IEEE LEOS LASERS & ELECTRO-OPTICS SOCIETY

# Nanoscale Imaging of Semiconductor and Biological Systems

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CENTER FOR NANOSCIENCE AND NANOBIOTECHNOLOGY

LEOS DL Talk – 1 2005

## Outline

- Nano-Optics – Aperture NSOM
  - Earlier results (brief)
- Solid Immersion Lens Microscopy
  - Numerical Aperture Increasing Lens (NAIL)
  - Applications in IC imaging, thermal microscopy
  - Quantum Dot Spectroscopy
- Spectral Self-interference Microscopy
  - Preliminary results on lipid bilayers
  - DNA conformation studies

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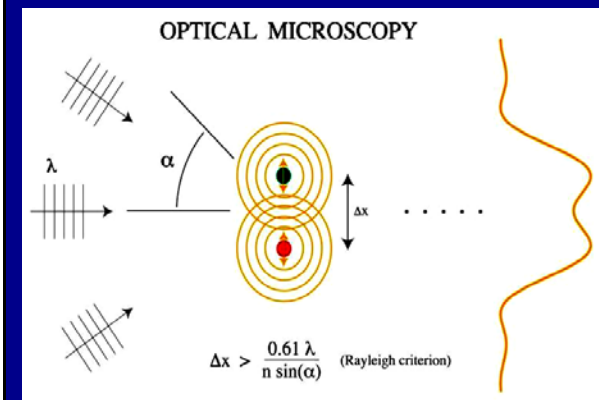
## Motivation: Resolution Limitation in Optics




$$\mathrm{NA} = n \sin \alpha$$

$$f_{\#} = \frac{f}{2w_{01}}$$

$$spotsize \approx \frac{2\lambda}{\pi \mathrm{NA}} = \frac{\lambda}{n}\frac{4}{\pi} f_{\#}$$

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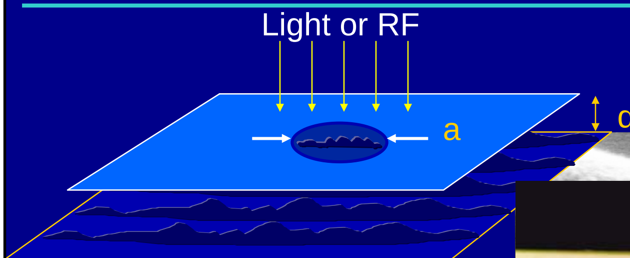
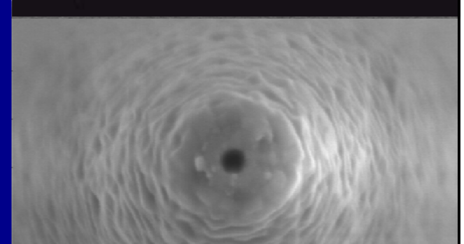
## Aperture Near-Field Microscopy







Resolution limited by *a* and *d*

Synge 1928
• concept, scanning
1970's RF metal plate

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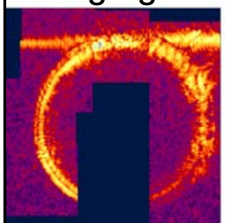
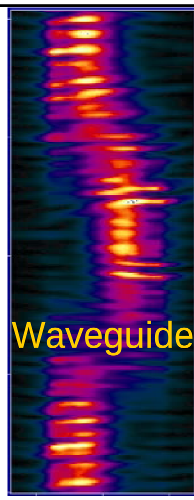
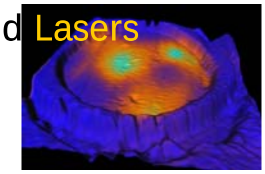
# Aperture NSOM

Imaging of PBG, Waveguide Devices and Lasers

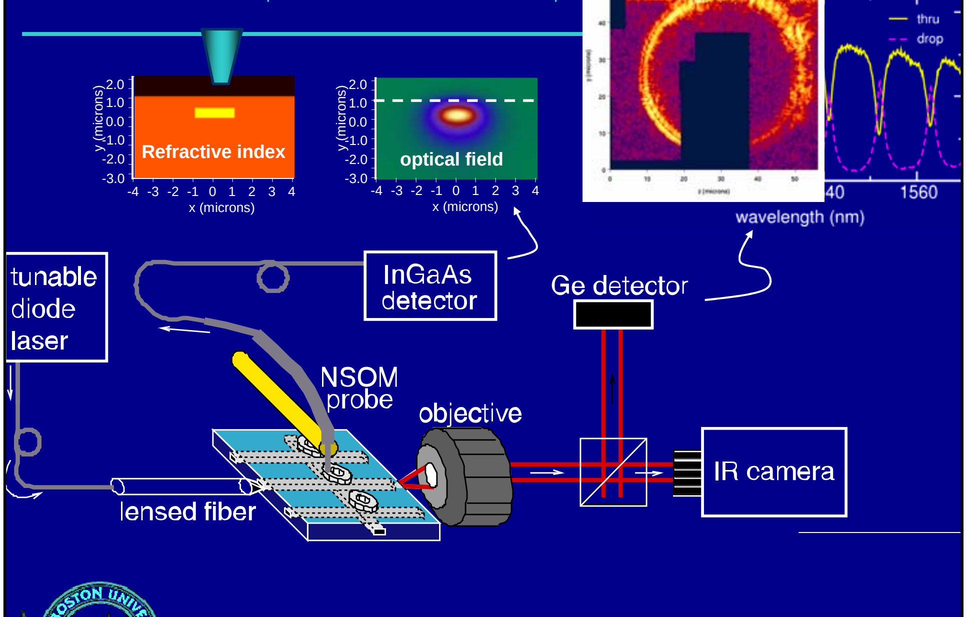






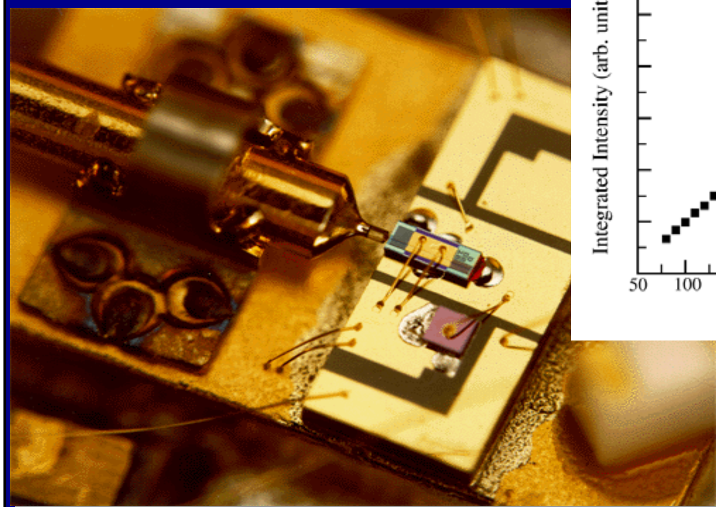


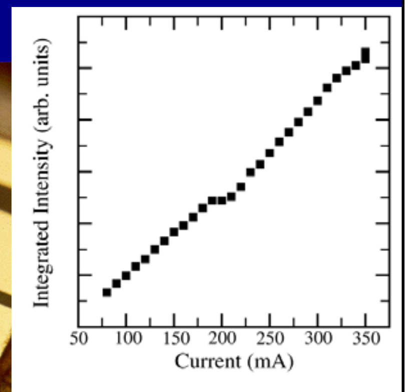
# Waveguide Experimental Setup



## Optical fiber with wedged lens and AR coating

980 nm GRINSCH LD



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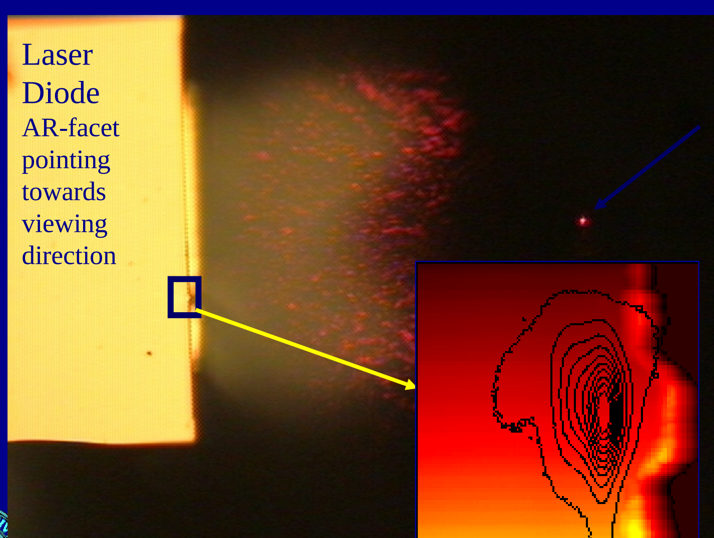
## Laser Diode Facet under 40X microscope




NSOM Probe pointing away from viewing direction

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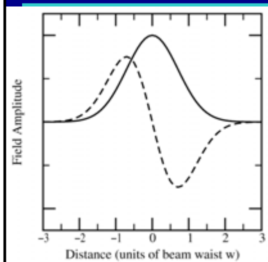
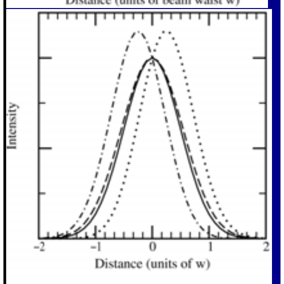
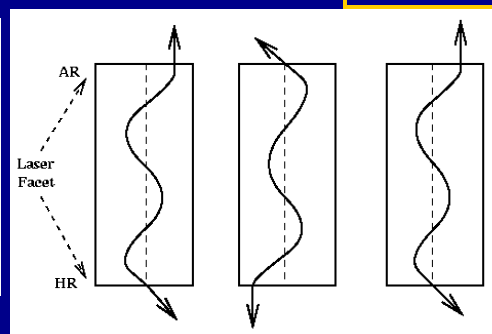
## Lateral Beam Shifts in the Near-Field and Pointing in the Far-Field due to Mode Beating




$$U_{l,m}(x,y,z) = A_{l,m}\left[\frac{w_0}{w(z)}\right] G_l\left[\frac{\sqrt{2}x}{w(z)}\right] G_m\left[\frac{\sqrt{2}y}{w(z)}\right]$$

$$\times \exp\left[-jkz - jk\frac{x^2+y^2}{2R(z)} + j(l+m+1)\times\tan^{-1}\left(z/z_0\right)\right]$$




PTL Dec 2000



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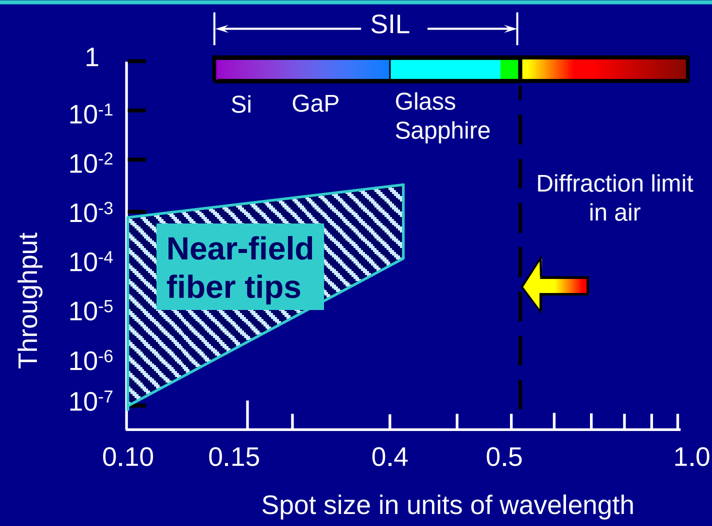
# Throughput vs. spot size




SIL with GaP

Q Wu, G.D. Feke, R.D. Grober and L.P. Ghislain, Appl. Phys. Lett. 75, 4064 (1999)



# Solid Immersion Lens Techniques

## Surface microscopy

Standard　　Solid Immersion Lens　　Super - SIL

## Subsurface microscopy
## Object is already "immersed"

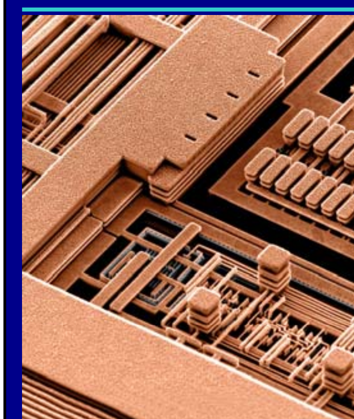
Standard
oil Immersion

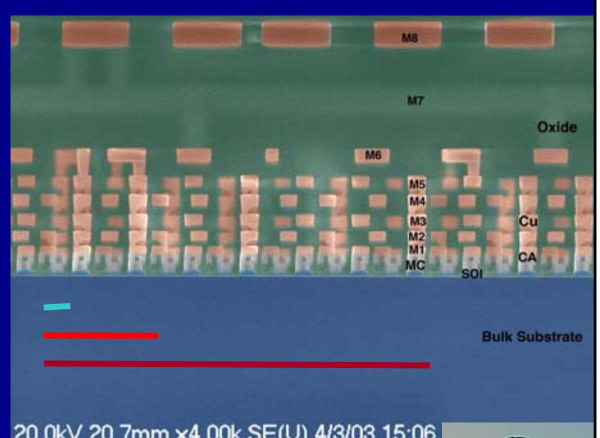
Standard
subsurface

Numerical Aperture
Increasing Lens (NAIL)

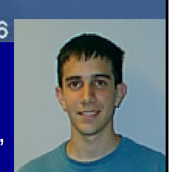


## Need for Backside Imaging for ICs

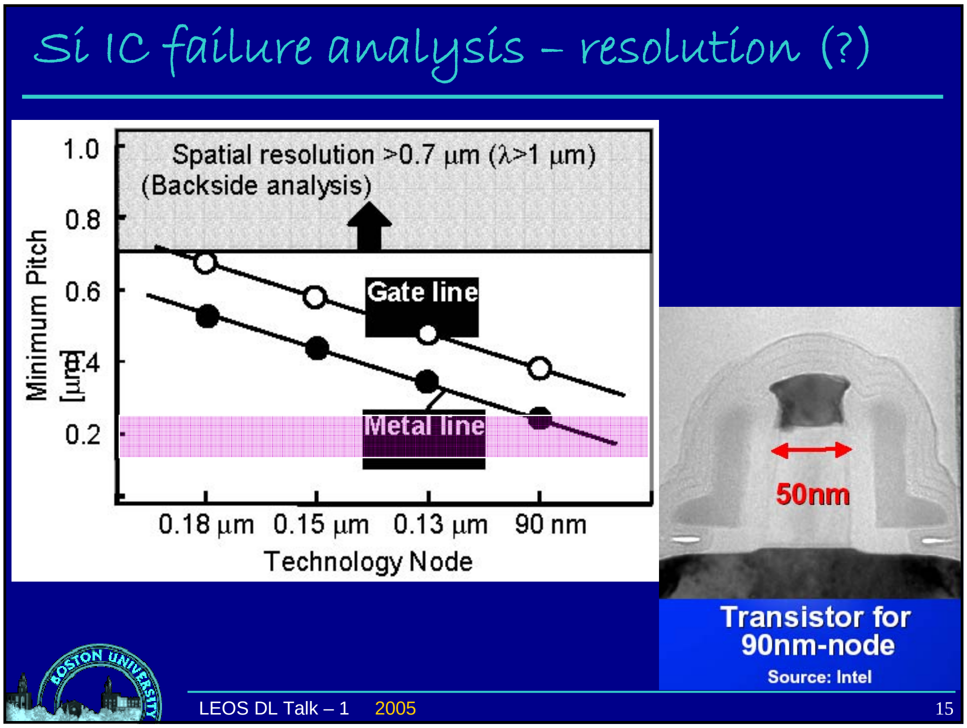





Opaque metal above buried devices often make imaging through the substrate preferable



Stephen Ippolito,
PhD May 2004


Si IC failure analysis – resolution (?)
1.0
0.8
0.6
0.4
0.2
Minimum Pitch [μm]
Spatial resolution >0.7 μm (λ>1 μm)
(Backside analysis)
Gate line
Metal line
0.18 μm
0.15 μm
0.13 μm
90 nm
Technology Node
50nm
Transistor for 90nm-node
Source: Intel
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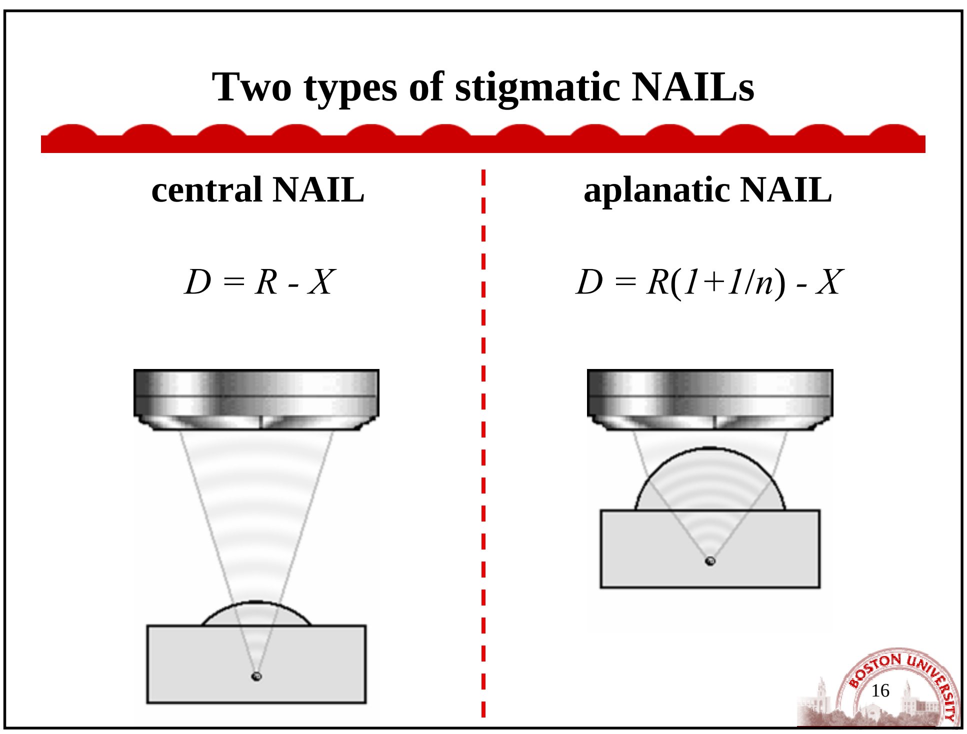
Two types of stigmatic NAILs
central NAIL
$D = R - X$
aplanatic NAIL
$D = R(1+1/n) - X$
BOSTON UNIVERSITY
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# Comparison of limitations

| conventional | NAIL |
|---|---|
| Light-gathering power | Light-gathering power |
| $\theta_a = \sin^{-1}(1/n)$ | $\theta_a = \pi/2$ |
| $NA = 1$ | $NA = n$ |
| Lateral spatial resolution | Lateral spatial resolution |
| $\lambda_0/2$ | $\lambda_0/2n$ |
| Longitudinal spatial resolution | Longitudinal spatial resolution |
| $n\lambda_0(1+\cos\theta_a)$ | $\lambda_0/n$ |

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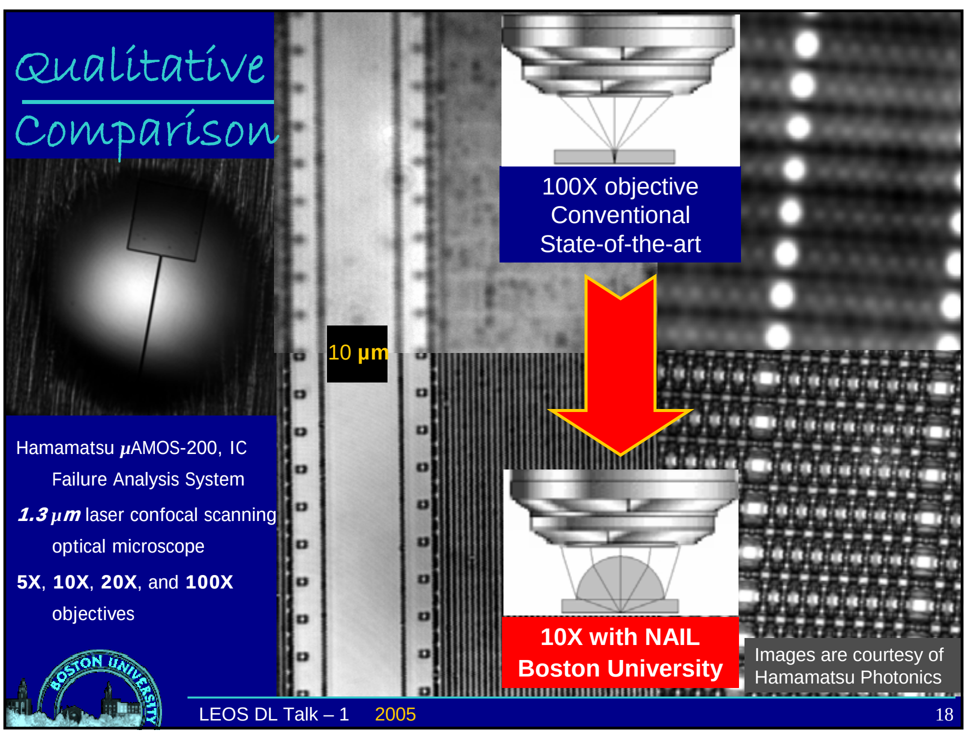
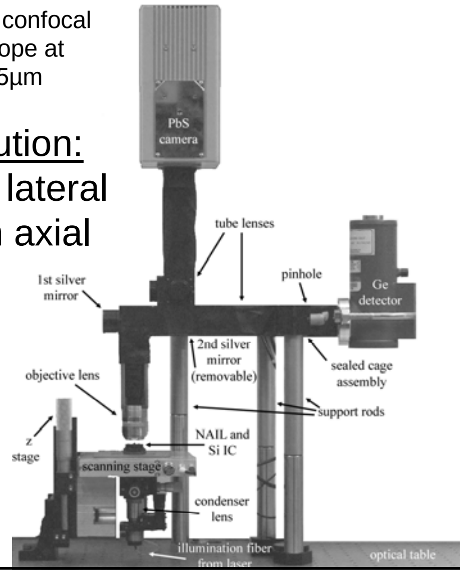
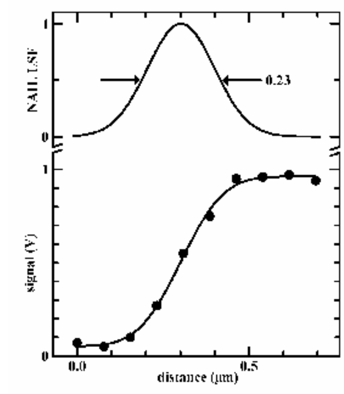


## High resolution NIR inspection microscope

Optimized confocal microscope at λ=1.05µm

Resolution:
230 nm lateral
1.3 µm axial

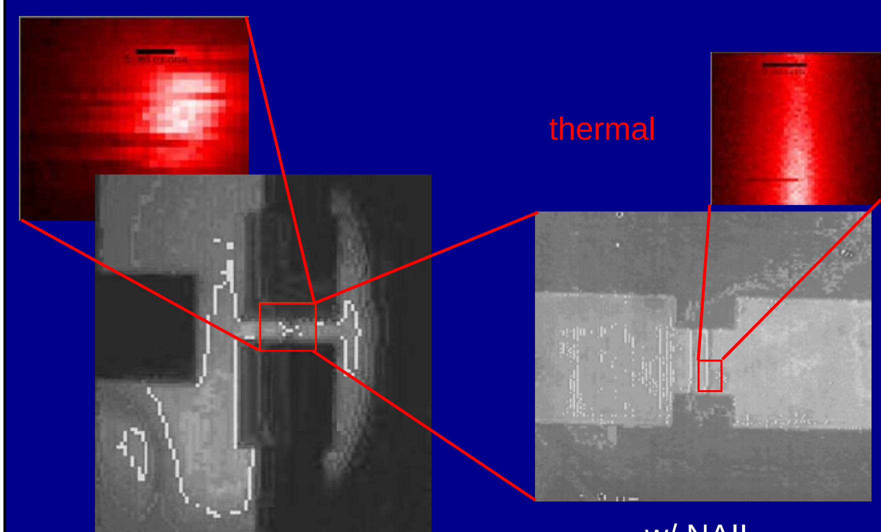



APL 2001



## Thermal Imaging on Al Wires

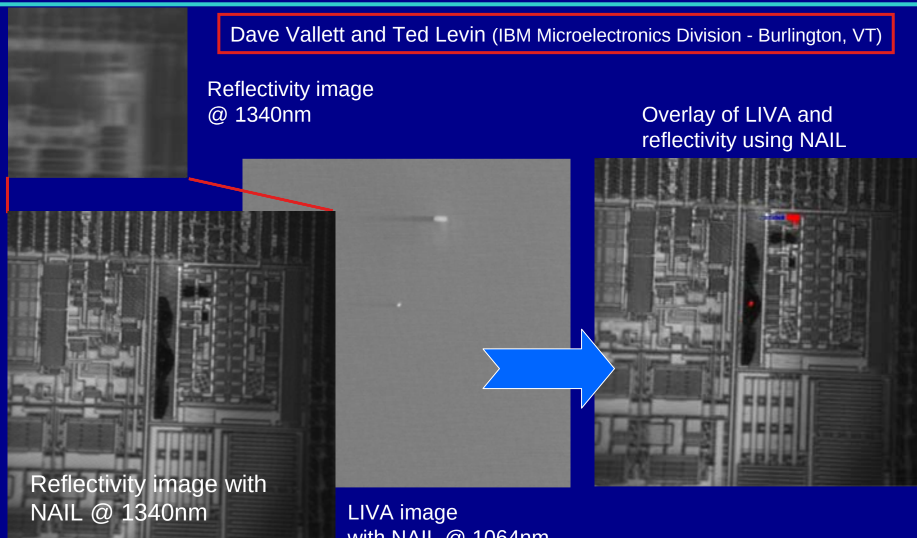



w/ NAIL

w/o NAIL

## Application: Failure Analysis

Dave Vallett and Ted Levin (IBM Microelectronics Division - Burlington, VT)

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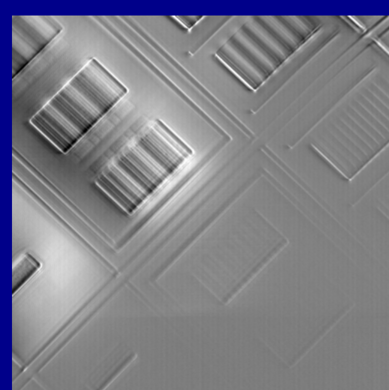
## LIVA images at 1064nm

50X + AR



20X + NAIL

10 µm

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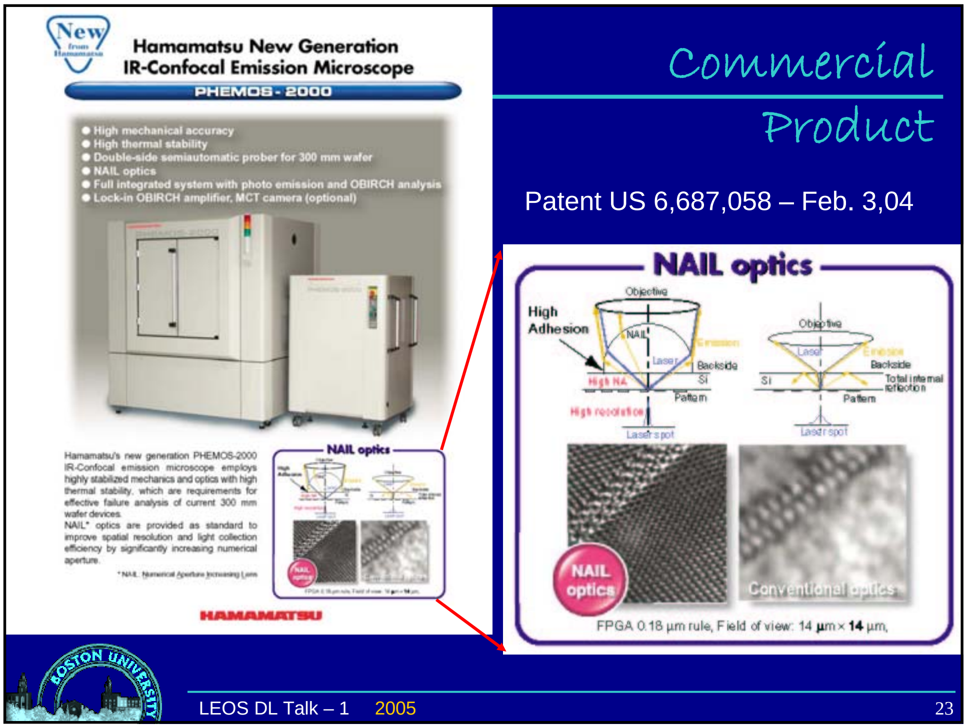
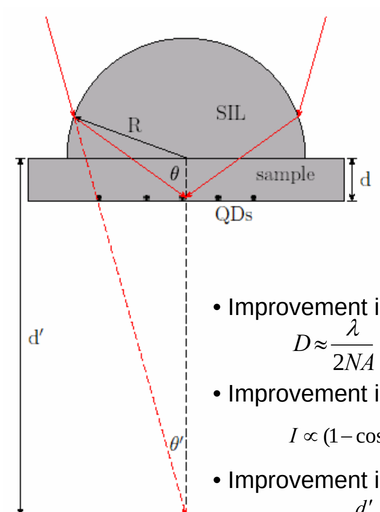
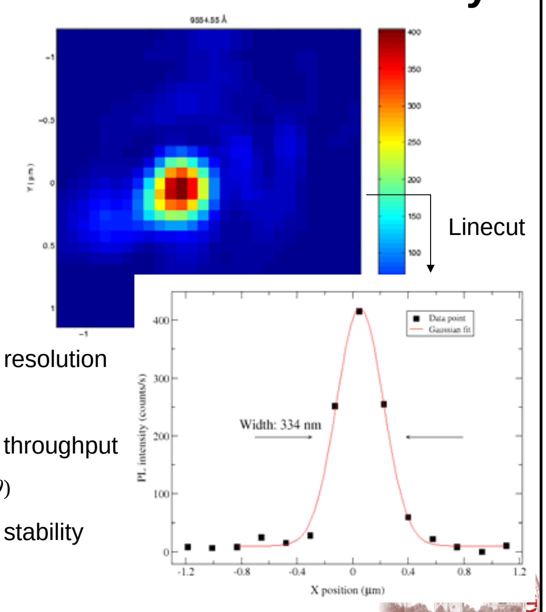



# QD Spectroscopy Resolution and stability




- Improvement in resolution

$$D \approx \frac{\lambda}{2NA}$$

- Improvement in throughput

$$I \propto (1-\cos\theta)$$

- Improvement in stability

$$M = \frac{d'}{d}$$

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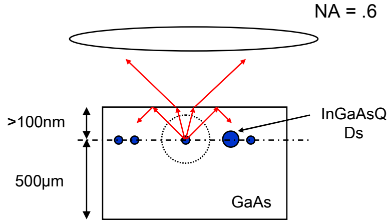
# Use of Aplanatic NAIL

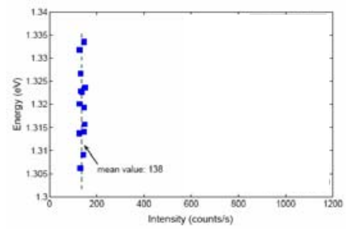
## Quantify Collection Efficiency Increase

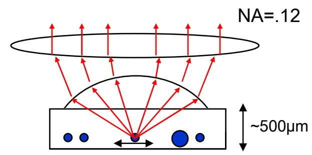



1st

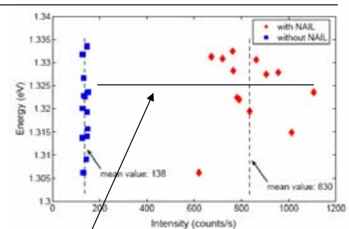
$\lambda_{ex}$ = 840nm

T = 8 K




2nd




How can we utilize this increase in colleciton efficiency??

~max 8x

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Mehmet Dogan, Physics, PhD 2006

Lev Moiseev, Bio, PhD May 2003

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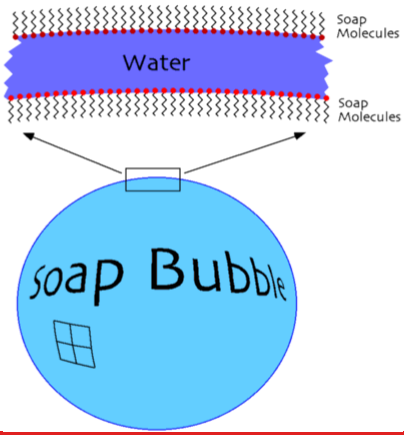
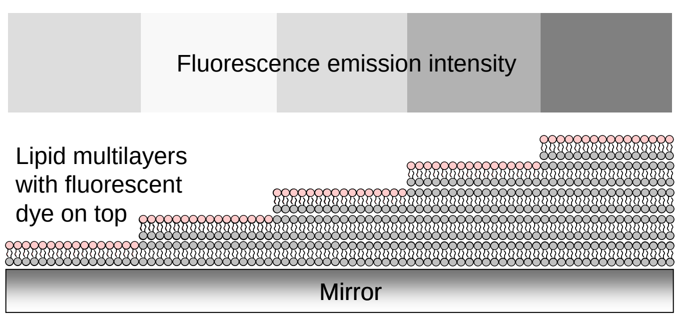
## Interference of Fluorescent Emission

- 1898 O. Wiener discovers standing waves on top of silver mirror covered with photosensitive material
- 1960's K. Drexhage studies fluorescence lifetime of dyes on lipid multilayers.
- 1996 P. Fromherz shows fluorescence interferometry can determine the height of buried emitters above mirror



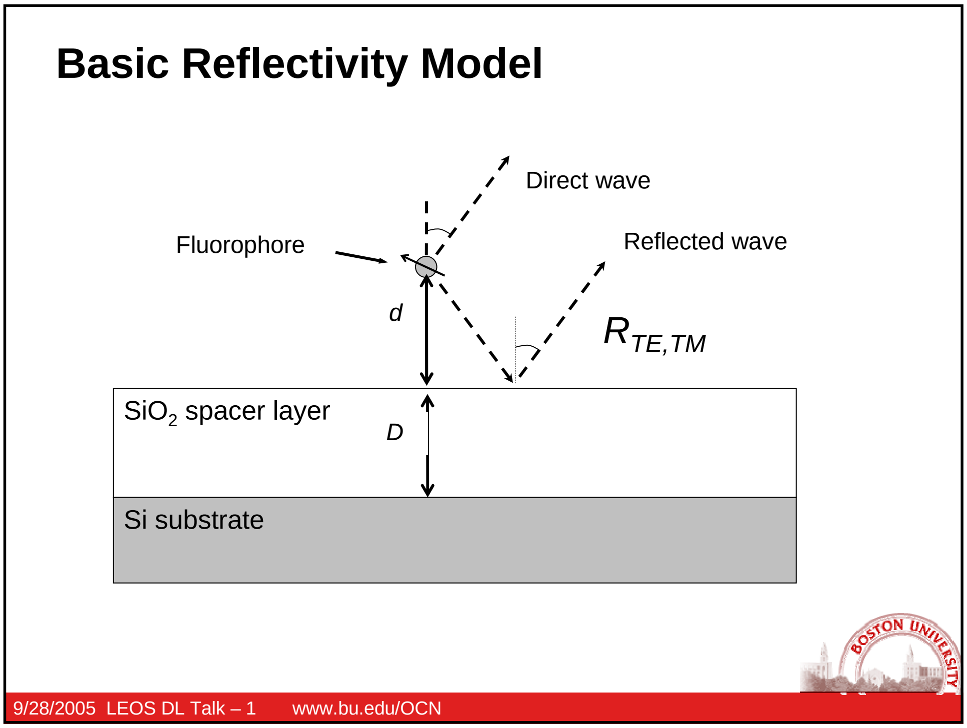



## Interference of Fluorescent Emission




**Monomolecular layers of fluorescent dyes on top of a stair-like lipid multilayers show dependence of fluorescent emission on the thickness of the lipid film**

Drexhage *et al*, *Prog. Optics*, **XII**, p. 163, 1974


Basic Reflectivity Model
Direct wave
Fluorophore
Reflected wave
d
R TE,TM
SiO2 spacer layer
D
Si substrate
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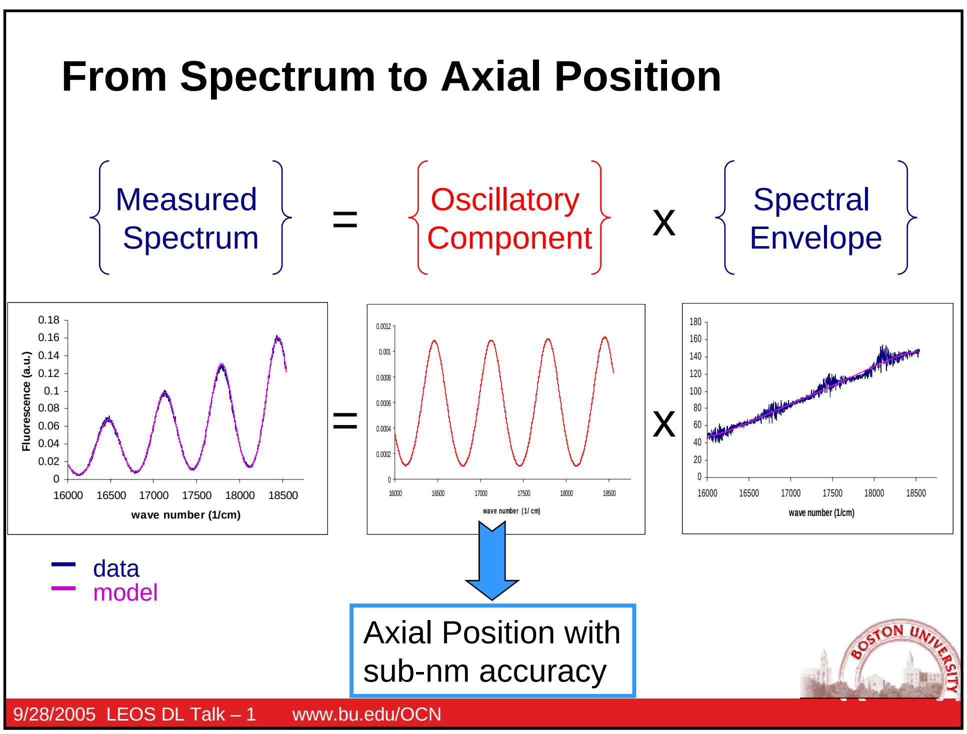
From Spectrum to Axial Position
Measured Spectrum
=
Oscillatory Component
x
Spectral Envelope
Fluorescence (a.u.)
wave number (1/cm)
wave number (1/cm)
=
x
data
model
Axial Position with sub-nm accuracy
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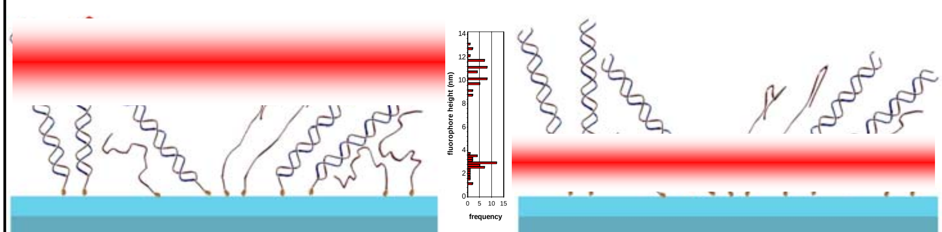
## Conformation of DNA immobilized on the surface

- Large DNA microarray industry dependent on hybridization of complementary sequences for detection and monitoring of gene expression
- Efficiency of hybridization depends on conformation of DNA molecules
- No known techniques (AFM, SPR, etc) that can measure extension of DNA above surface
- Utilize spectral self-interference to get a more in-depth picture of the structure and conformation of DNA molecules in an array

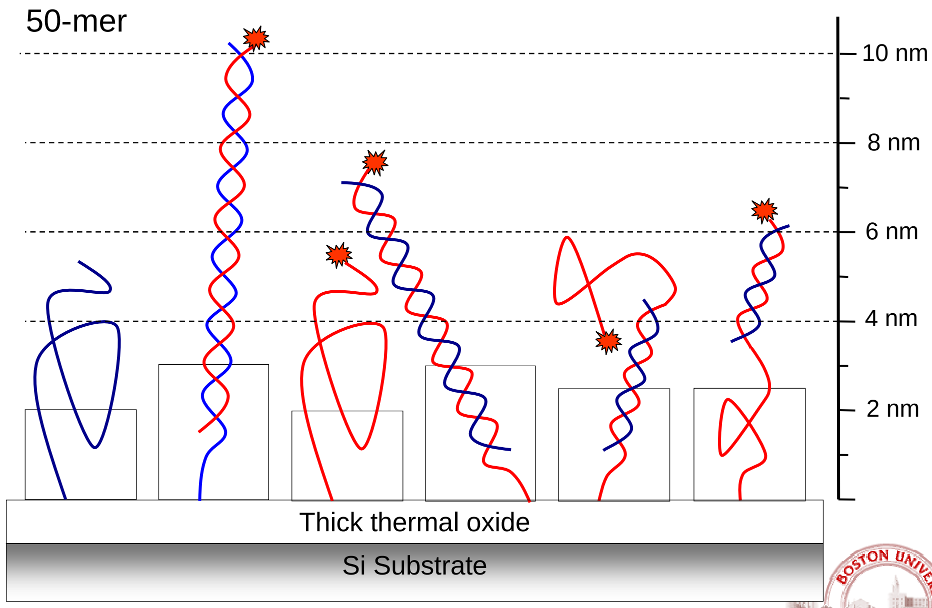
## DNA on surfaces

### Distal and proximal labeled second strand hybridization

- Optical density (*nd)* increases with hybridization
- 3’ labeled second strand 2-3 nm from surface
- 5’ labeled second strand 10-12 nm from surface



**Conformational changes on second strand hybridization**






## Conclusions on Spectral Interference

- Spectral self-interference is a novel technique for measuring the height of fluorescent molecules above a reflecting surface.
- A classical model of dipole emission that takes polarization effects into account can be used to precisely describe the oscillatory spectral component of fluorophores.
- Self-interference of the emitted light was used to trace the position of the fluorescent tag above the surface with sub-nanometer precision and thus determine the physical structure of the immobilized DNA.
- It was found that surface-bound ssDNA exists either in random coils or more extended forms depending on constraints from nearby molecules. After hybridization of a second strand the DNA adopts the conformation of a molecular brush, protruding from the surface.