Optical and Infrared FA Microscopy

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Author

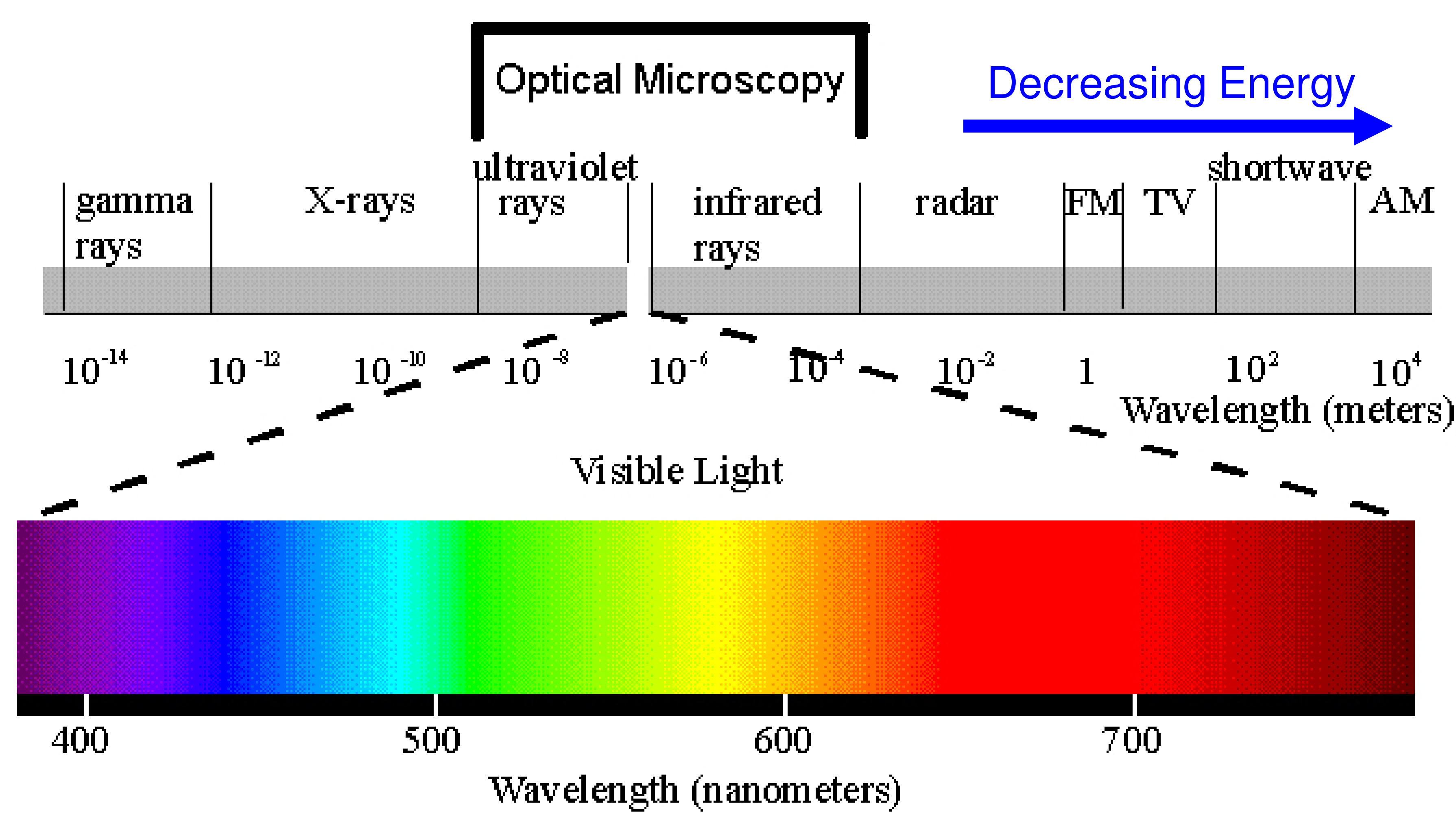
- 27 years of photonic instrument design
  - ~ Aerospace infrared vision systems, with and without crosshairs
  - ~ commercial infrared instruments
  - ~ microscopy and especially fault isolation microscopy.

Organization

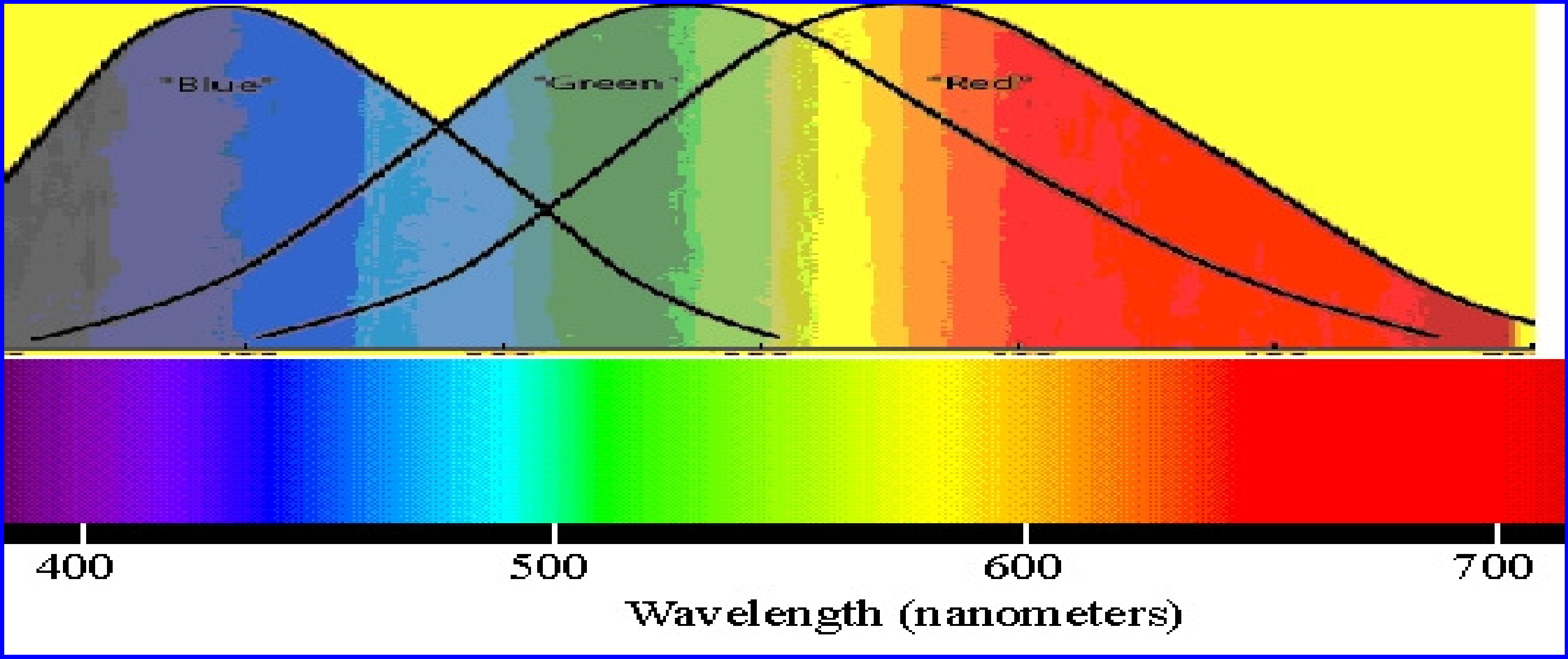
- Section 1 - Microscopy Physics
- Section 2 - Infrared Microscopy
- Section 3 - Specific FA Applications

Section 1 – Microscopy Physics

Optical Microscopy Spectrum



OBTW, Eye Response – R, G, & B Cones Overlap in Spectral Response



It is remarkable how well we distinguish color – a testament to our brain, our color image processor.

Atmosphere & Planck Radiation

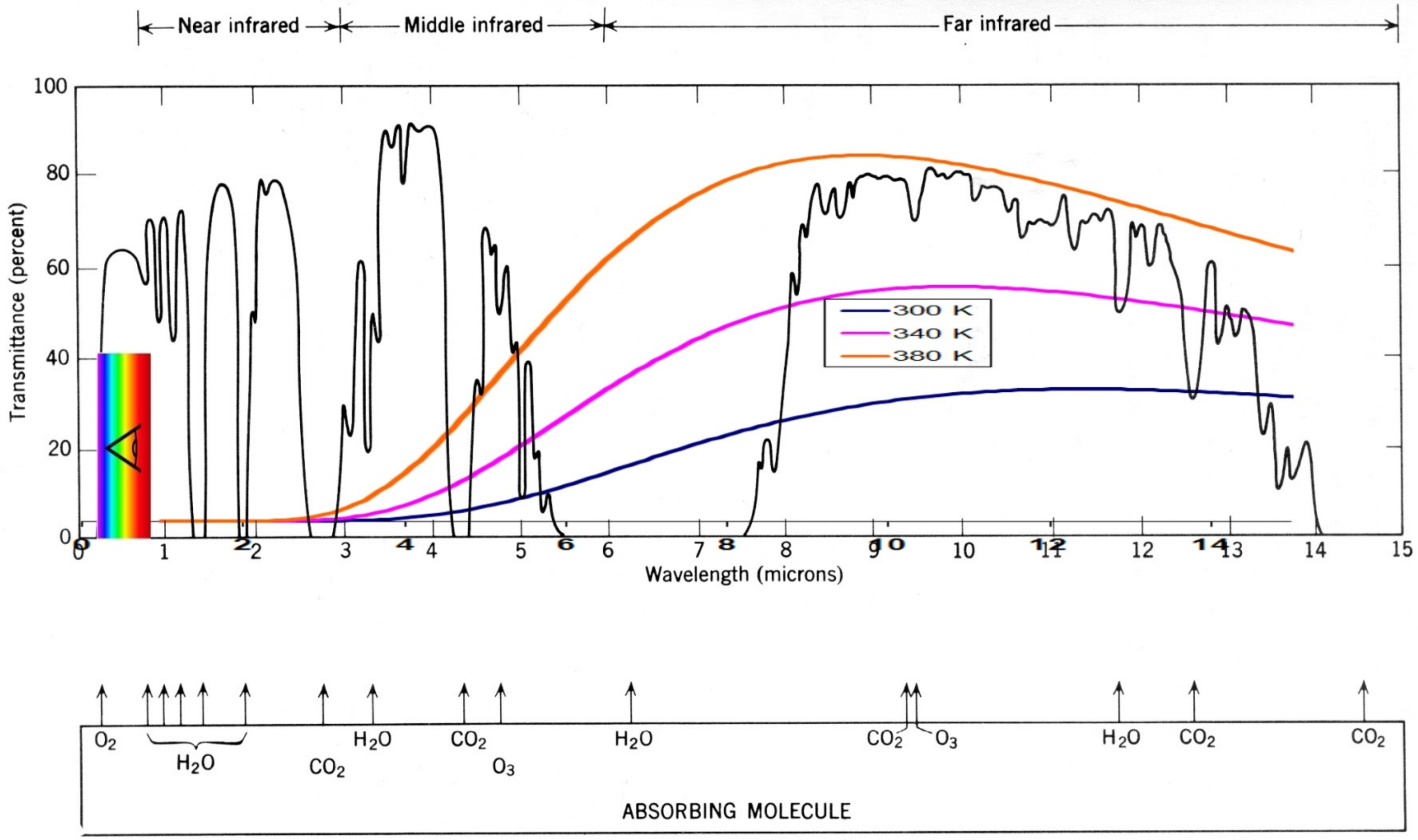


Figure 4.1 Transmittance of the atmosphere for a 6000 ft horizontal path at sea level containing 17 mm of precipitable water (adapted from Gebbie et al.[1]).

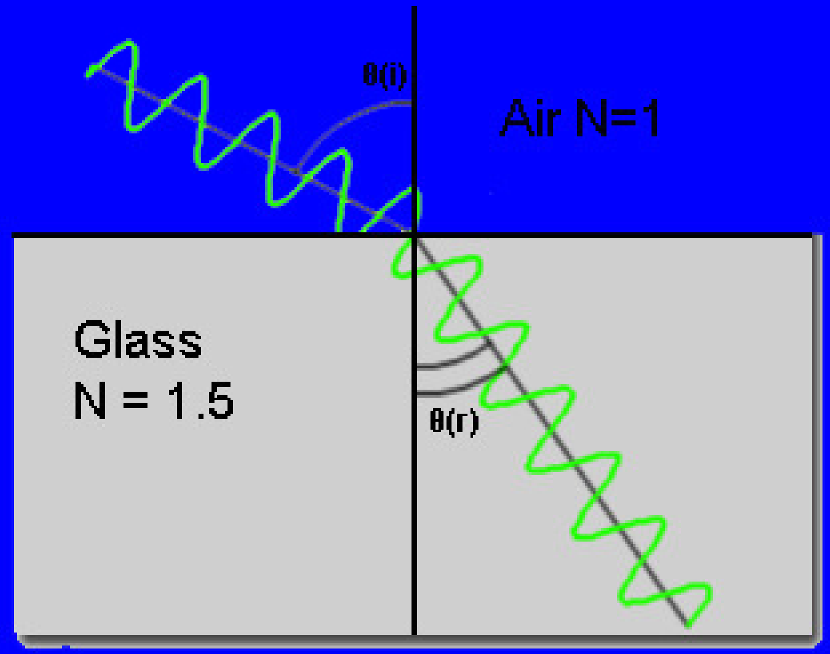
Failure Analysis Wavelengths

Ultraviolet			Photolithography
Visible	Violet to Blue	.4 - .45 um	Inspection / Probing
	Green	.5 um	Inspection / Probing
	Yellow to Red	.55 - .8 um	Inspection / Probing
Infrared	Near Infrared	.8 - 1.1 um	Emmi / OBIC
	Short Wave Infrared	1 - 1.7 um	Emmi / TIVA-XIVA
	Mid Wave Infrared	2 - 5 um	Hot spot, measuring temperature
	Long Wave Infrared	8 - 14 um	Military Night Vision

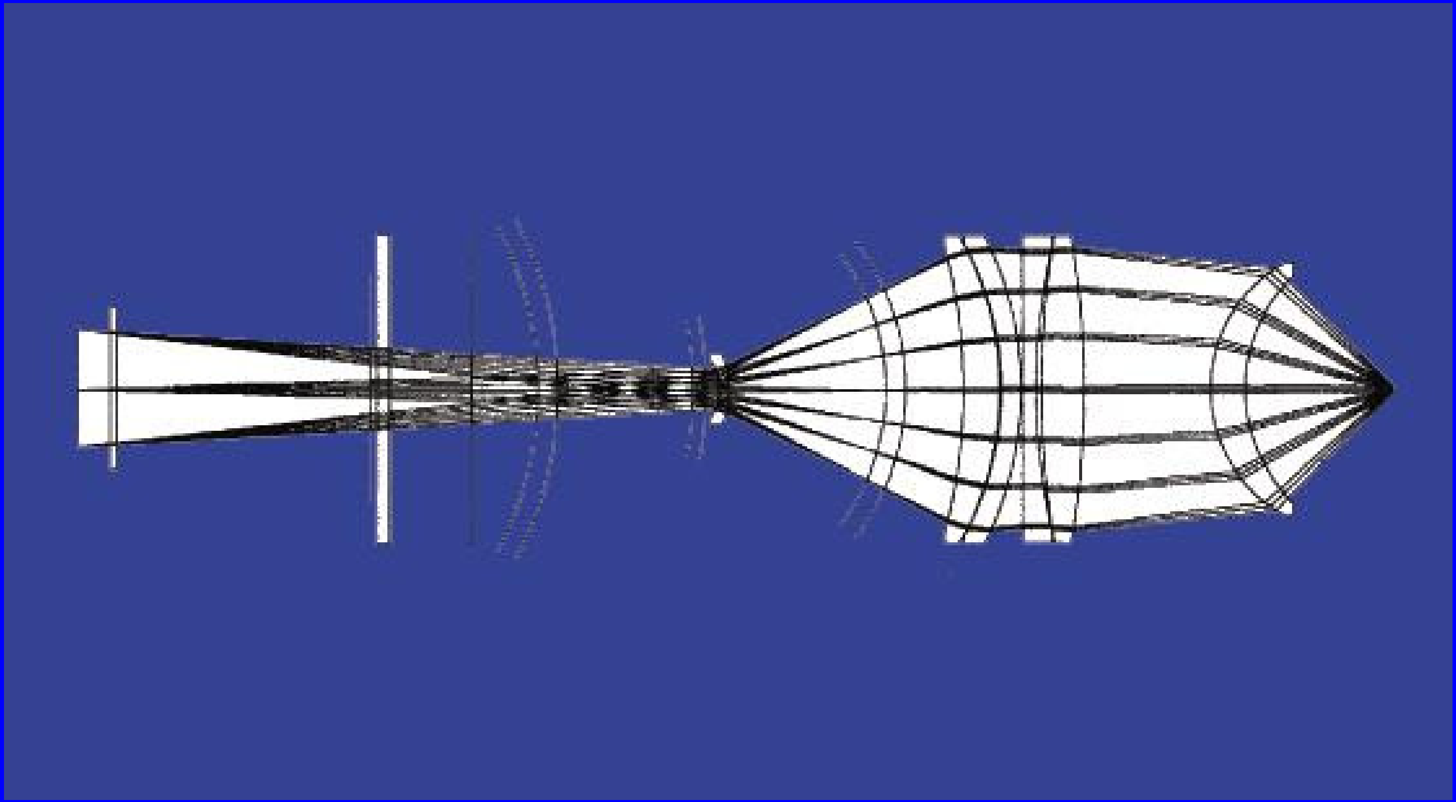
Index of Refraction

- Light bends when it encounters an index change.
- Imagine a car driving from pavement to sand.
- First wheel to strike slows down, causing car to turn.

$$\text{Index of Refraction N} = \frac{\text{Speed of Light in Vacuum}}{\text{Speed of Light in Medium}}$$

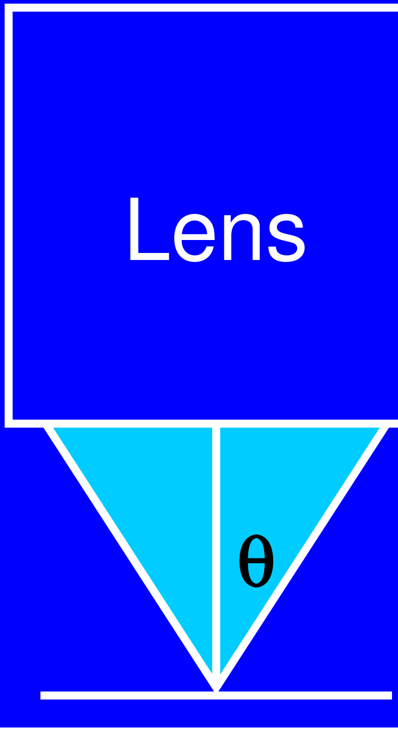


Using Varying Light Speed, i.e. Refractive Index, to bend light through lenses



Numerical Aperture is Fundamental to Microscopy

- Numerical Aperture (NA) is the sine of the collection half angle, multiplied by the index of the intervening medium.

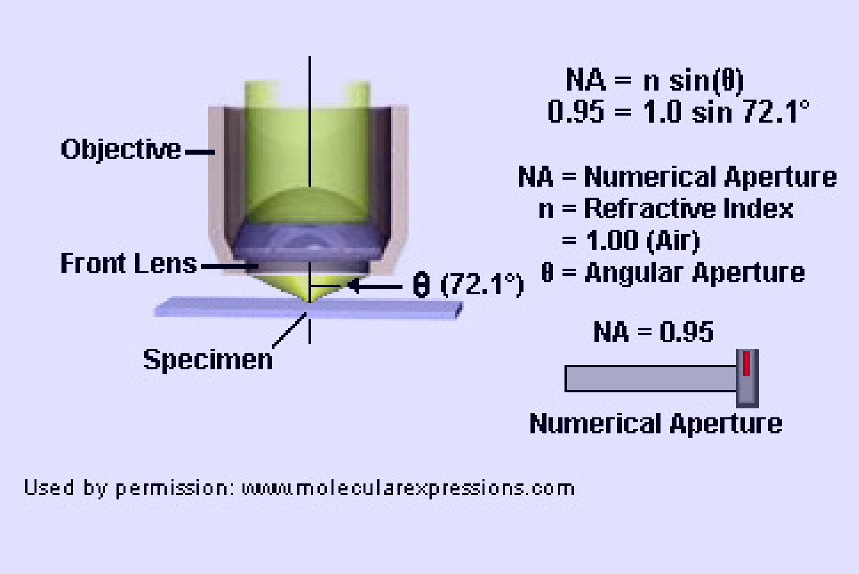


$$N.A. = NSin(\theta)$$

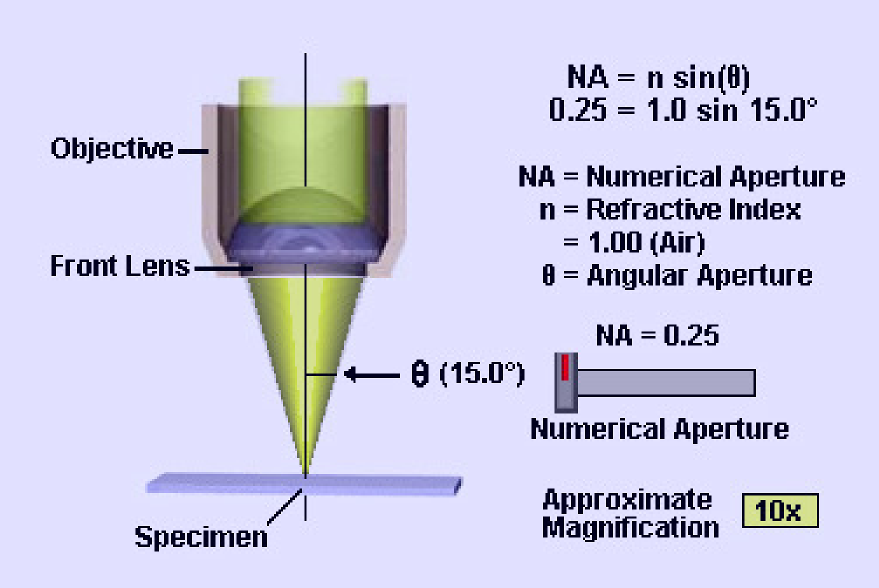
Numerical Aperture

The Numerical Aperture drives lens performance.

Large (Fast) NA



Used by permission: www.molecularexpressions.com



Small (Slow) NA

NA = N Sin θ

Numerical Aperture Governs the Lens Performance (and Cost)

- Controls Resolution via Airy Disk & Diffraction Limit.
- Controls the Sensitivity and Throughput of the lens.
- Drives working distance of the lens.
- Drives depth of field of the lens.
- Drives difficulty of manufacture and hence cost of the lens.

Why can’t I resolve fine details?

- When photons from a point source pass through a lens aperture, it becomes constrained in position.
- Quantum Physics requires that the photon’s angular uncertainty increase to preserve Heisenberg’s Uncertainty Relationship:

$$(\Delta\rho_x)(\Delta x) \geq h$$

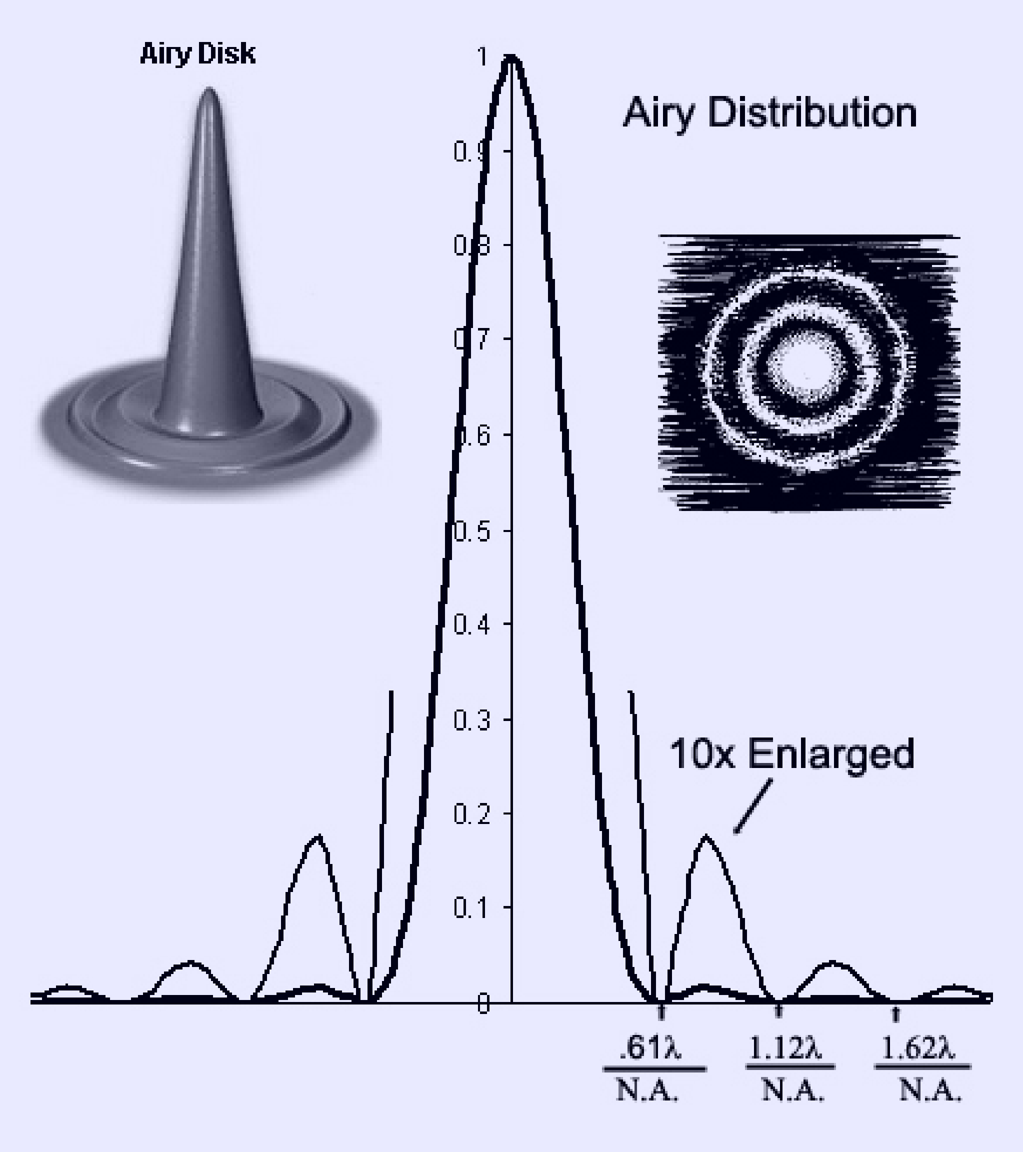
  - So the photons spread out into a classic pattern, the airy disk.

Resolution: Airy Disk

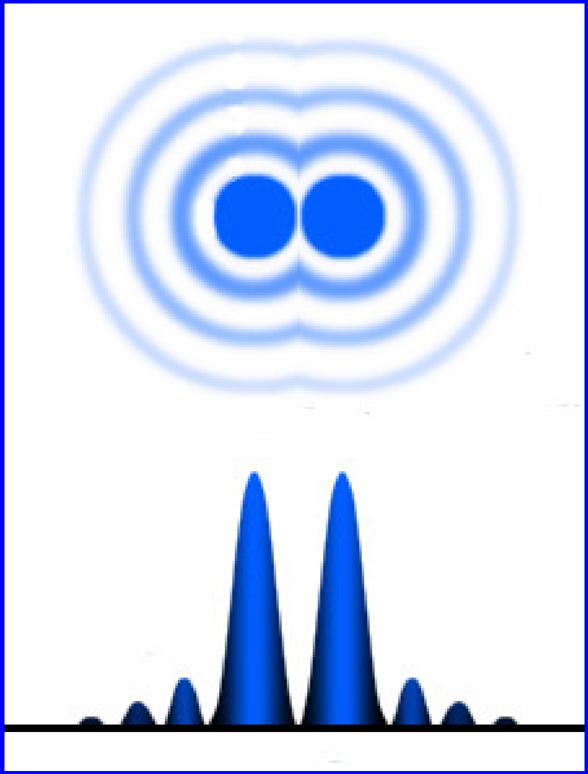
Photons from a point source, after passing through optics, form a classic diffraction pattern, called an Airy Disk.

The size of the Airy disk limits resolution.

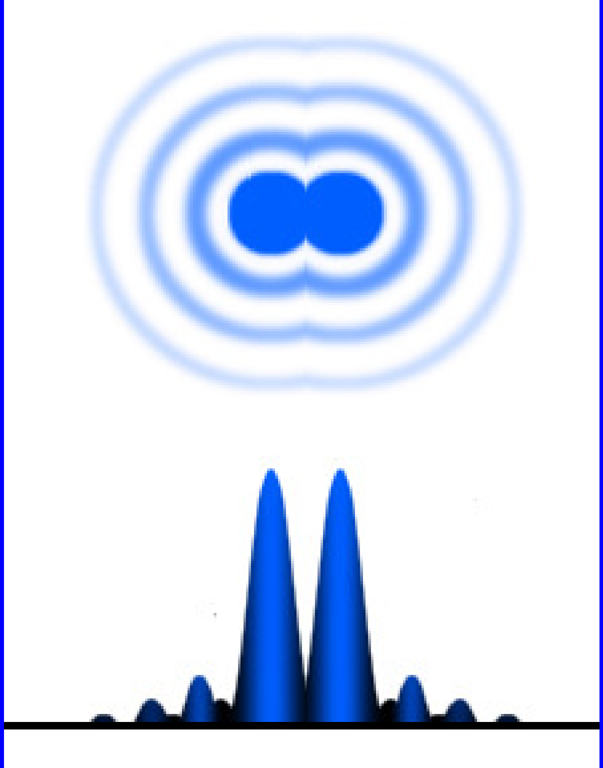
The size depends only on the wavelength and numerical aperture.



Rayleigh & Sparrow Examples

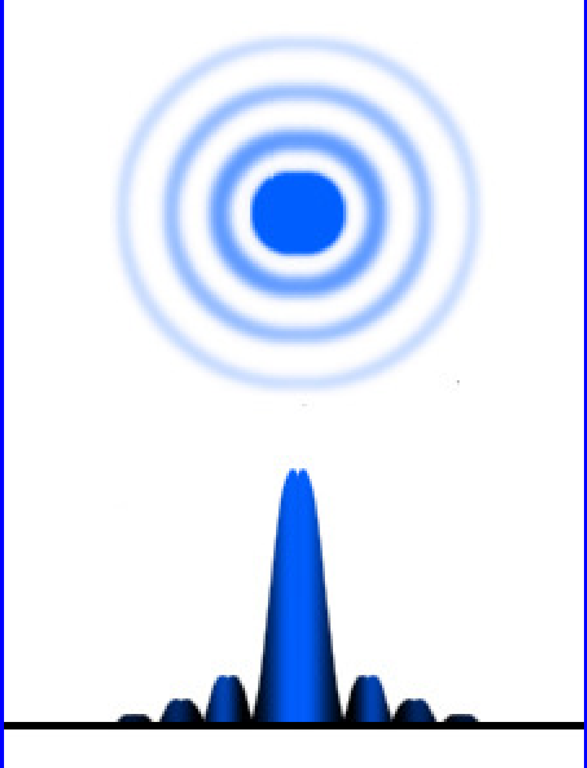


Easily Resolved



Rayleigh

$$D = \frac{0.62 \cdot \lambda}{N.A.}$$



Sparrow

$$D = \frac{0.5 \cdot \lambda}{N.A.}$$

Resolution Does Not Depend on Magnification

Rayleigh

(better known)

$$D = \frac{0.62 \cdot \lambda}{N.A.}$$

Sparrow

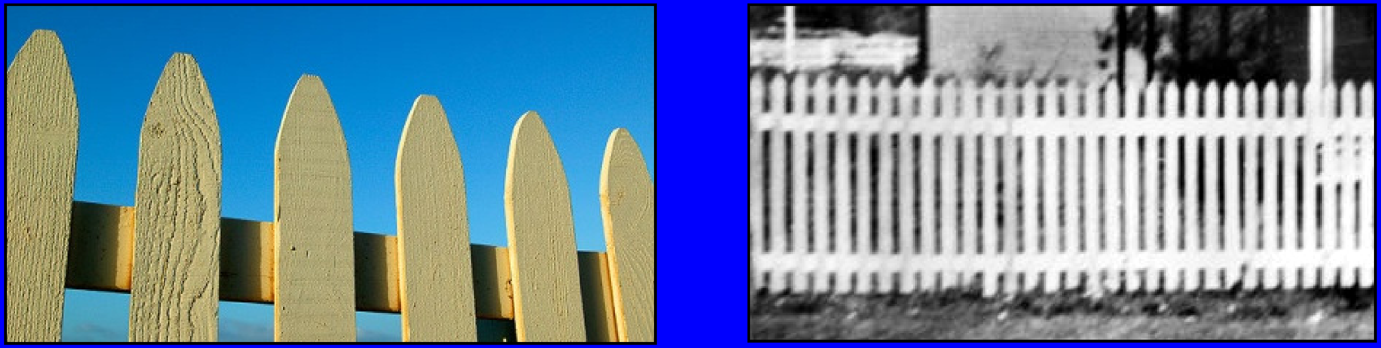
(more accurate)

$$D = \frac{0.5 \cdot \lambda}{N.A.}$$

Minimum Separation to resolve point sources

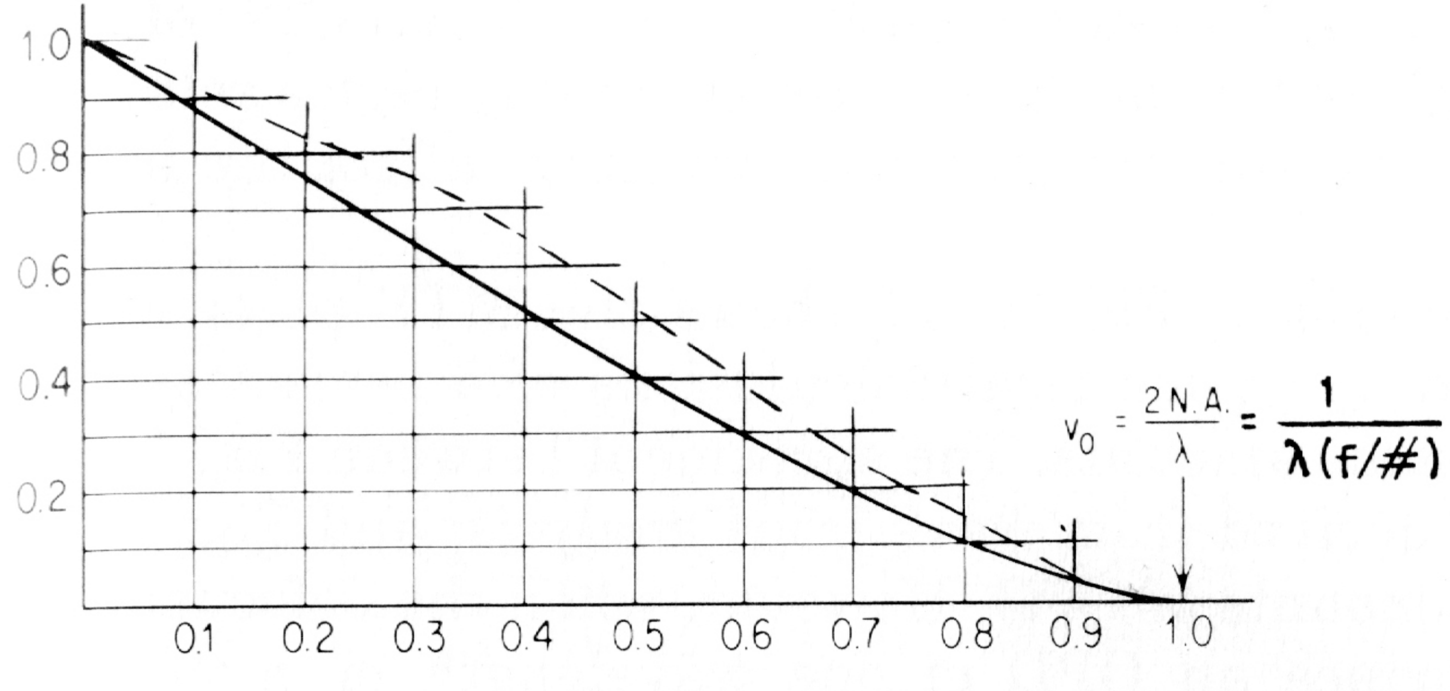
Or Use MTF for Resolution

- Modulation Transfer Function corresponds to Impulse Response in Electrical Engineering.
- Except Optical Designers use Spatial Frequency, which is analogous to a picket fence viewed through a camera.

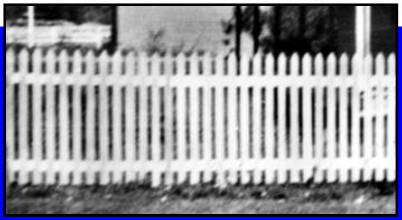


Low frequency – High Frequency

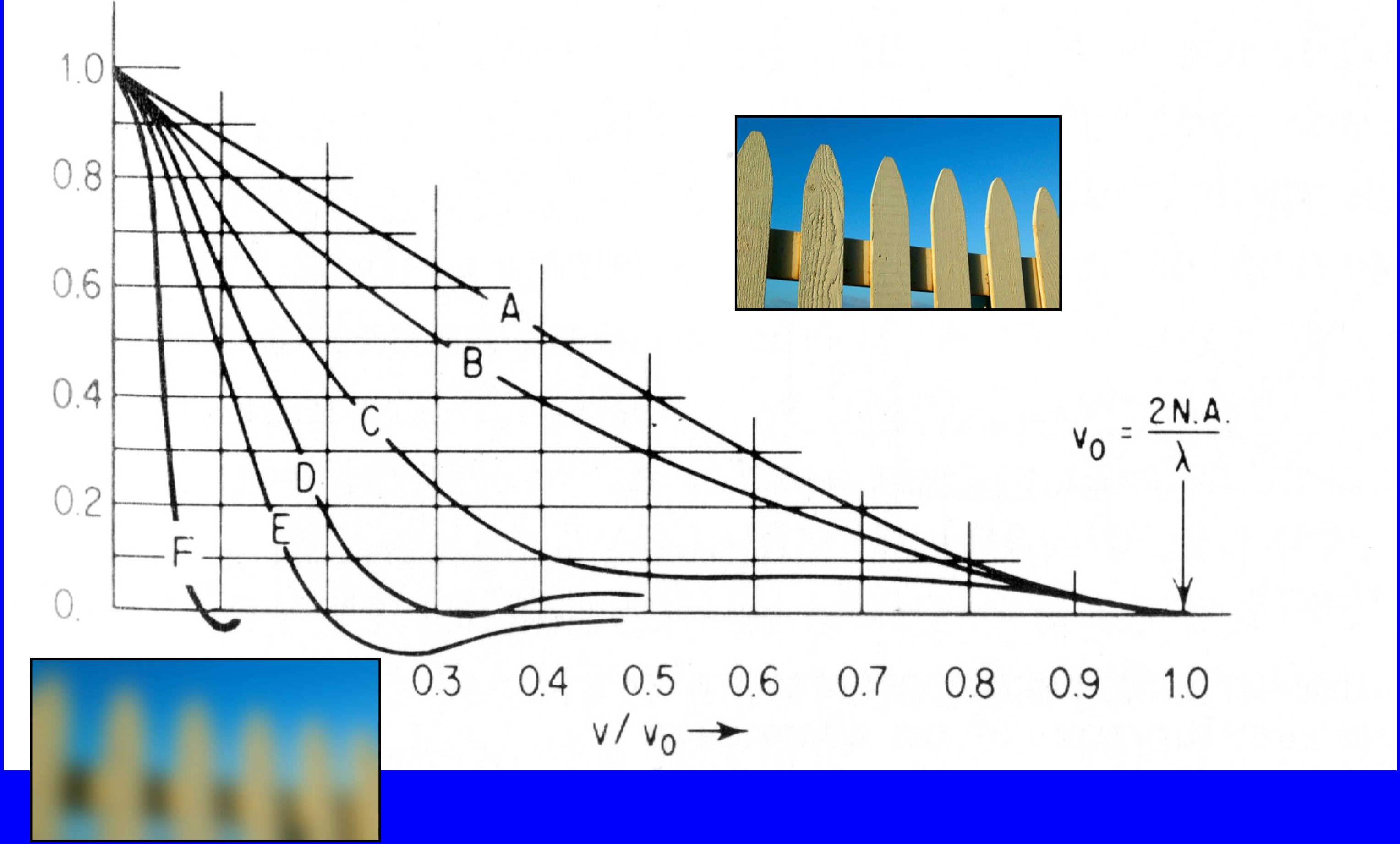
Diffraction MTF



$$v_0 = \frac{2\,N.A.}{\lambda} = \frac{1}{\lambda(f/\#)}$$



MTF Effect of Defocus

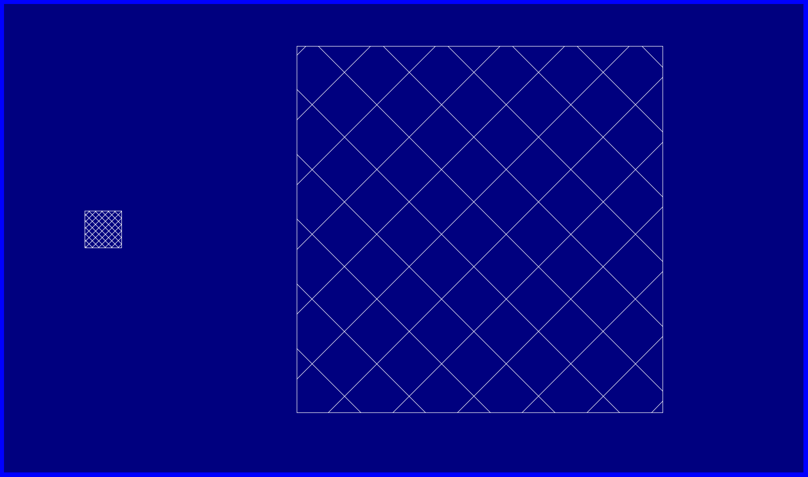


Slow N.A.'s Gather less Light

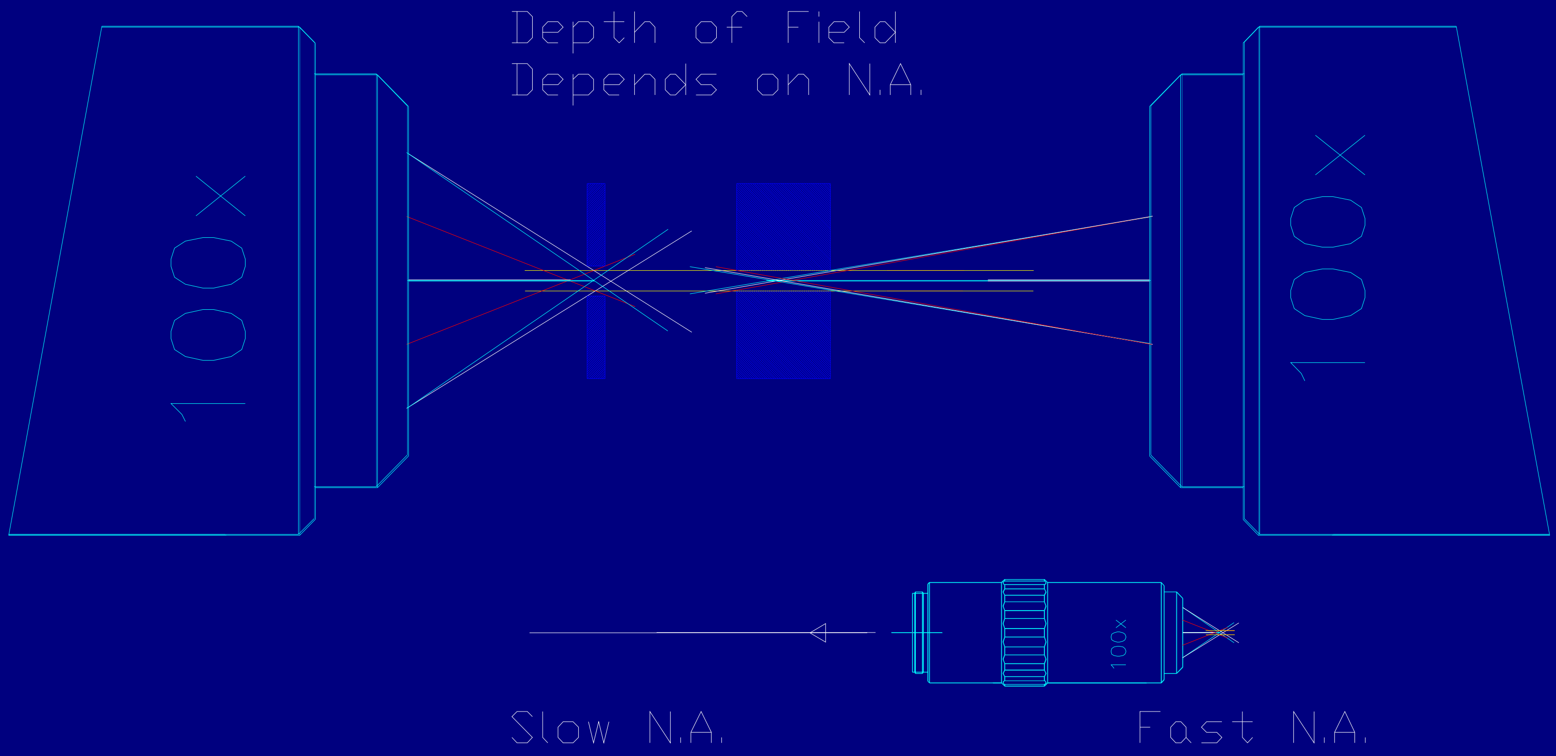
$$PhotonSignal \propto \frac{N.A.^2}{M^2}$$

10x magnification diffuses light over 100x the detector area.

Similar area function applies to lens collecting area N.A.



Depth of Field vs. NA



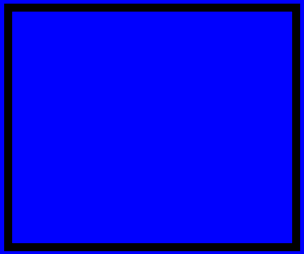
High N.A. Lenses Are Harder to Focus

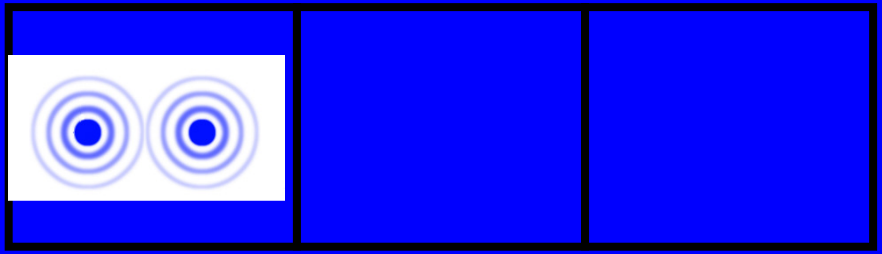
Doesn’t Magnification affect Resolution?

- Yes, but it is a secondary effect.
- The lens designer builds a lens with a fast NA to set the fundamental resolution limit separately from magnification.
- Next the lens designer must enlarge the image (magnification) to match the detector size.

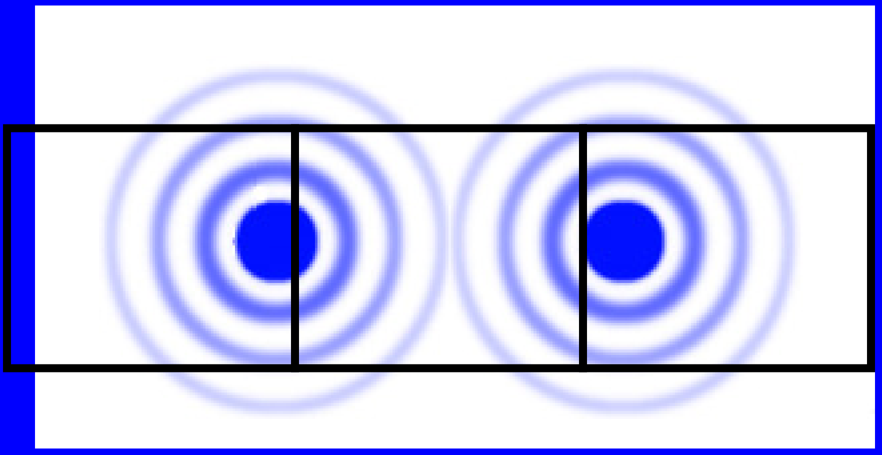
Magnification matches the resolved image to the detector

If this is the size of a camera pixel (e.g., 10um)





Then this resolved image needs more magnification



This image has been magnified just enough

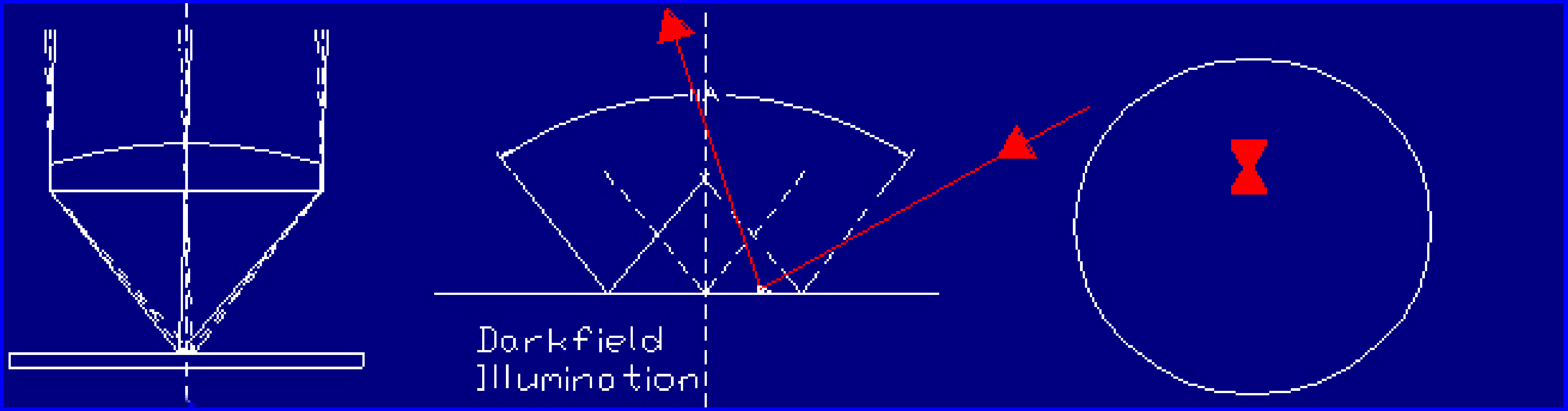
Magnification: You need enough, but not too much

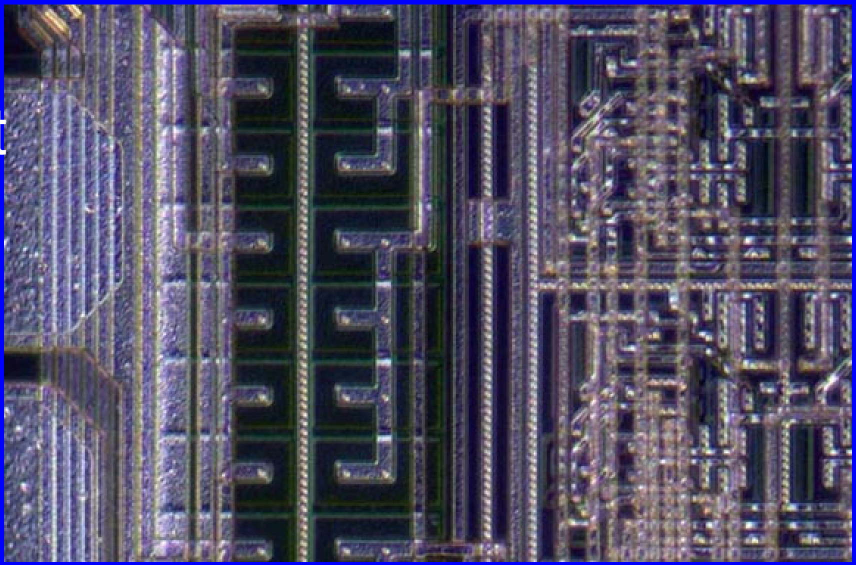
- Excess Vibration
  - Magnification beyond the resolution limit will not make the image clearer, but ambient vibration will be magnified perfectly, spoiling the image.
- Loss of Illumination
  - Lens throughput, $(NA/M)^2$ decreases rapidly with magnification. High magnification images are dark and noisy; bad for PEMs.

NA vs. Magnification

- **Take this away from this seminar**
  - Magnification doesn’t increase resolution, Numerical Aperture does.
  - You need enough magnification to preserve resolution from NA, (usually easy).
  - Buy good quality High NA lenses.
  - However, high NA’s sacrifice working distance, works against micro-probing.
  - Too much magnification is not good, e.g. Vibration or in an emmi, loss of sensitivity.

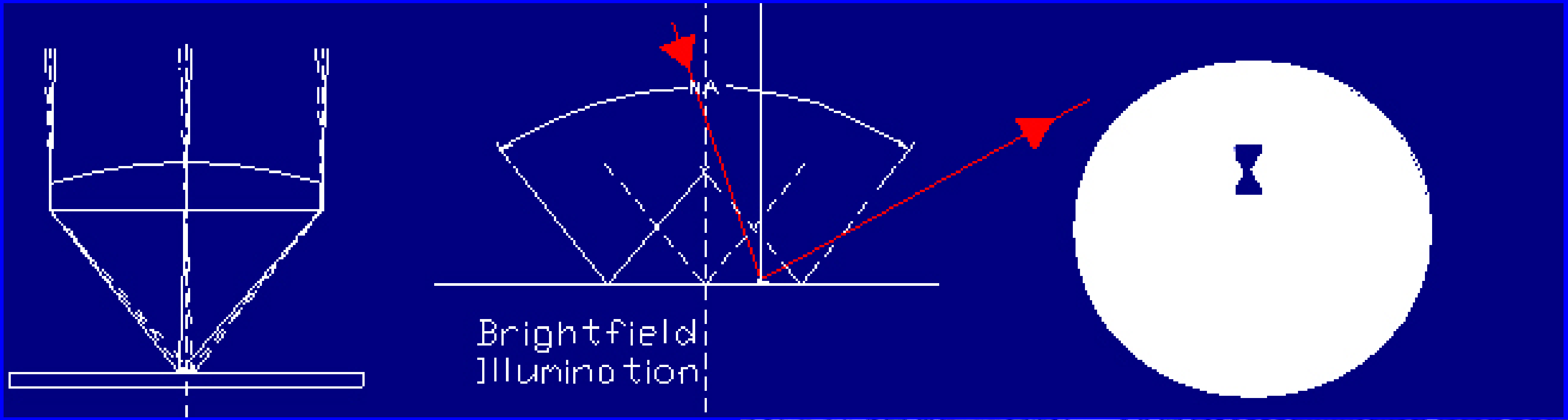
Darkfield Illumination





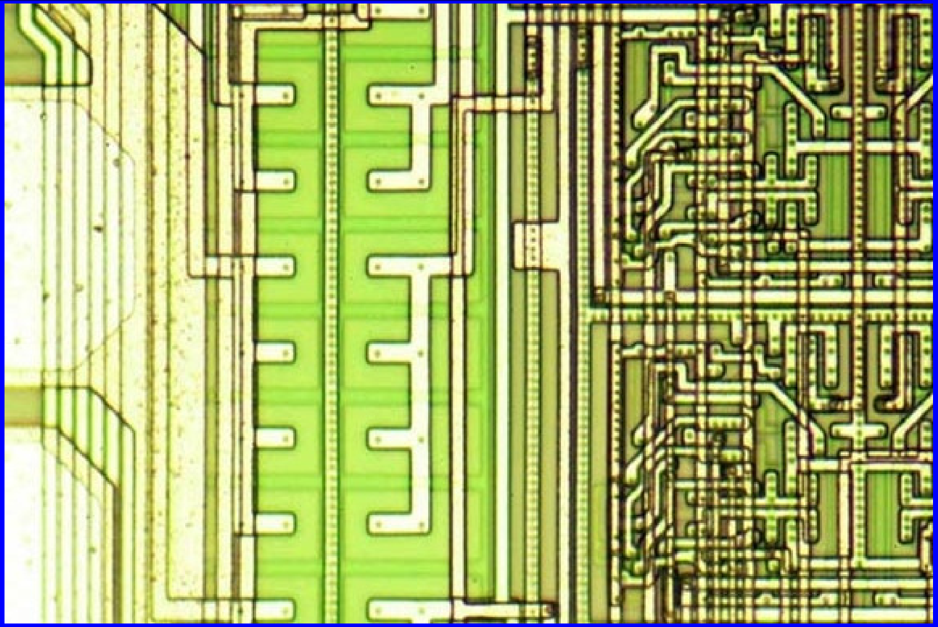
- In Darkfield Illumination, light from outside the Field, does not normally enter the objective.
- Light striking objects is displaced into the field.
- Objects appear bright against dark background.

Brightfield Illumination

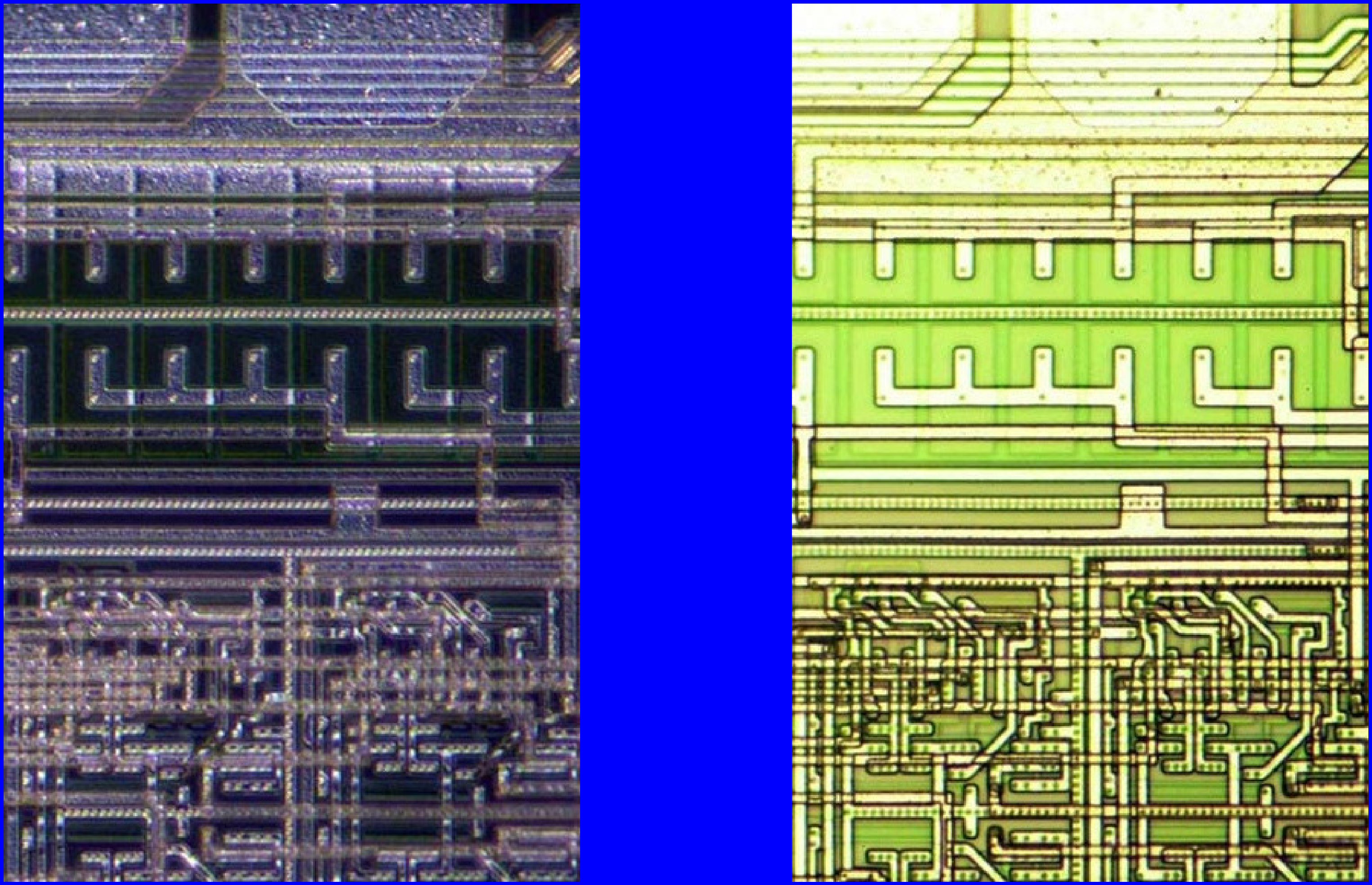


- In Brightfield Illumination, light from inside the Field floods the objective.

- Objects reflect light out of the field, making them dark against bright background.

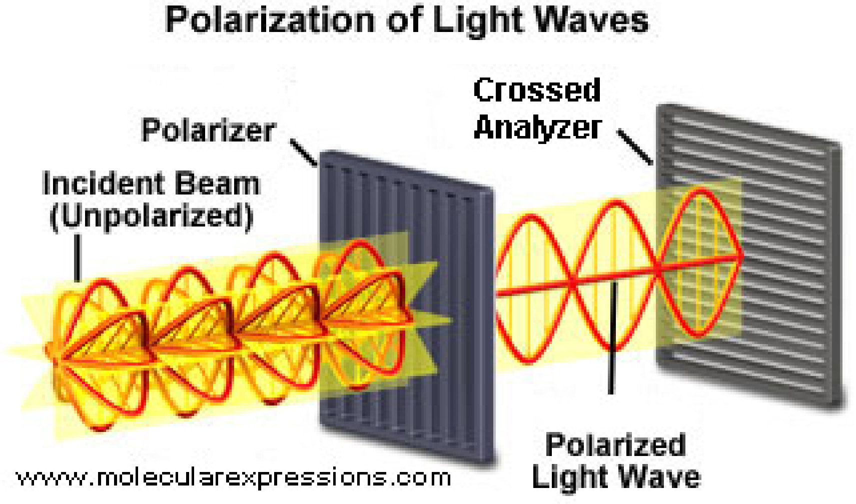


Bright & Dark Side by Side

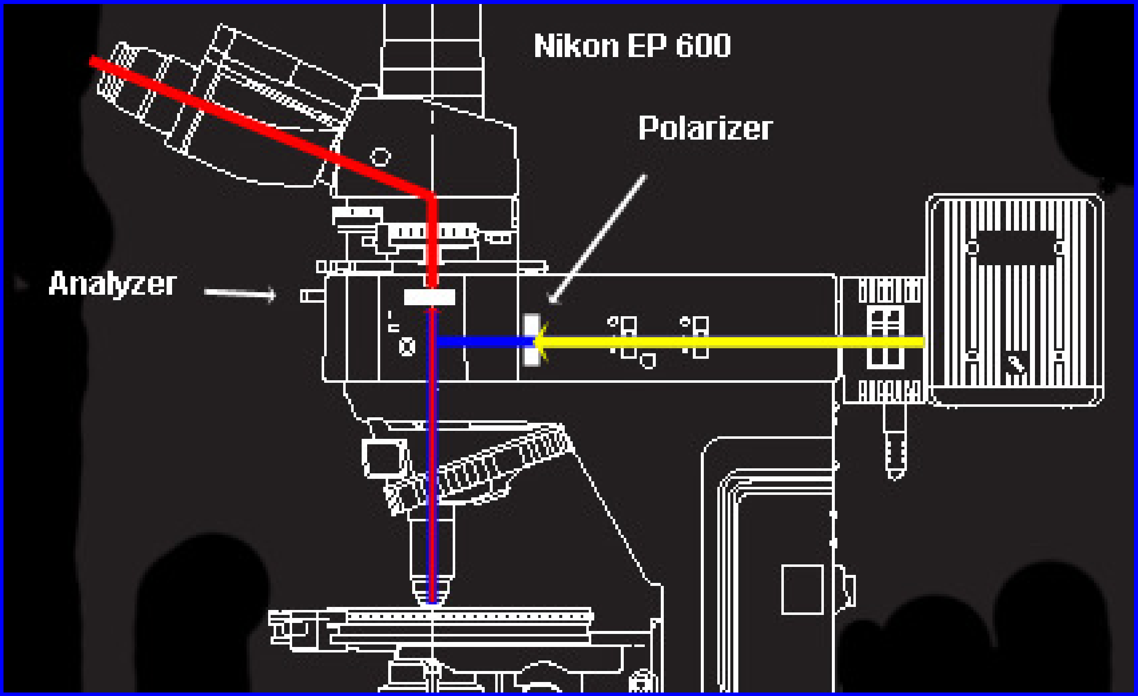


Polarized Microscopy

- Polarizers restrict light to a single polarization.
- Crossed Polarizers extinguish all light.



- Yellow – Unpolarized
- Blue – Polarized 1 axis (all the way to sample)
- Blue is blocked by analyzer.
- Red – polarization changed by sample, passes analyzer.



Liquid Crystal Hot Spot Detection

- LC has two liquid phases.
- Change occurs at temperature “**T**”.

acceleratedanalysis.com

- Below “**T**” - LC film rotates light polarity – rotated light passes analyzer, the circuit is visible.
- Above “**T**”, LC behaves as a simple liquid, light is not rotated, and is blocked by the analyzer. Circuit hot spot appears black on image of circuit.

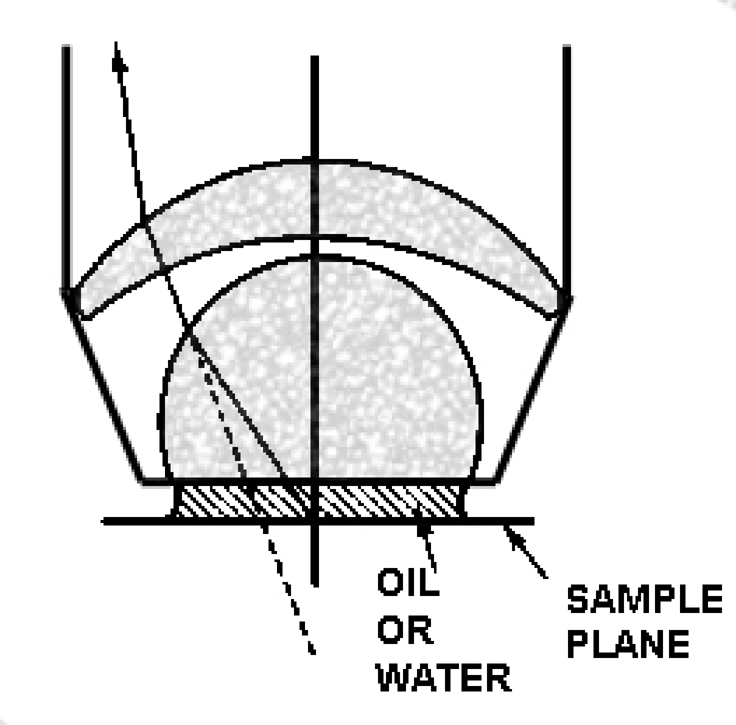
Immersion Lens Advantage

- Resolution

$$D = \frac{0.5 \cdot \lambda}{N.A.}$$

- Signal Throughput

$$PhotonSignal \propto \frac{N.A.^2}{M^2}$$



Signal and resolution improve with optically dense media

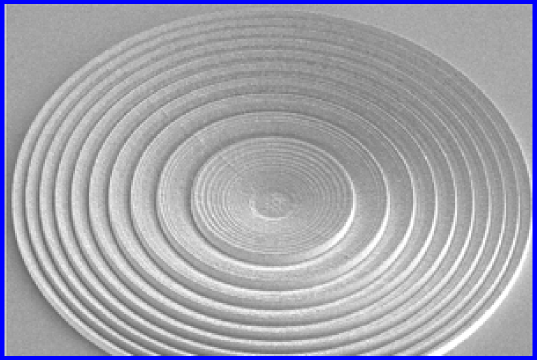
NA = N Sin θ

Types of Immersion Lens

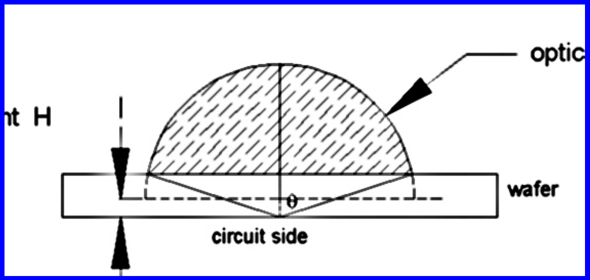
Air	N=1	Longer Working Distances
Water	N=1.2	20% better resolution 44% more signal Good for living biologics
Oil	N=1.5	50% better resolution 225% more signal Matches glass index
Solid Si (SIL)	N=3.5	Sub micron infrared resolution 12x increase in signal

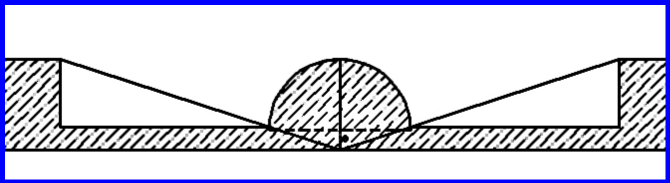
Some Solid Immersion Lenses

Solid Immersion lenses have caught on for Time Resolved emmi applications but are not in demand for standard emmi or infrared FA. Possibly too much trouble to make and use.



Zachariasse et. al. ISTFA 2005





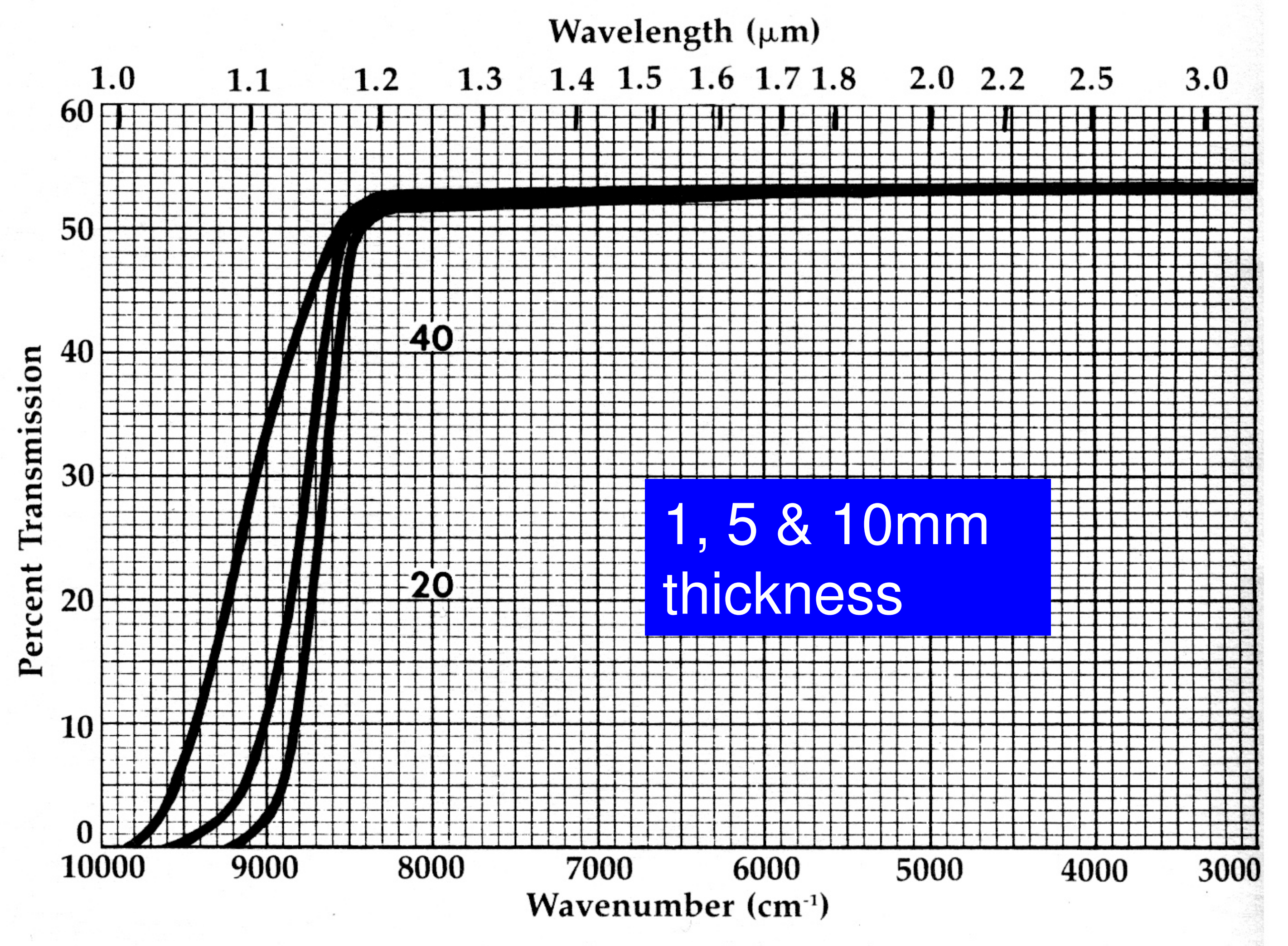
FOSSIL , Koyama IPRS 2003

Section 2 – Infrared Microscopy

Infrared Failure Analysis

- Multiple metal layers and flip-chip packaging can make front side circuit inspection impractical.
- Silicon is transparent at infrared wavelengths, so it is possible to examine the circuits from the back of the die or wafer with IR.
- Emmi and thermal signatures are stronger in the IR.

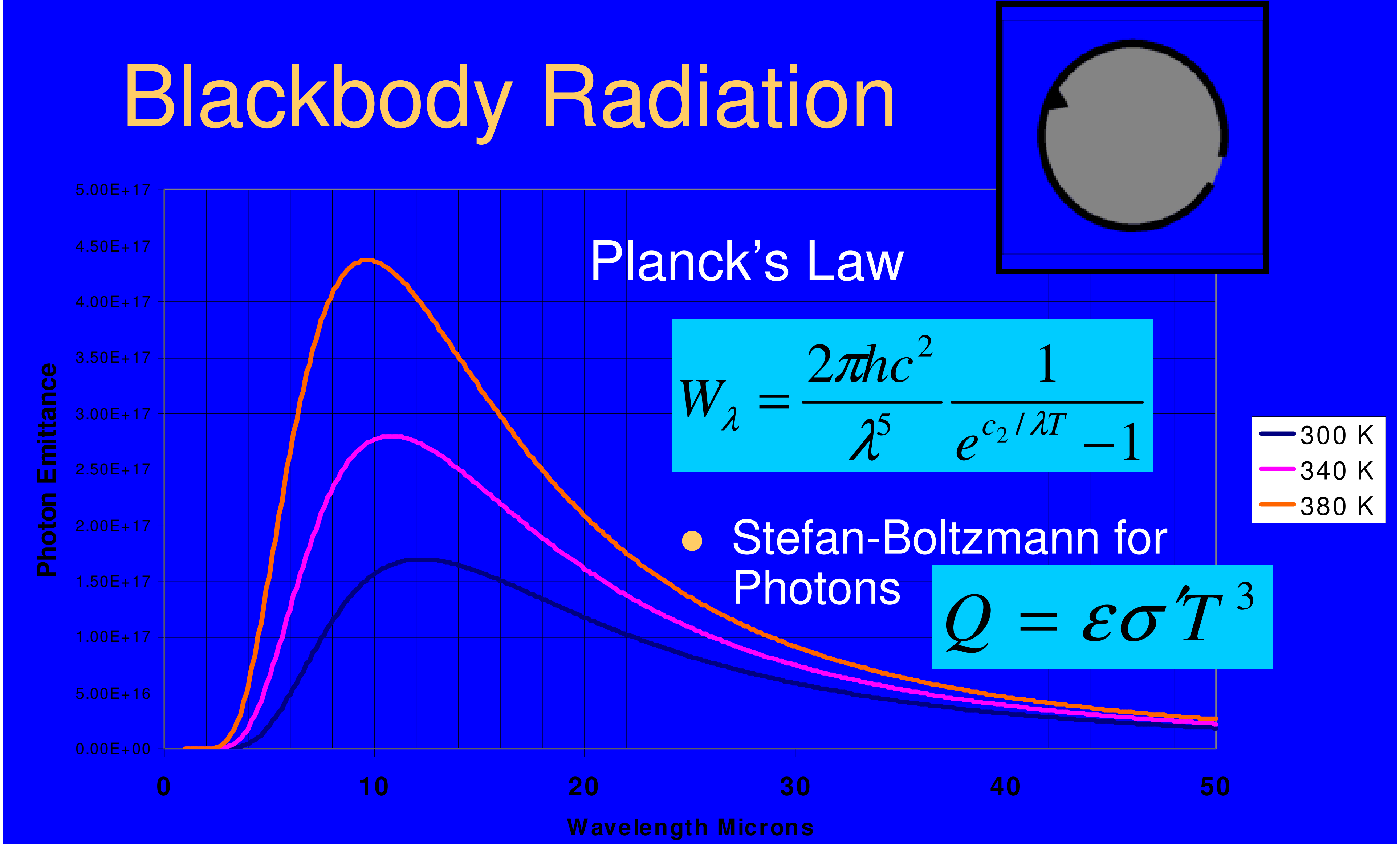
Silicon Transmission



1, 5 & 10mm thickness

From Eagle Picher Brochure

Blackbody Radiation



Planck's Law

$$W_\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{c_2/\lambda T}-1}$$

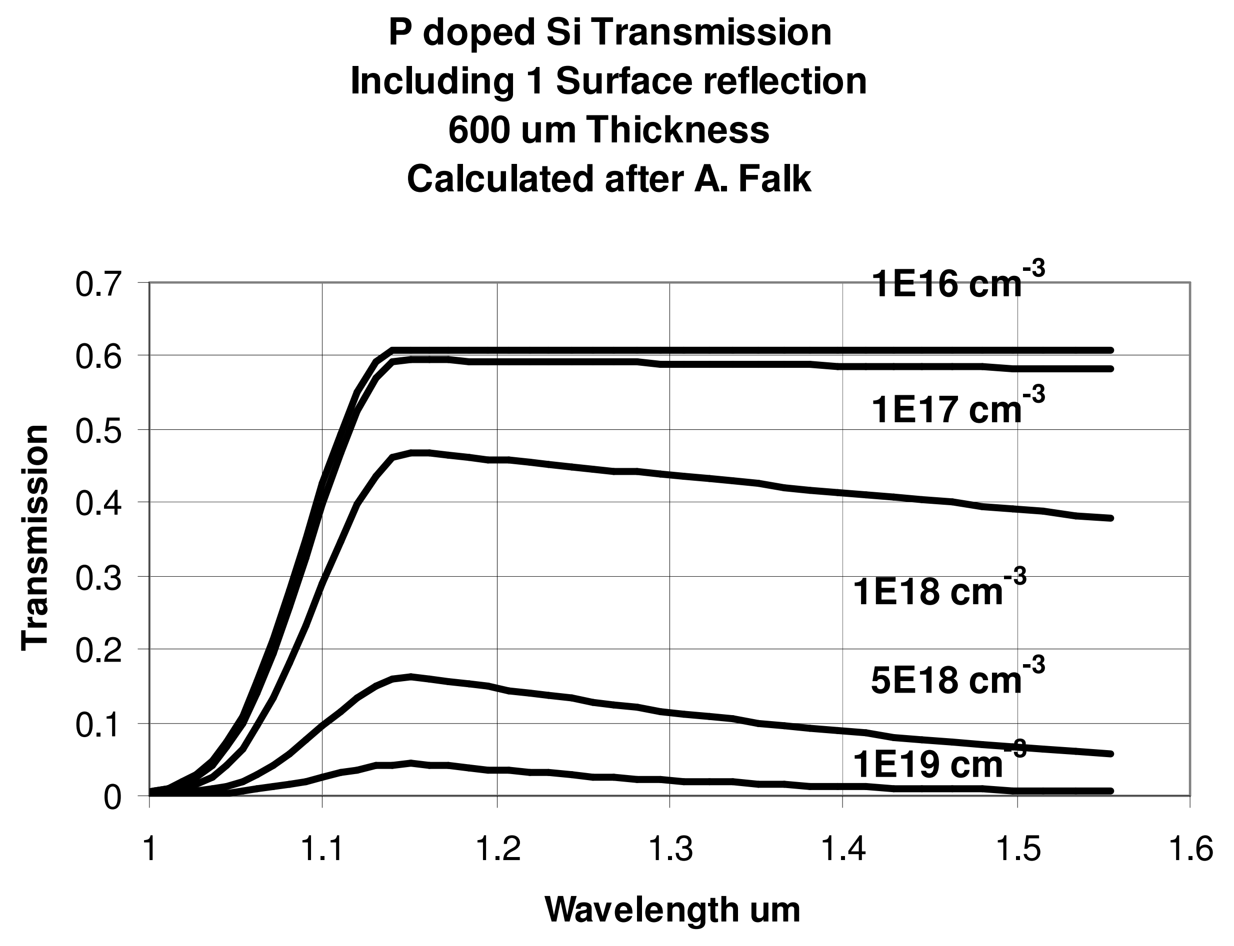
- Stefan-Boltzmann for Photons

$$Q = \varepsilon\sigma' T^3$$

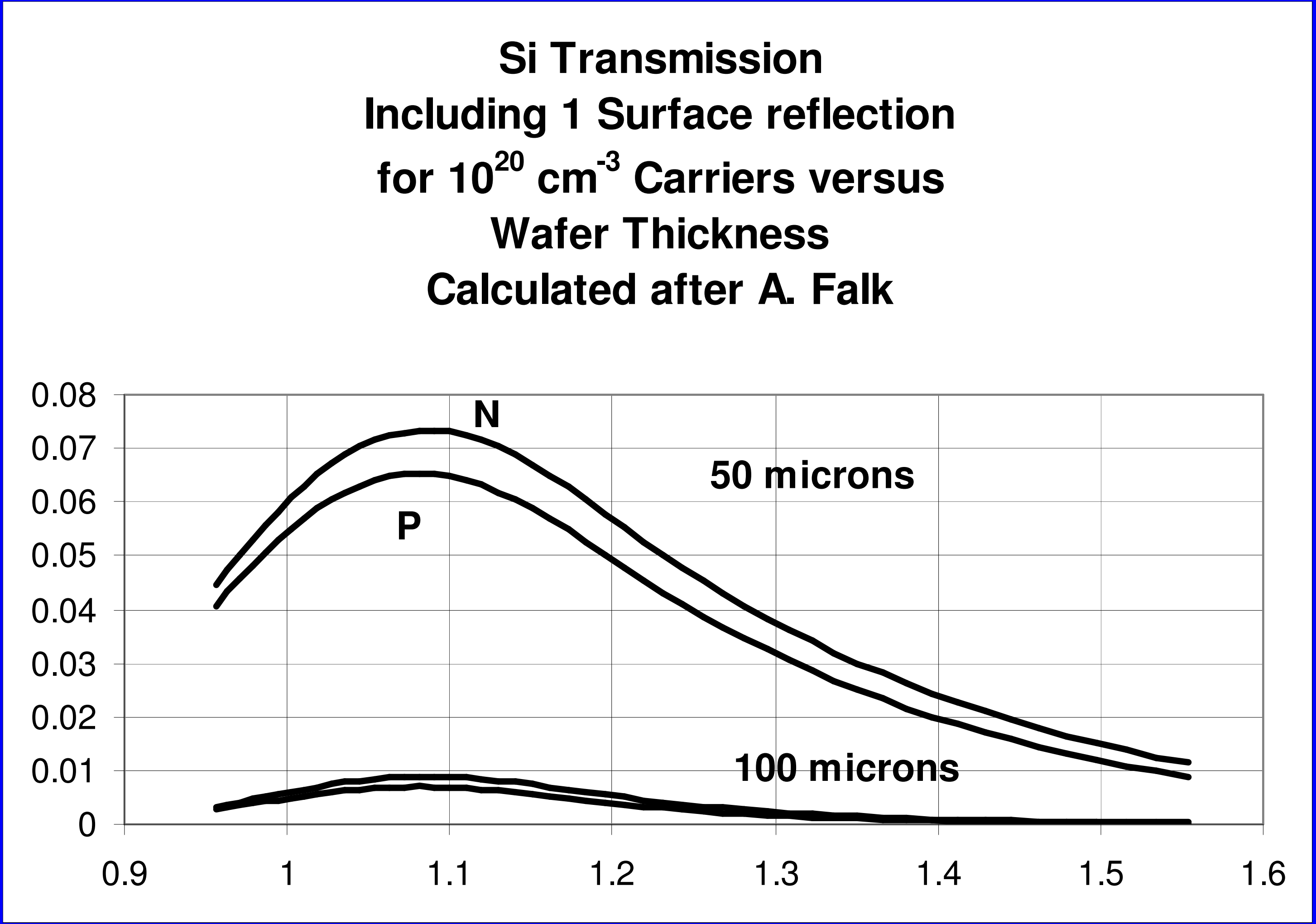
FA Infrared Techniques

1. Laser Signal Injection Microscopy to find opens and resistive shorts.
   - 1.06 microns and 1.34 microns wavelengths.
2. Emission Microscopy
   - Visible to 1.1 microns with lower cost Silicon CCDs.
   - 0.8 to 1.6 microns with exotic Short Wave Infrared detectors.
3. Thermal Microscopy
   - 2 to 4 microns for hot spot detection and thermal mapping (InSb detectors).

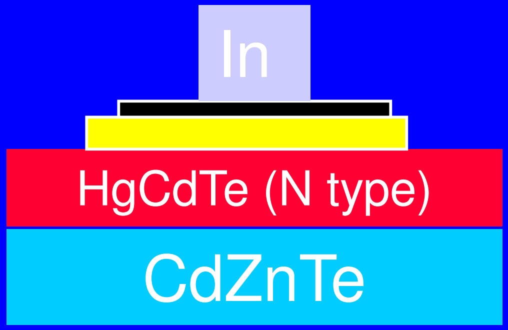
Doped Silicon is Opaque



High Dopant Wafers should be Thinned



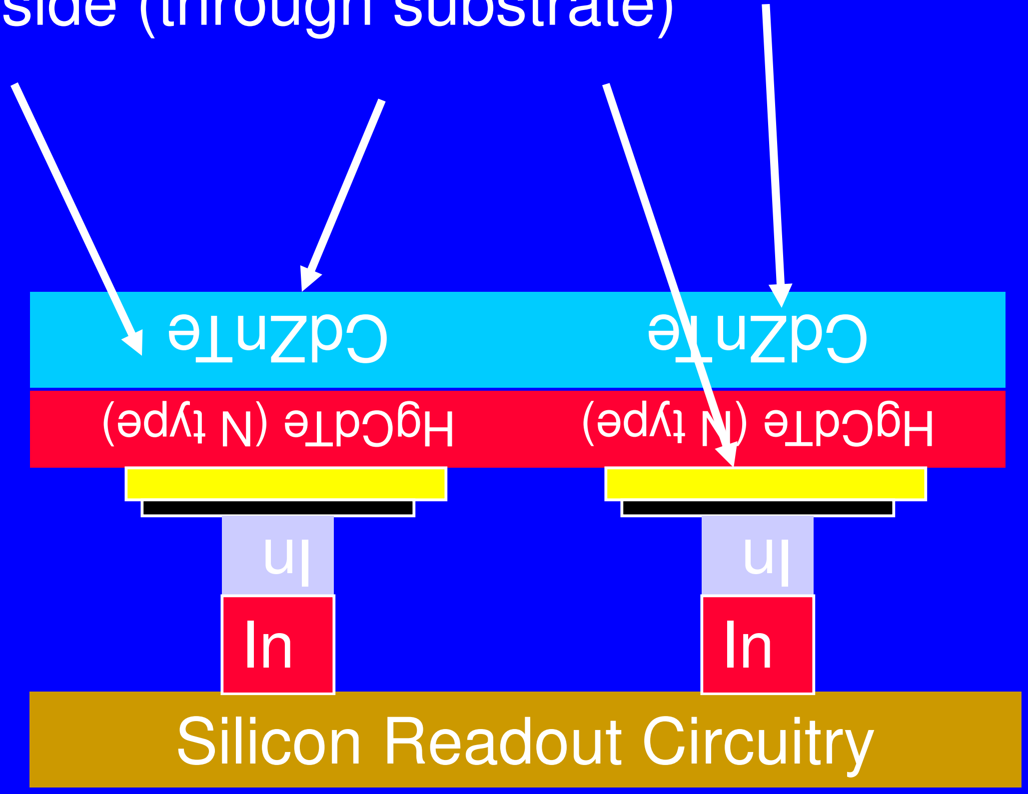
Growing an Infrared Detector



4. Add Indium Bump
3. Create diode and metal
2. Grow epi low-bandgap detector material
1. Start with suitable substrate

Invert & Bump to Si Readout

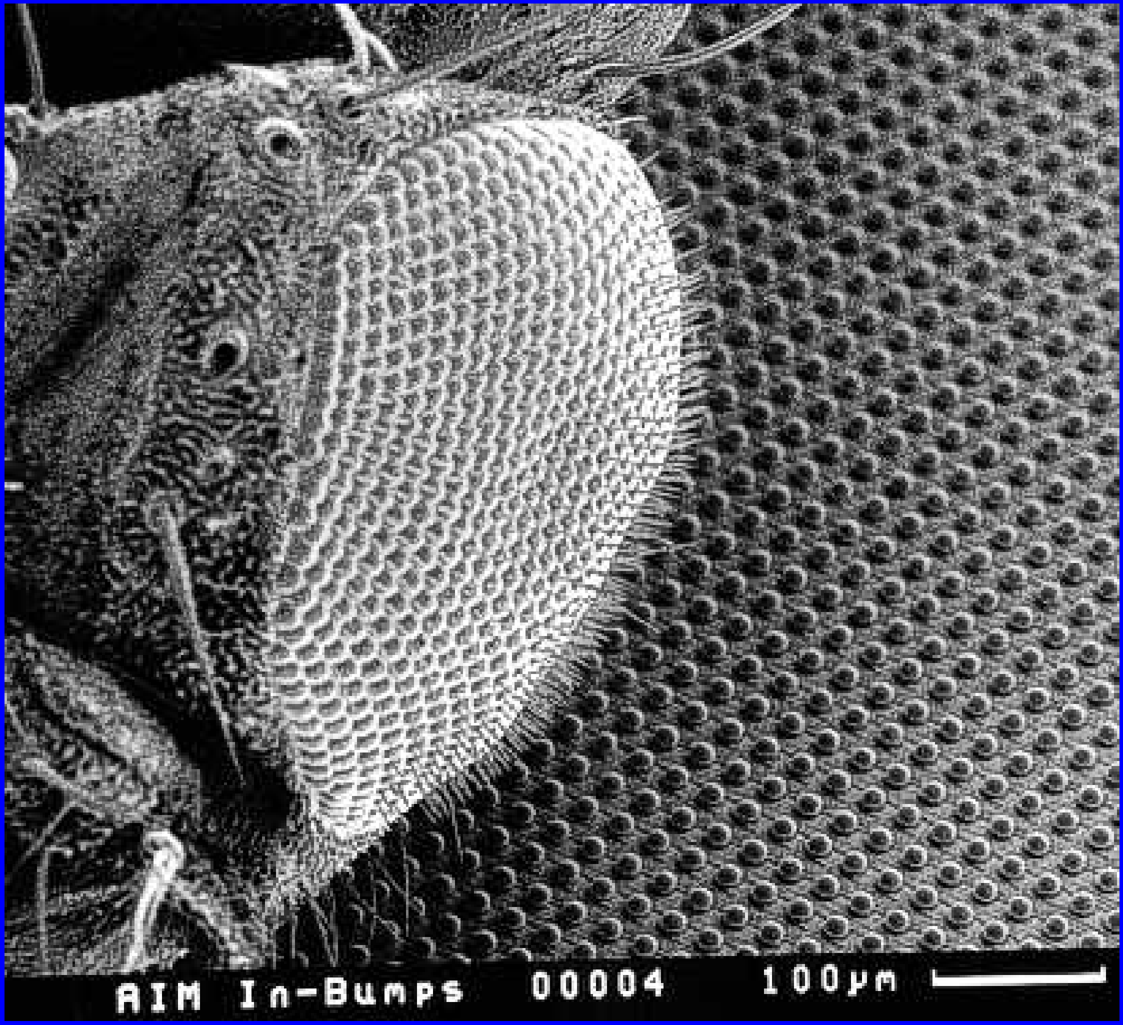
Incoming Infrared Photons this side (through substrate)



1. Invert Detector Array

2. Bump bond to Silicon Readout Circuitry

Indium Bumps and Fruit Fly Eye



From www.mm.fh-heilbronn.de/event/ihk0104.htm

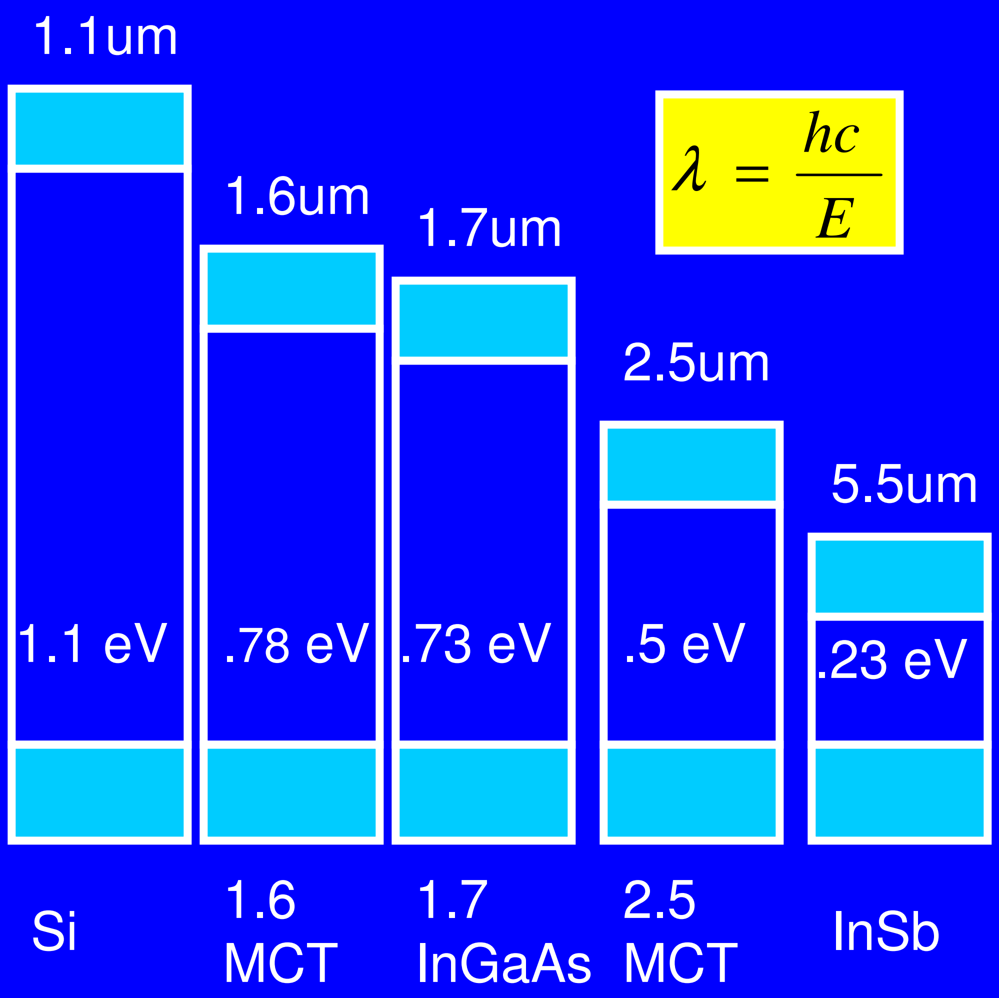
Detecting Faint IR energy requires small bandgap detector materials

- This equation (de Broglie's) relates a photon's wavelength to its energy.
- The Bandgap of silicon is too great to respond to infrared wavelengths
- Infrared Detectors must be made from small bandgap materials

$$\boxed{\lambda = \frac{hc}{E}}$$

- ***But this makes infrared detectors susceptible to thermal phonon noise.***

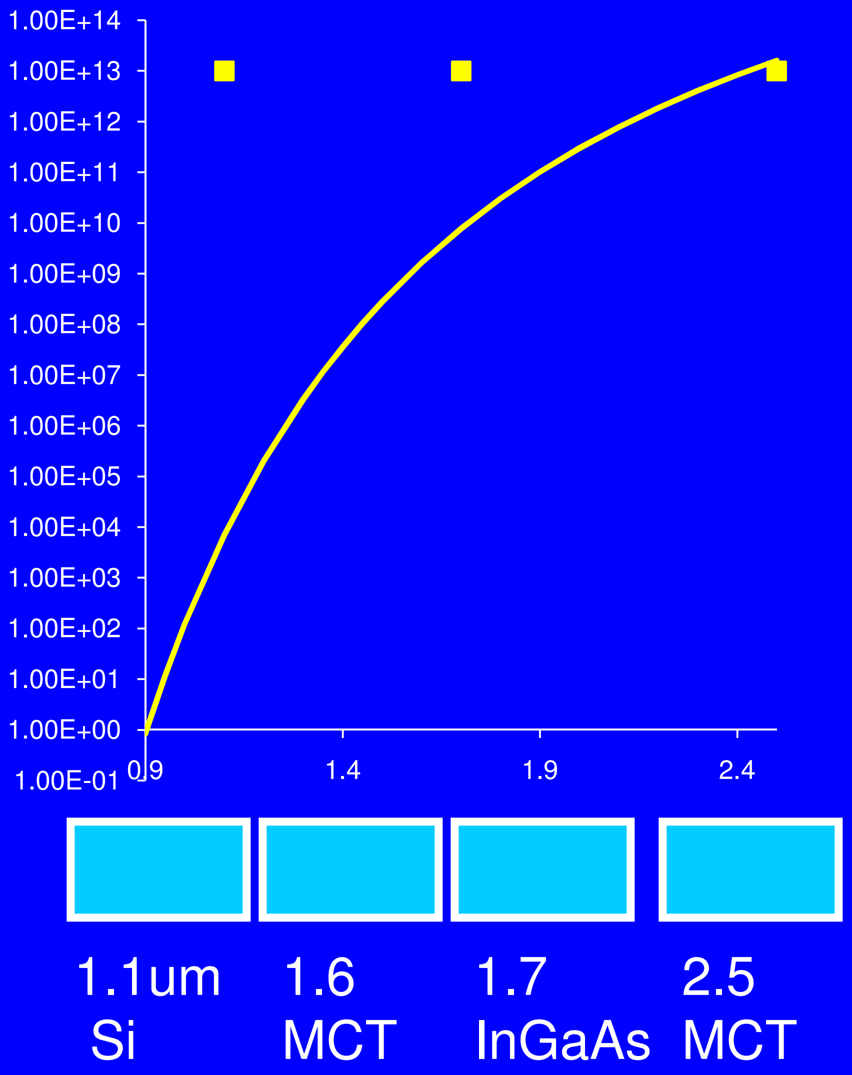
Detector Band Gaps



$$\lambda = \frac{hc}{E}$$

- Weak photons can only be detected with low bandgap detectors.
- Dark Current increases for small bandgaps.
- IR detectors must be cooled or thermal carriers will dominate.

IR Detectors Limited by Thermal IR



- Small band-gap detectors fill quickly with Planck Blackbody Radiation.
- In the case of the MCT & InGaAs Planck background, not dark current, limits integration time.
- Noise decreases with more T_{int} .
- We measure around 30s T_{int} for 1.7um but only seconds for 2.5 um MCT.
- So if the signal doesn’t increase w/ longer λ response the S/N will degrade.

Examples	Andor CCD Scientific - Si	Rockwell MCT
Array Temperature	TE Cooled 50 Celsius	LN2 (77 Kelvin)
Dark Current	0.5 e^- / s	<.5 e^- / s
Pixel Well	80,000 e^-	200,000 e^-
Time to Fill Well w/ I_D	44 Hours	110 Hours
Time to Fill w Planck BB IR	Negligible	1’s to 10’s of seconds

Camera Conclusions

- Both example Cameras have negligible dark current.
- SWIR camera integration time will be limited by Planck radiation.
- It isn’t clear and doesn’t match authors experience that the SWIR camera will be preferred given cost, ease of use, image quality & especially S/N.
- However the author notes in some cases only SWIR camera will detect emission.

Section 3 – FA Microscopy

Comparing Techniques - 1 of 3

	Emmi	Thermal Infrared	Laser 1340	Laser 1064
Applications	Oxide Defects	Ohmic Shorts	Ohmic Shorts	Opens, Junction defects
Physics	Photons: Electron-hole recombination	Planck radiation from I^2R heating	Plots V or I versus micro-local heating	Plots V or I versus micro-local carrier injection

Comparing Techniques - 2 of 3

	Emmi	Thermal Infrared	Laser 1340	Laser 1064
Pro	Very Sensitive, Easy, Intuitive	Passive works with Dynamic Circuits, Intuitive, Easy	Fine Resolution, Exquisite Sensitivity	Turns on Open Circuits, excites transistors, charges materials
Order	1 uA (really limited by time)	uW to mW	~uA	~?

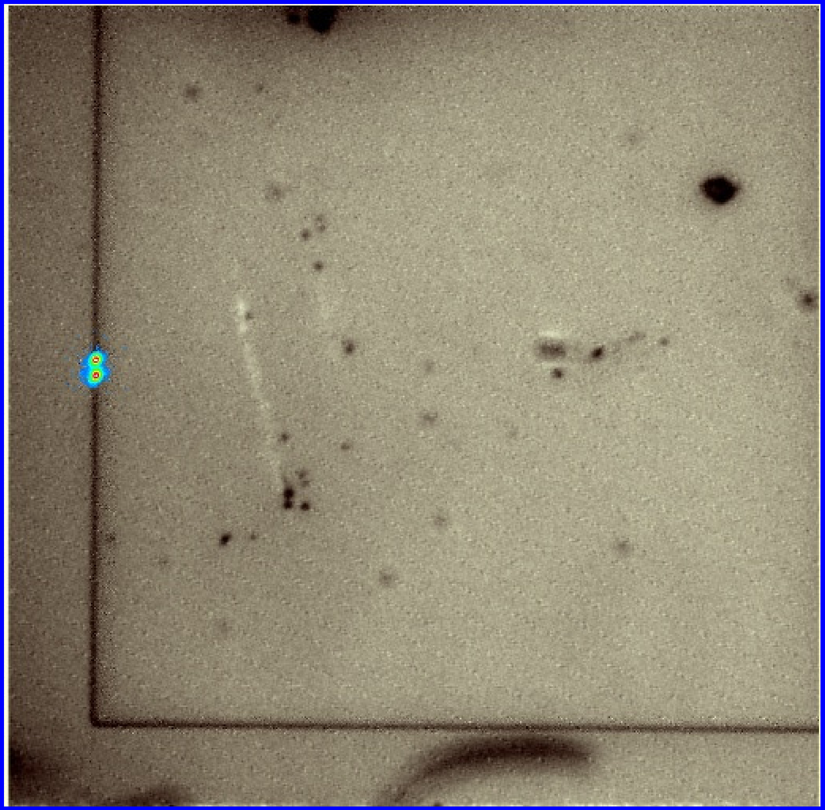
Comparing Techniques - 3 of 3

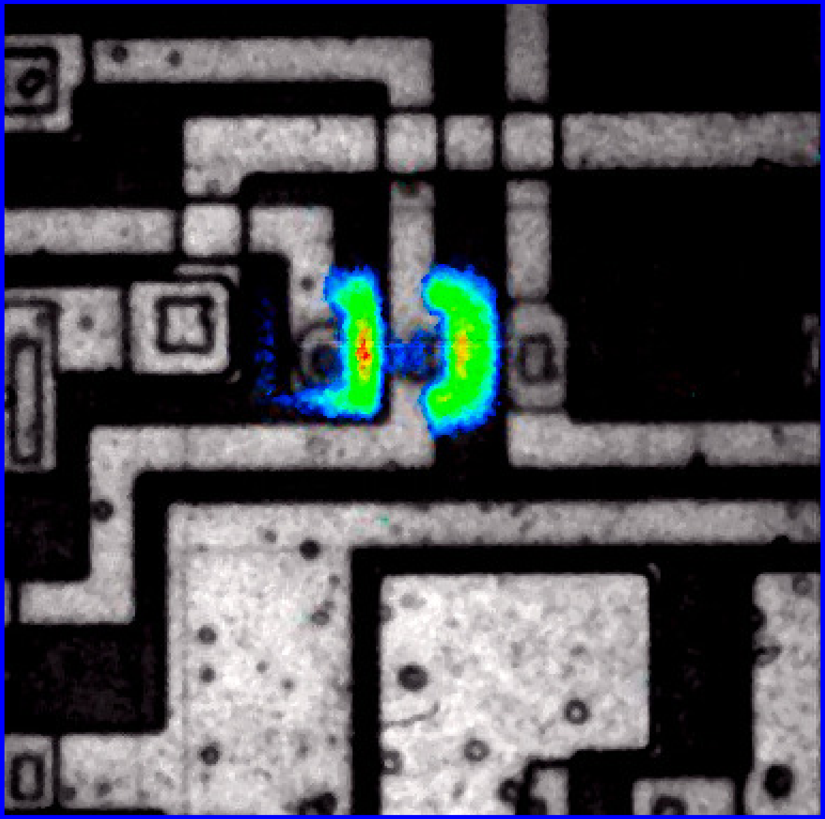
	Emmi	Thermal Infrared	Laser 1340	Laser 1064
Con	Only detects recombination events, blocked by metals or dense dopants.	Coarse Spatial Resolution, sometimes less sensitive than laser.	Slow, overwhelmed by dynamic circuits w/ charge pumps, clocks	Lights up too many things, hard to interpret

Emmi basic principles

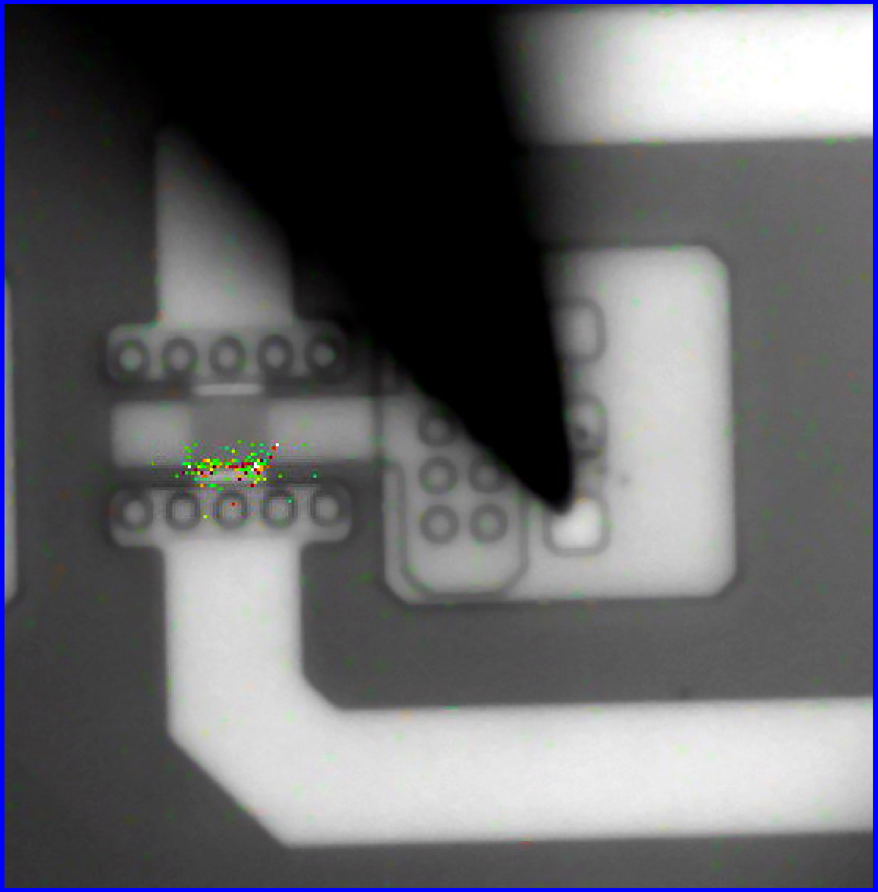
- CMOS Failure Sites often have unwanted or unexpected electron-hole recombination
- Electron-hole recombination is accompanied by weak photon emission
- Sensitive long exposure scientific cameras mounted in dark boxes can locate emission sites, saving time.
- Emissions are overlaid on reference image to register location.

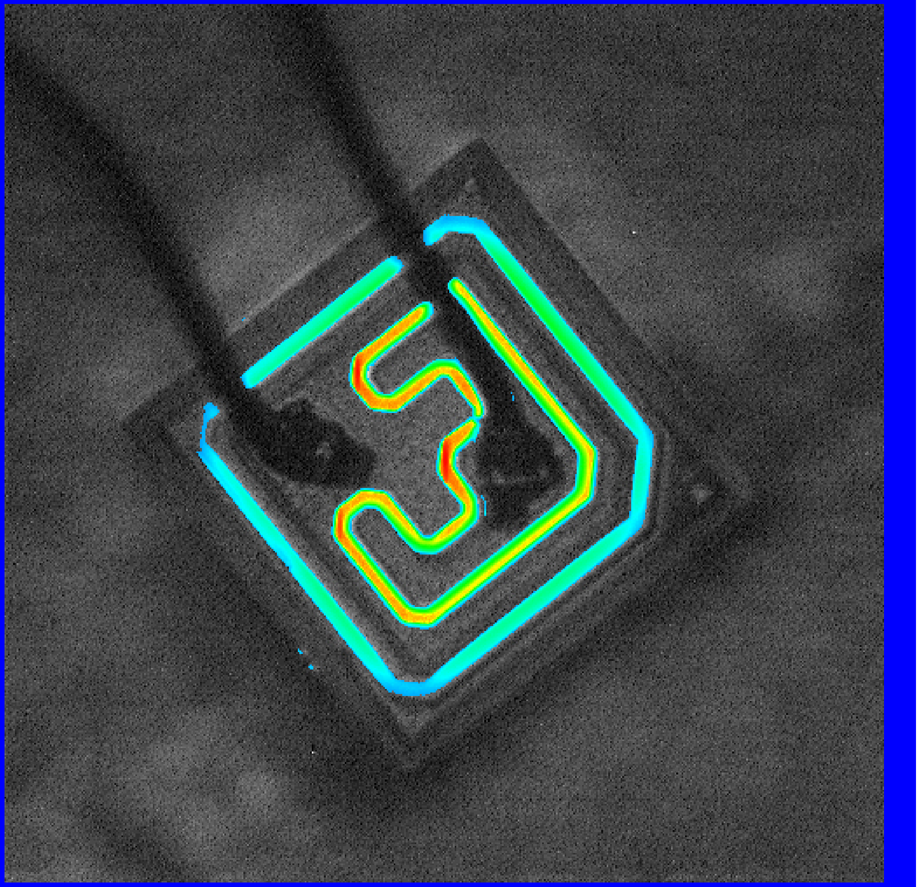
Emmi example images





Emmi example images2



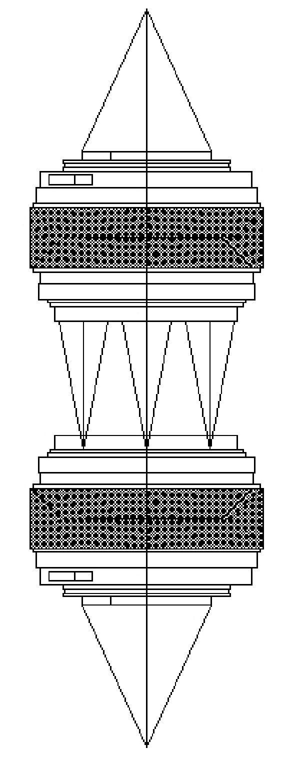


Keys to Emission Microscopy

1. Super Sensitive Scientific Cameras
   - Formerly Intensified Scientific CCDs
   - Now typically Deep Depletion Si or SWIR
2. Accurate Overlay Images
   - IC image illuminated with external light if practical.
   - Darkfield or CAD or Laser Overlay may be required
3. Super Sensitive Macros
   - 1x or 1/2x macros needed to view entire die
   - Commercial macros have e.g., N.A.=0.05 extremely poor sensitivity.
   - Custom (patented) High N.A. Macros have 50x more sensitivity.

Super Sensitive Macros

- Problem: 1x lenses naturally need equal front and back focal lengths.
- This is difficult for commercial lens sets with common par-focal lengths.
- Resulting commercial macros are compromised with very low NA, giving poor sensitivity.
- Original Intel / KLA patents describe “2 lens” technique for super sensitive emmi macro.

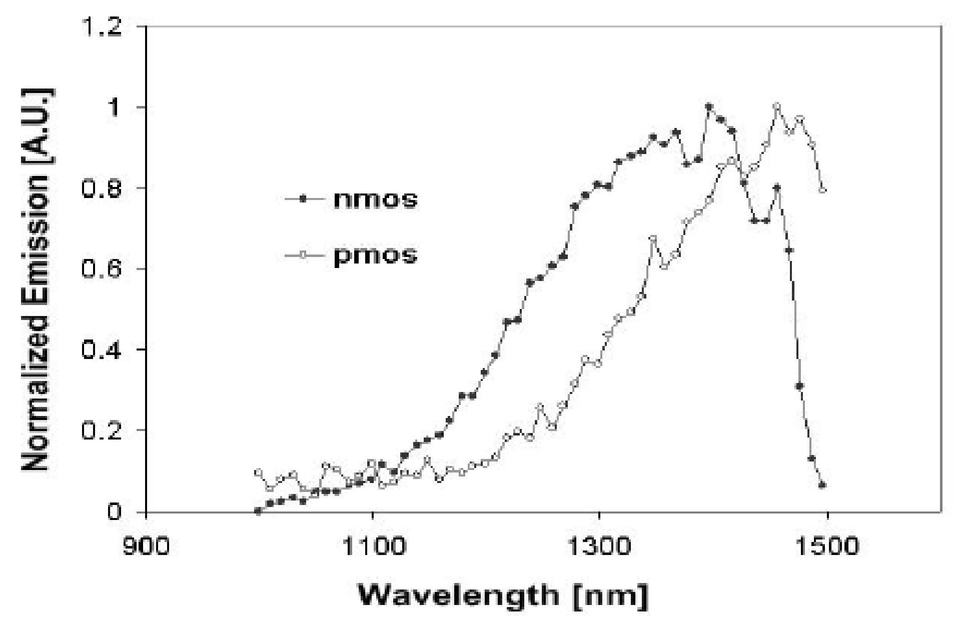


High NA Macro Pair

50x more sensitive than commercial macros

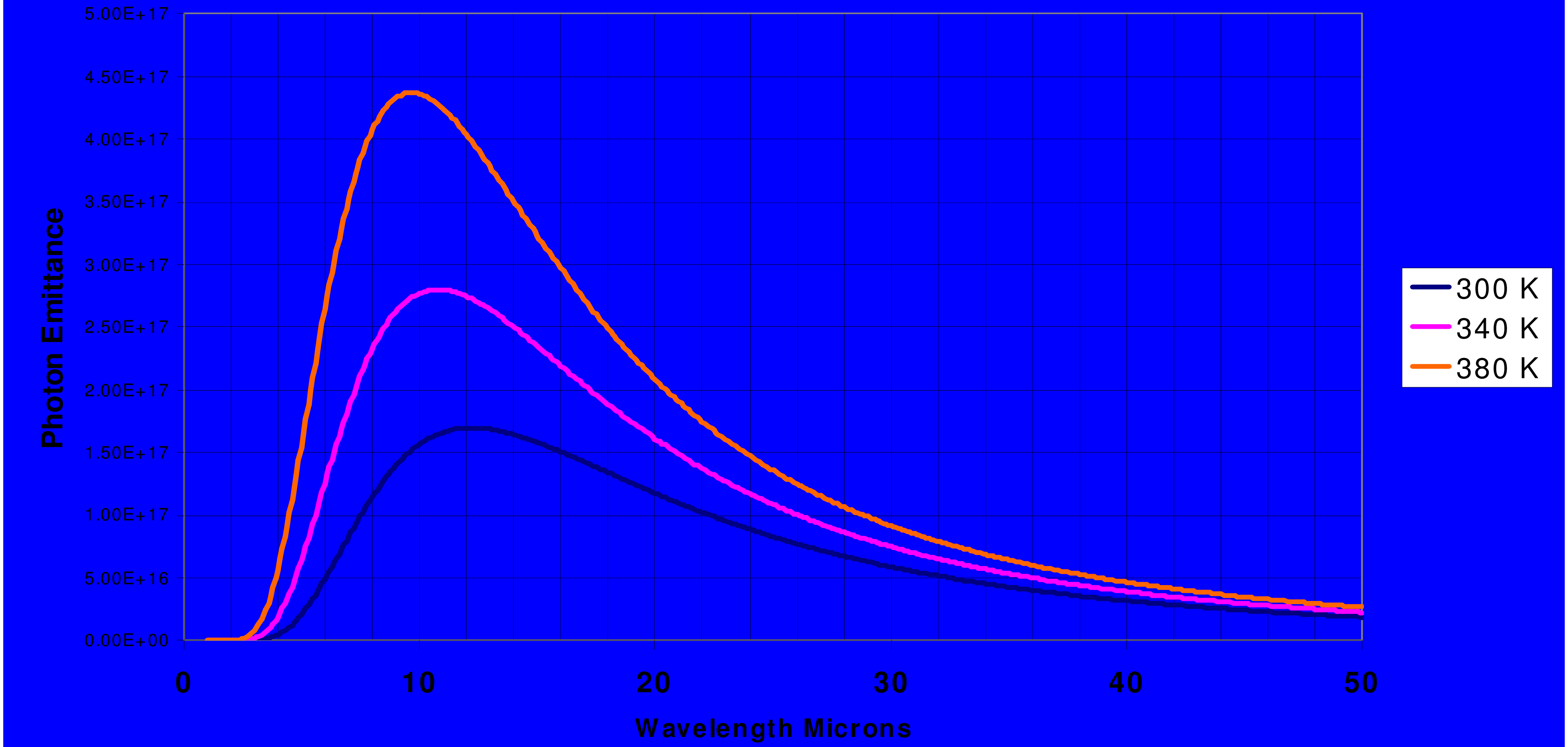
Emission Spectrum Questions

- There is very little published data on emission spectra.
- This Intel Paper on TRE data suggests that emissions increase to instrument cut-off.
- Is this Blackbody radiation?



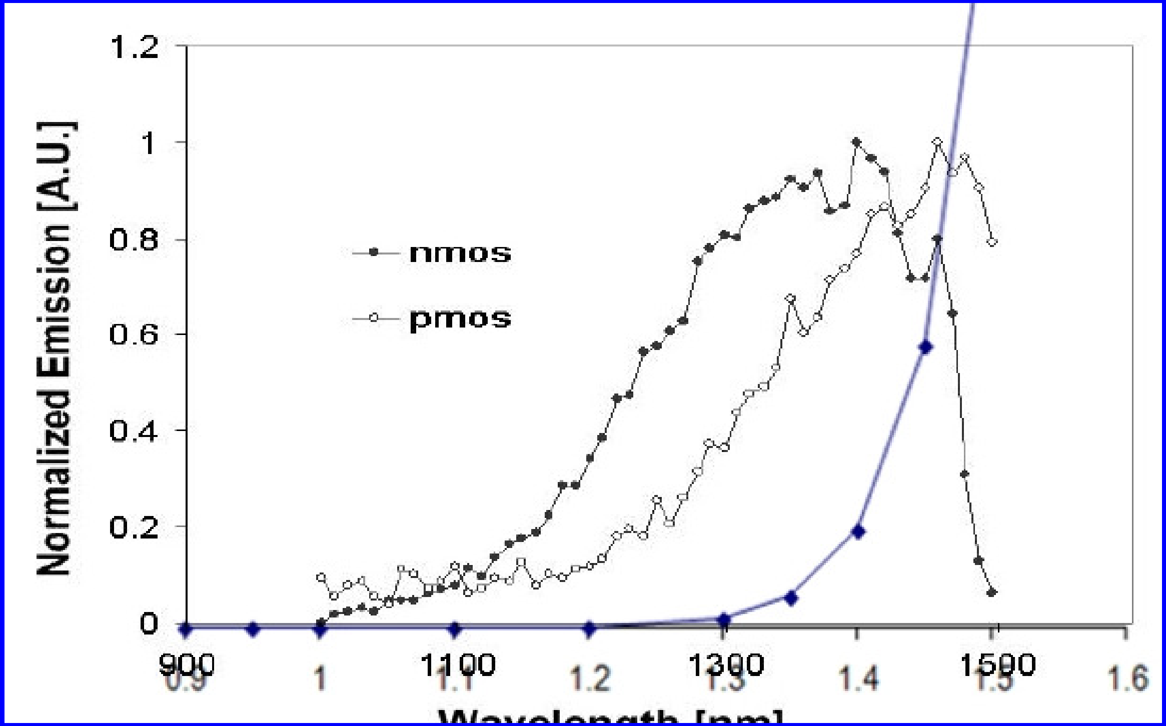
From J. Rowlette, E. Varner, S. Seidel, ‘*Hot Carrier Emission from 50 nm n and p-Channel MOSFET Devices” Conference on Lasers & Electro-Optics,(LEOS) 2003.*

Blackbody Radiation



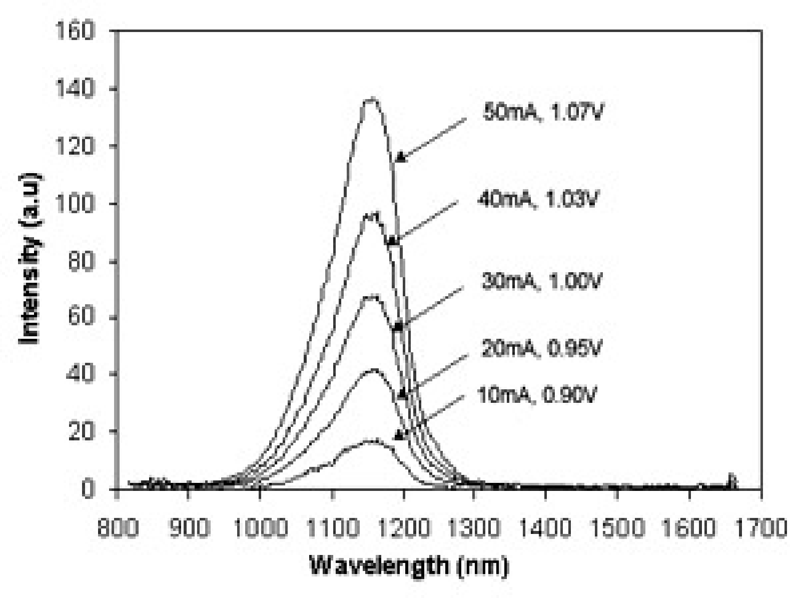
Rowlette Data with Blackbody

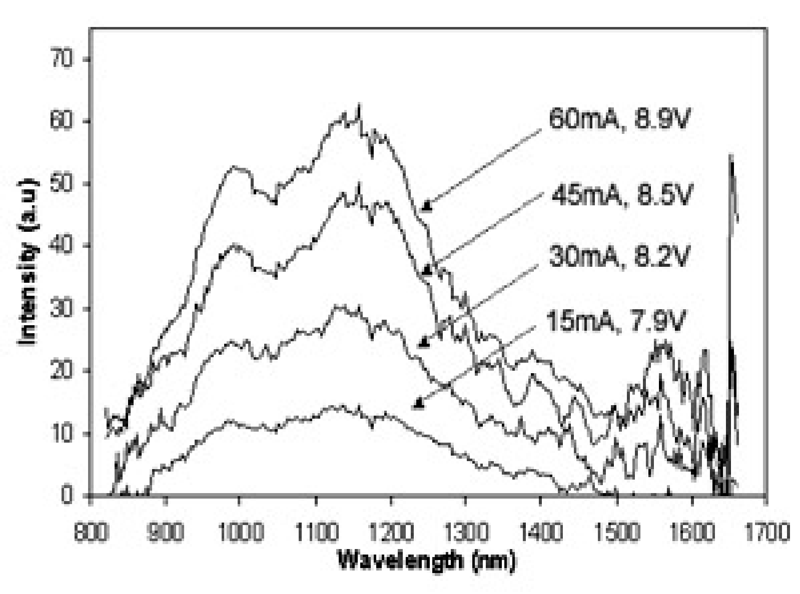
This superposition of 300K BB curve on the data makes one wonder if these otherwise good FETs are comparable to failures and oxide leaks.



National U. of Singapore Data

Spectrum from Len et. al. ISTFA 2003 suggests alternate peak nearer band gap.

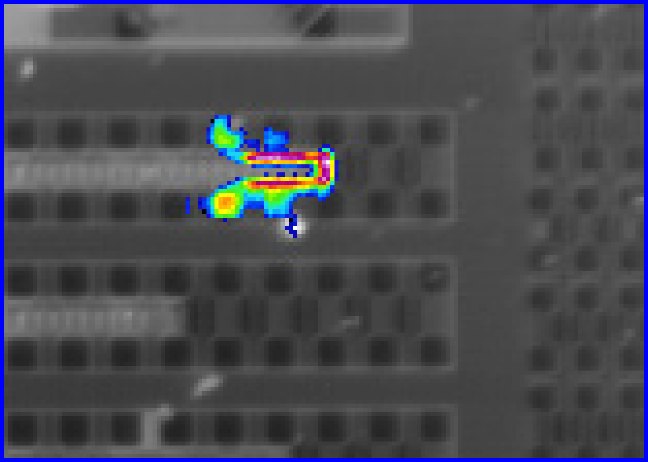




Ideal emmi Detector?

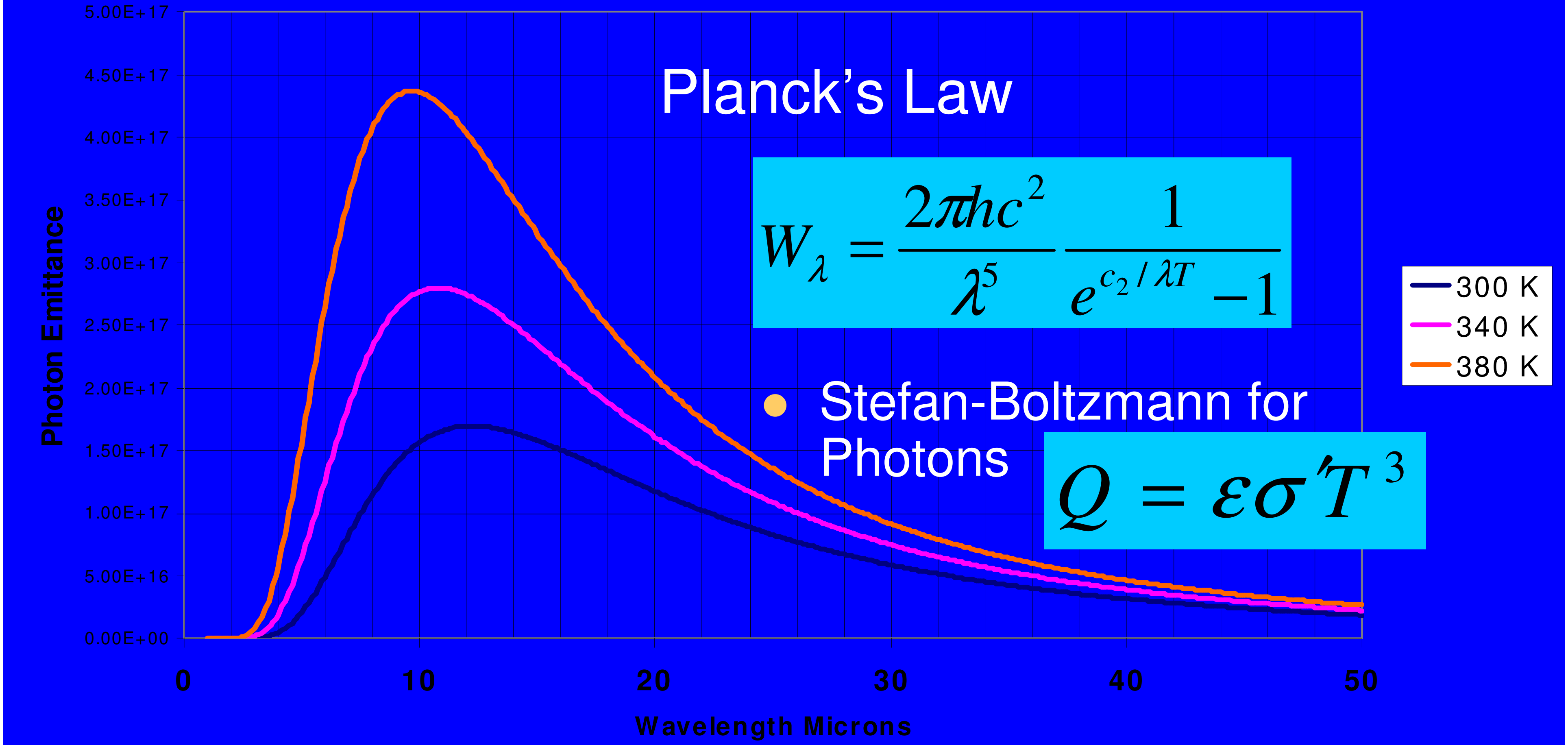
- Author’s experience suggests that SWIR may not be ideal, too much thermal response, thermal shot noise and pixel non-uniformity spoils the S/N.
- Newer deep depletion Si technology generally performs better except for rare emissions which are visible only to SWIR detectors.
- An ideal but unavailable emission detector probably extends beyond Si bandgap, but perhaps only to 1.2 or 1.3um.

Thermal Infrared Microscopy



- Locate shorts or Ohmic Current Leaks from the Front or Backside
- (See Brietenstein for Lock-In Thermography)

Blackbody Radiation



Planck's Law

$$W_\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{c_2/\lambda T}-1}$$

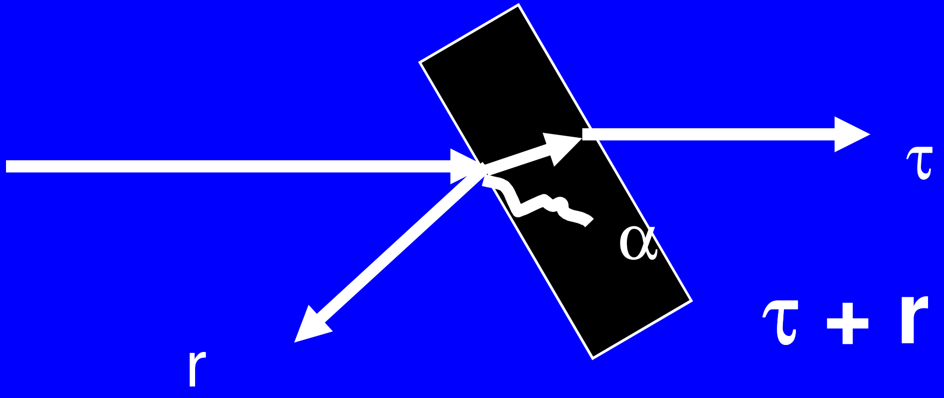
- Stefan-Boltzmann for Photons

$$Q = \varepsilon\sigma' T^3$$

Kirchhoff’s Law

- Conservation of Energy requires :

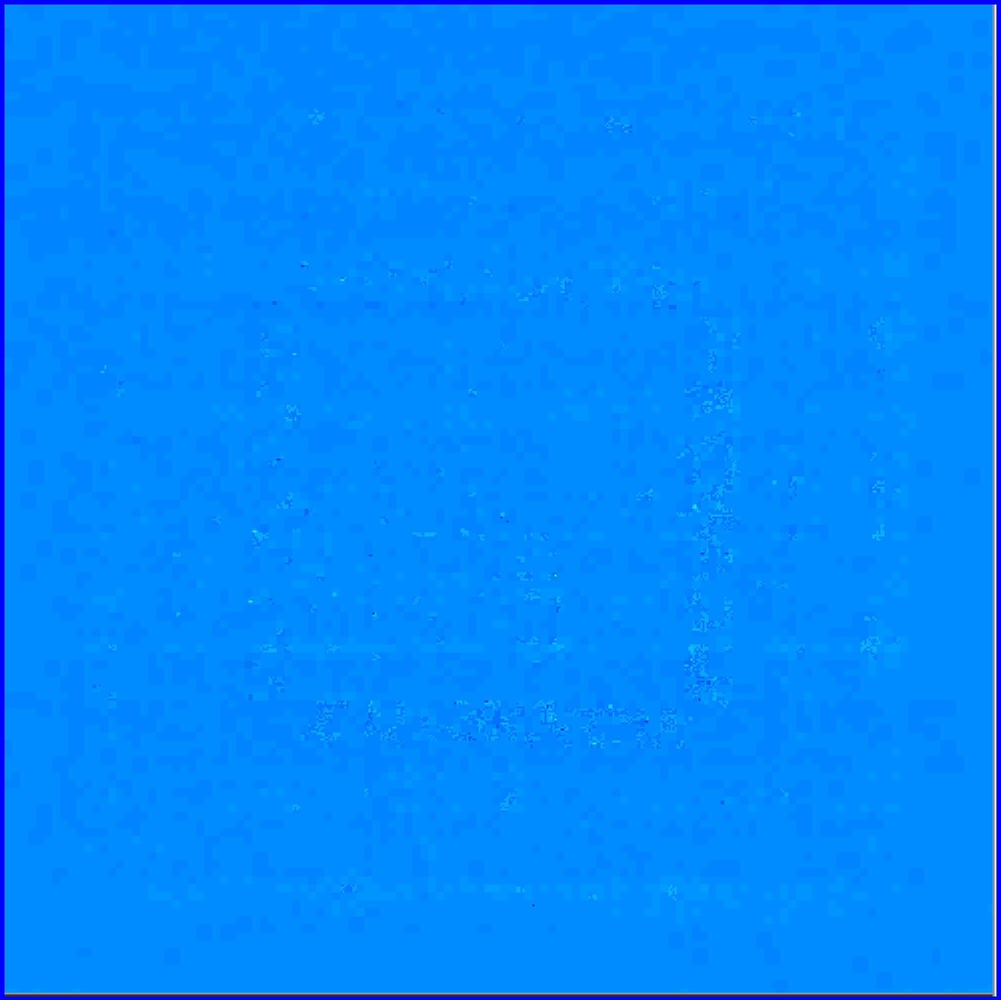
reflectivity + transmisivity + absorptivity = unity



$$\tau + r + \alpha = 1$$

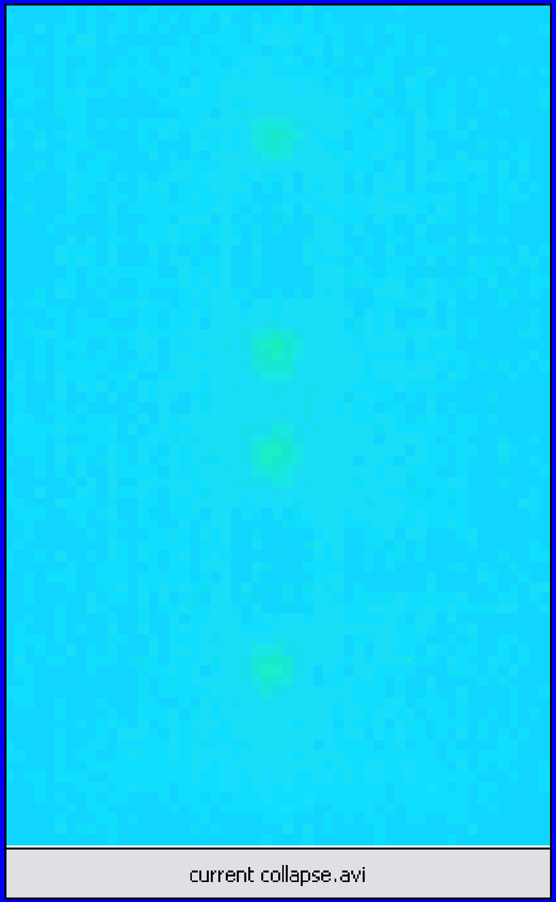
- absorptivity = emissivity ($\alpha = \varepsilon$)
- and $\alpha_\lambda = \varepsilon_\lambda$

Thermal IR Movie of Failure



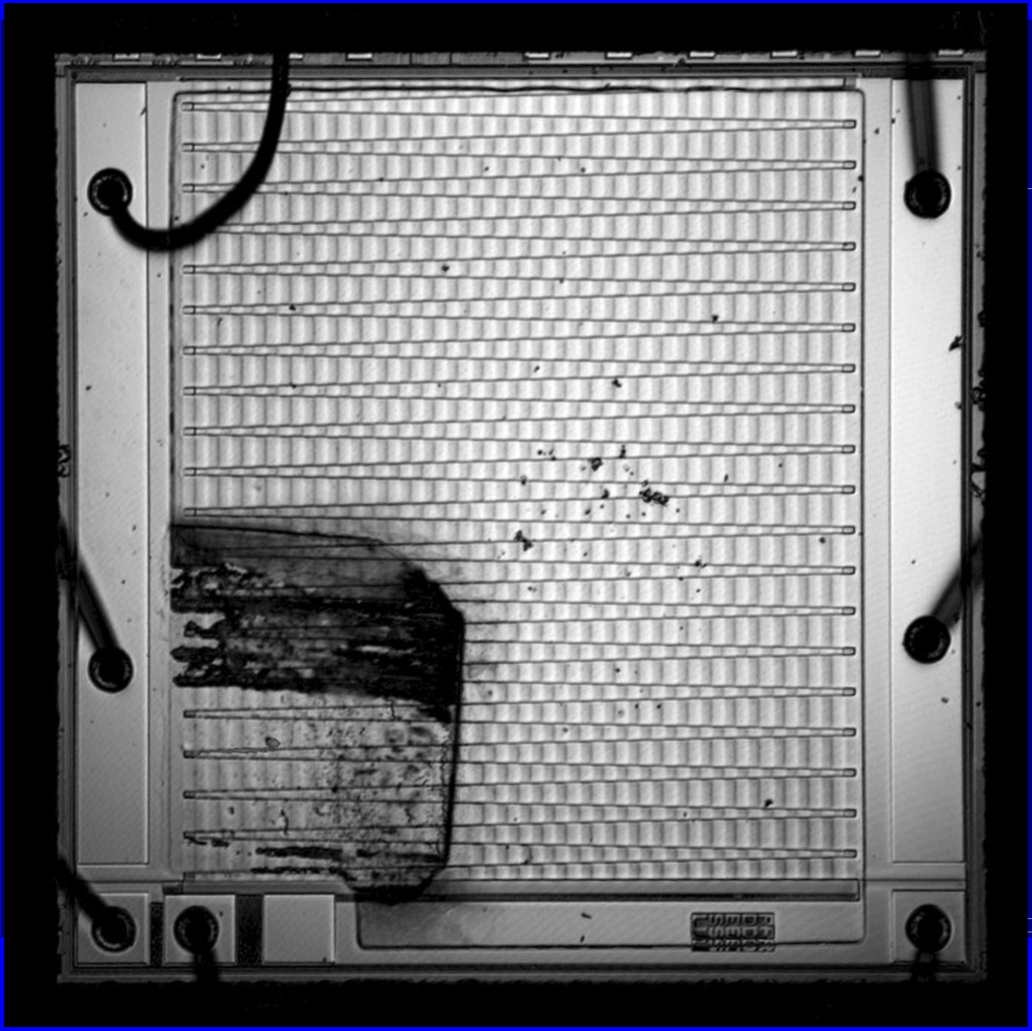
Thermal IR Movie of Current Collapse

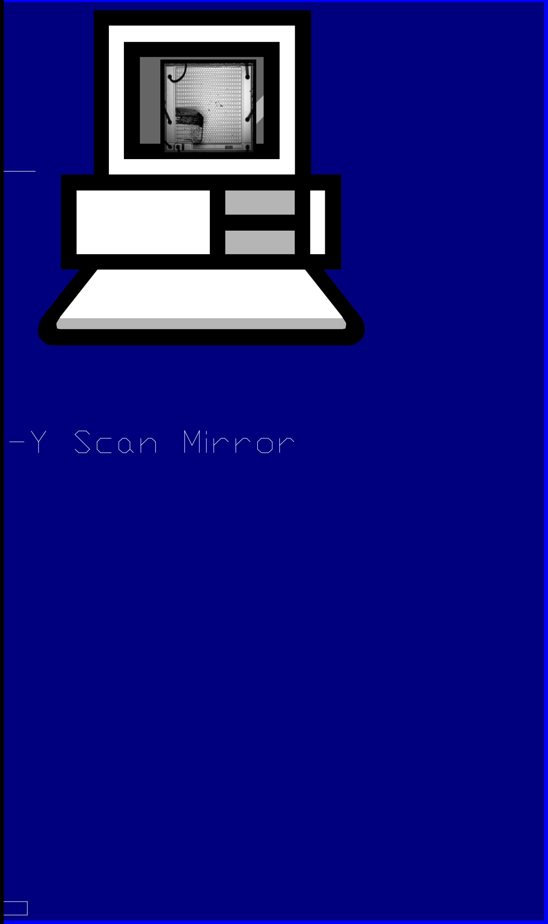
- RFIC Failure – at a critical power level 1 amplifier hogs all the current.



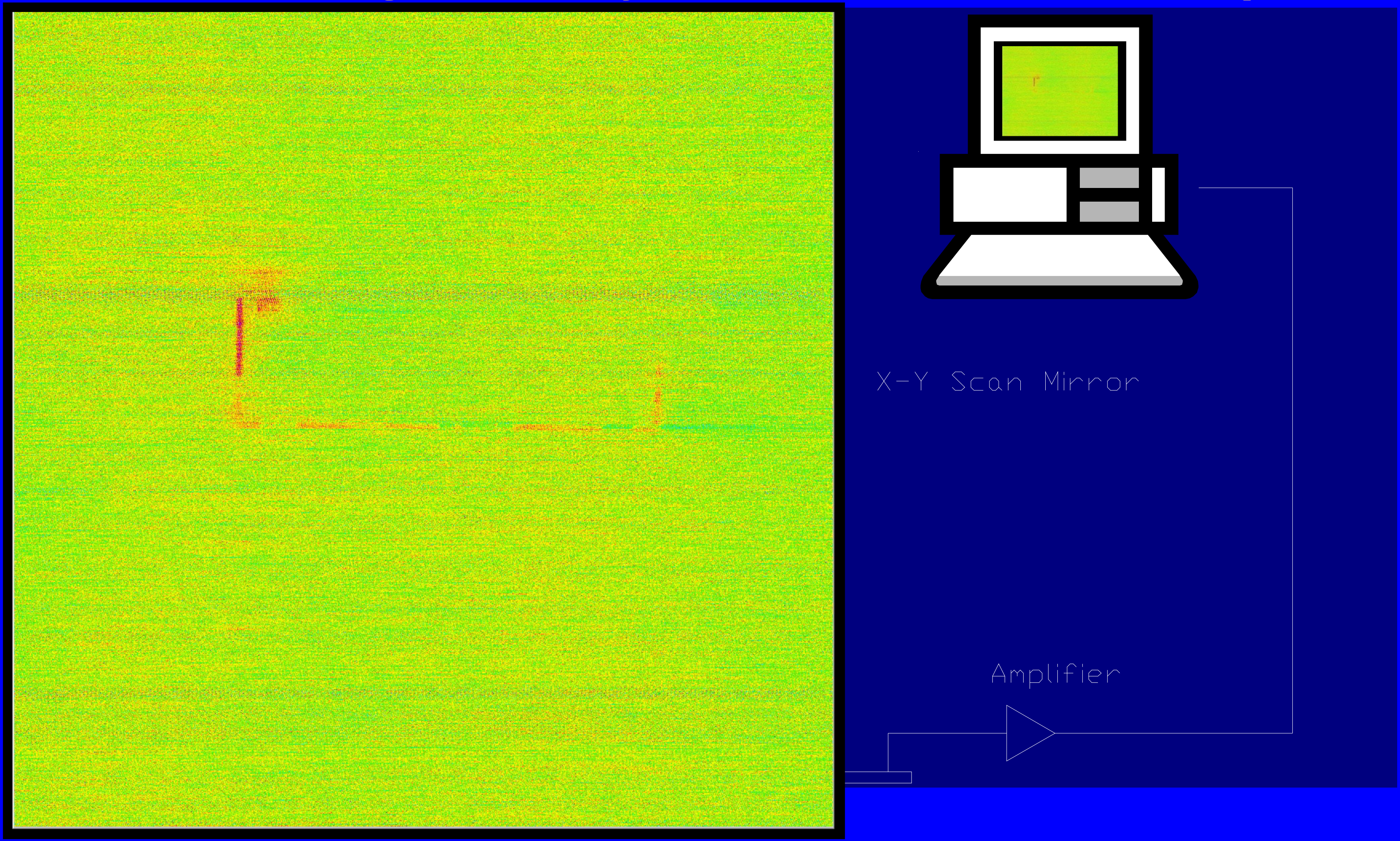
Laser FA Microscopy

Laser Scanning Microscope

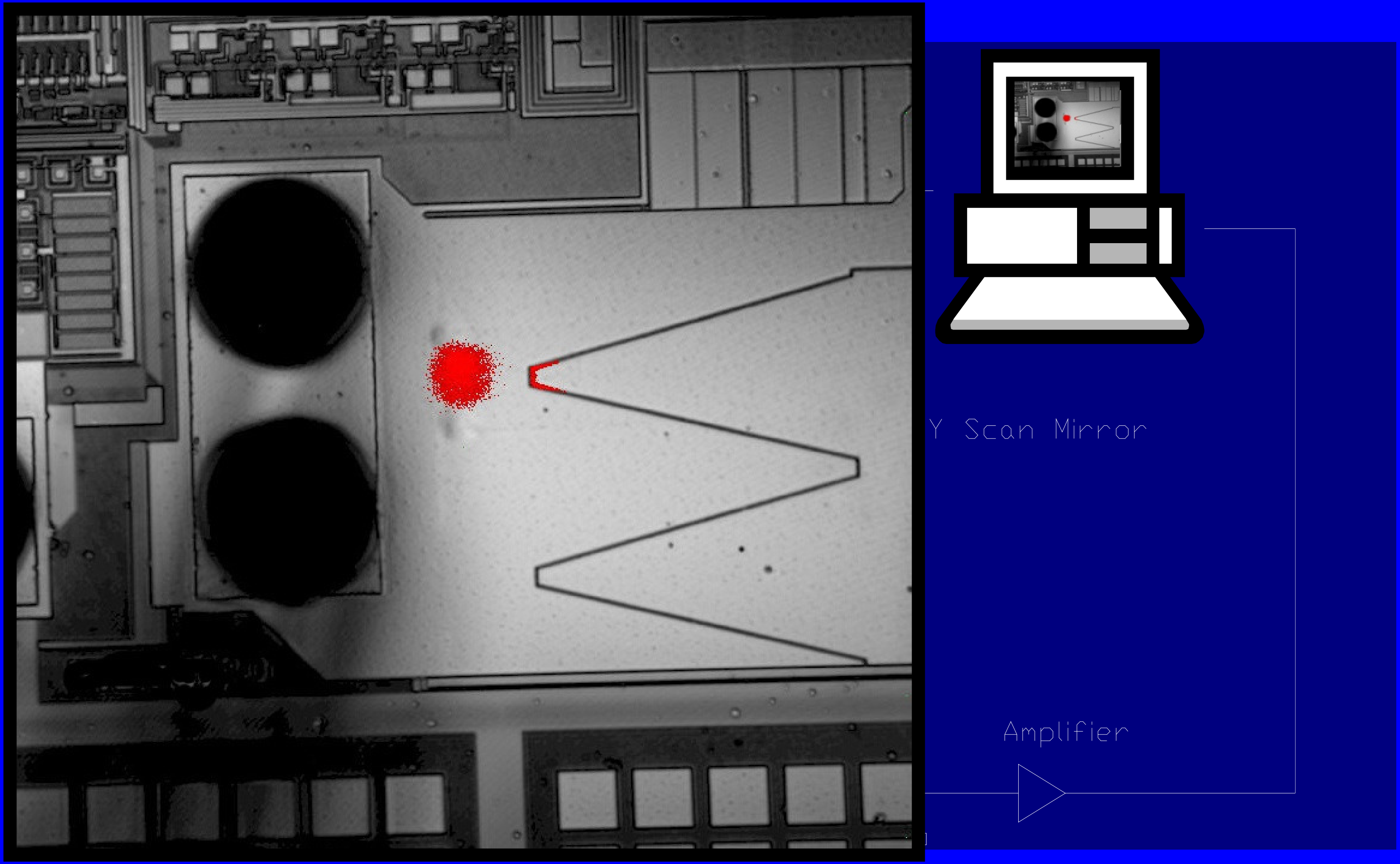




Laser Signal Injection Microscope

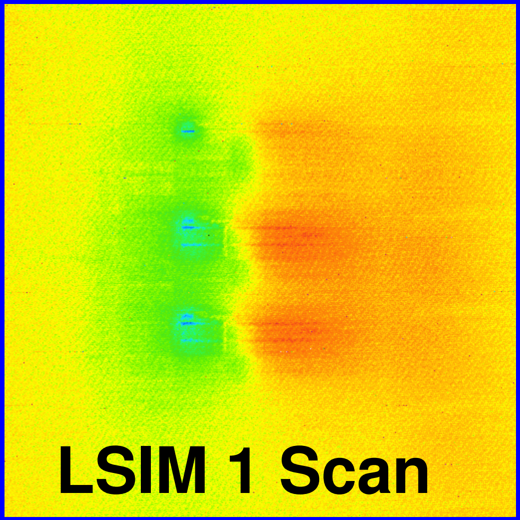


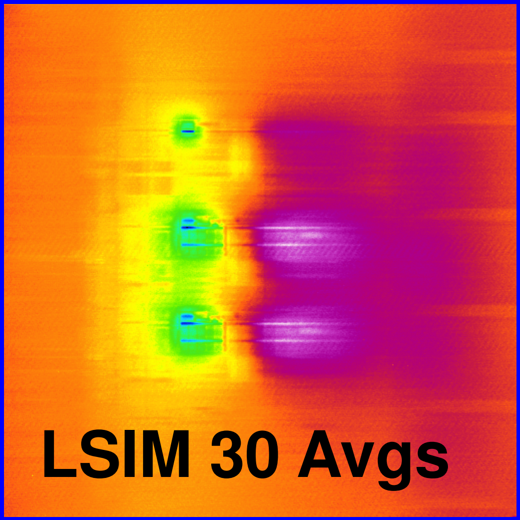
Combination LSM & LSIM

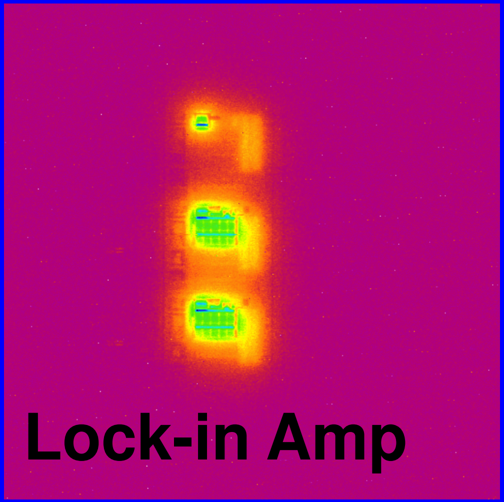


Lock In Amplifier Improvement

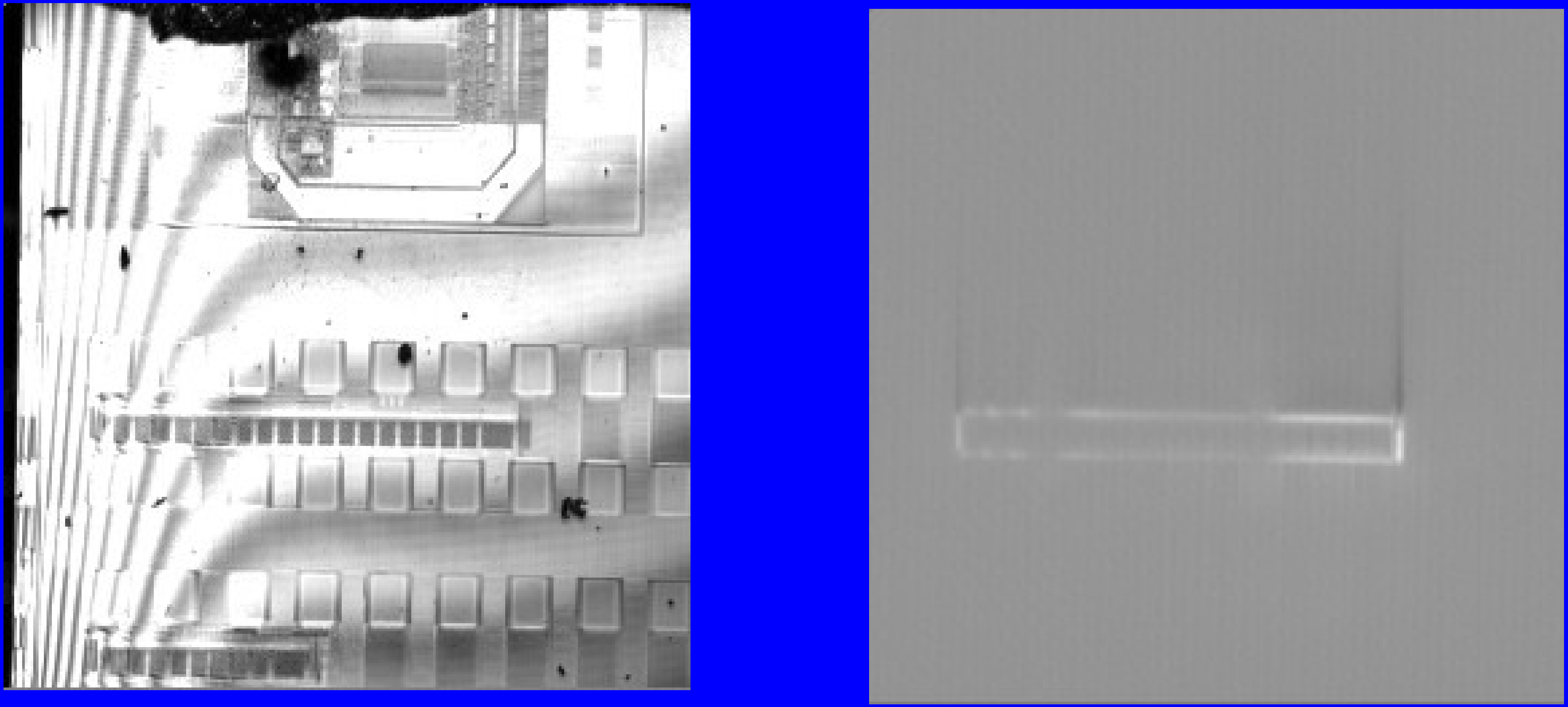
Chopping the laser and running the signal through a lock-in amplifier gives impressive S/N improvement.


LSIM 1 Scan


LSIM 30 Avgs


Lock-in Amp

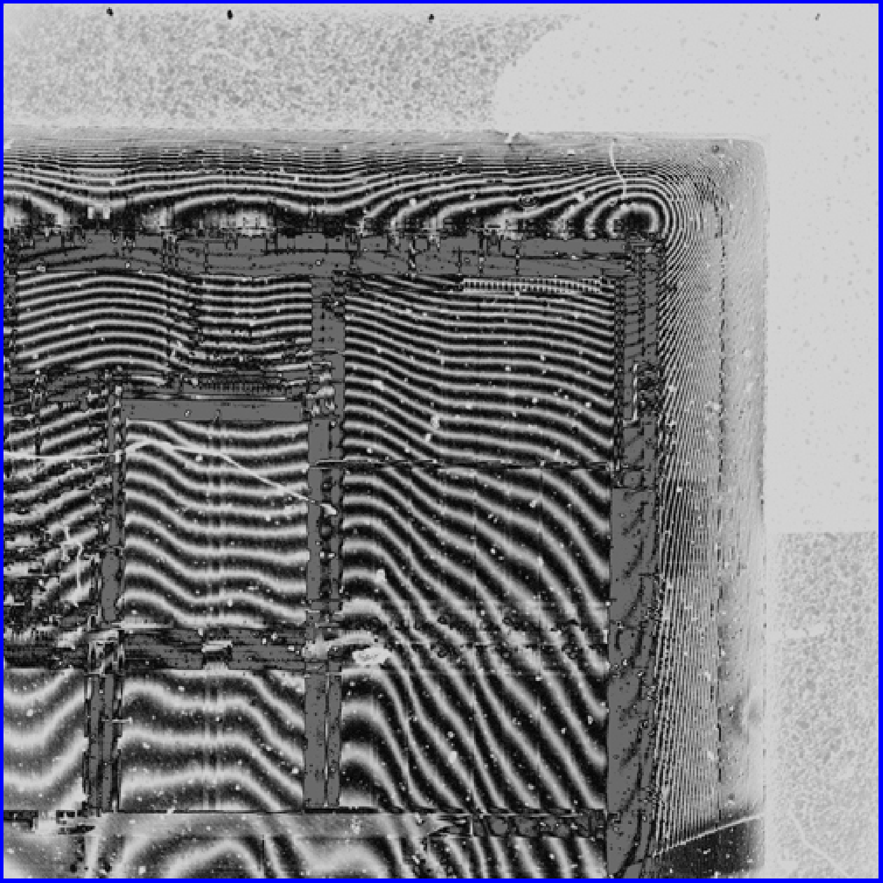
Backside LSIM Example



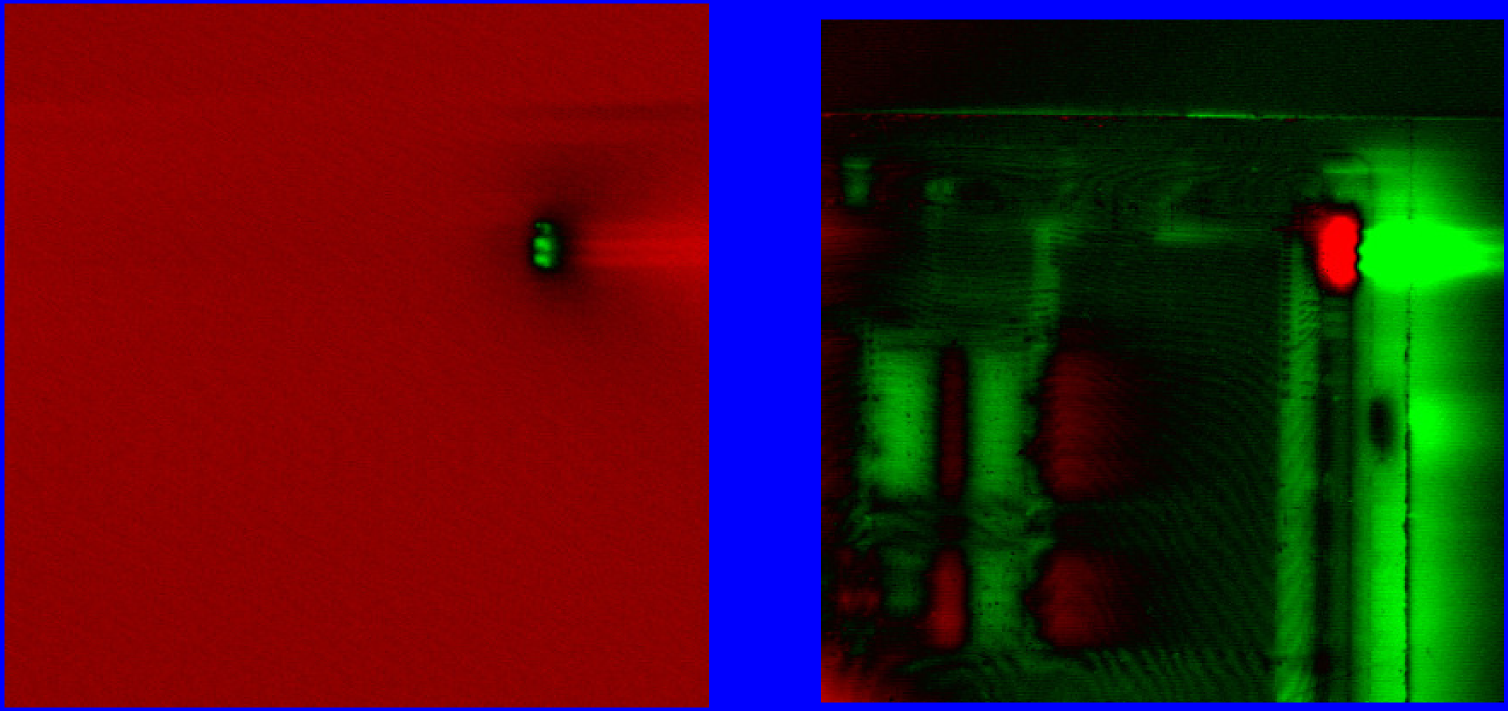
Sample courtesy of Martijn Goossens and Victor Zieren, Philips Research Labs, Eindhoven. LSIM images courtesy OptoMetrix, Seattle. Magnification 10x, I=46 mA

LSIM Images May Be Fringed

- Reflections from front and back surface may interfere creating Newton’s Rings.
- Mitigate with careful polishing or AR coatings.



Fwd Bias Diode: 1340 vs 1064



- 1340nm on Left, 1064nm on Right
- Micro Local Heating Left versus Carrier Injection Right
- Same conditions, same part as previous slide

Supplement

- Time doesn’t permit discussing every topic.
- The material after this slide, though not discussed in the seminar, may be useful.

Illumination Topics

- Introduce Collimated Light
- Conjugate Planes
- Field Planes
- Koehler Illumination
- DarkField / Brightfield

Illumination Terms

- Transmitted
- Epi

Next Slides

- Koehler
- Brightfield
- Darkfield

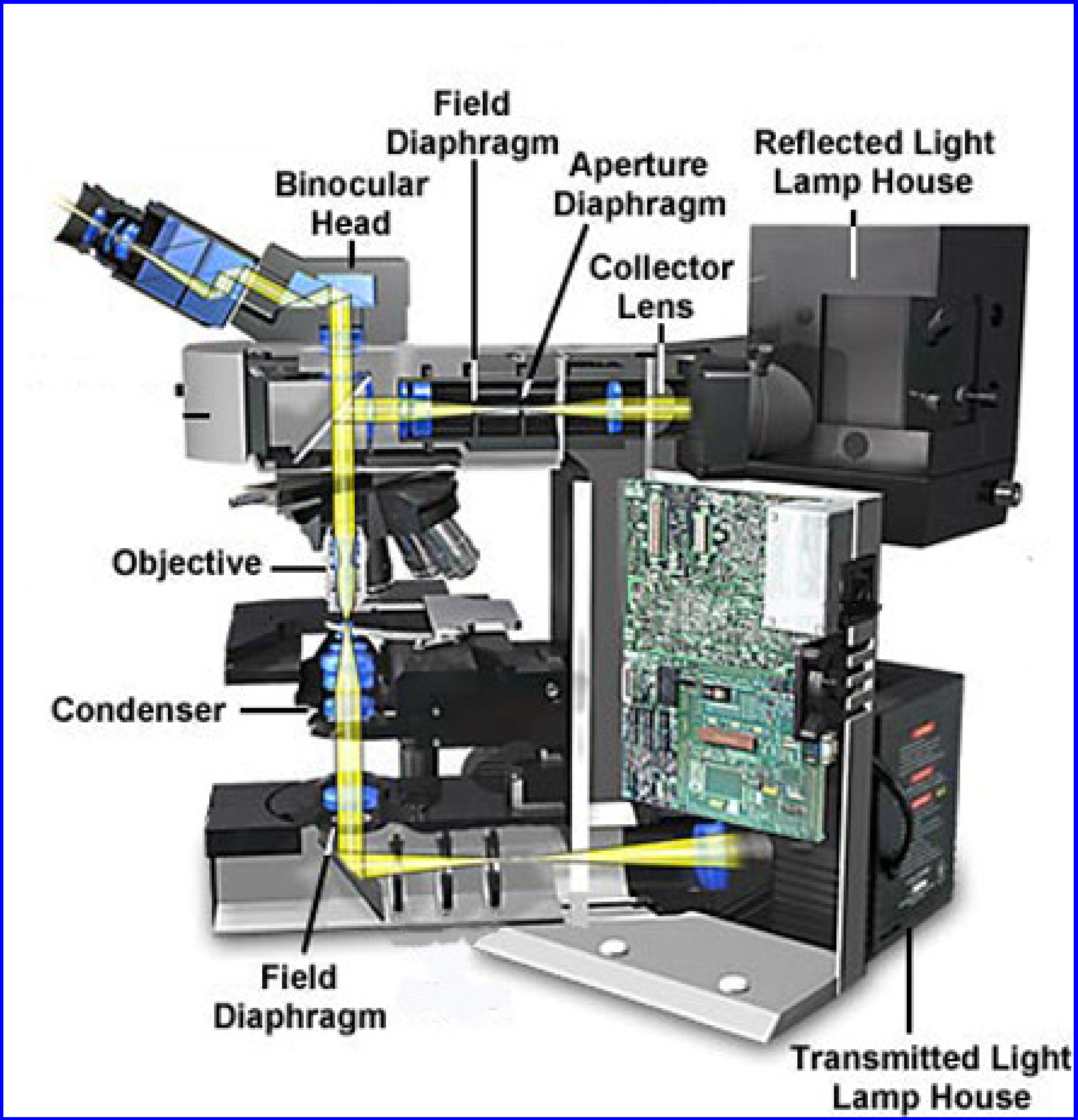
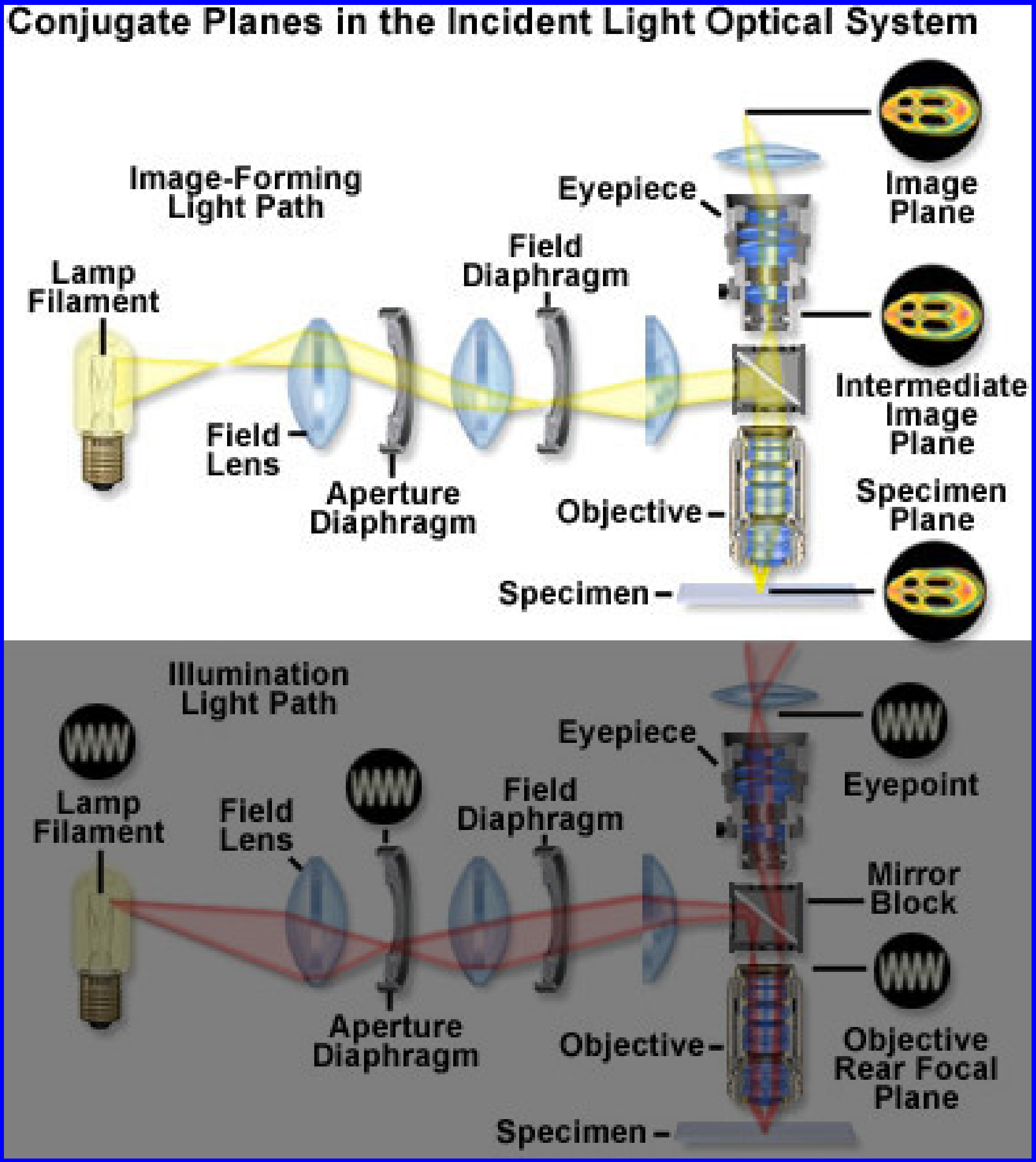


Image courtesy
www.molecularexpressions.com

Conjugate Planes

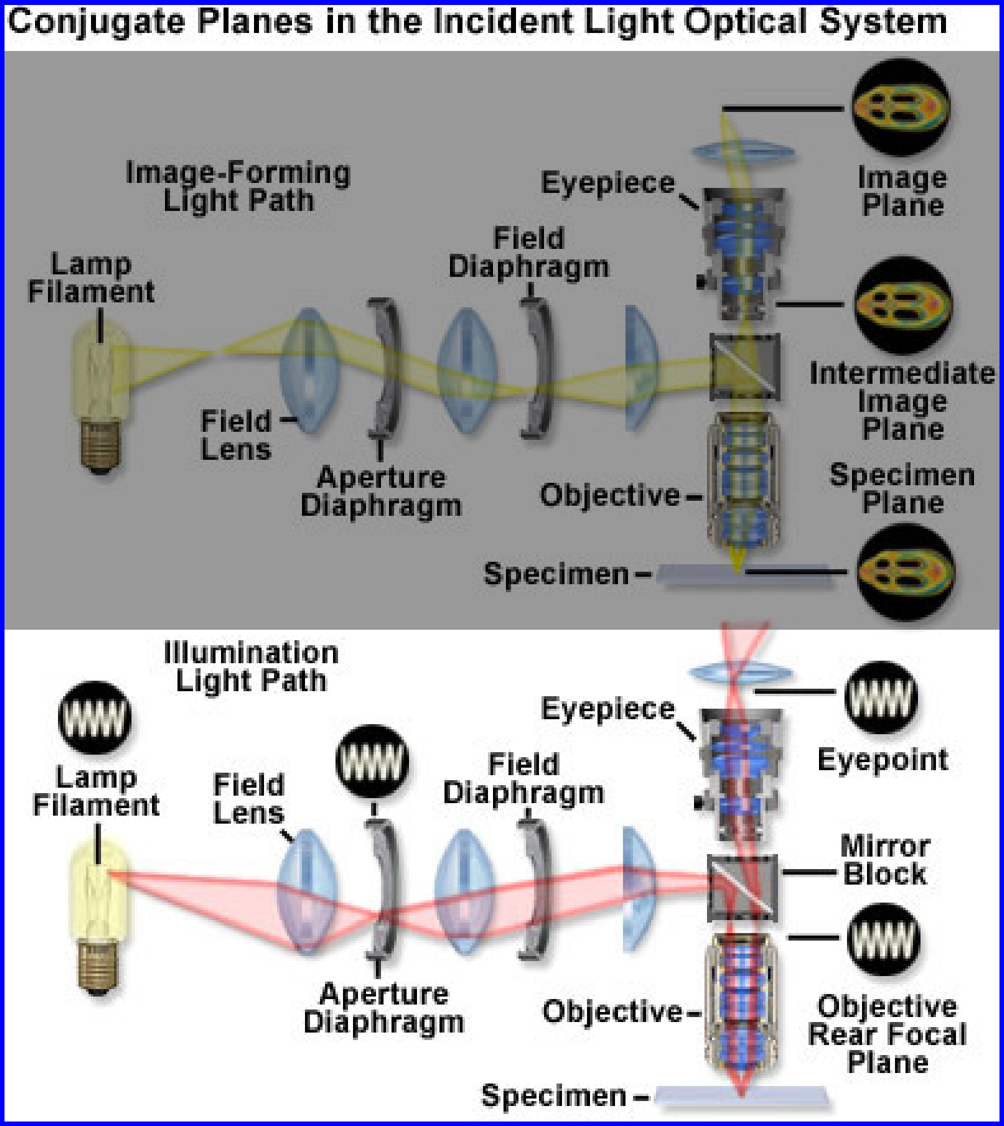
- Certain Planes in the Microscope repeat or copy, known as Conjugates.
- Field planes include the sample plane, and real & virtual images of the sample.



By permission from www.molecularexpressions.com

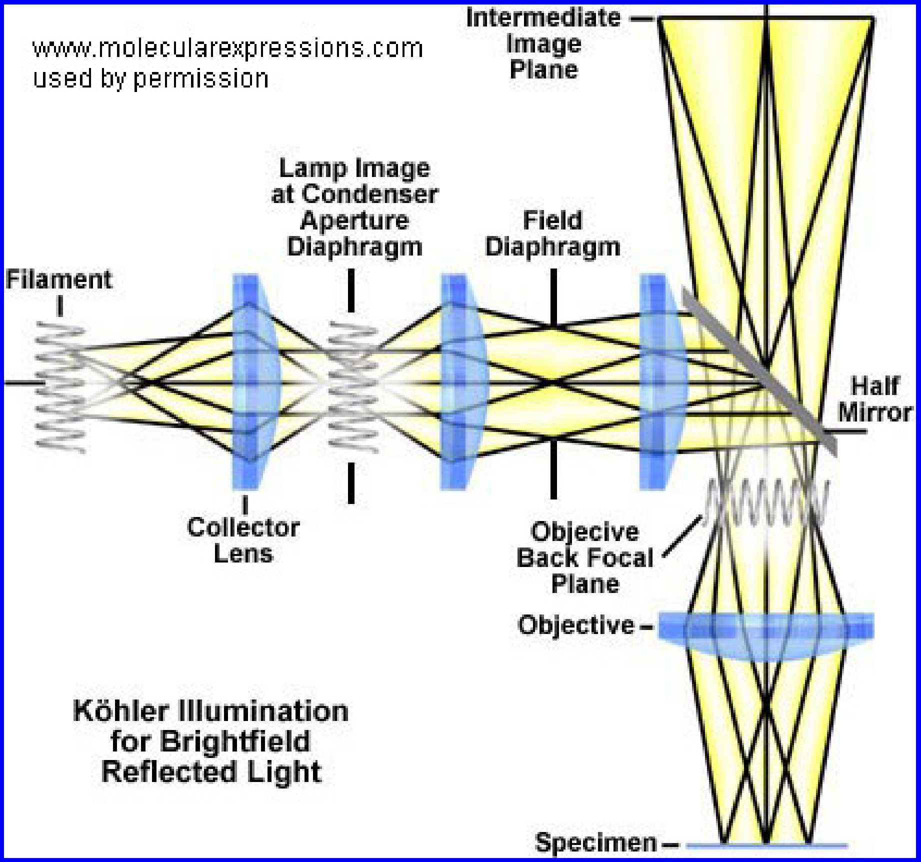
Aperture Planes

- Aperture Planes are the Fourier Transforms of the field planes.
- Aperture planes control the numerical aperture of the rays.
- Aperture planes are important for Koehler illumination.



Koehler Illumination

- Koehler Illumination deliberately places an image of the lamp filament at the aperture plane.
- The Filament image becomes perfectly collimated, diffuse, de-focused, and uniform at the sample plane.



Calculating Useful Magnification for a “Normal” Human Eye

- A standard eye resolves 75 microns at 250 mm distance, or 1 arc minute.
- For this example, consider an objective that resolves 0.5 microns (NA/0.5, visible light, typical for 50x objective).
- Calculate magnification required to enlarge spot to cover 2 eye elements (Nyquist Sampling).

$$Mag = \frac{2(resolution\_element)}{objective\_resolution} = \frac{2(75um)}{0.5um} = 300x$$

Eye Magnification Example Cont.

- From the previous slide, we need 300x magnification for a NA/0.5 objective.
- For a typical 10x eyepiece, we require a 30x objective to match the “normal” eye to a NA/0.5 objective.
- Our example 50x objective, coupled with 10x eyepiece yields 500x total magnification.
- The extra 200x is “Empty Magnification”.
- (Some of us do not have so young eyes, and make good use of the extra 200x.)

Additional Resources

- Optics – Hecht (excellent survey of optics)
- Video Microscopy – Shinya Inoue
- LSIM – www.optomet.com (good tutorial material on site)
- General Light Microscopy - http://www.microscopy.fsu.edu/ (outstanding tutorial website, really good)
- InfraRed Imaging – InfraRed Handbook, George J. Zissis (Editor),(borrow it: 1,700 pages, $480 used)

Additional Resources – 2

- Light Microscopy – Photography through the Microscope published by Kodak. Inexpensive, excellent basics incl. Equations.
- Theoretical Considerations for Si emission spectra:
  1. Bude et. al., Hot Carrier Luminescence in Silicon, Physical Reviews B, March 1992, Vol 45, #11.
  2. Wagner, Photoluminescence and Excitation Spectroscopy…in doped N and P silicon, Physical Review B, February 1984, Vol 29 #4

Referenced Papers 1

SIL Lens	1.S. B. Ippolito, et.al, "High Resolution Subsurface Microscopy Technique," Proceedings of IEEE Lasers and Electro-Optics Society 2000 Annual Meeting, Vol. 2, 13-16 November 2000, pp. 430-431
FOSSIL SIL Lens	T. Koyama, et.al.,: “*High Resolution Backside Fault Isolation Technique Using Directly Forming Si Substrate into Solid Immersion Lens*,” (IRPS), 2003, pp. 529-35
PEM emission spectrum	J. Rowlette, et.al., ‘*Hot Carrier Emission from 50 nm n and p-Channel MOSFET Devices” Conference on Lasers & Electro-Optics,(LEOS) 2003*
	Len, et. al., “*Near IR Continuous Wavelength Spectroscopy of Photon Emissions from Semiconductor Devices*” National University of Singapore, 29th ISTFA 2003.

Referenced Papers 2

Doped Si Absorption	R. A. Falk, "*Near IR Absorption in Heavily Doped Silicon - An Empirical Approach*", Proceedings of the 26th ISTFA, 2000
Silicon Fresnel lens Illustration	Brian Morgan, et. al. "*Development of a Deep Silicon Phase Fresnel Lens Using Gray-Scale Lithography and Deep Reactive Ion Etching*" JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 13, NO. 1, FEB 2004
Silicon Diffractive SIL lens	Frank Zachariasse, Martijn Goossens Philips, "*Diffractive Lenses for High Resolution Laser Based Failure Analysis*" Proceedings of the 31 International Symposium for Testing and Failure Analysis (ISTFA 2005) Nov 6–10, 2005, San Jose, California