Current Infrared Studies of Novel Materials at the ALS:

Metamaterials, Organic conductors, and Graphene

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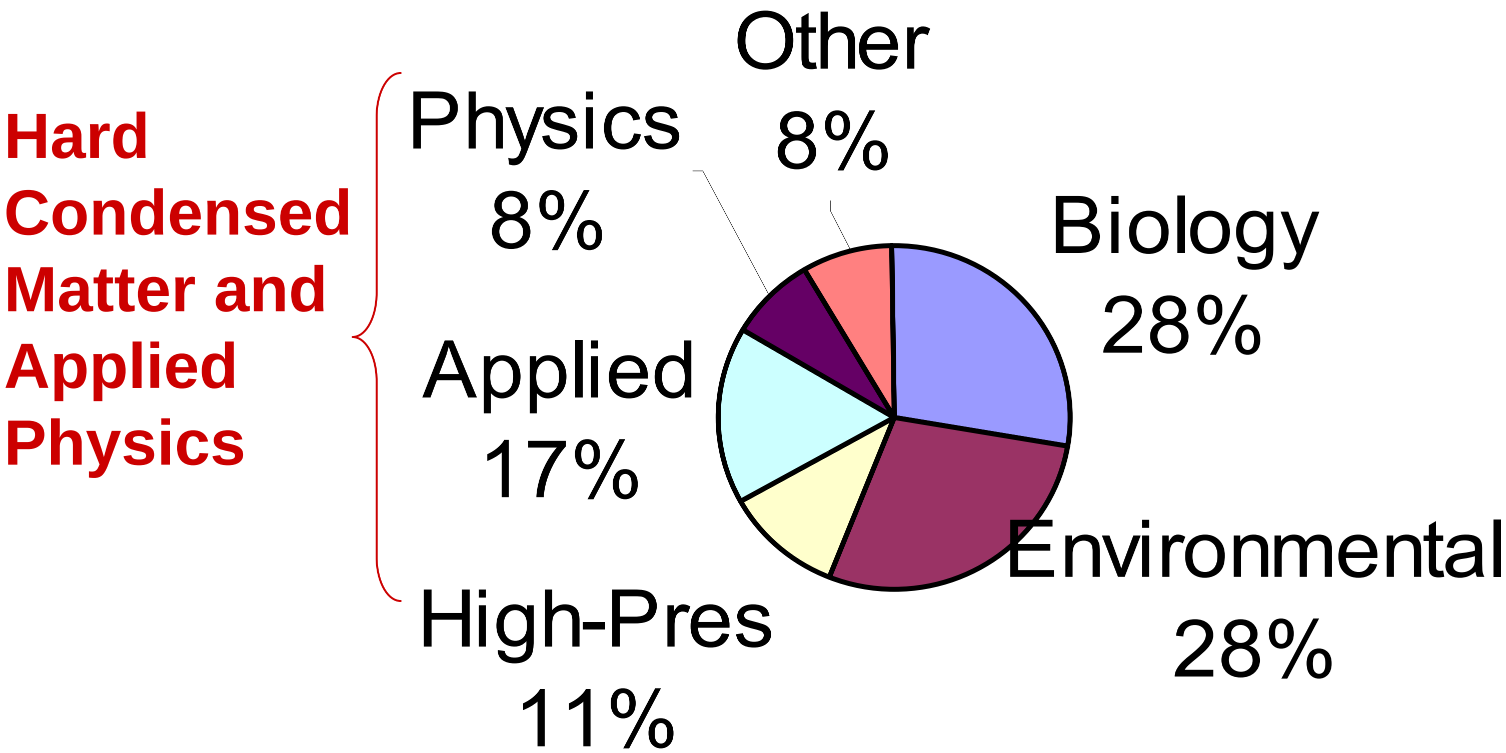
http://infrared.als.lbl.gov/

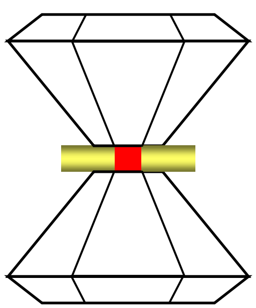
ALS IR Users (2007)

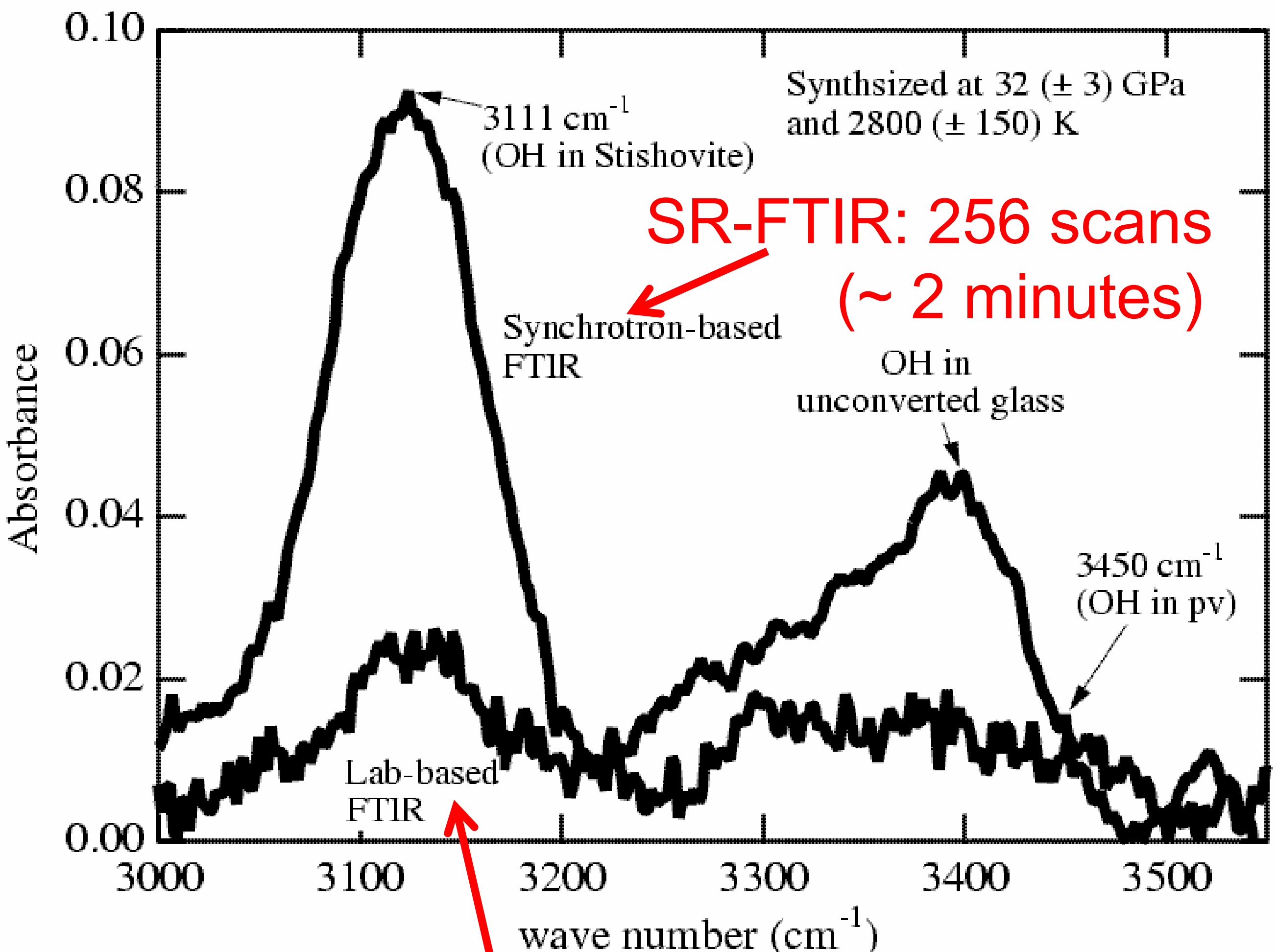


(The ALS IR beamlines are primarily mid-IR microscopy focused. NSLS-II will have this as well as more far-IR capabilities which will broaden the HCM&AP 'slice'.)

Example of Synchrotron's High Brightness: Geophysics

Mineral sample (ocean basalt) in diamond anvil cell at high pressure (32 GPa)





SR-FTIR: 256 scans (~ 2 minutes)

Lab FTIR: 60,000 scans averaged (~ 16 hours averaging!)

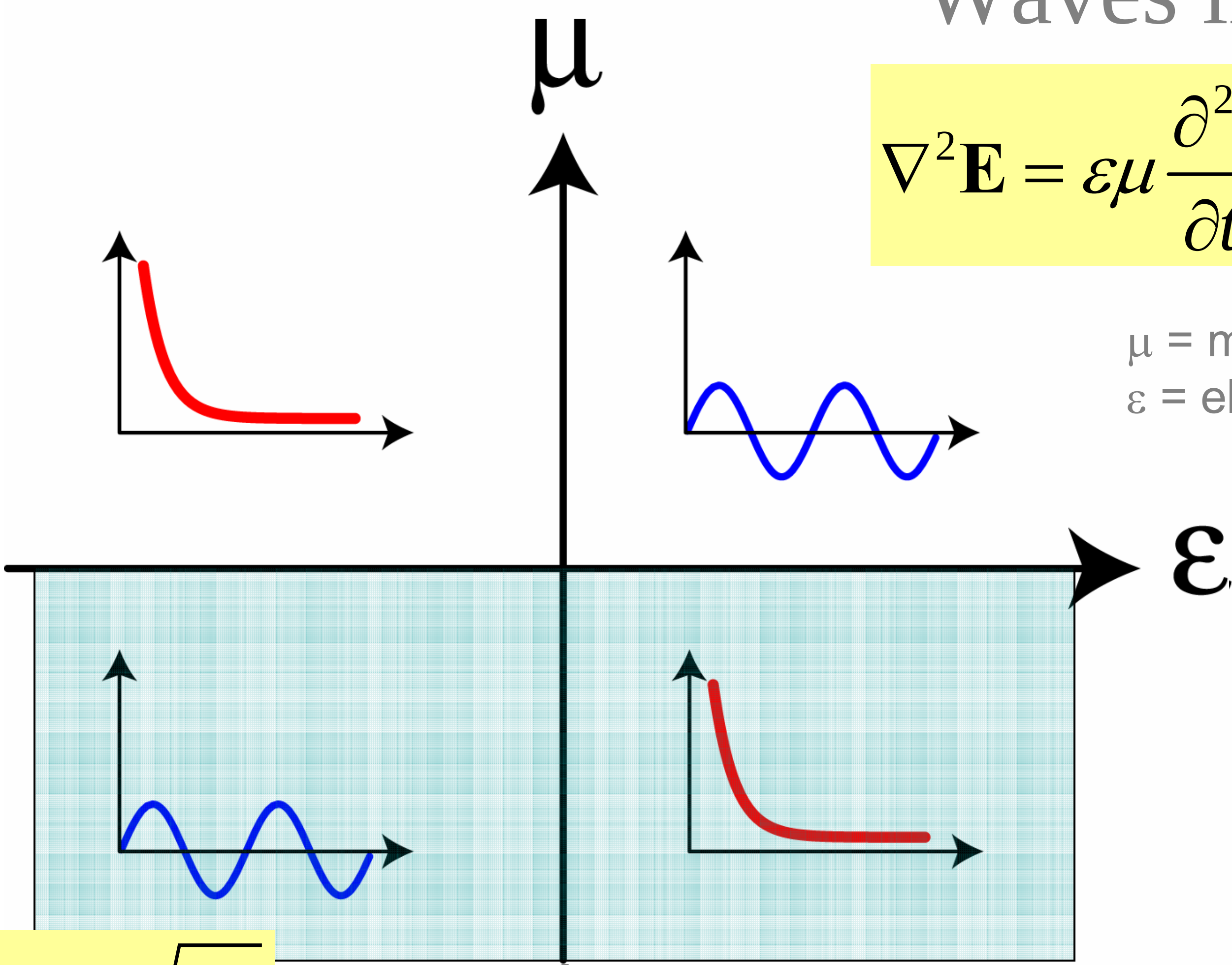
Panero, Benedetti, Jeanloz

Left Handed Materials

Waves in Media:

$$\nabla^2 \mathbf{E} = \varepsilon\mu \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad n = \sqrt{\varepsilon\mu}$$

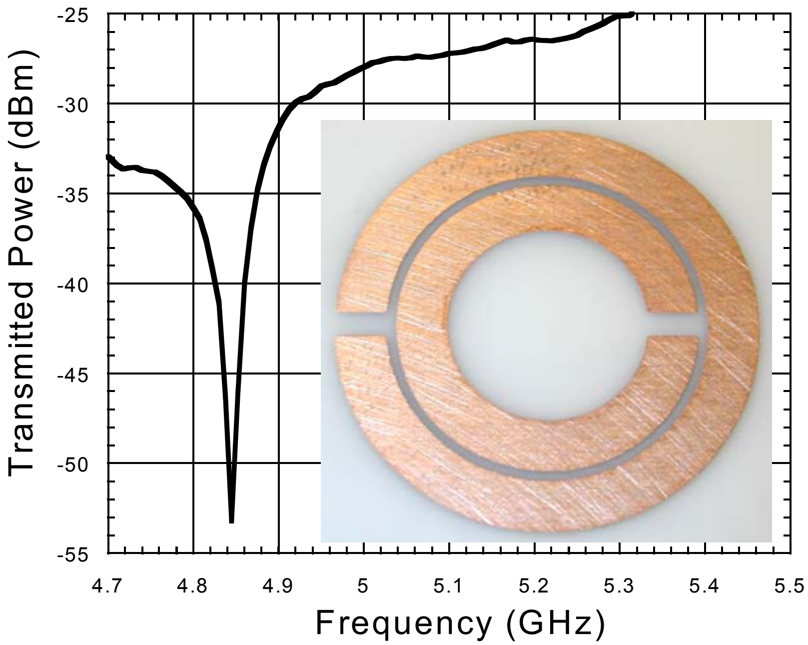
μ = magnetic permeability
ε = electric permittivity



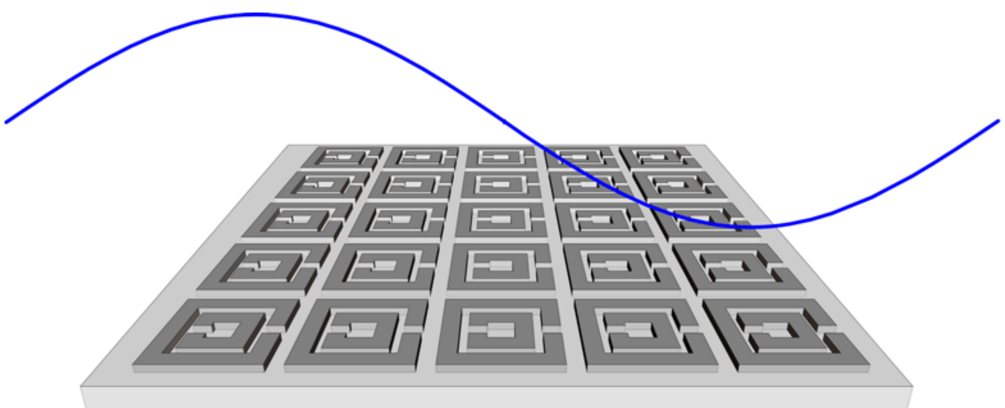
$$k = \omega\sqrt{\varepsilon\mu}$$

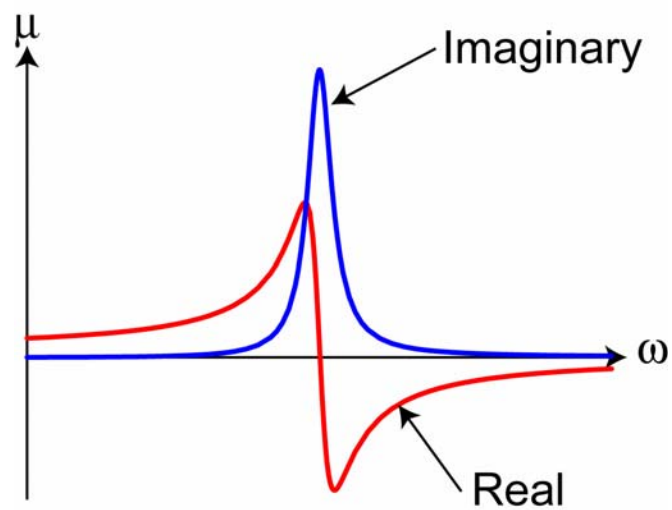
V.G. Veselago, Sov. Phys. USPEKHI **10**, 509 (1968).

A Magnetic “Atom”



Pendry et al. suggested that an array of ring resonators could respond to the magnetic component of incident radiation, displaying an effective negative permeability.





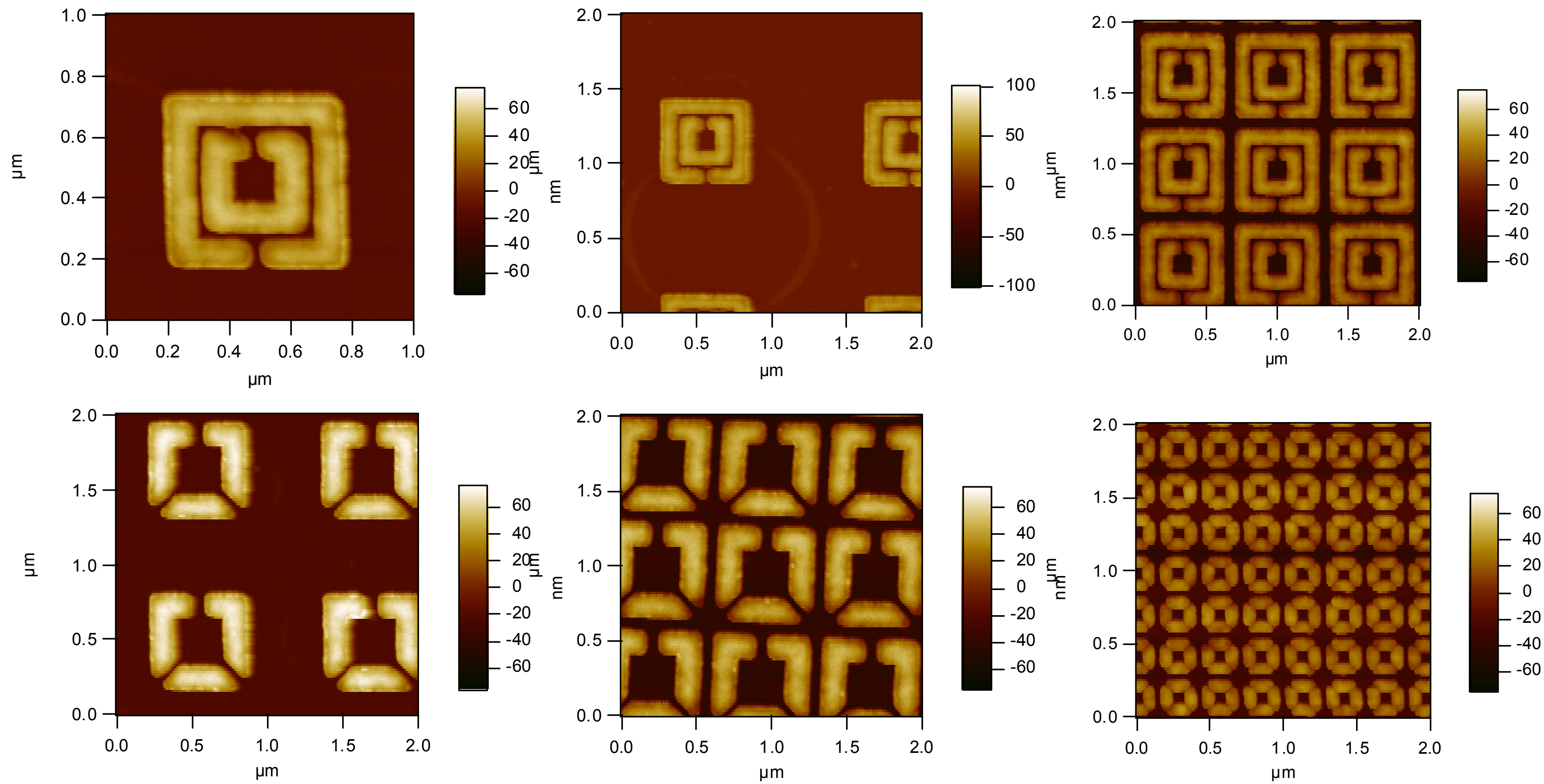
J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, “Magnetism from conductors and enhanced non-linear phenomena,” *IEEE Trans. MTT* **47**, 2075 (1999).

Nano-scale Metamaterials

Zhao Hao[1], Michael C. Martin[1], Bruce Hartneck[2], Stefano Cabrini[2], and Erik Anderson[3]
[1]Advanced Light Source Division, [2]Molecular Foundry, and [3]Center for X-Ray Optics, LBNL

E-beam lithography, gold plated structures, free-standing SiN_x substrate (100 nm thick)

Sample AFM images of various structures:

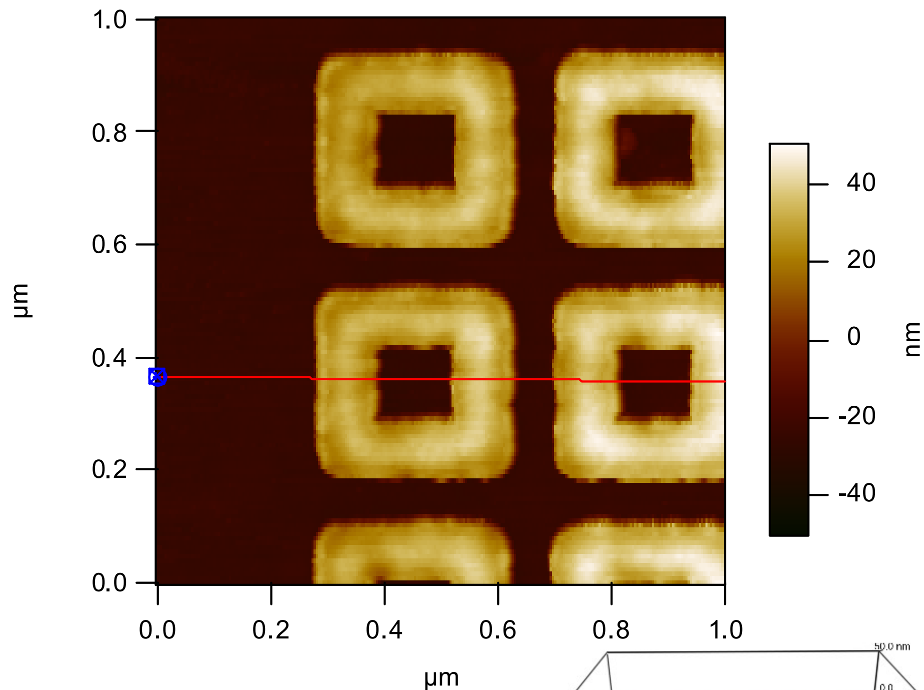


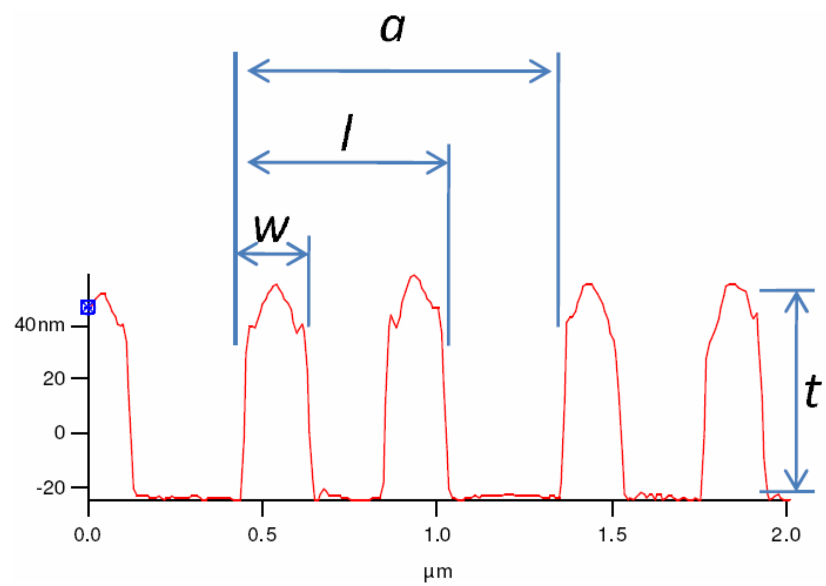
Line widths *w* = 40, 60, 100 nm; Lattice spacing *a* varies from 6 *w* to 10 *w*; thickness *t* ≈ *w*

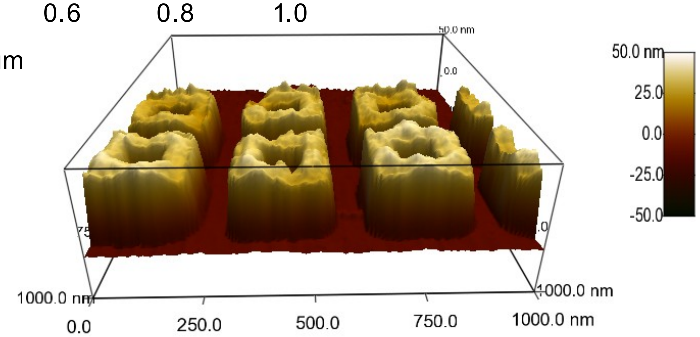
Closed Ring Structures

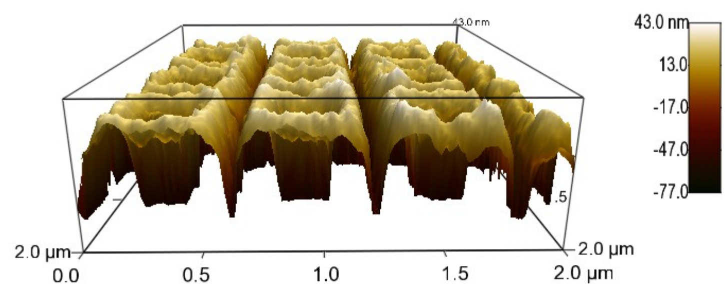
E-beam lithography, gold plated structures, free-standing SiN_x substrate (100 nm thick)

Sample AFM images of structures:





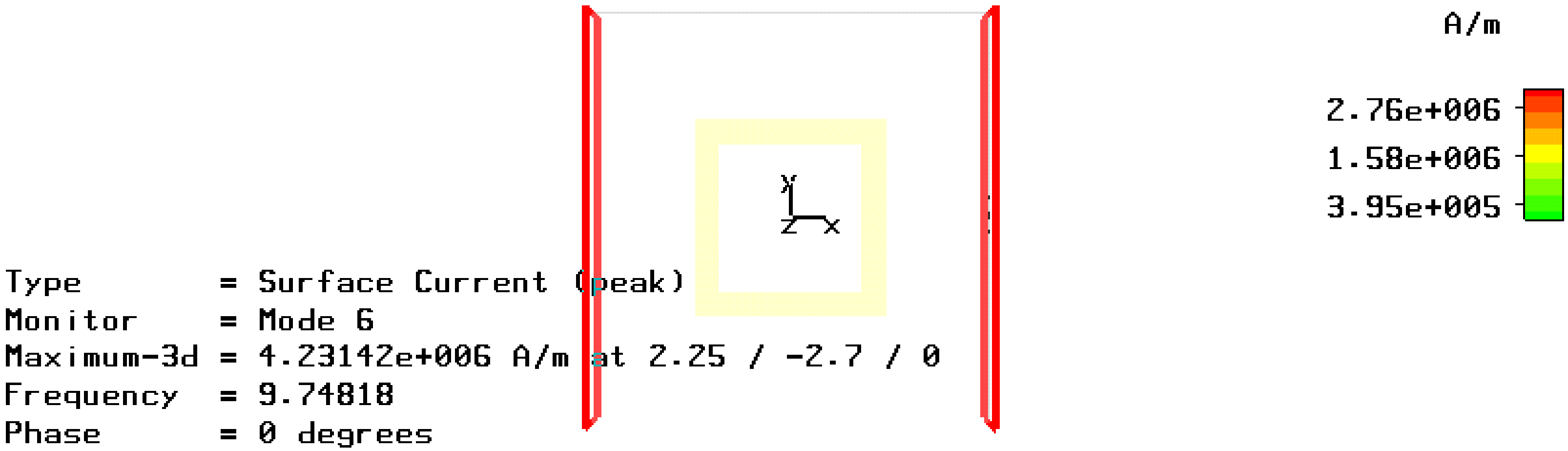




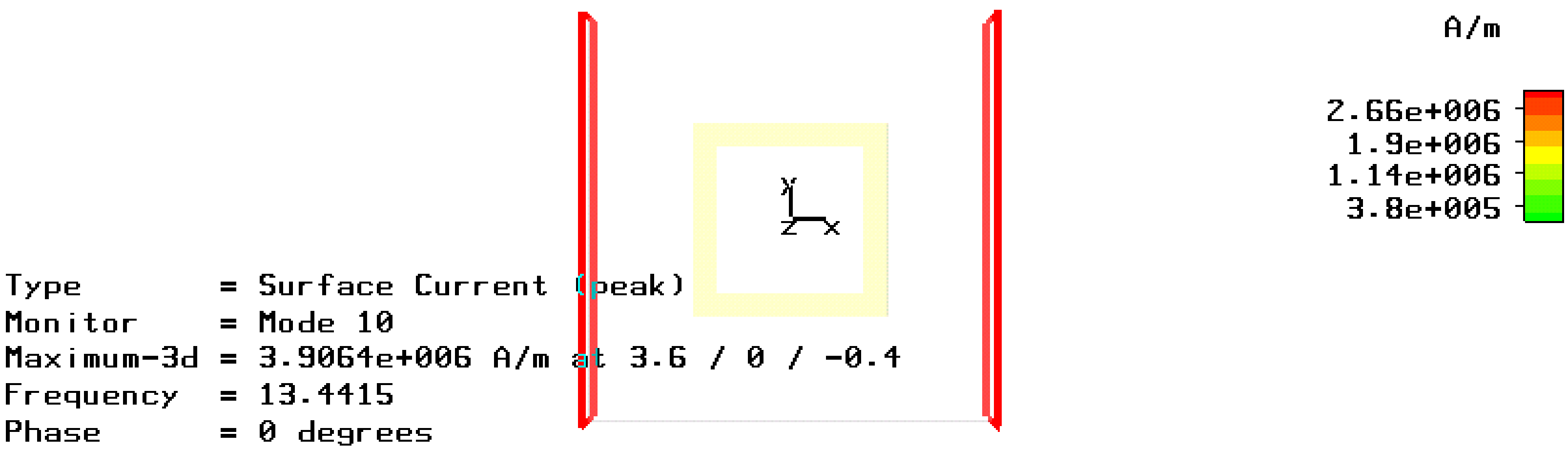
Z. Hao *et al.*, *Appl. Phys. Lett.* 91, 253119 (2007).

Line widths *w* = 40, 60, 100 nm; Lattice spacing *a* varies from 6 *w* to 10 *w*; thickness *t* ≈ *w*

E1 surface current distribution

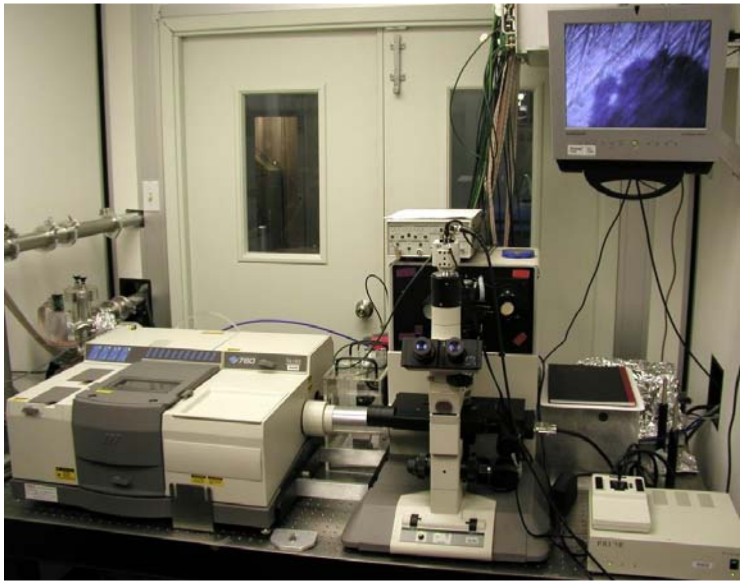


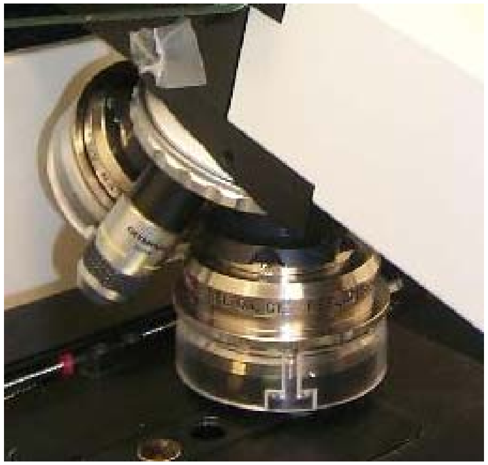
M1 surface current distribution



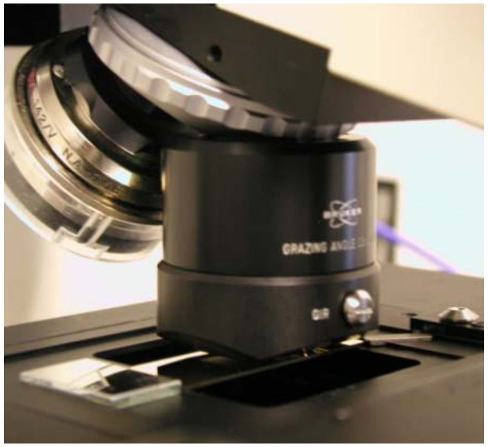
Measurement Setup

FTIR spectromicroscopy at ALS synchrotron BL1.4.3 and BL1.4.4





"Normal" Incidence Objective:
~26±8 degree

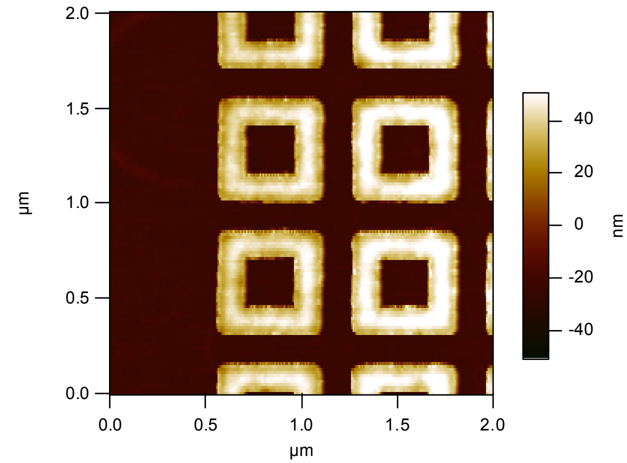


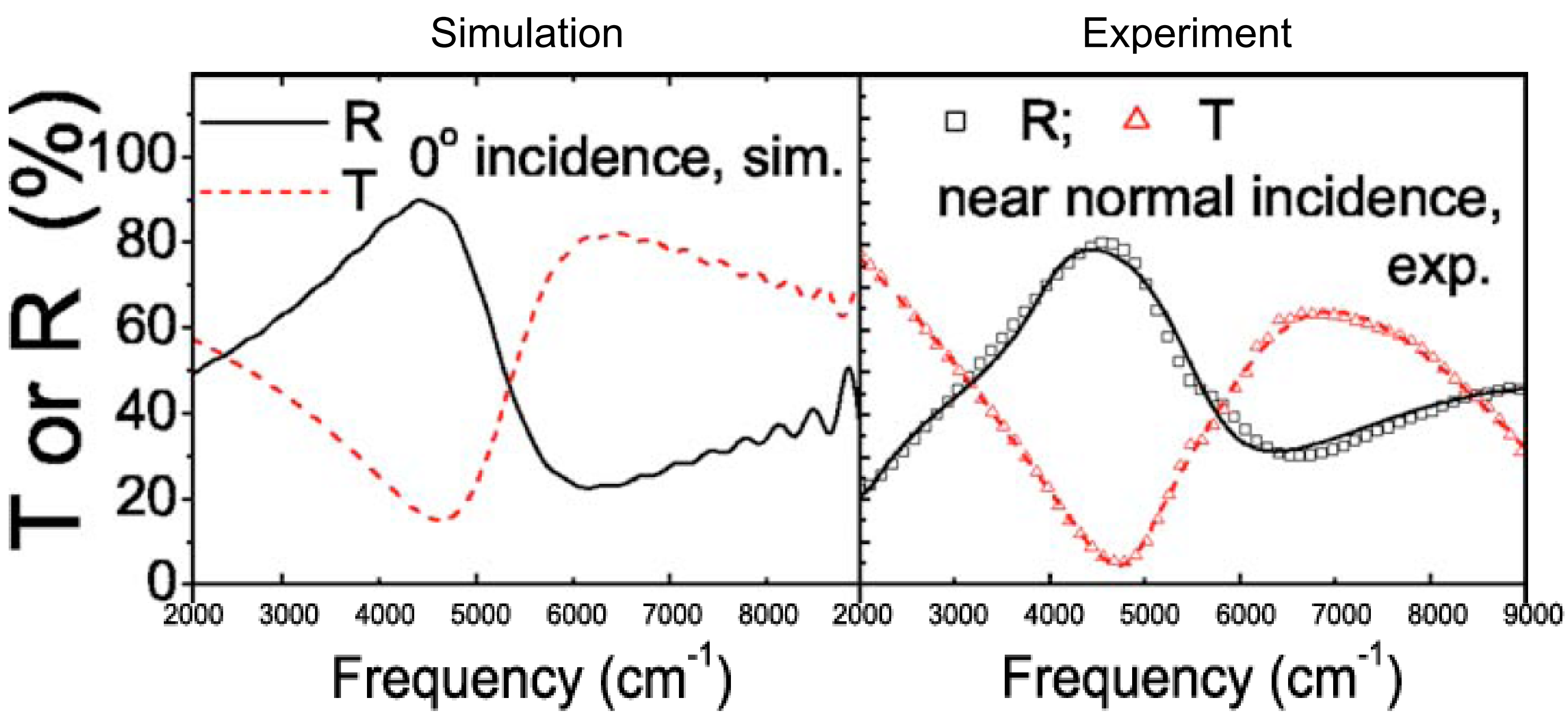
Grazing Angle Objective:
~85 degree

With full input/output polarization control

Near-normal incidence

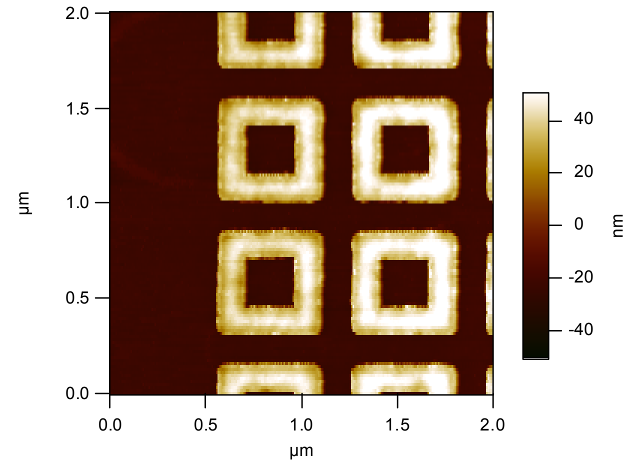
w=100 nm, l=500 nm, a=900 nm and t=73nm,
on 100 nm thick free-standing SiN_x membrane

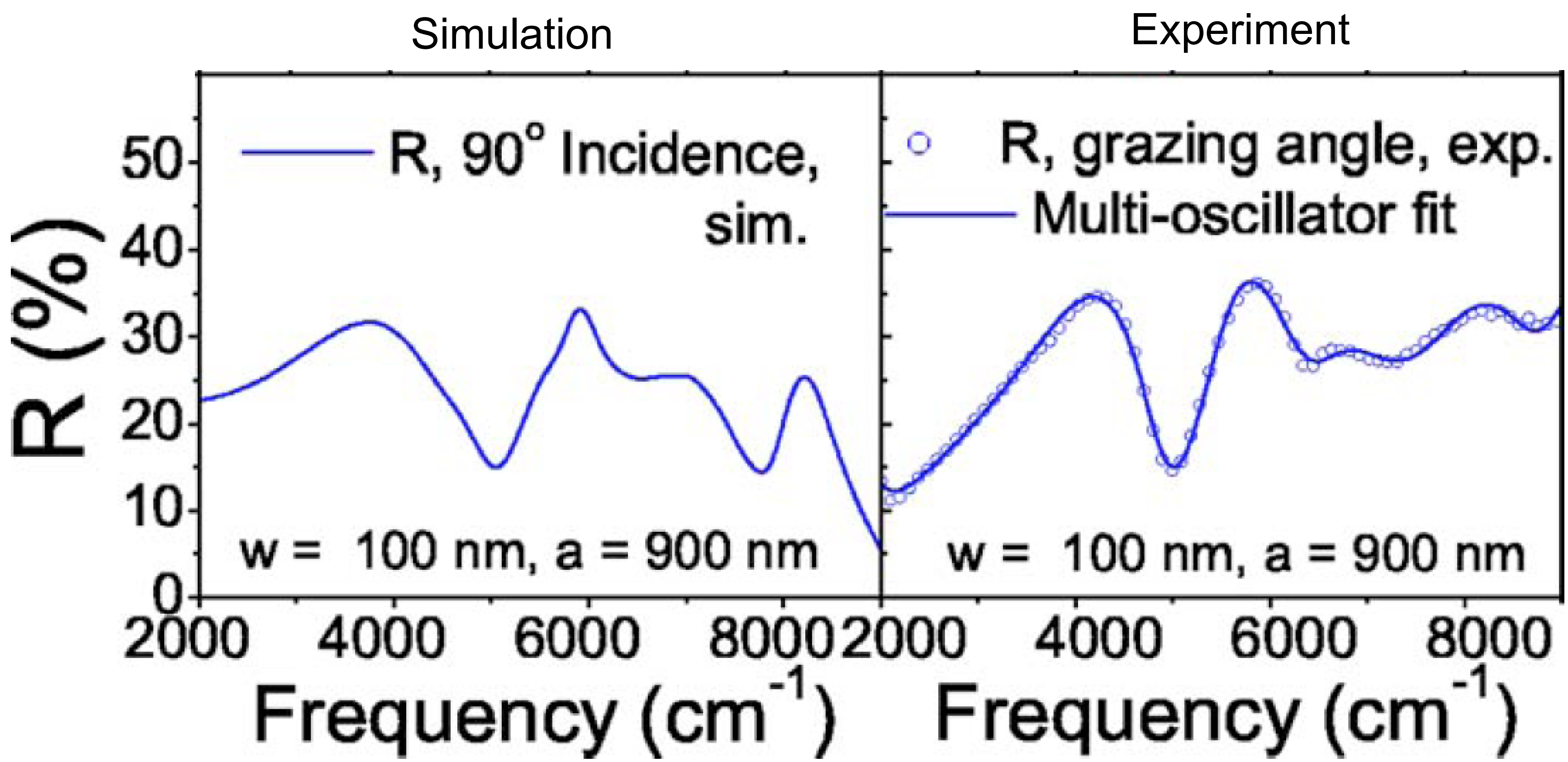




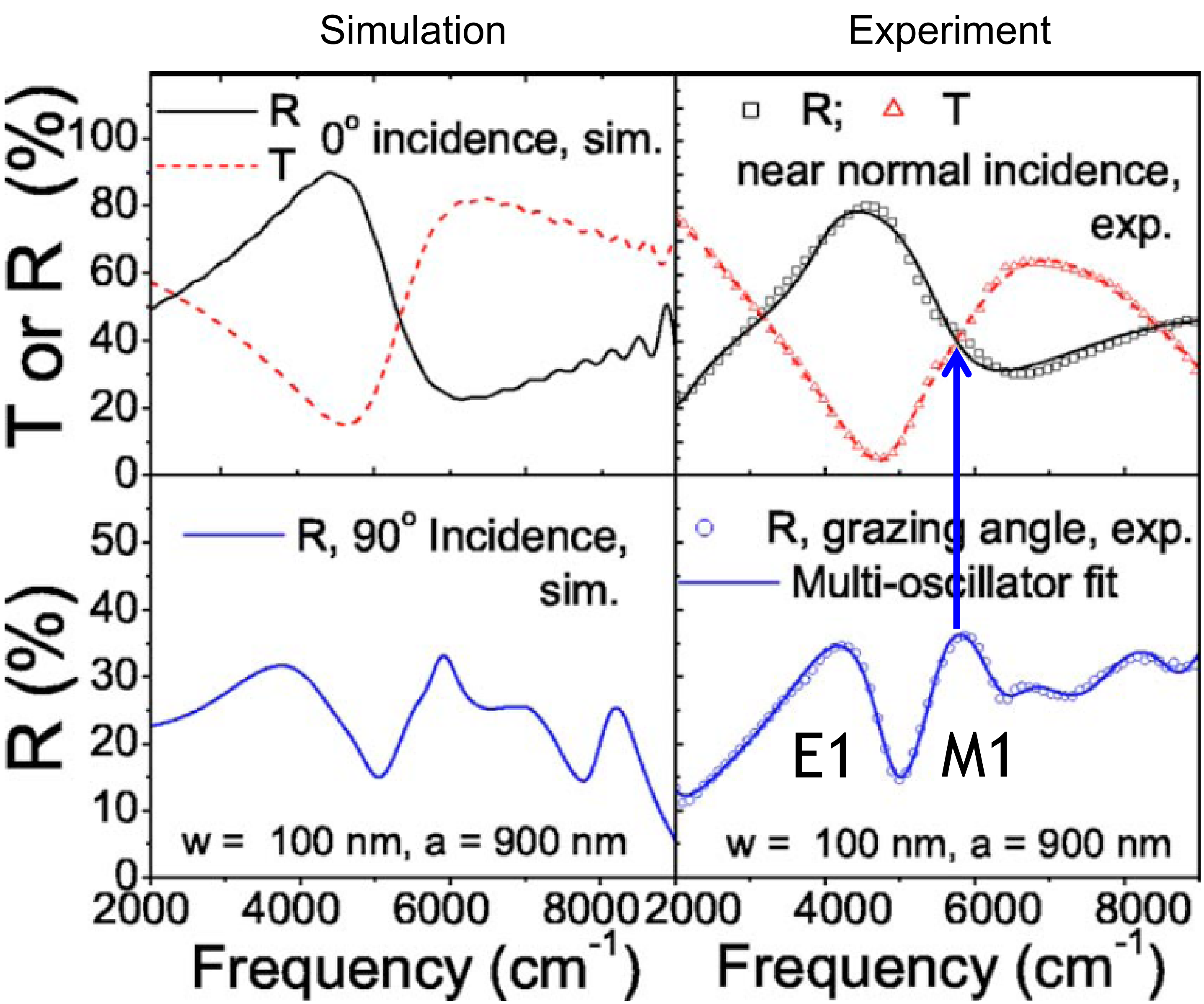
Grazing incidence

w=100 nm, l=500 nm, a=900 nm and t=73nm, on 100 nm thick free-standing SiN_x membrane

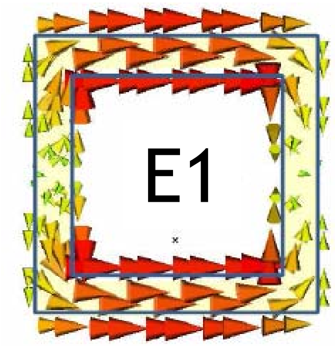


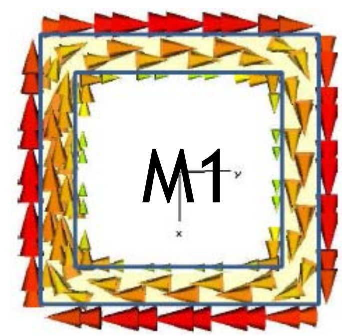


Compare Normal & Grazing

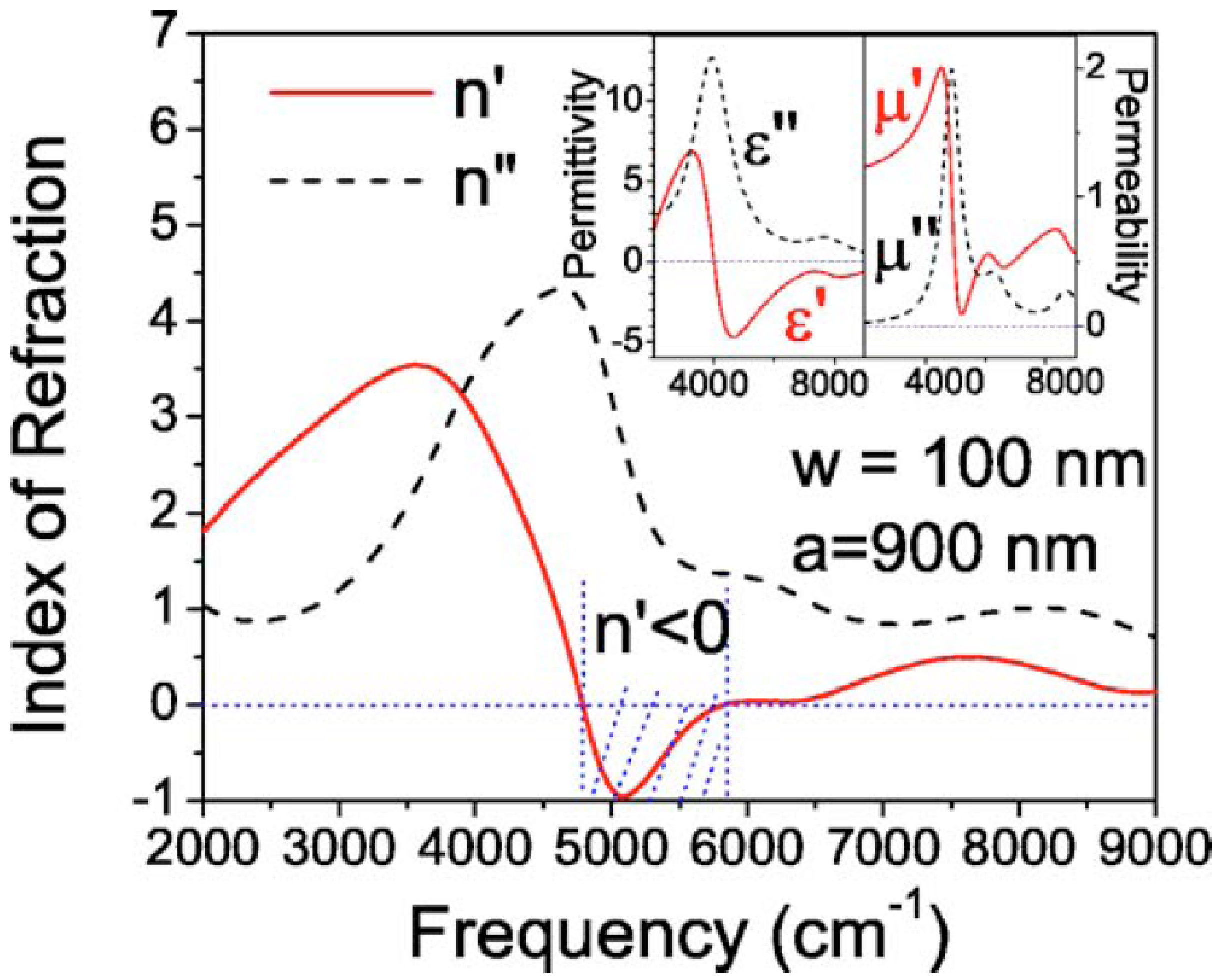


We can see that our 26 degrees “near-normal” incidence measurement includes some M1 seen in grazing incidence





Complex Index of Refraction



Z. Hao *et al.*, *Appl. Phys. Lett. 91*, *253119 (2007).*

Negative index is achieved where E1 and M1 overlap.

5000 cm^{-1} = 2 μm wavelength = 152 THz

Infrared Imaging of Charge Injection in Organic Field-Effect Transistors

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Support:

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D. Moses
A. J. Heeger
(UCSB)

V. Podzorov
M.E. Gershenson
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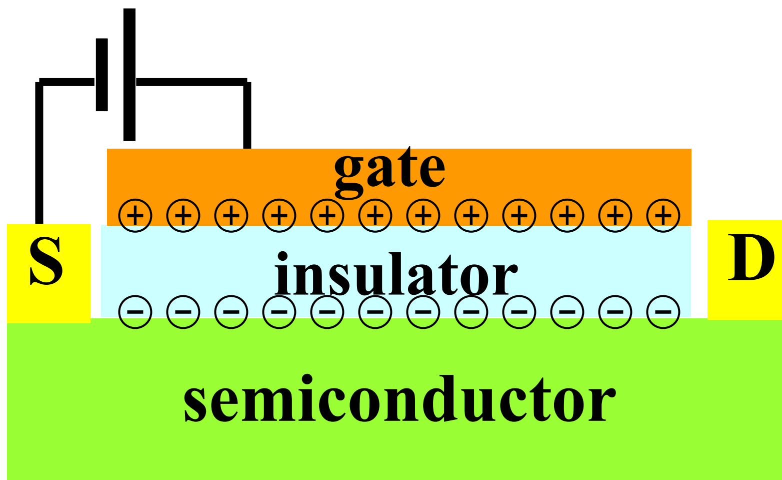
N.Sai
D. Meyertholen
M. M. Fogler
M. Di Ventra
(UCSD)

FET principle

FET is ubiquitous

$\sim 10^{18}$ **Si FETs manufactured every year**
(> 10^8 per person!)



Carrier density ⟶ conductance

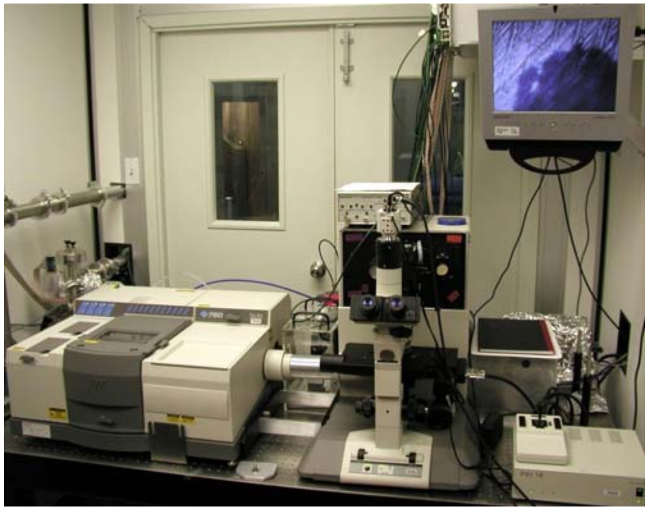
IR spectromicroscopy of FETs

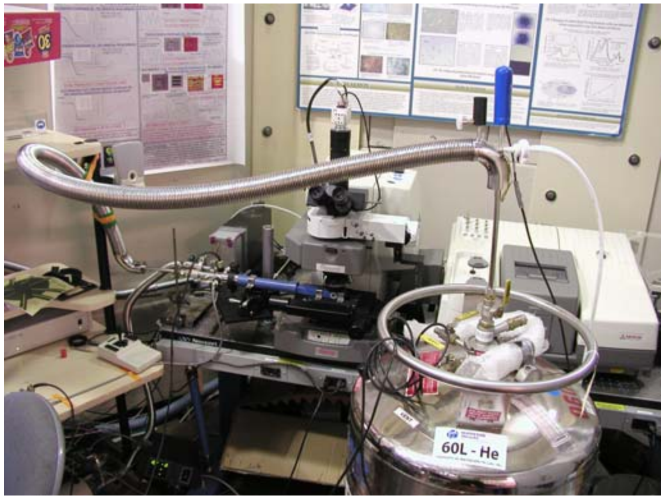
1: Broad energy range.

Sub-THz THz Far-IR Mid-IR Near-IR visible/UV

ALS IR Beamline 1.4

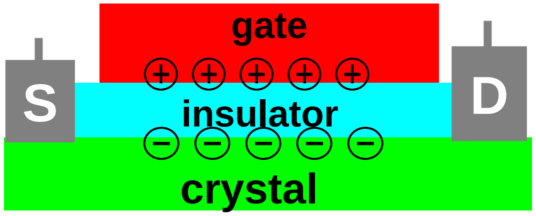
UCSD Basov lab

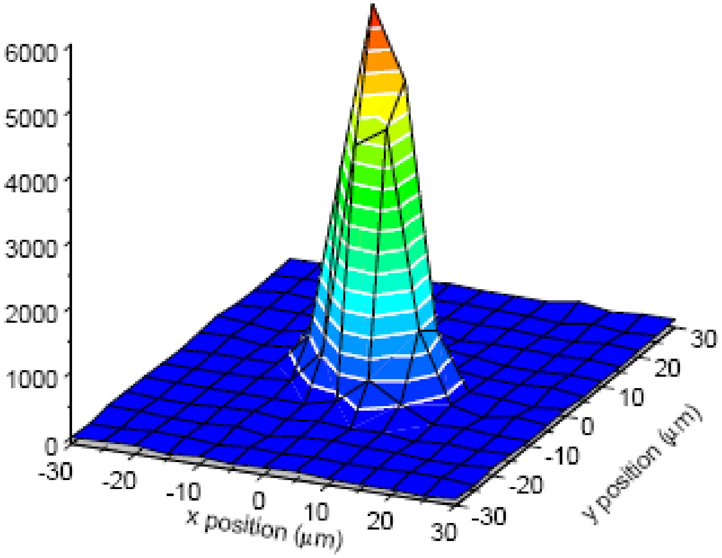




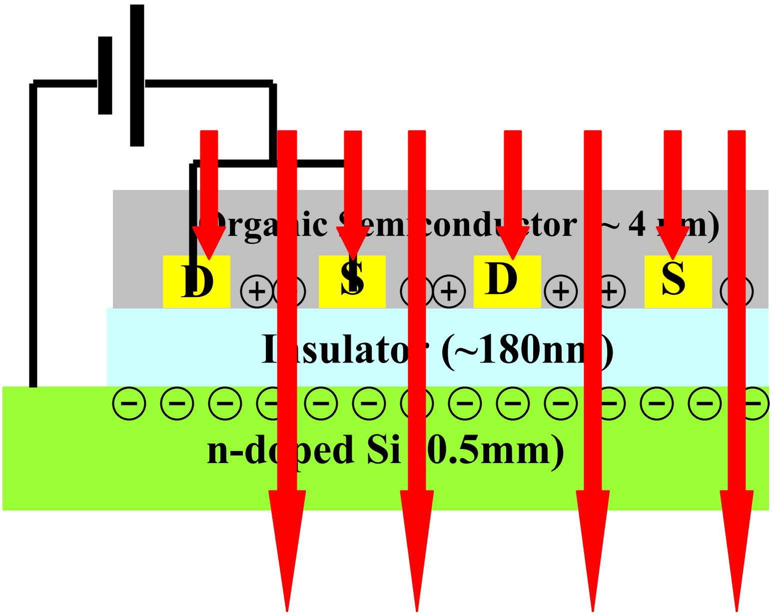
2: High spatial resolution, high brightness.

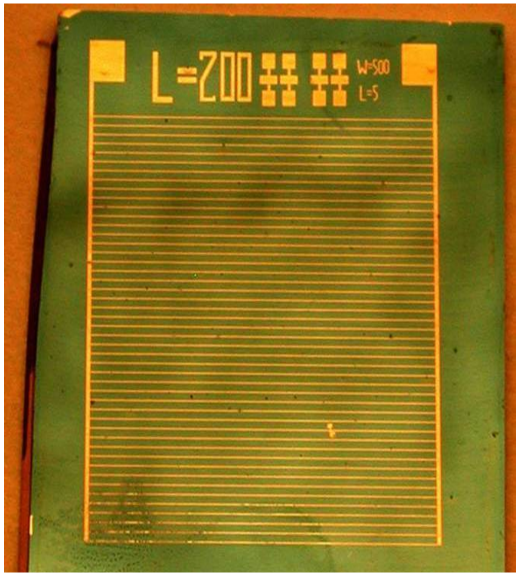
ALS IR Beamline 1.4



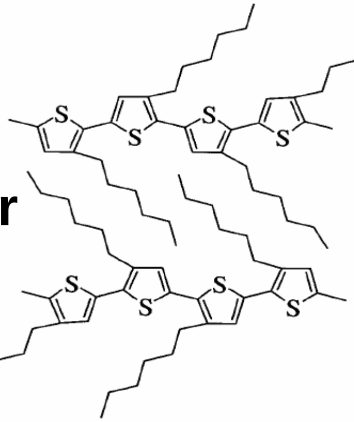


Large area FET devices





Organic conductor:
Poly(3-hexylthiophene) (P3HT)



Transmission as a function of gate voltage

$T(\omega, V_{GS})$

Direct probe of very thin charge accumulation layer

Insulator TiO_2 or SiO_2

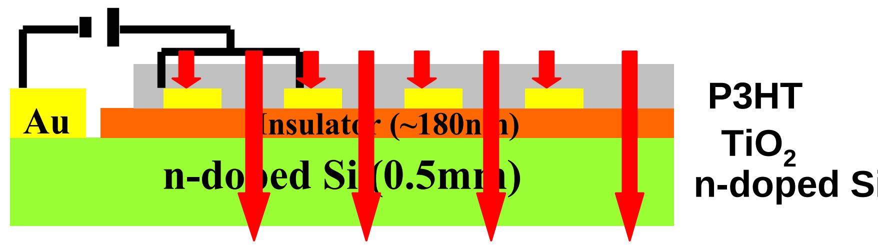
FET mobility: up to 0.7 $cm^2/V\,s$

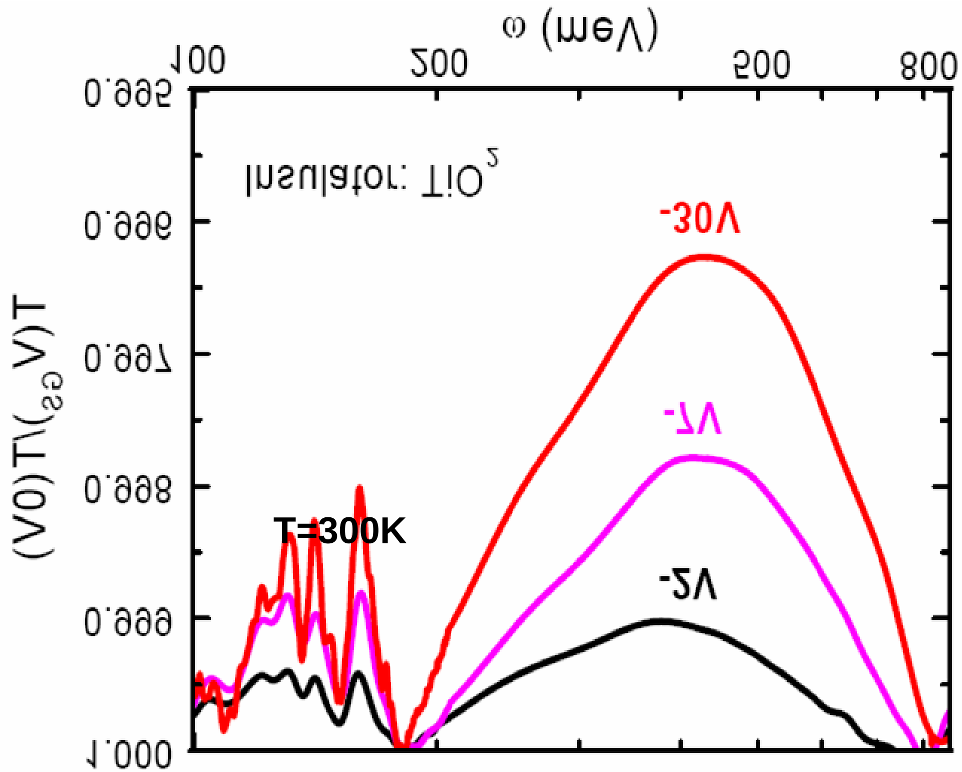
Z.Q. Li, et al, Nano Letters 6, 224 (2006).
Z.Q. Li, et al, *Appl. Phys. Lett.* 86, 223506 (2005).

IR spectroscopy of charge injection in P3HT

Voltage induced absorption:

$$\Delta \alpha d \sim 1 - T(V)/T(0V)$$



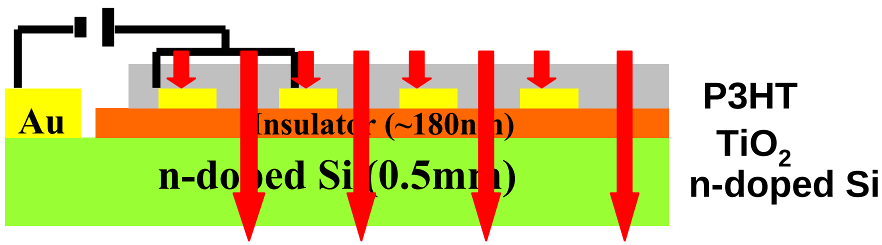


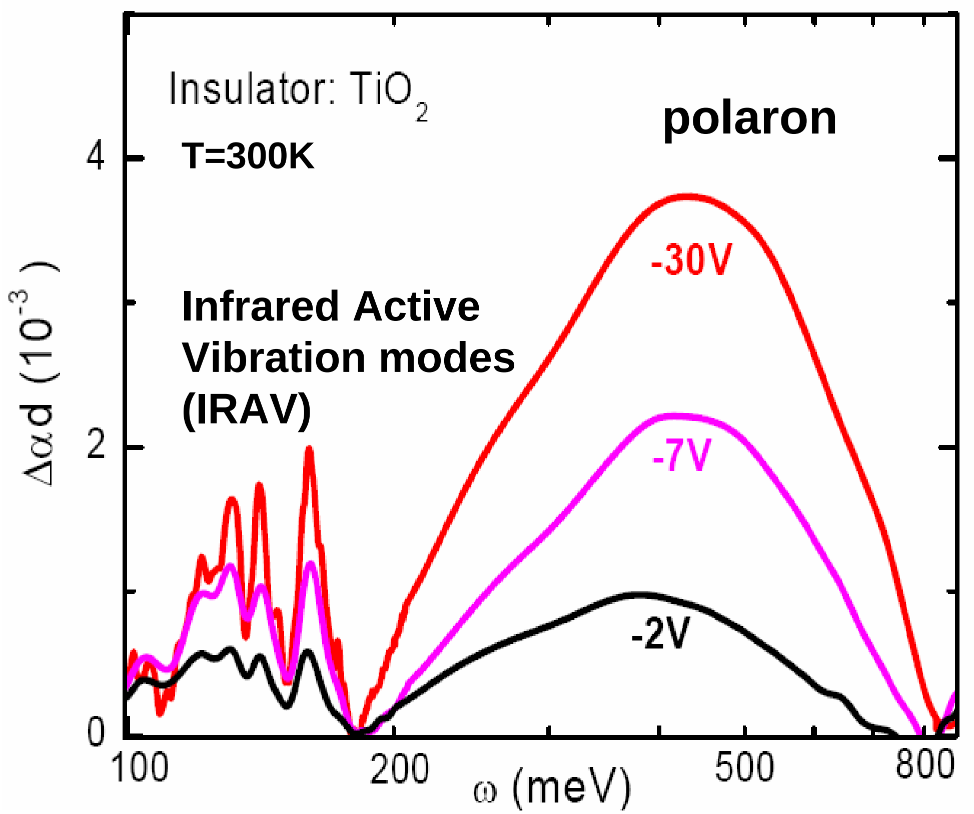
Z.Q. Li, et al, Nano Letters 6, 224 (2006).

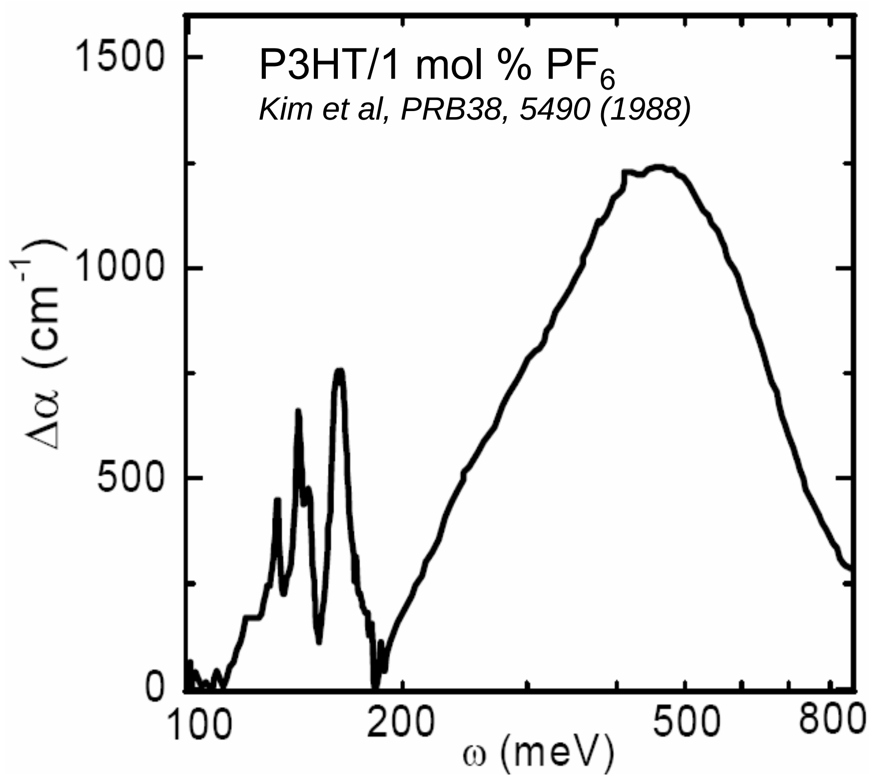
Electronic excitations in P3HT FET

Voltage induced absorption:

$$\Delta \alpha d \sim 1 - T(V)/T(0V)$$







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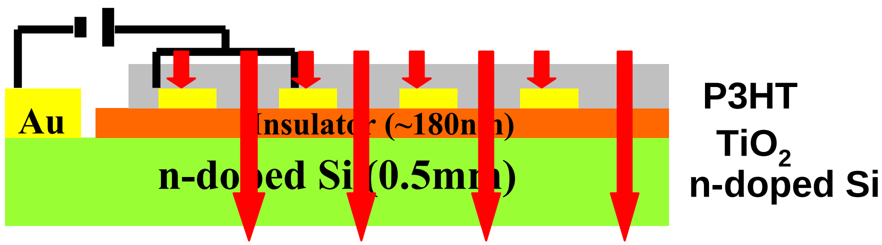
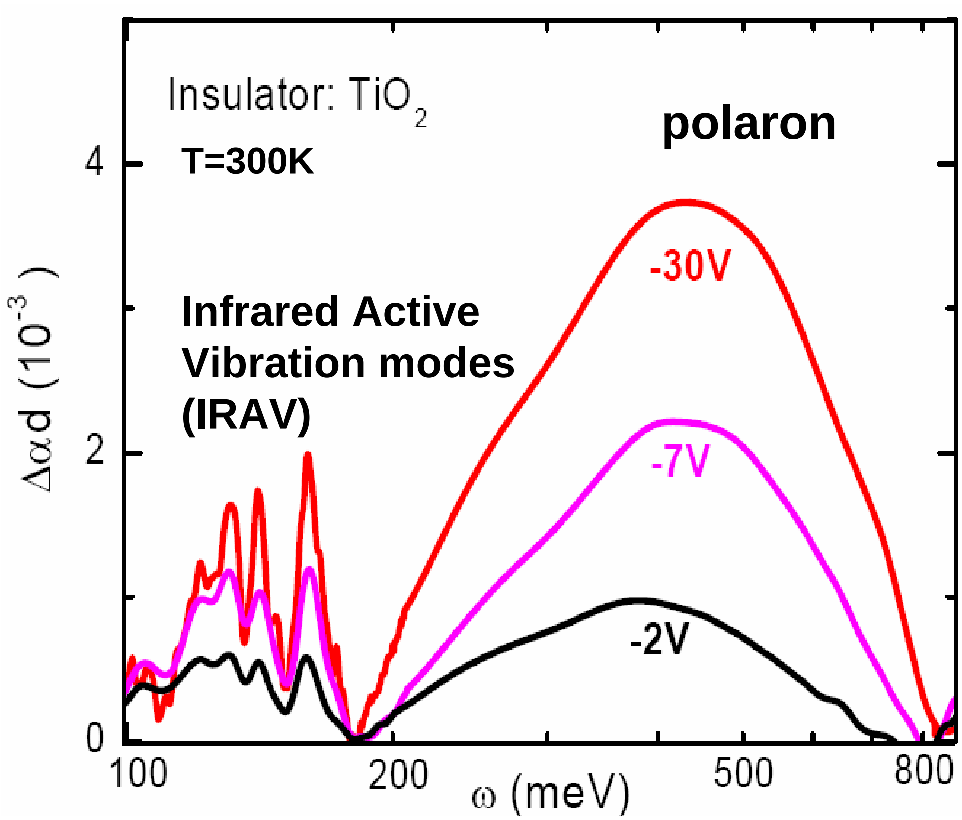
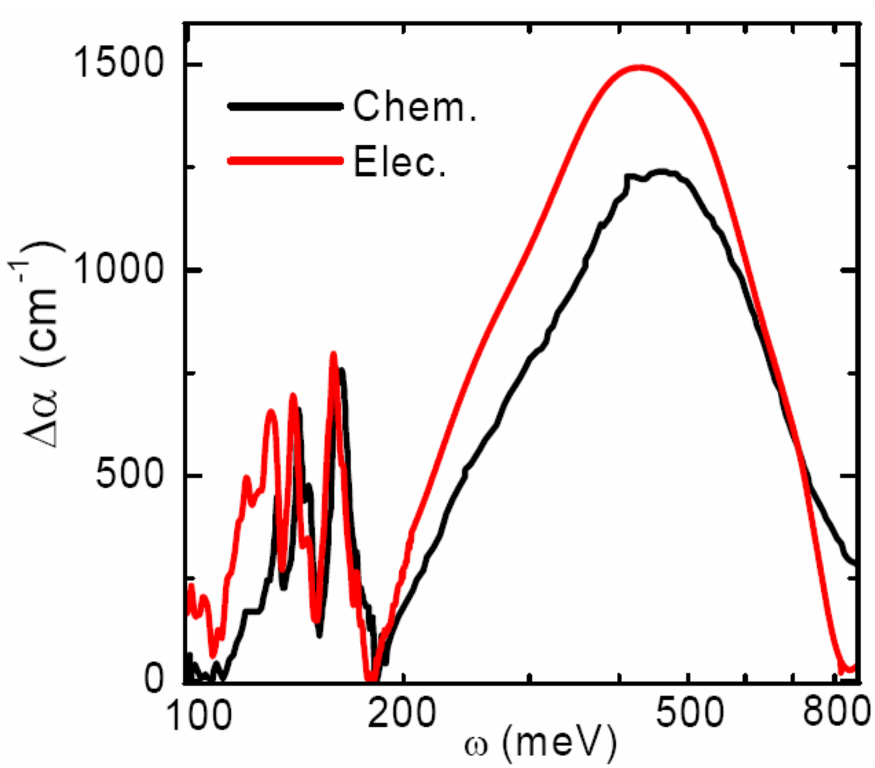
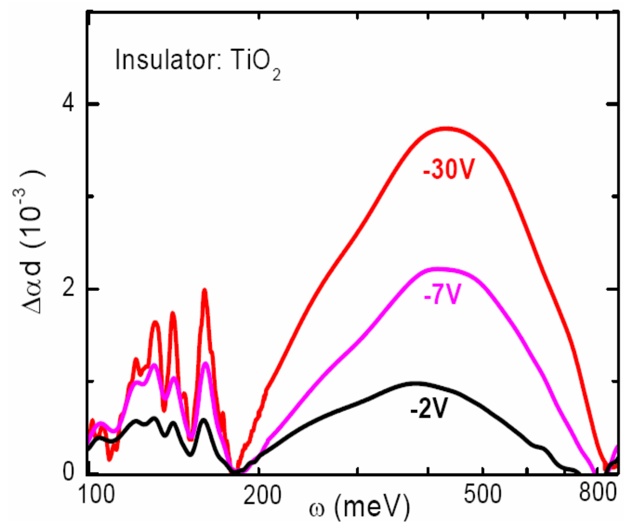


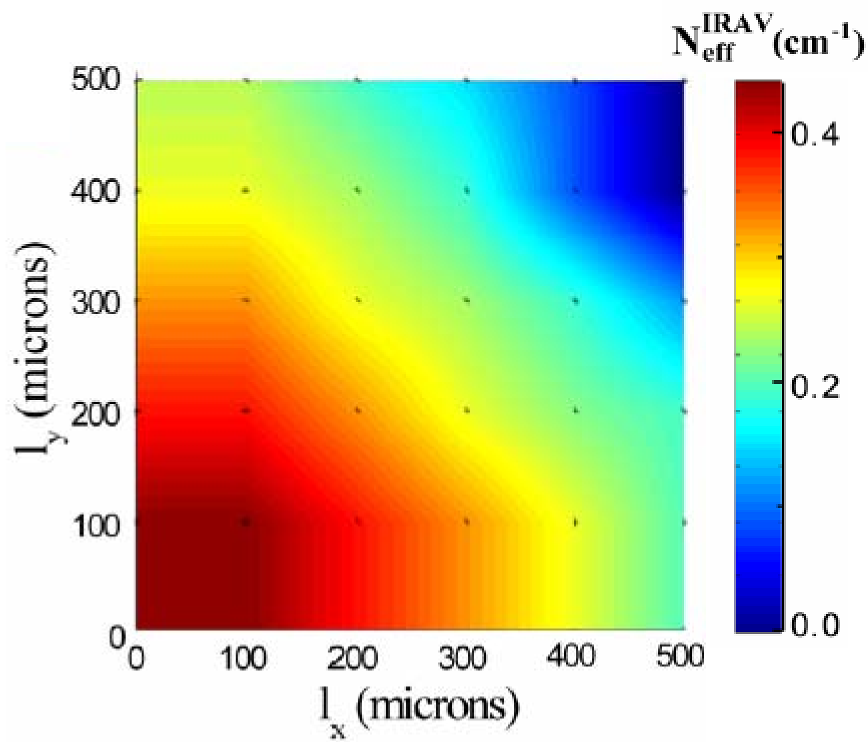


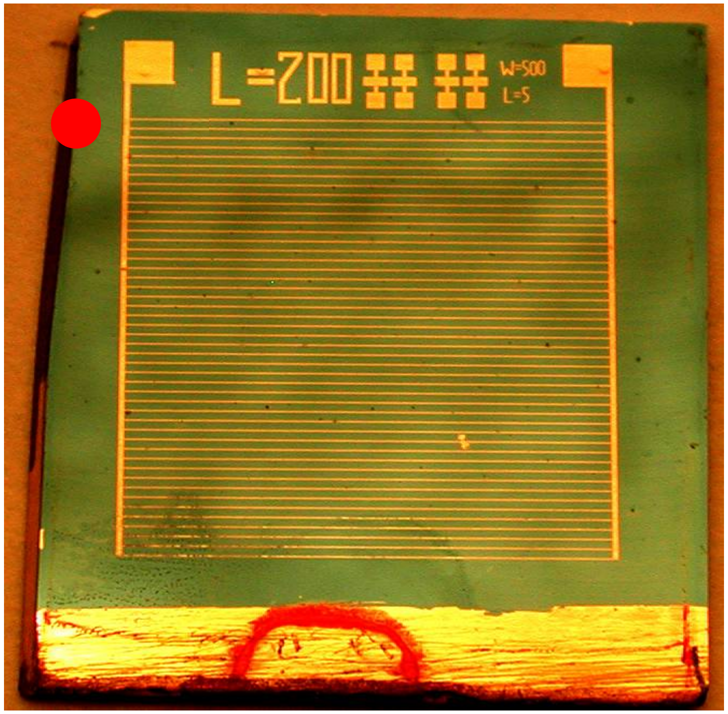


Z.Q. Li, et al, Nano Letters 6, 224 (2006).

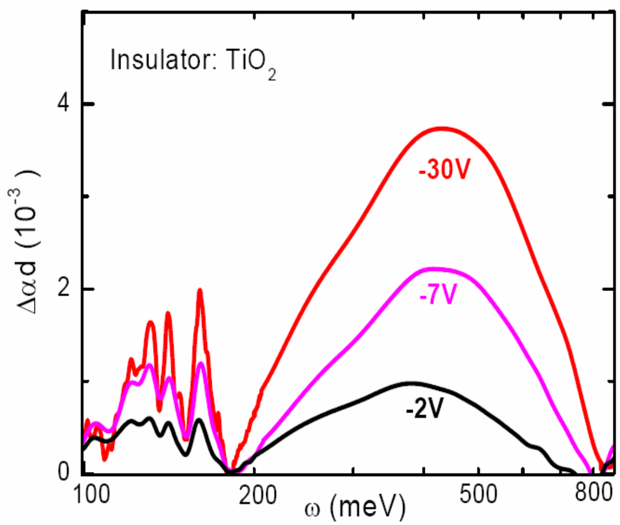
Microscopic study of charge injection

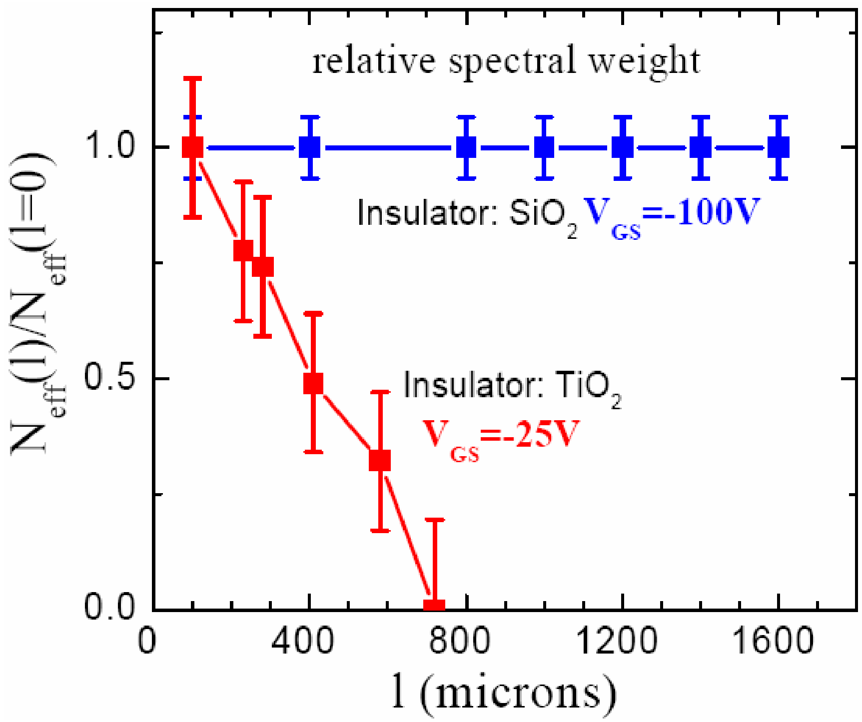


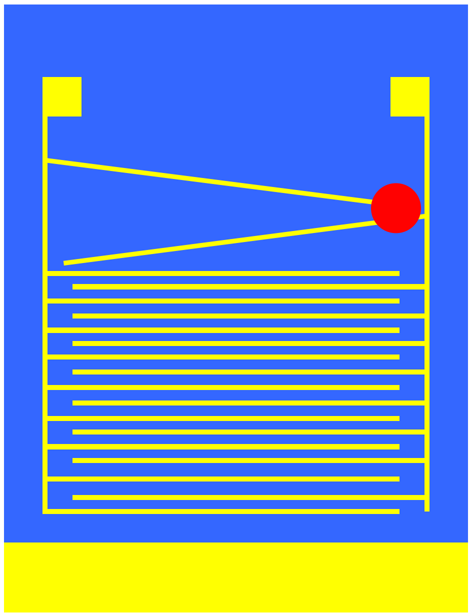




Microscopic study of charge injection



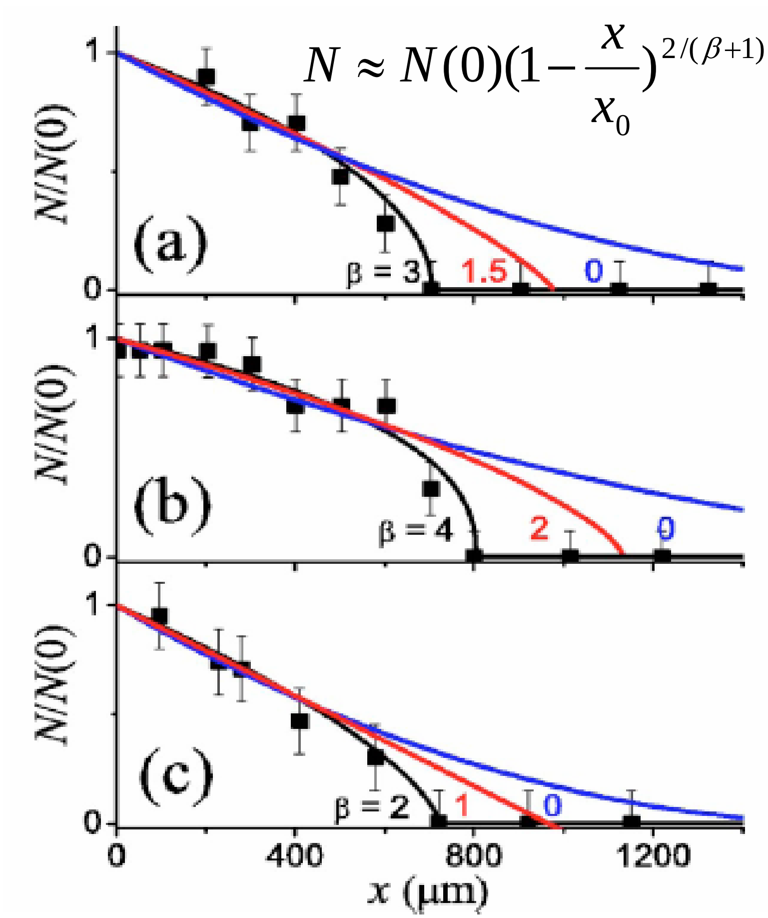


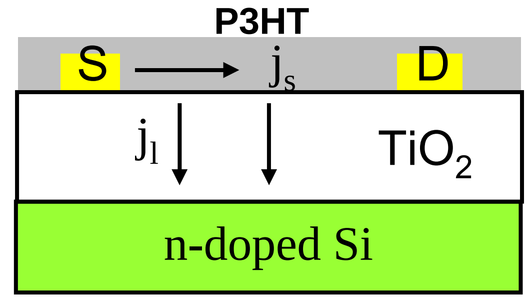


Microscopic study of charge injection

Insulator TiO_2

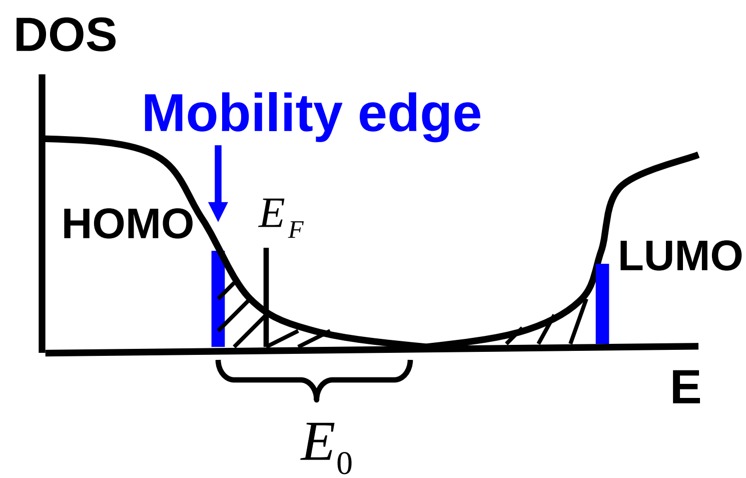
$$N \approx N(0)(1-\frac{x}{x_0})^{2/(\beta+1)}$$





$$-\nabla j_s = j_l$$

$$\nabla(N\nabla N) = N/(e\mu\rho_l)$$



Charge-induced localized states: bipolarons

$$\mu \sim N^{\beta}$$

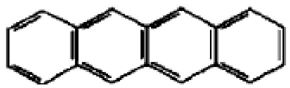
$$\beta = E_0 / k_B T - 1 \geq 0$$

A. D. Meyertholen, et al., Appl. Phys. Lett. 90, 222108 (2007).
N. Sai, et al., Phys. Rev. B 75, 045307 (2007).

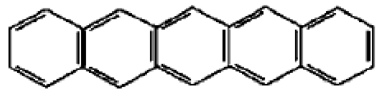
Charge transport in organic molecular crystals

Small molecule organic semiconductors:

Tetracene

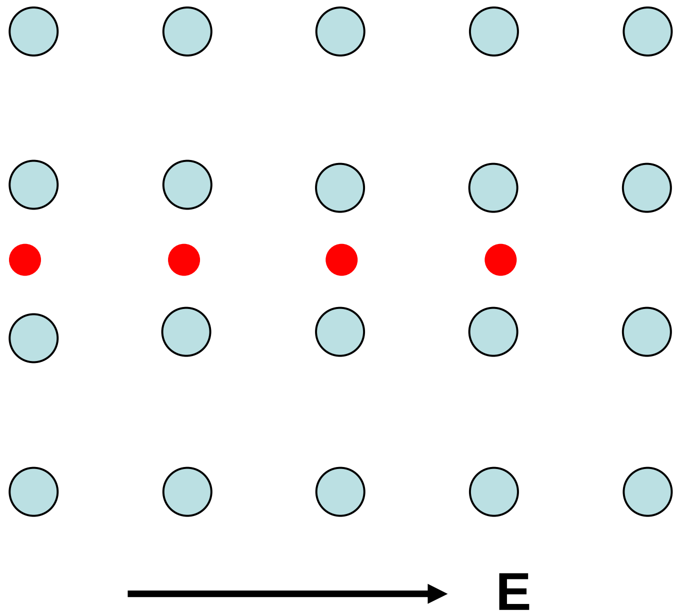


Pentacene



What is the nature of excitations responsible for charge transport?

Small polarons



Effective mass:

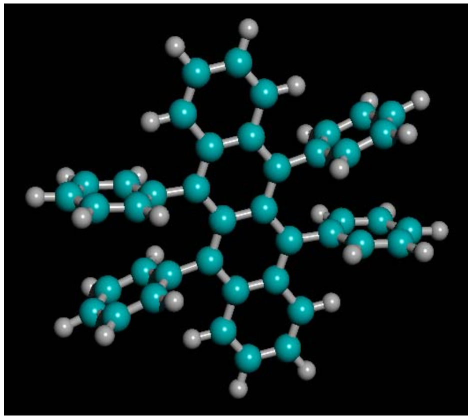
10-1000 band mass

E. A. Silinsh & V. Capek (AIP Press, New York, 1994).

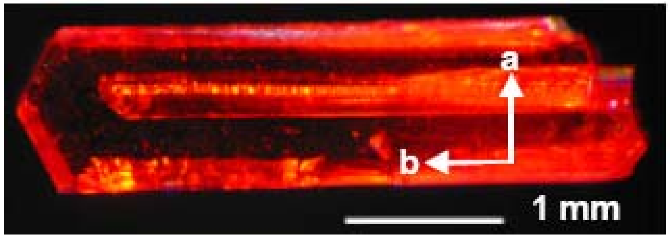
M. Pope, & C. E. Swenberg (Oxford University Press, New York, London, 1999).

IR study of single crystal rubrene FETs

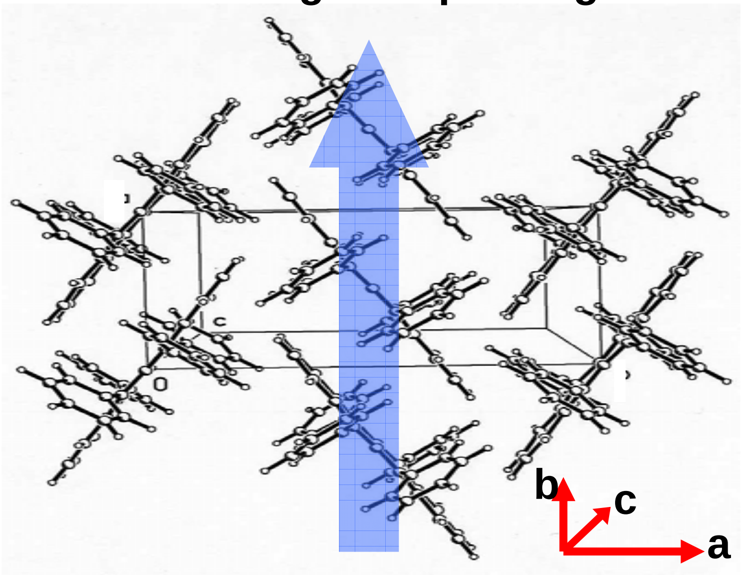
Rubrene: $C_{42}H_{28}$



V. Podzorov, et al, APL 82, 1739 (2003).



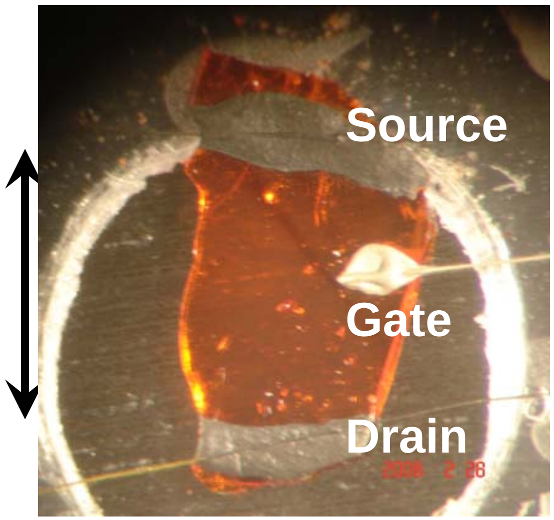
herringbone packing

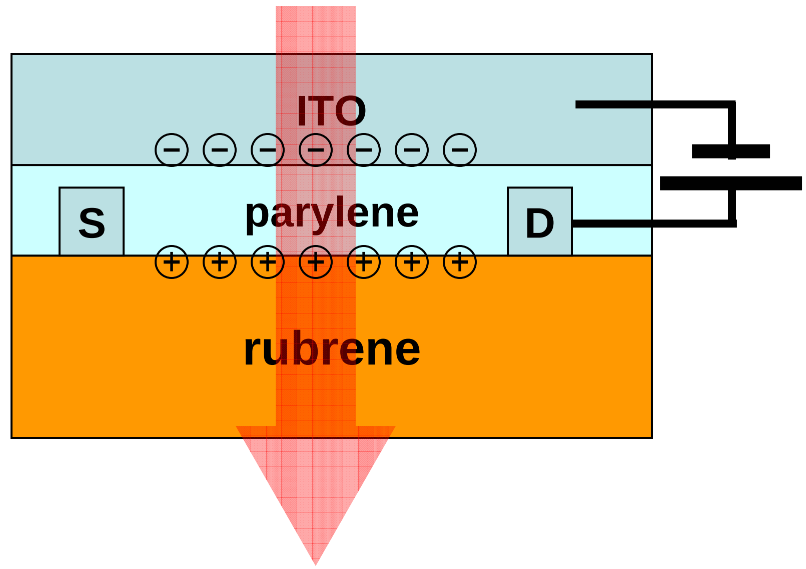


M. E. Gershenson et al, Rev. Mod. Phys. 78, 973 (2006).
V. Podzorov et al, PRL 93, 086602 (2004).

IR study of single crystal rubrene FETs

5mm





b axis $\mu \approx 5\ cm^2 / Vs$

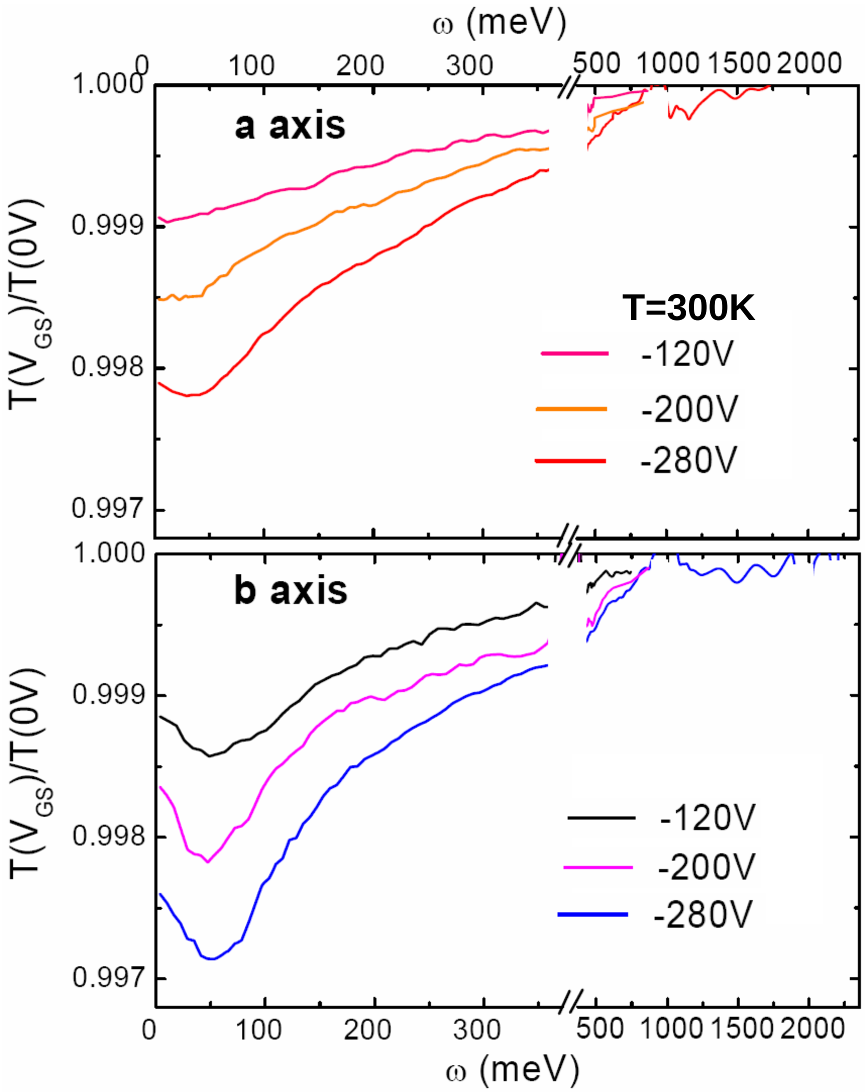
ITO = Indium Tin Oxide

Transmission as a function of gate voltage

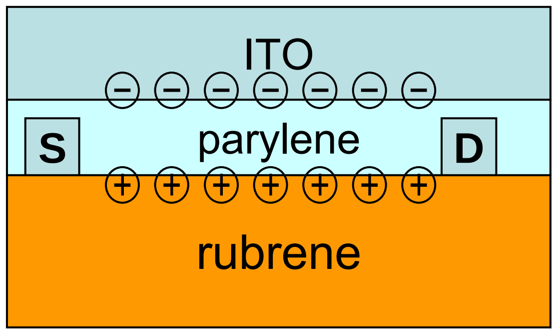
$$T(\omega, V_{GS})$$

Z.Q. Li, et al, PRL 99, 016403 (2007) .

IR response of rubrene FETs



Z.Q. Li, et al, PRL 99, 016403 (2007) .

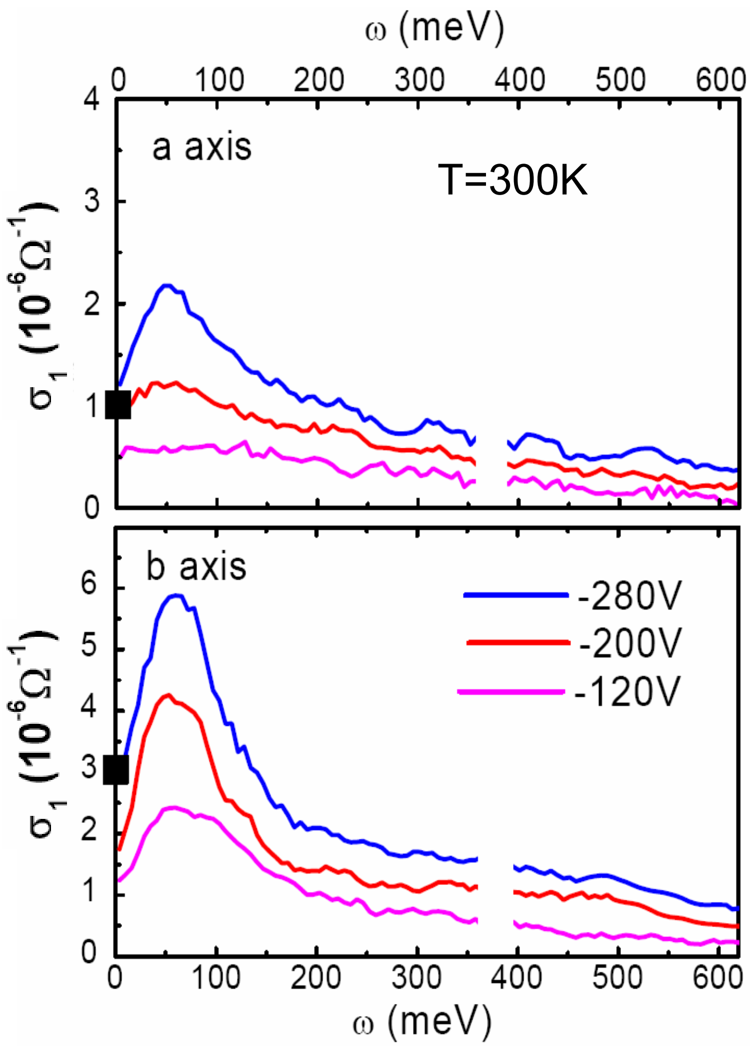


(1) Reflection, transmission and ellipsometric measurements

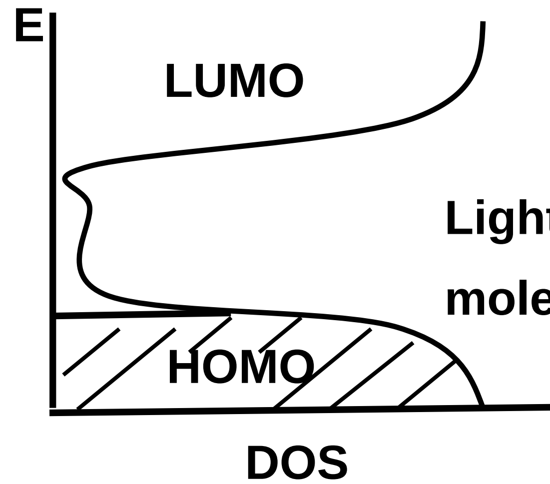
(2) Multi-layer modeling

Optical constants of the accumulation layer in rubrene

Charge transport in rubrene FETs



Z.Q. Li, et al, PRL 99, 016403 (2007) .



Light quasiparticles in molecular orbital bands

1: No low-energy gap in the optical conductivity

2: Anisotropy of transport properties and optical conductivity.

3: Small values of effective masses

$$\frac{n_{2D}}{m^*} = \frac{2}{\pi e^2}\int_0^{\Omega_c} \sigma_1(\omega)d\omega$$

$$m_a^* \approx 1.85 m_e \qquad m_b^* \approx 0.80 m_e$$

<u>**No prominent polaronic effects at 300K.**</u>

Spectroscopy and Charge Injection in Graphene

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Bell Labs, Alcatel-Lucent, Murray Hill

Zhao Hao, Michael C. Martin
Advanced Light Source, Berkeley

[Data to be published soon …]

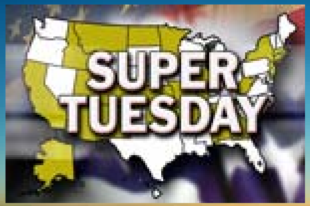
Synchrotron FTIR and HCM&MP

Synchrotron FTIR

- Microscopy on small samples or effect regions
- Broad optical conductivity capabilities
- Combined with:
  - cryogenics, high-fields, high pressure,
  - current-injection, optical pumps, THz pumps, …

Many Opportunities for Hard Condensed Matter & Materials Physics Applications.

MCMartin@lbl.gov



http://infrared.als.lbl.gov/