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Application of surface polaritons in thin SiC films to sub-wavelength lithography and compact particle acceleration

Gennady Shvets, University of Texas at Austin

Collaborators:

Alan Feinerman (UIC)
Chris Zorman (Case Western)
Herman Geraskin (UT)
Yaroslav Urzhumov (UT)

ATF Users Workshop, Brookhaven National Laboratory, January 9, 2004

What is proposed?

Test several near-field concepts at the ATF facility using its short-pulse CO_2 lasers:

-Sub-micron patterning of surfaces with a CO_2 laser

-Development of a SiC “single-wafer” accelerator/electron injector, also driven by a CO_2 laser

Who funds (or may fund) this?

- NSF’s Nanoscience and Engineering Research (NSER) Program → sub-wavelength lithography
- Argonne’s LDRD → cold tests and fabrication of SiC high-gradient accelerator structure
- DOE HEP → proposal in preparation

Collaborators and the team for this proposal

PI: Gennady Shvets, University of Texas at Austin

Senior researchers:

Alan Feinerman (UIC) → fabrication facility
Chris Zorman (Case Western) → growth of SiC films
Dmitry Korobkin (postdoc, joint UT/Argonne) → experiment (fabrication, thermoresist, laser testing)

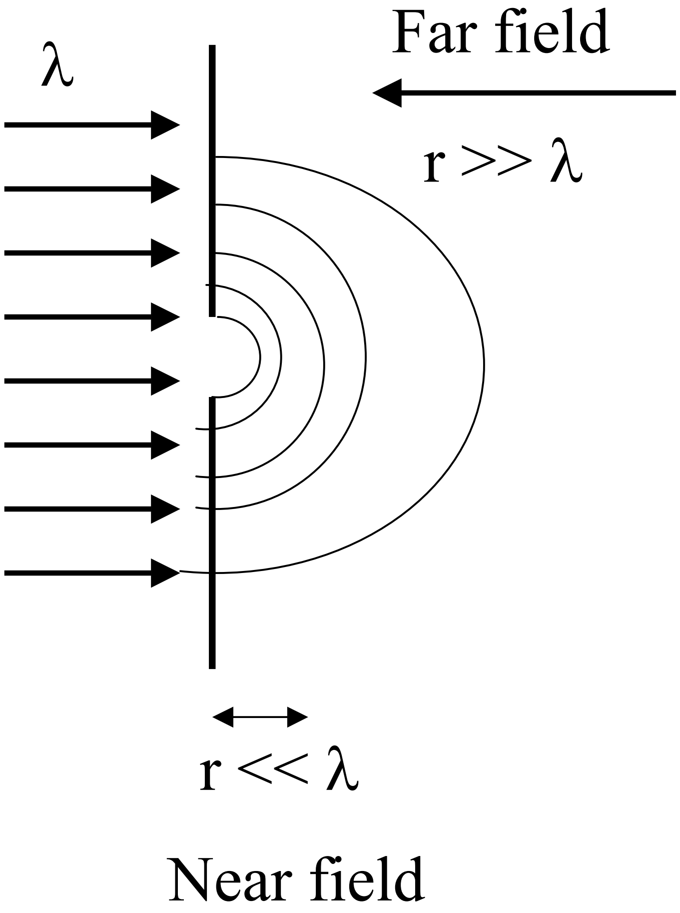
Graduate students:
Herman Geraskin (UT) → experiment, simulations

ATF: Igor Pogorelsky, Vitaly Yakimenko, Igor Pavlishin

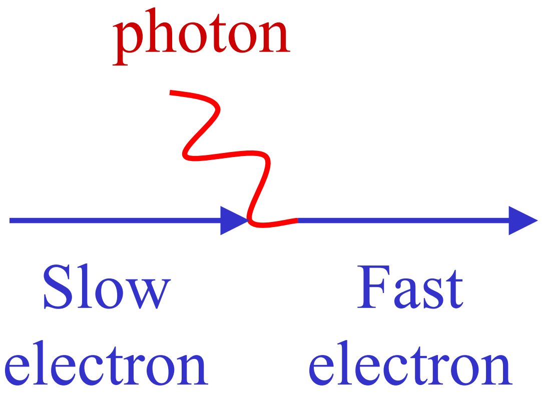
LDRD-funded effort at Argonne:

Wei Gai, John Power

What's wrong with far field, or What do nano-lithography and accelerators have in common?

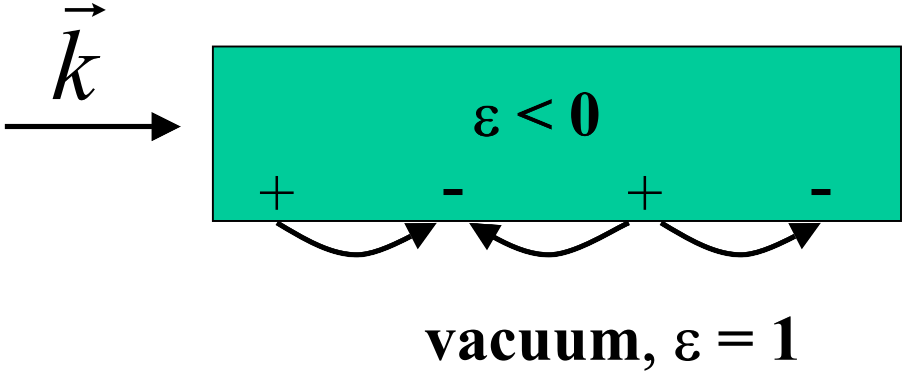


- Impossibility of linear in electric field acceleration (Woodward-Palmer's theorem)



- Impossibility of sub-wavelength resolution in far field (Abbe's resolution limit)

Near-field example: surface waves



$$k^2 = \frac{\omega^2}{c^2}\frac{\varepsilon}{\varepsilon + 1}$$

- Exponentially decays away from the interface
- Can accelerate non-relativistic charged particles
- Can be resonantly excited in the near-field

We propose to excite surface waves in mid-IR with a CO_2 laser and use it for lithography and accelerator applications

Outline of the talk

- **Motivation: why near field in mid-IR?**
- **Beating diffraction with a “super-lens”: Enhanced Near-Field Imaging**
  1. PENFIL: Phonon-Enhanced Near-Field Infrared Lithography with silicon carbide
- **SiC-based miniature surface wave accelerator :**
  1. Principle of operation and advantages
  2. Wafer fabrication
  3. Deposition of SiC films and testing

Why sub-λ resolution in mid- to far-IR?

•Many materials (plastic, ceramics, polymers) strongly absorb in IR → "sculpting" various surfaces on a nanoscale by delivering IR to small (100 nm)^3 volumes (laser ablation)

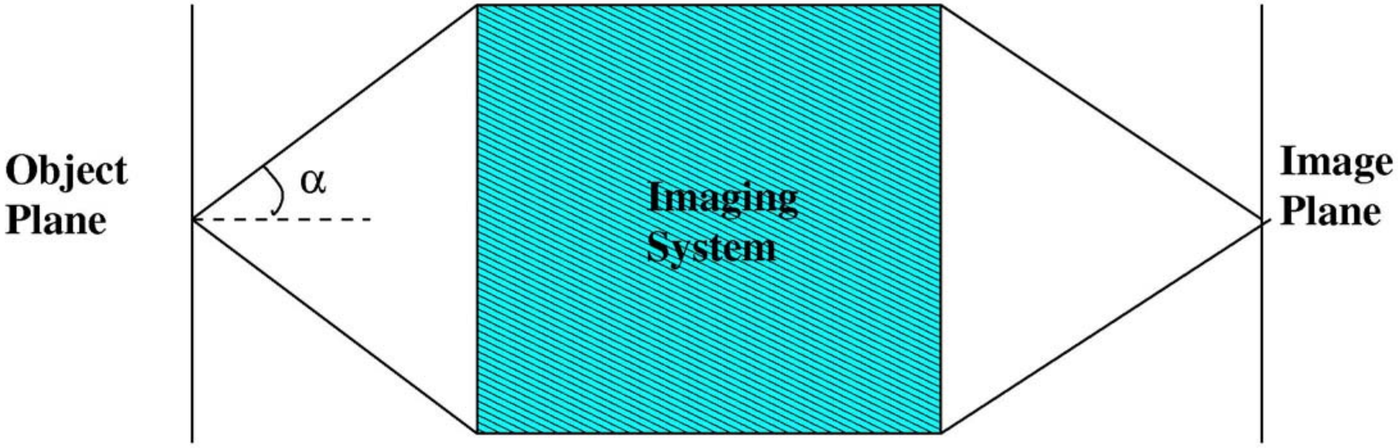
•Small biological objects (e.g., spores) can be imaged one at a time, by studying infrared Raman resonances.

•IR imaging and manipulation of biological molecules can be preferable to shorter wavelengths because it does not alter chemical composition.

•Ultra-compact accelerators driven by CO_2 lasers

EM fields predominantly longitudinal for very small (sub-λ) gaps

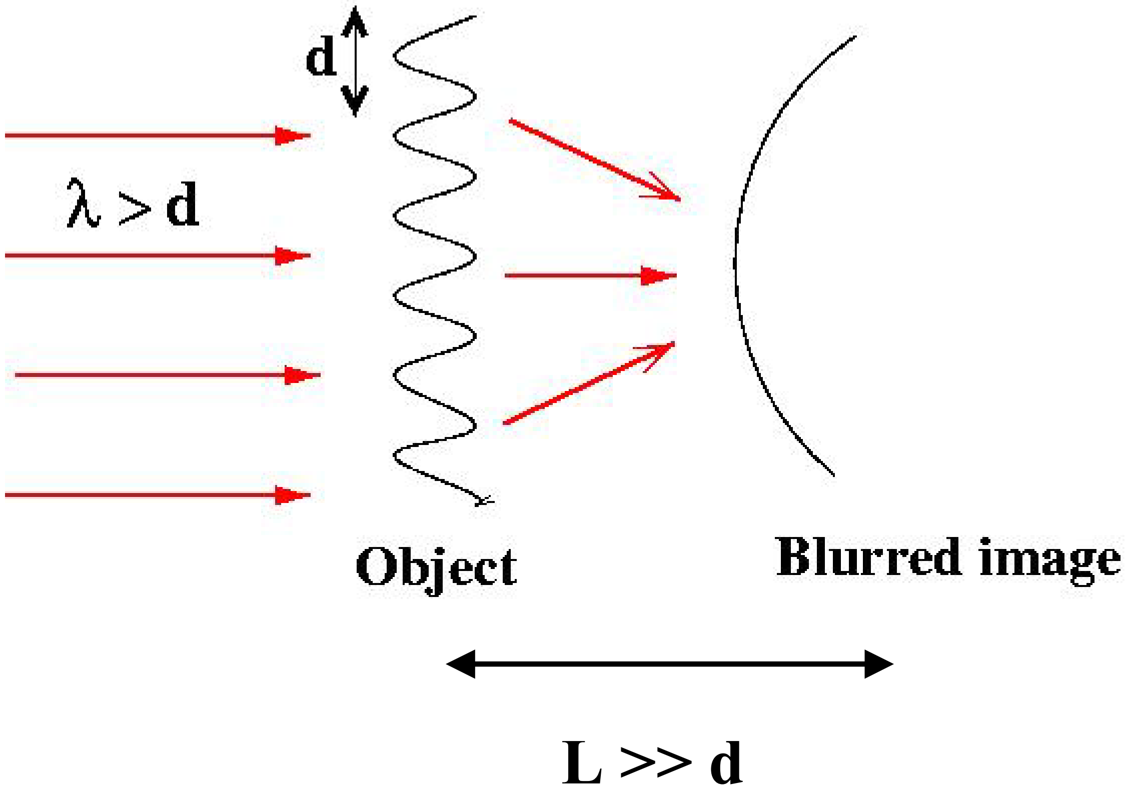
Abbe's Resolution Limit for Optical Microscope



$$\Delta x = -\frac{1.22\lambda}{2n\sin(\alpha)}$$

→ **Hard to resolve objects much smaller than ½ λ using conventional far-field optics.**

Imaging small-feature objects in far field



Small features (or large wavenumbers) of the object are lost because of the exponential decay of evanescent waves

Exponential decay of large-k waves

- **Magnetic and electric fields in the object plane are represented by a sum of plane waves:**

$$\mathrm{H}_z(x=0,y)=\int dk_\perp\ A(k_\perp)e^{ik_\perp y}$$

Spectral width Δk → feature size $\Delta y = \Delta k^{-1}$

- **Image reconstruction → propagation of A(k) through vacuum, medium, and lenses:**

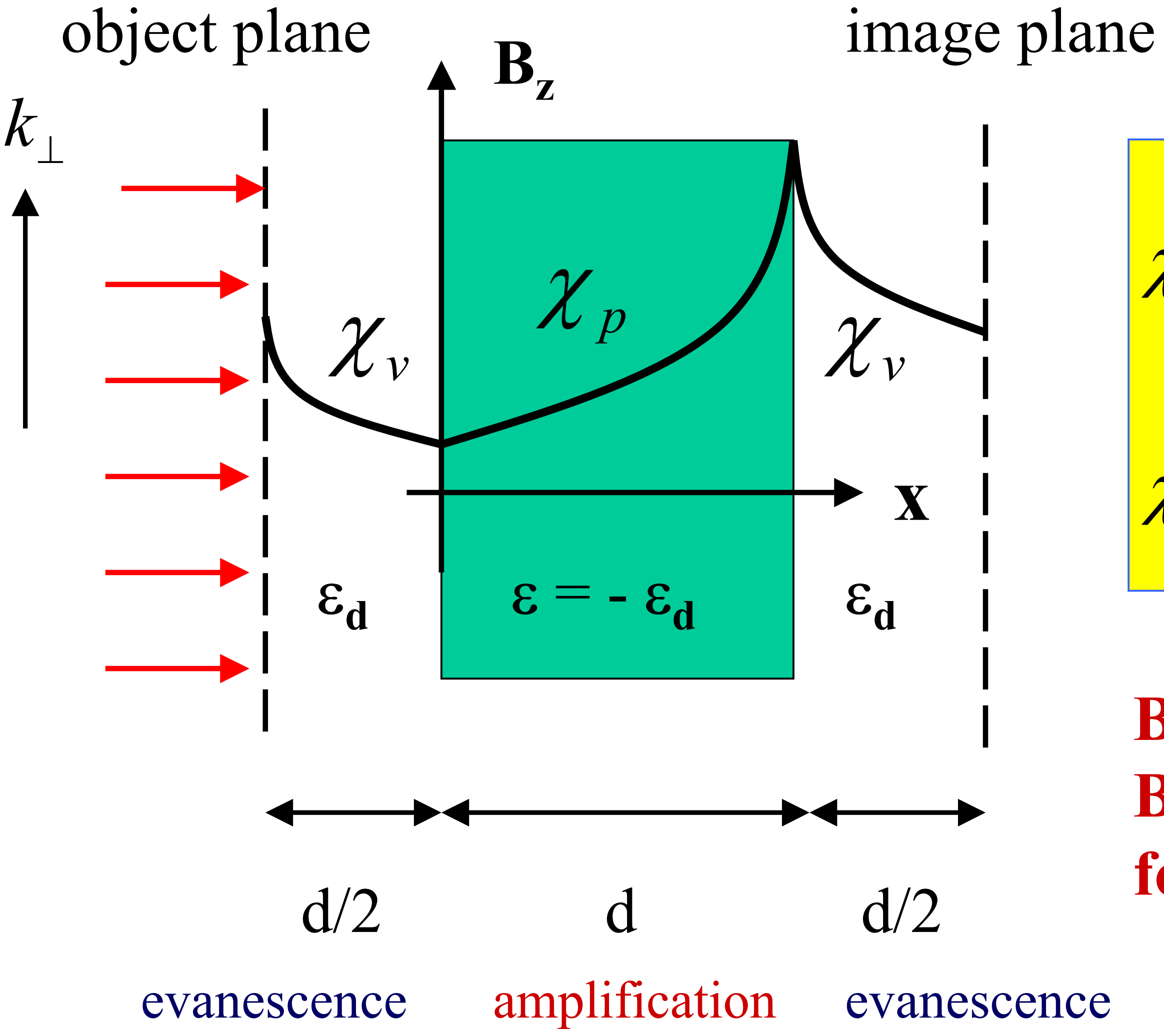
In vacuum

$$\begin{cases} A(k_\perp)\propto e^{i\sqrt{k_0^2-k_\perp^2}\,x} & \text{For smooth features with } k < k_0 = \omega_0/c \\ A(k_\perp)\propto e^{-\sqrt{k_\perp^2-k_0^2}\,x} & \text{For sharp features with } k > k_0 = \omega_0/c \end{cases}$$

•How to overcome decay?
Go near-field!

(a) get real close (L < d)
(b) **amplify evanescent waves**

Surface waves enable super-lensing



object plane

$\mathbf{B_z}$

image plane

$k_\perp$

χ_v χ_p χ_v

$\mathbf{x}$

$\varepsilon_{\mathbf{d}}$ $\varepsilon = -\varepsilon_{\mathbf{d}}$ $\varepsilon_{\mathbf{d}}$

d/2 d d/2

evanescence amplification evanescence

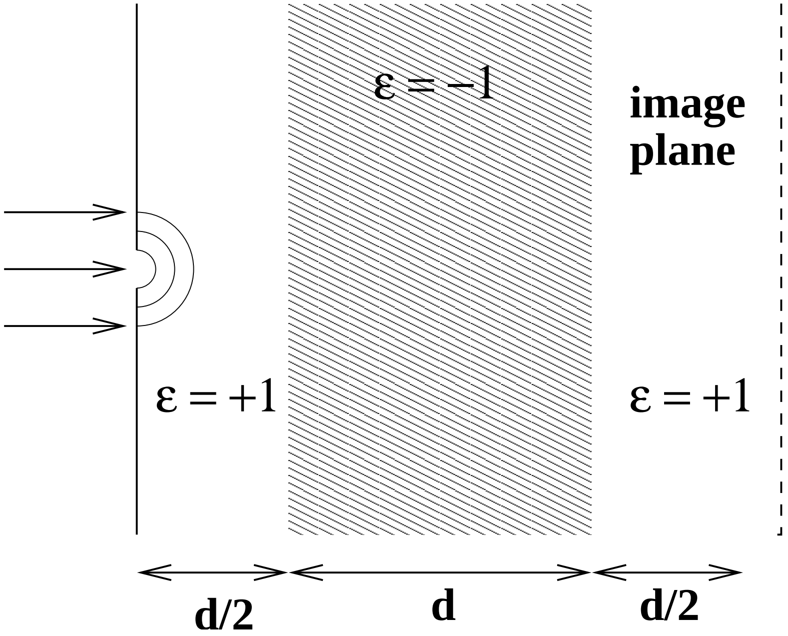
$$\chi_v = \sqrt{k_\perp^2 - \varepsilon_d \mu_d \frac{\omega_0^2}{c^2}}$$

$$\chi_p = \sqrt{k_\perp^2 - \varepsilon \mu \frac{\omega_0^2}{c^2}}$$

$\mathbf{B_z}$(object plane) =
$\mathbf{B_z}$(image plane)
for $\mu = -1$, $\varepsilon = -\varepsilon_{\mathbf{d}}$

$\mu = +1$ works too!

Poor man's super-lens: $\varepsilon < 0$, $\mu = 1$



What determines the accuracy of image reconstruction in the image plane?

1. **Retardation (finite lens thickness) → Important for $\mu = 1$ even if $\varepsilon = -\varepsilon_d$**
2. **Losses → $\varepsilon = -\varepsilon_d + i\,\sigma$**

$$\boxed{T = \frac{4(\chi_v/\varepsilon_v)(\chi_p/\varepsilon_p)\exp(-\chi_v d)}{(\chi_p/\varepsilon_p + \chi_v/\varepsilon_v)^2\exp(\chi_p d) - (\chi_p/\varepsilon_p - \chi_v/\varepsilon_v)^2\exp(-\chi_p d)}}$$

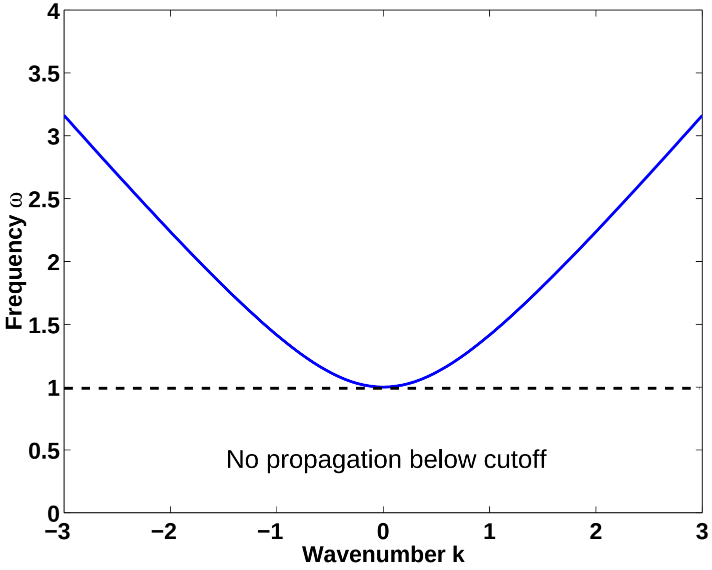
Ideally, want T = 1, but issues (1) and (2) interfere…

Choose a low-loss negative ε materials and design a near-field "super-lens"!

- **Plasma:** $\varepsilon = 1 - \omega_p^2/\omega^2$

  $\omega_p^2 = 4\pi e^2 n/m$

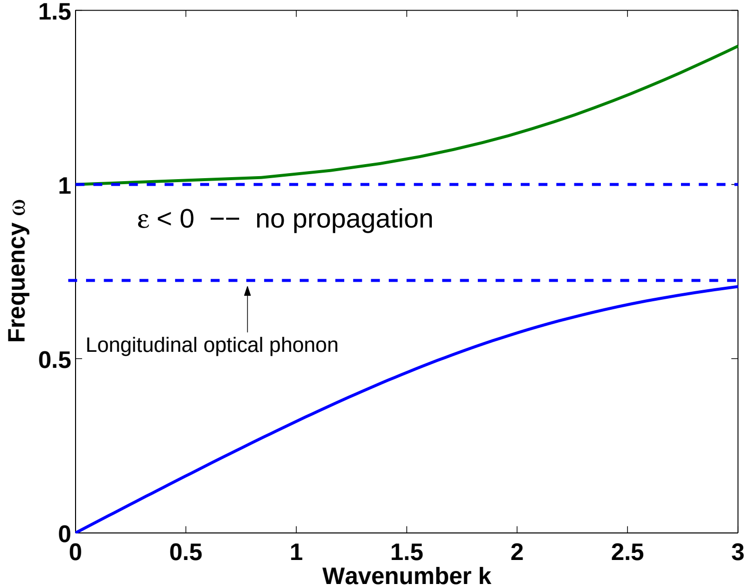
  Typically, ω_p is in 10^{15} Hz range in metals → surface plasmons



- **Polaritonic crystals (ZnSe, SiC):**

$$\varepsilon = \varepsilon(\infty)\frac{\omega_L^2 - \omega^2 + i\gamma\omega}{\omega_T^2 - \omega^2 + i\gamma\omega}$$

Typically, ω_T and ω_L are in 1-30 THz range → surface phonons



Proven properties of phononic materials

- **Smaller damping of IR phonons (reduced by cooling)**

$$\varepsilon = \varepsilon(\infty)\frac{\omega_L^2 - \omega^2 + i\gamma\omega}{\omega_T^2 - \omega^2 + i\gamma\omega}$$

For SiC $\gamma/\omega_L = 0.005 \ll 1$

For ZnSe $\gamma/\omega_L = 0.001 \ll 1$

- **Higher sensitivity to surface quality and laser frequency is explored in surface science! (Hillenbrand et. al., Nature 2002)**

- **Desirable $\varepsilon = -1$ regime is not accessible in mid-IR using metal films**

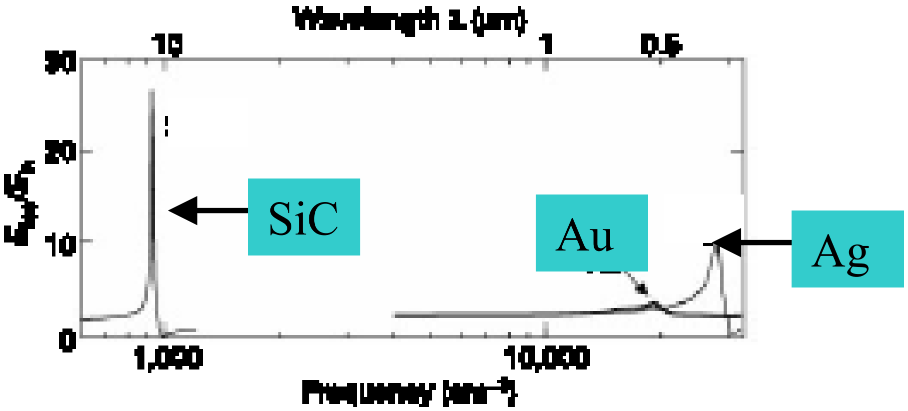
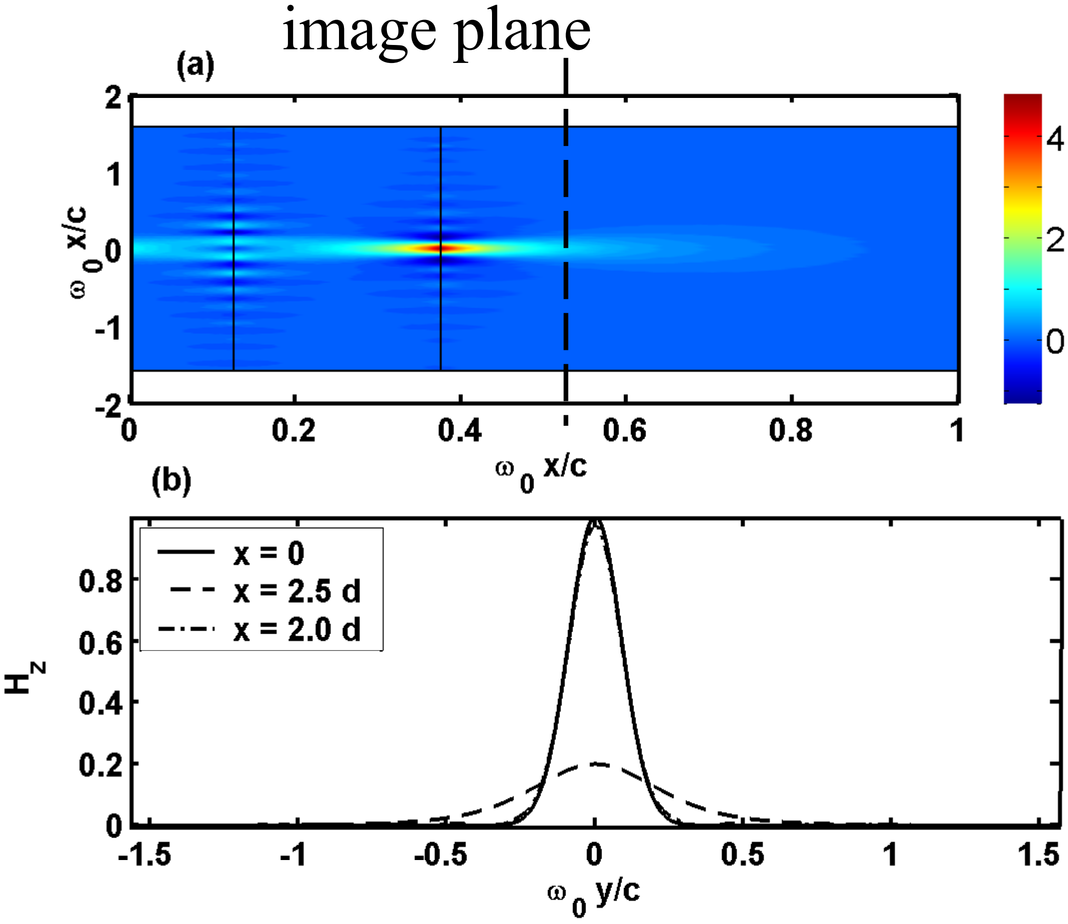


Figure 1 Calculated field enhancement E_{loc}/E_{in} due to Fröhlich resonance at the surface of a 10-nm-diameter sphere. The infrared lattice vibration (phonon) of a polar dielectric (SiC) induces a considerably stronger near-field amplitude than the green/blue electronic excitation (plasmon) of a noble metal (Au, Ag).

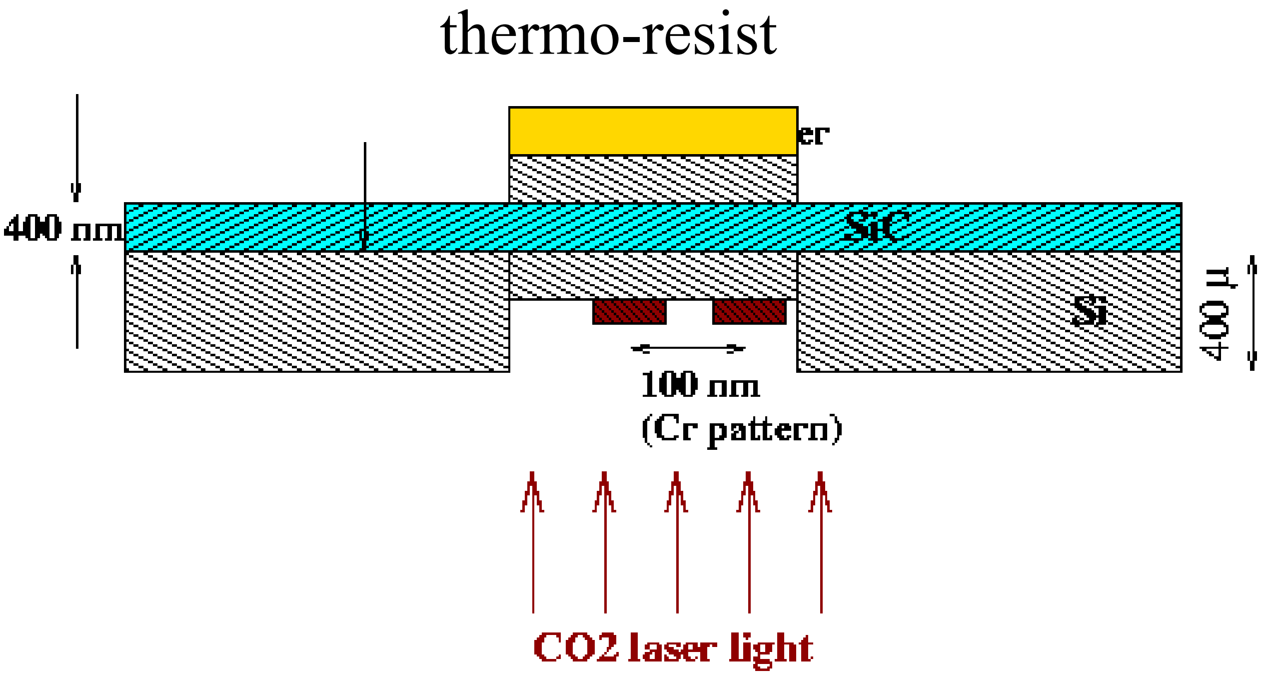
Enhanced Near-Field Imaging (from Shvets, Phys Rev B 2003)



- Object: thin slit of width w = 0.21 μm = λ/50 at x=0
- Lens: between x=d/2 and x=1.5d planes (SiC with ε = -1)
- Image: in x=2d plane
- Blurred image (conventional near-field): in x=2.5d

Observe significant image improvement with SiC lens

Phonon Enhanced Near Field Infrared Lithography (PENFIL)



Why do we need ATF's lasers?

- Short pulse duration (melt before heat spreads)
- Low heat conductance/heat capacitance for absorber
- Surface phonon resonance requires $\varepsilon_{SiC} = -\varepsilon_{Si}$ → tunability

Applications of miniature accelerators

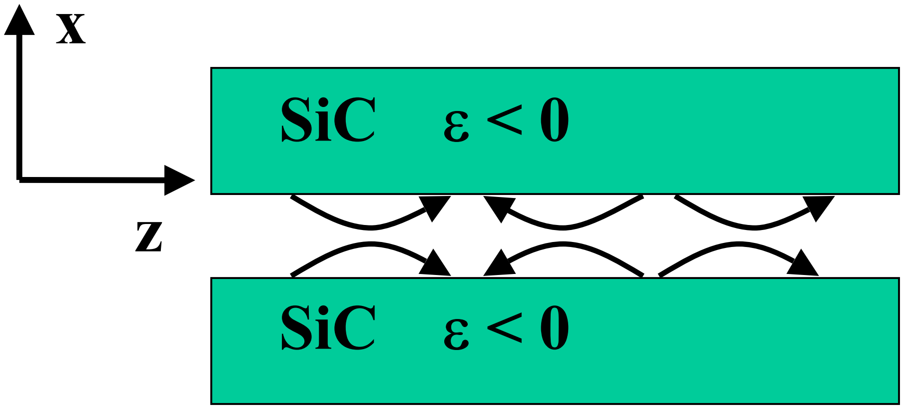
Otto Zhou (2002): 14keV X-ray image using CNT cathode

- Miniature X-ray sources for medical imaging
- Novel high-gradient HEP accelerators
- Injectors into plasma accelerators
- Tiny cathodes exist for tiny accelerators: CNTs in 50nm bundles
    - Durable (field emission v.s thermal)

Challenge: increase electron energy (100's keV for medicine, 10's MeV/wafer for HEP)

Solution: single-wafer surface-wave accelerator

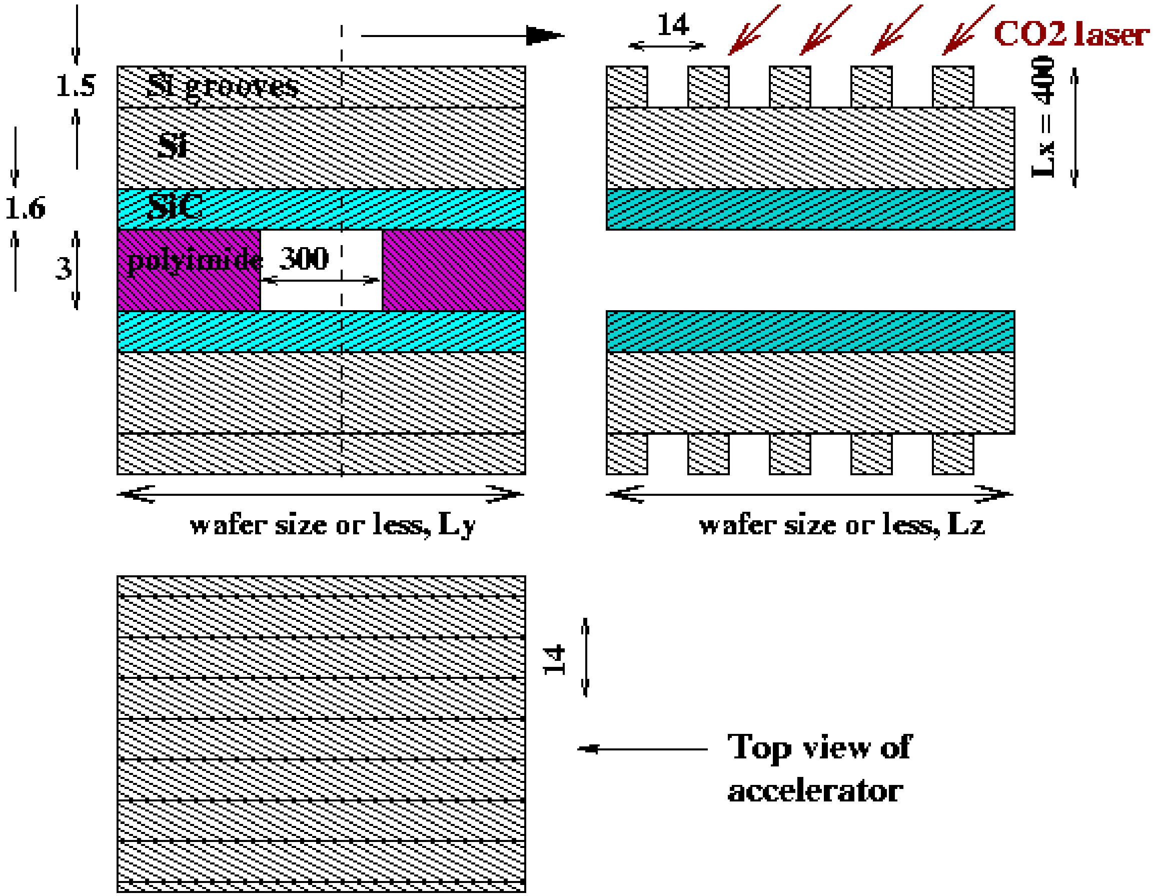
Novel miniature surface-wave accelerator



- Supports $\omega = kc$ mode
- Near field (small gap) → attractive ratio E_z/E_x

- Can support high fields → no breakdown (for W=300 Mev/m DC) because of large band gap: 2.3 eV for 3C-SiC
- Supports high frequency surface waves ($\varepsilon = -1.2$ for $\lambda = 10.6\ \mu m$) excitable by CO_2 laser.

Schematic of SiC Surface Wave Accelerator



- Grating necessary to couple into Si with appropriate wavenumber
- Accelerating mode “leaks” from cavity into Si → high-Q coupling
- Cold tests: study reflection and transmission coefficients as functions of incident angle and frequency

Accelerating surface mode: $\omega = \omega(k)$

Microfabrication Applications Laboratory

MicroFluidics Center

Initial fabrication was done at

Microfabrication Applications Laboratory

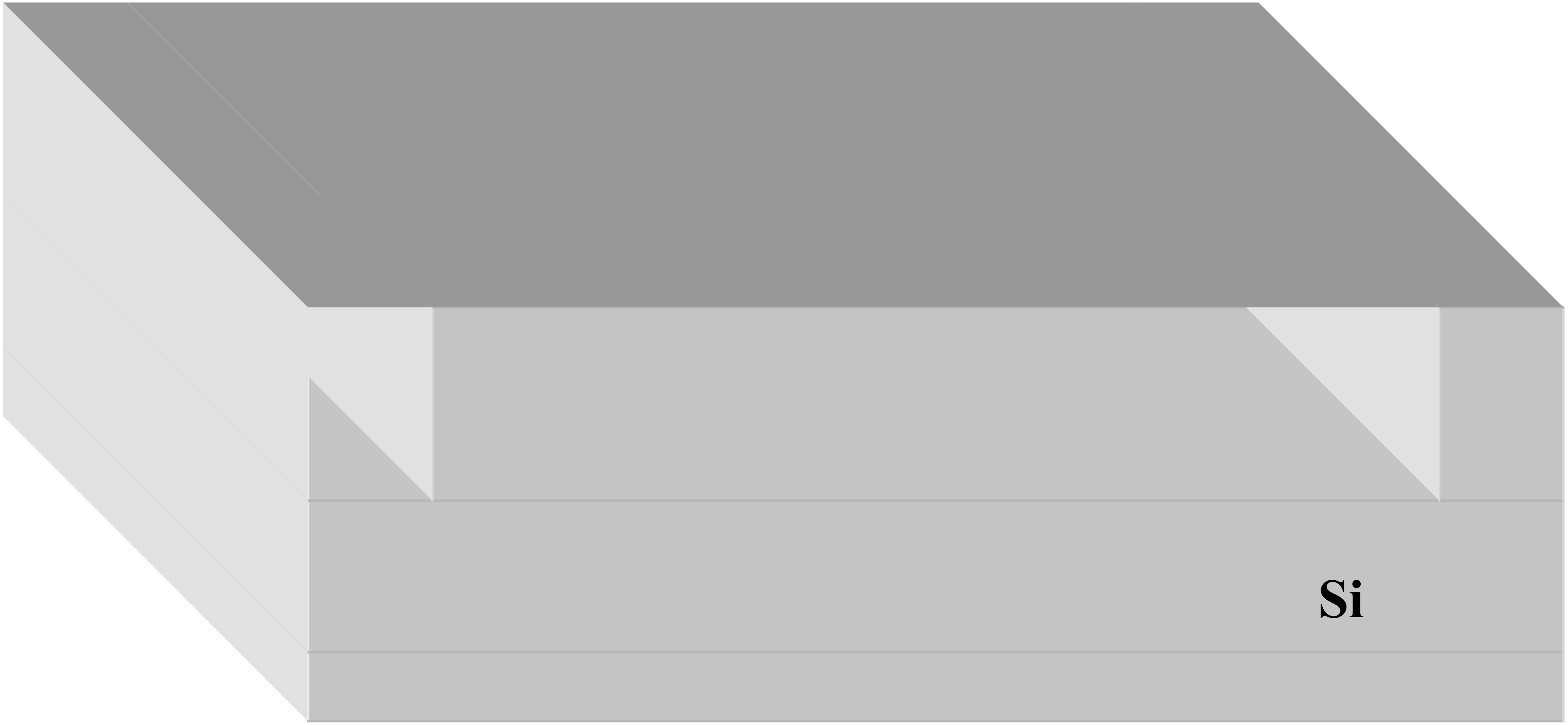
at University of Illinois at Chicago

http://www.mal.uic.edu/

Summer 2003

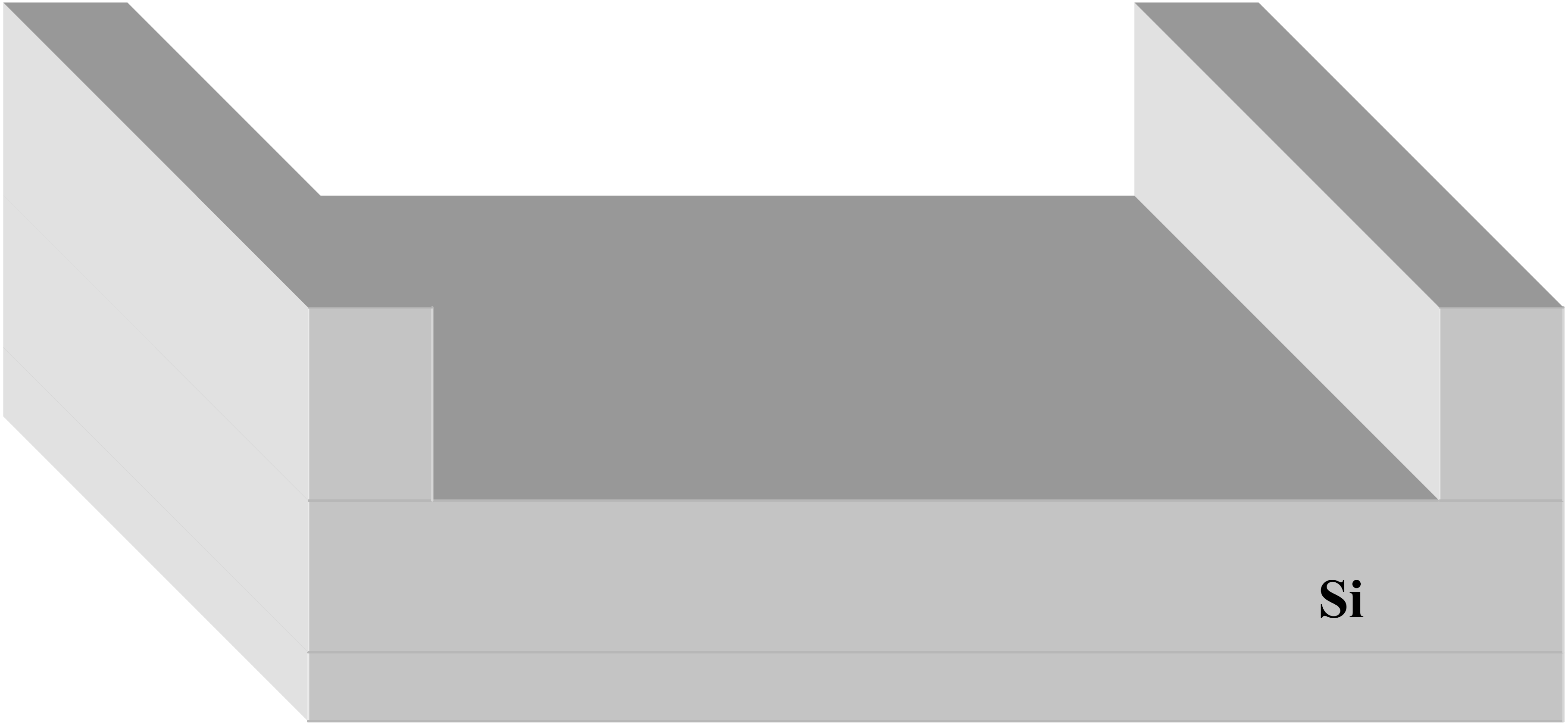
Schematic representation of fabrication method

As a base of acceleration structure we use conventional Silicon wafers:



Schematic representation of fabrication method

3 – 4 microns deep cavity is made on one side of the wafer:



Schematic representation of fabrication method

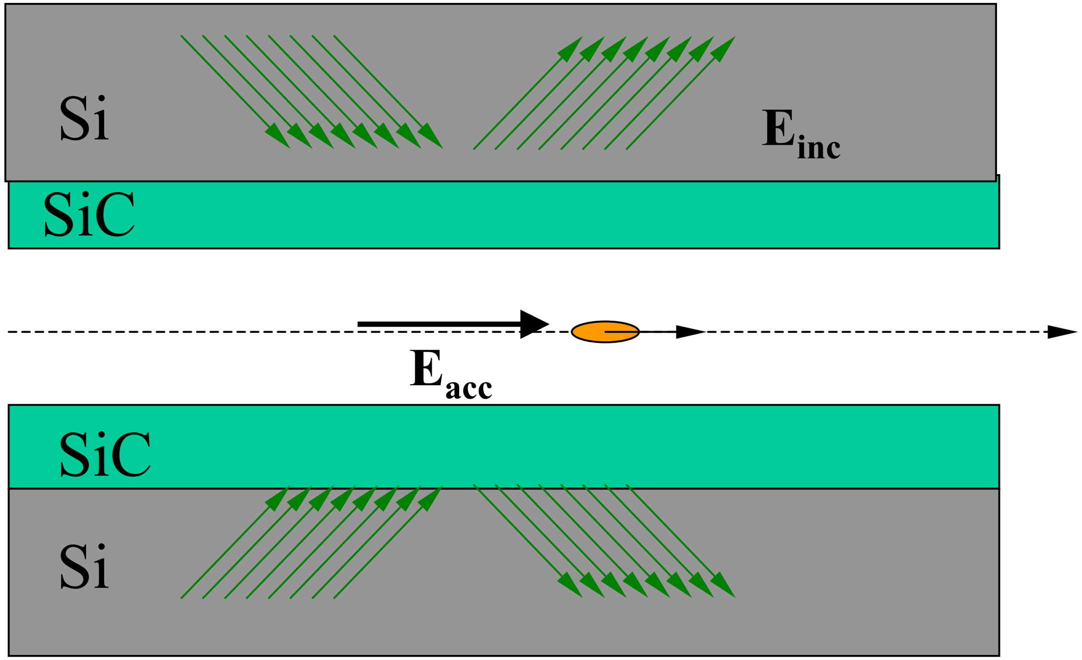
1.5 – 2 microns SiC film is deposited on the internal surface of cavity (done at CWRU)

Schematic representation of fabrication method

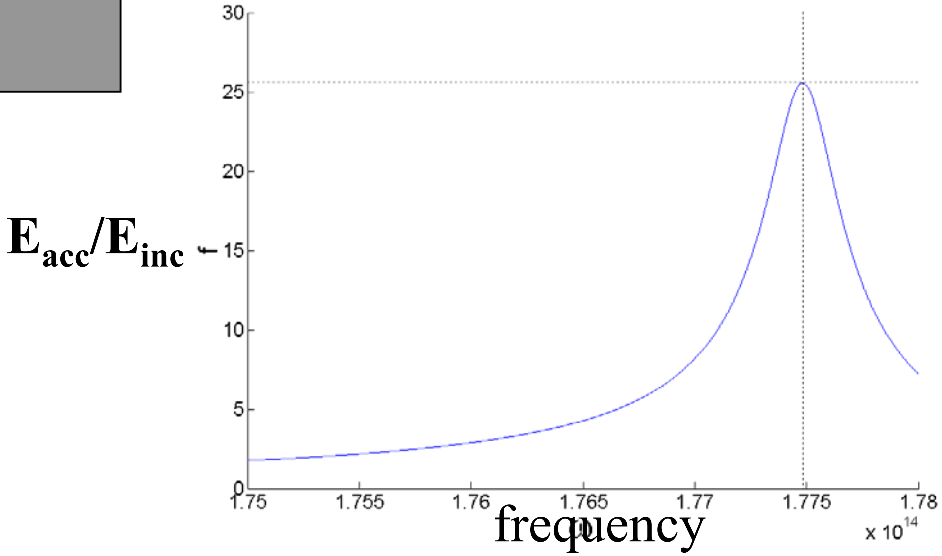
Diffraction grating is made on the other side of wafer:

Wafers are bonded together – accelerator is ready!

What’s so great about this accelerator?

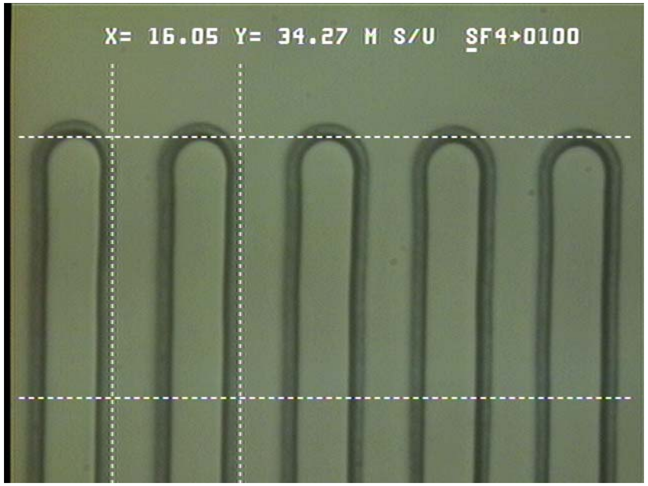


- **Can maximize the ratio E_{acc}/E_{inc} → resonance!**
- **Seek this maximum by varying laser frequency or incidence angle → drop in reflectivity**

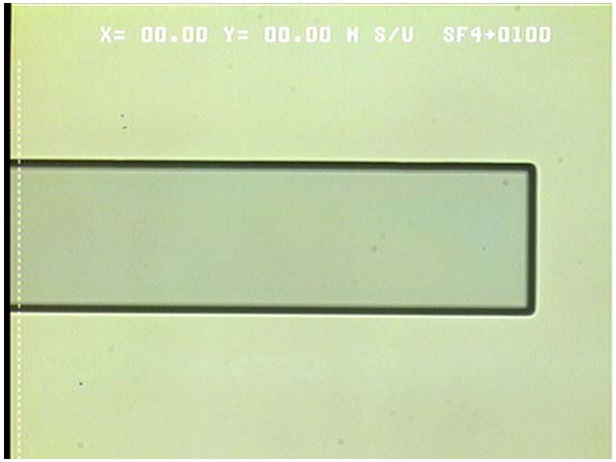


For 2 μm SiC film find field enhancement = 25

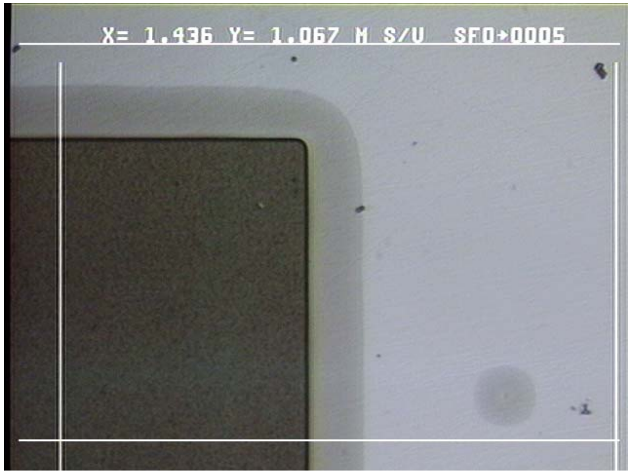
Fabrication Progress



Coupling grating, spacing = 16 μm, depth = 1.6 μm



Accelerating cavity, depth = 3.0 μm



1.5 μm layer of SiC at the bottom of the Si cavity has been deposited

Conclusions

“Explosive” combination of a low-loss polaritonic material (SiC) and a short-pulse high-power driver (CO_2 laser) can be explored at the ATF for two promising applications

•Enhanced near-field nano-lithography in IR

•New advanced accelerator concept: not metallic, not dielectric, not plasma → single-wafer surface wave accelerator. Uses standard wafer processing techniques → potentially cheap!

We already know how to fabricate the structures. Preliminary proof-of-principle cold tests will be done at UT and Argonne.

We need short-pulse (30 – 100 ps) CO2 laser to demonstrate lithography and to test the accelerating structure. We are undemanding users: don’t require a beam, don’t ask for 2 ps pulses.