Industrial Applications of Ultrafast Lasers: From Photomask Repair to Device Physics

Richard Haight
IBM TJ Watson Research Center
PO Box 218
Yorktown Hts., NY 10598

Collaborators
Al Wagner
Pete Longo
Daeyoung Lim
Outline

• Applications of Ultrafast Lasers

  ❑ Femtosecond Photoelectron Spectroscopy with Harmonics
    Ultrafast electron dynamics ➔ femtosecond ablation

  ❑ Femtosecond Ablation
    Development and implementation of MARS: a manufacturing tool for photomask defect repair

  ❑ Photoelectron Spectroscopy
    Photovoltage experiments on MOS devices

• Potential Experiments on the FEL

  ❑ Can we generate high harmonics?
    High repetition rate ➔ small structures, very weak excited state signals
HARMONIC LASER PHOTOEMISSION

Photon energies from 15-60 eV

parabolic mirror

TOF detector

High KE

Main Chamber

High Harmonic Generation

Ar jet

800 nm ~35fs

Pump, 800 nm, ~35fs

sample

800 nm ~35fs
Electron-phonon scattering at GaAs surface

Probe photon 11 eV

Pump-probe photoelectron spectroscopy

GaAs (110)

Electron-phonon scattering time → 400 fs

"heat" is generated

PRL 62, 815 (1989)
WHAT ARE THE IMPLICATIONS FOR FS ABLATION

• For laser pulses $>>$ 1ps, ablation will be dominated by thermal processes i.e. the material will absorb light, heat up and evaporate.

• For laser pulses $<<$ 1ps, the material will be converted to a plasma on a time scale shorter than that required to emit phonons and generate “heat”

For femtosecond pulses the ablation process is DIFFERENT
Photomask SEMs

Nanosecond laser
- thermal process
- metal splatter
- poor resolution
- glass damage

Femtosecond laser
- non-thermal
- no metal splatter
- no glass damage
- high resolution
How masks are used to print chips

As many as 25-30 masks may be needed to produce a chip
Cost/mask ~ >$100K
Advanced Photomask with Resolution Enhancements

Optical micrograph

Defect
Scanned Gaussian Tool in IBM’s Burlington Mask House
Ablation Resolution

sub 150 nm lines and dots

Optical micrograph

0.75 micron
Ablation Resolution
Below the diffraction limit

SEM
Photomask Repair Comparison

Before

After

248 nm transmitted light optical images
Slope = 22.77 +/- 0.12 nm per step

Mean Edge Error: -0.1 nm
Maximum Edge Error: +/- 9 nm
RMS Edge Error: 5.1 nm
FEMTOSECOND DEPOSITION TO “WRITE” MATERIAL

- Saturated organometallic and carrier gas
- Adsorbed organometallic layer
- High intensity in focal region

Photomask

- 400 nm, 100 fs
DEPOSITION SETUP

- Laser light pulse in
- Objective with jacket
- Photomask
- Organic charge
- Carrier gas flow
- Stage
1 micron | 0.2 micron

248 nm trans light

365 nm refl. light

SEM

Mag = 68.07 K X 100nm
Laser pulsewidth
120 fs

Cr deposition threshold power

Laser power ($10^6$ watts)

Laser Repetition Rate (kHz)

Threshold pulse intensity ($10^{11}$ watts/cm²)

Laser Repetition rate (kHz)

Deposition not thermally driven

Data Shows that initial metal growth is achieved through photolytic decomposition of the Cr(CO)$_6$.

**BUT, There’s More**
MULTIPLE SCANS

365 nm reflected light

SEM

Mag = 6.12 K X

1µm
Intense 400 nm fs pulse

• Electrons excited by interaction of fs pulse with metal
• Continued metal growth through electron stimulated dissociation

Electron mean free path ~ 1 micron
e flux = 3x10^{16}/cm^2/sec

Laser induced e excitation enhanced at asperities ✓ amplifies roughness
Cr deposition on Au

100 nm width

100 nm

Mag = 8.60 K X  
EHT = 5.00 kV  
WD = 6 mm  
Date: 1 May 2002  
File Name = image134.tif
**Model for Deposition**

- **On transparent substrates** multiphoton absorption of 400 nm light in adsorbed molecule initiates decomposition and metal deposition.

- **Continued deposition** is combination of multiphoton and thermal decomposition (in creation of line or patch) smooth metallic deposits are observed.

- **On absorbing substrates:**
  - Intense femtosecond pulses excite electrons within the absorber.
  - Electron stimulated dissociation occurs laser induced electron excitation is enhanced at asperities amplifies roughness during continued metal growth.
“Machining” of Deposited Patch

Deposited Cr patch

Section of patch removed with fs laser
Generation of 193 nm light for ablation

30 fs 800 nm Ti:sapphire laser 1 mJ/pls

2nd harm generator

400 nm

Delay line

800 nm

Ar gas cell

capillary

photomask

reflective objective

Output at 193 nm

\[ 4\omega = 2 \times \omega + 2\omega \]
\[ 4\omega = 2 \times 3\omega - 2\omega \]
\[ 4\omega = 2\omega + 3\omega - \omega \]
\[ 4\omega = 3 \times 2\omega - 2 \times \omega \]

Misoguti, Backus, Durfee, Bartels, Murnane, Kapteyn, PRL, 87 013601-1 (2001)
Ablation with 30 fs 193 nm light pulses
Femtosecond Photomask Repair

• Fs ablation provides significant improvement in quality and placement of repair

• Both ablative and additive repair

• High throughput, spatial control big win

• Machine presently operating in IBM’s BTV Mask House

• >10^8 $$ in mask value repaired
PHOTOVOLTAGE MEASUREMENTS OF METAL OXIDE SEMICONDUCTOR STRUCTURES USING PUMP-PROBE FS PHOTOELECTRON SPECTROSCOPY

P-FET

N- Si (100)

channel

source

P +

Gate oxide

Gate metal

drain

P +

oxide
HfO$_2$/SiON/Si(100)- n

**Graphical Representation:**
- **Counts (arb. units):** The y-axis represents the counts on an arbitrary scale.
- **Binding energy (eV):** The x-axis represents the binding energy in electron volts (eV).
- **Graph Details:** The graph shows a peak labeled $\text{eV}_{bb}$ and annotations for $n$-Si, SiON, HfO$_2$, pump, and thick Hf metal.

**Textual Information:**
- **Photon energy:** 26.35 eV
Band Bending and Charge Transfer in HfO₂/Si(100)

Fig. 4
Fig. 6

photon energy = 48.05 eV

counts (arb. units)

binding energy (eV)

clean Si (100)
Hf metal
950C
900C
840C
800C
700C
as-dep HfO₂
SiON

crystallization
IN A NUTSHELL:

High temp anneal ➔ oxygen vacancy formation

Electrons tunnel into defects and become trapped
Possible Experiments on the FEL

• Can we generate high harmonics on the FEL?

\[ E_{\text{max}} = E_i + 3.2 U_p \]
\[ U_p = \frac{e^2 E^2}{4m \omega^2} \]
need temporally short IR pulse
high intensity (100’s µJ ➞ mJ)

• FEL could provide big advantage in repetition rate \((10^3 – 10^4)\) to look at weak signals, small structures
ORGANIC LIGHT EMITTERS

Alq

Normalized Intensity (arb. units)

Energy (eV)

HOMO LUMO

(a) Alq

(b) BAlq

(c) DPVBi

×200

×400

×4000

Alq

O

N

O

O

N

O
SUMMARY

- Applications of intense fs pulses to:
  - photoelectron spectroscopy of excited states
  - photovoltage measurements of MOS structures
  - ablation and deposition
  - photomask repair
  - manufacturing tool

- Ideas for FEL related work
  - High repetition rate
  - high harmonic photoelectron spectroscopy of small structures and weak signals