Laser Flash Photography and Thermal Imaging of Microscale Structures

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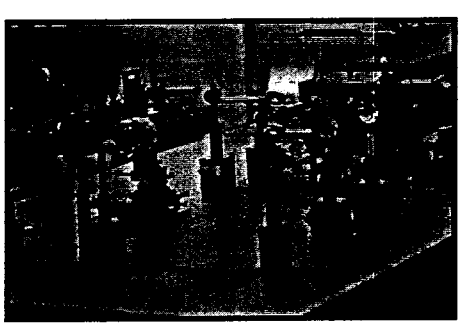
Outline

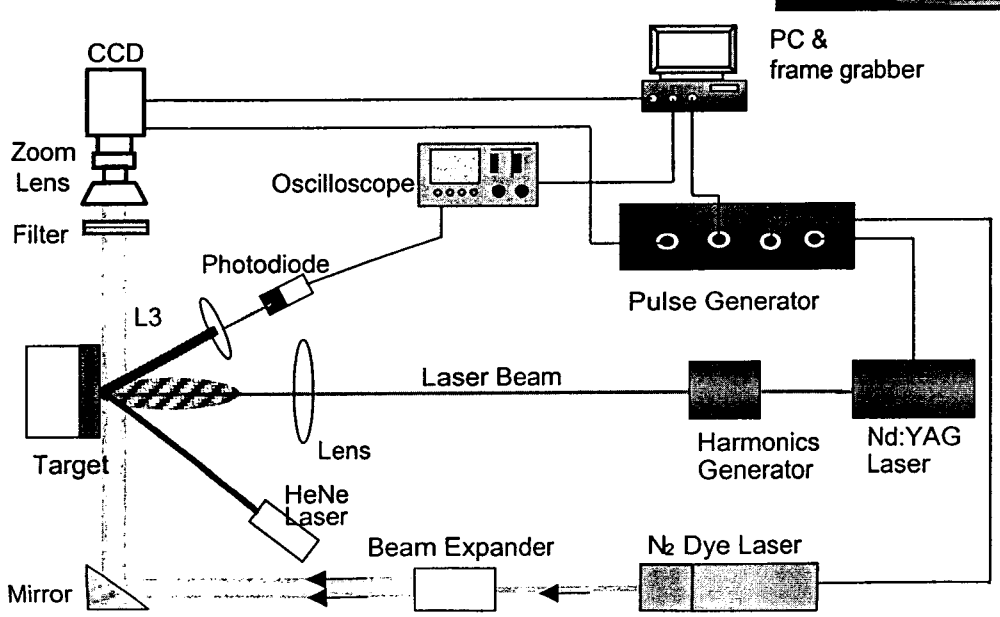
- Introduction
- Laser flash shadowgraphy and applications in laser-materials processing
  - Modeling of laser-material interaction
  - Laser nanoparticle synthesis
  - Laser cleaning
  - Ultrafast laser processing (pump-and-probe imaging)
- Thermal imaging of MEMS & Microstructures
  - Scanning Thermal-Wave Microscopy
  - Cross-Sectional Thermal Imaging of an Operating MOSFET

Laser flash photography

- Motivation
  - Effective for probing rapid thermal phenomena (high temporal resolution ~ laser pulse duration)
  - Non-intrusive imaging
  - Low cost but single-frame per incidence
  - Quantitative measurement often difficult

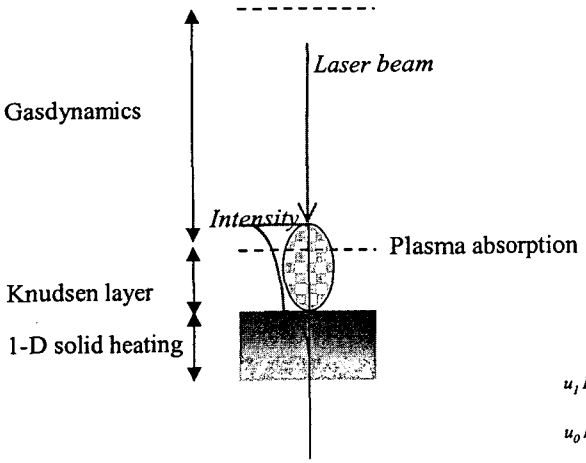
- Measurement modes
  - Scattered light, shadowgraph, Schlieren image, LIF (laser-induced fluorescence)
  - Pump-and-probe or two-laser set up

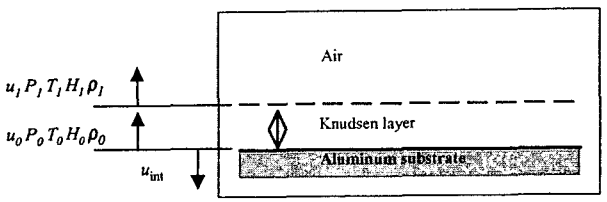


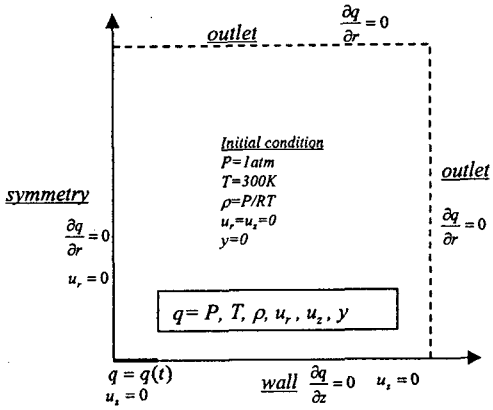


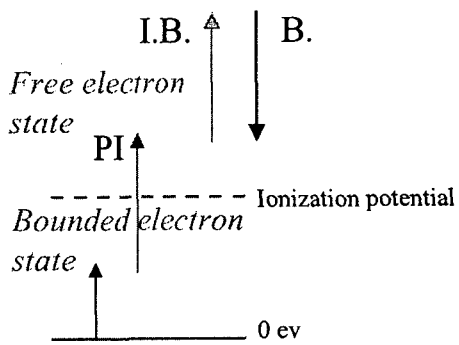
Numerical modeling of pulsed laser ablation

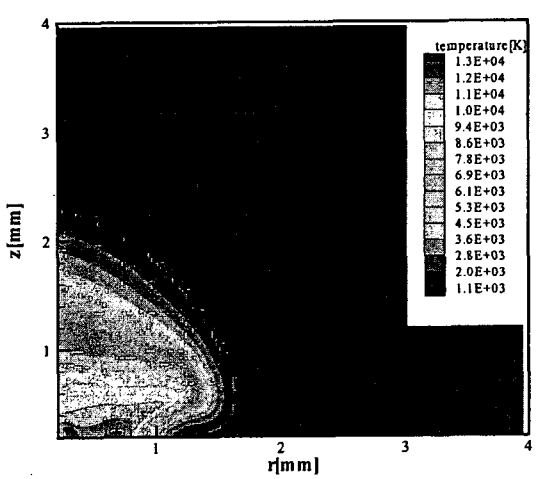
- Substrate model
- Vaporization model
- Jump conditions over Knudsen layer
- Gas Dynamics
- Plasma absorption mechanism

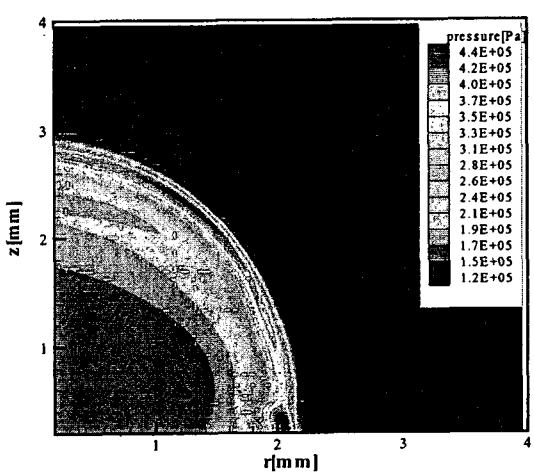


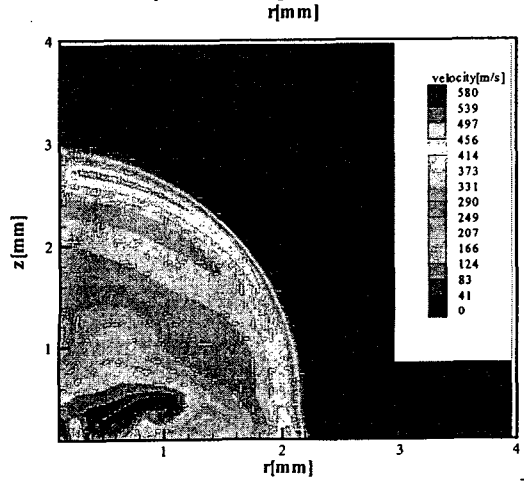


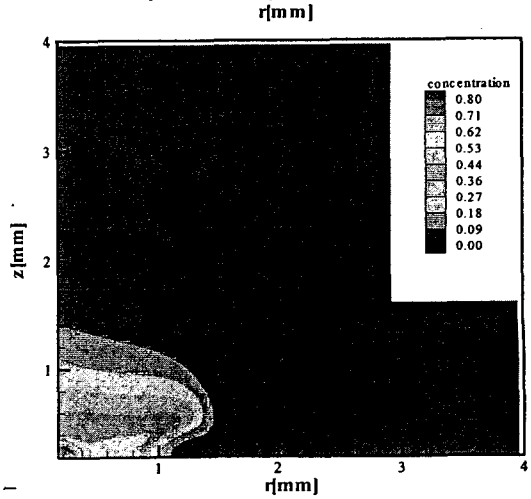




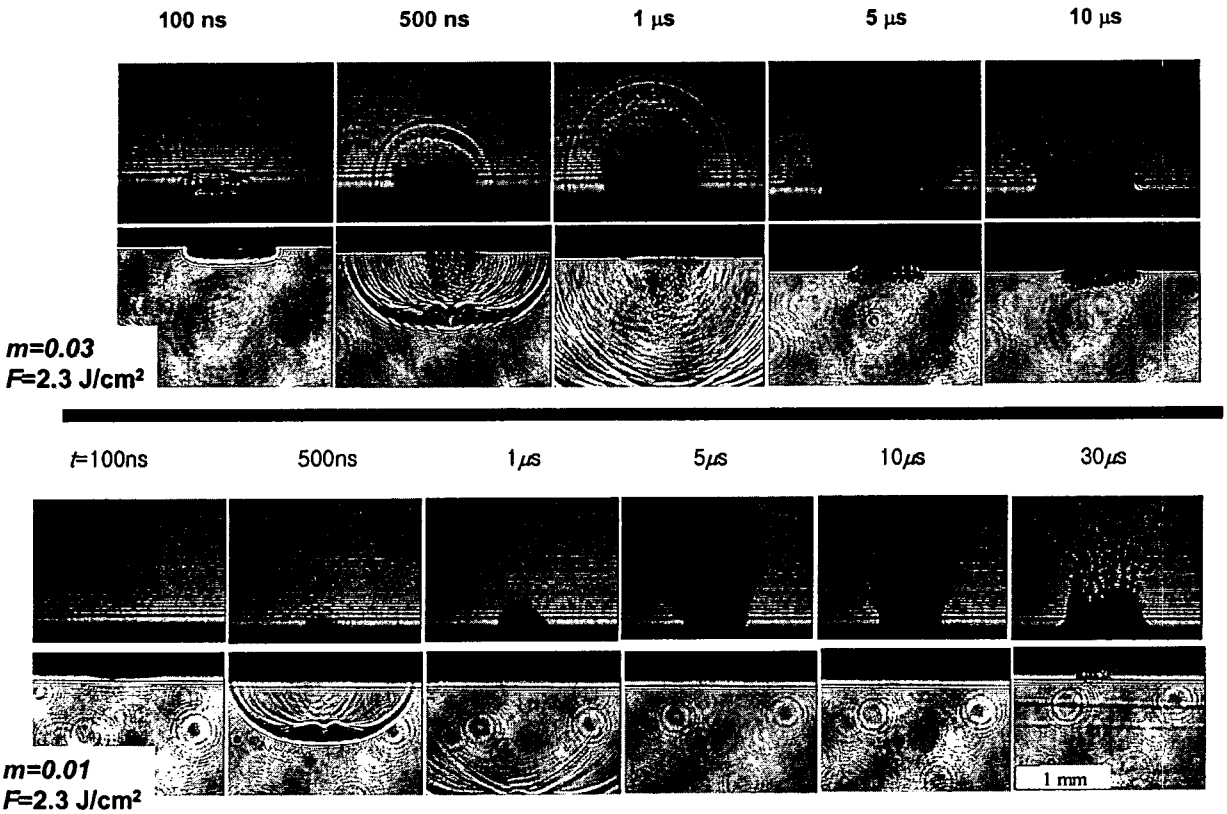




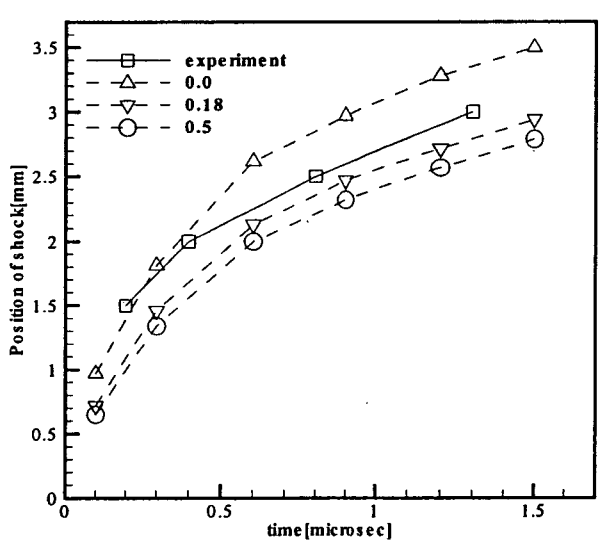


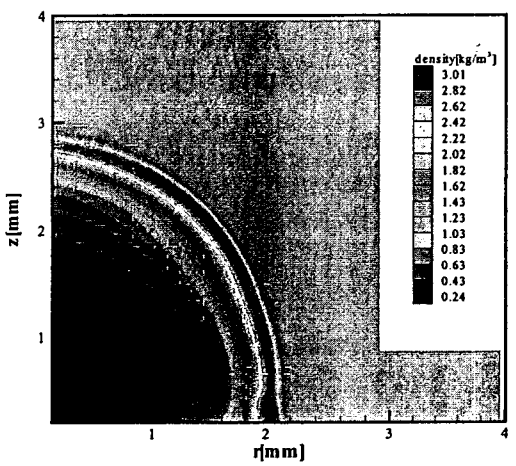


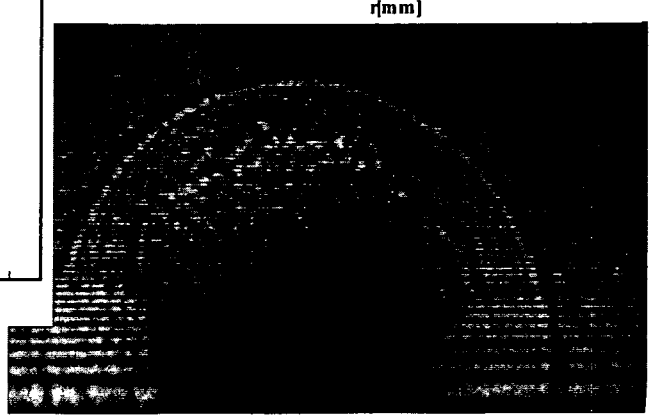
Ablation of K_2CrO_4 solutions



Comparison with numerical calculation

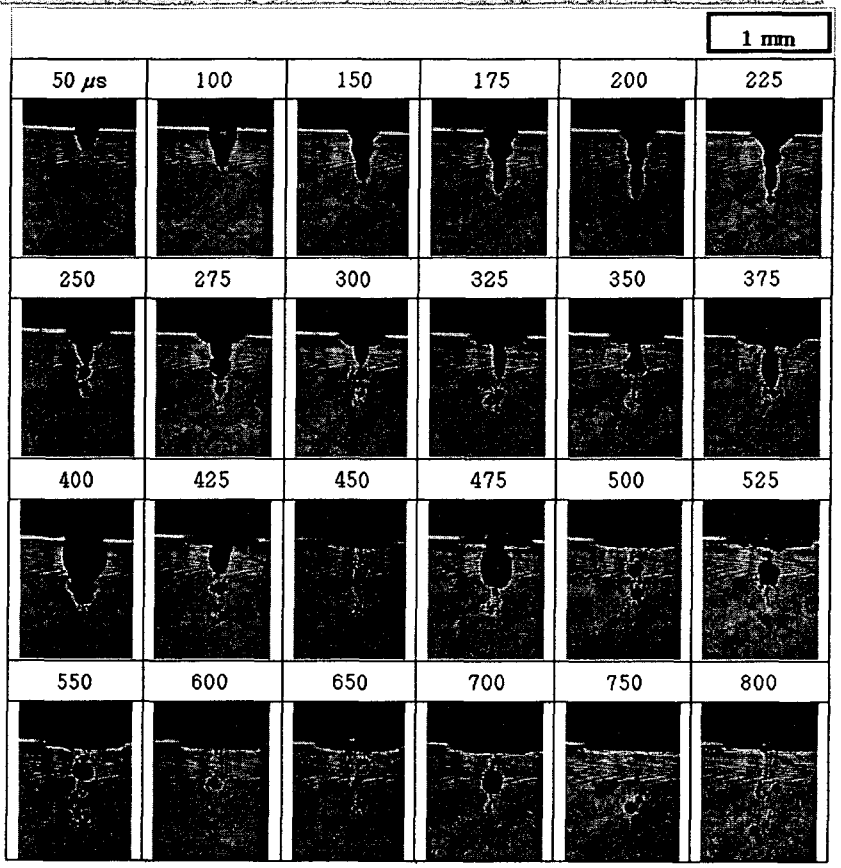


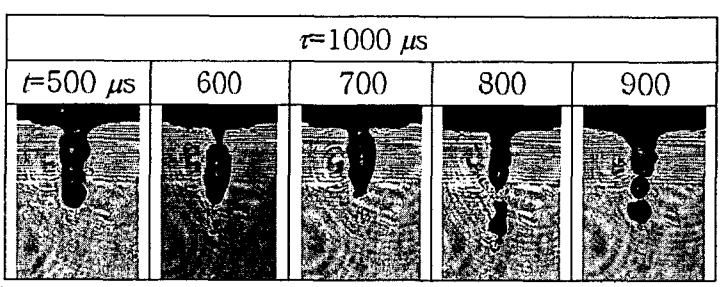


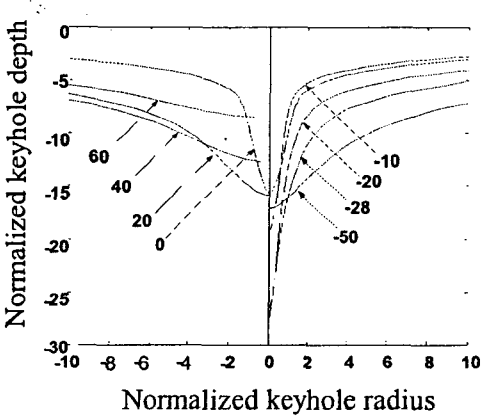


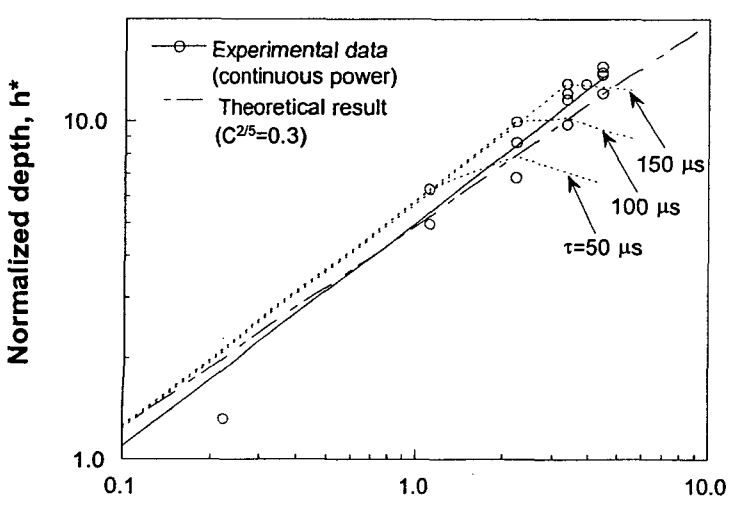
Laser-induced keyhole structure and stability

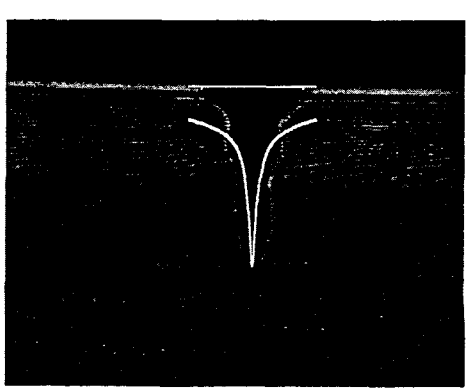
CO_2 laser vaporization of liquid and keyhole formation



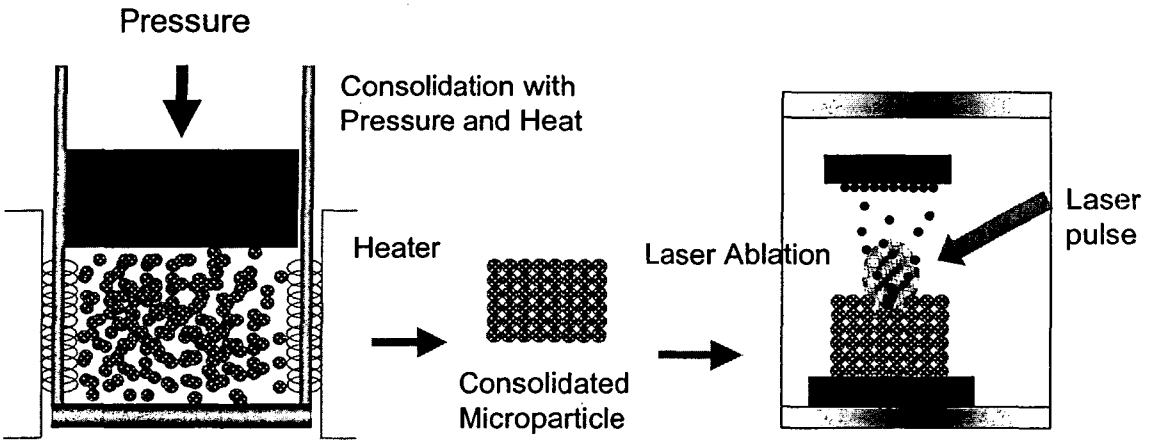


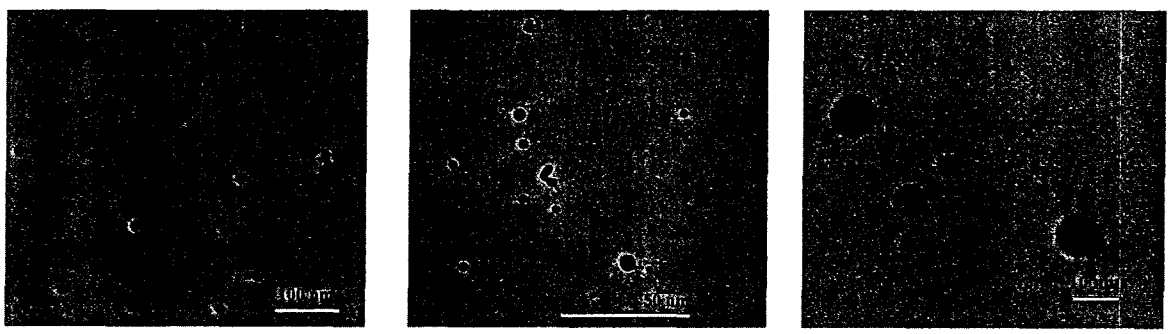






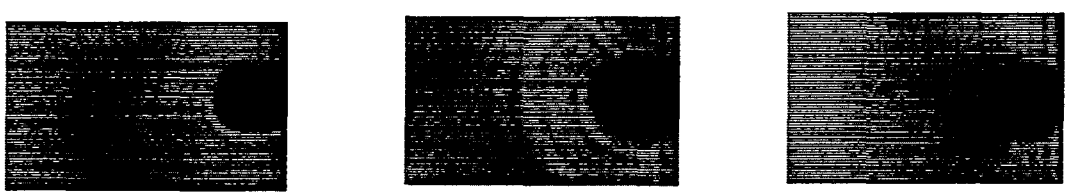
Nanoparticle/nanfluid synthesis by high power pulsed laser



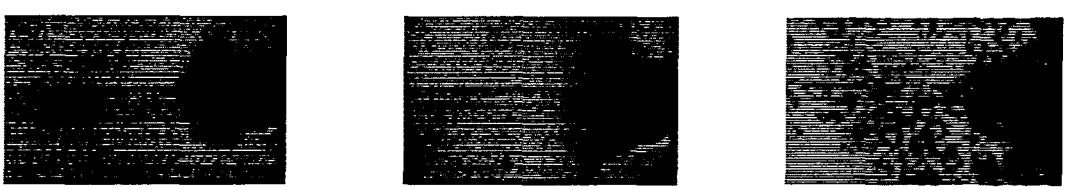


Particle explosion process

Short time scale phenomenon



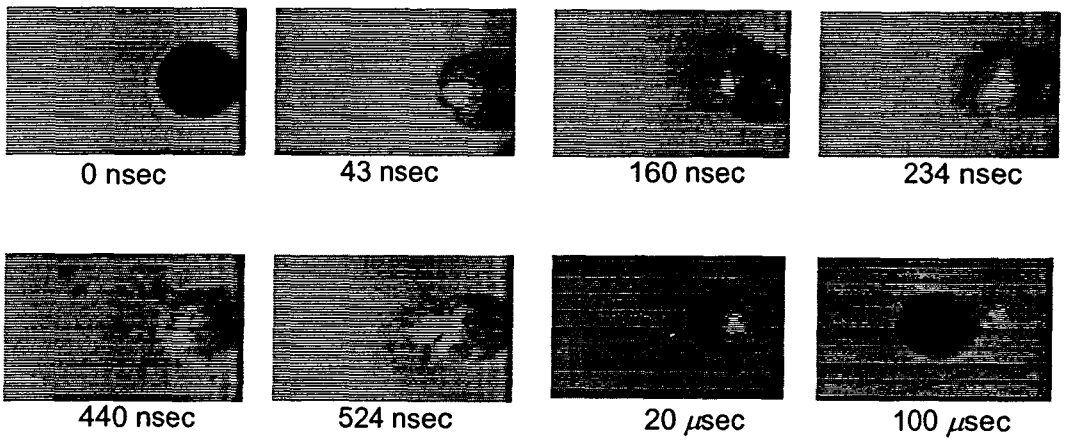
0 nsec | 50 nsec | 90 nsec



200 nsec | 300 nsec | 400 nsec

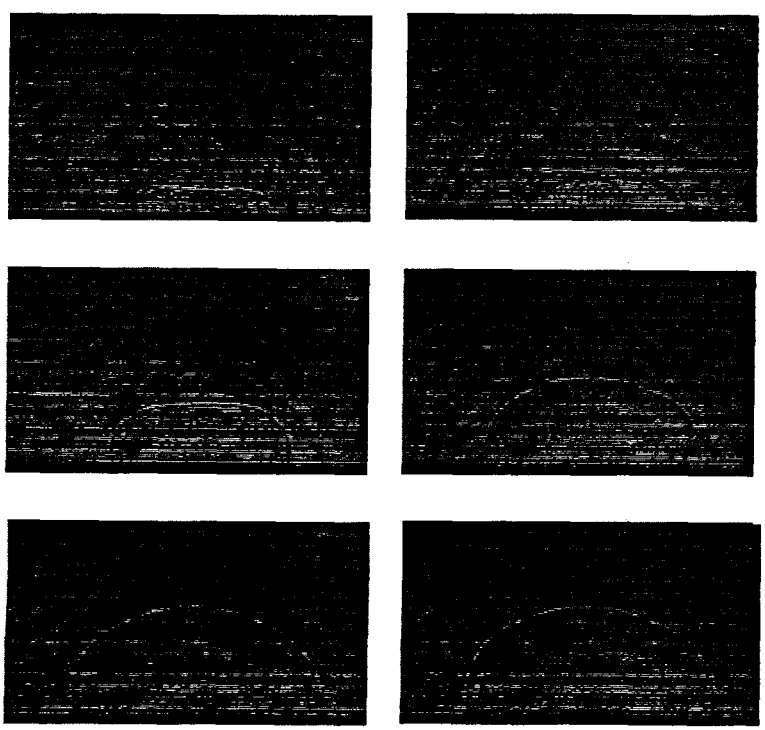
Shadow images of the exploding Cu micropaticle at various delay times
Incident laser wavelength 355 nm (~ 1 J/cm2)

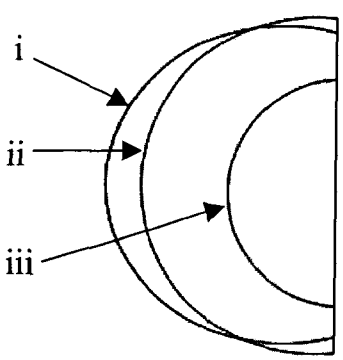
Particle ablation and ejection



Shadow images of the exploding Cu micropaticle at various delay times
Incident laser wavelength 532 nm
Fluence : 1.8 J/cm^2
(refractive index : 1.07+2.59i, normal reflection coefficient : 0.61)

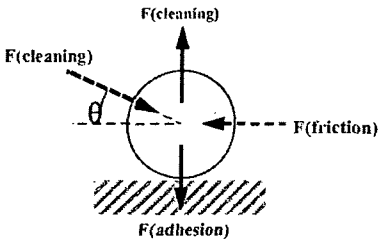
Shock formation in nanoparticle synthesis





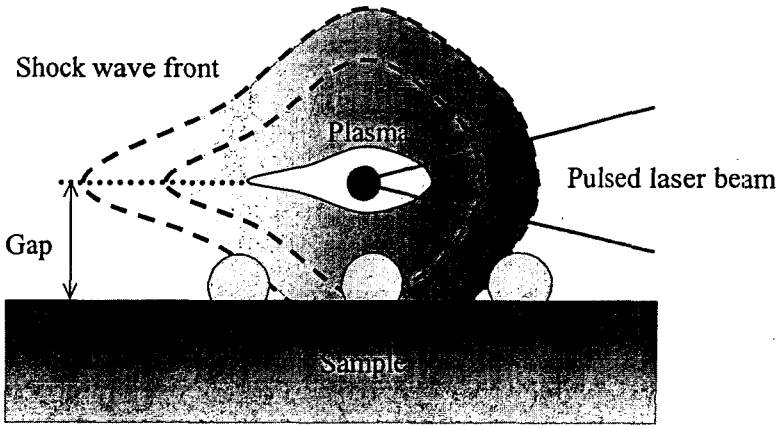
- **i: smooth solid Cu target**
- **ii : consolidated Cu microparticles**
- **iii : Cu microparticles deposited by a liquid suspension**

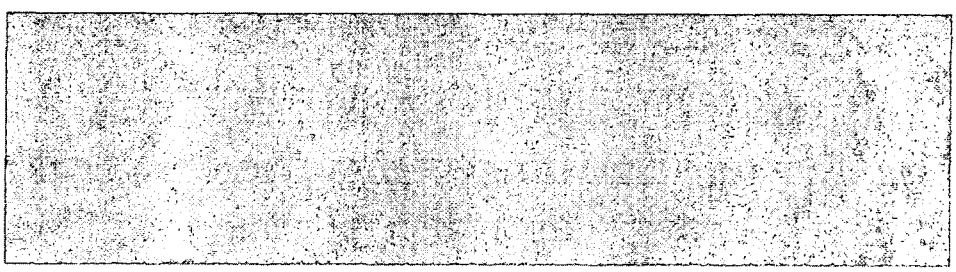
Laser-shock cleaning nanoscale contaminants



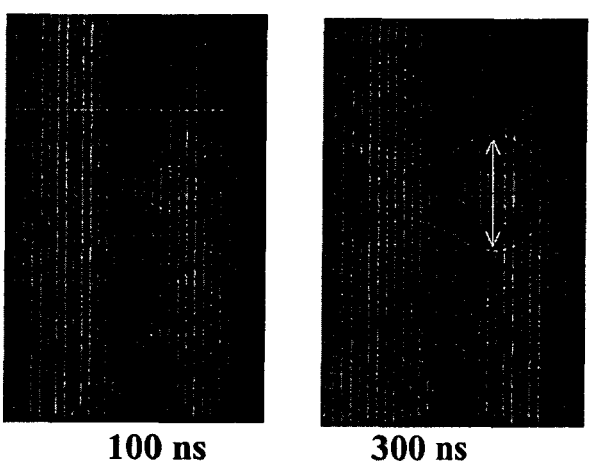
$$F_c \cos\theta > \mu \cdot (F_{ad} + F_c \sin\theta)$$

$$(\mu \approx 1)$$



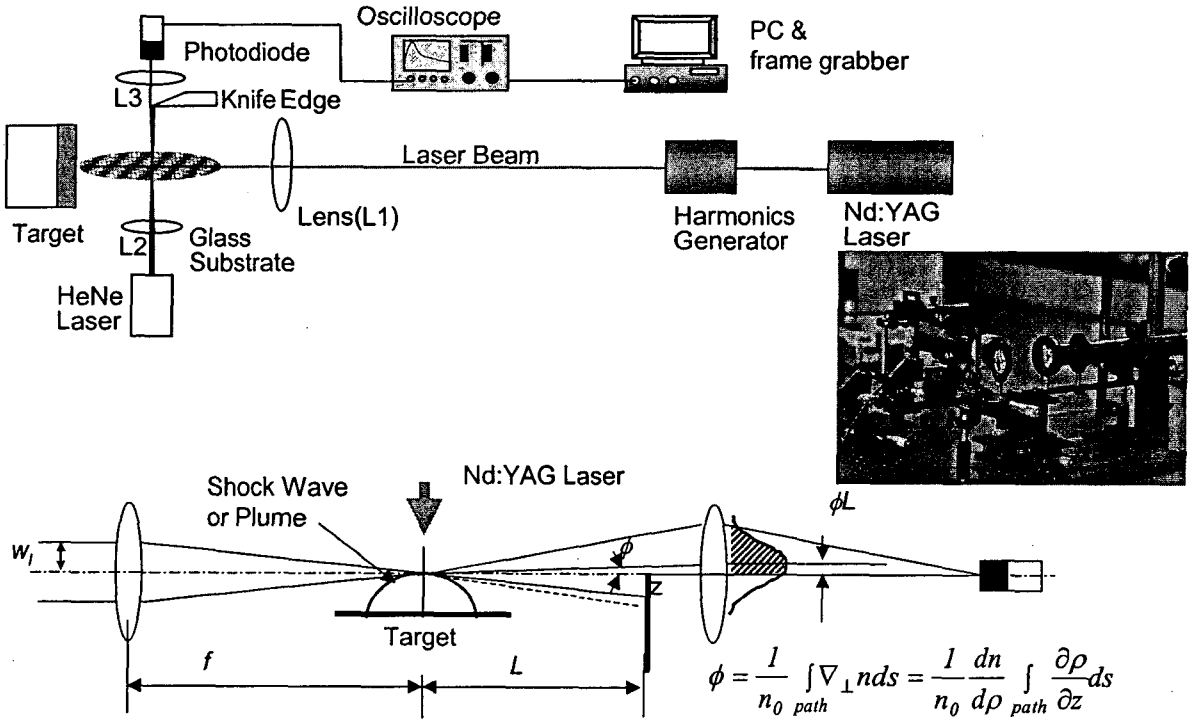


Air breakdown and shock formation



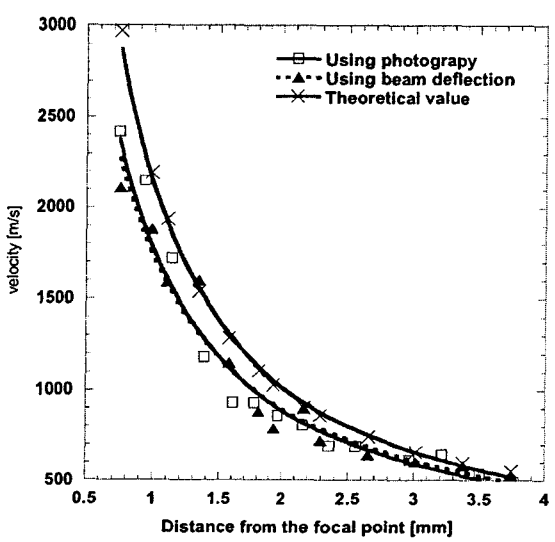
Air, 3.81×10^{12} W/cm^2

Measurement of Shock Speed by Probe-Beam Deflection

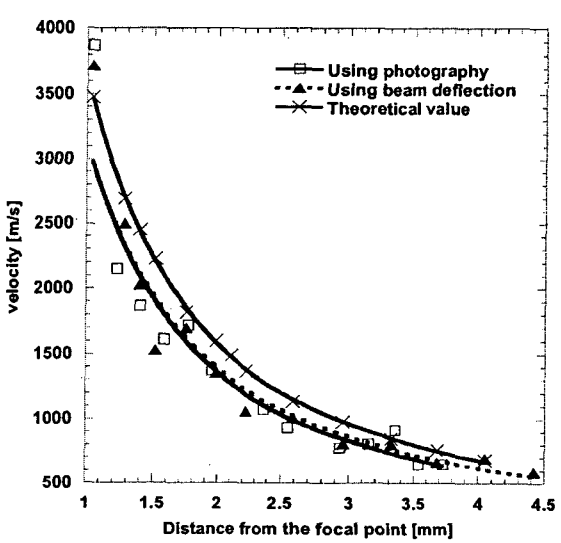


Velocity Measurement in Two Processes

Wavelength=1064nm, FWHM=6ns

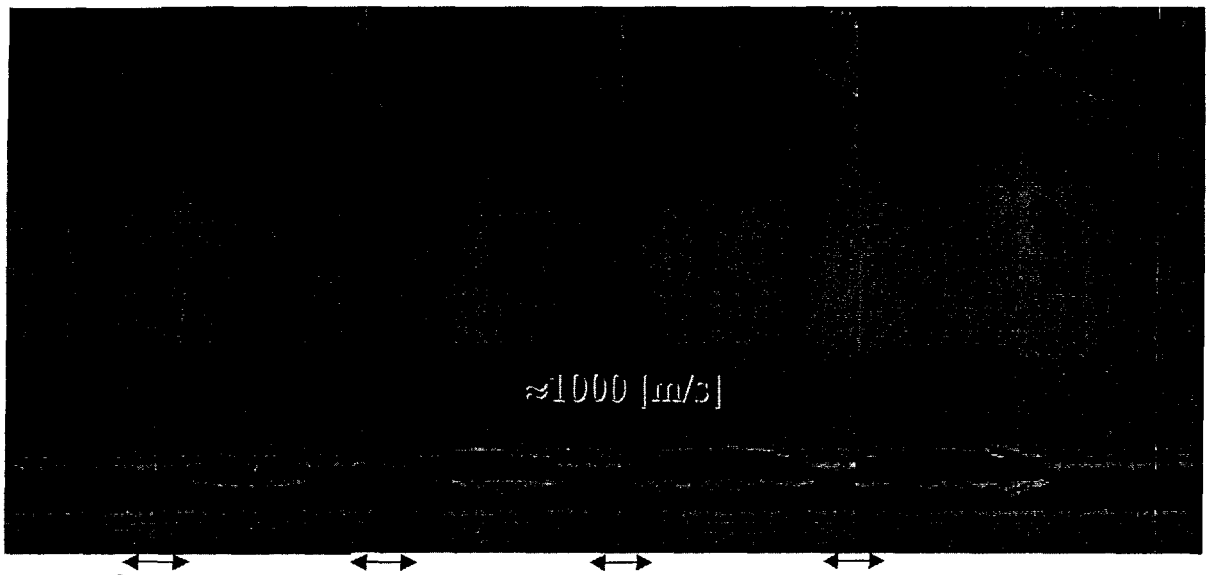


3.81×10^{12} [W/cm^2]



1.52×10^{13} [W/cm^2]

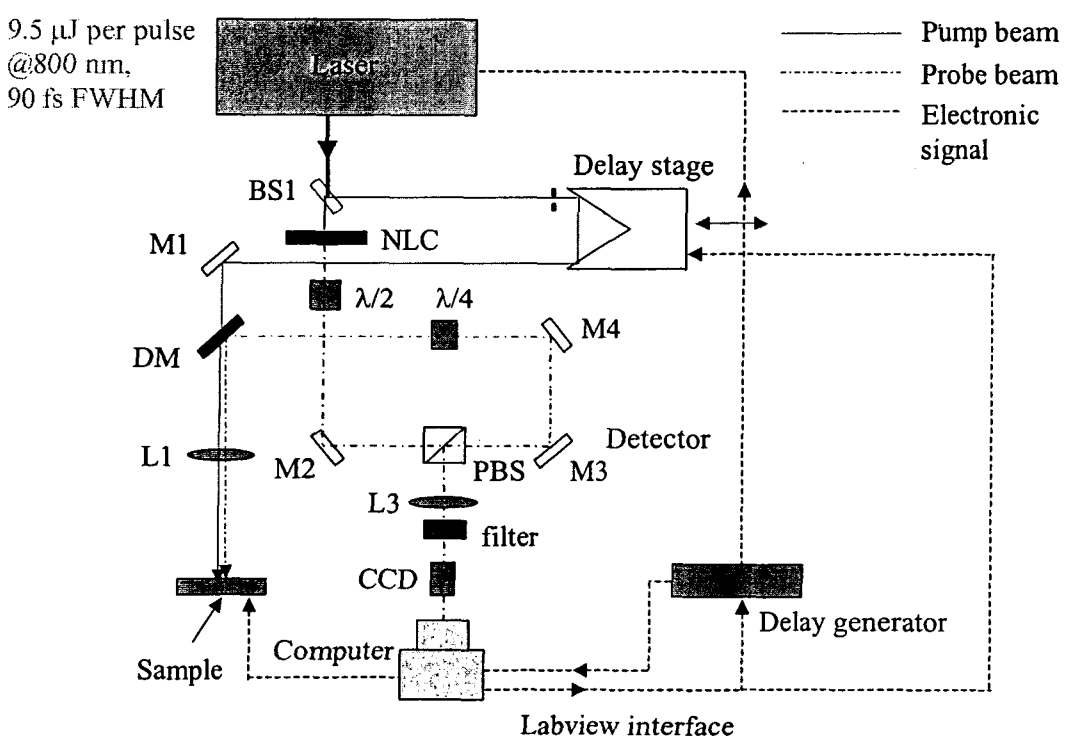
Shock-surface interaction



210 ns 60 ns 60 ns 90 ns

1.52×10^{13} [W/cm^2]

Pump-and-probe imaging of femtosecond laser-induced thermal phenomena



Courtesy of Dr. T. Y. Choi (Swiss Federal Institute of Technology Zurich)

Time resolved surface image (90 fs FWHM, Fluence of 0.12 J/cm^2)

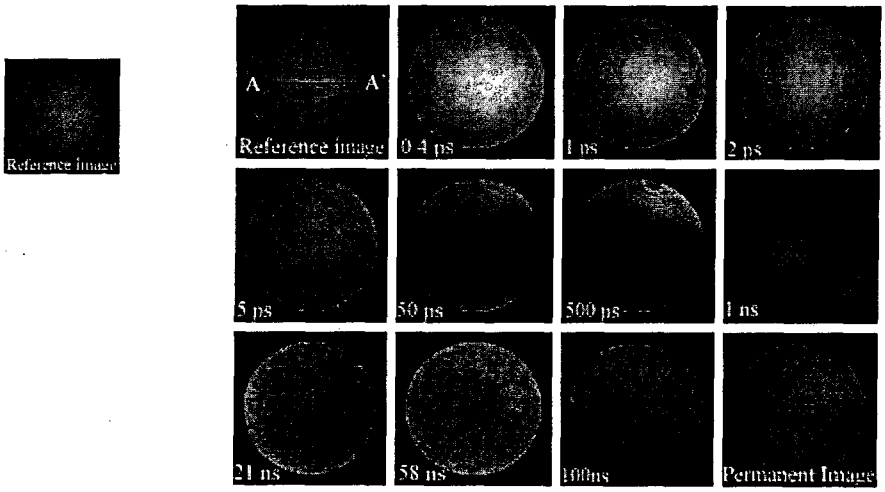
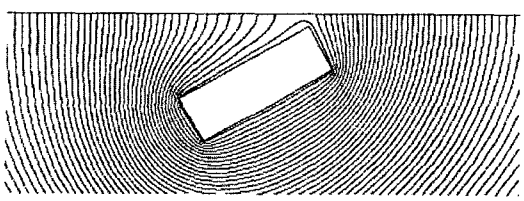


Fig. 4 Time-resolved images

Courtesy of Dr. T. Y. Choi (Swiss Federal Institute of Technology Zurich)

Scanning Thermal Microscopy

- Rapid development of micro- and nanoengineering (Microelectronics, MEMS, ...)
- Surface imaging tool (SEM, AFM,...)
- Non-destructive evaluation (NDE) tool for sub-surface structure on the sub-micrometer scale (STWM ?)



Why Thermal Wave?

- Wave Speed $v = 2\sqrt{\pi D f}$ $\lambda = 2\sqrt{\pi D / f}$

  In pyrex glass, f = 100 kHz, v = 90 cm/sec, λ = 9 μm

  f = 1 kHz, v = 9 cm/sec, λ = 90 μm

  1° of phase lag corresponds to 25 nm of distance.

  Phase resolution of lock-in technology: 0.001°

- Wave Decay

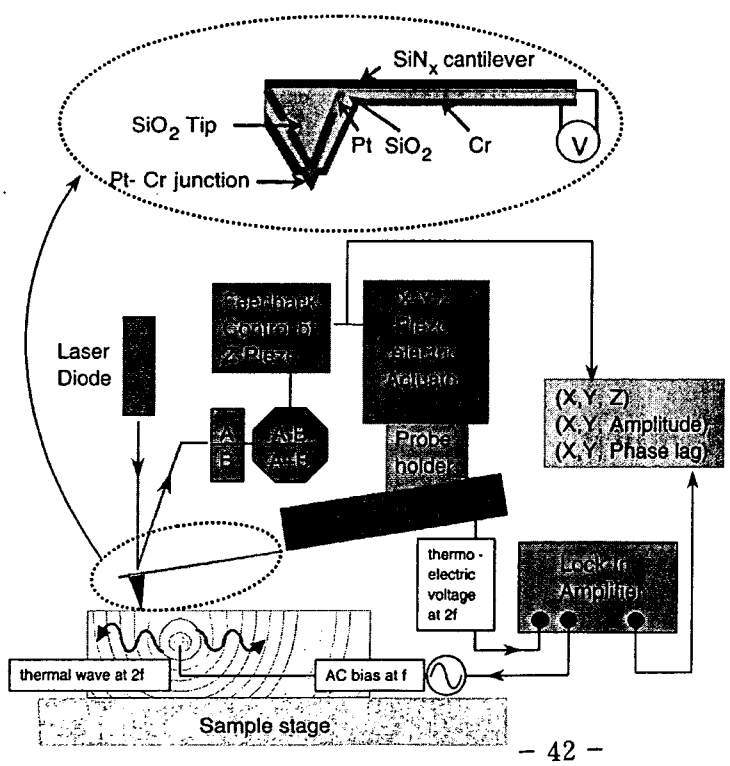
$$Amplitude \sim \exp\left(-2\pi x / \lambda\right) \qquad \exp(-2\pi) \cong 0.002$$

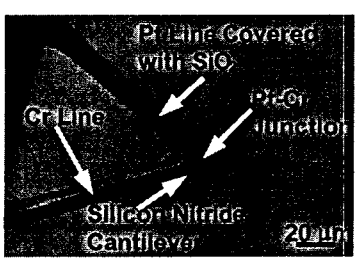
Two Aspects of the NDE Technique

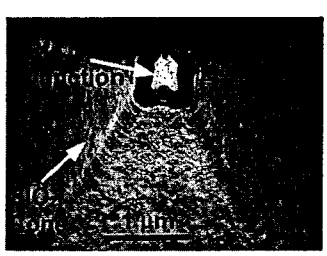
- Accurate measurement of thermal wave propagation
- Interpretation of measurement results

Scanning Thermal Microscopy

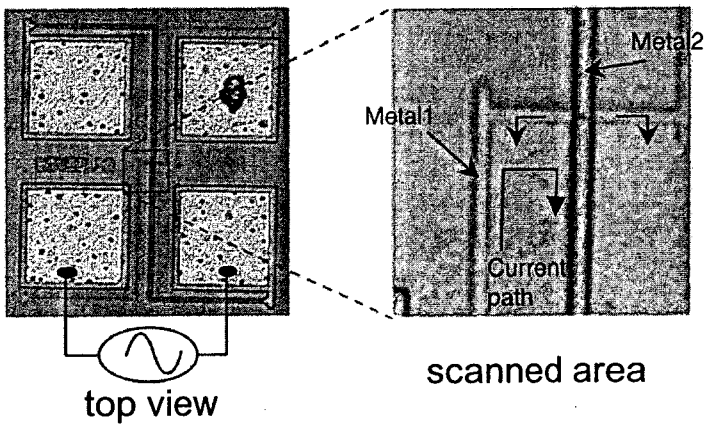
Atomic Force Microscope (AFM) + Thermal Probe

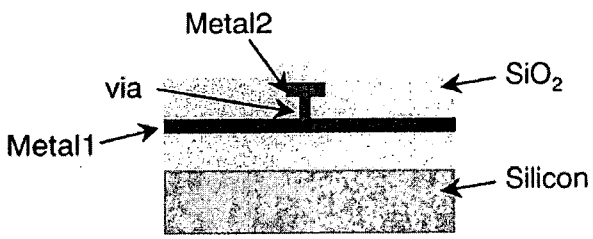




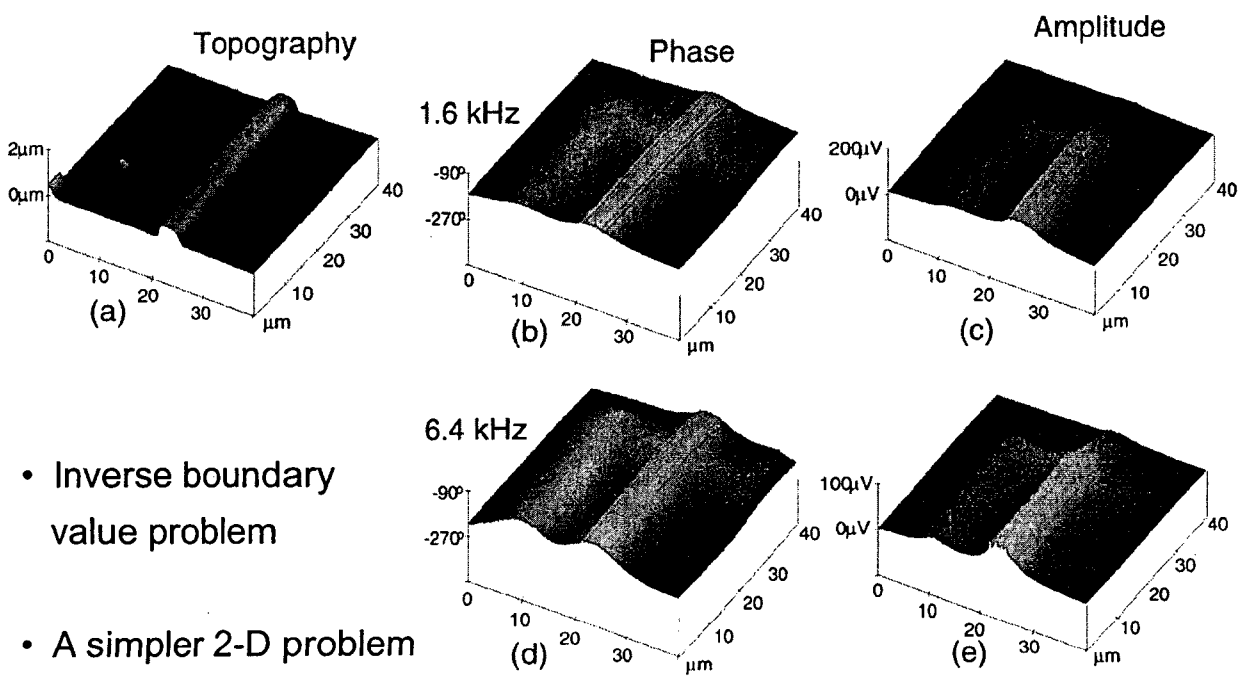


Thermal waves from buried heat sources



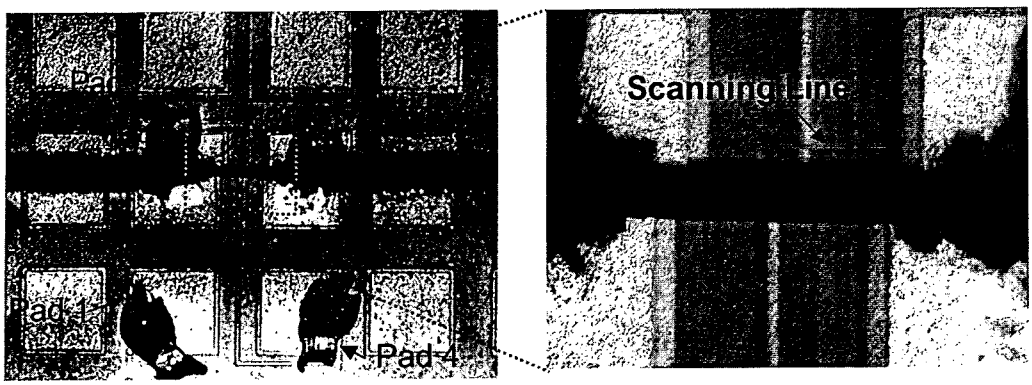


Thermal waves from buried heat sources



- Inverse boundary value problem
- A simpler 2-D problem

A simple 2-D case



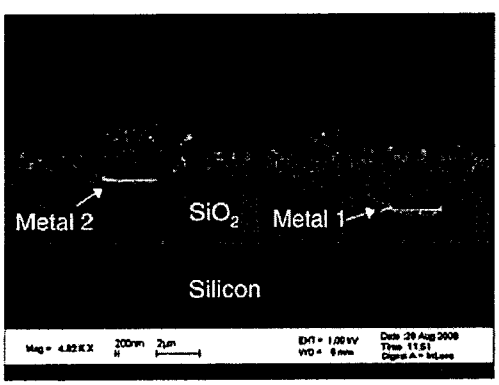
(1) Electrical resistance measurement ~ heat generation

(2) Amplitude and phase lag distribution measurement at 3 modes of heat generation (pad2 and 3, 1 and 3, 2 and 4) ~ wave interference

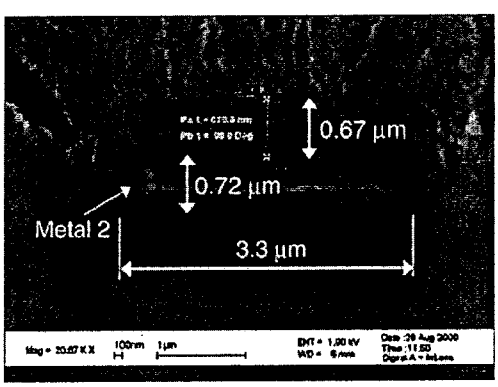
(3) cleavage of the sample

(4) FEM simulation → validation of measurement and some insight about wave propagation

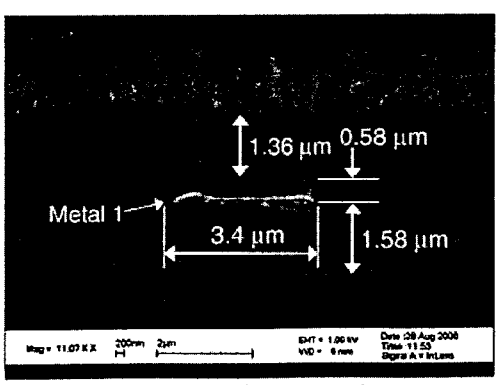
Cross sectional structure



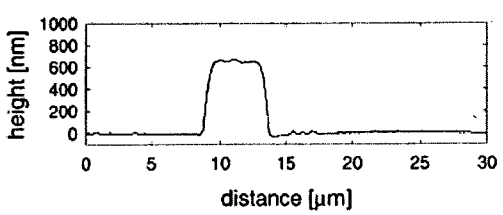
The structure under the scanning line



The shape of metal 2

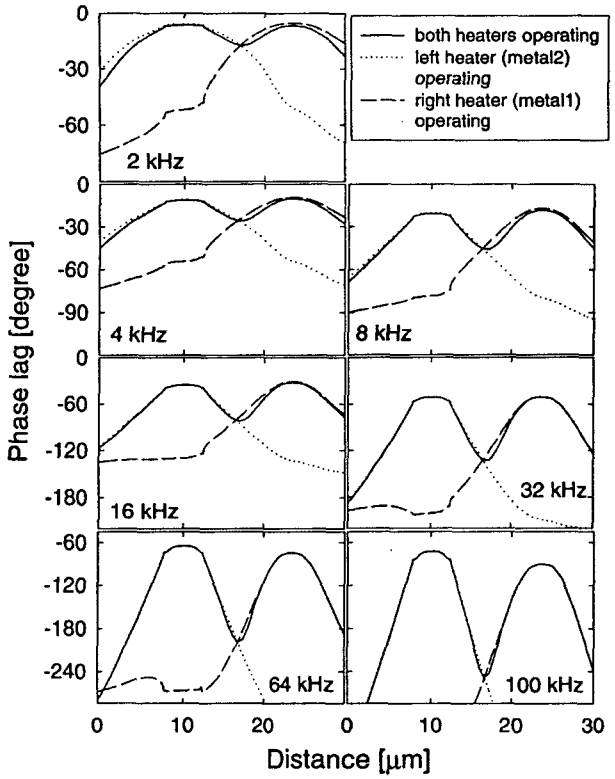


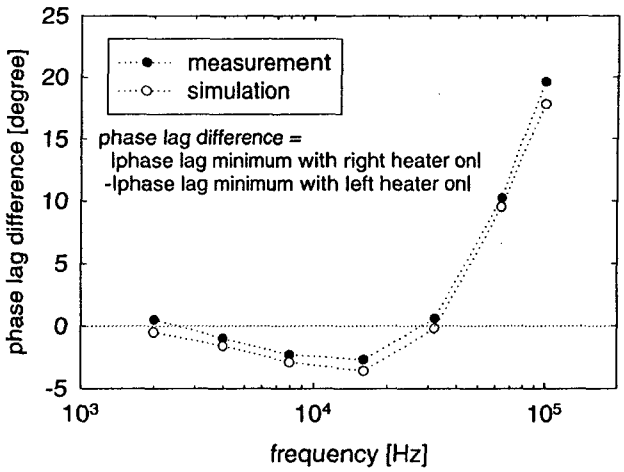
The shape of metal 1



Topography of the sample surface (AFM)

Simulation Result (phase lag)

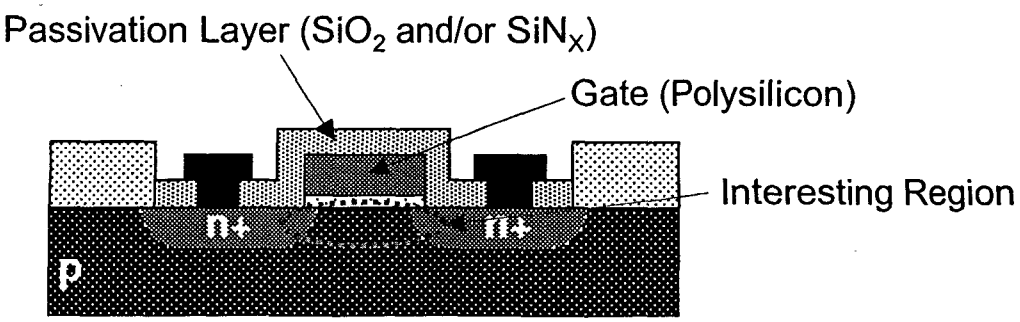




- Why is phase lag difference behave this way?

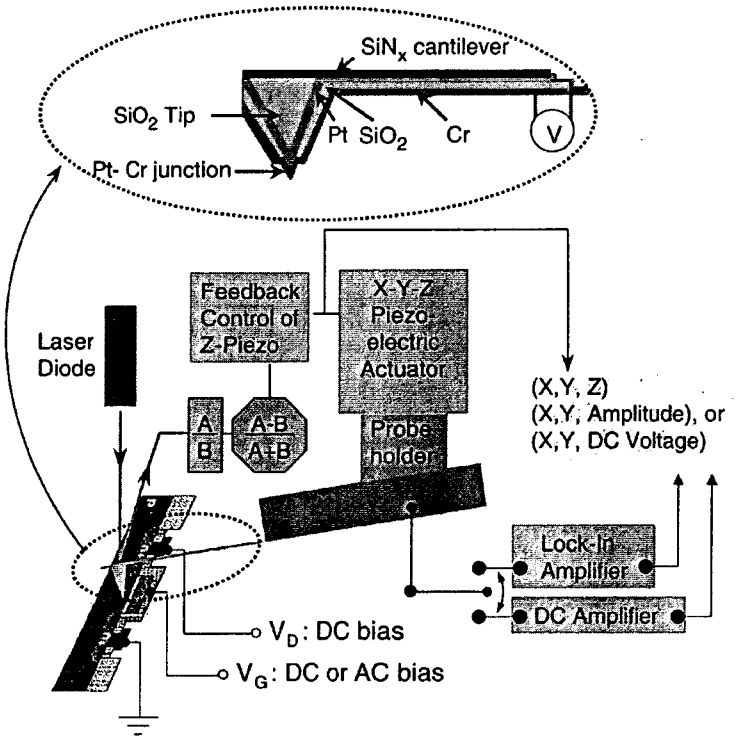
Cross-sectional Thermal Imaging of an Operating MOSFET

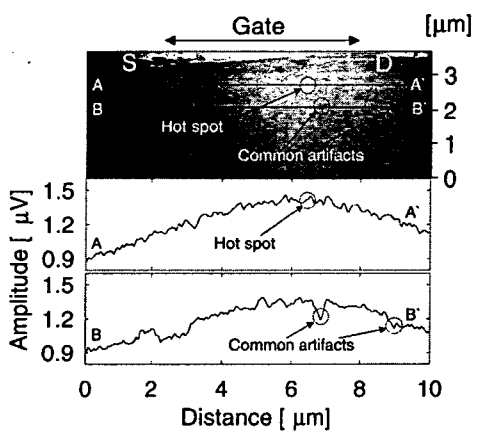
- MOSFET is the Main Components of IC
- Thermal management of the whole IC
  - Increasing Device Integration
  - Excessive Heat Generation
- Analysis of MOSFET operation
  - Local Heat Generation ∝ electric field x electric current density



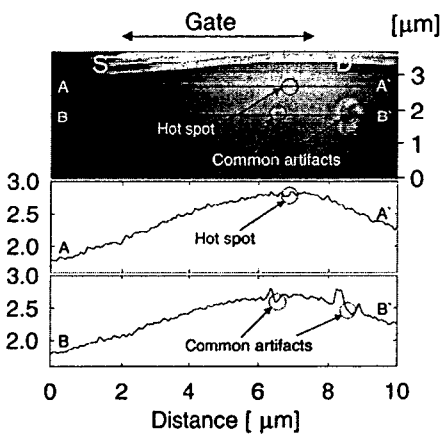
Apparatus

- In DC mode
  - Source: grounded
  - Gate : DC bias
  - Temperature
- In AC mode
  - Source: grounded
  - Gate : AC bias
  - Amplitude
  - Signal from Gating Action

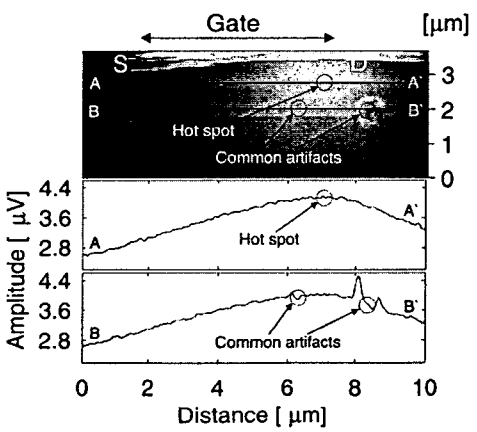




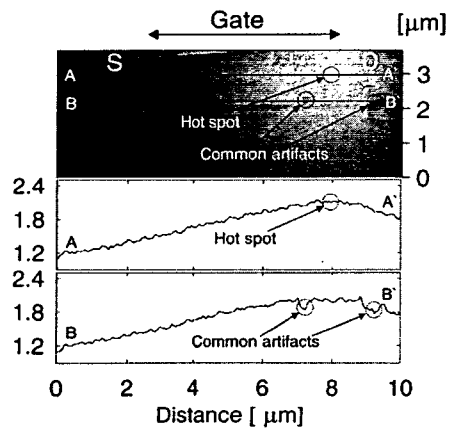
$V_{gs} = 2\sin(2\pi ft)+2$, $V_{ds} = 4$



$V_{gs} = 2\sin(2\pi ft)+2$, $V_{ds} = 7$



$V_{gs} = 2\sin(2\pi ft)+2$, $V_{ds} = 10$



$V_{gs} = \sin(2\pi ft)+1$, $V_{ds} = 10$