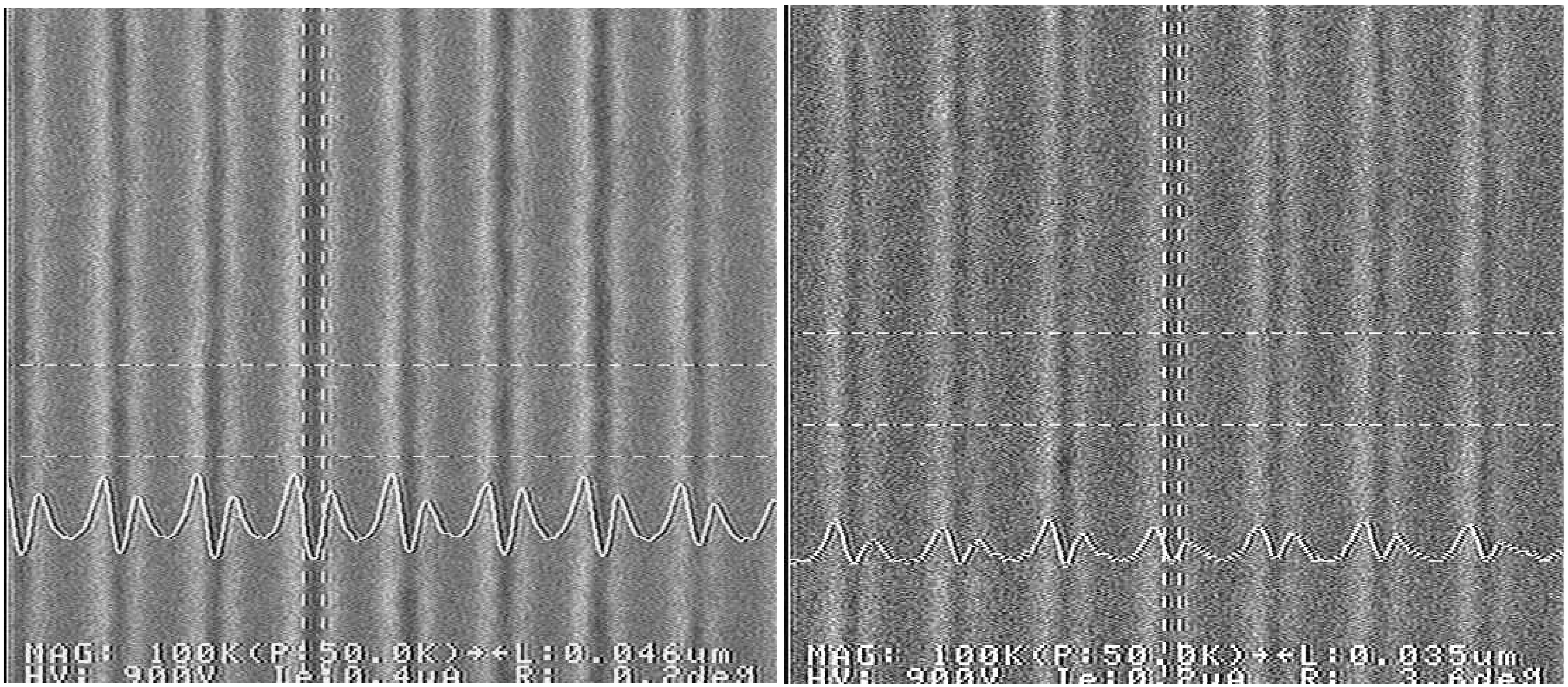


printed line width 81 nm



2.3X demagnification achieved at 30 μm mask/wafer gap in 0.5μm thick negative resist using mask with nested features

3.5X Demagnification - Finer Features



46 nm and 35 nm lines produced in positive resist from 150 nm spaces in mask

Absence of Resolution Degradation in X-ray Lithography

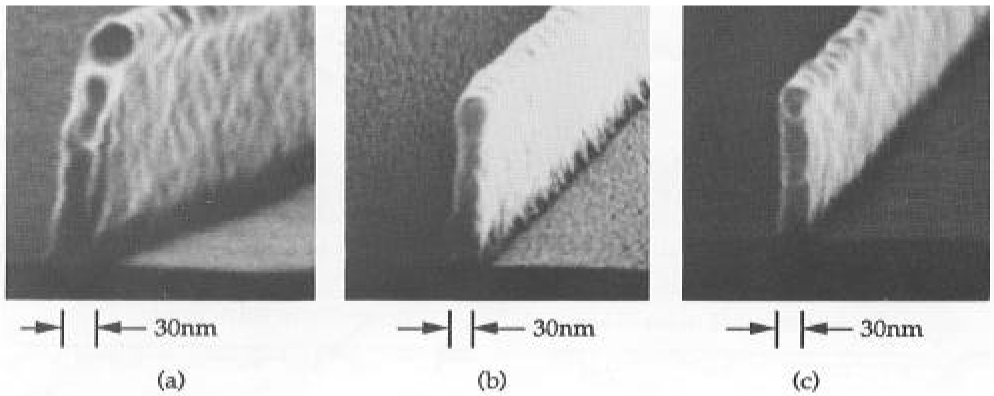


Figure 3. Replication in PMMA of a 30nm-wide gold absorber line with (a) C_K (λ= 4.5nm), (b) Cu_L (λ = 1.3nm), and (c) Al_K (λ = 0.83nm).

K.Early, et al.: Absence of resolution degradation in X-ray lithography , *Microelectronic Engineering* **11** (1990) 317-321

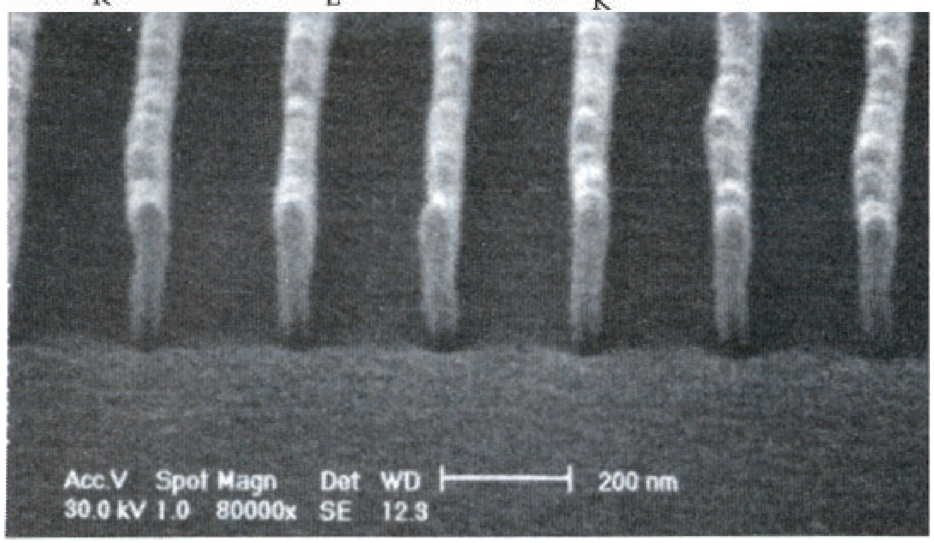


FIG. 6. SEM image of 20 nm lines replicated in PMMA under soft-contact printing condition ($g<2\ \mu$m).

Chen et al.: Edge diffraction enhanced printability in X-ray lithography , *J. Vac. Sci. Technol.* **B 16 (6)** , Nov/Dec 1998, 3521-3525

Absence of resolution degradation

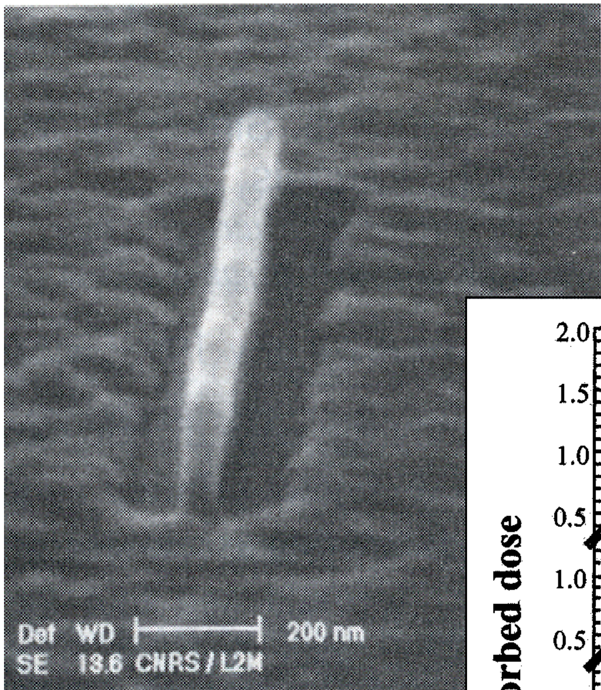


FIG. 3. SEM images of the PMMA resist profiles of an isolated line obtained at 1 μm with approximately 75% of the full expose condition showing the *edge diffraction effect*.

Chen et al.: Edge diffraction enhanced printability in X-ray lithography , *J. Vac. Sci. Technol.* **B 16 (6)** , Nov/Dec 1998, 3521-3525

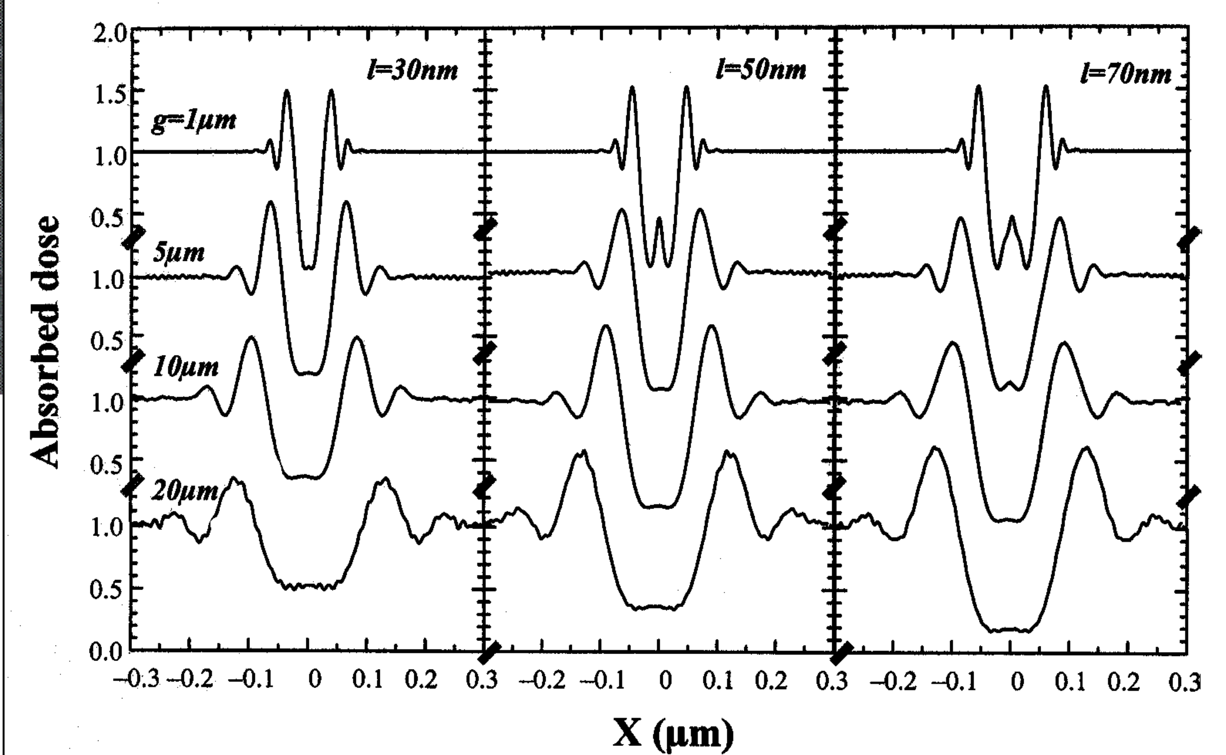
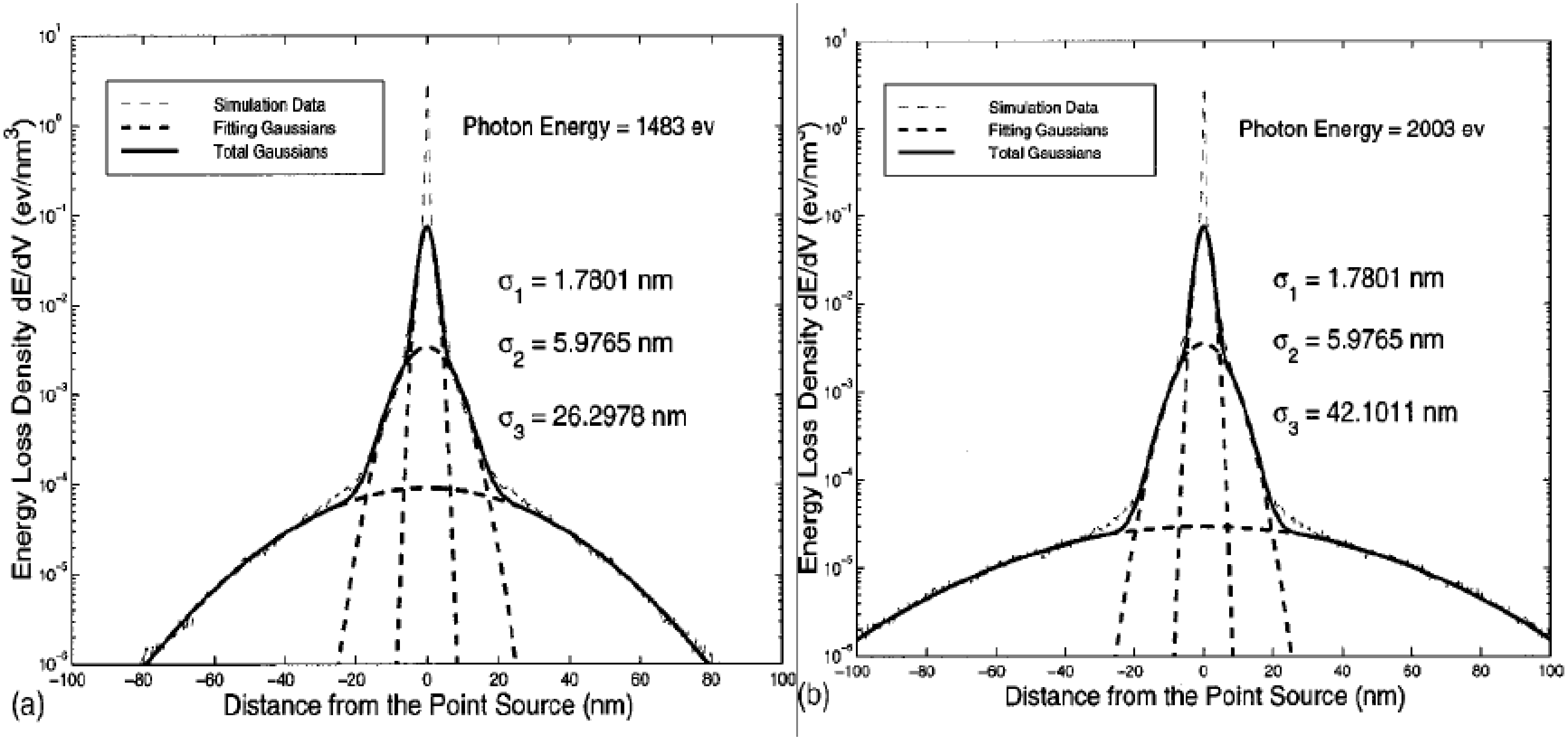


FIG. 4. Calculated dose profiles of 30 (a), 50 (b), and 70 nm (c) isolated line at four gaps.

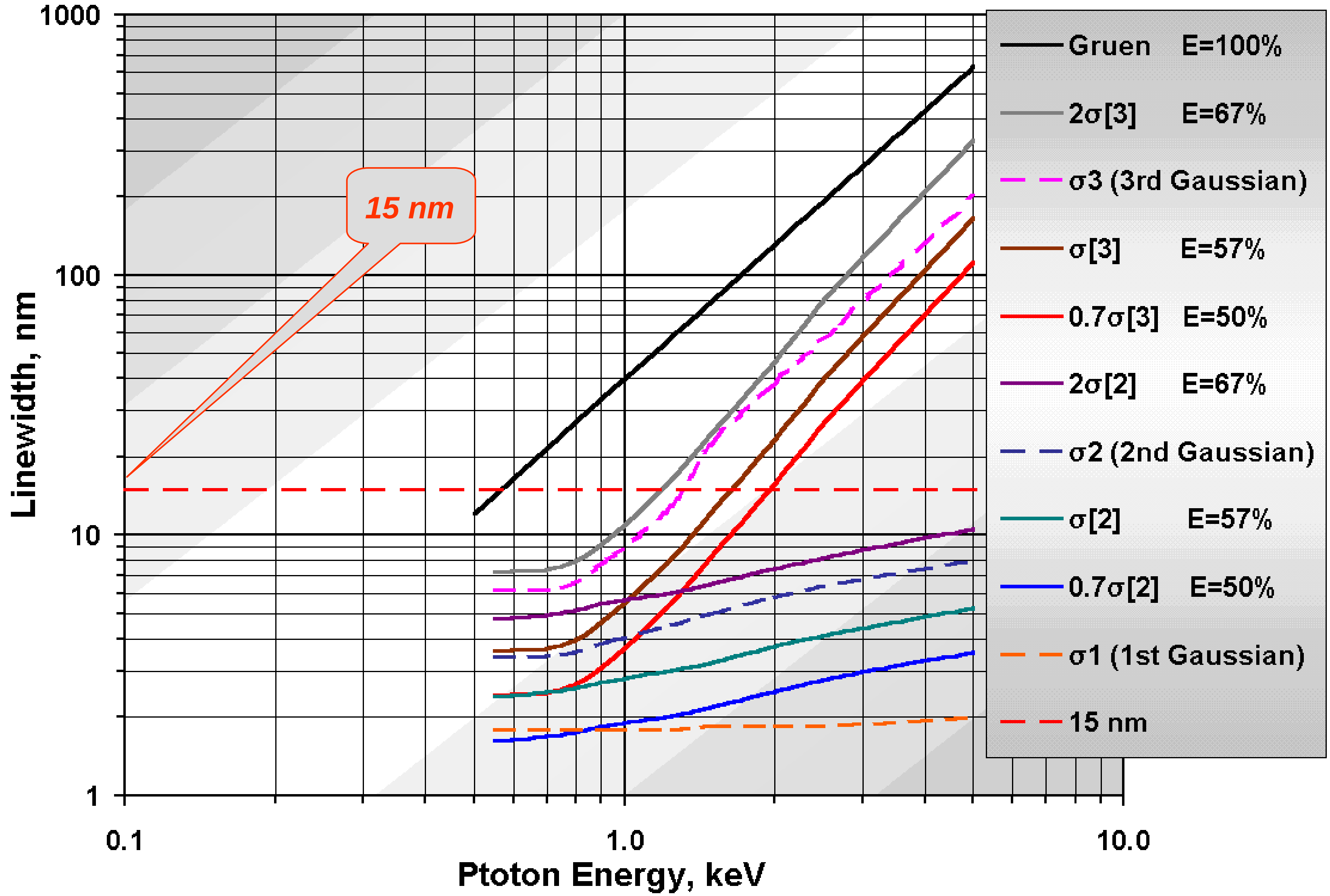
Photoelectron Blur Components



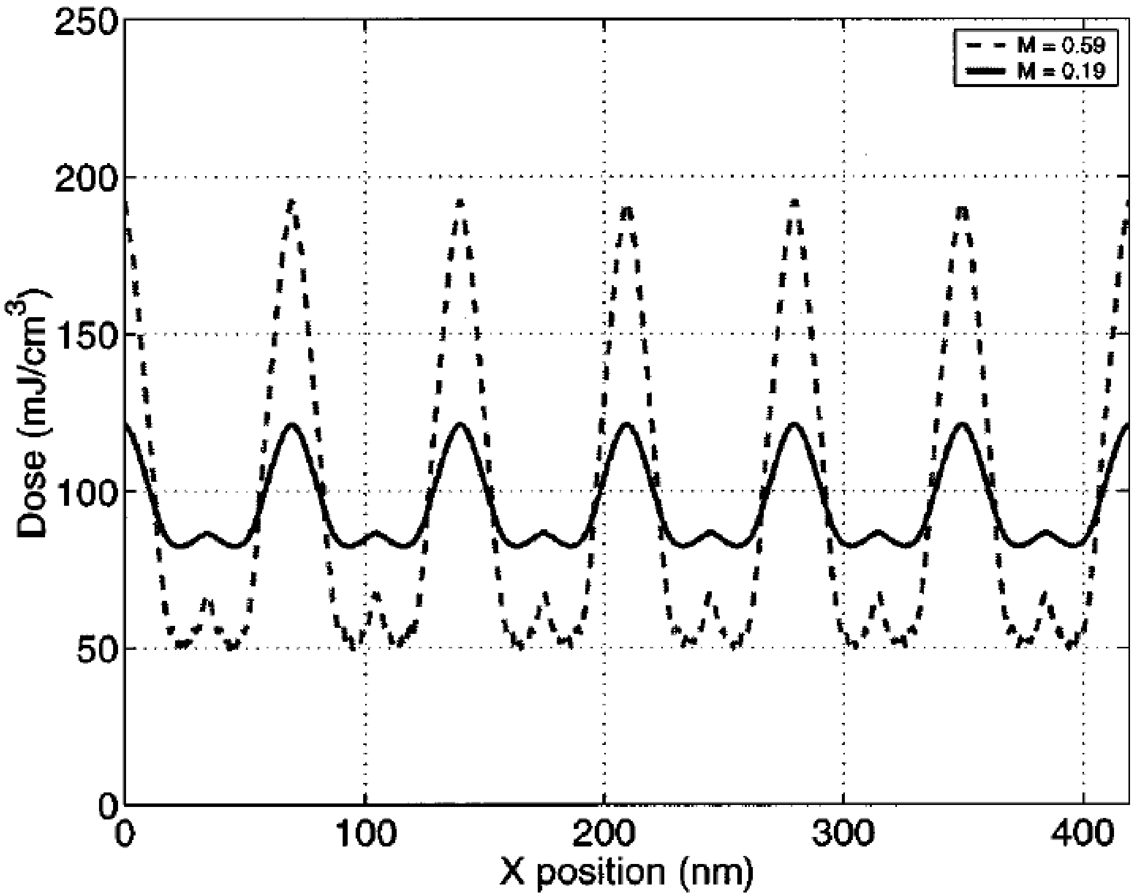
Electron blur for two different photon energies in PMMA.
The two Gaussian fits s_1 and s_2 refer to Auger electrons (photon independent!) and s_3 to the photoelectrons.
a) Softer spectrum b) Harder spectrum

Khan et al.: Extension of x-ray lithography to 50 nm, *J. Vac. Sci. Technol.* **B 17 (6**) , Nov/Dec 1999, 3426-3432

Photoelectron impact on PXL resolution



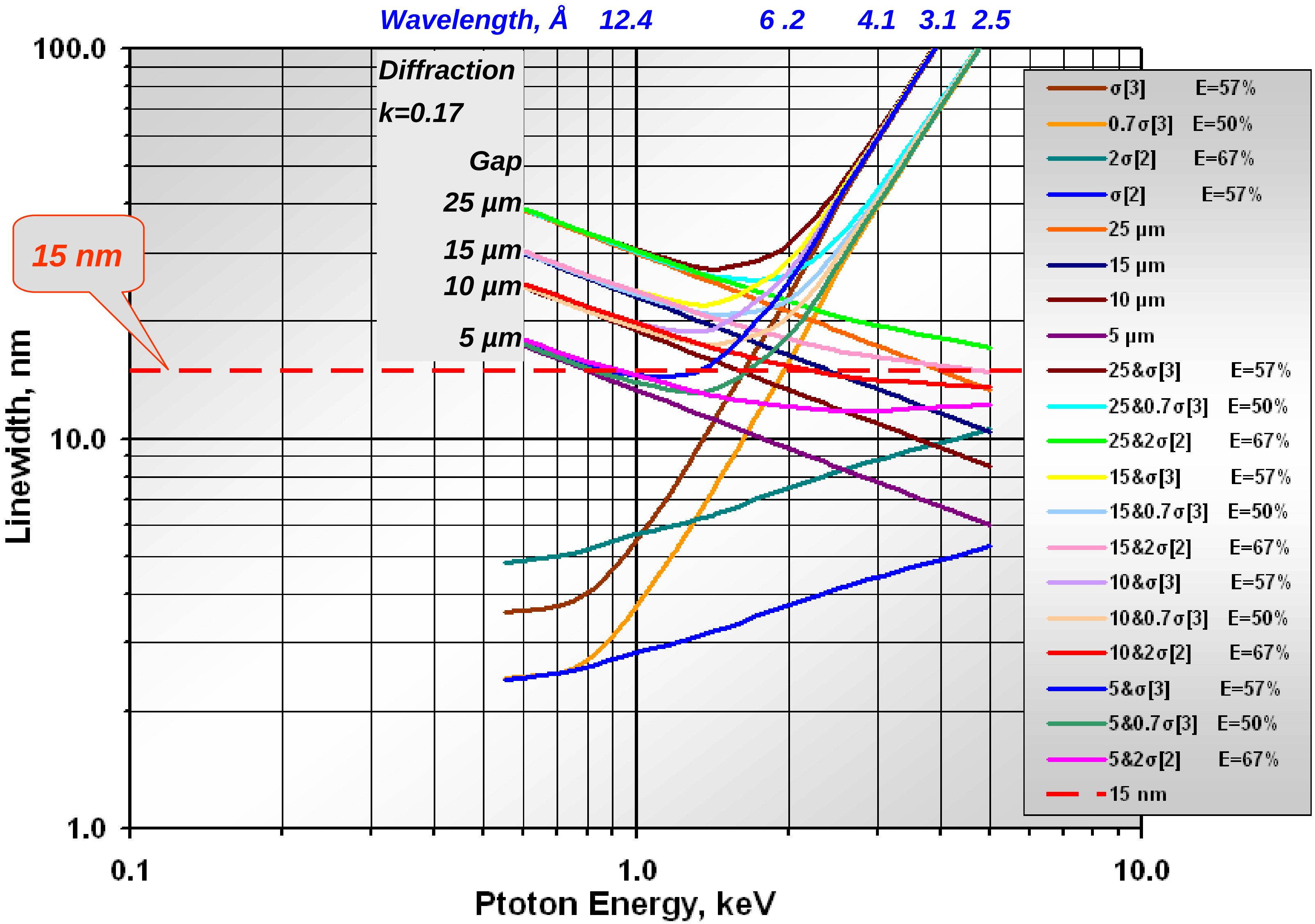
Impact of Photoelectrons in PXL



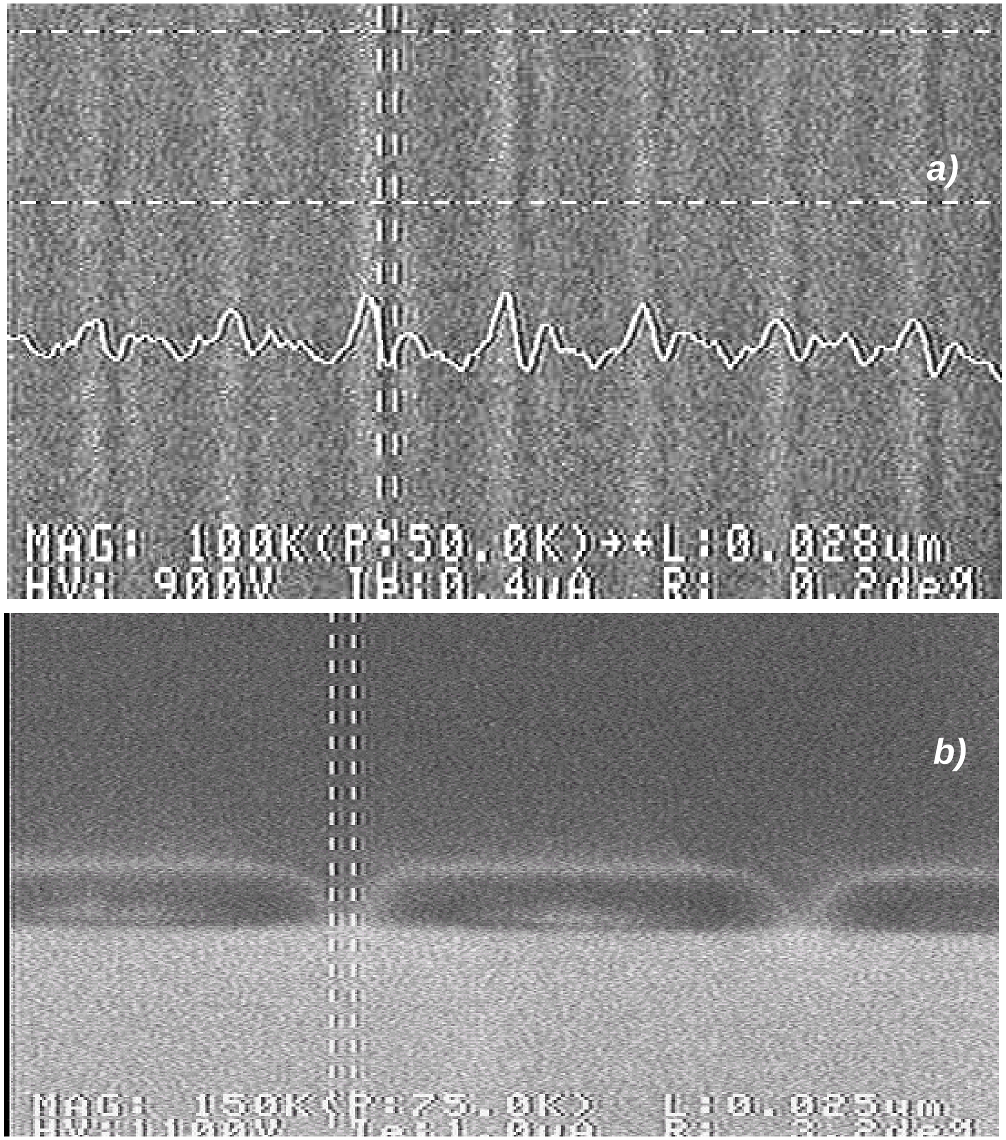
Effect of photoelectron and Auger electron blur on image modulation at 2.7 keV for a 35 nm L/S pattern, using UV5 resist exposed at a gap of 5 *m*m. The dashed line shows the effect of only diffraction, and the solid line includes photoelectron and Auger electron blur as well: Effective loss of contrast

Khan et al.: Can PXL print 35 nm features? Yes, *J. Vac. Sci. Technol.* B, **Vol. 19, No. 6**, Nov/Dec 2001, 2423-2427

Extensibility of PXL to 15 nm linewidth



Demagnification in PXL - 25 nm features

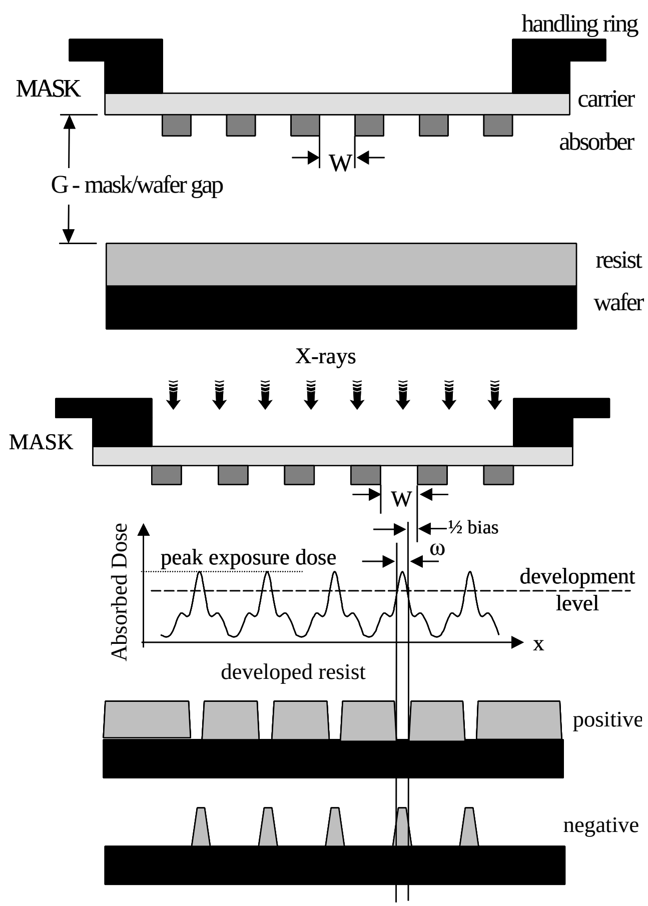


PXL Patterning at 0.18 < k < 0.22

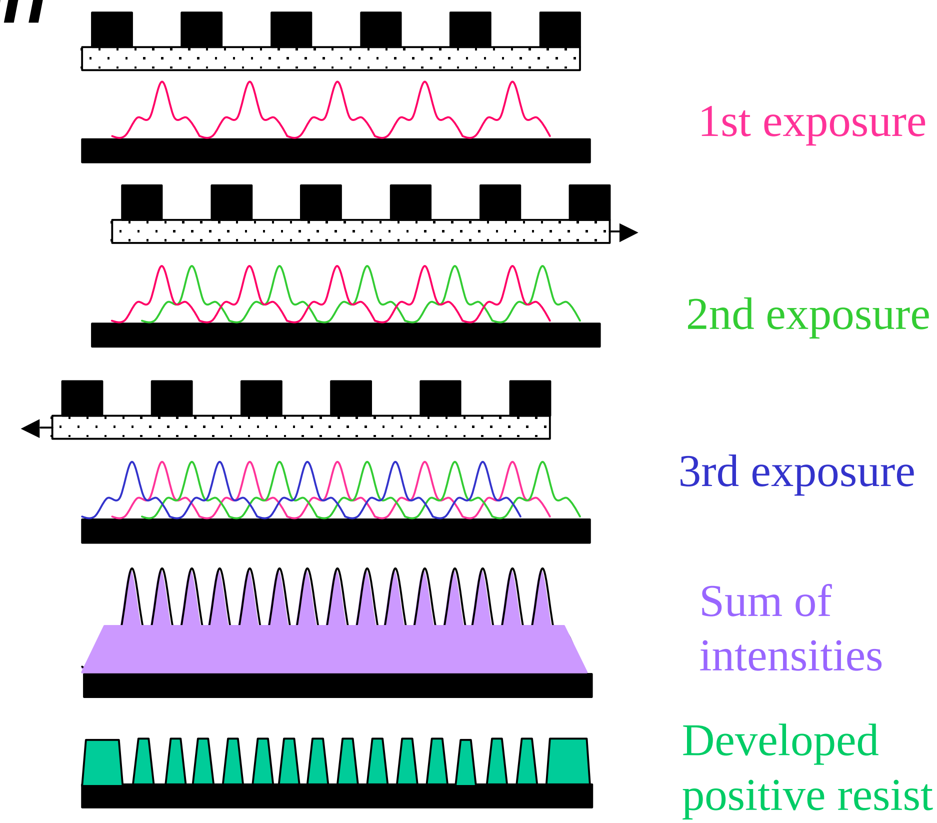
SEM micrograph of (a) 28 nm and (b) cross-section of 25nm features printed into ~80nm thick PMMA resist at 25 µm mask/wafer gap

Low k -Factor in Proximity Imaging for X-Ray Lithography Resolution Enhancement, J. K. Reng, Y. Vladimirksy, and Q. Leonard, Presented at MNE2000 (2000)

Nested lines formation in PXRL with demagnification

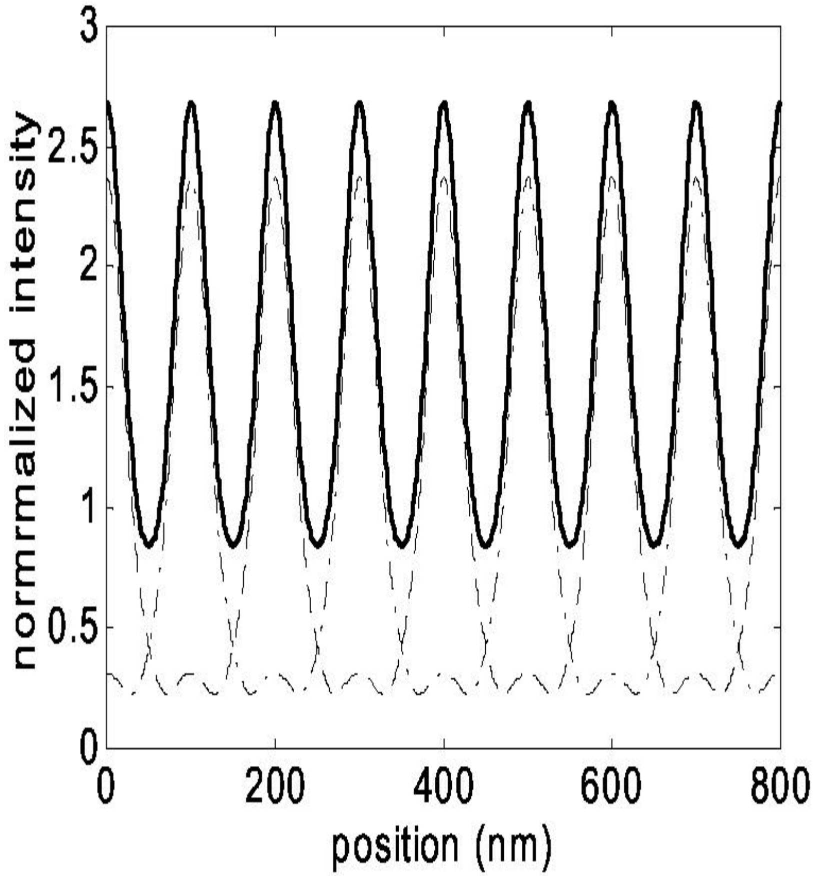


Resist processing

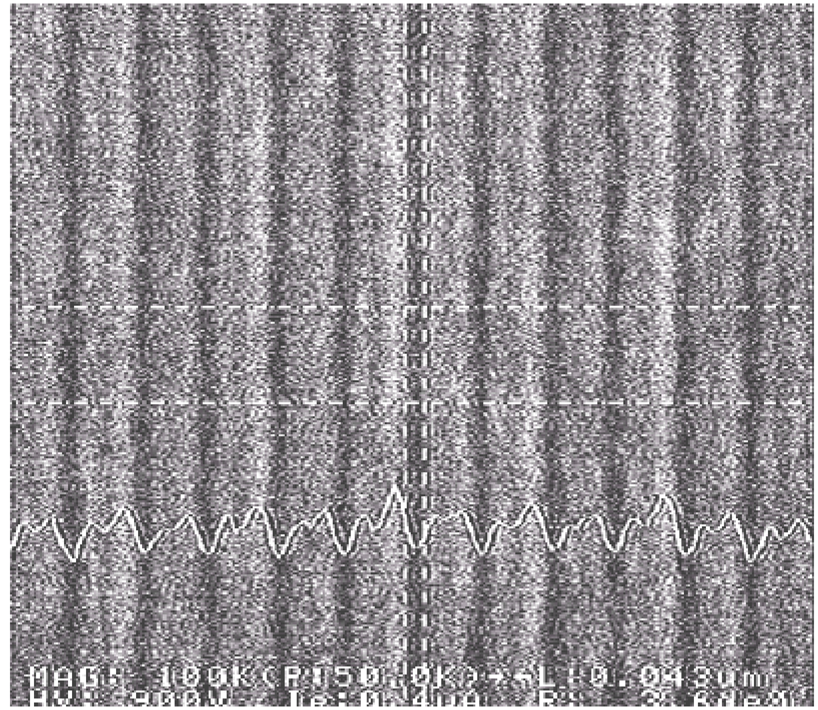


- **nested features formation in positive and negative resists by multiple sequential exposure and single development step**

Double Exposure-Single Development



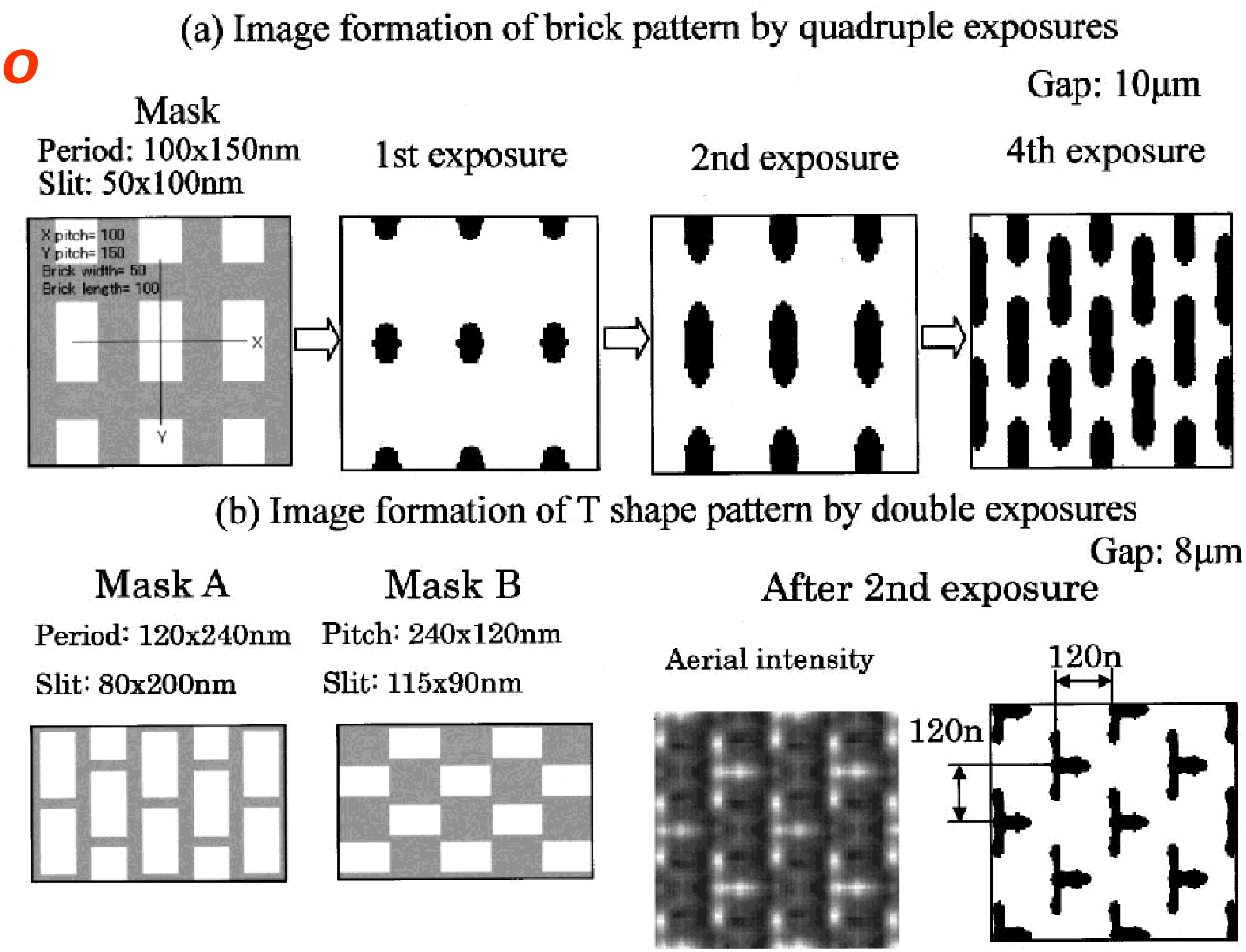
Simulation results showing double exposure



43 nm lines with155 nm pitch obtained by a double exposure-single development technique (mask pattern with 310 nm period and 160 nm features)

Multiple Exposures - Single Development

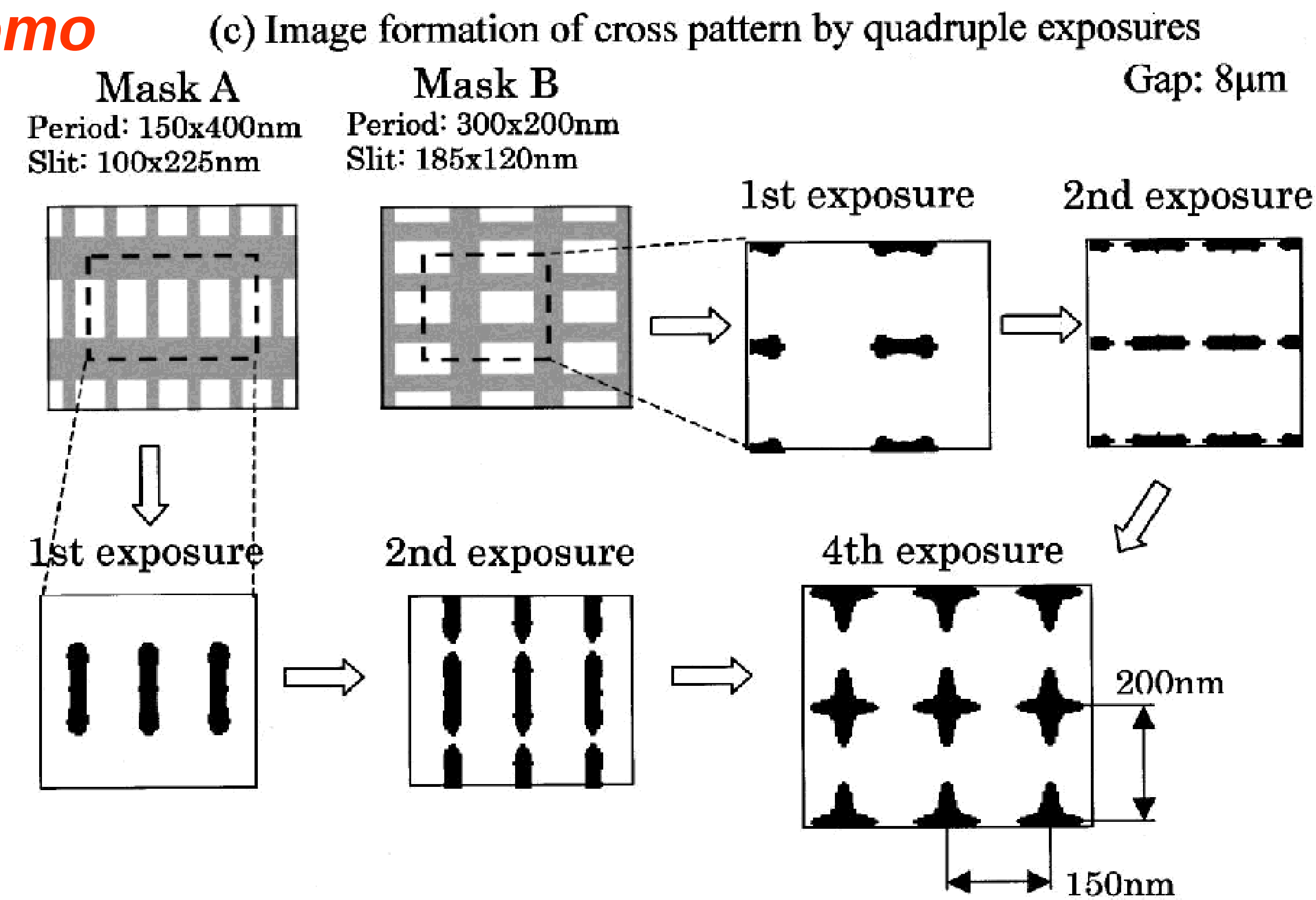
Sumitomo



Toyota et al.: Technique for 25 nm x-ray nanolithography, *J. Vac. Sci. Technol*. **B, Vol. 19, No. 6,** Nov/Dec 2001

Quadruple Exposure-Single Development

Sumitomo



Toyota et al.: Technique for 25 nm x-ray nanolithography, *J. Vac. Sci. Technol.* **B, Vol. 19, No. 6,** Nov/Dec 2001

Multiple Exposures-Single Development

Sumitomo

- Use of *enlarged* pattern masks enables to form 25 nm features at a 8 µm gap.
- Interference slit masks provide <25 nm features from the interference images at 8–12 mm gaps.
- Both masks can form dense images using multiple exposures.

(c) Image formation of by quadrangular slit
(Interval: 120nm, Slit: 30x90nm, Gap: 8µm)

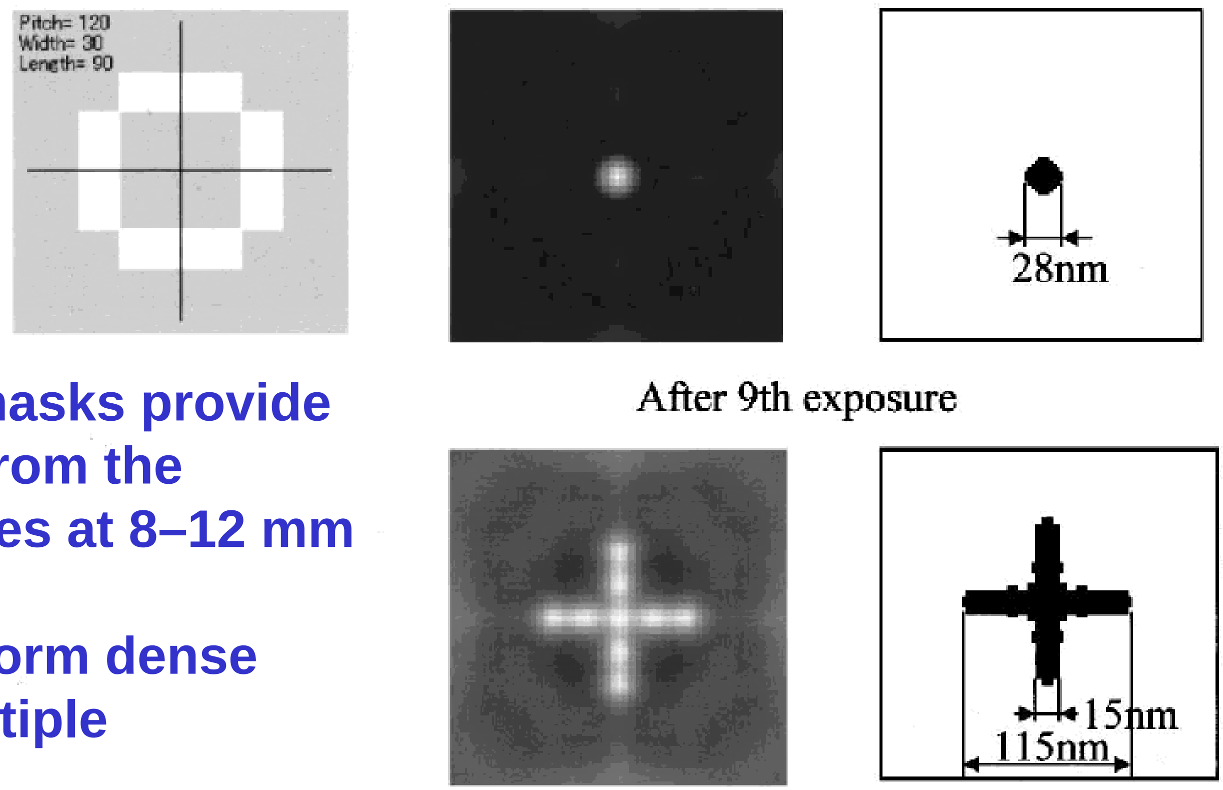
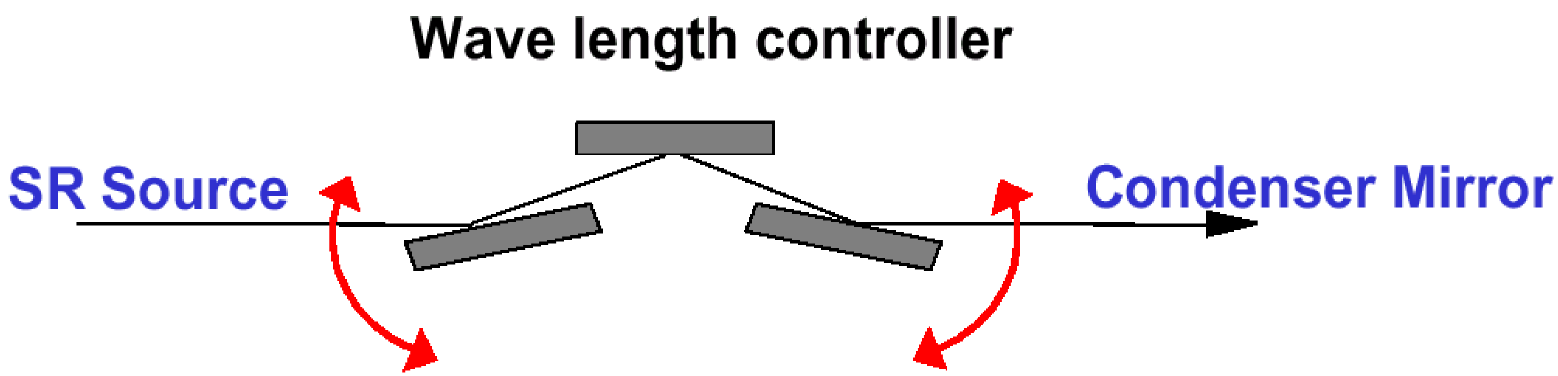


FIG. 5. Examples of image formation using interference slit masks.

Toyota et al.: Technique for 25 nm x-ray nanolithography, *J. Vac. Sci. Technol.* **B, Vol. 19, No. 6,** Nov/Dec 2001

Wave Length Tuner



Wave length of exposure beam is selectable according to wafer process.

Shorter Wavelength Exploration - Canon

NGL, Dec. 7 ’99

Extendibility – Image Contrast

Resolution

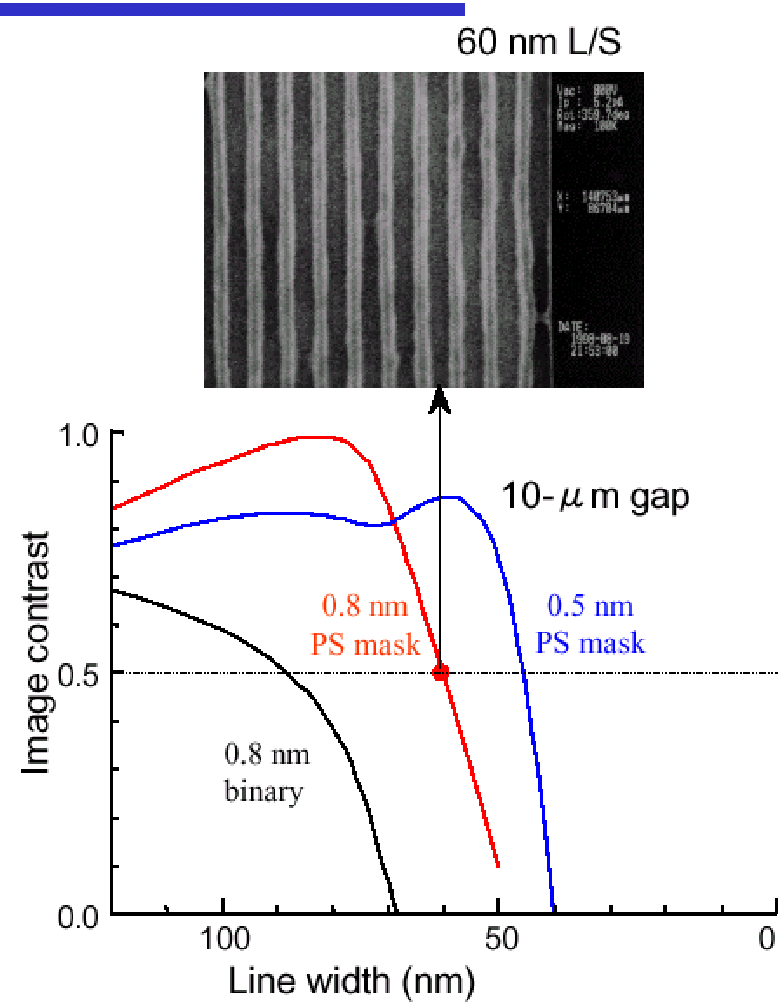
$$R = k\sqrt{\lambda \cdot g}$$

Binary mask: k = 1.0

PS mask: k = 0.65

Narrow-gap exposure

λ (nm)	0.8			0.5	
g (µm)	10	8	6	8	6
R (nm)	60	51	45	42	36



Exposure Tool Generation

$$K1 = \frac{\text{Resolution}}{\sqrt{\lambda * \text{Gap}}}$$

λ	Gap	130	120	110	100	90	80	70	60	50	40	30	20	10
0.8	15	1.19	1.10	1.00	0.91	0.82	0.73	0.64	0.55	0.46	0.37	0.27	0.18	0.09
	10	1.45	1.34	1.23	1.12	1.01	0.89	0.78	0.67	0.56	0.45	0.34	0.22	0.11
	7	1.74	1.60	1.47	1.34	1.20	1.07	0.94	0.80	0.67	0.53	0.40	0.27	0.13
0.5	10	1.84	1.70	1.56	1.41	1.27	1.13	0.99	0.85	0.71	0.57	0.42	0.28	0.14
	7	2.20	2.03	1.86	1.69	1.52	1.35	1.18	1.01	0.85	0.68	0.51	0.34	0.17
	5	2.60	2.40	2.20	2.00	1.80	1.60	1.40	1.20	1.00	0.80	0.60	0.40	0.20

Shorter Wavelength Exploration IV

NGL, Dec. 7 '99

Extendibility – Summary of 50nm System

	100nm System	50nm System
Mirror Surface	SiC	Ru, Rh
Mask Membrane	SiC (2µm)	Diamond (4µm)
Absorber Thickness	0.3 µm	0.2 µm
Resolution	< 70nm	< 35 nm
Throughput (300mm)	60 W/Hr	90 W/Hr

Diamond Membrane

Shorter Wavelength Exploration V

Canon

NGL, DEC. 7, '99

Road Map in PXL Technology

	100	70	50	35
Stepper				
XRA-1000 GAP=10um TP > 44 (SR:$I_{AVE.}$=500mA)	XRA-1000+ GAP=10um TP > 80 (SR:$I_{AVE.}$=1000mA)	XRA-2000 GAP=8um TP > 110 (SR:$I_{AVE.}$=1000mA)	Next Generation PXL Stepper	

Technology

- Illumination(Blur) Control
- Narrow Band Filtering
- Small Gap →5 um
- λ →0.5 nm

New Resist System

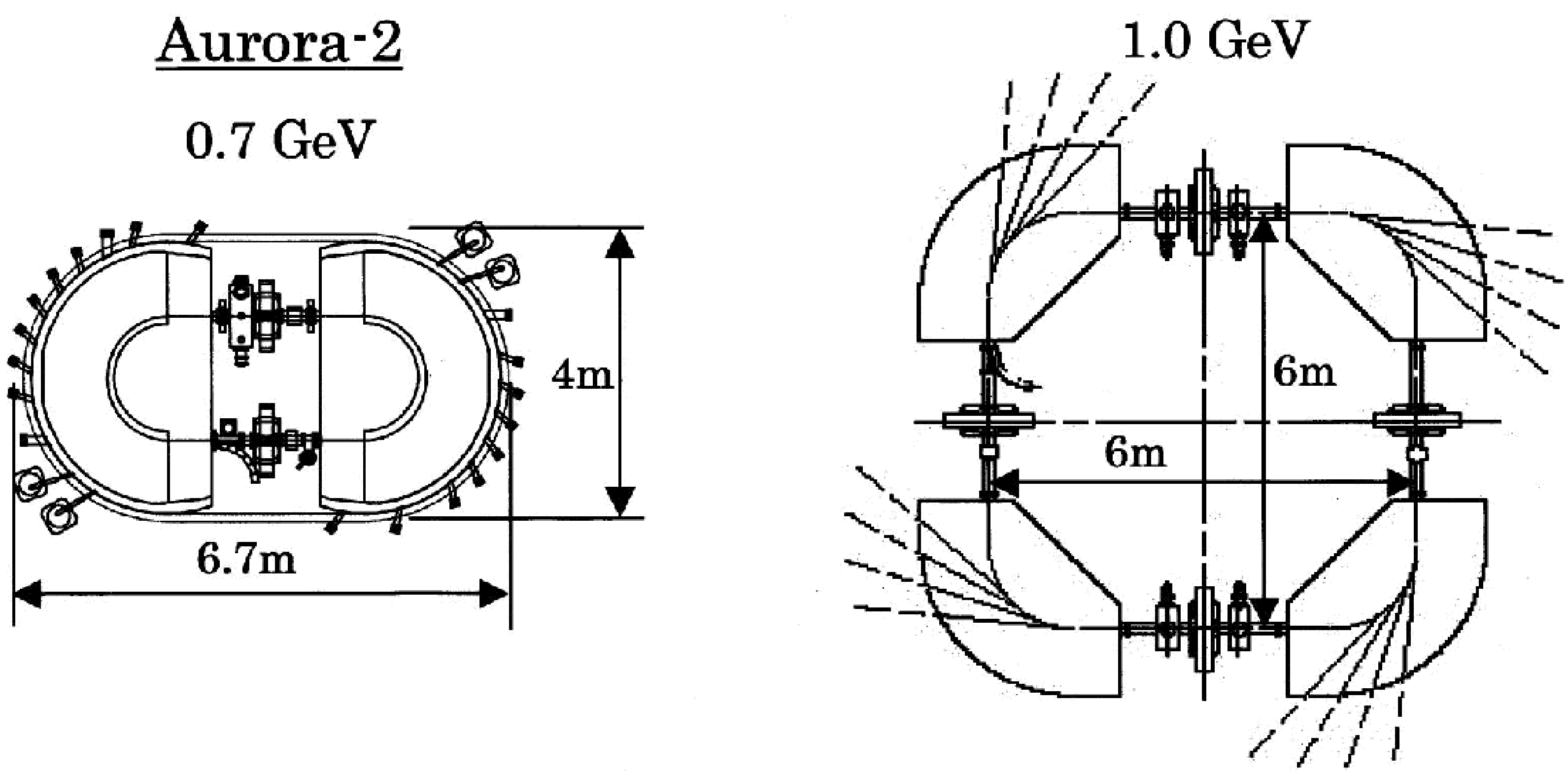
Blur→reduce

Optics & Nanotechnology Research Laboratories

Shorter Wavelength Exploration VI

Sumitomo

(a) Light source



Shorter Wavelength Exploration VII - Sumitomo

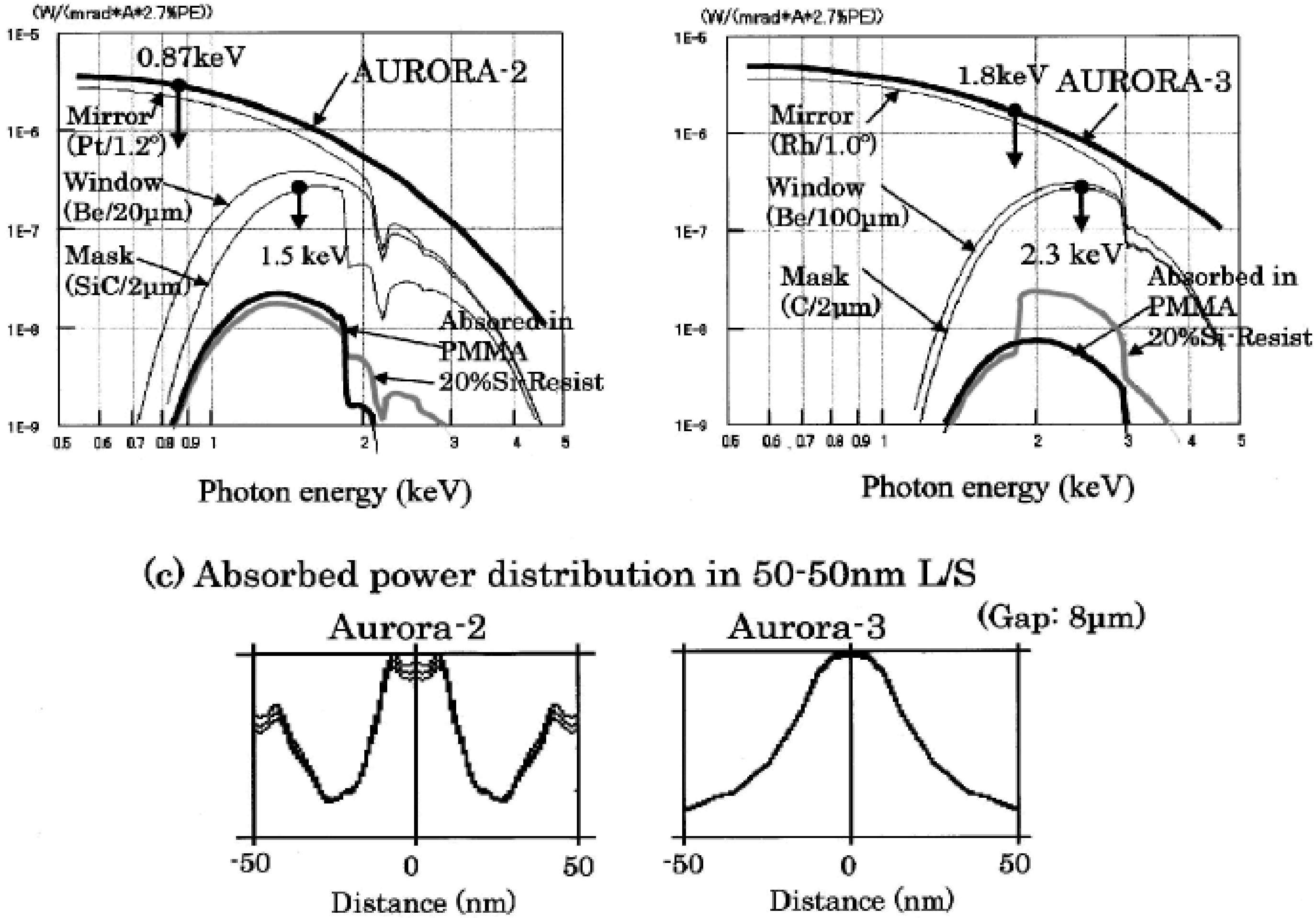


FIG. 1. Comparison of beam performance between Aurora-2 and Aurora-3.
~b) power spectra. ~c) absorbed power images at resist surface, middle height, and bottom.
Toyota et al.: Technique for 25 nm x-ray nanolithography, *J. Vac. Sci. Technol.* **B, Vol. 19, No. 6,** Nov/Dec 2001

Shorter Wavelength Exploration - CNTech

TABLE I. Requirements for 35 nm PXL.

Mirror	Cobalt, Nickel, Rhenium, Rhodium
Filters	Diamond
$E_m(\lambda_m)$	2.6 to 2.7 keV (0.48–0.46 nm)
Mirror angle	1.0°
Absorber	W:Ti, Ta; 200–250 nm
Membrane	Diamond
Mask bias	0–5 nm
Gap	$\leqslant$5 μm, $\approx$10 μm with RET
Resist material	Similar to resist doped with 30%–40% Si
Resist contrast	$\gamma>8$
Resist thickness	$\leqslant$150 nm ("collapse limited")
Back antiemission coating (BAEC)	$\approx$60 nm of low-Z material (3% dose variation)

Khan et al.: Extension of x-ray lithography to 50 nm, *J. Vac. Sci. Technol.* **B 17 (6**) , Nov/Dec 1999, 3426-3432

Shorter Wavelength Exploration - Franco

TABLE II. Summary of results.

Issue	Softer spectrum	Harder spectrum
Photoelectron blur for $\geqslant$50 mm CD	ok	ok
Printability of $\approx$80 nm mask CD	[gap]$\approx 20\mu$	[gap]$\approx 30\mu$
Printability of $\approx$50 mm mask CD	gap$< 10\mu$	[gap]$\approx 15\mu$
Exposure latitude	ok	slightly better
Power utilization	86.3%	80.8%
Exposure time	1 s	1.84 s
Fresnel number for 50 nm/15 μ	0.2	0.27

Khan et al.: Extension of x-ray lithography to 50 nm, *J. Vac. Sci. Technol.* **B 17 (6**) , Nov/Dec 1999, 3426-3432

25 nm X-Ray Lithography - Sumitomo

- **Use of *enlarged* pattern masks enables to form 25 nm two-dimensional features from the normal images at a 8 µm gap.**
- **Interference slit masks provide <25 nm features from the interference images at 8–12 mm gaps. Both masks can form dense images using multiple exposures.**
- **For the preparatory work we designed a new high-energy light source Aurora-3 yielding a shorter wavelength x-ray**

Shorter Wavelength Exploration

- **Recent developments in PXL were also directed to shorter median wavelength 4Å-6Å in order to increase the working mask/wafer gap: Sumitomo and Canon (Japan), CNTech (Wisconsin)**
- **This can be achieved by increasing the energy of the storage ring, decreasing the incident angle on the beamline mirror, and utilizing a diamond mask substrate.**
- **System optimization can be realized by proper choice of the storage ring and beamline parameters to minimize the resist exposure time.**
- **The results of the calculations indicate that the effect of the photoelectron contribution on can be <u>neglected</u> for the features down to 50 nm.**
- **<u>As it was shown in this presentation</u>, the photoelectron blur can be <u>controlled</u> for the features down to ~10 nm**

Demagnification by Bias - Conclusion

Demagnification (2X-6X) in Proximity printing

- Proximity X-Ray Lithography allows to perform local **2x-6x demagnification** of the pattern with *k*- values down to $k_w < 0.2$.
- The demagnification provides proven **extensibility of PXRL to 15 nm** (possibly below) for isolated features with **high quality** (smooth edges), **large fields**, reasonable **large mask/wafer gaps**, and **large mask features**.
- The PXL approach offers the **same advantage of relaxed mask CD** requirements, as in 4X and 5X projection lithography.
- The method can be **directly applied to print isolated lines** in MIMIC and MPU fabrication applications.
- For **half-pitch** formation multiple exposure-single development was demonstrated
- Exploratory work in use of harder X-ray Litho is on the way

Appendix C   - Talk 3

Hadis Morkoc, VCU

VCU

How I can be of help!

- Academic Support with students, research associates, and faculty,
- Mask making by providing manpower and facilities for the effort
- User, and therefore feedback, of nanolithography for novel devices and breaking bottleneck issues in new semiconductor materials research and development

VCU

School of Engineering Virginia Commonwealth University

VCU

Virginia Microelectronics Center
27,000 sq. ft.

5000 sq. ft. Si fab.
2500 sq.ft. Research Lab
Class 1000

People / Expertise

VCU

Aswini Pradha	**Asst Prof**	**Oxides/Spintronics**
Dan Johnston	**Assoc Prof**	**Electrical Characterizat**
Allison Baski	**Assoc Prof**	**Surface Characterizatio**
Rob Pearson	**Assoc Prof**	**Processing**
Gary Atkinson	**Assoc Prof**	**Processing**
Hadis Morkoç	**Prof**	**Semiconductors**
Seydi Dogan	Visiting Prof	Fabrication/Devices
Ali Teke	Visiting Prof	Optical Devices
Ramiah K-Subb	Post-Doc	MOCVD/Characterization
LiangHong Liu	Post-Doc	E beam Lith/MOCVD
Deliang Wang	Post-Doc	Growth MBE
Chunli (Amy) Liu	Post-Doc	Oxides/Spintronics
Sang-Jun Cho	Post-Doc	E beam Lith/fabrication
Michael Reshch	Research Scie	Optical /Defects
Feng Yun	Research Scie	Fabrication / Characteriza

Lei He	Student	Growth MBE
Marc Redmond	Student	Oxides/Spintronics
Anna Pamarico	Student	Surface Characterization
Josh Spradlin	Student	Electrical Characterizatio
Shariar Sabukta	Student	Surface Characterization
Steve Puntigan	Student	Growth MBE
Mark Mikkelson	Student	Surface Characterization
Yi Fu	Student	Growth MOCVD
Faxian Xiu (D	Student	Growth MBE
Andy Xie	Student	Nanon Imprint Lith
Jiawei Li	Student	Optical Props/Press

Existing Capabilities

VCU

- **Facilities - 2500 sq. ft. class 1000 cleanroom**
- **Growth - Molecular Beam Epitaxy, Metalorganic Chemical Vapor Deposition, Sputtering (adding Hydride Vapor Phase Epitaxy)**
- **Characterization**
  - Structural – X-Ray, Atomic Force Microscopy
  - Optical – Photoluminescence (CW, time resolved, high pressure)
  - Complete electrical and surface probe for characterization
- **Fabrication – optical and e-beam lithography, contacts, dry/wet etching, rapid thermal anneal**
- **6” Si fabrication facility in a 5000 sq.ft. class 1000 cleanroom**

VCU

VCU

VCU

Undergraduate, Dmitriy Shneyder, with e beam pattern generator

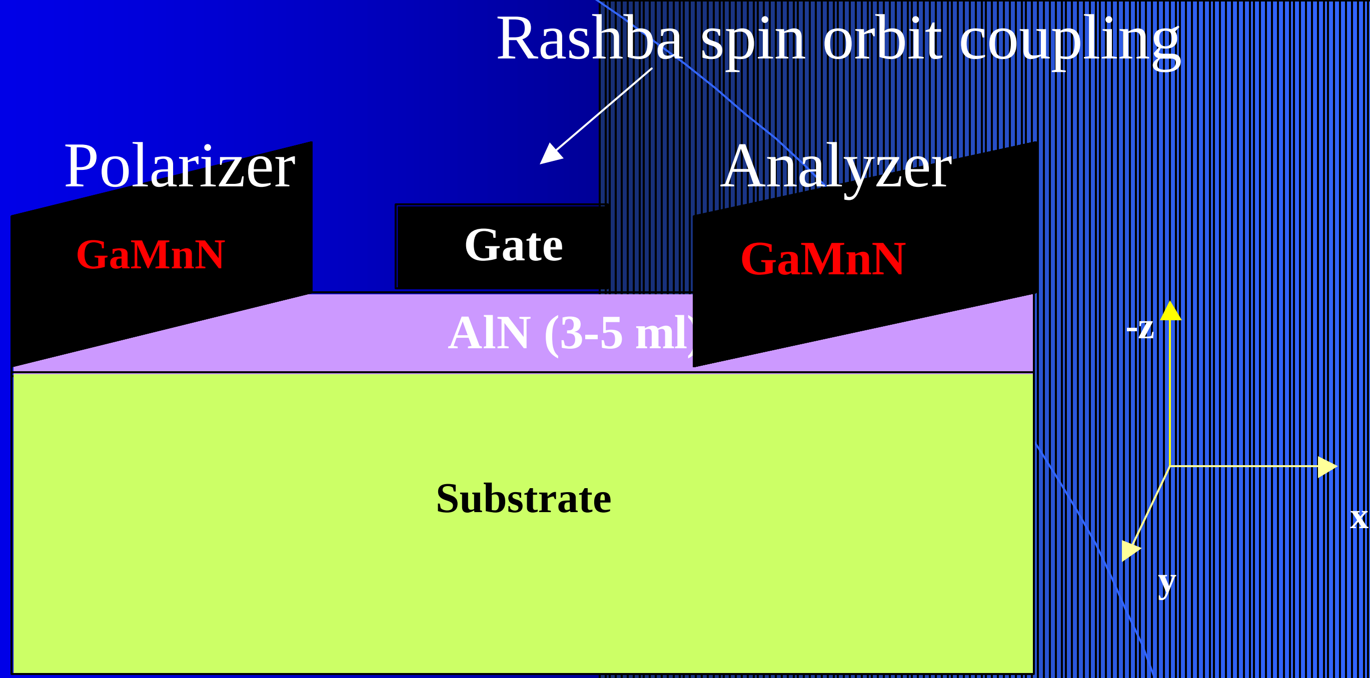
will add

- Nano Imprint Lithography (NIL) facility with about 30 nm capability
- Does not generate pattern, but would be useful in making multiple copies of masks, (a clear benefit to the mask making capability)

Two examples of Nanolith needs at VCU

VCU

SpinFET



Why SpinFET?

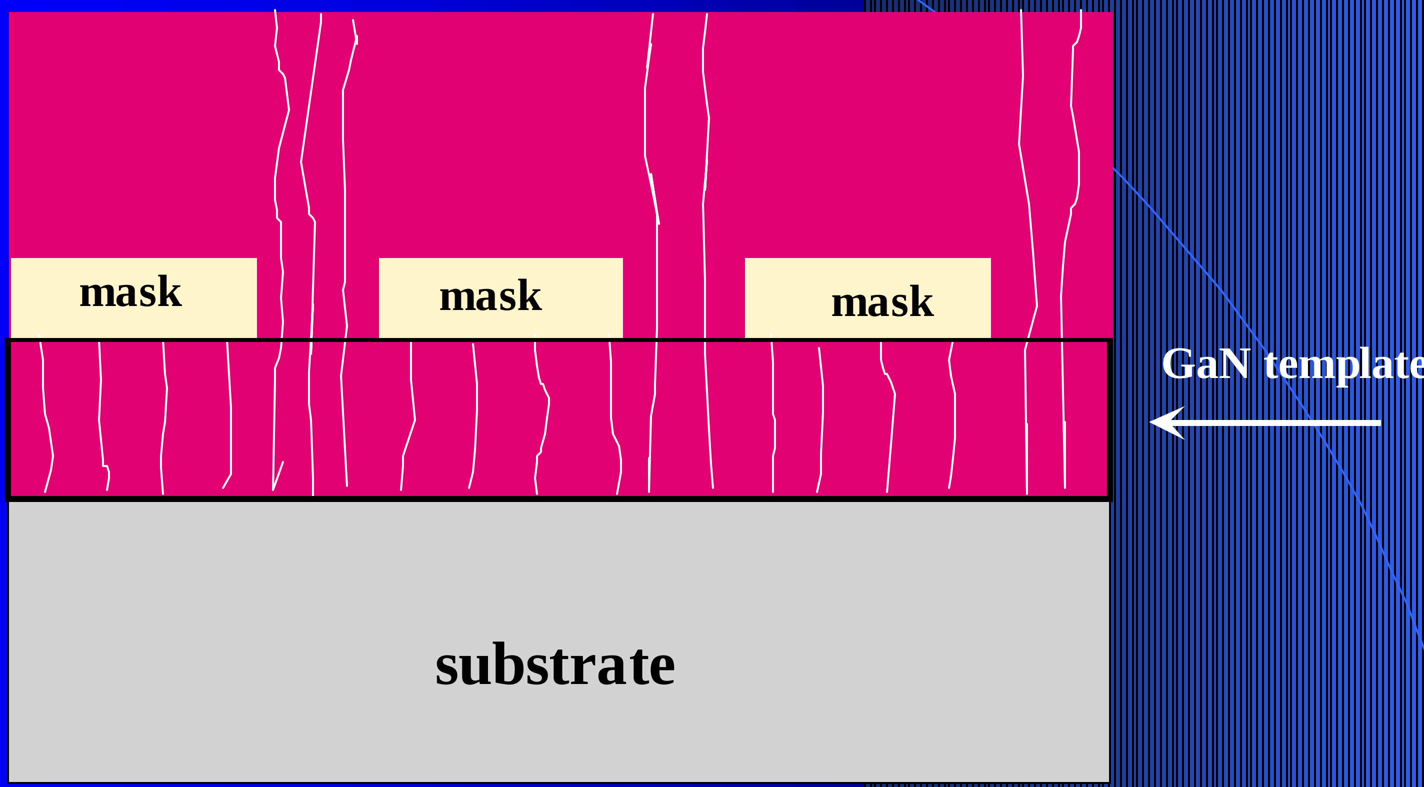
- •Low noise
- • Low power consumption

Critical issues:

- •Ferromagnetic contact engineering
- •Reduced dephasing along the channel: L_{S-D} <100 nm

Lateral Epitaxial Overgrowth

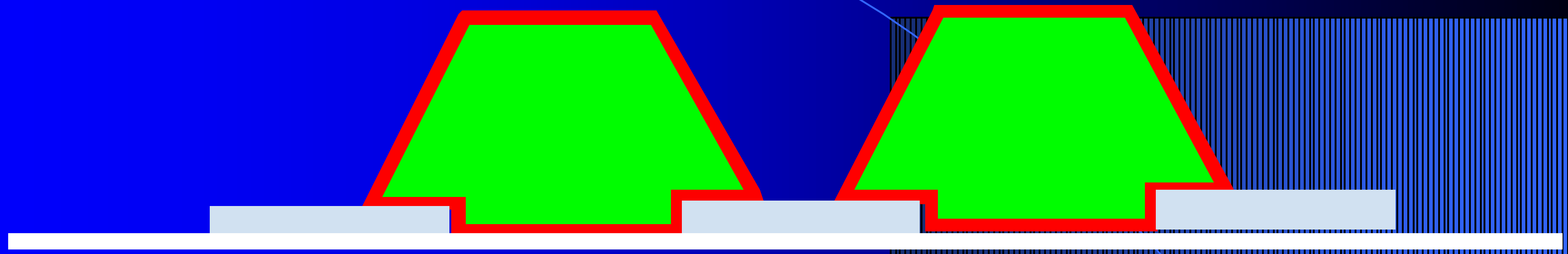
VCU



Single step LEO

VCU

Why Nano LEO?



In LEO: Dimensions are about 5 microns voids and defects form at the coalescence boundaries and over the window

In nanoLEO: Dimensions are about 20-30 nm stripes, Indexing and registry will be correct eliminating the voids and defects

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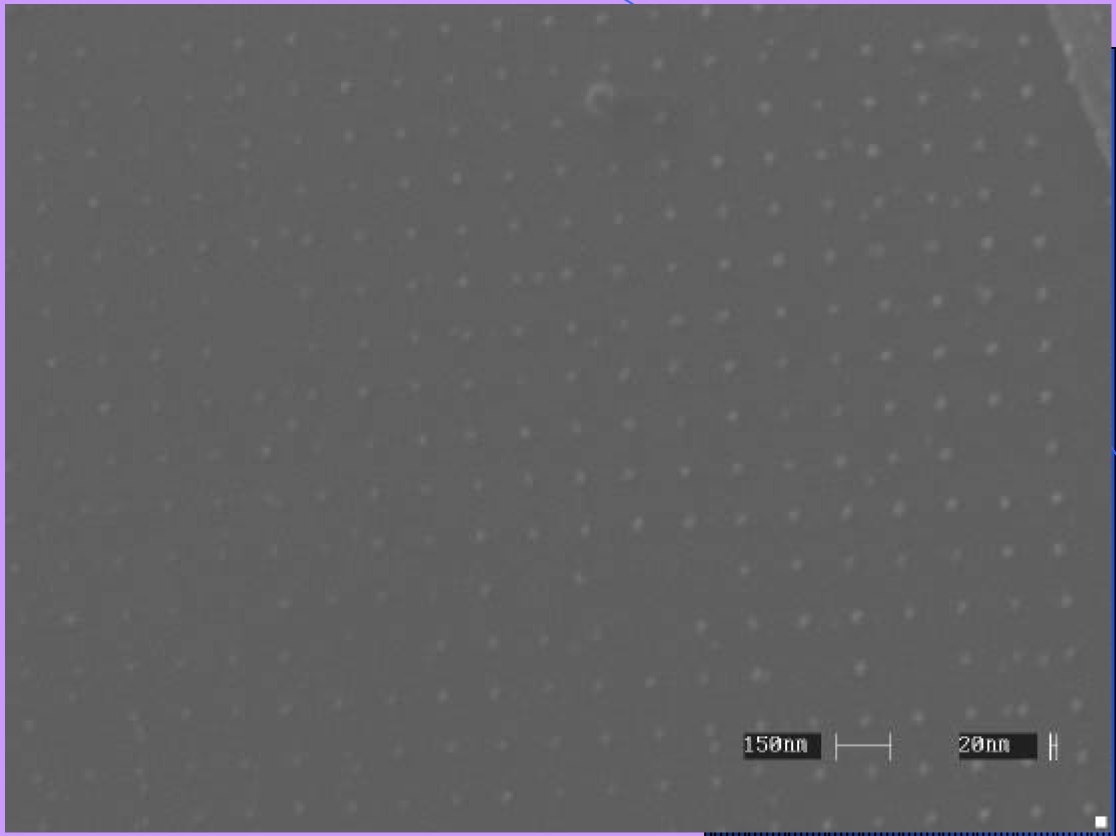
Dot patterns

Results (I)



Sample# 35-325

Point dose: 3.5 fc, i.e. 350 msec/point, Dot size 20~25 nm

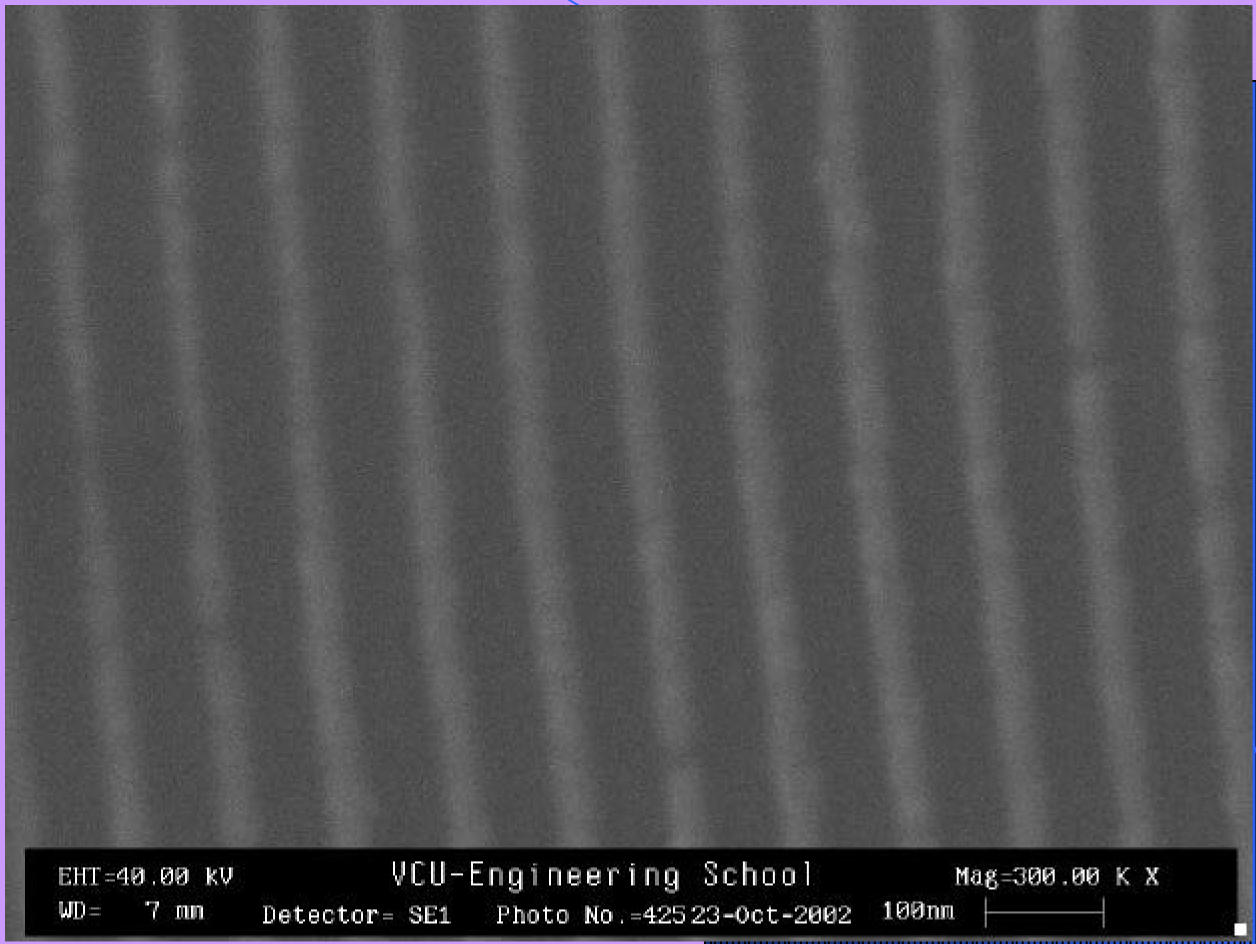
Develop time: 70s

Line patterns

Results (II)

VCU

Sample# 22-2-4
Line Dose: 1.5 nC/cm
L-L distance: 100 nm
C-C distance: 16 nm



Linewidth: 25~30 nm

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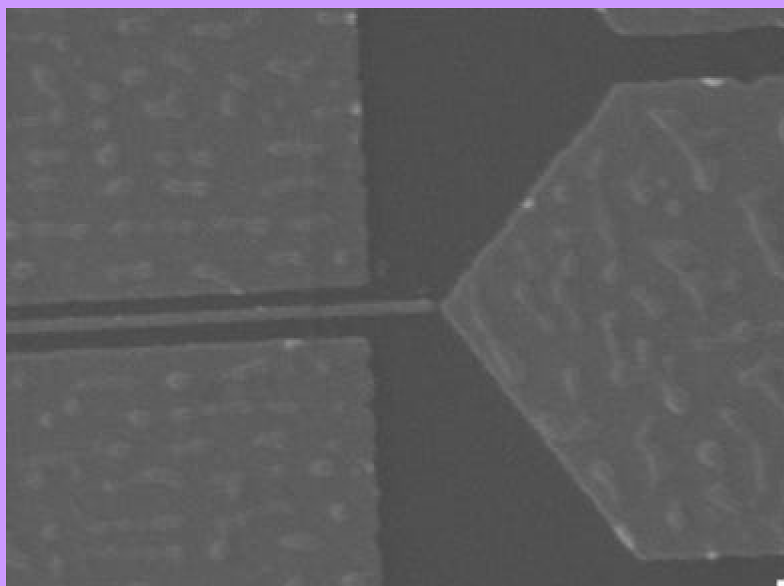
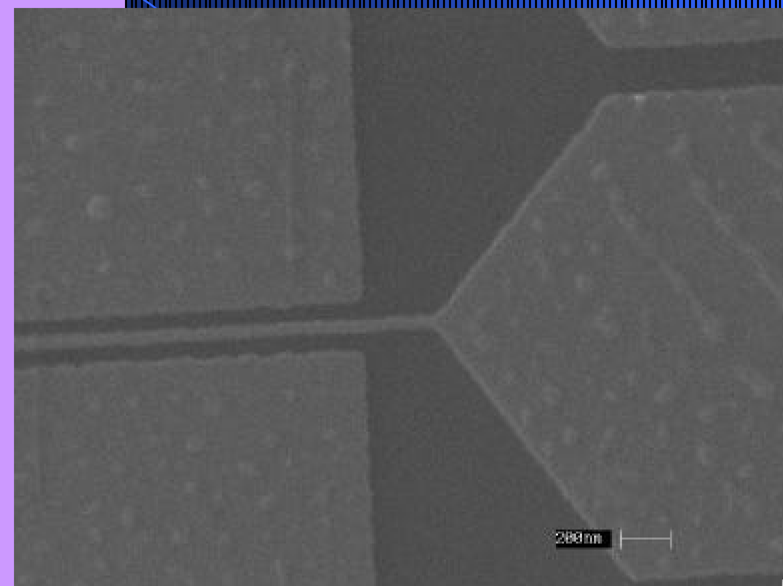
SpinFET structure -1

Results (III)



Sample# 35-1-3
Line dose: 1.9 nC/cm
Area dose: 250 mC/cm^2
L-L distance: 25.5 nm
C-C distance: 12.7 nm



Sample# 35-1-5
Line dose: 1.9 nC/cm
Area dose: 350 mC/cm^2
L-L distance: 25.5 nm
C-C distance: 12.7 nm

Source-Drain Distance: 187~196 nm

VCU

Conclusions

- Academic support with students and faculty
- Facilities support that could help the eventual program toward i.e. mask making
- Novel devices and structures requiring nanolithography capability such as PXL.
  - SpinFET requires a few tens of nm S-D spacing
  - NanoLEO requires a few tens of nm stripes.

Appendix C – Talk 4

Om Nolamasu - RPI

Role of Materials in Extending Resolution Limits of Fabrication Technology: Challenges for <30 nm Lithography

Om Nalamasu

Director, Center for Integrated Electronics
Professor of Materials Science & Engg.
Professor of Chemistry
Rensselaer Polytechnic Institute (www.RPI.edu)
Troy, NY

and
Chief Technical Officer,
NJ Nanotechnology Consortium (www.NJNano.org)
Murray Hill, NJ

Rensselaer

Lucent Technologies
Bell Labs Innovations

Role of Materials in Extending Resolution Limits of Fabrication Technology

OUTLINE

Introduction

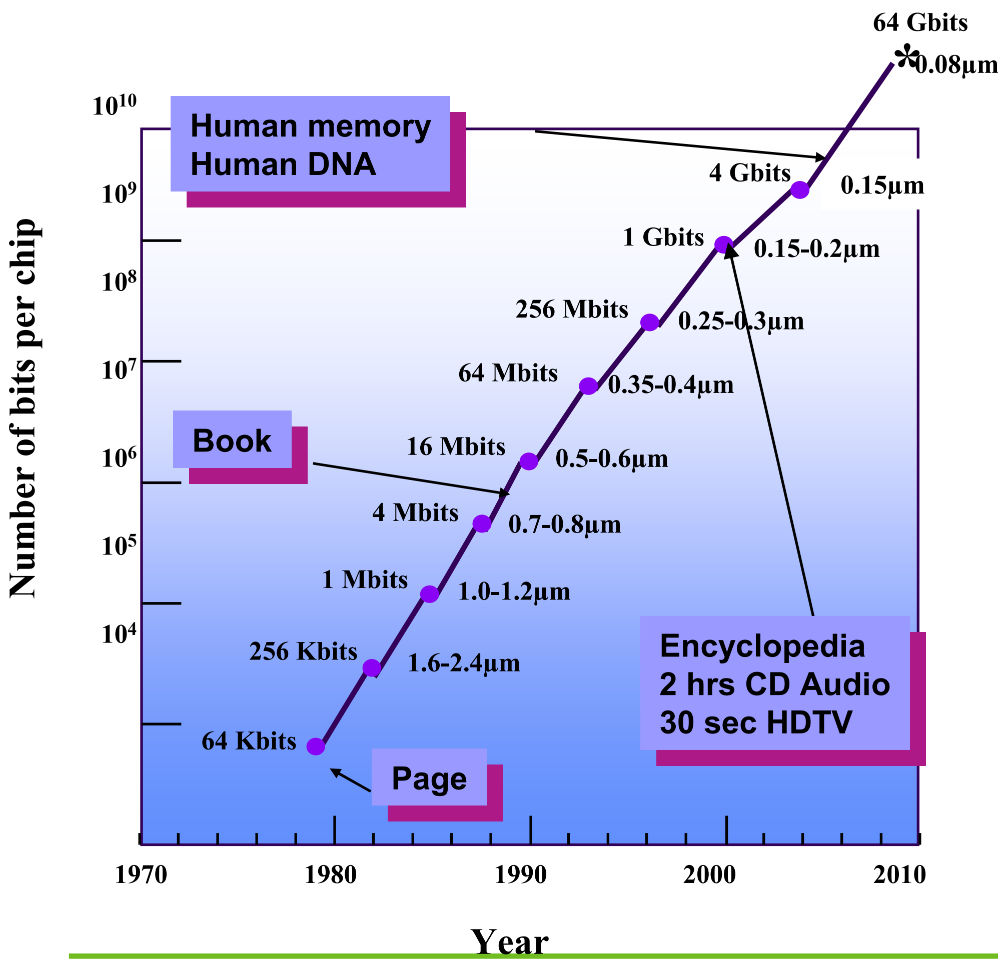
Lithography Drivers

Resists

Materials for Electronics and Photonics : Performance by Design thru a platform approach

Conclusions and opportunities

Moore’s Law



MSI

LSI

VLSI

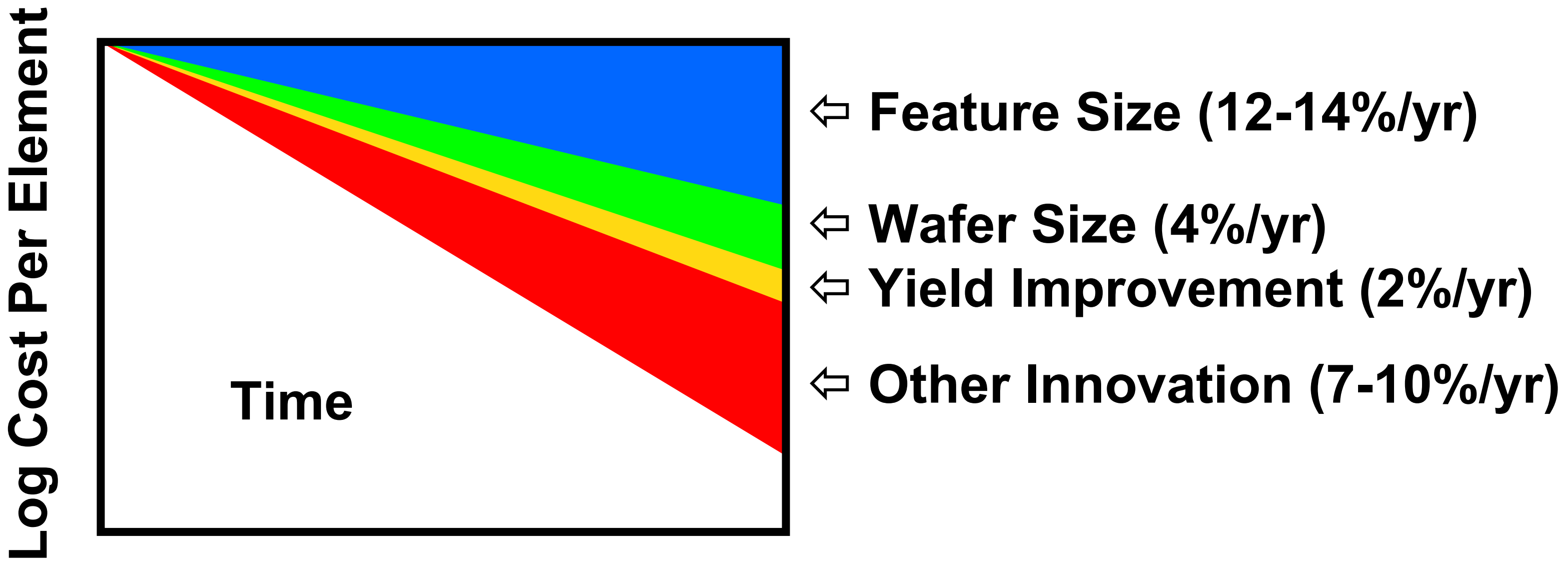
ULSI

RLSI

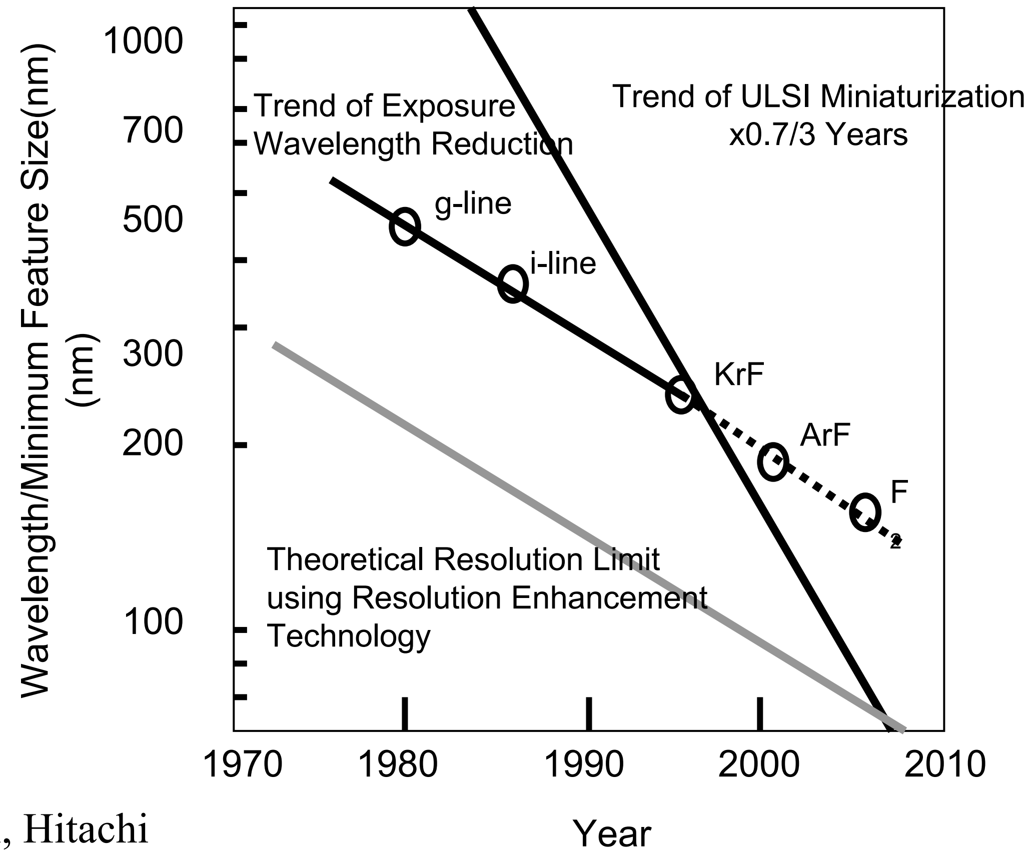
Integration

Challenge

Cost Per Function is a Primary Driver

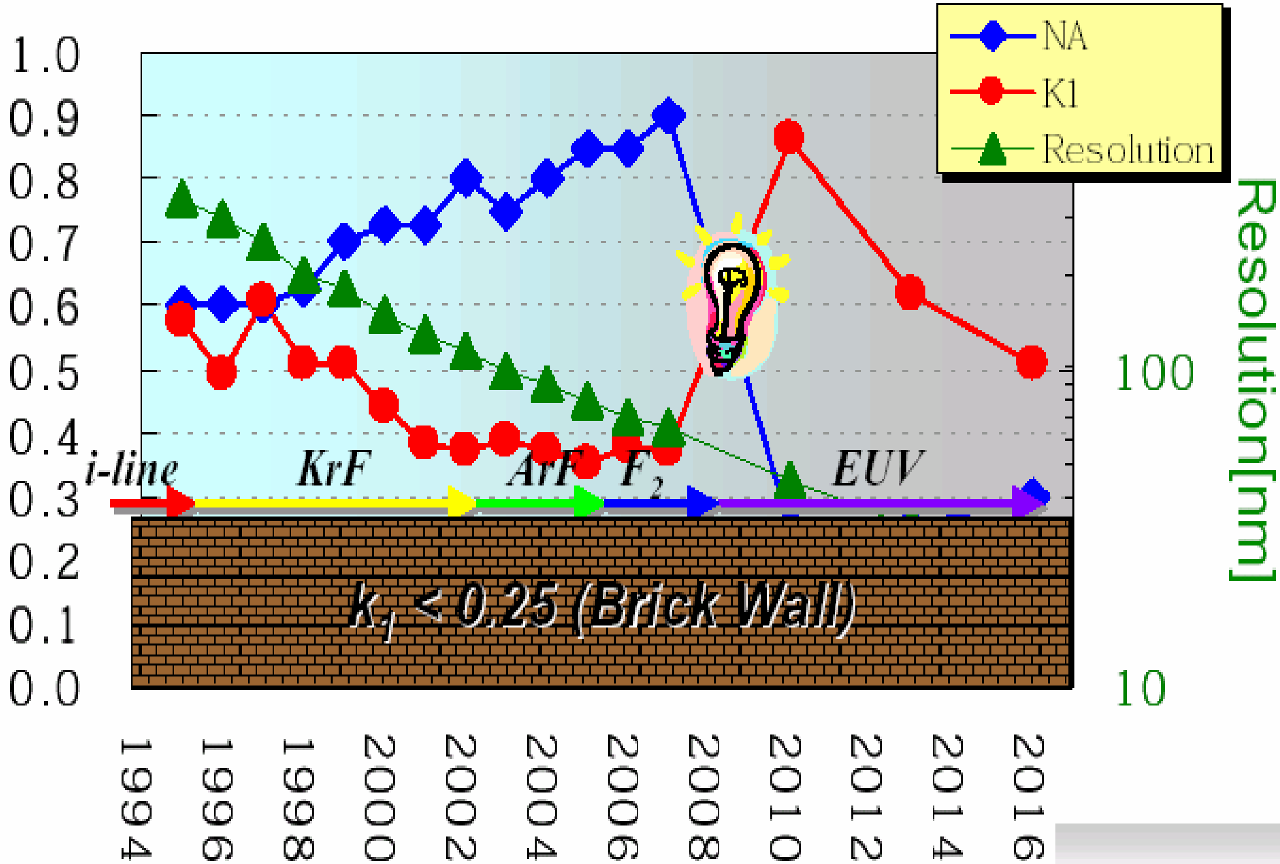


Lithography Challenge



Courtesy: S. Okazaki, Hitachi

Hitting the Brick Wall



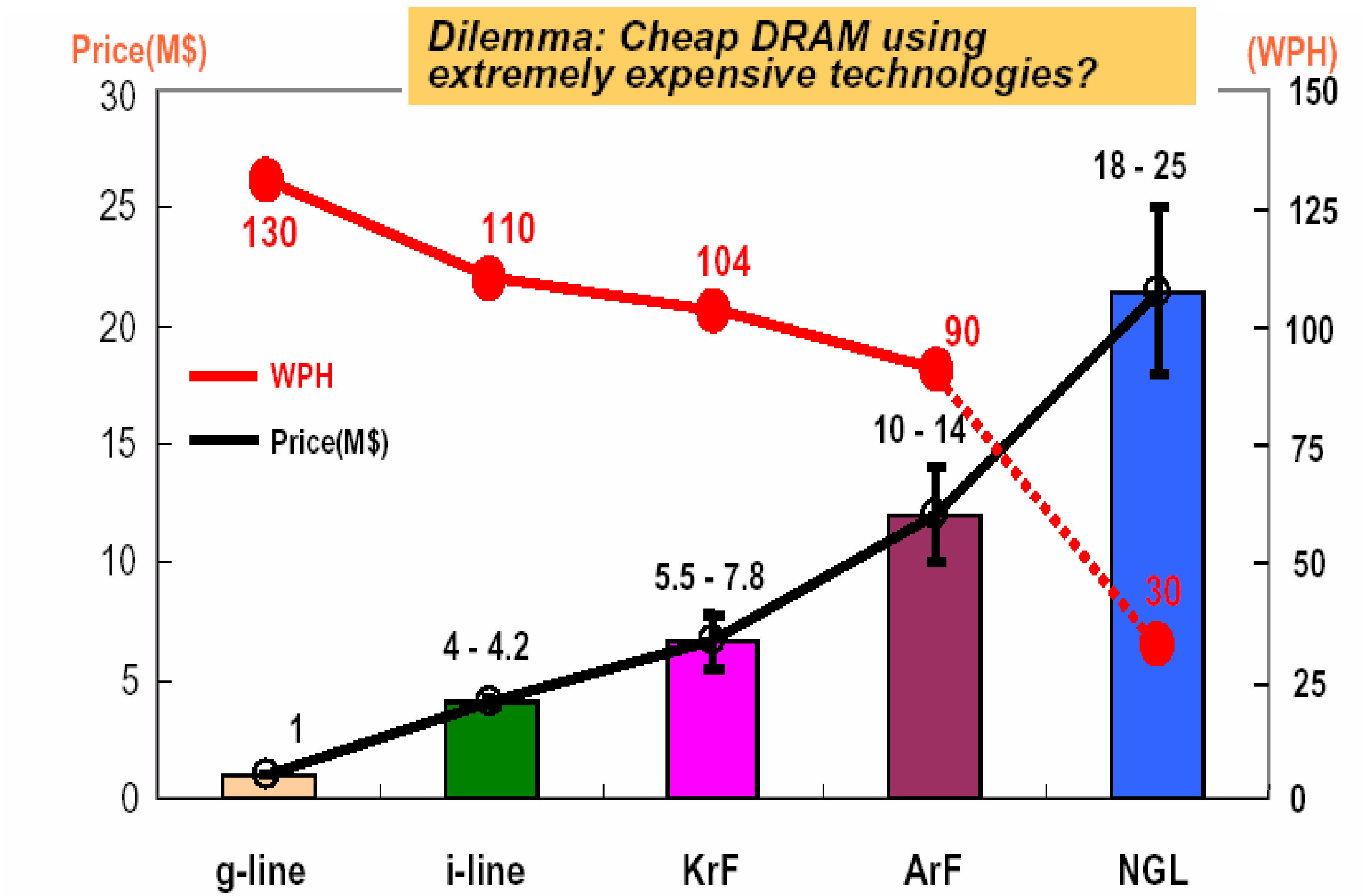
$$\text{Resolution} = k_1 \frac{\lambda}{NA}$$

Courtesy: Samsung Electronics

Rensselaer

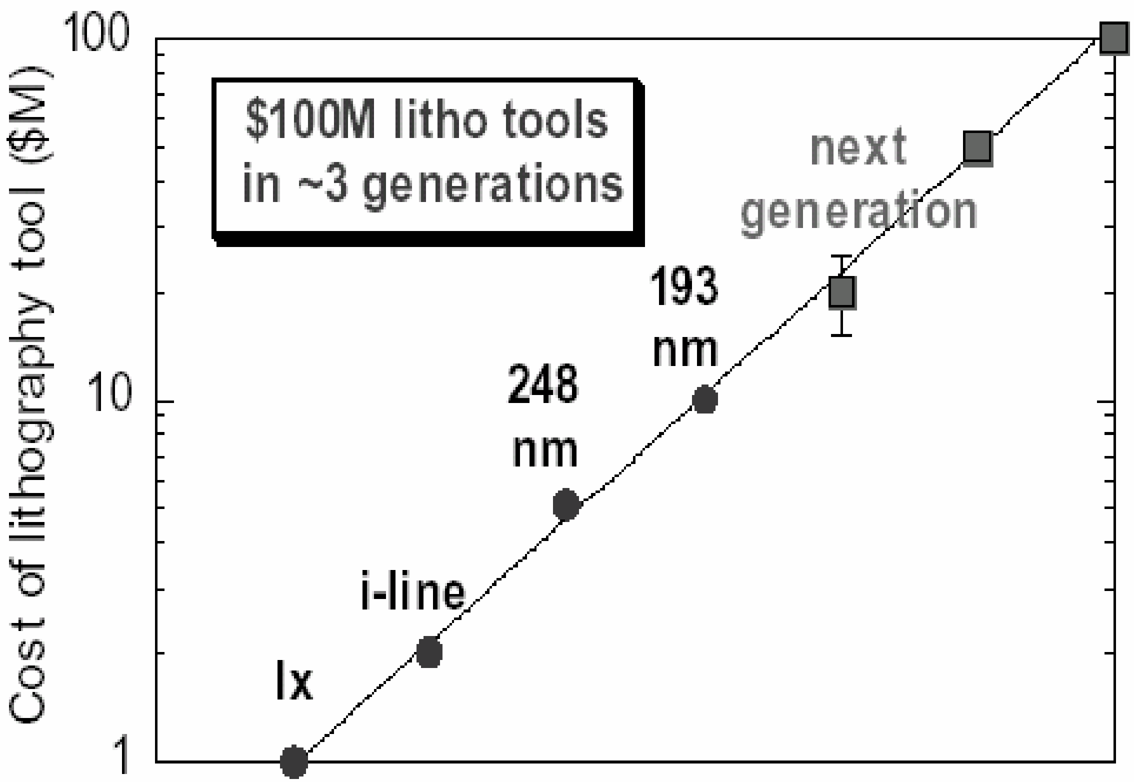
Lucent Technologies
Bell Labs Innovations

Lithography Crisis



Courtesy: Samsung Electronics

Lithography Tool Costs



Courtesy of K. Brown [NIST]

Mask Prices Crisis

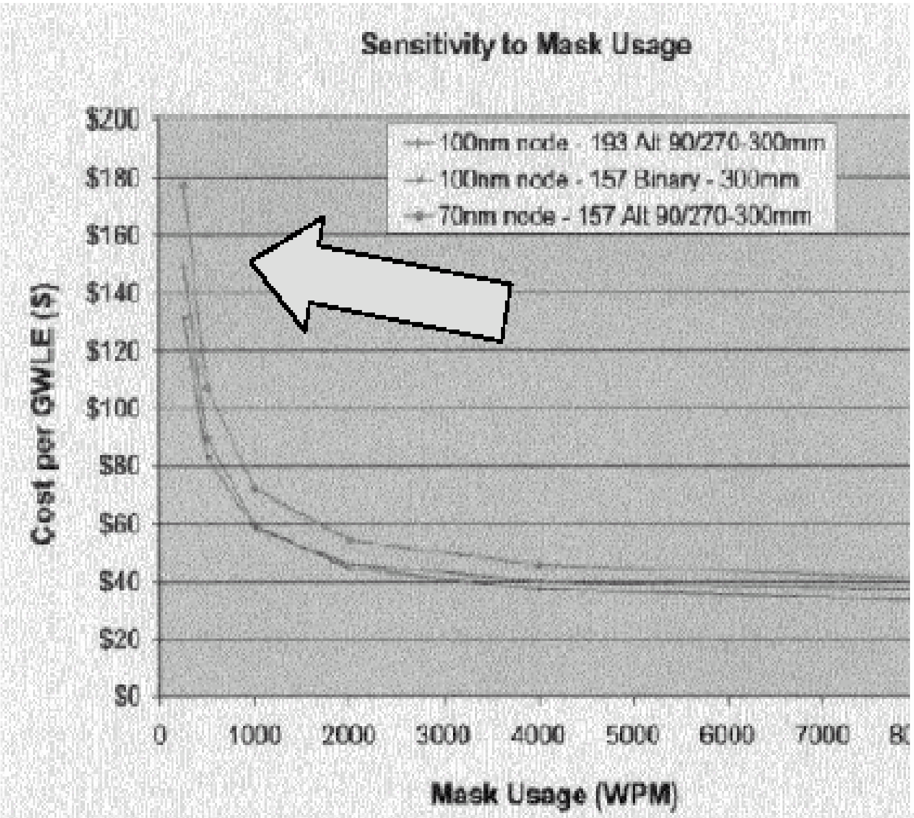


Figure 1 COO Sensitivity to Mask Usage

Source: Ed Muzio, International Sematech

Projected Annual Mask Costs:

ASIC Companies:

~$600 M/yr 100 nm node[a]

~$900 M/yr 50 nm node[a]

[a] at one design test per day

IC Manufacturers:

~$ 90 M/yr 100 nm node[b]

~$130 M/yr 50 nm node[b]

[b] at one mask set per week

Production Impact ~ $10/chip

IC Technology : Optical Lithography

Driver: SIA Lithography Roadmap

Solutions:

Future : New Lithographic technologies : 157 nm, EUV, Projection e-beam, X-ray, Maskless approaches, Other Novel ideas

Current: Optical Enhancement Technology : Illumination Modifications, Mask Enhancements, Multiple Exposures, Wafer Plane Enhancements

New Photoresist Materials

Integration of Enhancements for Device Fabrication

Resist Materials Chemistry

Novolacs

Chemically Amplified Resists - First Paradigm Shift

193 nm Resists - Second Paradigm Shift

157 nm Resists or Ultra Thin Layer Resists

Other novel resolution enhancement technologies

CA Resists : Implementation Problems

Invention to Insertion : >12 years

Surface Inhibition and Substrate Contamination:

Cause: Acid deactivation at the polymer surface or on the substrate (Ti Nitride or Si Nitride)

Solution(s): Processing in "base free" environment, or Weakly acidic overcoat

Poor Etch Resistance

Cause: Protective group removal during etch with acid and light

Solution(s): Decrease protecting group size and amount of protection

Large change in CD (Critical Dimension) with PEB Temperature

Cause: High catalytic chain length

Solution(s): Decrease catalytic chain length, lower activation energy systems

Resist Materials Chemistry : 2nd Paradigm Shift
Invention to Insertion : >6 years

Problem: Aromatic and Olefinic Moieties are Too Absorptive at 193 nm

Challenge: Design Resist Materials that are Structurally different from Novolacs, yet Functionally superior to them with nominally the same process

Materials Design Principles : 193 nm Resists

- **Matrix Resin**
  - **Alicyclic moieties that afford etching resistance**
  - **Maleic anhydride facilitates metal-ion free synthesis**
  - **Acrylate functionalities afford differential solubility**

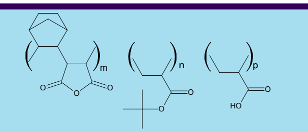
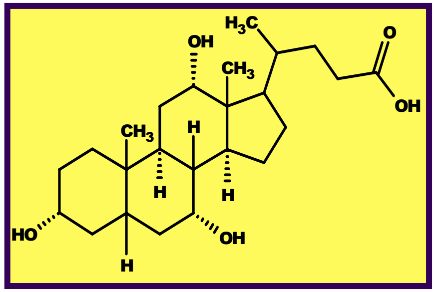


Figure 2. Repeating units used in the polymers of this study: norbornene-alt-maleic anhydride, t-butyl acrylate, and acrylic acid.

- **Dissolution Inhibitor**
  - **Occupies large molecular volume leading to greater unit volume change in solubility (High Contrast)**
  - **Miscible with polar matrix resins**
  - **Transparent at exposing wavelength**
  - **Readily available**



- **Photoacid Generator**
  - **Miscible with resist components**
  - **Affords strong acid**
  - **Generates 'non-volatile' by-products upon irradiation**

$Ph_2I \quad O_3S-CF_2CF_2CF_2CF_3$

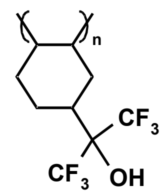
157 nm Resist Approaches

Invention to Insertion : >?? years

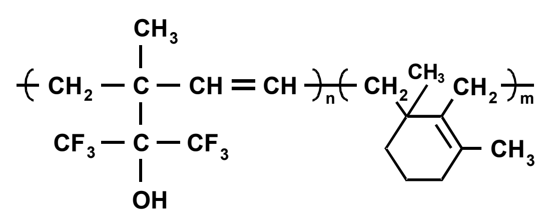
- Materials Transparency
- Materials Transparency
- Materials Transparency
- Materials Transparency

Polymer Platform Alternatives

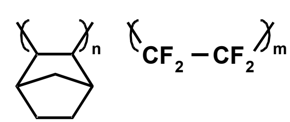
- Hydrosilsequioxanes (0.06AU/μm)
- Polymeric fluorocarbons (0.7AU/μm)
- Partially esterified hydrofluorocarbons (2.6AU/ μm)
- UTL (Ultra thun layer resists) with Hardmask



Willson, et al[24]



Ober, et al[25]



Crawford, et al[26]

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Bell Labs Innovations

O. Nalamasu, 01/24/03

Resist Performance Parameters

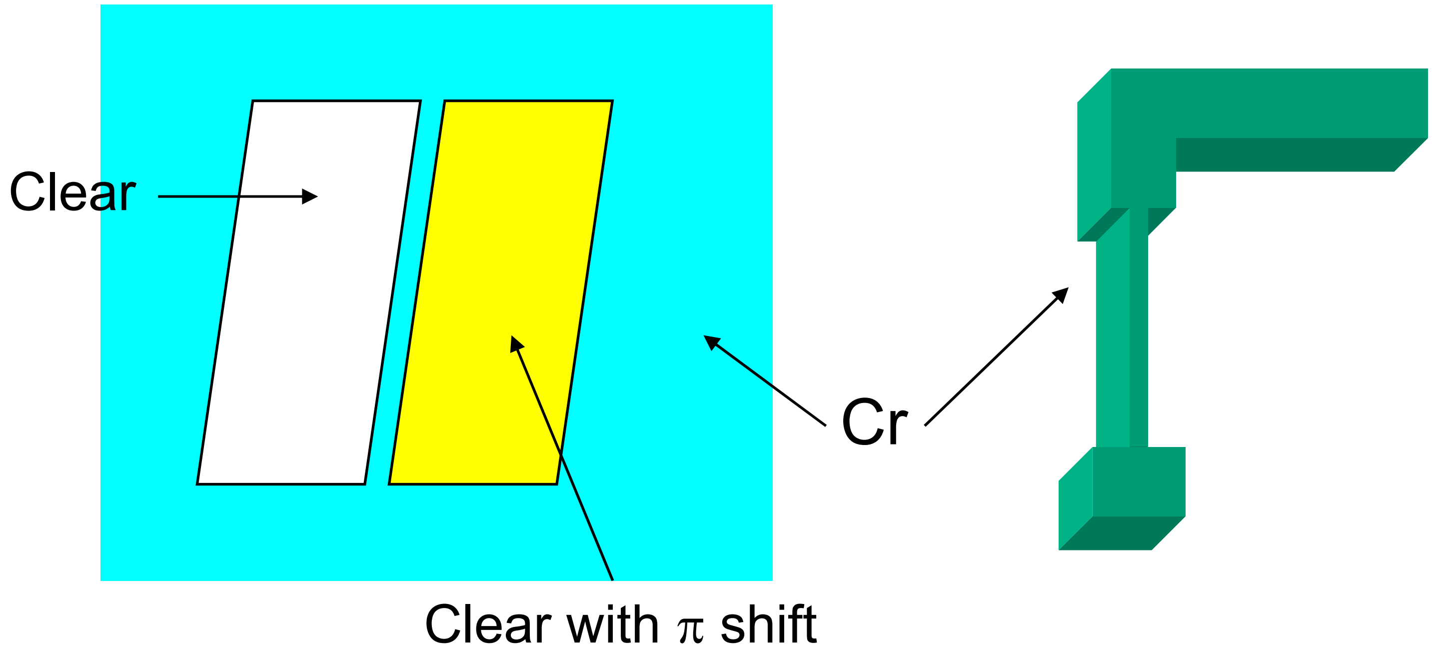
- Radiation response
  - Sensitivity, Contrast
- Resolution
- Linewidth control
- Defect density
- Etching resistance
- Others: Adhesion, Supply and quality assurance,
  Shelf life, cost

Performance → Molecular Properties

Lithographic Parameter	*Molecular Characteristic*
Absorption	No olefinic or aromatic moiety
Etching stability	High levels of structural carbon, low oxygen content
Aqueous base solubility	Base solubilizing groups such as OH, COOH, NH, etc.
Substrate adhesion	Presence of polar moieties
Sensitivity or photospeed	Catalytic chain length for acidolysis, quantum yield for acid generation, acid generation, acid strength, protective group chemistry
Post-exposure delay and substrate substrate sensitivity	Catalytic chain length for acidolysis, protective group chemistry, acid strength acid strength
Outgassing	Protective group and photoacid generator chemistry
Aspect ratio of images	Surface tension effects and mechanical strength
Low metal ion content	Synthesis and scale-up methodology
Manufacturability and cost	Synthesis and materials scale-up methodology and lithographic process process requirements

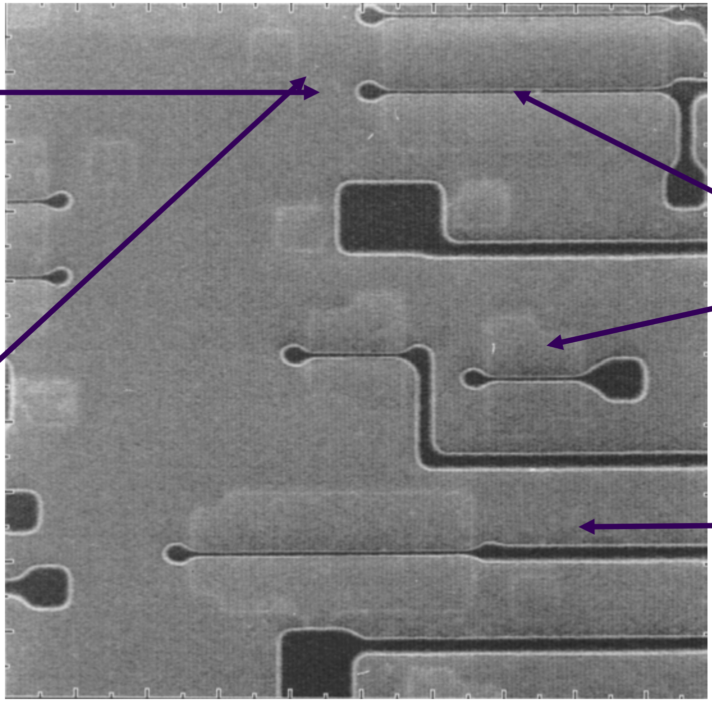
Numerical Technologies Dual Exposure Method

- First PSM exposure defines gate between rectangles. Phase shifting improves contrast, process latitude and CD control of gate
- Second exposure shadows first line and images rest of the features at larger design rules



DSP Cell Layout

Variety of gate lengths
Only 240 nm sized features are phase shifted
Contact pads and runners are unchanged

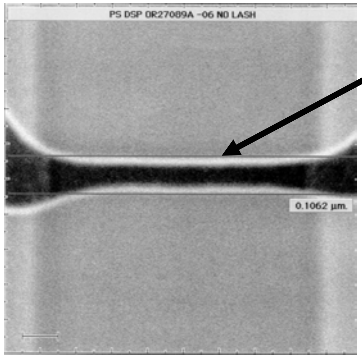


Fully Functional 3 M transistor circuits based on PSM

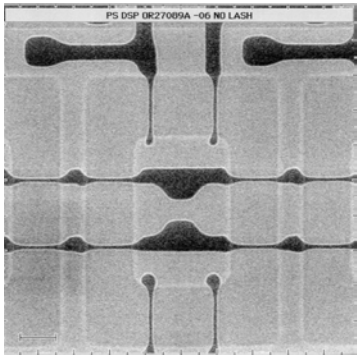
Liquid Ashing (Lashing) Process

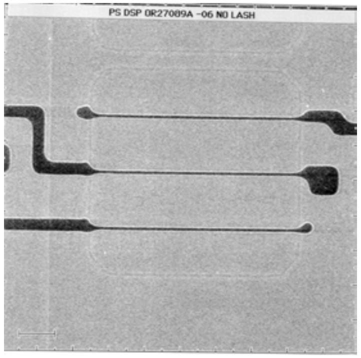
- Post-development treatment to reduce feature dimension
- Involves heat and or light treatment followed by develoment (~ 1 nm/sec.)
- Side wall roughness is reduced during the Lashing Process
- Vertical side walls remain unchanged after the Lashing Process
- 50 nm DSP gates have been achieved using the Lashing Process
- Pattern transfer into the Hard mask layer has been achieved
- Fundamental mechanistic understanding is necessary

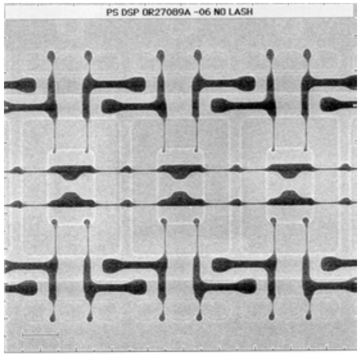
DSP 1628G Printed with Phase Shift Reticle As Printed “Resist”

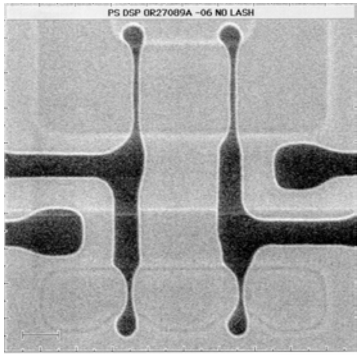


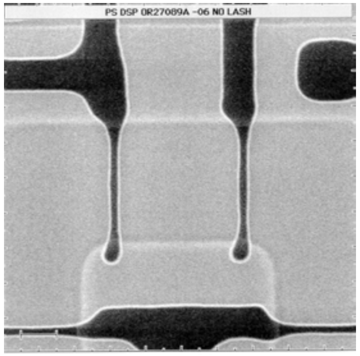
0.106 µm Gate





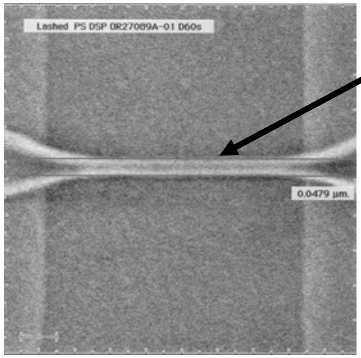


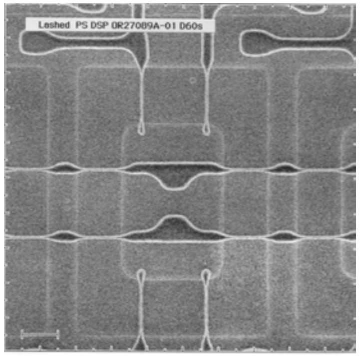


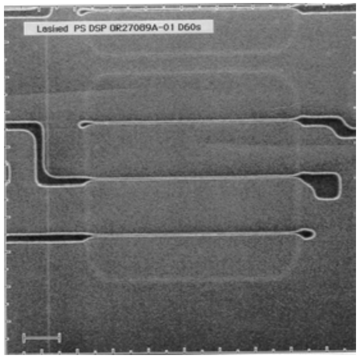


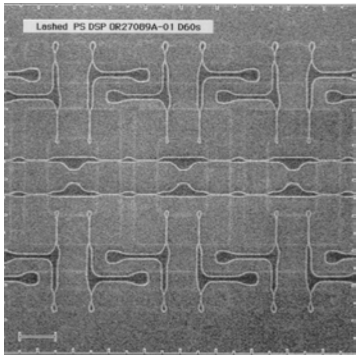
DSP 1628G Printed with Phase Shift Reticle, with “LASHING”

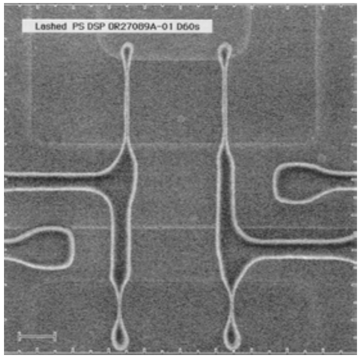
0.048 µm Gate

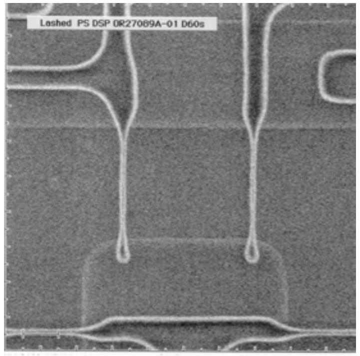




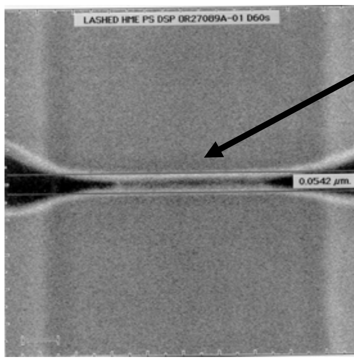




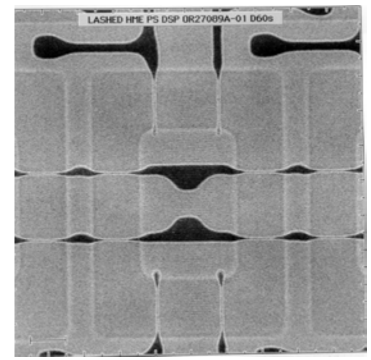


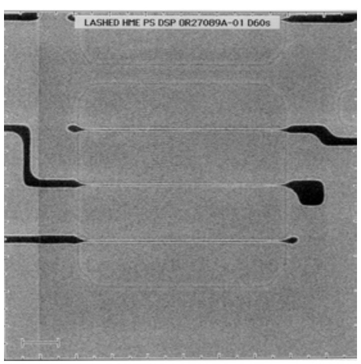


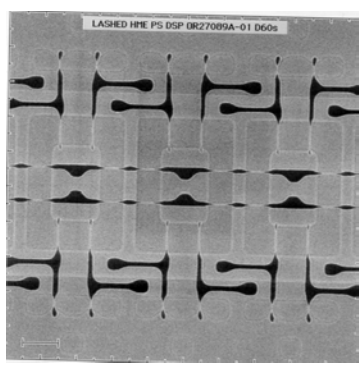
DSP 1628G After the "LASHING" Process and Hard Mask Etch

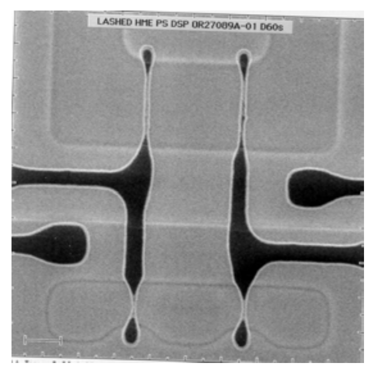


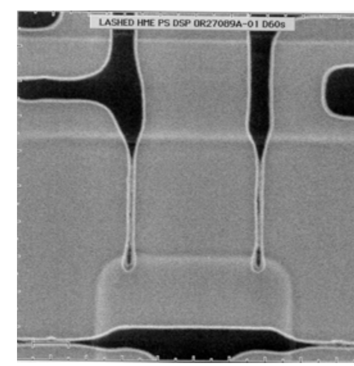
0.054 µm Gate





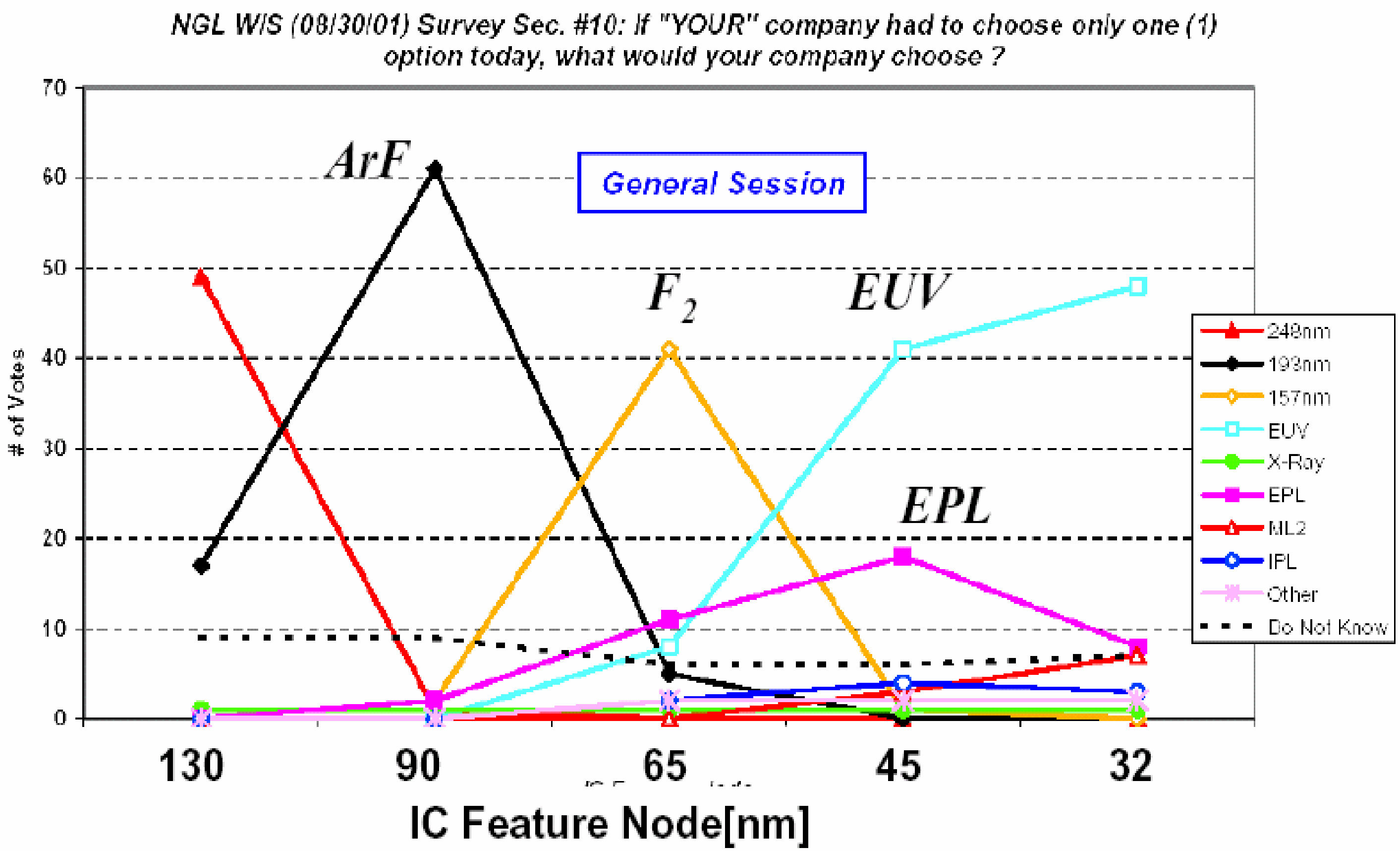






Snapshot of Opinions

ISMT 2001 NGL Workshop Survey



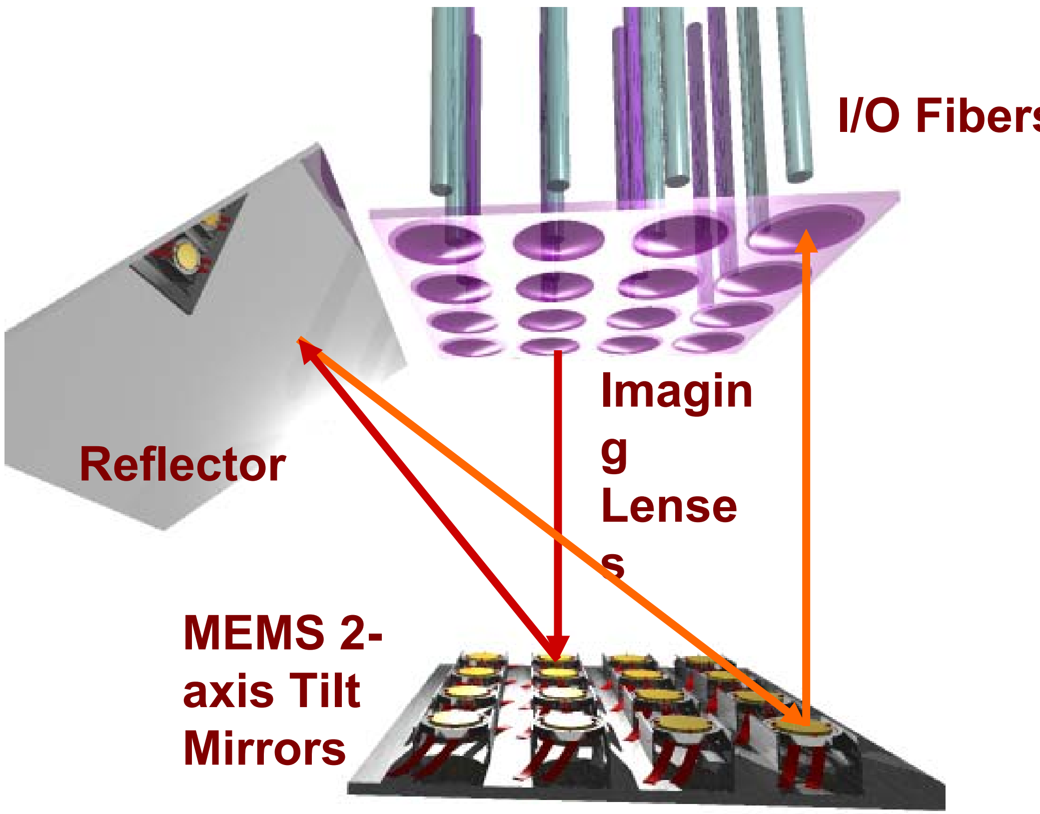
Lucent Technologies
Bell Labs Innovations

Research Opportunities

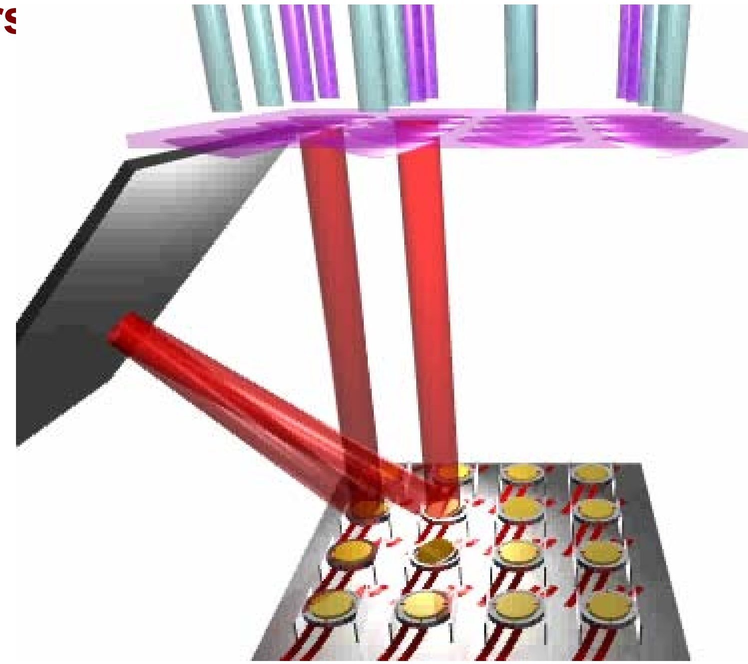
Electronic and Photonic Materials involving a Platform approach

- Fluorocarbon, Silicates for microlenses, low k, Wave Guide and 157 nm resist applications
- Environmentally benign materials through plasma polymerization and development
- **Fundamental understanding of imaging materials (polymeric or small molecules) and processing especially in the nanodomain**

MEMS OXC-- 2N Mirror Design

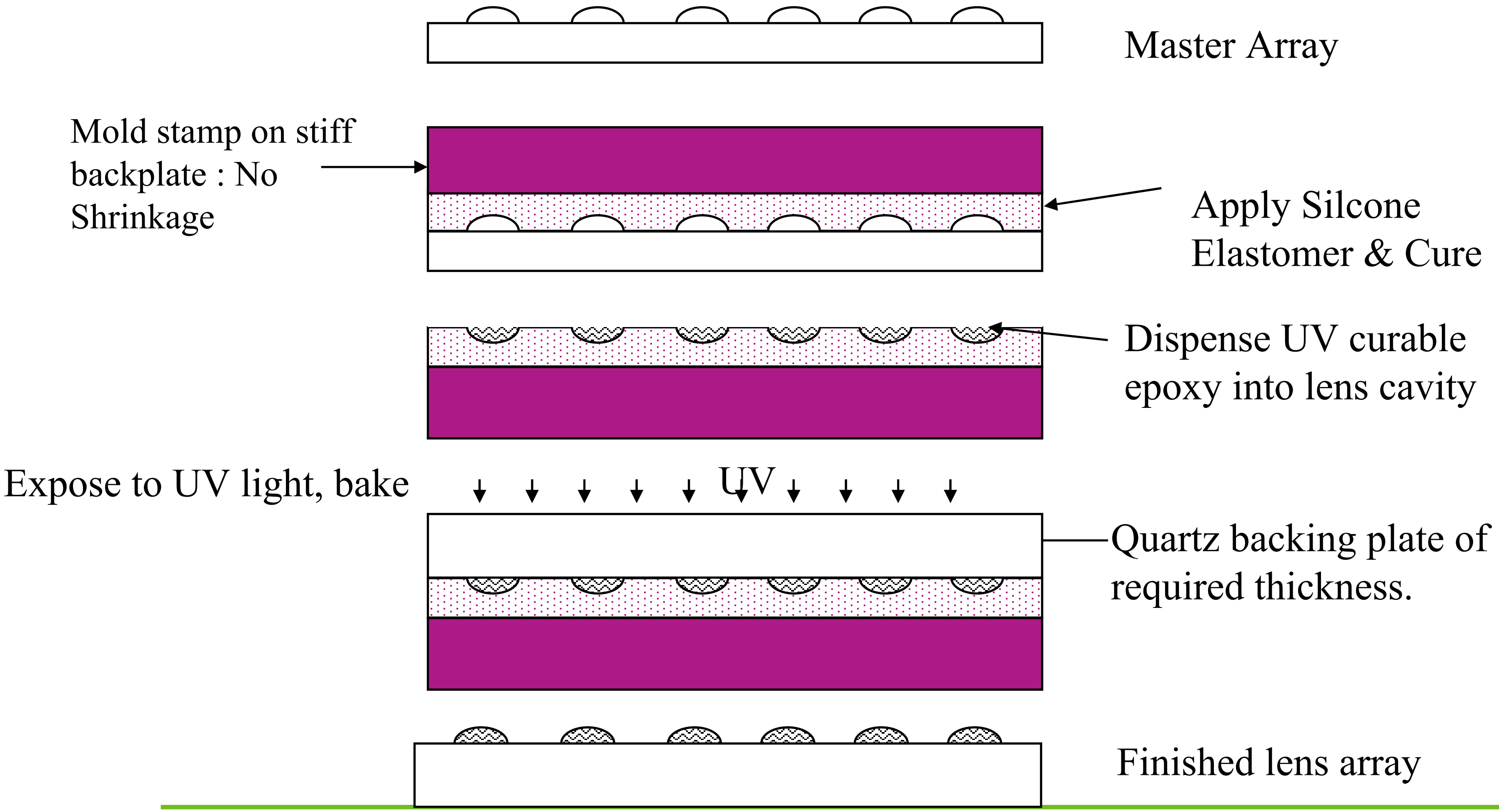


2N MEMS mirrors in an NxN single-mode fiber optical crossconnect.



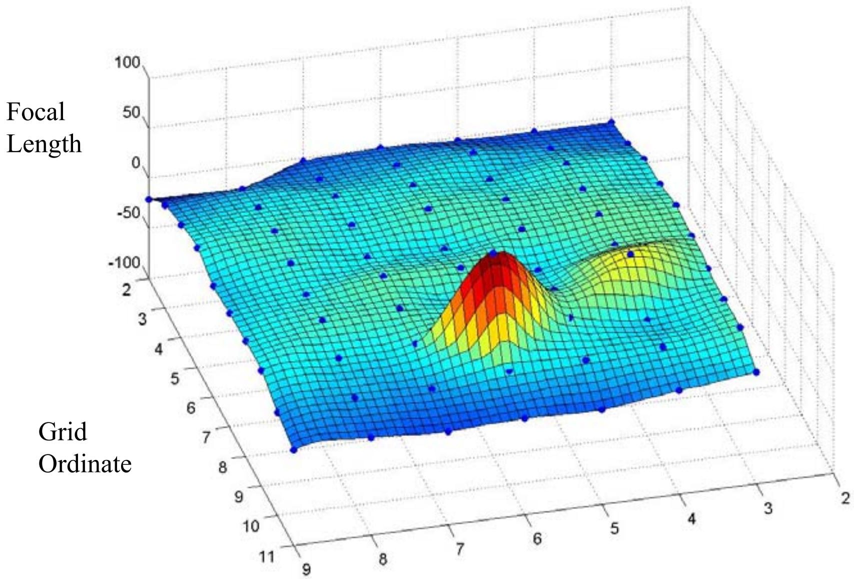
Beam scanning during connection setup.

Lens Array - Fabrication

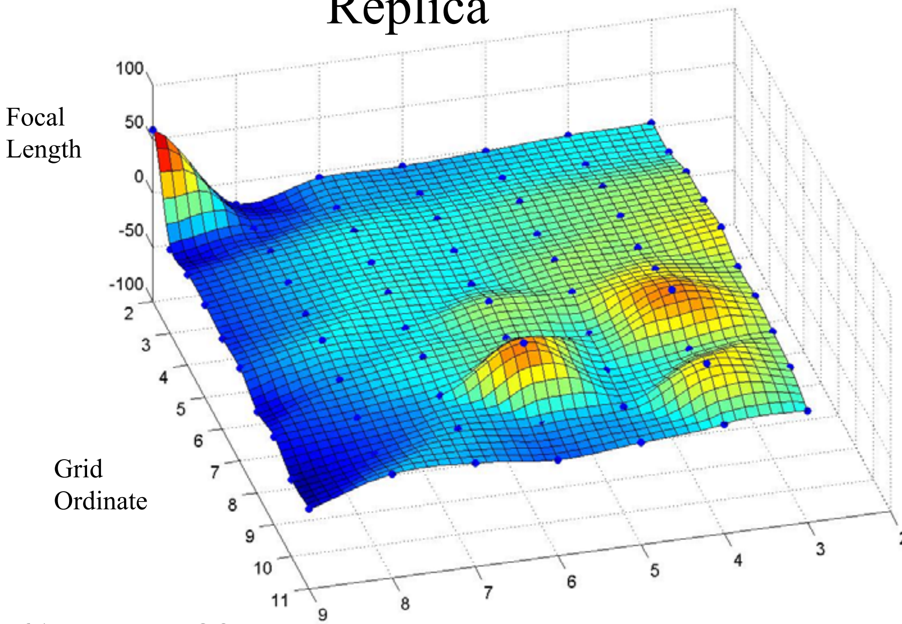


Focal Length Profiles

Master



Replica



Focal-length range:	61 µm	82 µm
Avg. insertion loss:	1.89dB	1.83 dB
Insertion-loss spread:	0.79dB	1.47 dB

- Systematic/edge variations minimized by controlling polymer dispense

Problems and Opportunities

- Convergence of information and nanotechnology
- What sort of LER control required for 15-30 nm lithography that requires ±1.5-3 nm line width control
- What is the best litho solution : Top-down lithography or soft lithography or self-assembly
- Fundamental understanding of lithography processes at nm control is imperative (LER, aspect ratio, surface tension effects, pattern transfer methods, Schott noise)
- Patterning at the interface of materials, biology and medicine
- Scalable, cost-effective, well understood and robust materials platform needs to be developed
- Every problem is an opportunity for research funding – Doing my Professorial tin cup routine

Problems and Opportunities

Scalable, cost-effective, well understood and robust lithography technology and materials platform is imperative

Market size and business opportunity are grossly out of scale compared to the investment required to develop a new resist

Some industrial organizations with heritage of developing resist technology exited the field

What is the new model for replenishing the pot?

Some Ideas

US competitiveness in a critical industry (Lithography enables $240 Billion IC Industry) is vital to economic prosperity and defense of the nation

Possible Models: Consortia, and/or Public/private partnerships to conduct pre-competitive research (IP problems are difficult but are not insurmountable)

Benefits:

- Cost-effective
- Aligned and concurrent tool, material, process and device development (like it used to be, Is it back to the future???)

Problem Definition

- Cost of ownership (address tool, mask, and resist cost, throughput)
- Proof of principle, scalability, industry support
- Triple helix (industry, university and govt. support)
- Relative position (Positive: Resists, Pellicles, embedded rings; Concerns: Masks, Masks, and Masks)
- Spillover benefits (past: LIGA, Future: Nanotechnology)

Appendix C – Talk 5

John Heaton – BAE Systems

BAE SYSTEMS

Application of X-ray Lithography to MMIC Fabrication for Military Applications

John Heaton

January 24, 2002

Need for X-Ray Lithography

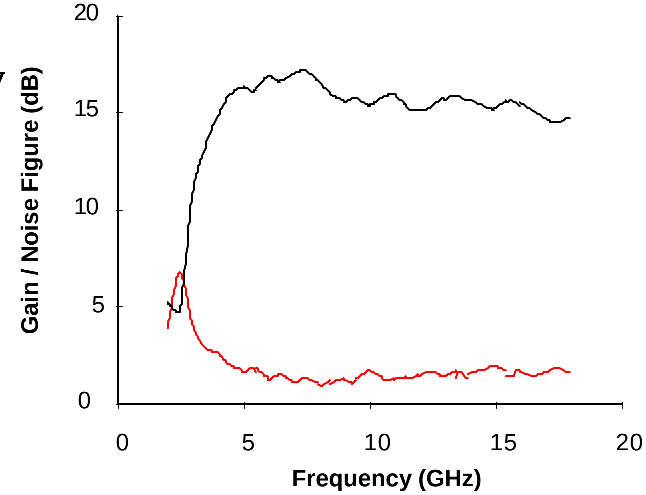
BAE SYSTEMS

- MMIC chips are backbone of radar, EW, missile seeker and communication systems
- Highest performance MMIC chips require sub 100 nm feature sizes.
  - W band and higher applications ultimately need sub 100 nm MMICs for highest possible power added efficiency and lowest possible noise figure
  - Provide performance margin for high yield manufacturing
- Currently, fabrication of 0.12 micron MMICs accomplished through direct write electron beam lithography; sub 100 nm chips cannot be fabricated with available e-beam systems at reasonable throughput
  - Very expensive and slow
- Alternate approach uses X-Ray Lithography System

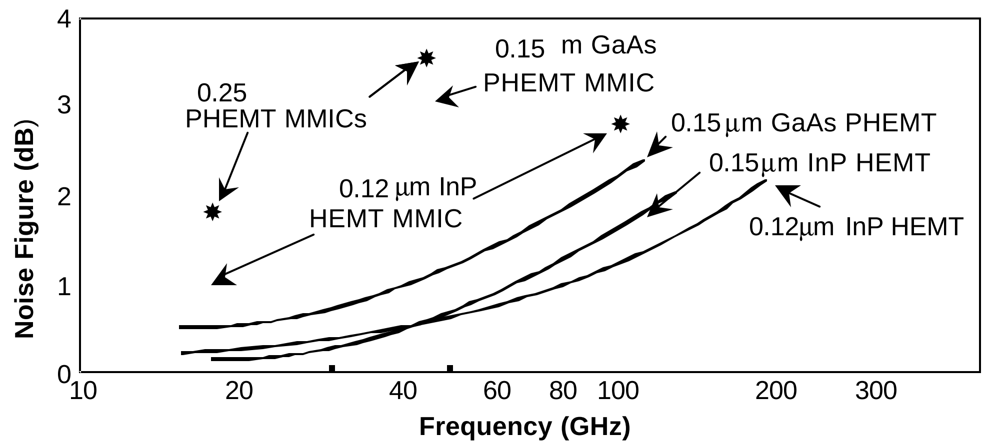
MMIC Performance Drivers

BAE SYSTEMS

- **Required performance improvements**
  - **Higher power per millimeter of periphery**
  - **Higher efficiency**
  - **Lower noise figure**
  - **Lower receive power dissipation**
  - **Smaller Size**
  - **Higher gain**
  - **Improved linearity**
- **Required device improvement**
  - **Reduced gate length**
  - **Advanced materials structures**
    - **PHEMT**
    - **InP HEMT**
    - **Metamorphic HEMT**



Gain and Noise Figure Performance of Wideband LNA for Military Application



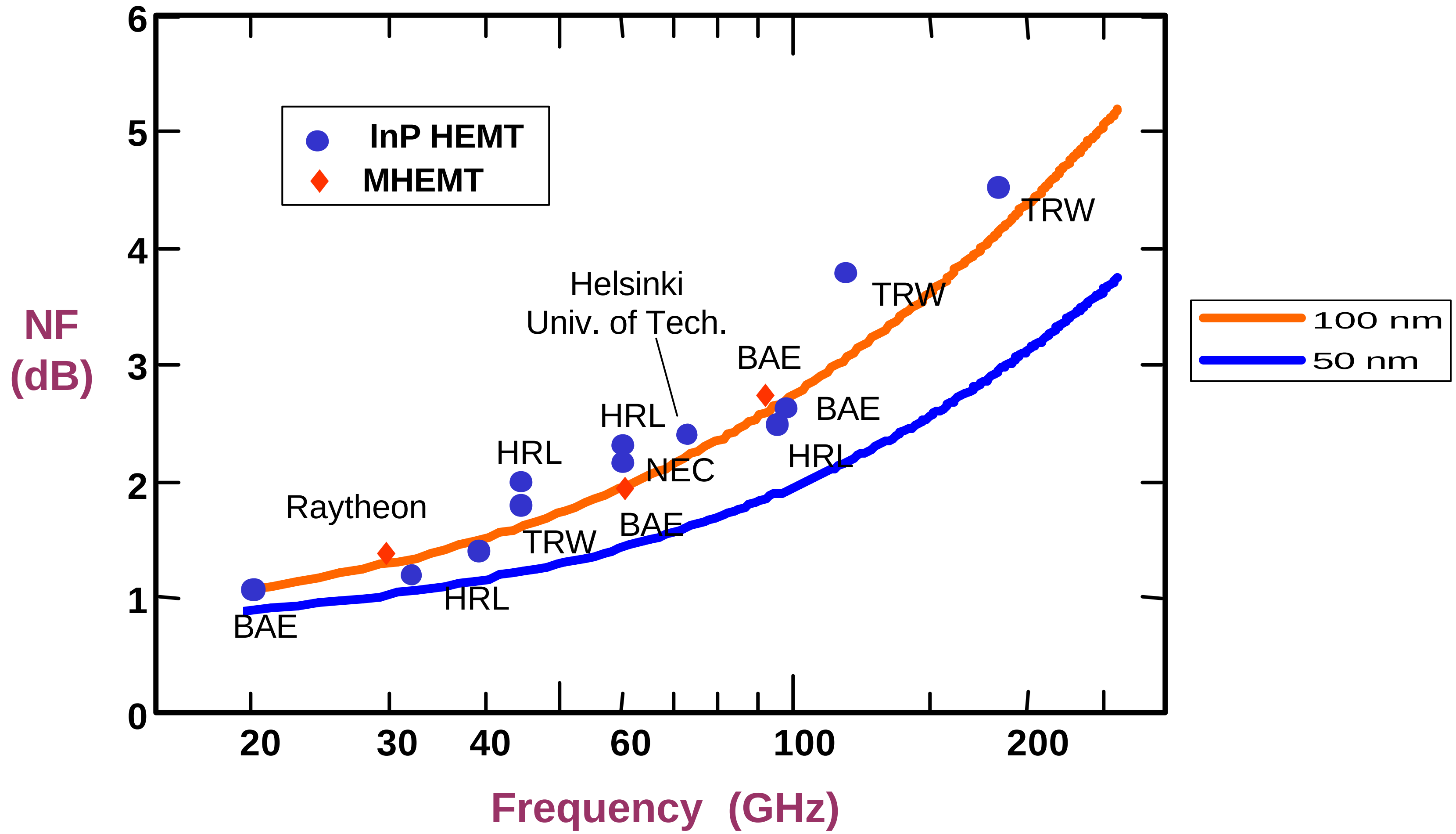
Transition to Advanced Materials and Smaller Gate Length Improves MMIC Noise Figure

Military Applications for 50 nm MMICs

BAE SYSTEMS

Application	Freq, (GHz)	Comments
Active Seeker	94/140	140GHz allows smaller beam, better signal/clutter ratios
Concealed Weapons Detection, (CWD), and Through the Wall Surveillance, (TWS)	94/140	Passive and active video rate imaging; lower noise at 94GHz allows lower cost sparser array; higher resolution at 140GHz for hand held units
Autonomous Landing System, (ASL), and Independent Landing Monitor, (ILM)	94/140	All weather aircraft operation using video rate passive imaging; low noise and high resolution advantages at 94/140 respectively
Passive Seeker	94/140/220	All weather, high resolution, difficult countermeasures, LPI, straight down, video rate, end game applications
Airborne Surveillance	94/140	All weather, adverse environment, passive video rate imaging, battlefield surveillance and detection of relocatable targets
Hazard Avoidance Radar	220	Helicopter hazard avoidance; high cross section of suspended cables at 220 GHz makes it ideal
Meteorological Satellite, (METSAT)	183	Ground state of water vapor molecules at 183GHz; ideal for profiling atmospheric water vapor; key to METSAT forecasts
Earth Observation Satellites, (EOS)	100 to 500	Many molecular transitions of key atmospheric species; ideal for atmospheric sounding and other remote sensing applications
Vehicle Radar	150	Autonomous collision avoidance applications; vehicle stylists want smaller sensors provided by 150GHz operation

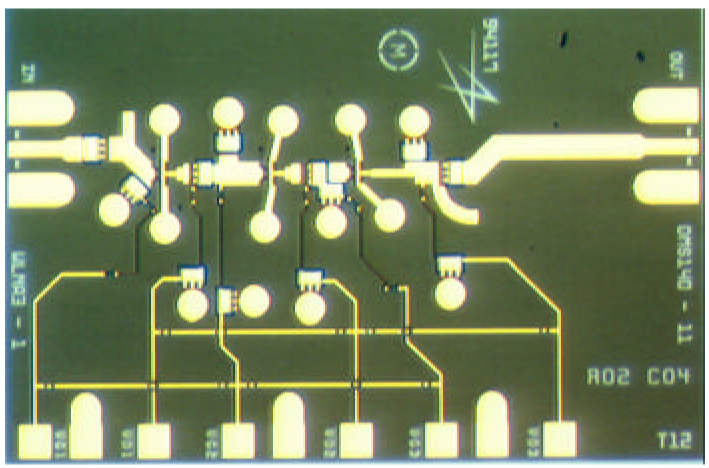
Best Reported MMIC LNAs



Missile Seeker Radar

BAE SYSTEMS

- Current radar based Missile Seekers use single T/R Module and twist plate beam steering
- High G force missiles for ABM application need strapped down seekers
- Based on today's cost of $50mm², phased array millimeter wave seekers are unaffordable
- Cost savings of 50 nm MMICs built using X-ray lithography will enable phased array millimeter seekers at 140 GHz

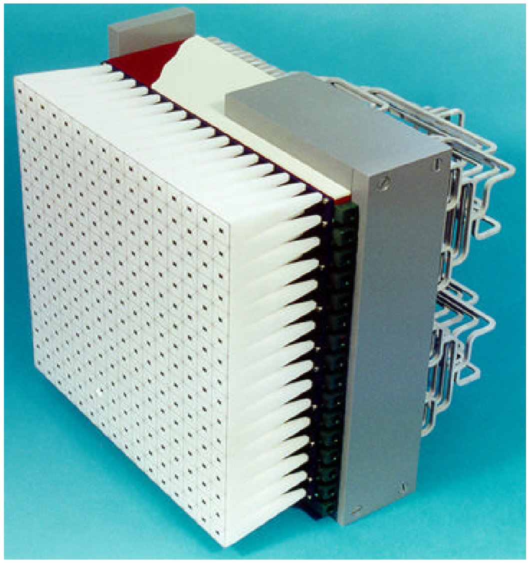


W band LNA MMIC

X-Ray Lithography Impact for Phased Arrays

BAE SYSTEMS

- Military applications of phased array antennas have significant MMIC content
- Large arrays required for spaced based imaging or communications
  - 25,000 elements
  - 300,000 MMICs
- X- Ray makes high performance arrays affordable
- X- Ray enables mass production of 0.05 micron gate MMICs
  - Very low power dissipation LNAs reduce array power dissipation



Prototype Millimeter wave Phased Array

Roadblocks

BAE SYSTEMS

- MMIC industry cannot afford synchrotron installation, need stand alone system
  - Existing point source systems are immature; more work needed to improve throughput, reliability
- Mask availability
  - IBM X-ray mask shop may close
  - 1X masks impede sub-100nm development
  - Phase shift reduction printing attractive but no commercial source for X-ray phase shift masks

Conclusions

BAE SYSTEMS

- Military requirement exists for affordable high performance millimeter wave MMICs for missile seekers
- 50 nm Gate Lengths are required for 160 to 220 GHz operation
- X-ray lithography has potential for producing such MMICs
- More investment is needed to assure availability of masks and to mature existing point source systems

Appendix C – Talk 6

Bob Selzer
JMAR/SAL

X-ray Lithography, towards 15 nm

JSAL Steppers

Presented to: Jefferson Labs XRL Workshop

Newport News, VA

By: Bob Selzer

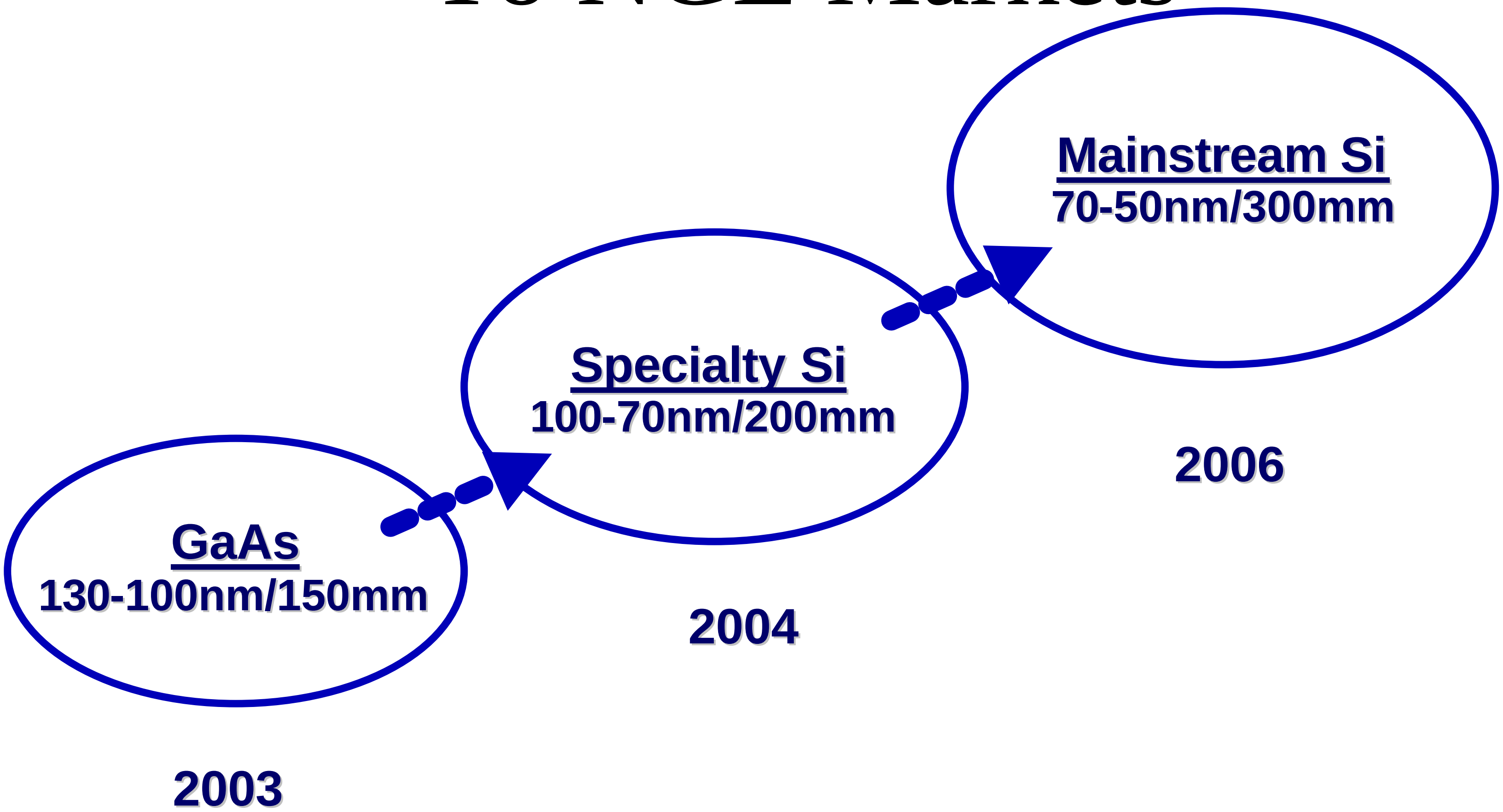
Senior VP, Technology

24 January 2003

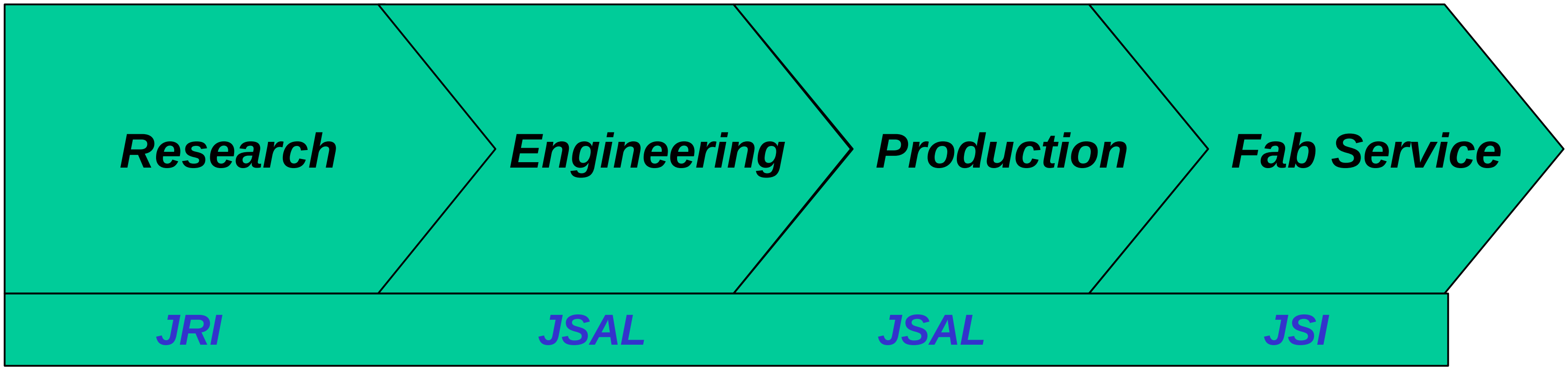
Outline

- JSAL Strategy & Systems approach
- Hardware built, integrated & delivered
  - Stepper
  - Source(s) – SRL, JRI & SOR
  - System Integration
- Proof of X-ray technology
- Summary

Steppingstone Approach To NGL Markets



JMAR Operations Flow



- ***R&D***
- ***Proof of Concept***

- ***Product Development***
- ***Application Engineering***
- ***Hardware Design***
- ***Mask Design***
- ***Program Management***

- ***Mfg Engineering***
- ***Assembly***
- ***Integration & Test***
- ***Quality Assurance***

- ***Fab Equip Installation***
- ***Operator Training***
- ***Equipment Maintenance***
- ***Process Development***

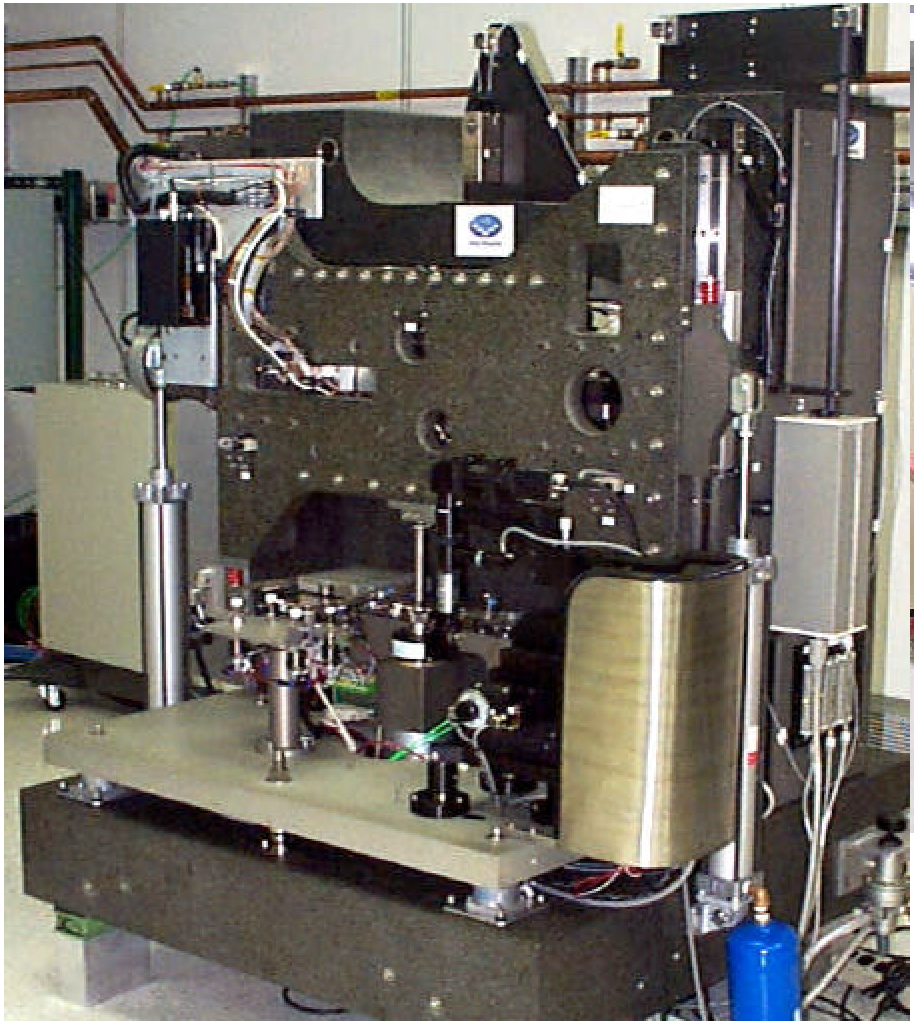
System Hardware

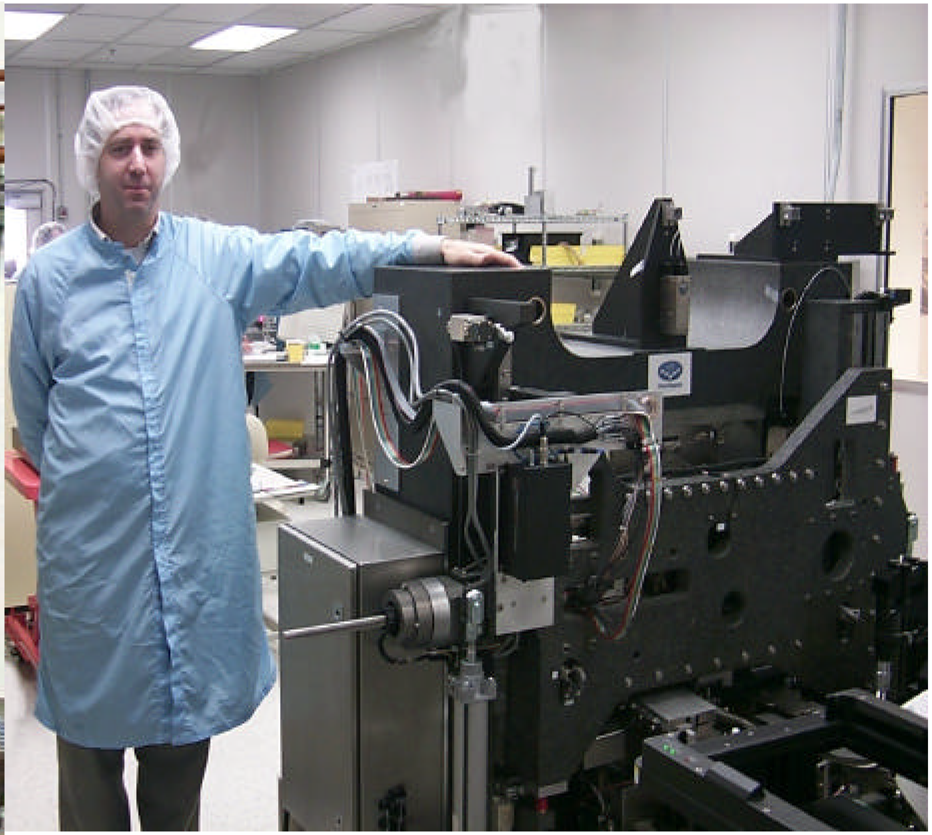
- X-Ray stepper - JSAL
- Chamber and MTS - JSAL/ Asyst
- Bake/ Coat Station - JSAL/ KSA
- Point Source(s) – SRL/ JRI
- He Beamline/ Chamber - JSAL
- Masks – JSAL design/ IBM build
- Facility & Demo - Install, test and demonstrate system at BAES – 09/1999
- Install Beta JMAR system at JSAL – 02/2003

JSAL XRS Stepper Specifications

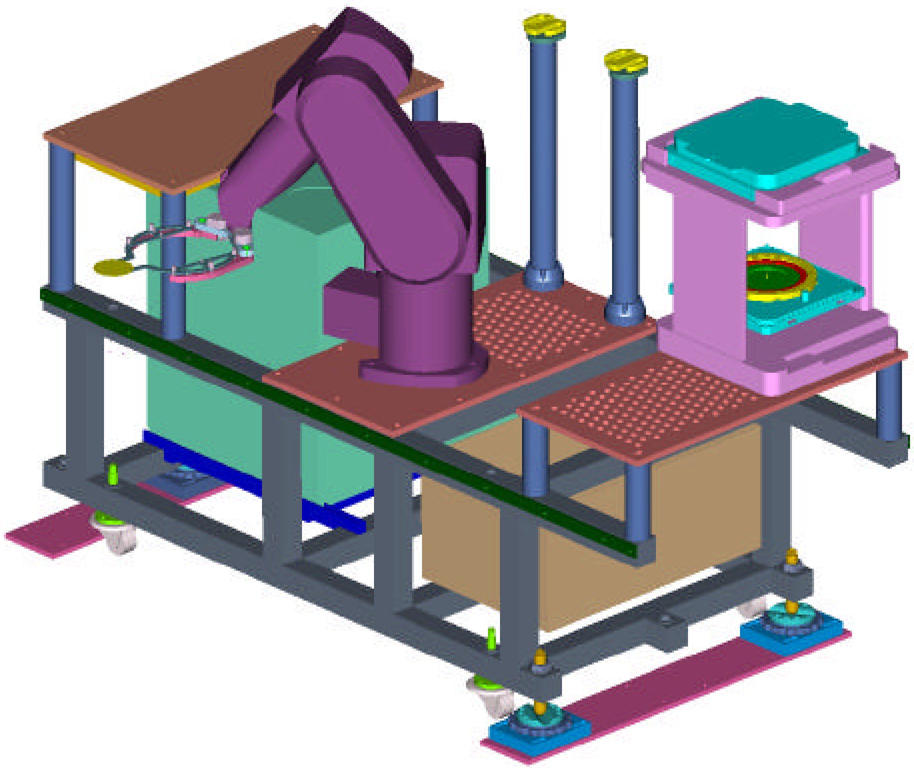
Features	XRS 2000/1	XRS 2000/2	XRS 3000/1
Pattern Resolution [mm]	*0.15 - 0.10*	*0.10 ~ 0.70*	*0.07 - 0.05*
Linewidth Control [nm]	*<10 nm*	*<7 nm*	*5 nm*
Alignment Technique	*ALX/2-4*	*ALX/4*	*IBBI & ALX/4*
Modes	*Die-by-Die/ Global*	*Die-by-Die/Global*	*Die-by-Die/Global*
Accuracy [nm]	*12*	*8*	*1*
Proximity Gap [mm]	*15 - 50*	*10 - 50*	*5 - 50*
Accuracy [nm]	*+/- 500*	*+/- 250*	*+/- 125*
Repeatability	*+/- 350*	*+/- 200*	*+/- 100*
Throughput Global	*20*	*40*	*75*
X-ray Source	*SOR or Pt. Source*	*SOR or Pt. Source*	*SOR or Pt. Source*
Overlay [nm]			
Tool-to Tool	*70*	*35*	*22*
Tool-to-Self	*50*	*25*	*15*
Field Size [mm]	*50 x 50*	*50 x 50*	*50 x 50*
Wafer Size [mm]	*75 - 200*	*75 - 200*	*100 - 300*
Handler Wafer/ Mask	*SMIF/ Cassette*	*SMIF/ Cassette*	*SMIF*

SAL XRS 2000/2 Stepper

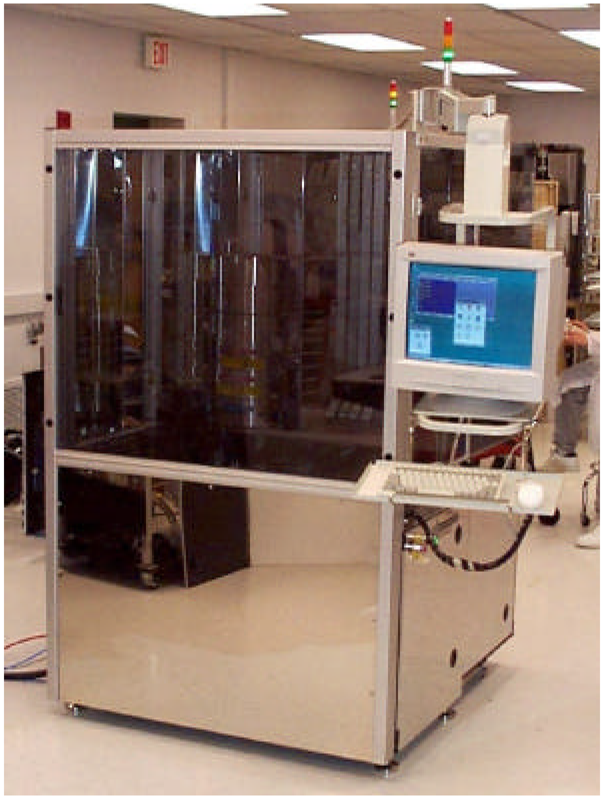




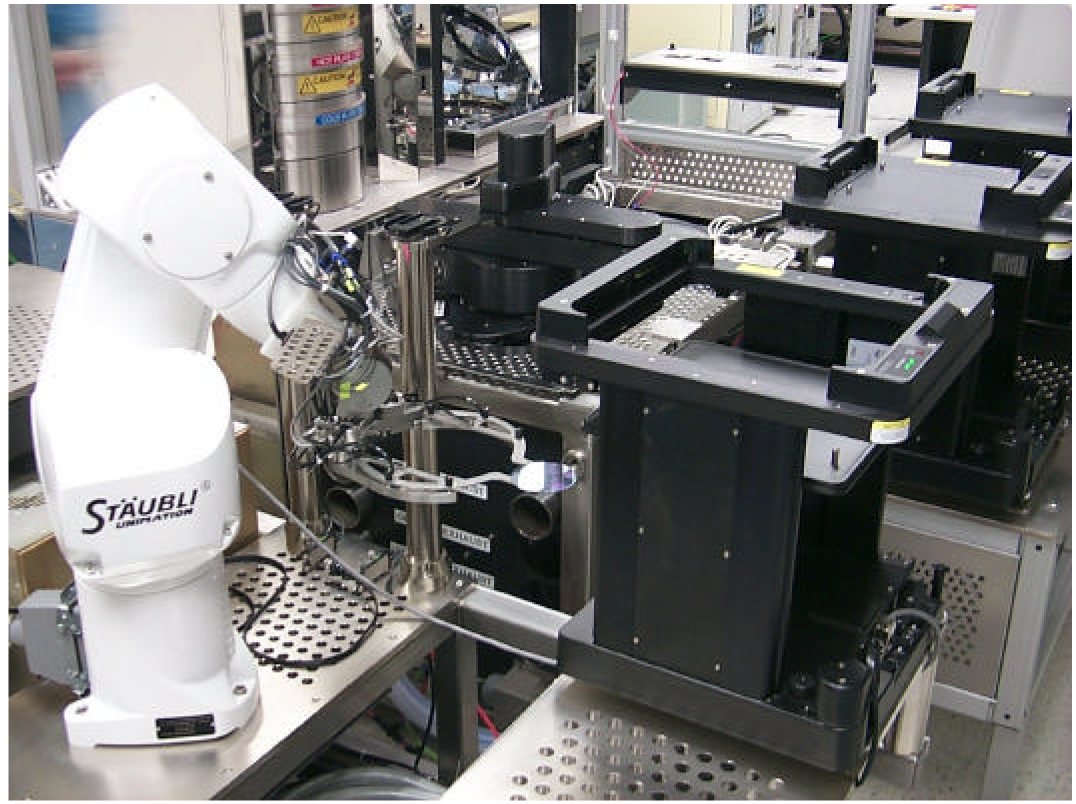
Material Transfer System (MTS)



MHS - Bake/ Coat Station



Exterior View

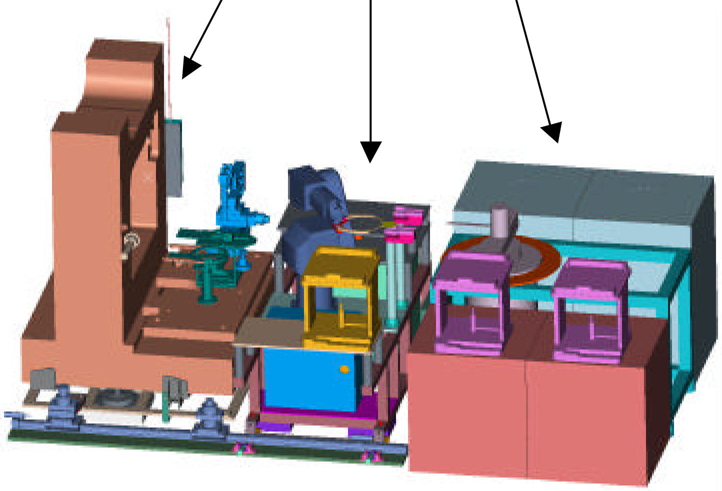


Interior View

SAL Environmental Chamber

Class 1 Chamber

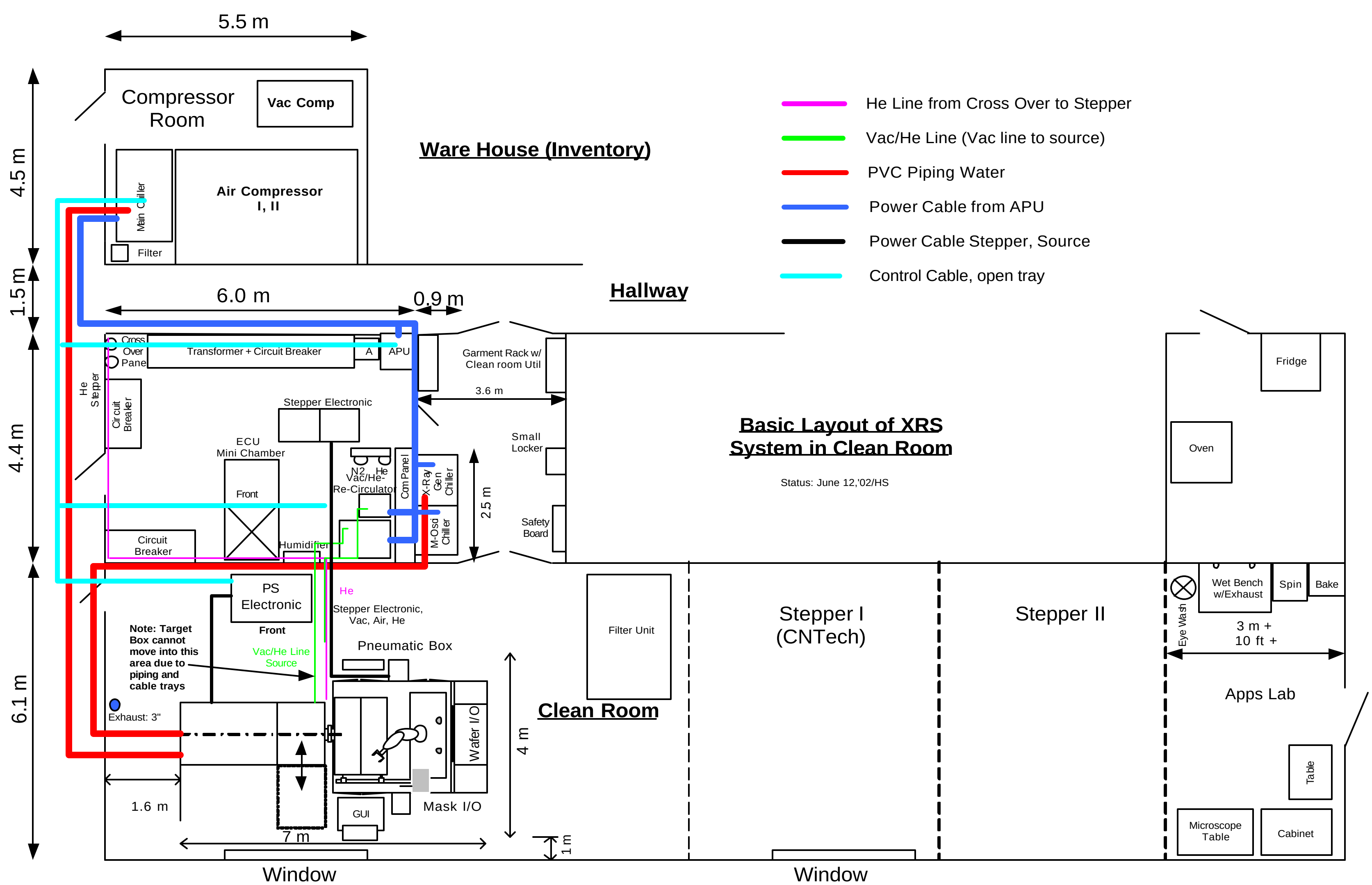
Stepper MTS MHS



SAL Specs: Class <1 with Carbon Filter System

Temp 18 - 27° C ± 0.10° C

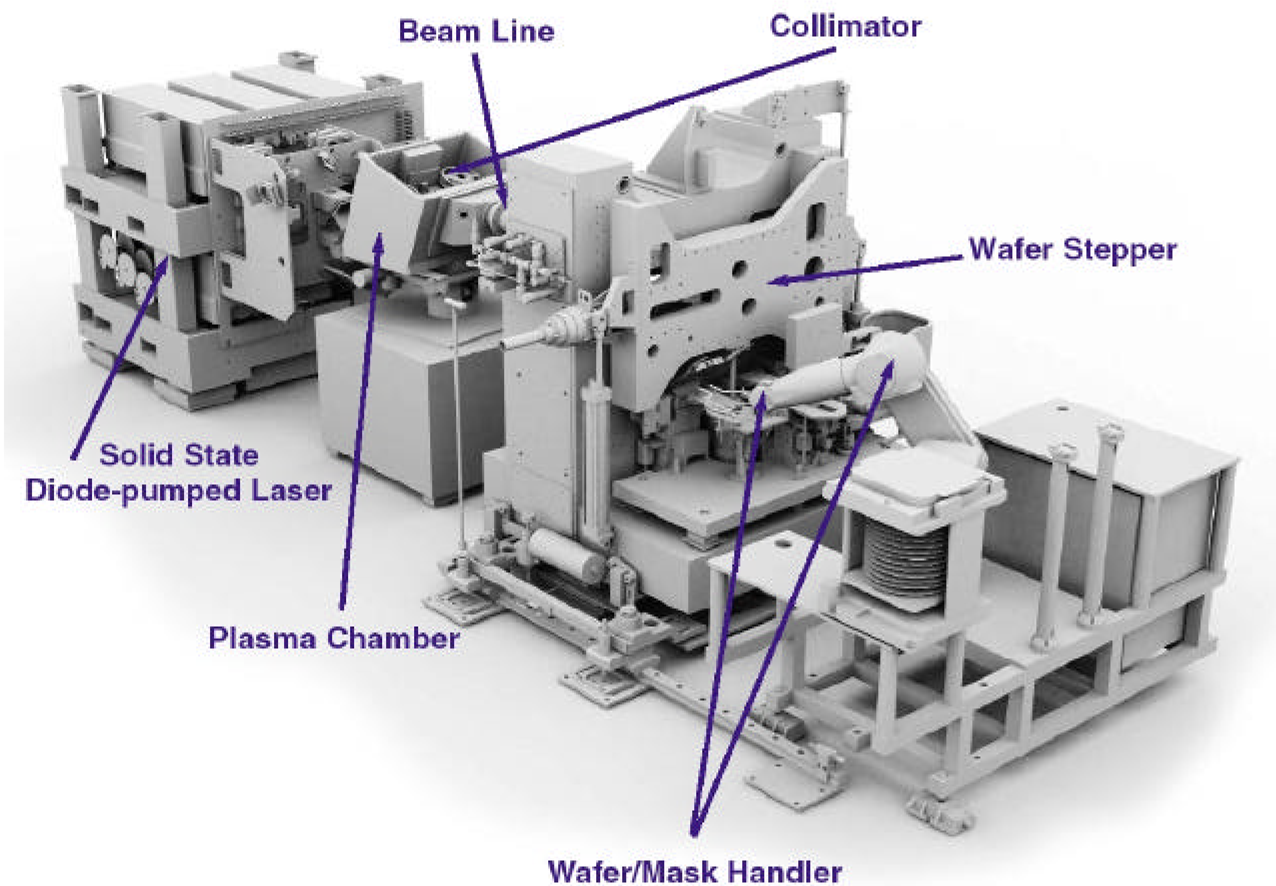
Humidity 35 - 45% ± 0.5%



JSAL System Layout

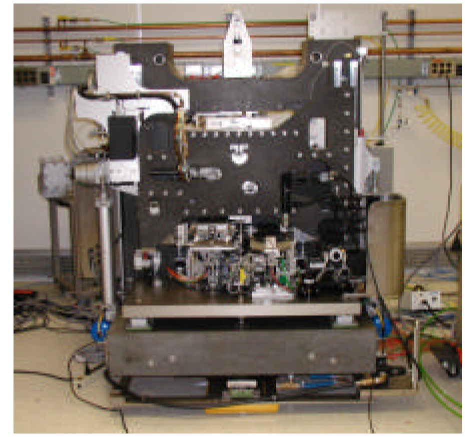
X-ray system at BAES

JSAL CPL System Overview



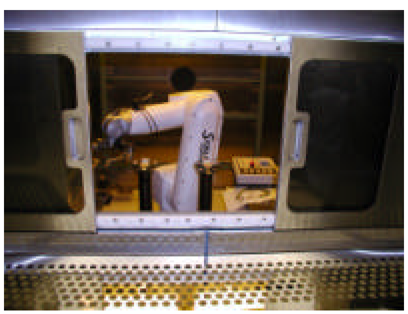
Total System Area = 21 square meters

JSAL CPL System Overview



? JSAL Stepper

? Class 1 Chamber



? Material Transfer System

Program Results to Date

- Built & integrated an X-ray point source system under DOD sponsorship.
- New JRI source due in Feb 2003 for integration
- Established an experienced "X-ray Team"
- MMIC demo at BAES (0.15μm and below)
- Continue Mask Supply/ Sourcing
- Provide easy entry into X-ray lithography for other device suppliers

Longbow Program

- Details omitted at the request of BAES program managers

F-22 Program

- Details omitted at the request of BAES program managers

Acknowledgements

- DARPA/ NRL/ NavAir
- BAES (Nashua, NH)
- JRI - JMAR Research, Inc
- SRL - Science Research Laboratories
- CNTech - Center for Nano Technology
- Masks from JSAL/ IBM
- UVM, Mechanical Engineering Department
- Shipley
- MIT, Nanostructures Lab