OPTICALLY LITHOGRAPHED WSi_X SUPERCONDUCTING NANOWIRE SINGLE PHOTON DETECTORS (SNSPDs) DEMONSTRATED NEAR 1550 NM

Andrew D. Beyer, F. Marsili, M.D. Shaw, R.M Briggs, J.P. Allmaras and W.H. Farr.
Jet Propulsion Laboratory, California Institute of Technology
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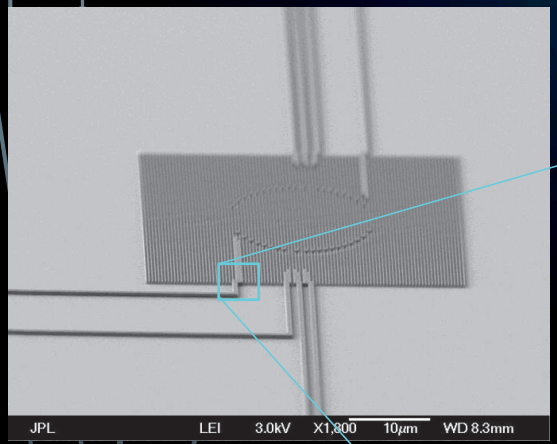
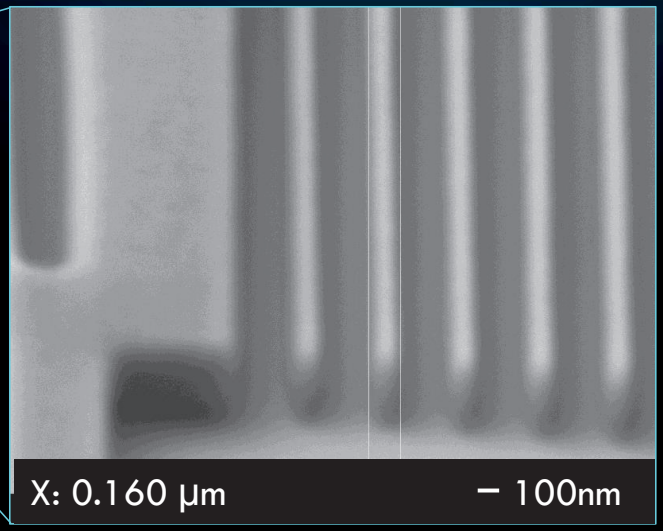
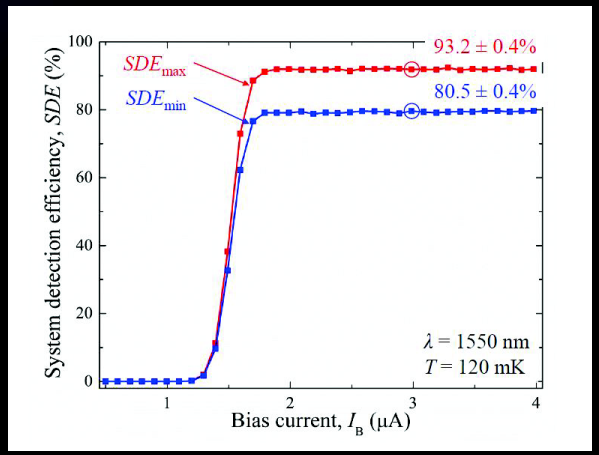






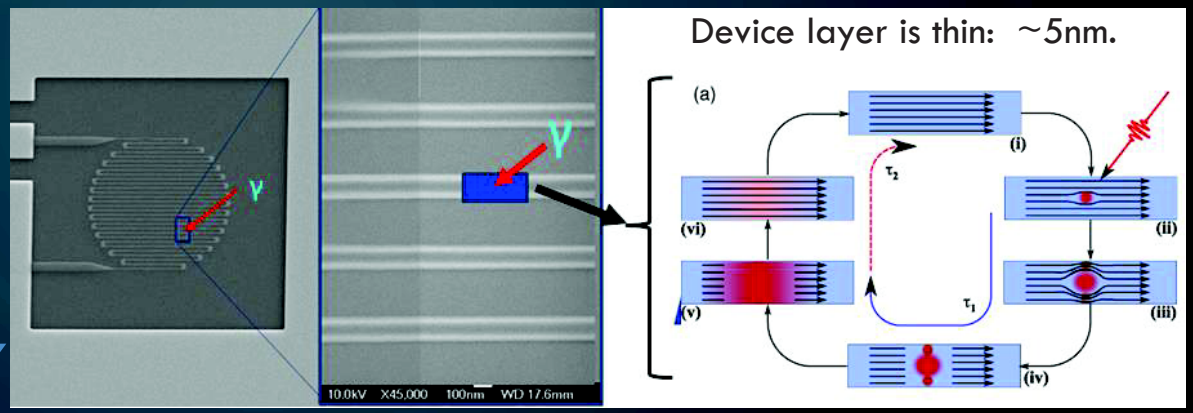
OUTLINE

- Overview: SNSPDs & advantages of WSi.
- Fabrication: Electron-beam lithography vs. Photolithography.
  - Resolution enhancement techniques.
- Results: Demonstrated high-efficiency single pixels & results on SNSPD arrays.
- Conclusion.

SUPERCONDUCTING NANOWIRE SINGLE PHOTON DETECTORS (SNSPDs)

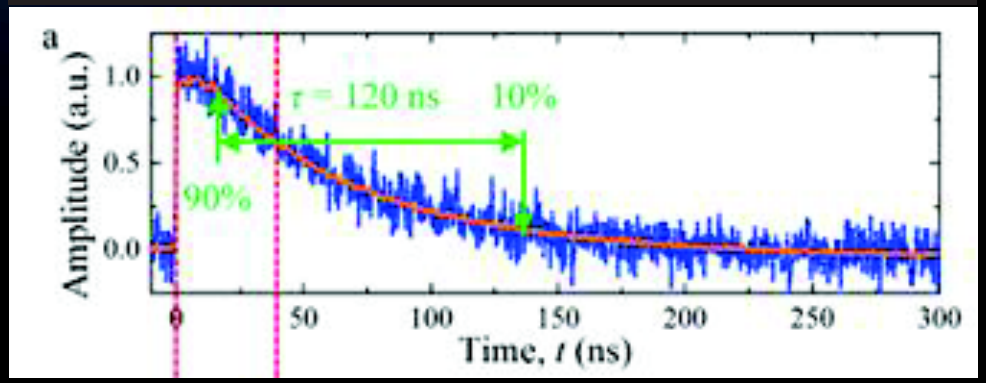
Photon Detection:

- Nanowires meander across active area.
- Biased with $I < I_C$.
- Hotspot generated by absorbed infrared photon generates electrical pulse.



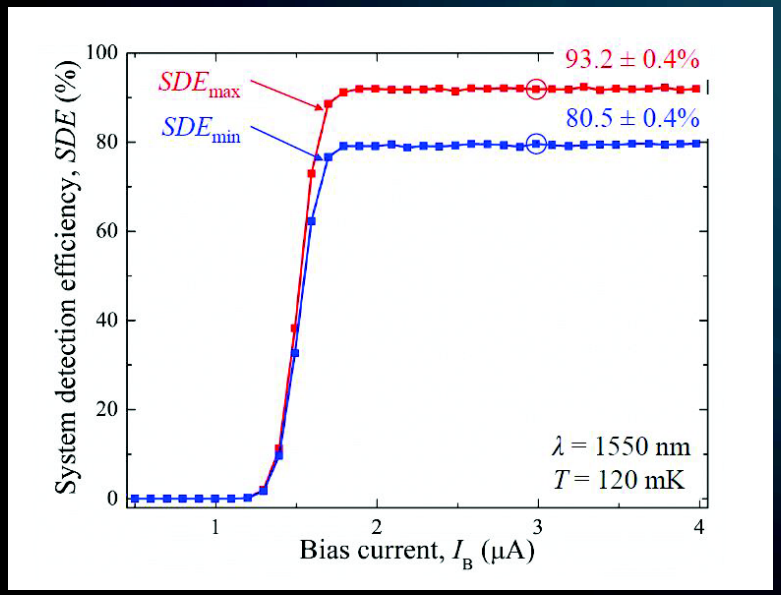
Modified from Chandra M Natarajan et al 2012 Supercond. Sci. Technol. ***25*** *063001.*

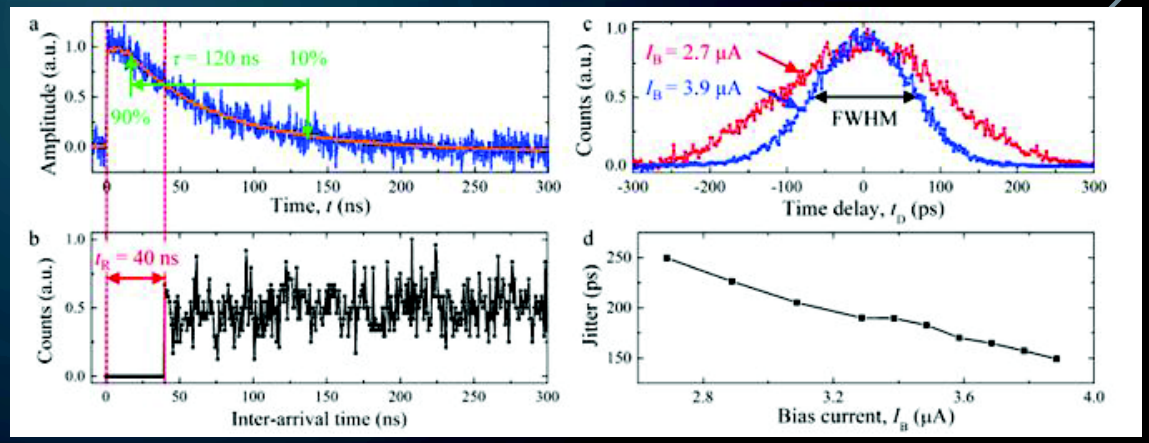
Response



Marsili et al, Nature Photonics ***7****, 210 (2013).*

SNSPDs: EXCELLENT SINGLE PHOTON DETECTORS





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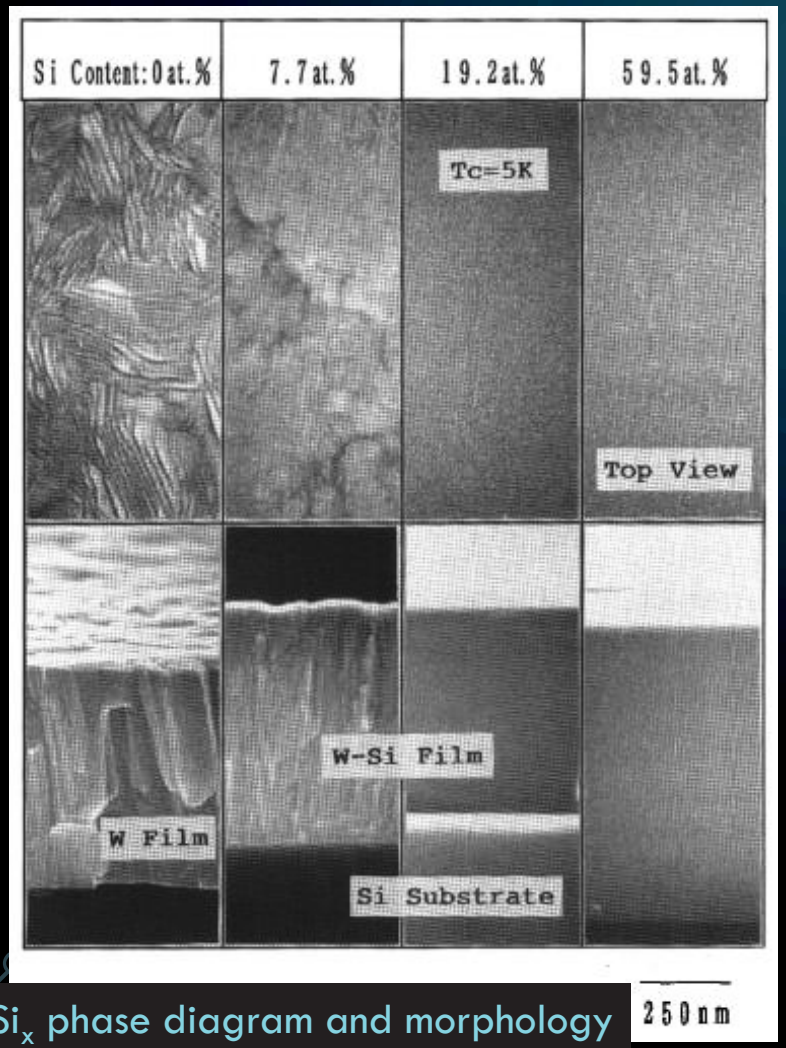
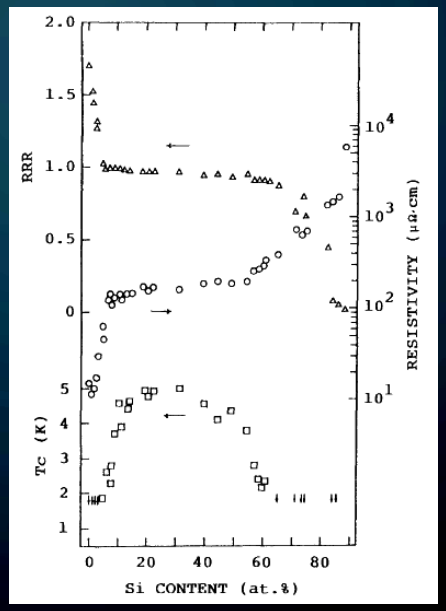
Salient SNSPD performance features:

- Dark Rates:
  Intrinsic < 1 cps; Background Limited ~ 1 kcps.
- Enhanced SDE via on-chip optical cavity @~1.55 μm.
- Operating temperature ~1 K to 5 K.
- 93% System Detection Efficiency (SDE) achieved.
- ~15 ps -150 ps timing jitter.
- 20-60 ns recovery time.

COMMON MATERIALS: WSi_x vs NbN



WSi_x phase diagram and morphology



Images from S. Kondo., J. Mater. Res., Vol. 7, No. 4, Apr 1992.

WSi_x advantages over NbN:

-Amorphous, extreme structural homogeneity
→ Simpler optical cavities, easier fabrication.

-Larger hotspots: More Cooper pairs broken per γ.
→ Wider wires possible
(120 to 220 nm for infrared apps.)

-Bias plateau with saturated efficiency.

NbN demonstrated performance advantages:
-Lowest jitter to date , <20ps.
-Faster reset times,
t_R ~2-3ns.

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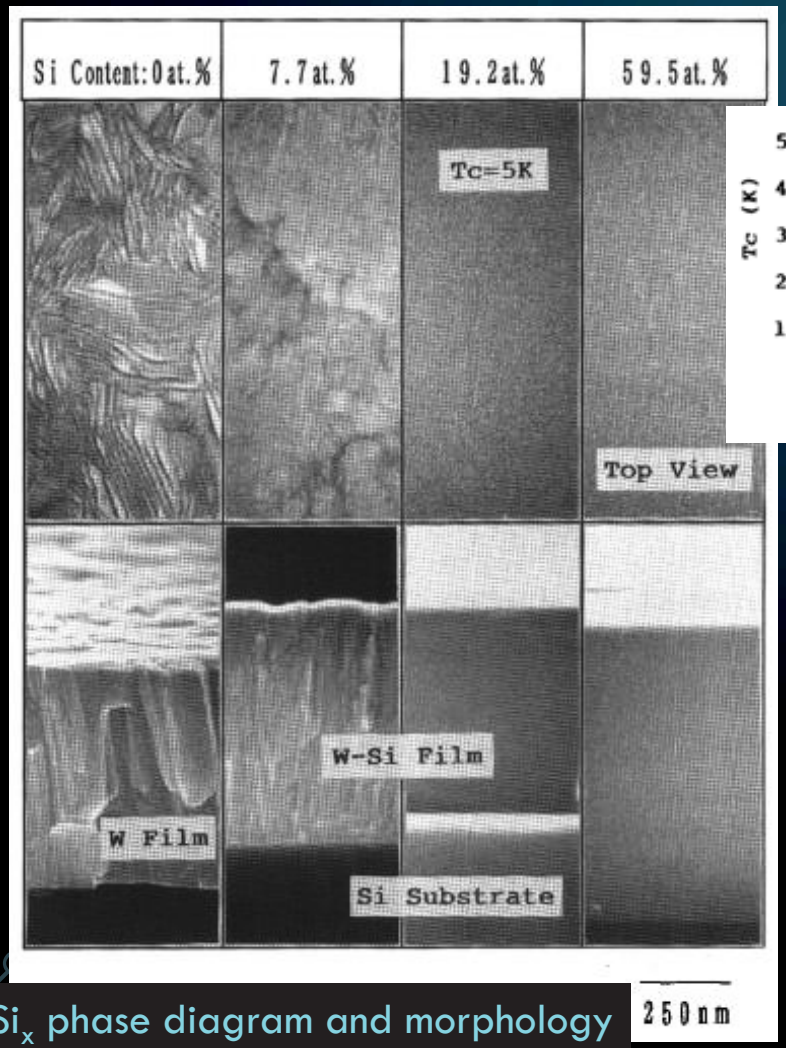

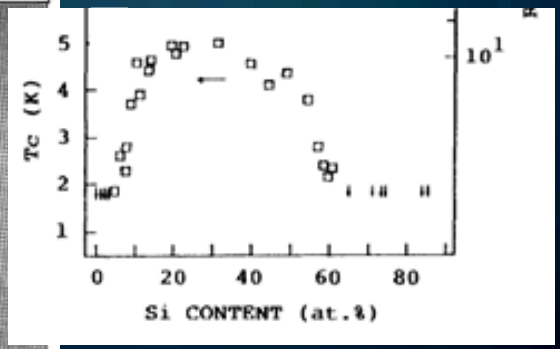

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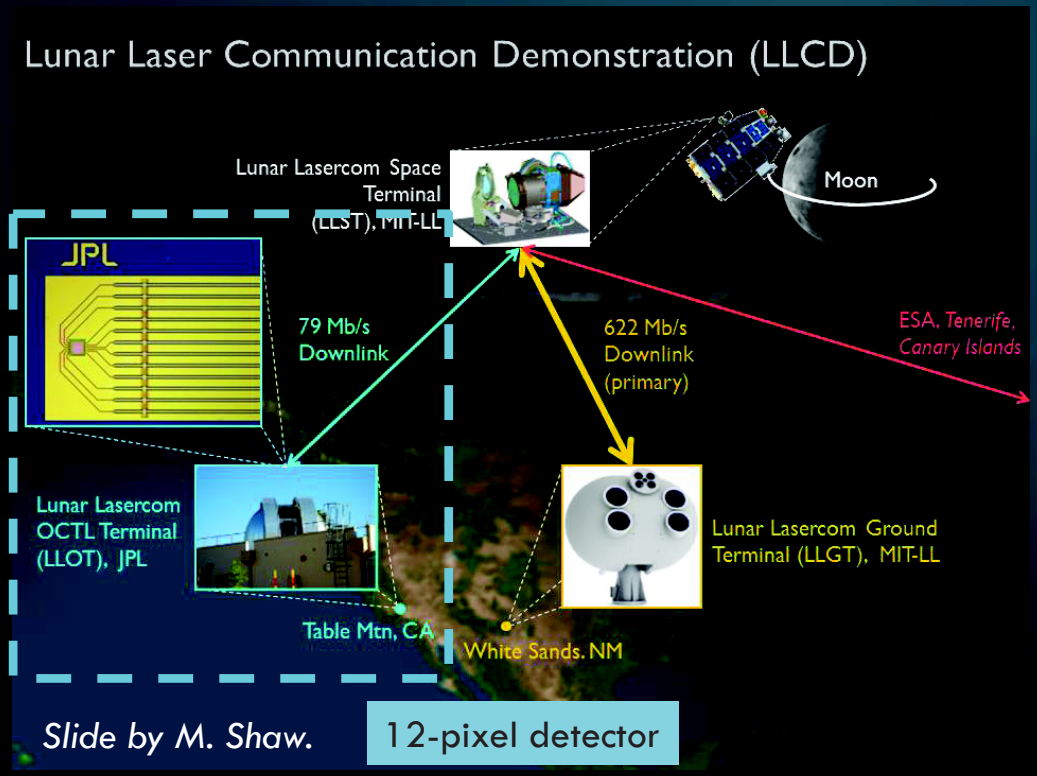
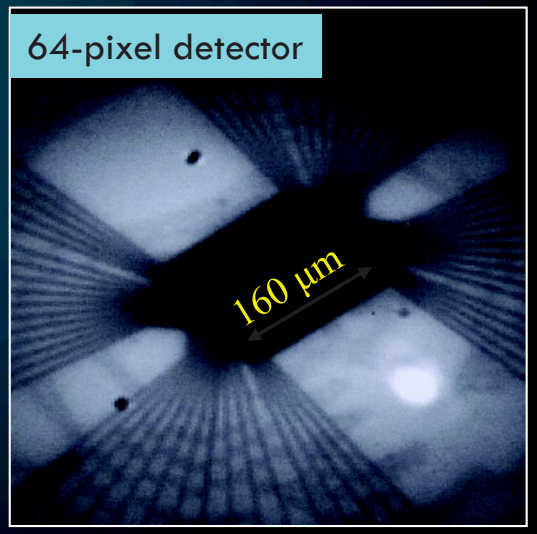
MULTI-PIXEL DETECTORS





Above image: 64-pixel, free space coupled detector with laser spot.

12-pixel detector: 12 interleaved SNSPD pixels in 64µm active area. Fiber coupled.
64-pixel detector: 2 x 32 array of SNSPDs covering 160µm active area. Free space coupled.
64-pixel: Demonstrated closed link at 47Mb/s using 14 of 64 pixels. Full 64P demo coming.
→ **Trend is toward larger active area and more SNSPD pixels per detector.**

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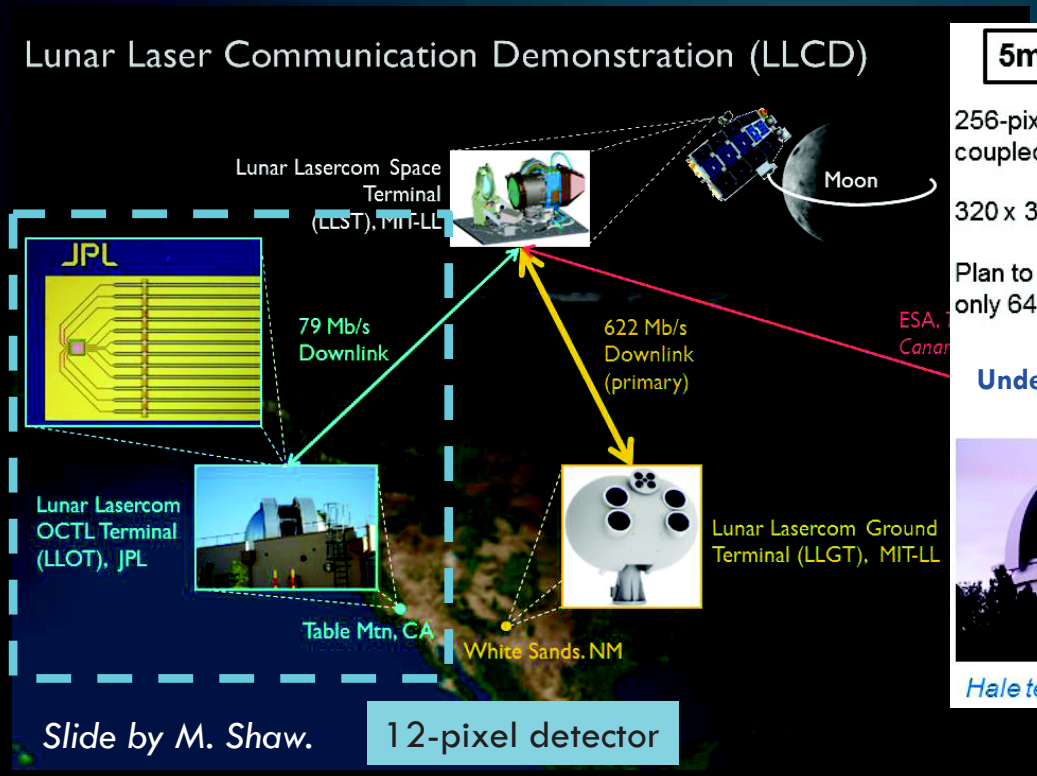

5m Telescope	12m Telescope
256-pixel free space coupled SNSPD array	Kilopixel-class free space coupled SNSPD array
320 x 320 µm active area	Required for future deep space optical communication ground terminals
Plan to read out using only 64 readout channels	
Under development	
Hale telescope, Palomar	*Future Optical DSN*

Slide by M. Shaw.

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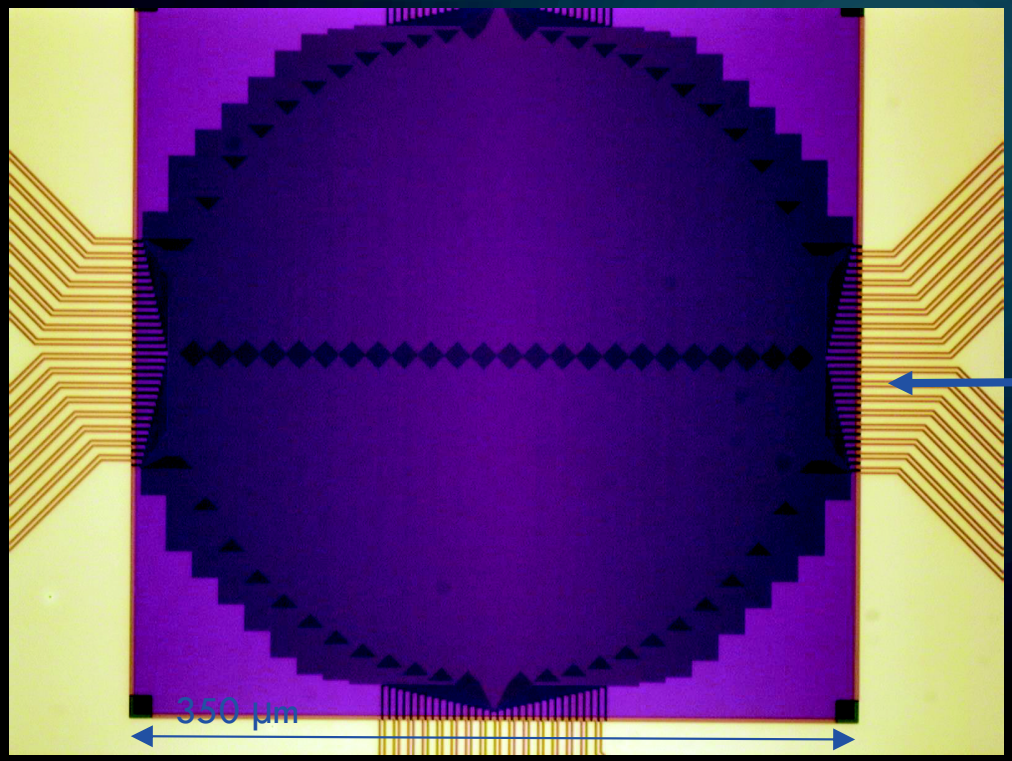

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  - Sub-wavelength photolithography.
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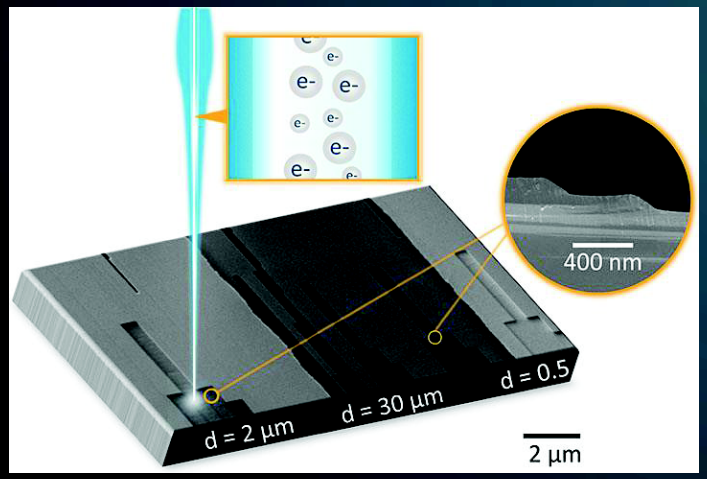
E-BEAM LITHO. VS. PHOTOLITHOGRAPHY

1



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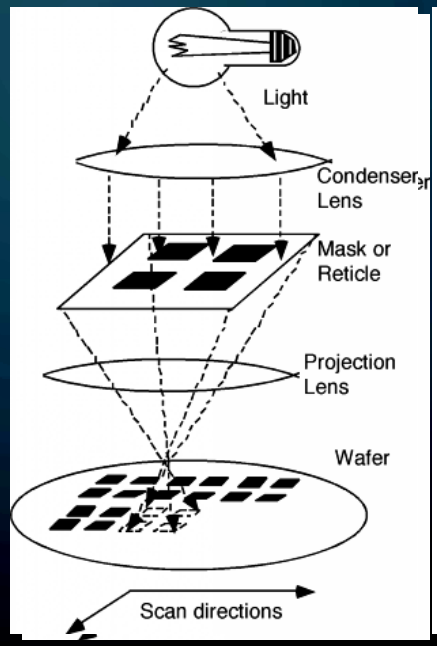

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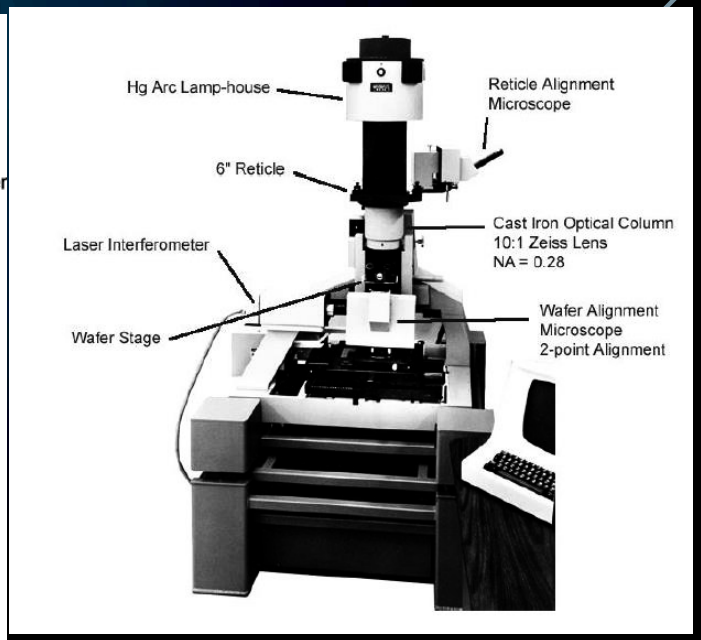


Electron beam lithography:

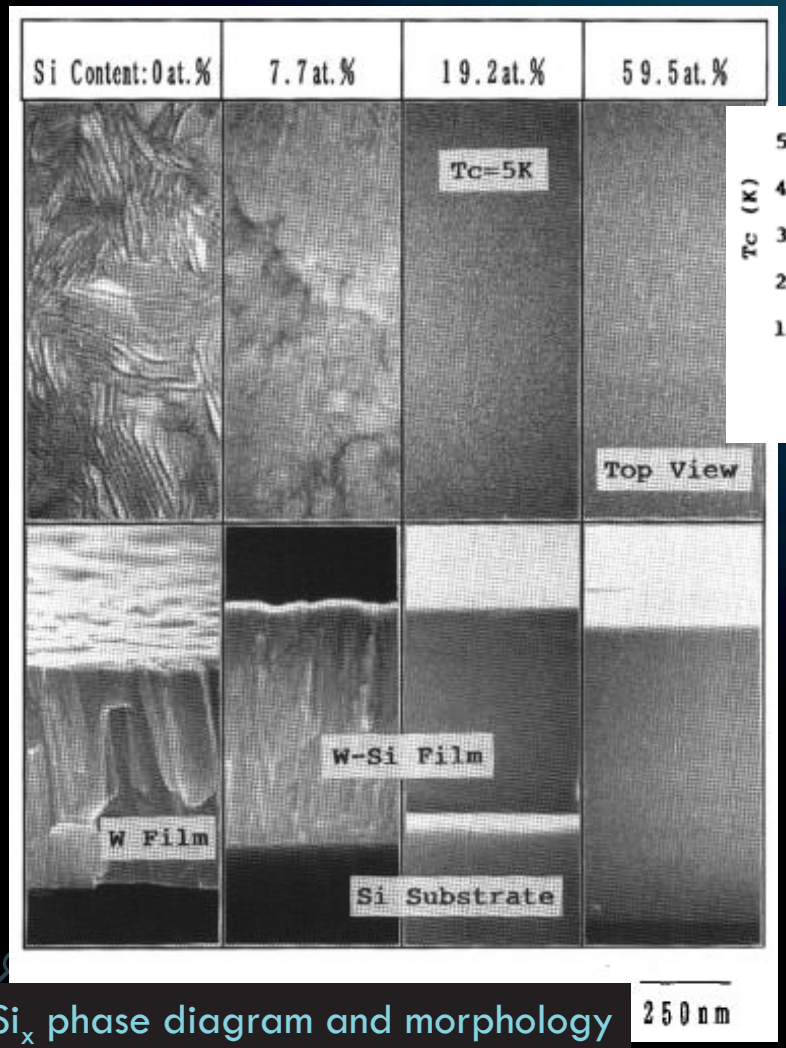
- Serial write technique→ lower throughput.
- Superior resolution, nm spot sizes easily achieved.

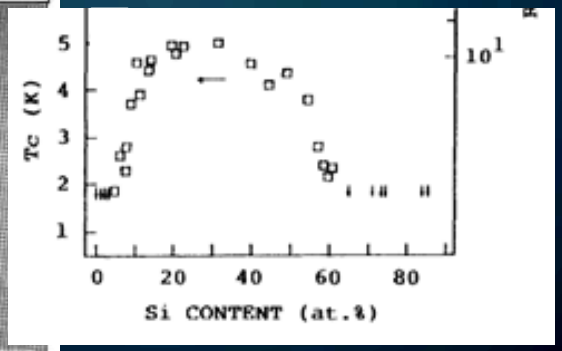
Optical lithography

- Parallel write technique → high throughput (semiconductor manu.)
- Sub-wavelength resolution possible, but $\lambda > 100$ nm.

1. V. Luciani, http://www.nist.gov/cnst/3d_ebeam_photolithography.cfm
2. Andrew R. Barron, Photolithography. OpenStax CNX. Feb 10, 2010 http://cnx.org/contents/fd6647f3-ae19-4657-918d-13e48a3fbd42@1
3. John H. Bruning; Optical lithography: 40 years and holding. Proc. SPIE 6520, 652004 (2007).

COMMON MATERIALS: WSi_x vs NbN



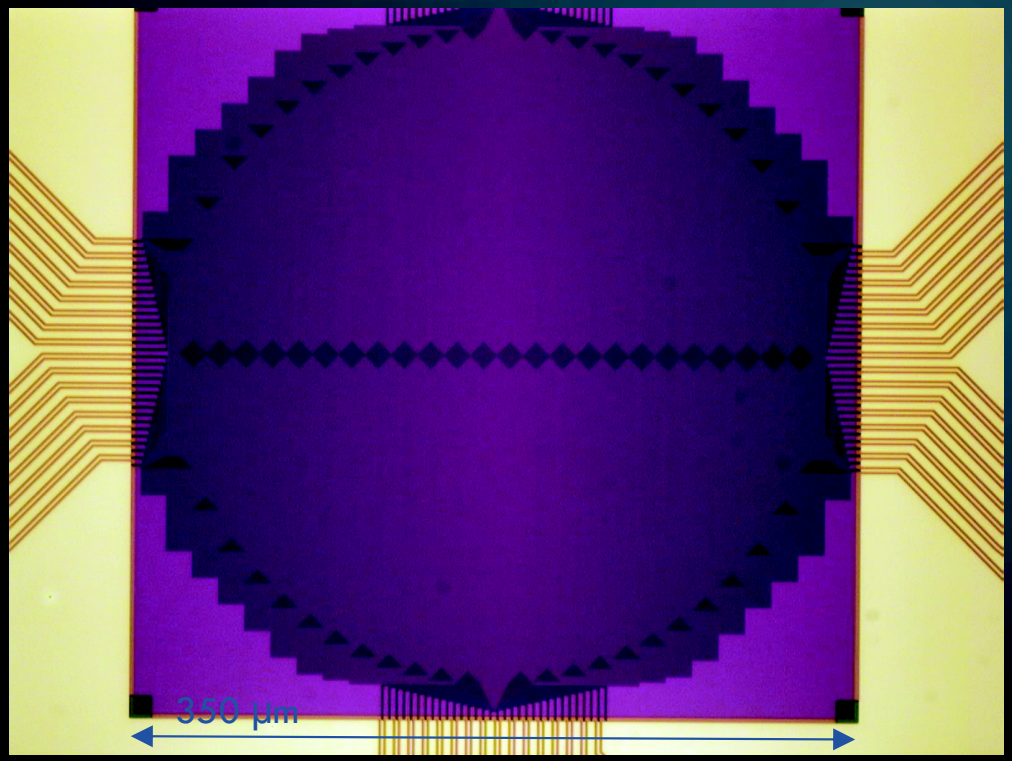


WSi_x phase diagram and morphology

WSi_x advantages over NbN:

→ Wider wires possible
(120 to 220 nm for infrared apps.)

CURRENT FABRICATION EXAMPLE



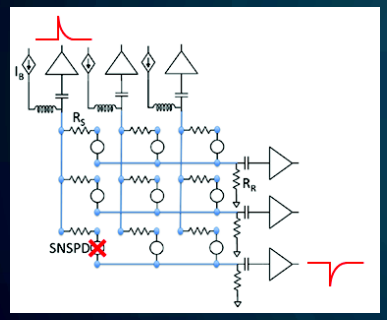
- E-beam lithography: for 64P detector with 320 µm x 320 µm active area,
  time ~ 1 to 2 hours
  for 10 nm beam size.

- Optical photolithography,
  time ~ 15 minutes.

- Not a big advantage for research throughput levels at this # of pixels & active area size.

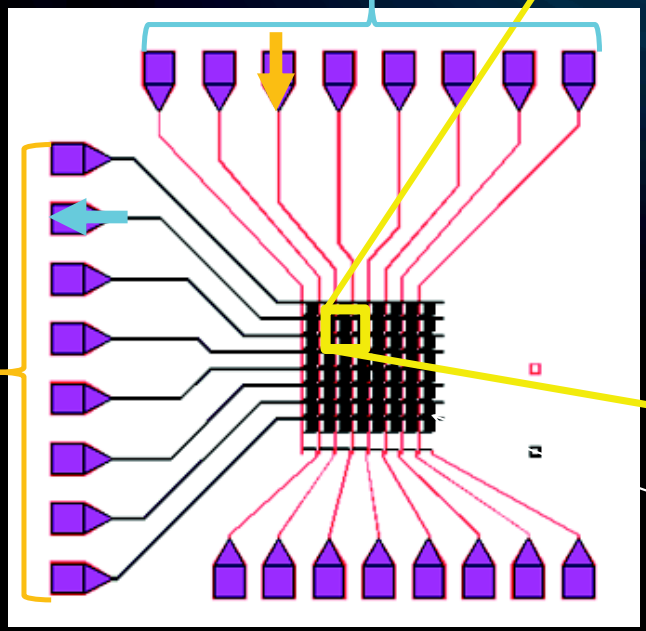
Both times calculated for 10 mm x 10 mm die size, populating a 100 mm wafer.

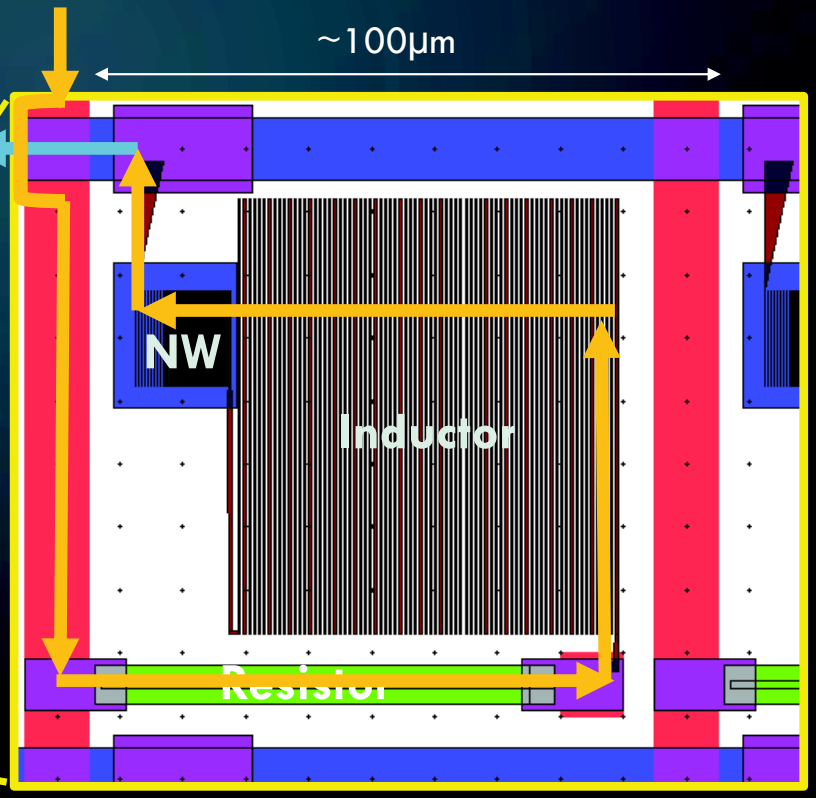
MORE COMPLEX EXAMPLE: ROW/COLUMN SCHEME



Row connections

Column connections.





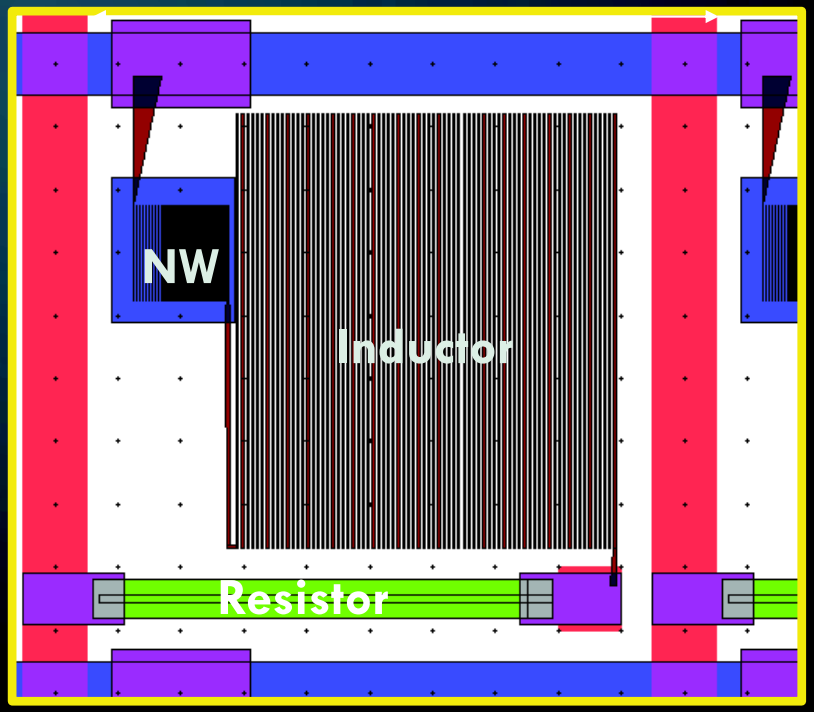
8 x 8 template. Can also fabricate a smaller detector (e.g. 3 x 3).

Scheme: V. Verma, et. al. Appl. Phys. Lett. ***104****, 051115 (2014).*

MORE COMPLEX EXAMPLE: ROW/COLUMN SCHEME

Colu	Row	Format															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
2	x	x	x	x	P1-400	P2-400	P2-400	P1-400	P1-400	P2-400	P2-400	P2-400	P1-400	x	x	x	
3	x	x	x	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	x	x	
4	x	x	P3-400	P2-400	P2-400	P2-400	P2-400	P3-400	P3-400	P2-400	P2-400	P2-400	P2-400	P2-400	P3-400	x	
5	x	P4-400	P4-400	P2-400	P2-400	P2-400	P2-400	P4-400	P4-400	P2-400	P2-400	P2-400	P2-400	P2-400	P4-400	P4-400	
6	x	P1-450	P2-450	P2-450	P2-450	P2-450	P2-450	P1-450	P1-450	P1-450	P2-450	P2-450	P2-450	P2-450	P2-450	P1-450	
7	x	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	
8	x	P3-450	P2-450	P2-450	P2-450	P2-450	P2-450	P3-450	P3-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P3-450	
9	WM	P4-450	P2-450	P2-450	P2-450	P2-450	P2-450	P4-450	P4-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P4-450	WM
10	x	P1-500	P2-500	P2-500	P2-500	P2-500	P2-500	P1-500	P1-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P1-500	
11	x	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	
12	x	P3-500	P2-500	P2-500	P2-500	P2-500	P2-500	P3-500	P3-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P3-500	
13	x	P4-500	P2-500	P2-500	P2-500	P2-500	P2-500	P4-500	P4-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P4-500	
14	x	x	P1-550	P2-550	P2-550	P2-550	P2-550	P1-550	P1-550	P2-550	P2-550	P2-550	P2-550	P2-550	P1-550	x	
15	x	x	x	P4-550	P2-550	P2-550	P2-550	P4-550	P4-550	P2-550	P2-550	P2-550	P2-550	P4-550	x	x	
16	x	x	x	x	P3-550	P2-550	P2-550	P3-550	P3-550	P2-550	P2-550	P2-550	P3-550	x	x	x	

Map of 3.5 x 3.5mm dies on 4” wafer.
Different colors = slightly different designs



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3	x	x	x	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	P2-400	x	x	
4	x	x	P3-400	P2-400	P2-400	P2-400	P2-400	P3-400	P3-400	P2-400	P2-400	P2-400	P2-400	P2-400	P3-400	x	
5	x	P4-400	P4-400	P2-400	P2-400	P2-400	P2-400	P4-400	P4-400	P2-400	P2-400	P2-400	P2-400	P2-400	P4-400	P4-400	
6	x	P1-450	P2-450	P2-450	P2-450	P2-450	P2-450	P1-450	P1-450	P1-450	P2-450	P2-450	P2-450	P2-450	P2-450	P1-450	
7	x	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	P2-450	
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10	x	P1-500	P2-500	P2-500	P2-500	P2-500	P2-500	P1-500	P1-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P1-500	
11	x	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	
12	x	P3-500	P2-500	P2-500	P2-500	P2-500	P2-500	P3-500	P3-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P3-500	
13	x	P4-500	P2-500	P2-500	P2-500	P2-500	P2-500	P4-500	P4-500	P2-500	P2-500	P2-500	P2-500	P2-500	P2-500	P4-500	
14	x	x	P1-550	P2-550	P2-550	P2-550	P2-550	P1-550	P1-550	P2-550	P2-550	P2-550	P2-550	P2-550	P1-550	x	
15	x	x	x	P4-550	P2-550	P2-550	P2-550	P4-550	P4-550	P2-550	P2-550	P2-550	P2-550	P4-550	x	x	
16	x	x	x	x	P3-550	P2-550	P2-550	P3-550	P3-550	P2-550	P2-550	P2-550	P3-550	x	x	x	

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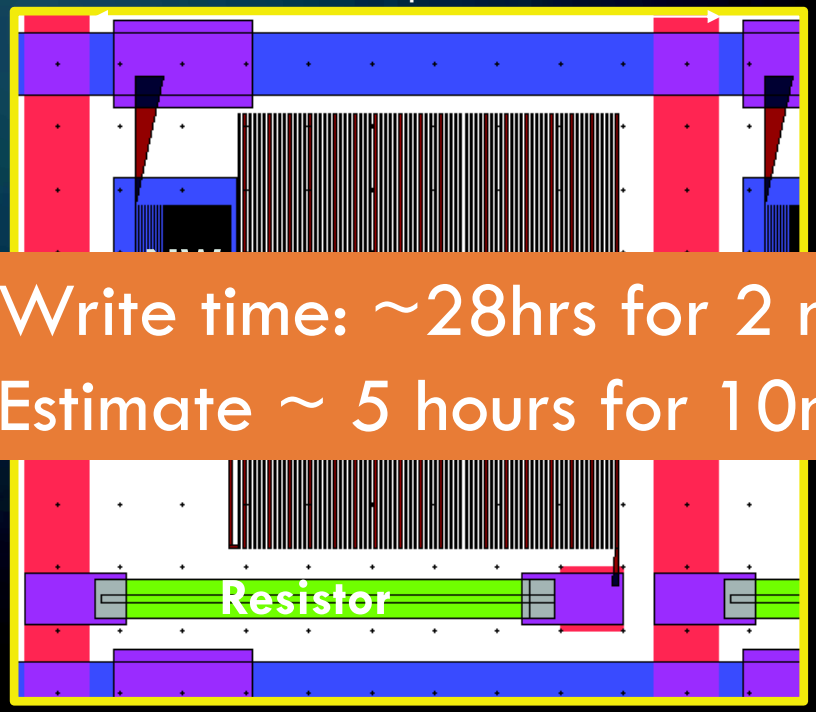
~100µm



Write time: ~28hrs for 2 nm spot.
Estimate ~ 5 hours for 10nm spot.

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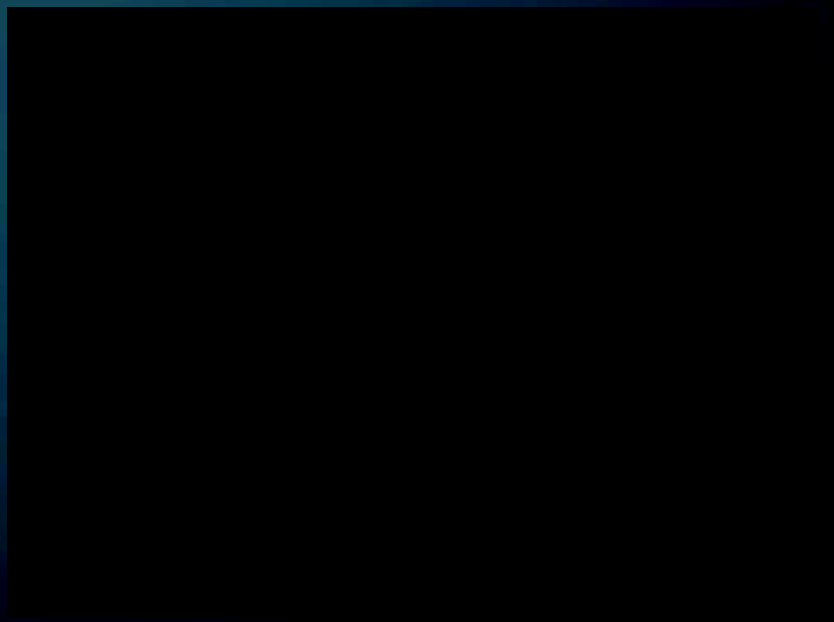
OPTICAL LITHOGRAPHY: JPL'S STEPPERS



Video from Canon EX3 stepper manual

Resolution:

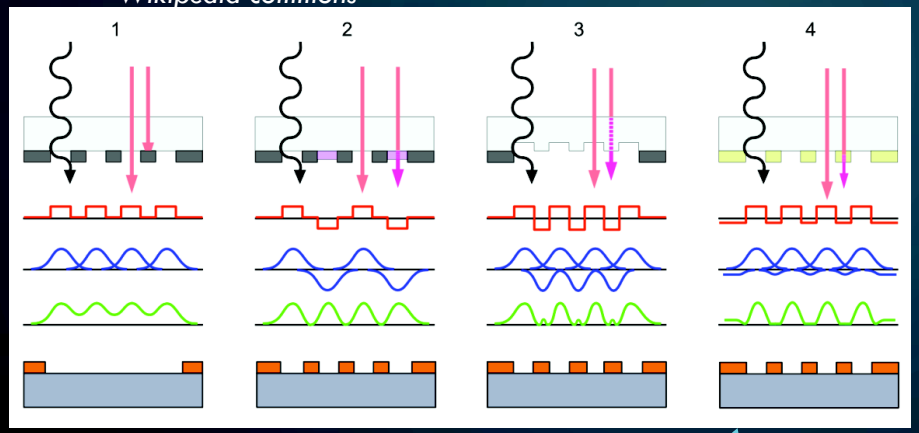
Critical dimension = CD= $k_1 \frac{\lambda}{NA}$.

CD ~228nm, *in theory.*

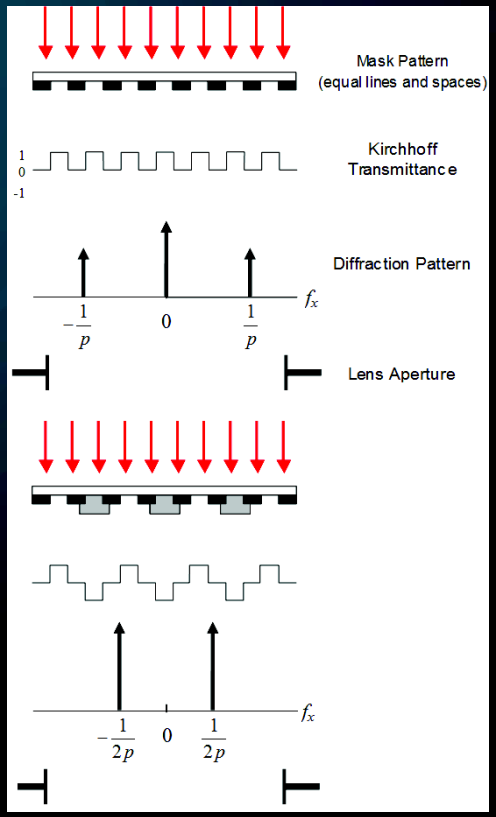
λ: wavelength of light,
NA: numerical aperture,
k: process-related factors.
λ: 248nm (KrF)
NA: 0.6 or 0.65,
k: ~0.6.

SUB-WAVELENGTH LITHOGRAPHY (KrF λ=248 nm)

Wikipedia commons



C. Mack, Litho. Expert Winter 2001.



Phase shift masks ($$).

BARC: Backside anti-reflection coating.

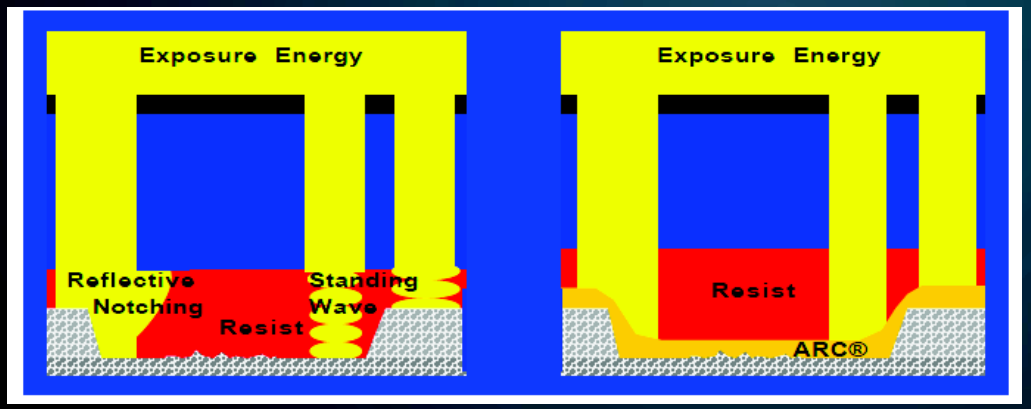
Off-axis illumination.

Optical Proximity Correction.

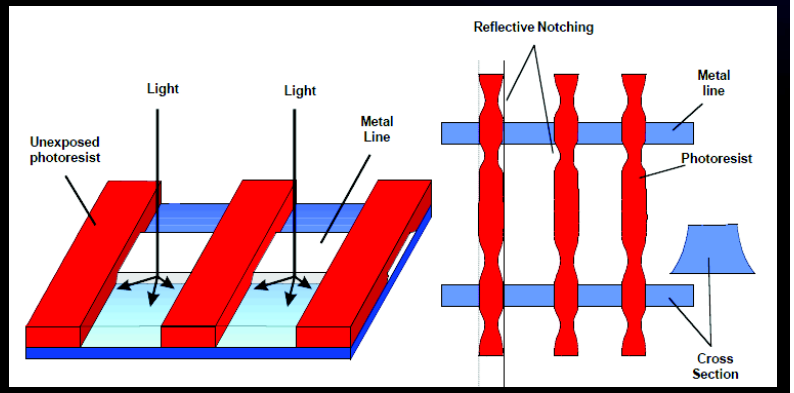
Iso-dense bias: Isolated line vs. dense lines →

BACKSIDE ANTI-REFLECTION COATING (BARC)

From pamphlet: Understanding BARC from Brewer Science.



- Improves repeatability of process.
- Can improve depth of focus.



BACKSIDE ANTI-REFLECTION COATING (BARC)

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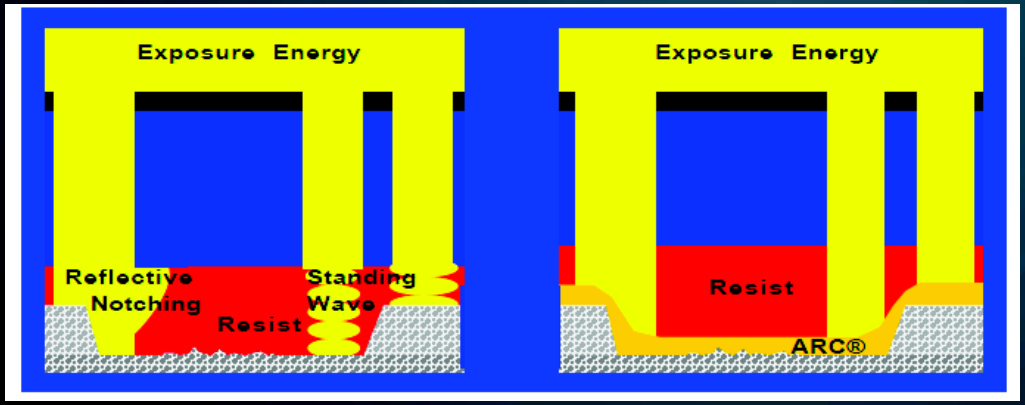

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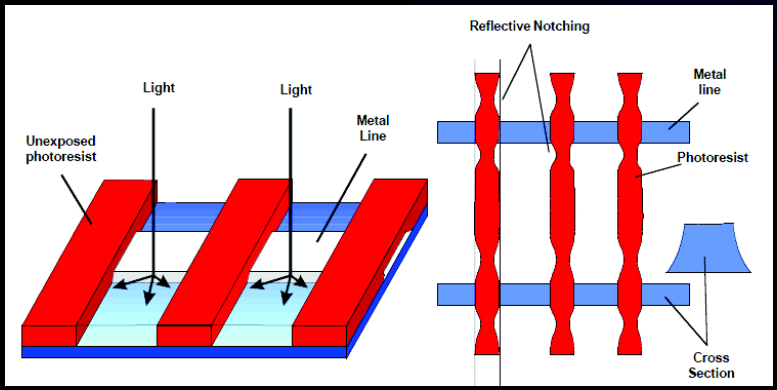
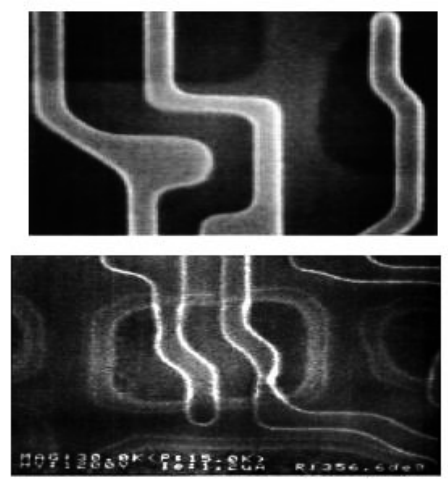


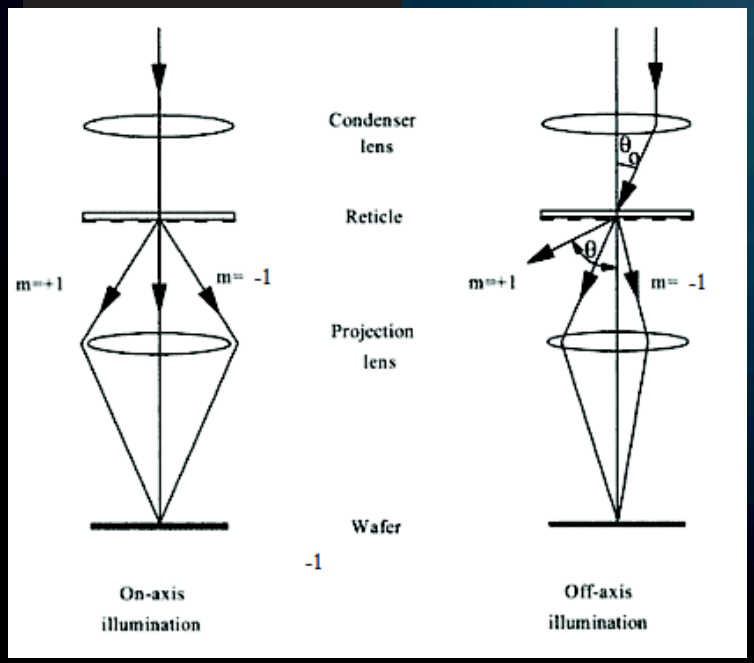


BARC

No BARC

OFF-AXIS ILLUMINATION

Off-axis illumination .



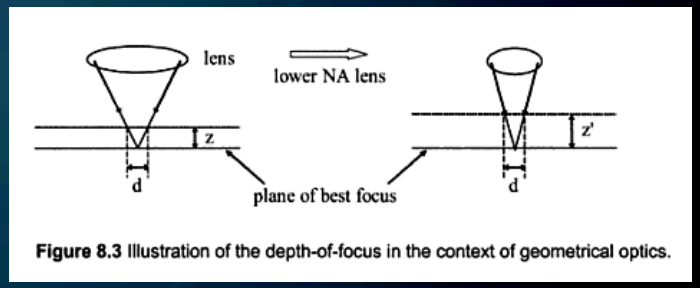


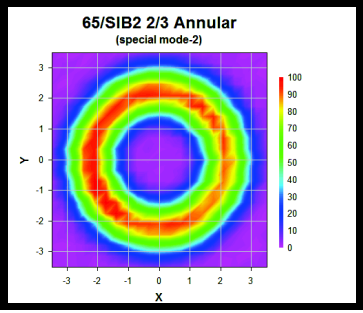
Figure 8.3 Illustration of the depth-of-focus in the context of geometrical optics.

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

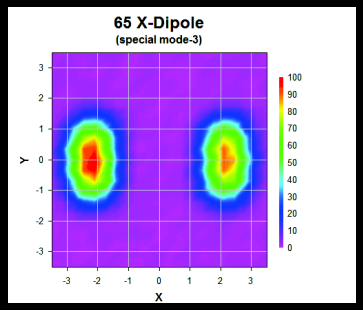
$$\text{Depth of focus} = k_2 \frac{\lambda}{(NA)^2}.$$

Improves both at cost of contrast.

Annular illumination.



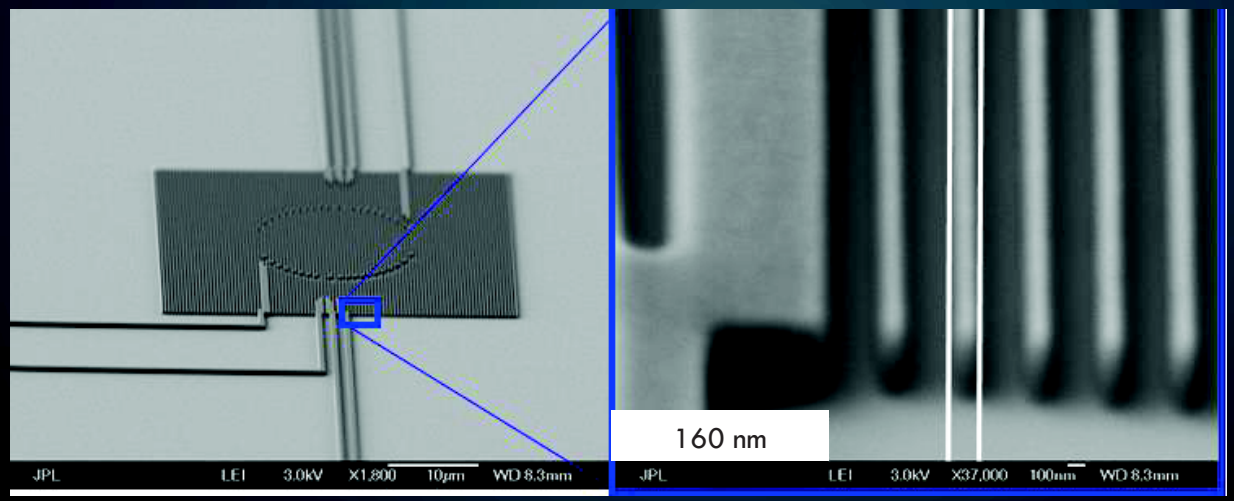
Dipole illumination.



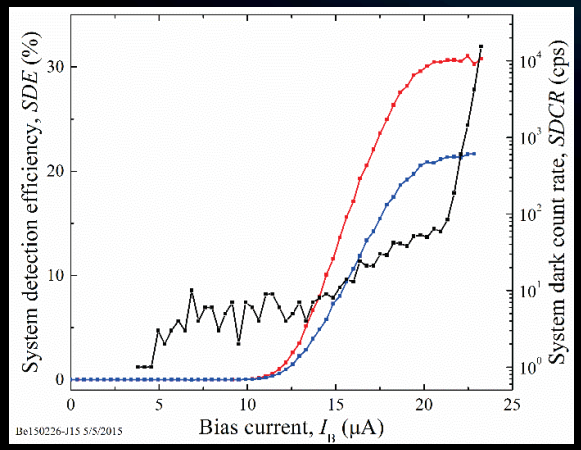
OUTLINE

- Overview: SNSPDs & advantages of WSi.
- Fabrication: Electron-beam lithography vs. Photolithography.
  - Sub-wavelength photolithography.
- Results: Demonstrated high-efficiency single pixels & results on SNSPD arrays.
- Conclusion.

1ST SINGLE PIXEL SNSPD FABRICATION



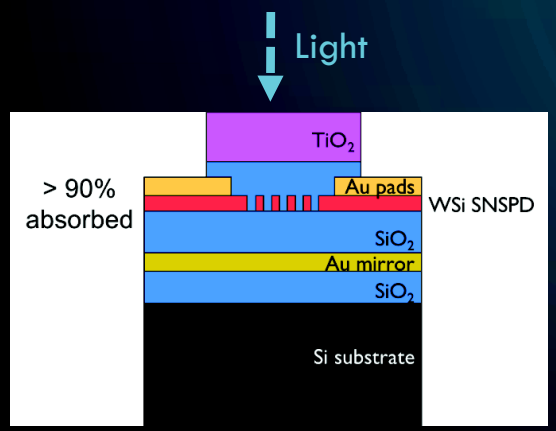
Successful 160 nm wire photoresist pattern.

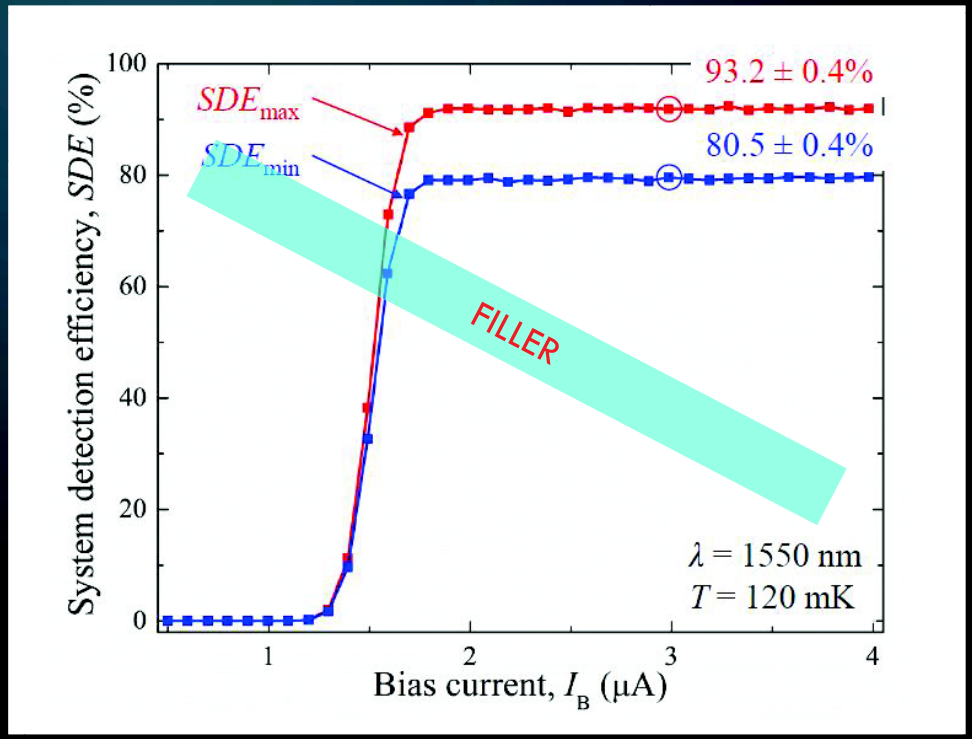


- Demonstrated system detection efficiency (SDE) up to ~30% in optically lithographed SNSPDs.
- Narrow plateau in SDE shown: saturated internal quantum efficiency.

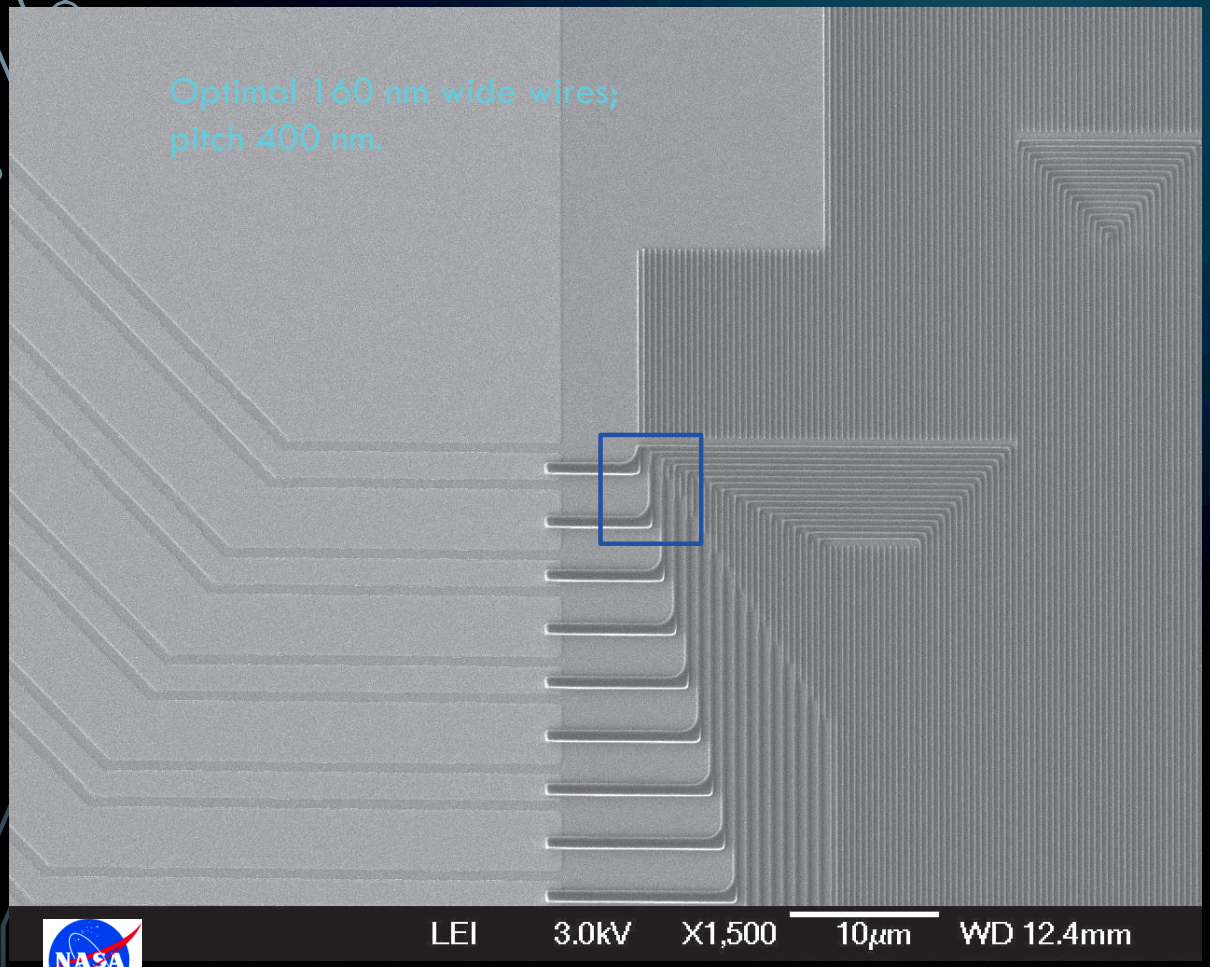
ADDING AN ANTI REFLECTION STACK

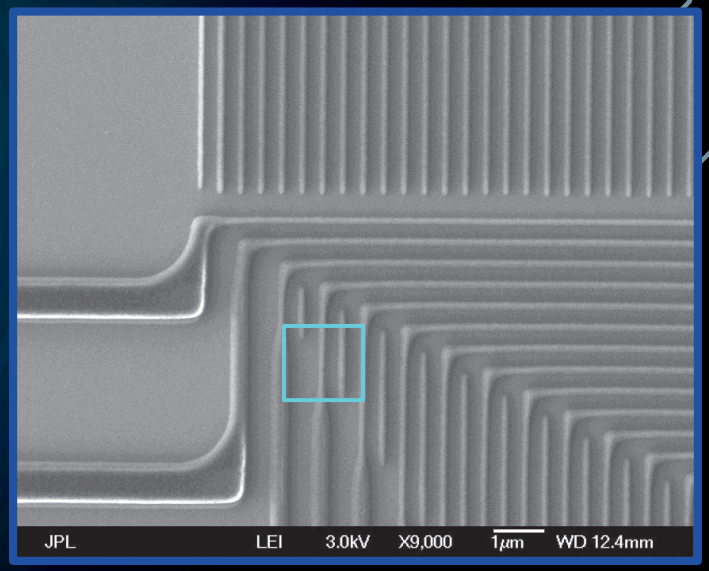
High SDE, optically lithographed SNSPD, 1-pixel

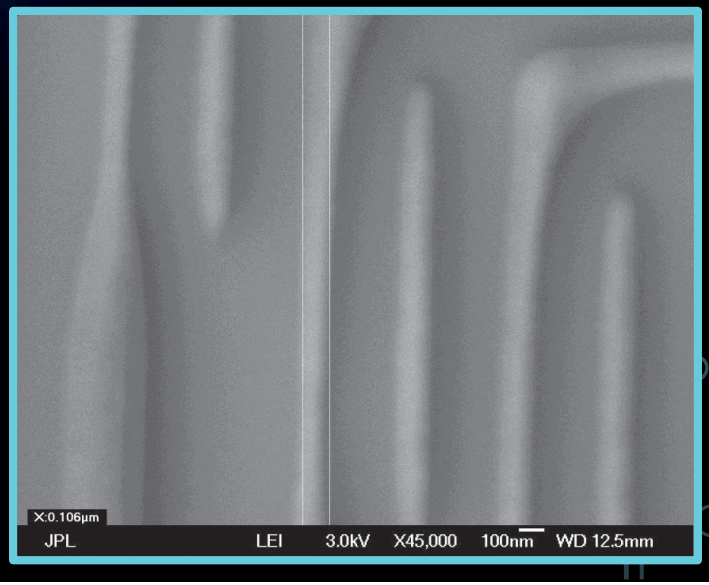




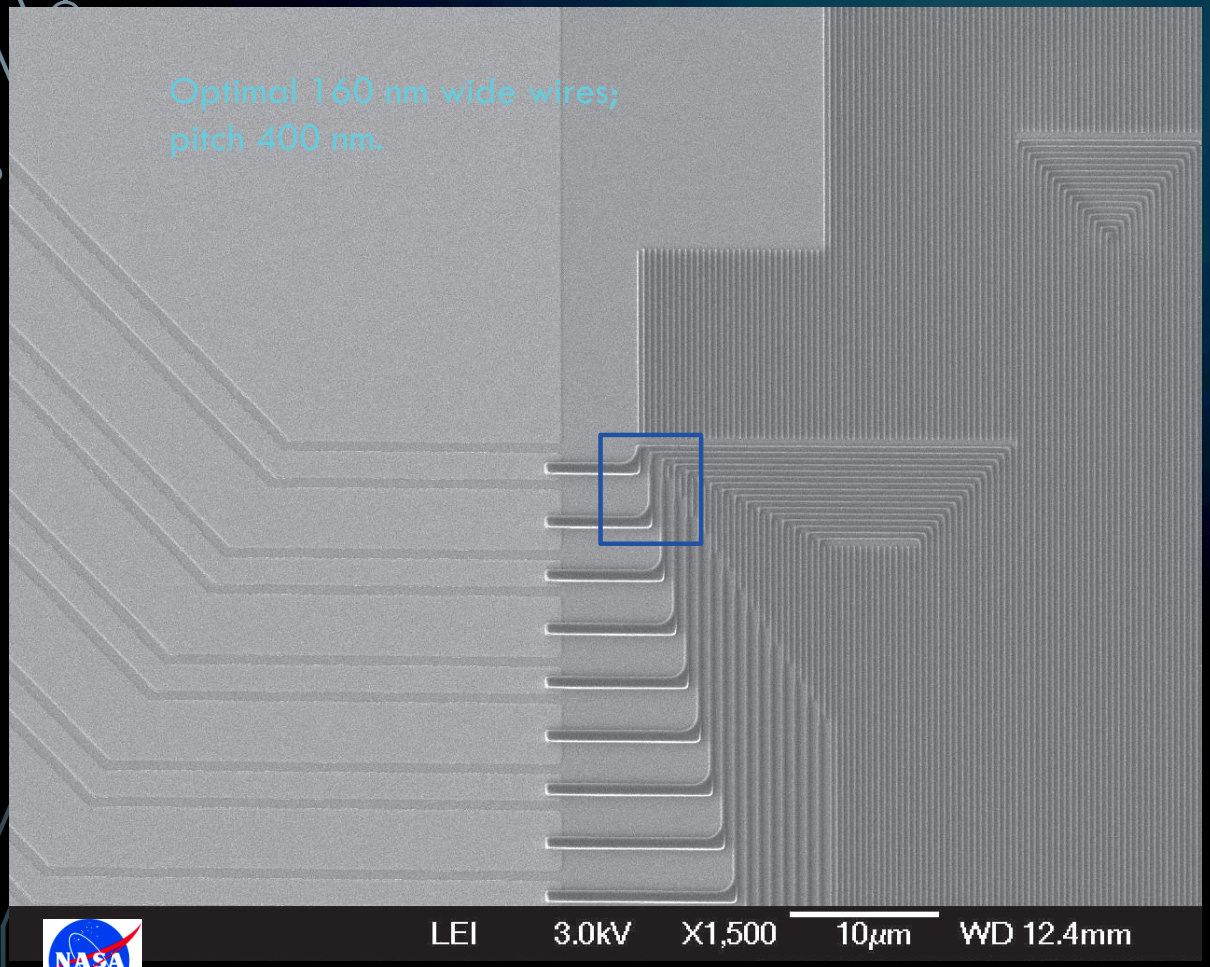
64P DETECTOR PHOTOLITHOGRAPHY

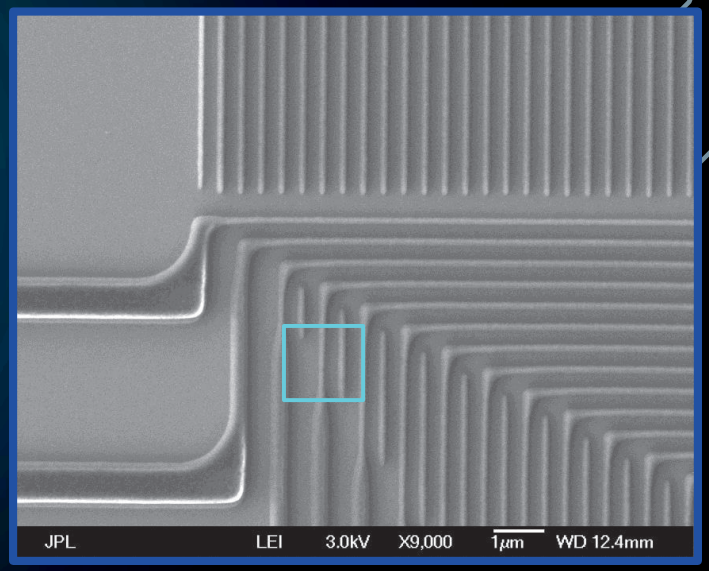


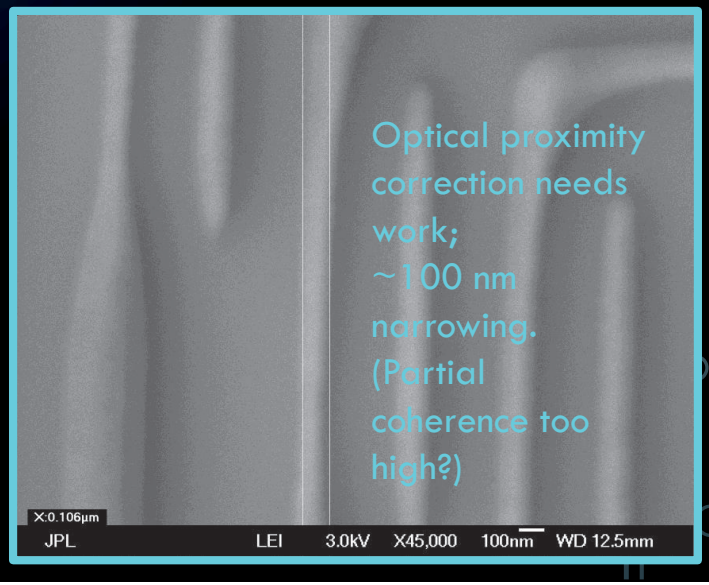




64P DETECTOR PHOTOLITHOGRAPHY



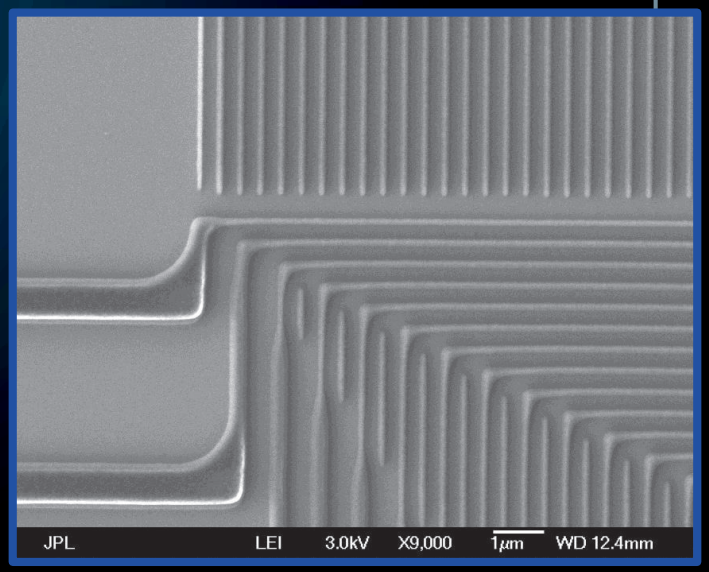




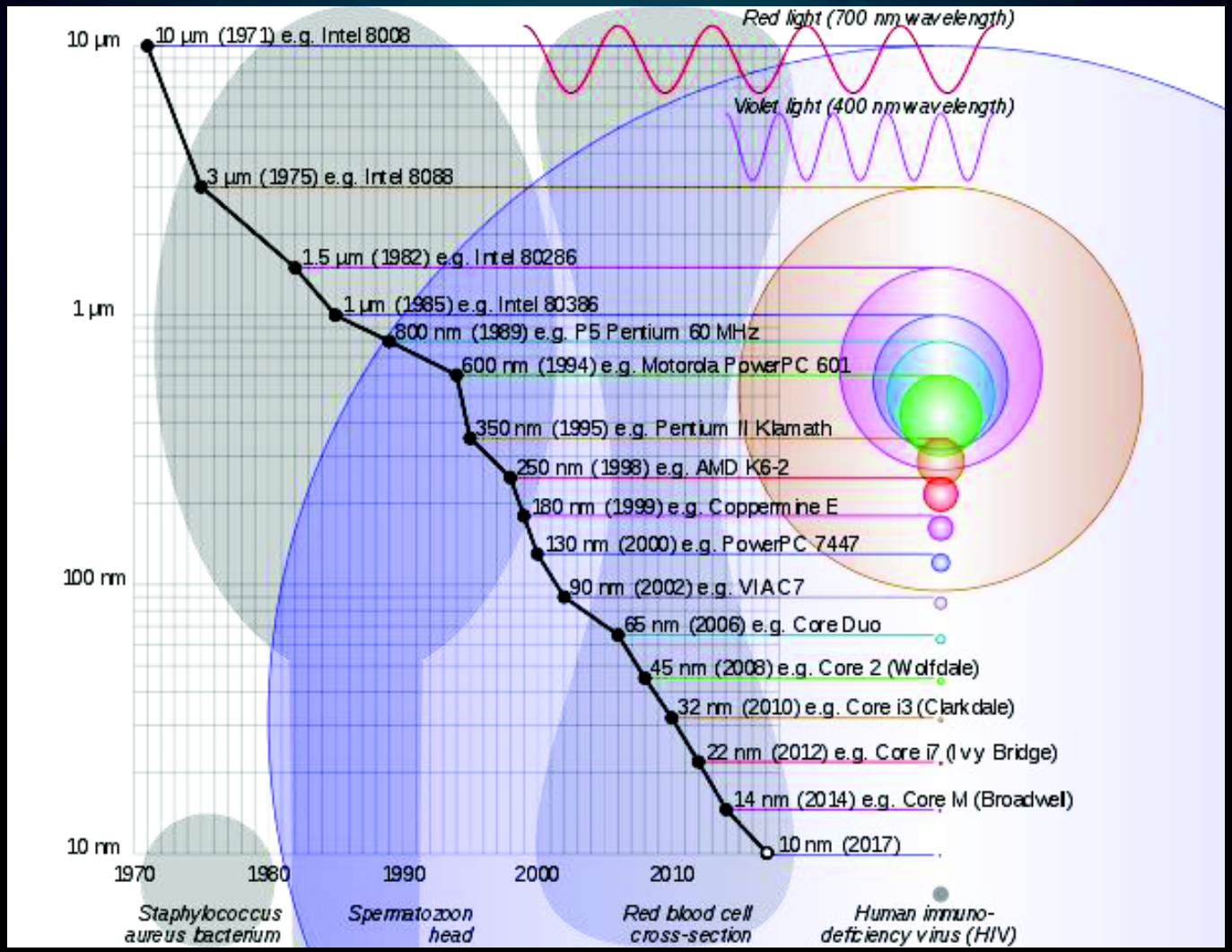
OPTICAL PROXIMITY CORRECTION

http://www.toshiba.co.jp/tosmec/english/jigyou/07.html

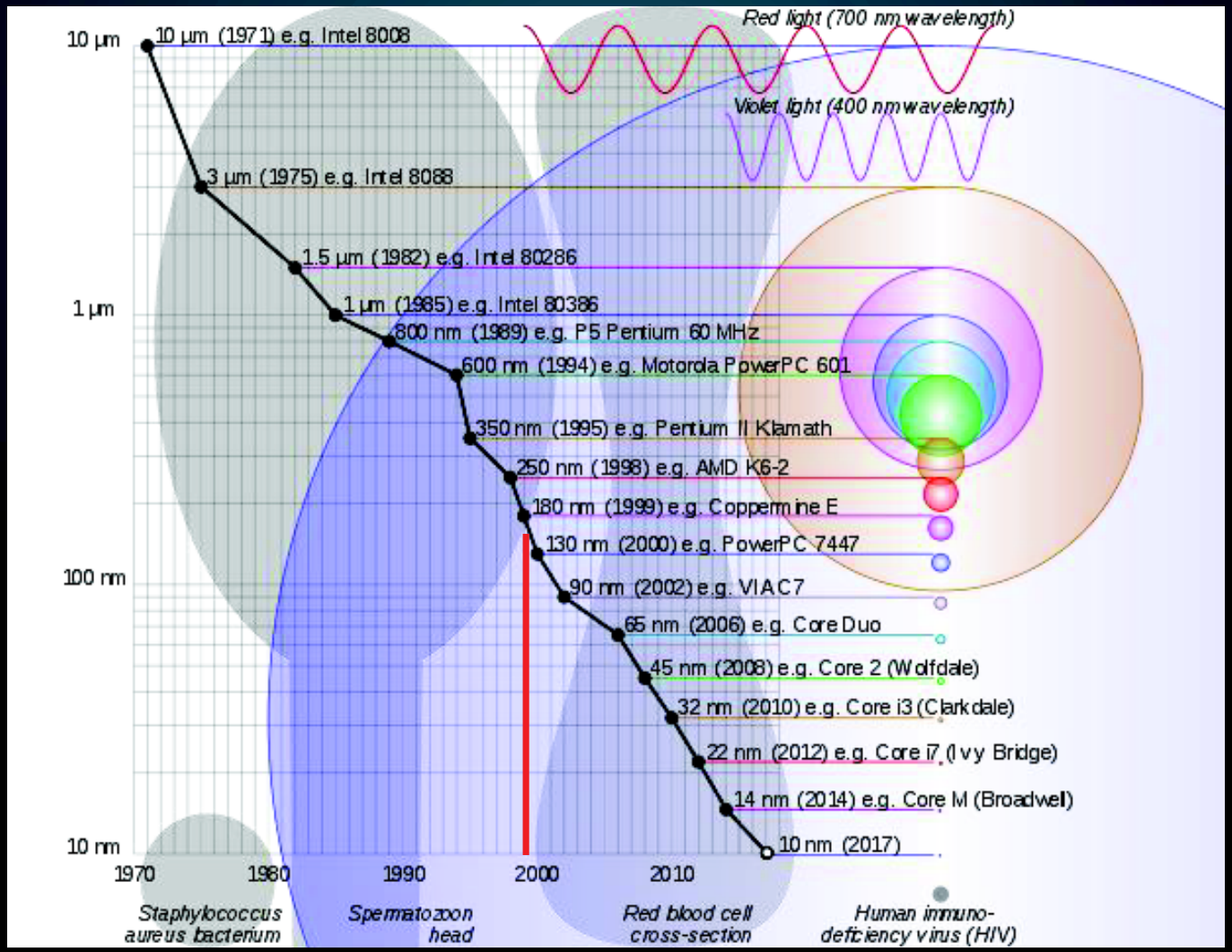
Fix mask



- Software : $$$.
- Develop quick & dirty rules for mask design.



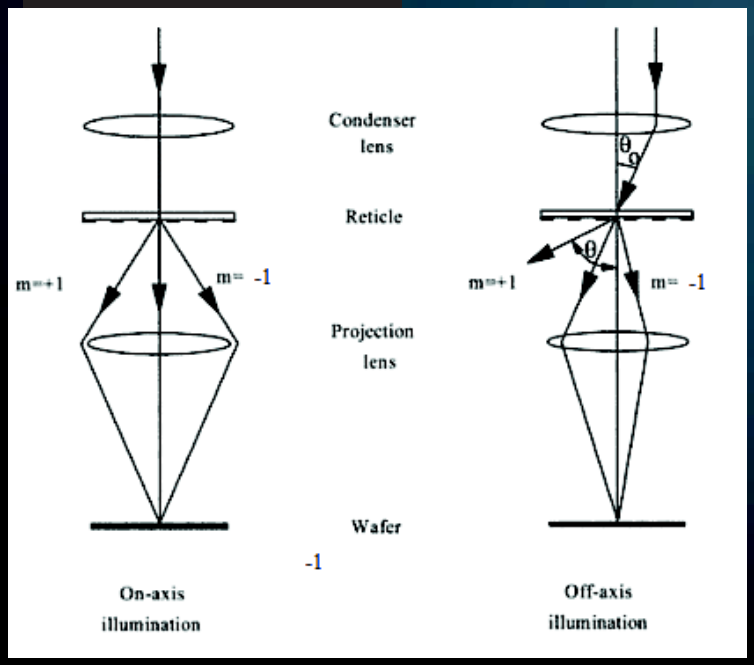
By Cmglee - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16991155



By Cmglee - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=16991155

DEPTH OF FOCUS ISSUE

Off-axis illumination .



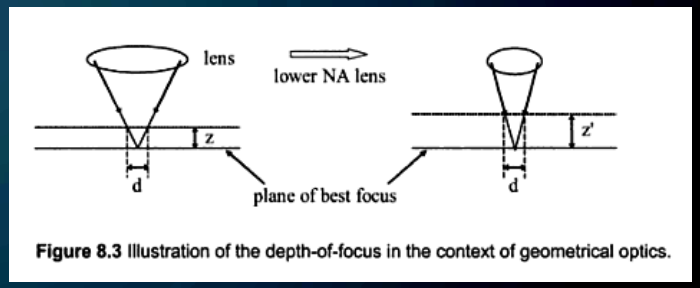
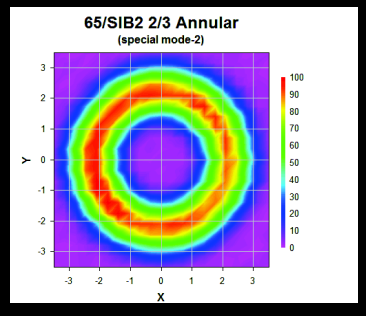


Figure 8.3 Illustration of the depth-of-focus in the context of geometrical optics.



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

$$\text{Depth of focus} = k_2 \frac{\lambda}{(NA)^2}.$$

DEPTH OF FOCUS ISSUE

From *Principles of Lithography*, H. Levinson (2001).

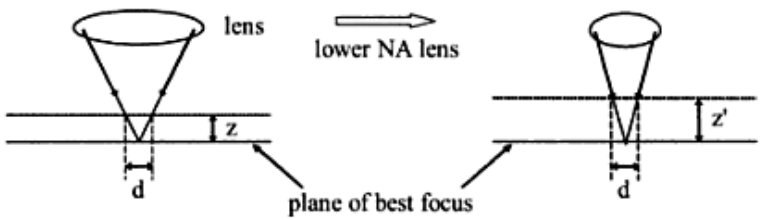
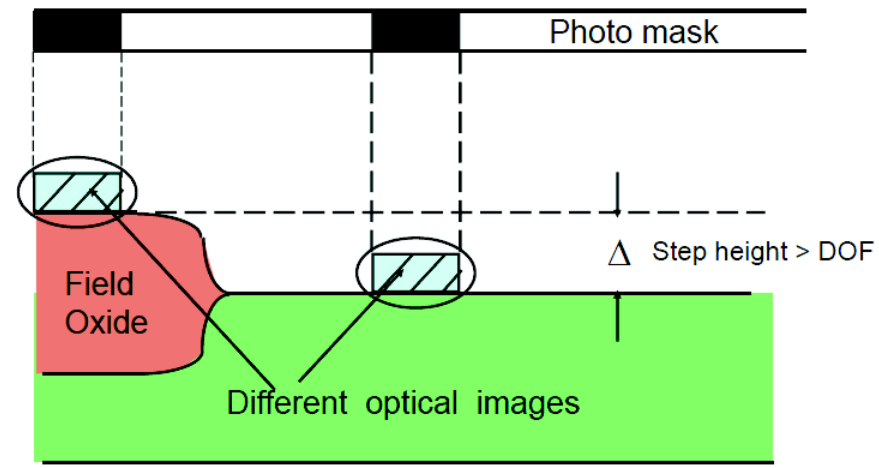


Figure 8.3 Illustration of the depth-of-focus in the context of geometrical optics.

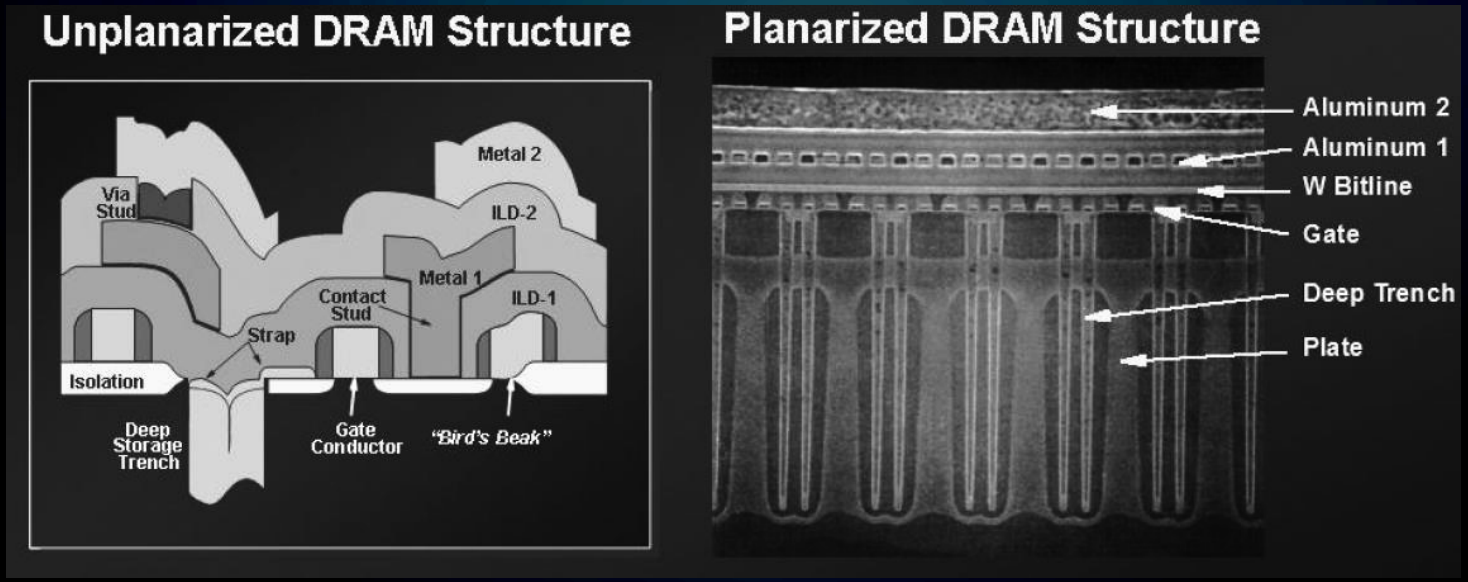
Lecture from N. Cheung, UC Berkeley Lecture online.



Depth of focus (DOF):

$$= k_2 \frac{\lambda}{(NA)^2}.$$

DEPTH OF FOCUS ISSUE



John H. Bruning; Optical lithography: 40 years and holding. Proc. SPIE 6520, 652004 (2007).

Depth of focus (DOF):

$$= k_2 \frac{\lambda}{(NA)^2}.$$

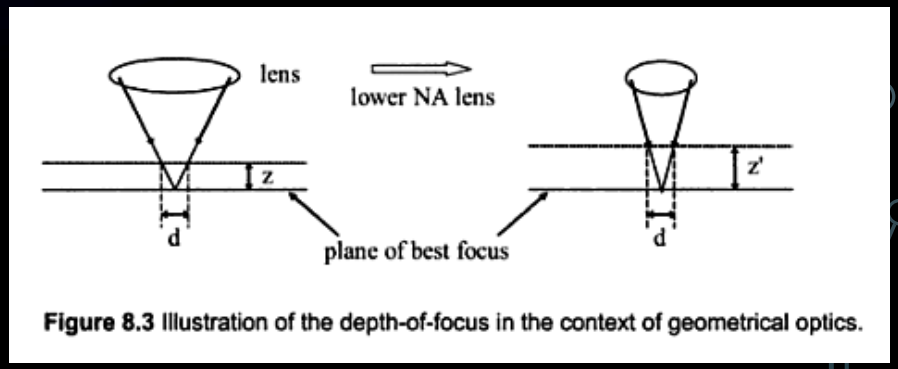


Figure 8.3 Illustration of the depth-of-focus in the context of geometrical optics.

From *Principles of Lithography*, H. Levinson (2001).

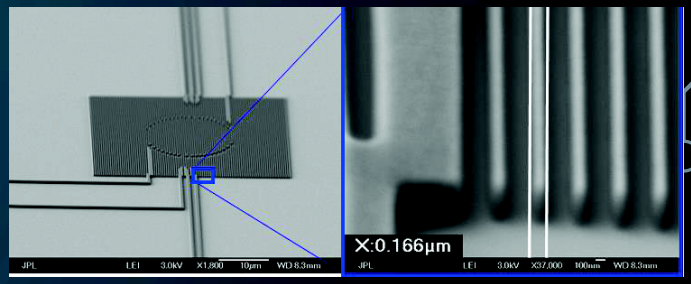
CONCLUSIONS ON EBL VS OPTICAL LITHOGRAPHY

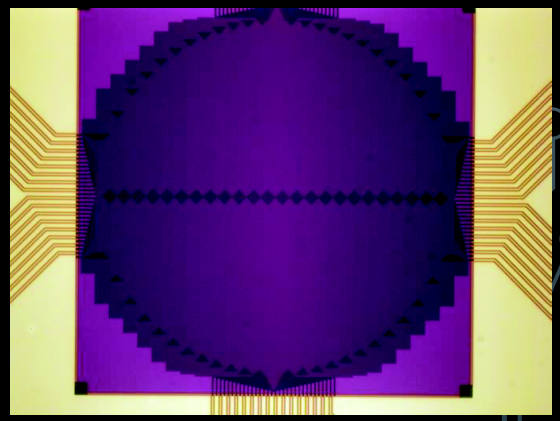
- Successfully fabricated ~ 91 % SDE SNSPD w/ 160 nm wide wires.
- Typical research throughput, EBL not that much slower than opt. lith.

  If # of pixels/active area increases, more throughput favors opt. litho.

  E.g. If SNSPD die-size → wafer-scale die-size
  like Cosmic Microwave Background production tiles.
- Opt. litho. simpler with quick/dirty mask design for optical proximity corrections.

  EBL has software to adjust dose. Opt. lith. has software to model: too costly for research?
-





EBL ~ hours vs. Optical lithography ~ minutes.