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

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Outline

- ***Applications of Ultrafast Lasers***

  - ❑ ***Femtosecond Photoelectron Spectroscopy with Harmonics***
    Ultrafast electron dynamics → femtosecond ablation

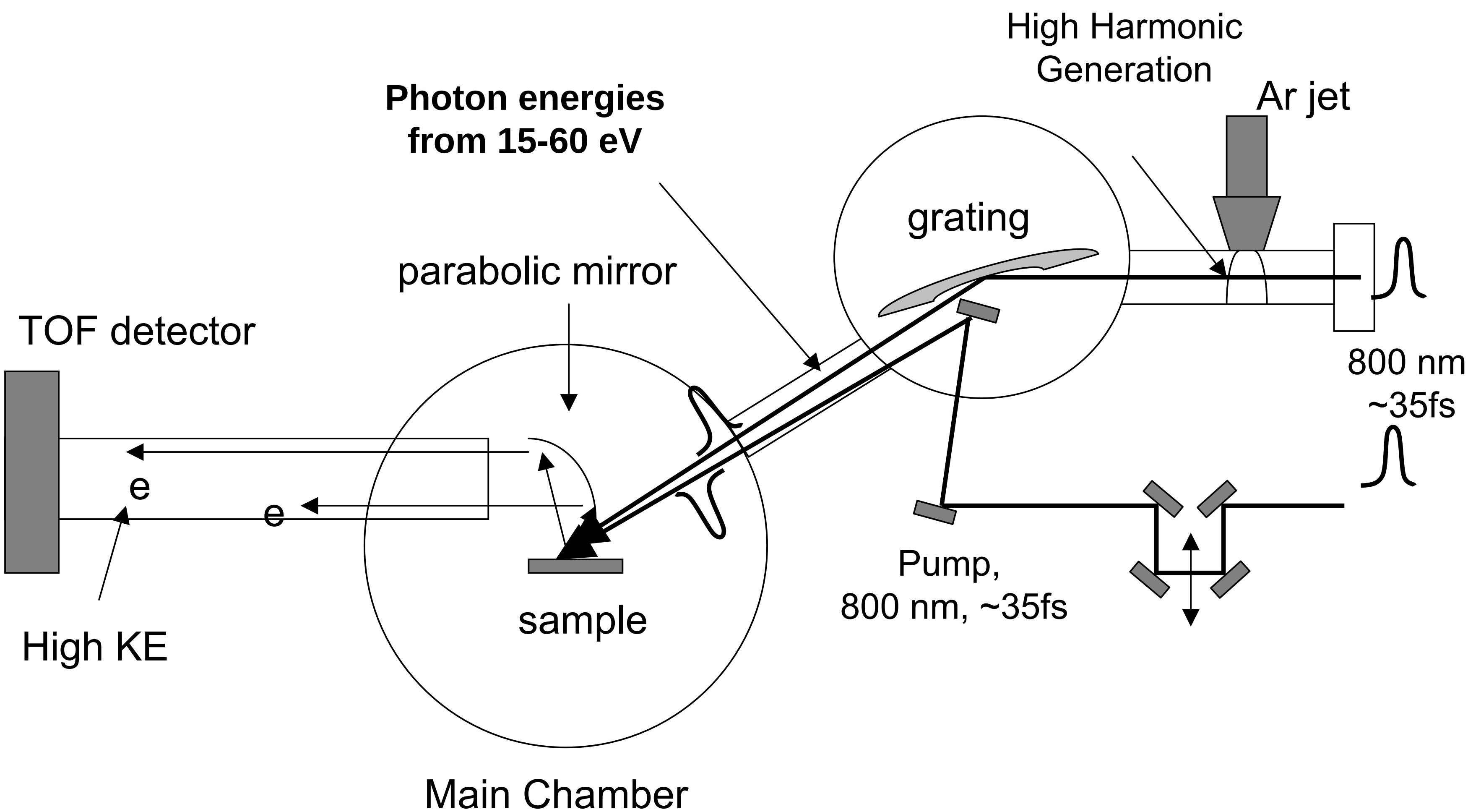
  - ❑ ***Femtosecond Ablation***
    Development and implementation of MARS: a manufacturing tool for photomask defect repair

  - ❑ ***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

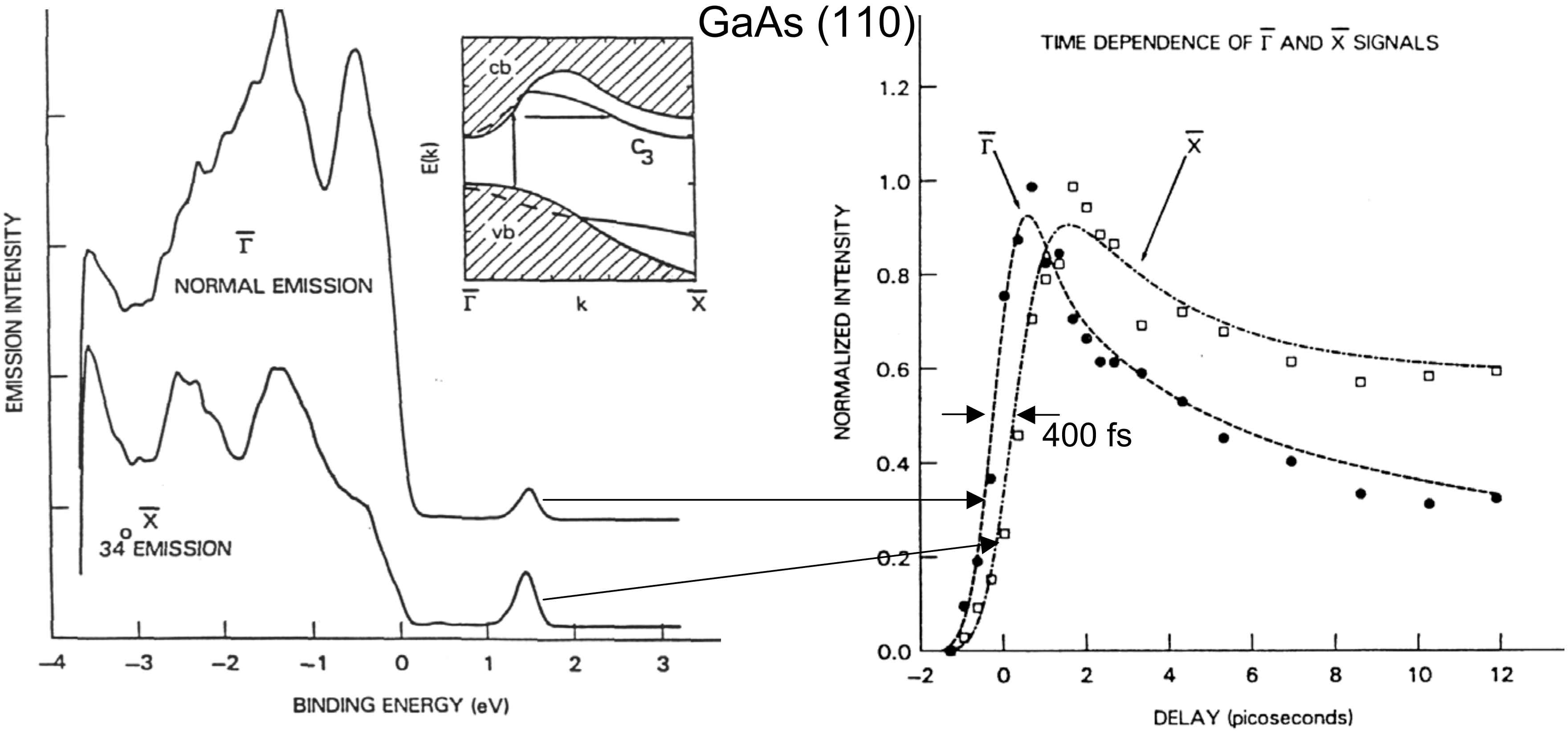
HARMONIC LASER PHOTOEMISSION



Electron-phonon scattering at GaAs surface

Probe photon 11 eV

Pump-probe photoelectron spectroscopy



Electron-phonon scattering time ➔ 400 fs

"heat" is generated

PRL 62, 815 (1989)

WHAT ARE THE IMPLICATIONS FOR FS ABLATION

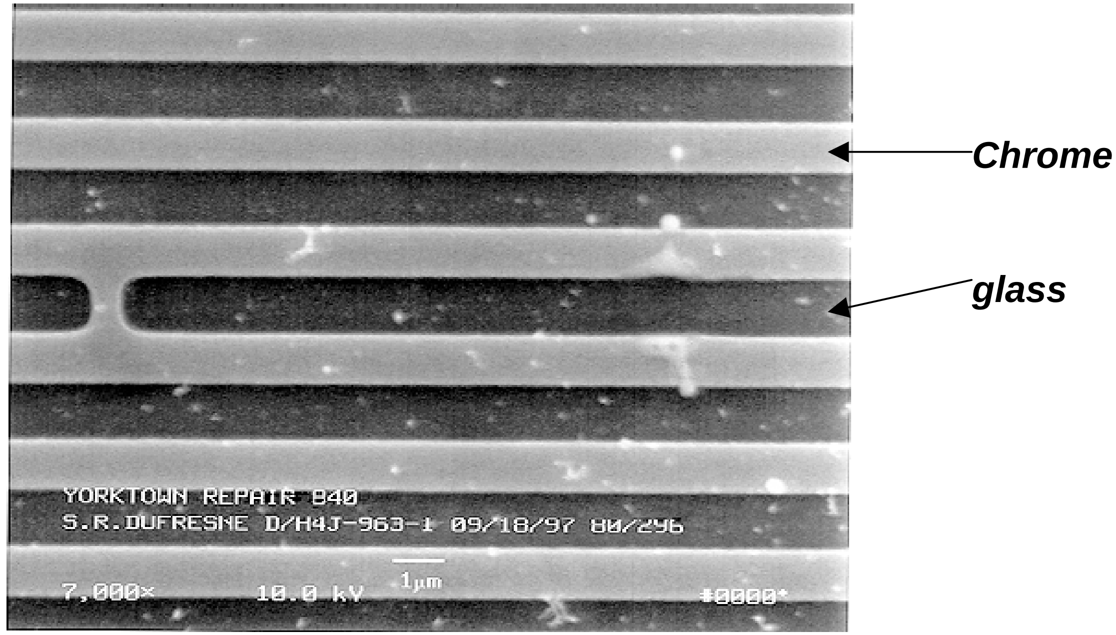
- ***For laser pulses >> 1ps, ablation will be dominated by thermal processes I.e. the material will absorb light, heat up and evaporate.***

- ***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"***

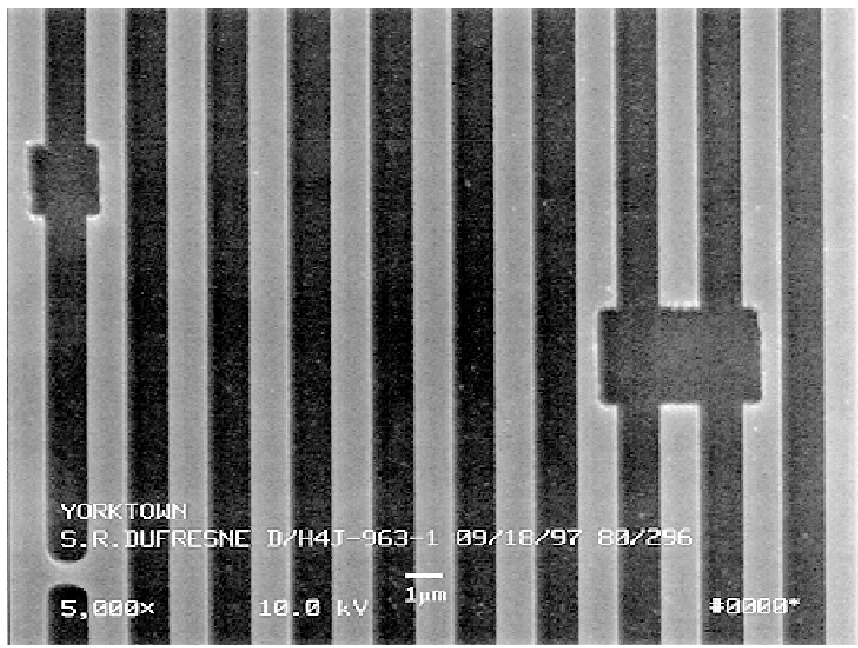
For femtosecond pulses the ablation process is DIFFERENT

Photomask SEMs

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

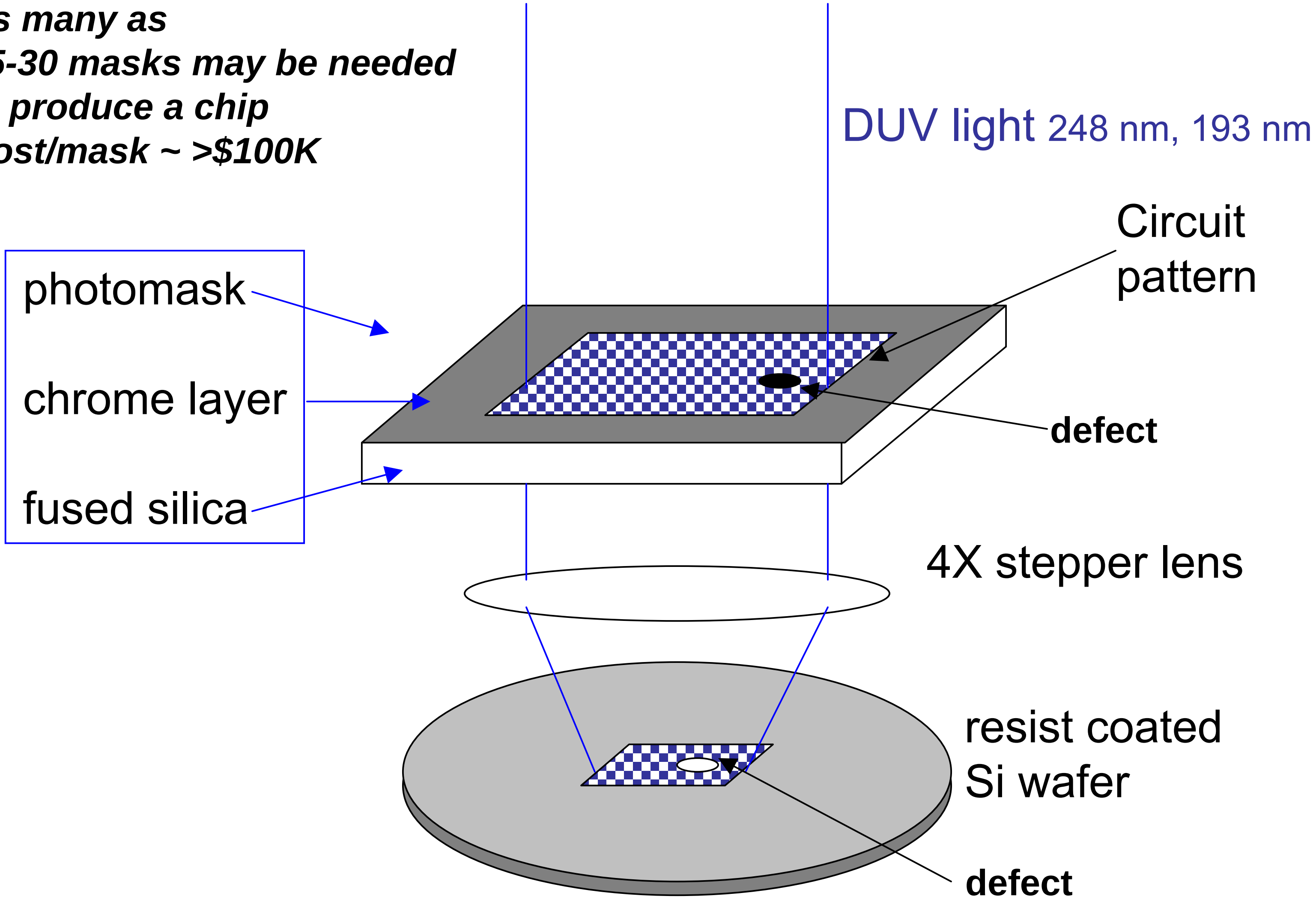


Femtosecond laser
- non-thermal
- no metal splatter
- no glass damage
- high resolution

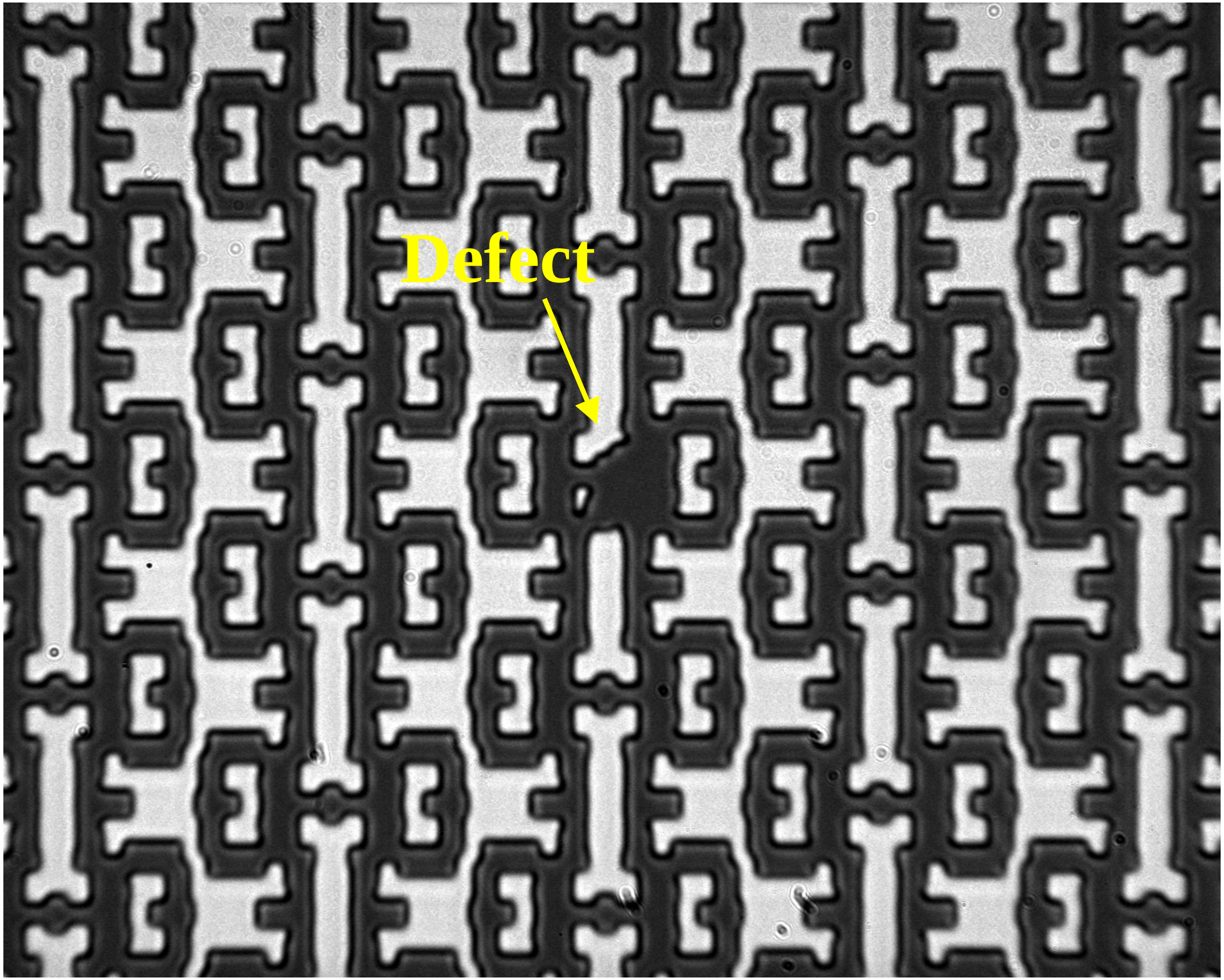


How masks are used to print chips

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

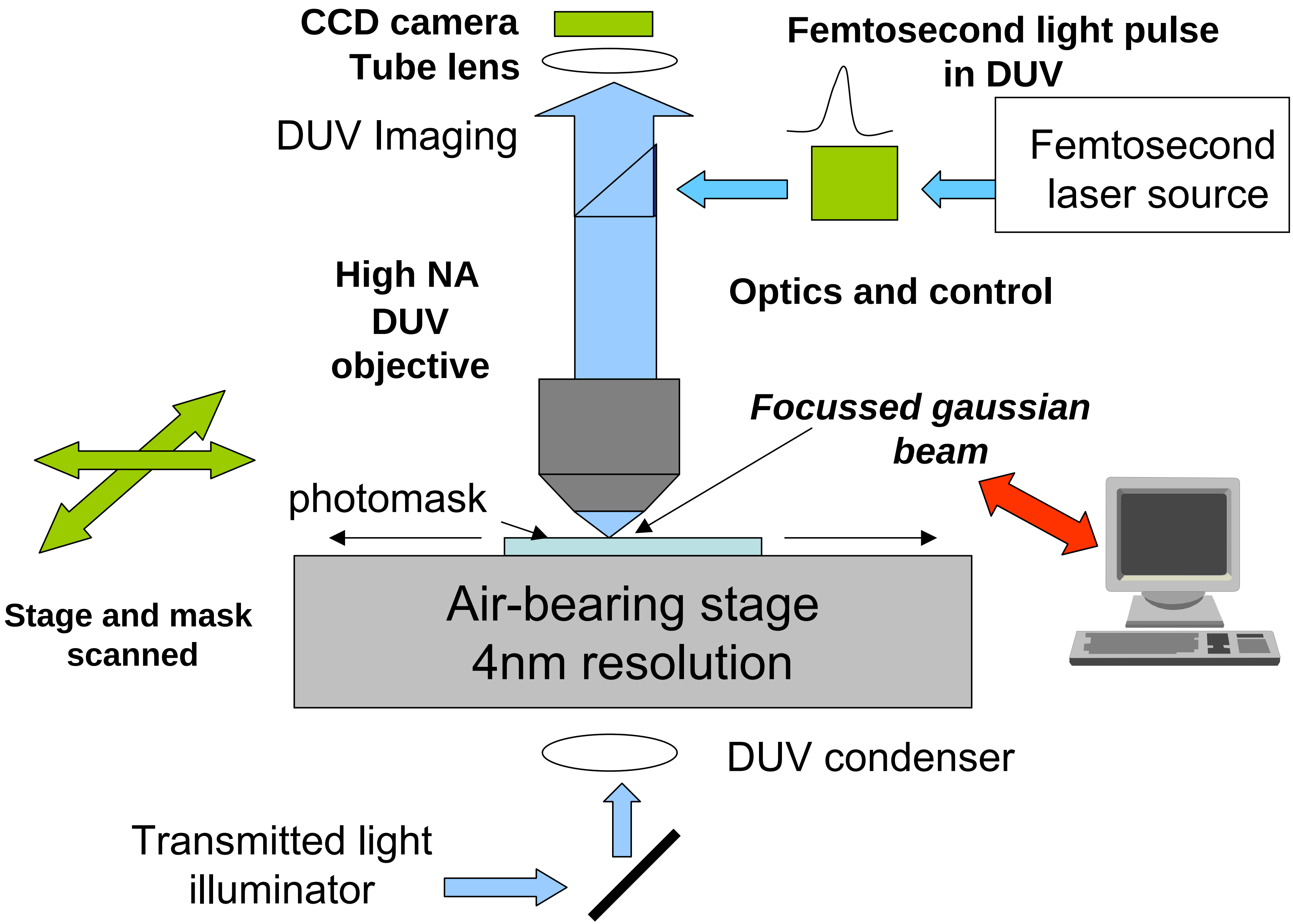


Advanced Photomask with Resolution Enhancements



Optical micrograph

SCANNED GAUSSIAN PROCESS

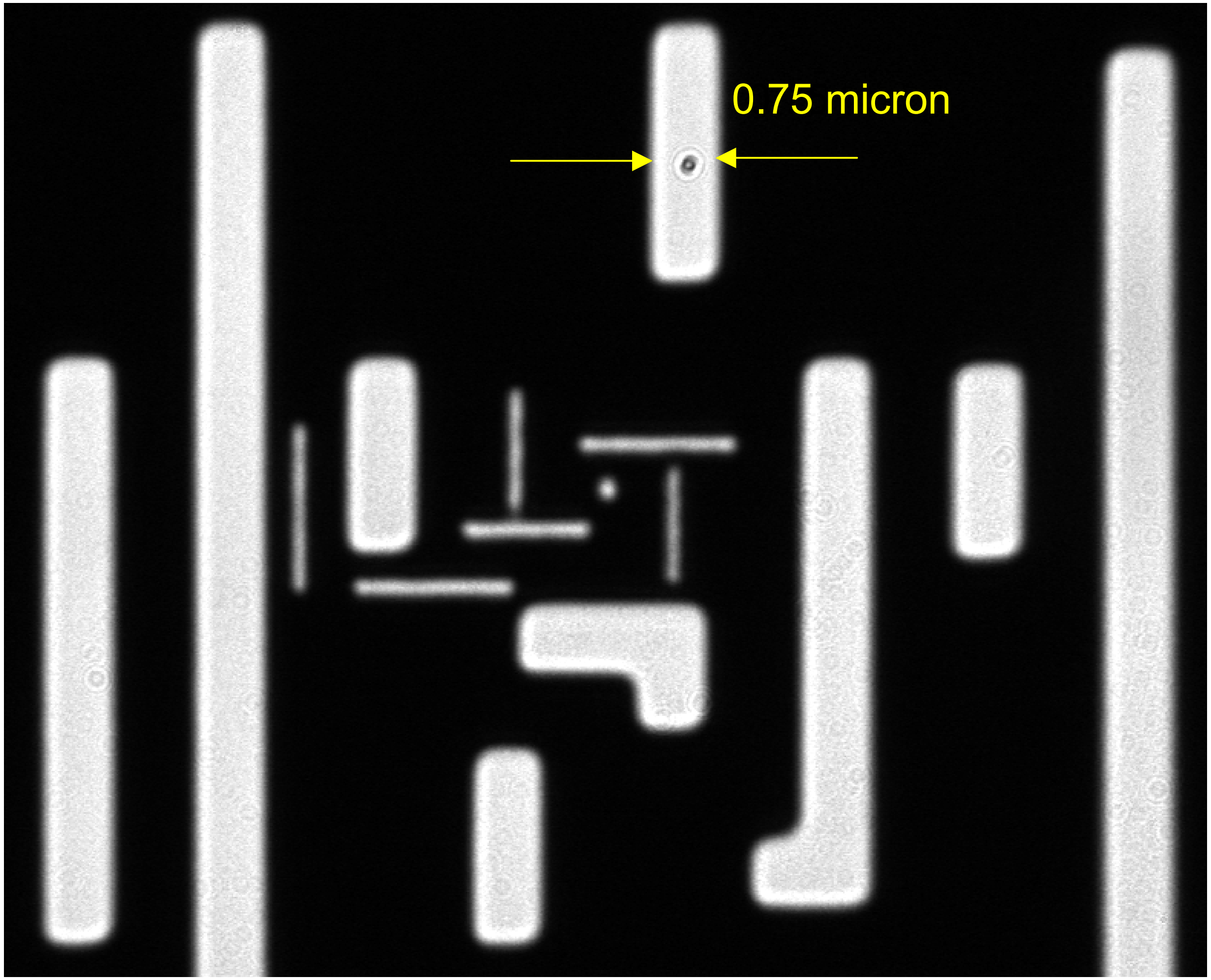


Scanned Gaussian Tool in IBM's Burlington Mask House

Ablation Resolution

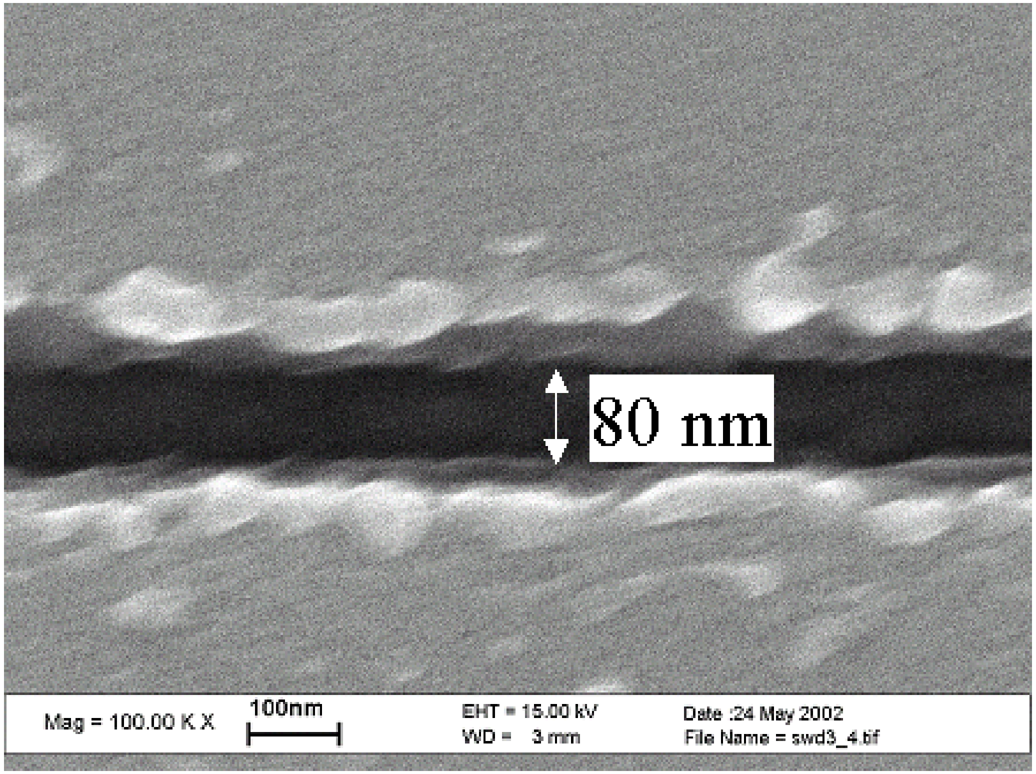
sub 150 nm lines and dots

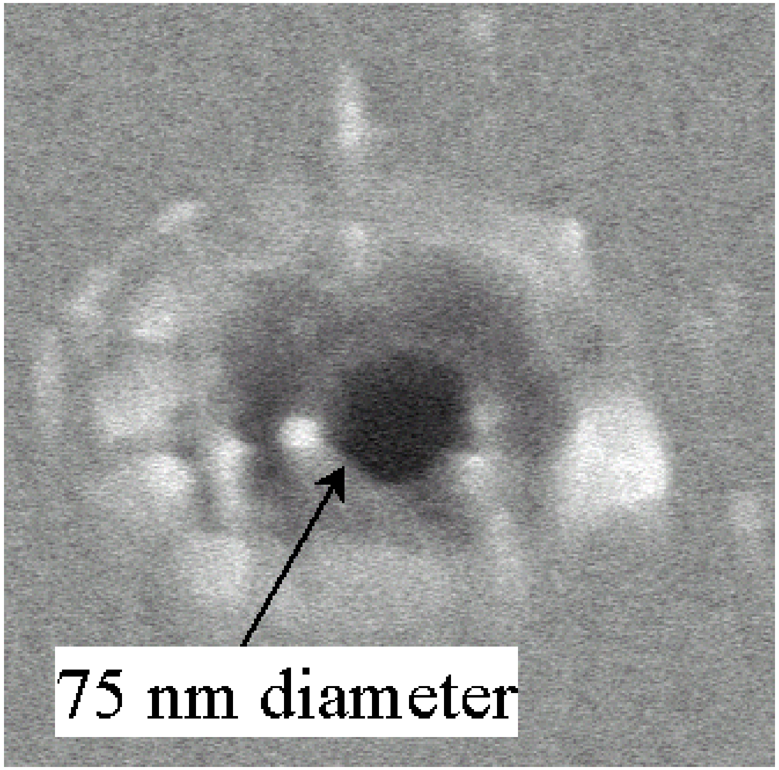
Optical micrograph



Ablation Resolution

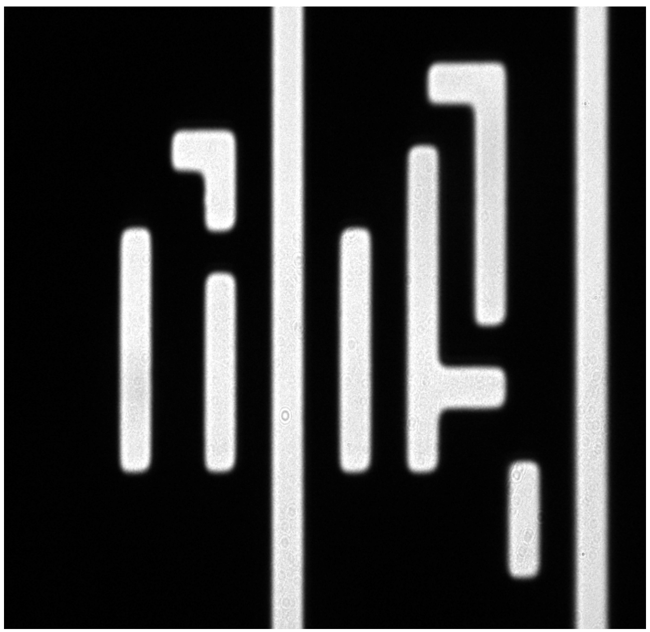
Below the diffraction limit



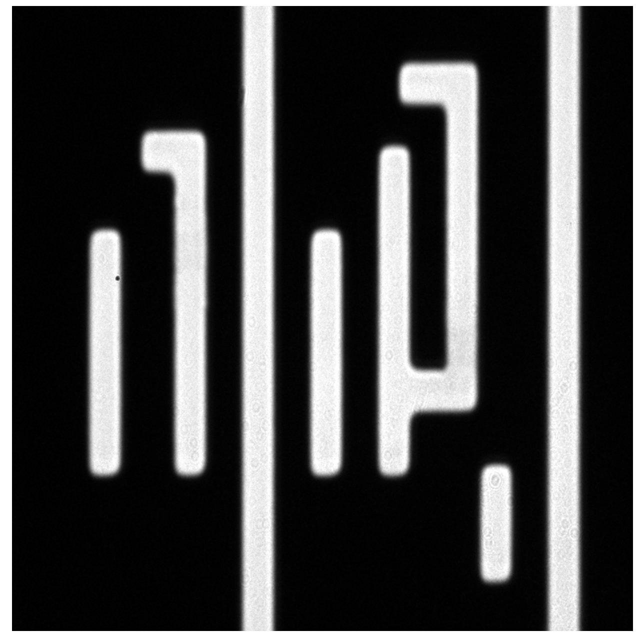


SEM

Photomask Repair Comparison

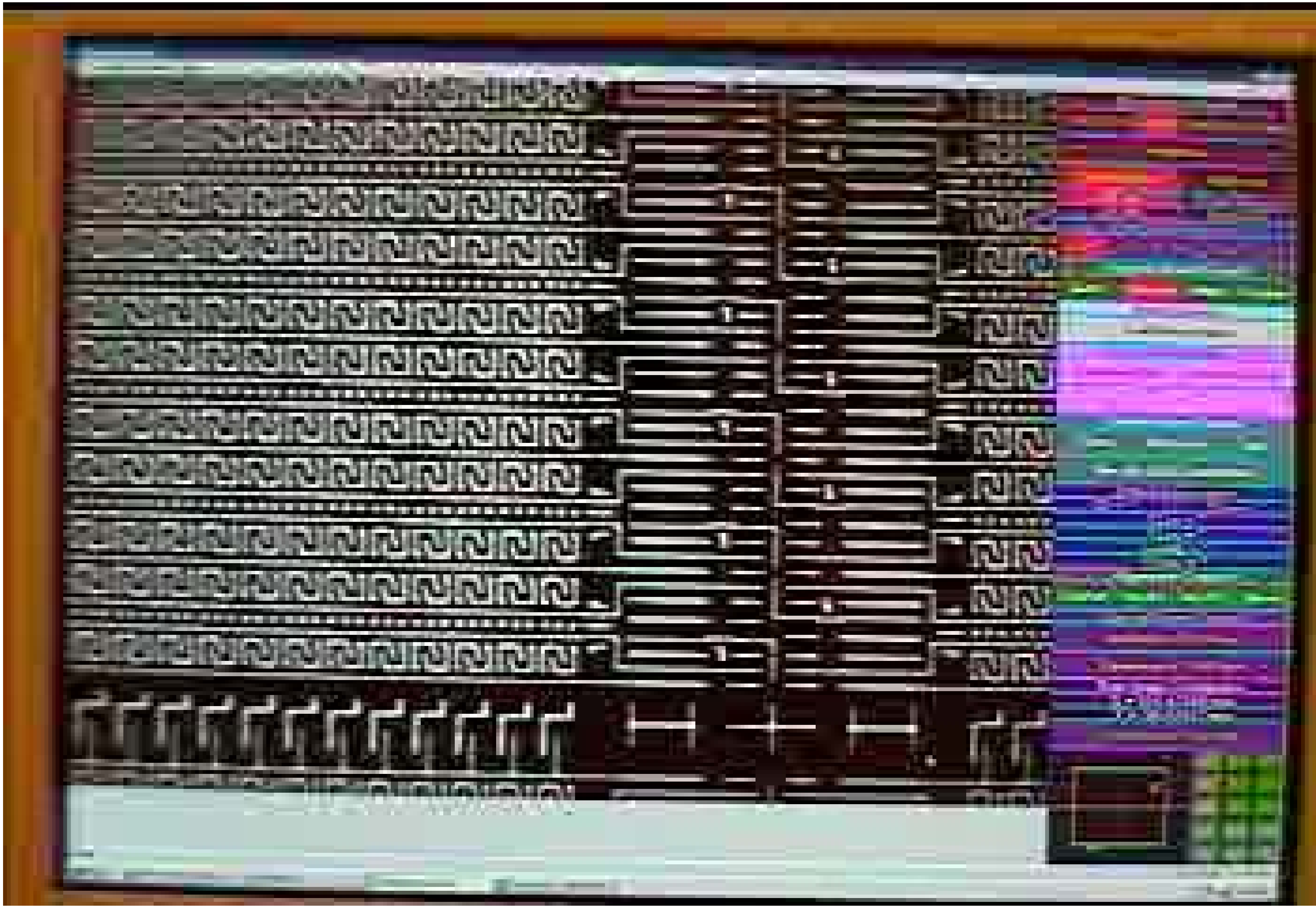


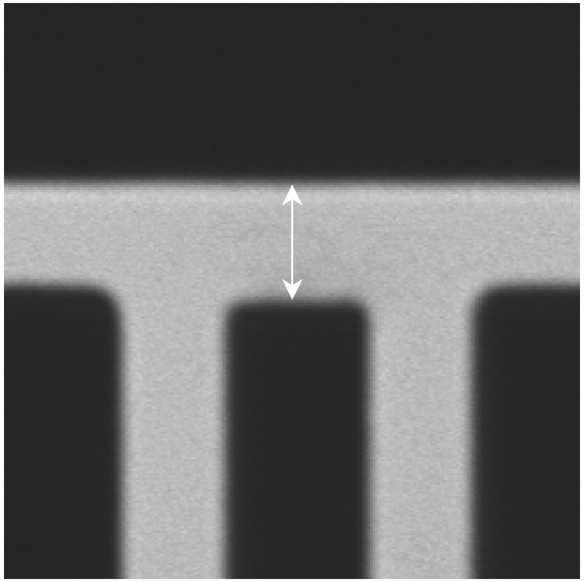
Before

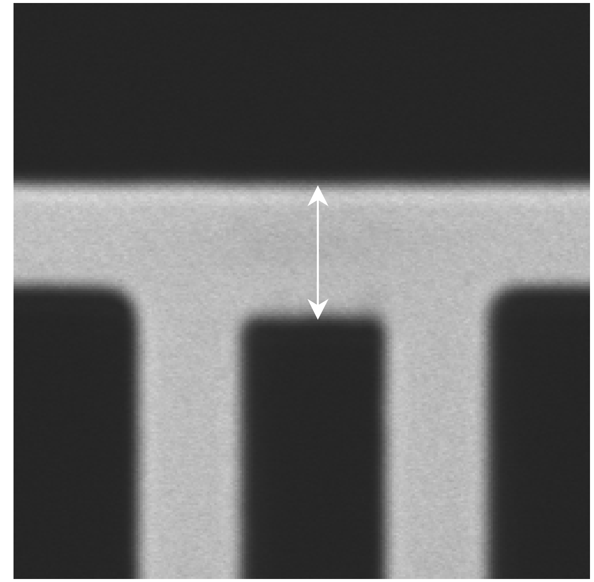


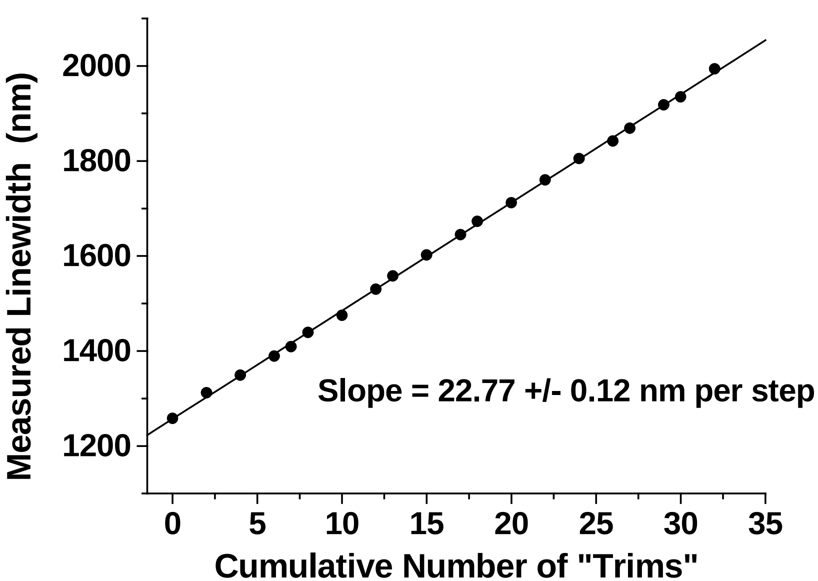
After

248 nm transmitted light optical images

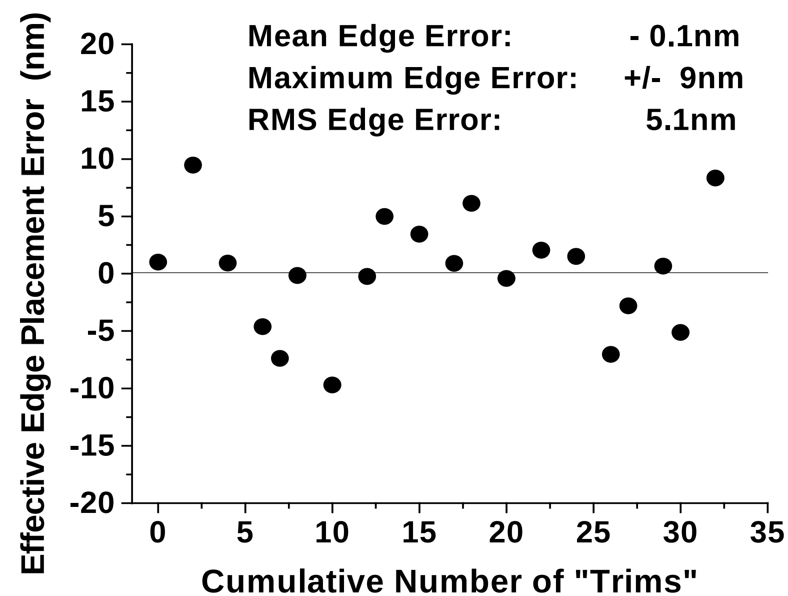






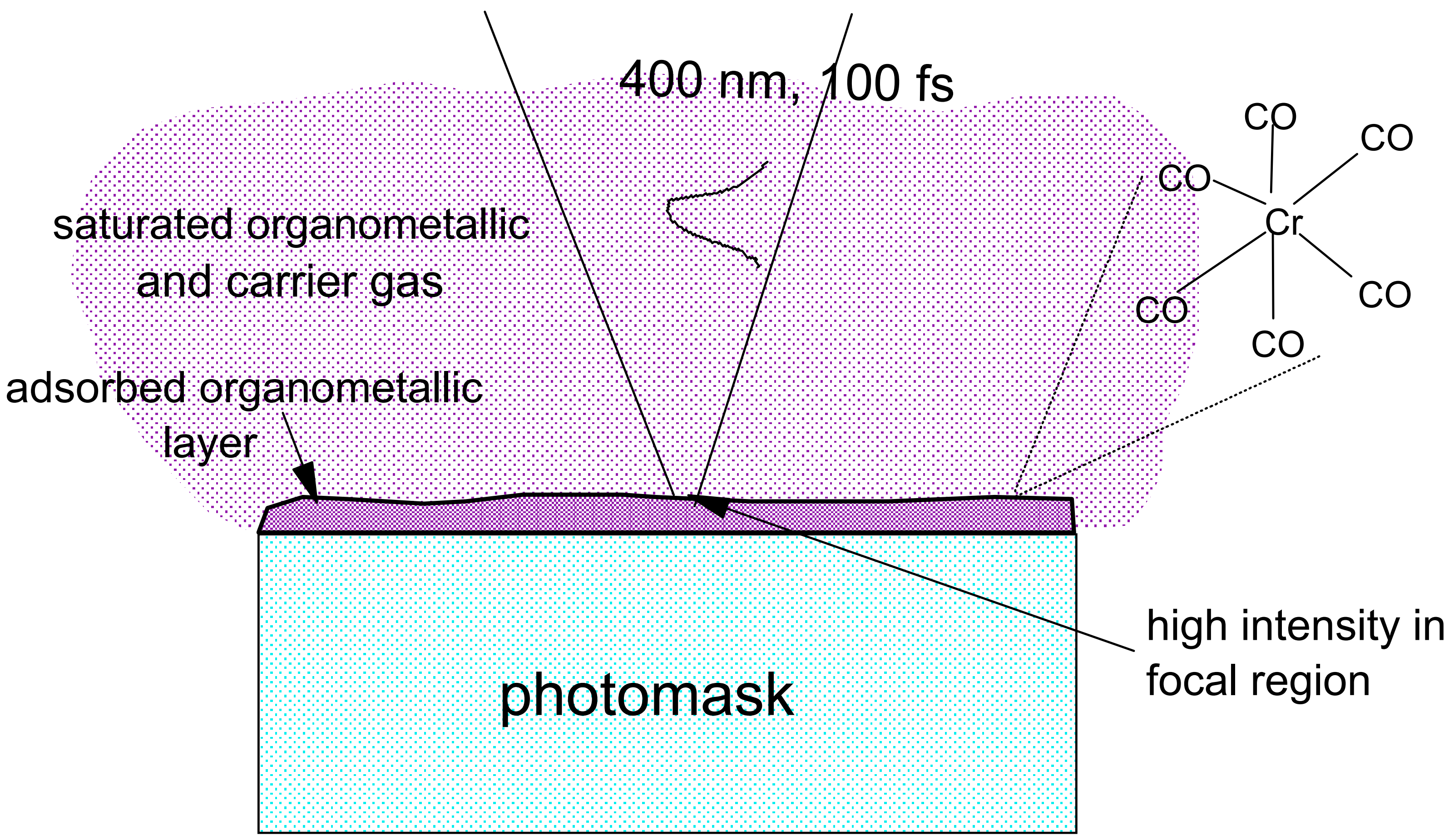


Measured Linewidth (nm)
2000
1800
1600
1400
1200
Slope = 22.77 +/- 0.12 nm per step
0
5
10
15
20
25
30
35
Cumulative Number of "Trims"

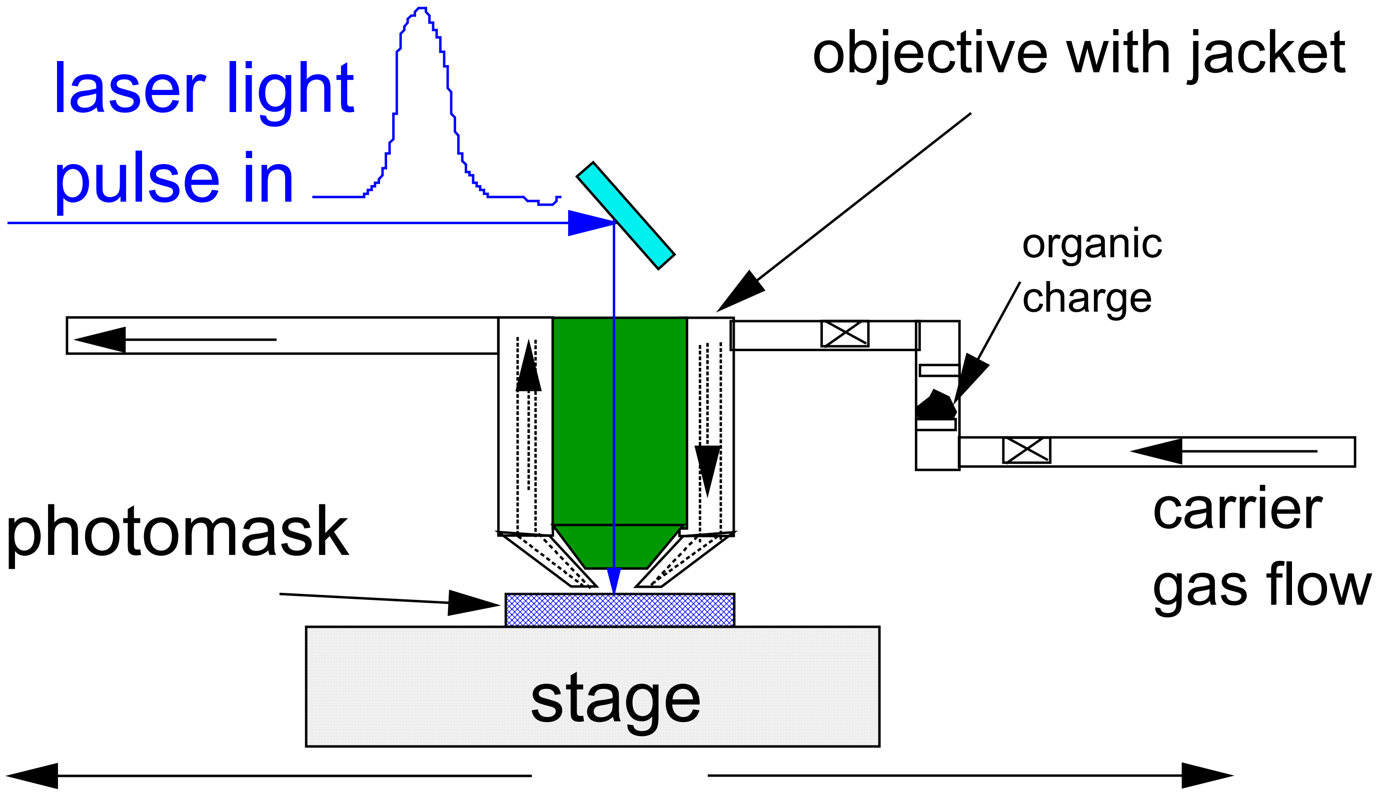


Effective Edge Placement Error (nm)
Mean Edge Error: - 0.1nm
Maximum Edge Error: +/- 9nm
RMS Edge Error: 5.1nm
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
20
25
30
35
Cumulative Number of "Trims"

FEMTOSECOND DEPOSITION TO "WRITE" MATERIAL

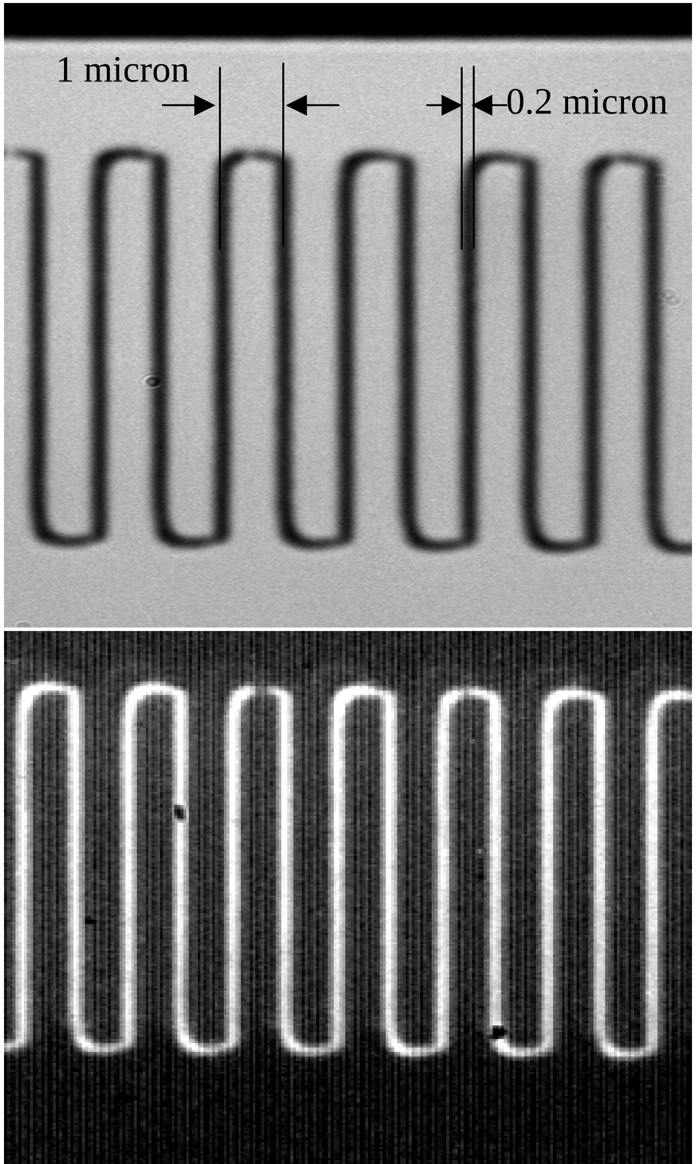


DEPOSITION SETUP

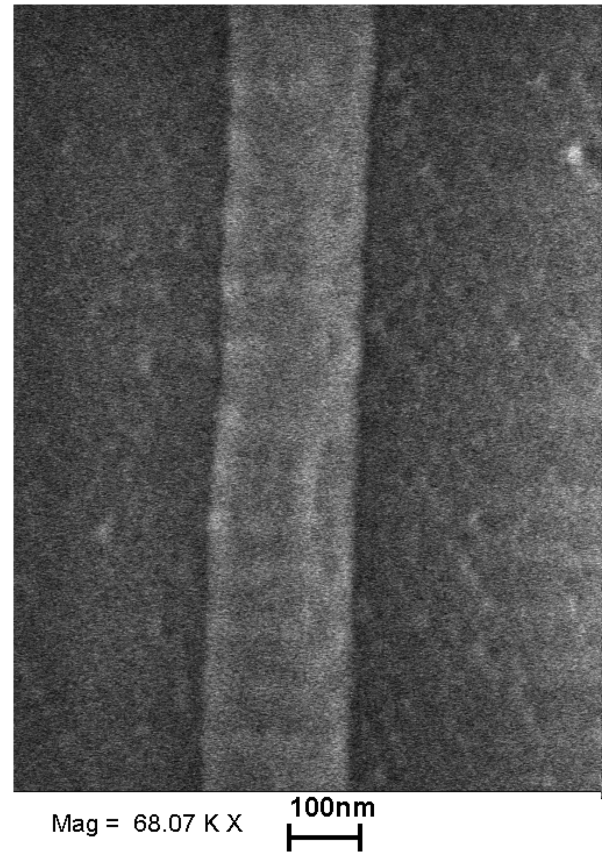


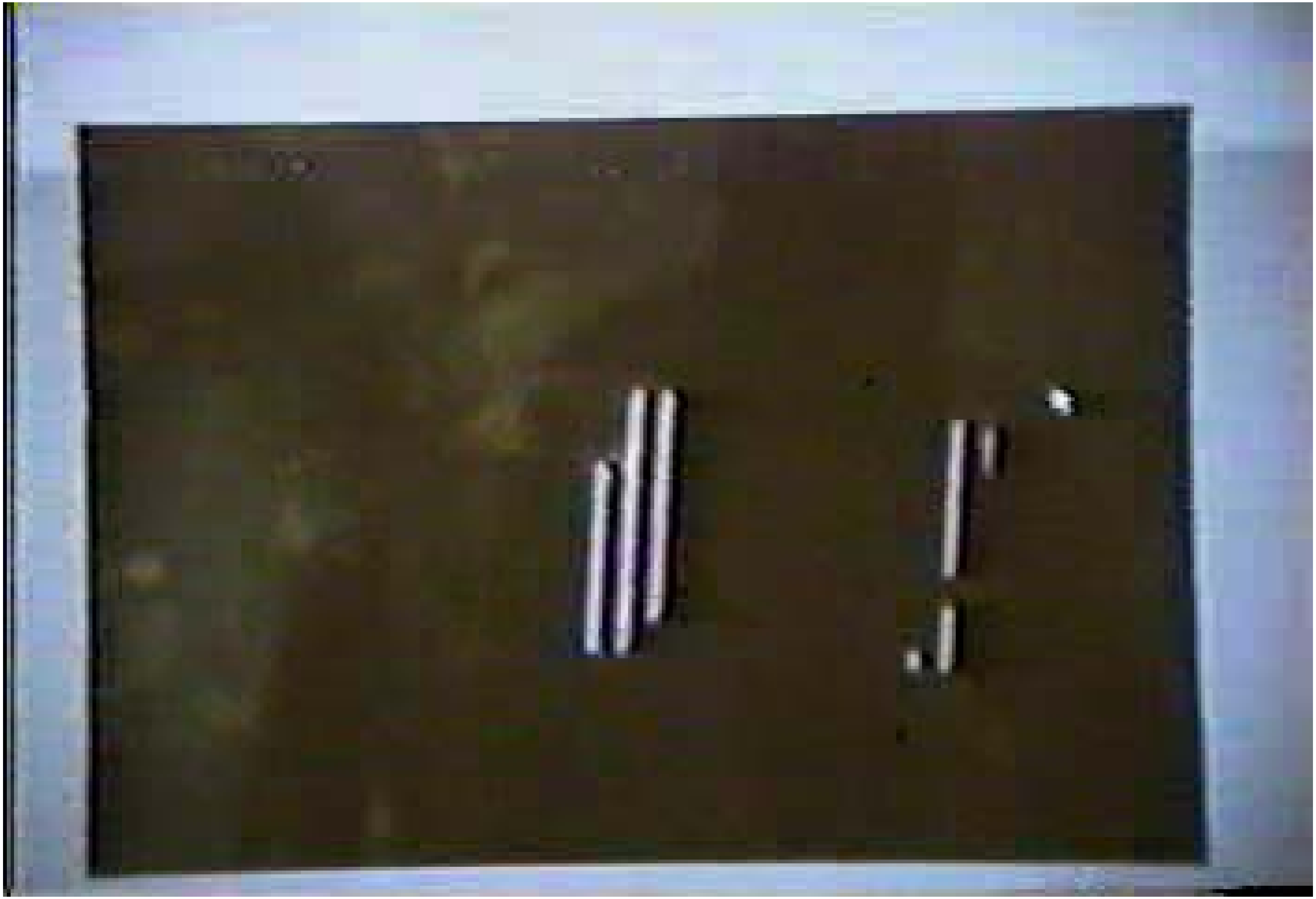
248 nm trans light

365 nm refl. light

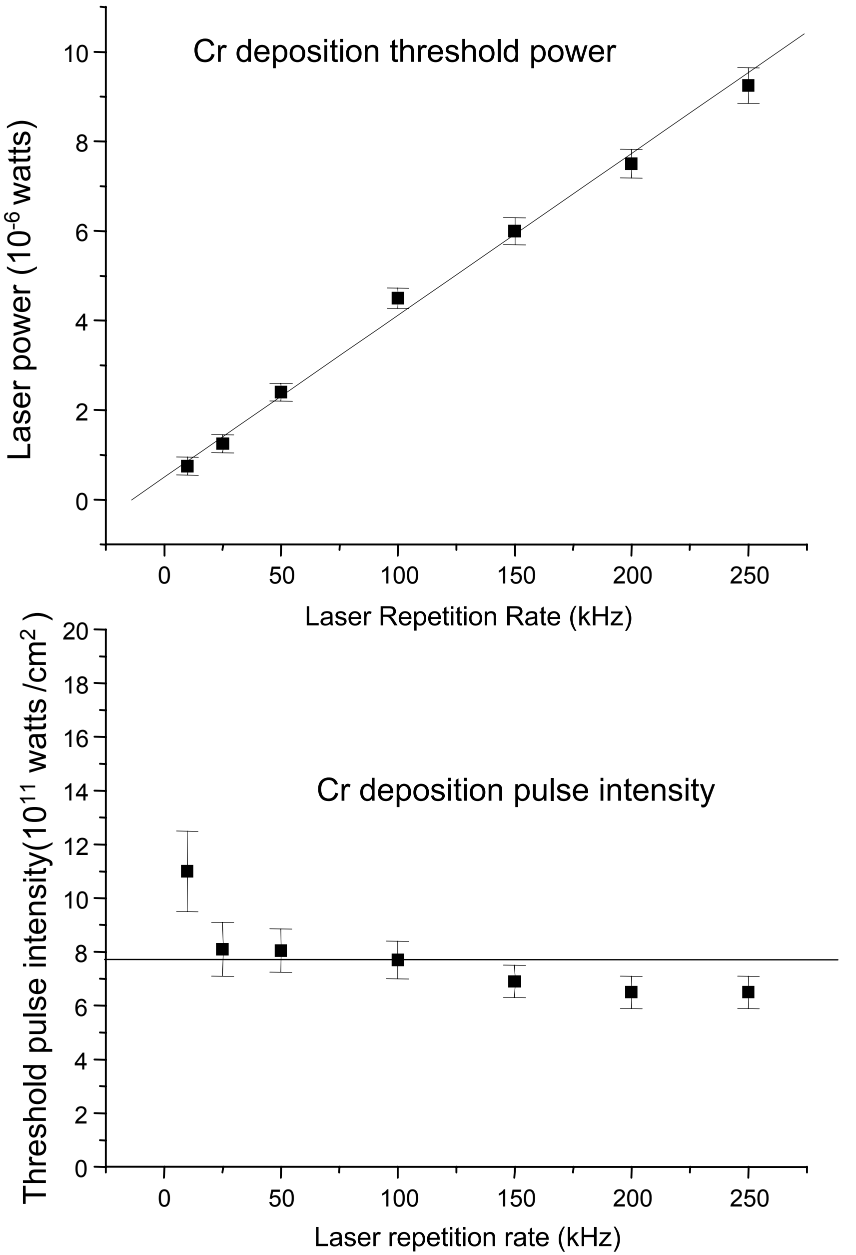


SEM





Laser pulsewidth
120 fs



Deposition **not** thermally driven

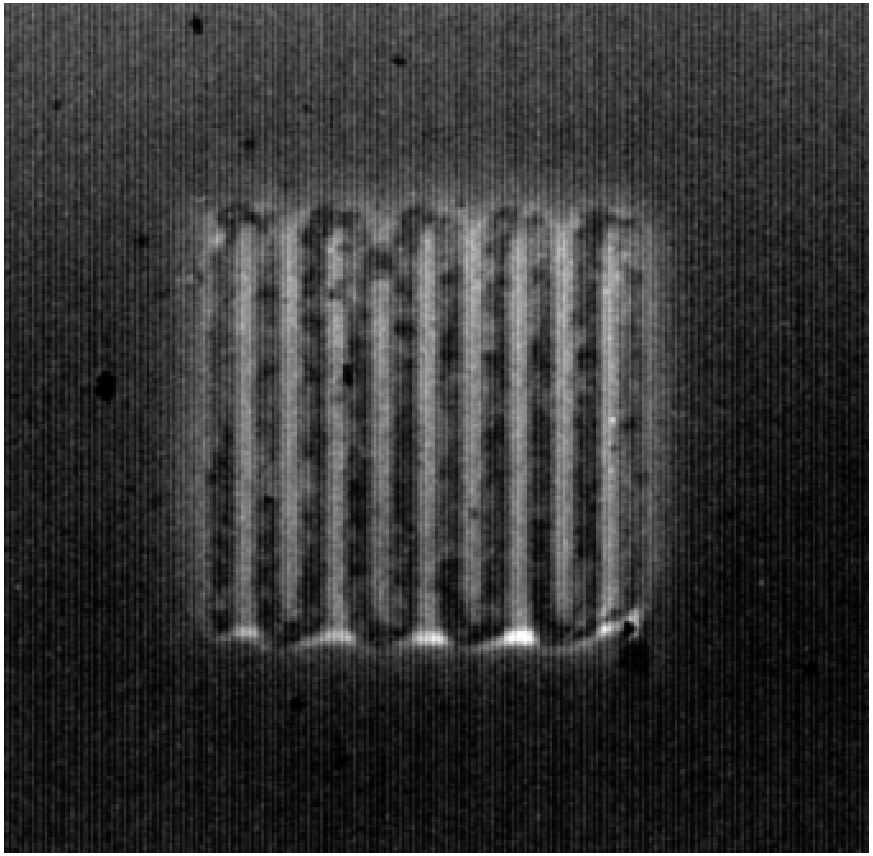
J.Vac. Sci. Technol.
A 21, 649 (2003)

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

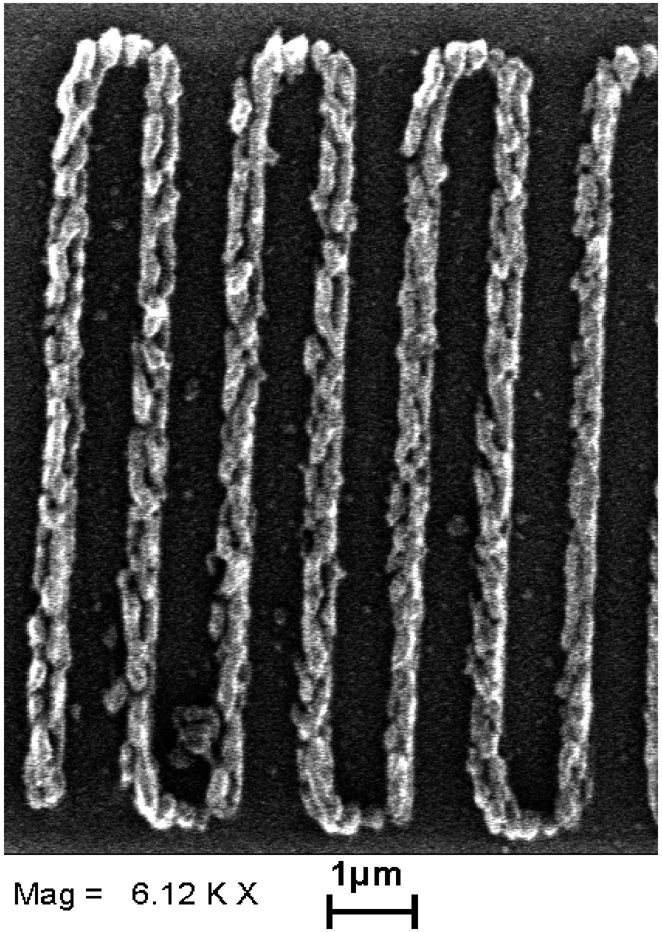
BUT, There's More

MULTIPLE SCANS

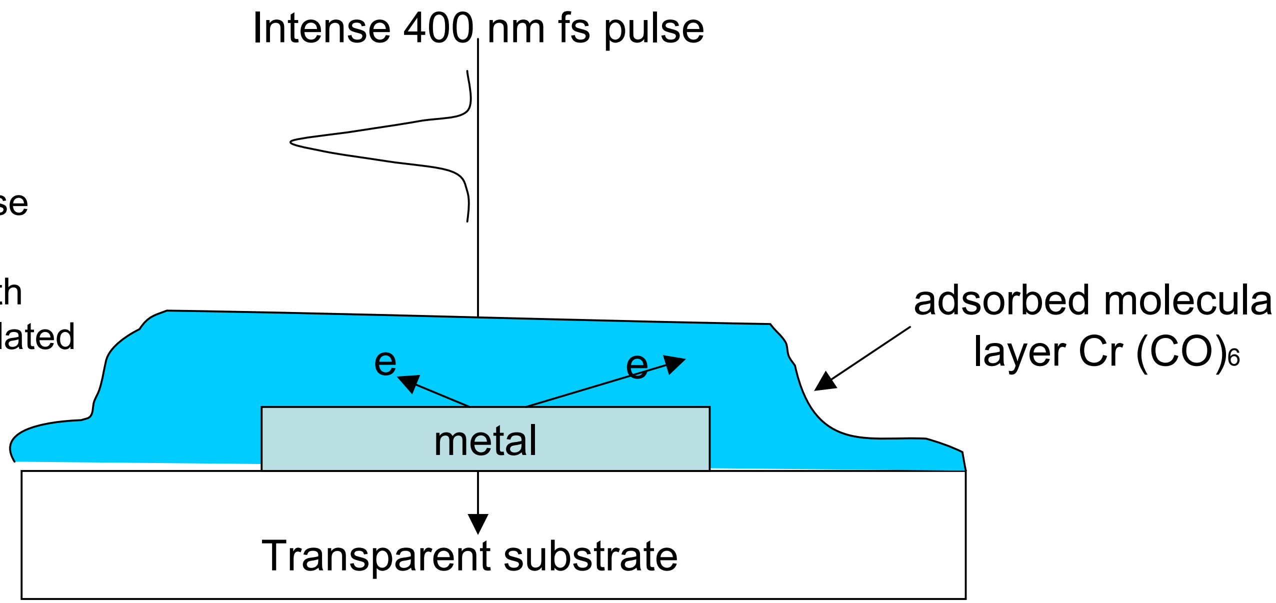
365 nm reflected light



SEM

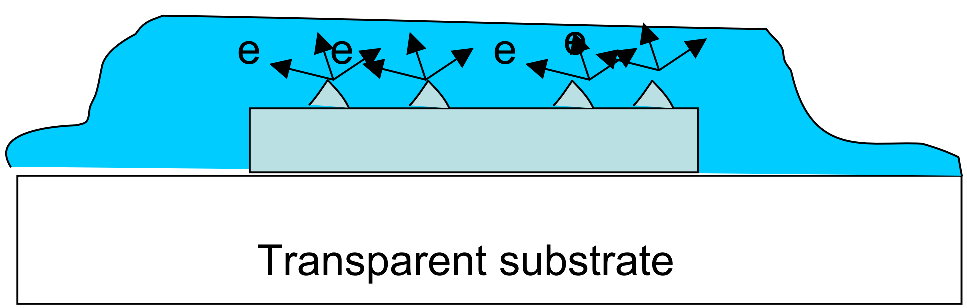


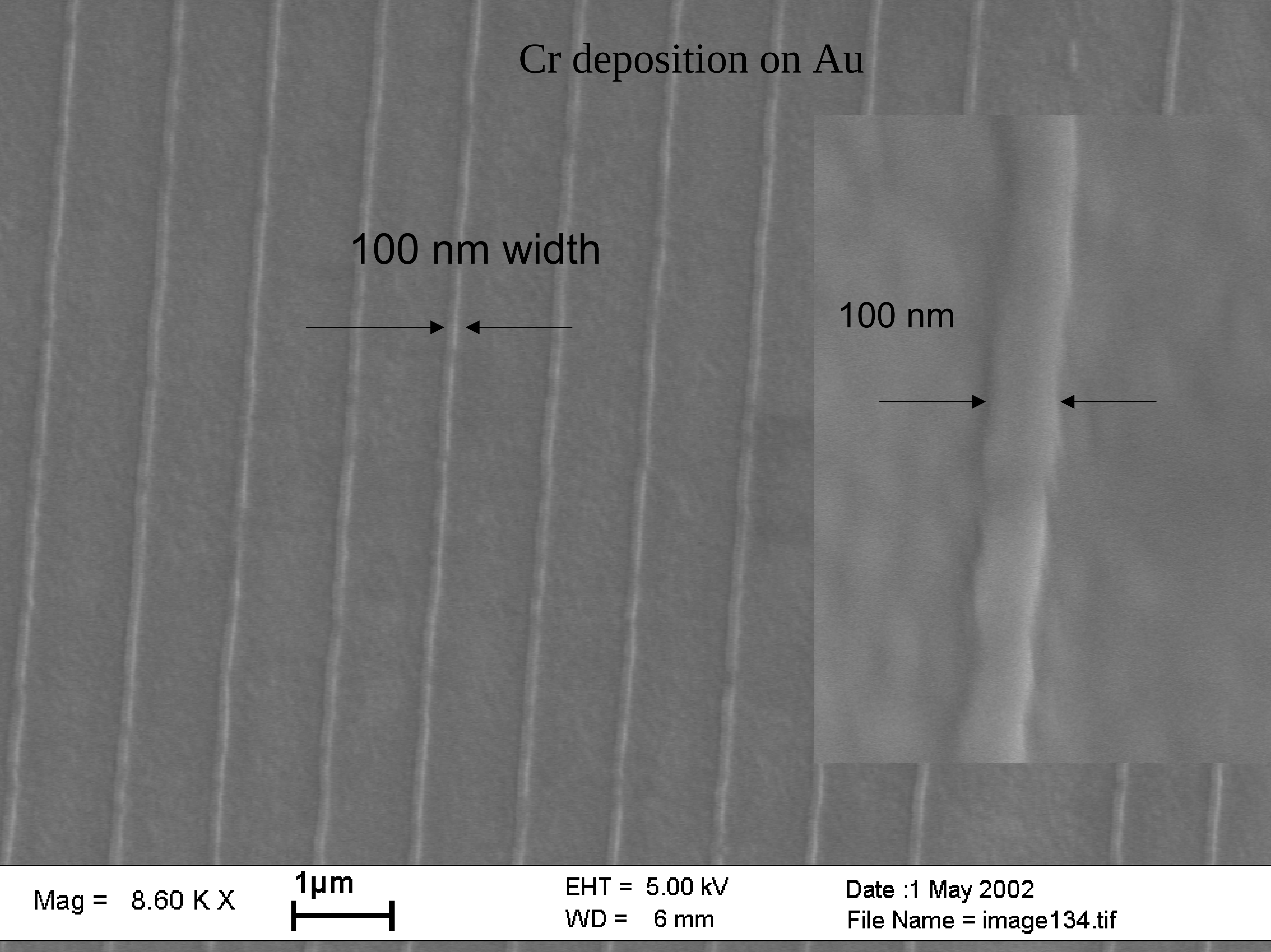
- Electrons excited by interaction of fs pulse with metal
- Continued metal growth through electron stimulated dissociation



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

Laser induced e excitation enhanced at asperities ➔ amplifies roughness




Cr deposition on Au
100 nm width
100 nm
Mag = 8.60 K X
1µm
EHT = 5.00 kV
WD = 6 mm
Date :1 May 2002
File Name = image134.tif

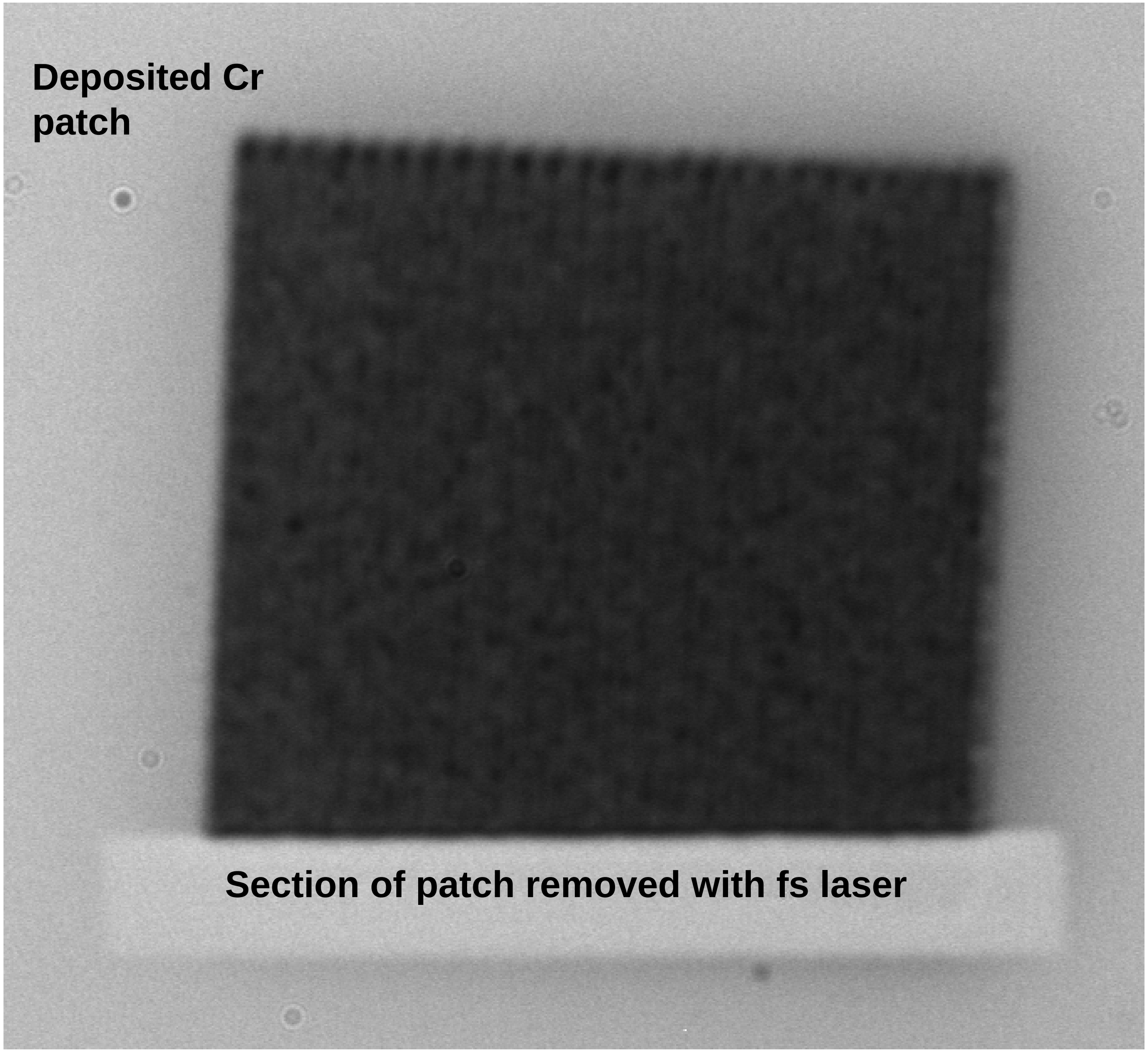
Model for Deposition

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

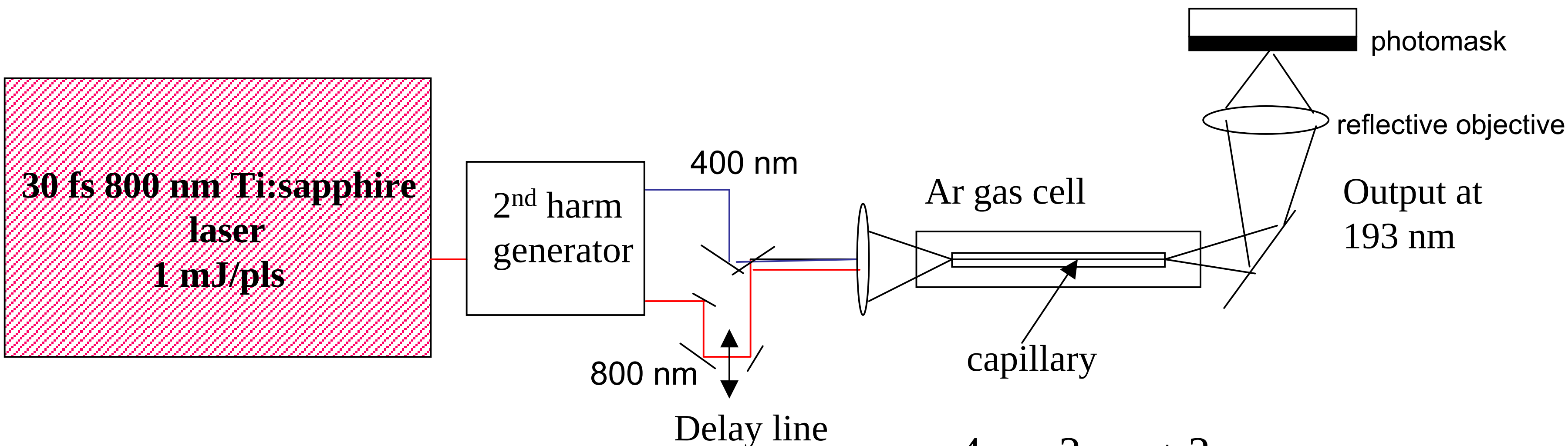
- *Continued deposition is combination of multiphoton and thermal decomposition (in creation of line or patch) ➔smooth metallic deposits are observed*

- *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



Generation of 193 nm light for ablation



$$4\omega = 2\times\omega + 2\omega$$

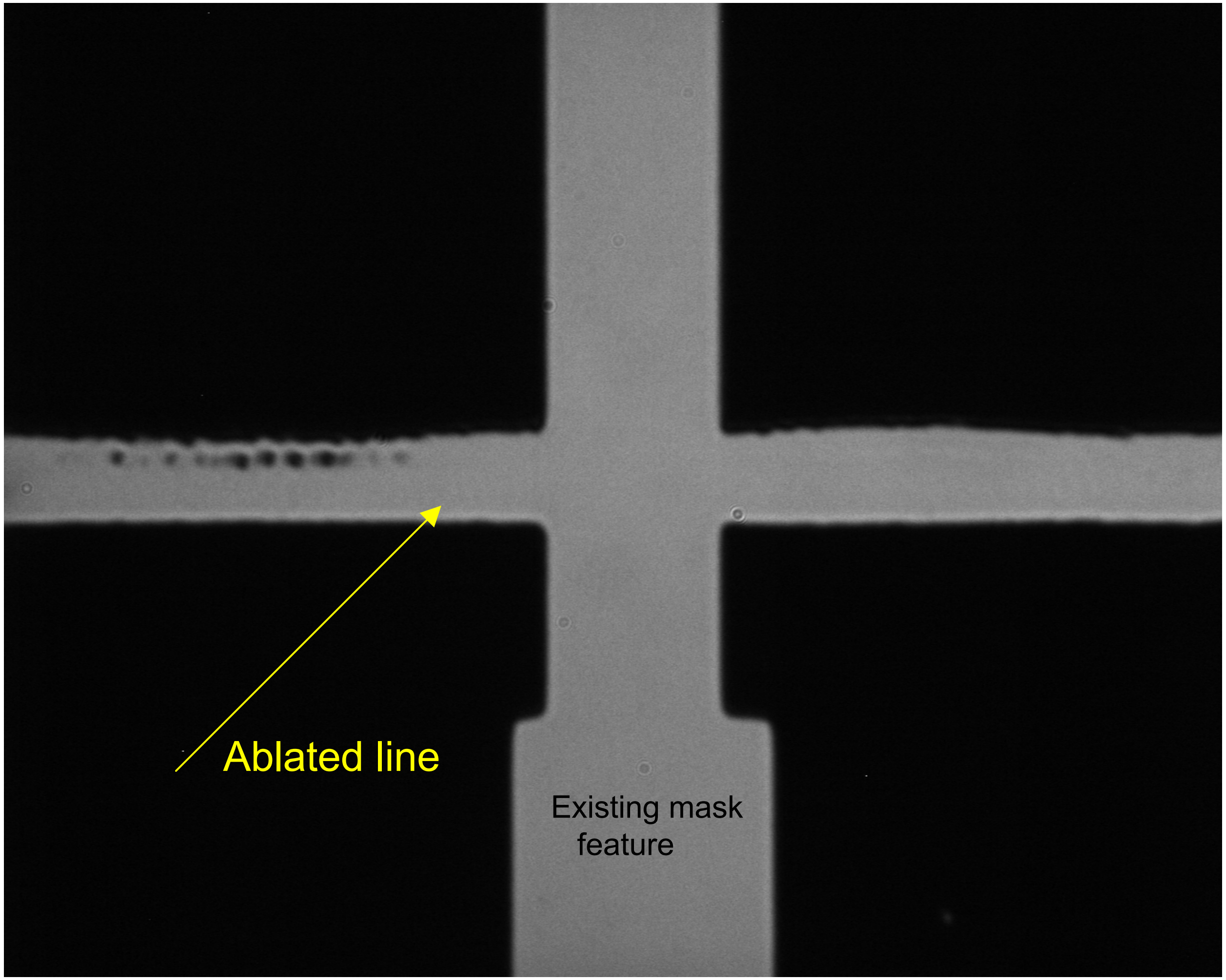
$$4\omega = 2\times 3\omega - 2\omega$$

$$4\omega = 2\omega + 3\omega - \omega$$

$$4\omega = 3\times 2\omega - 2\times\omega$$

Misoguti, Backus, Durfee, Bartels, Murnane, Kapteyn, PRL, 87 013601-1 (2001)

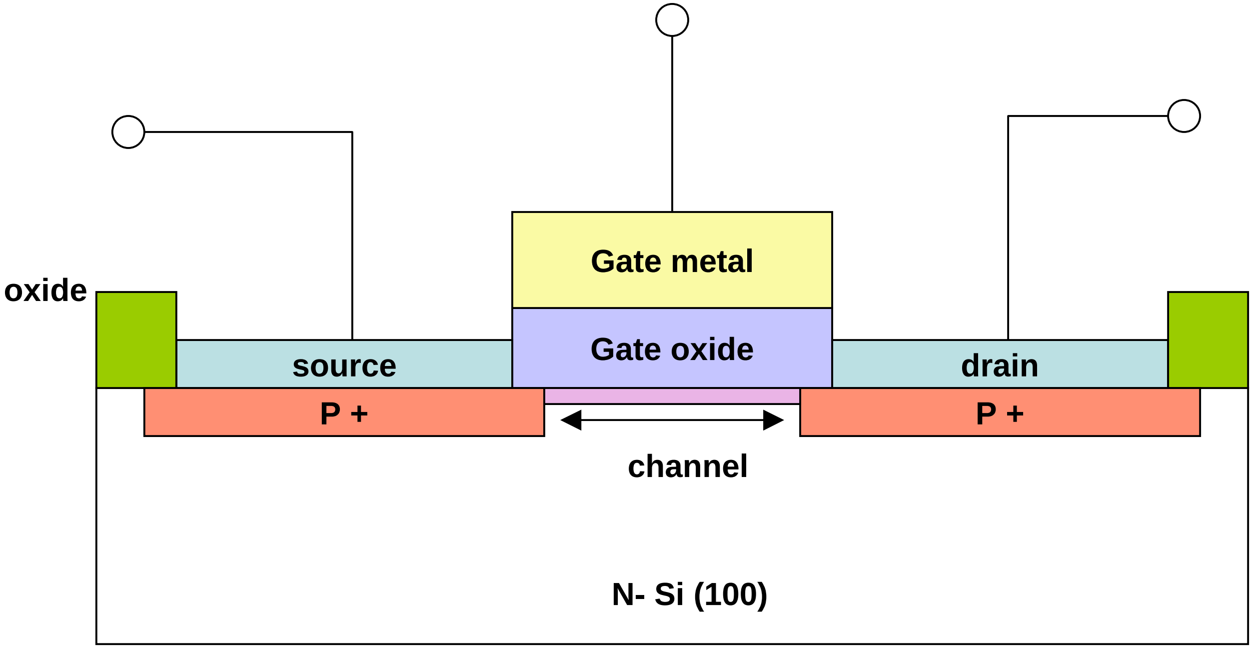
Ablation with 30 fs 193 nm light pulses



Femtosecond Photomask Repair

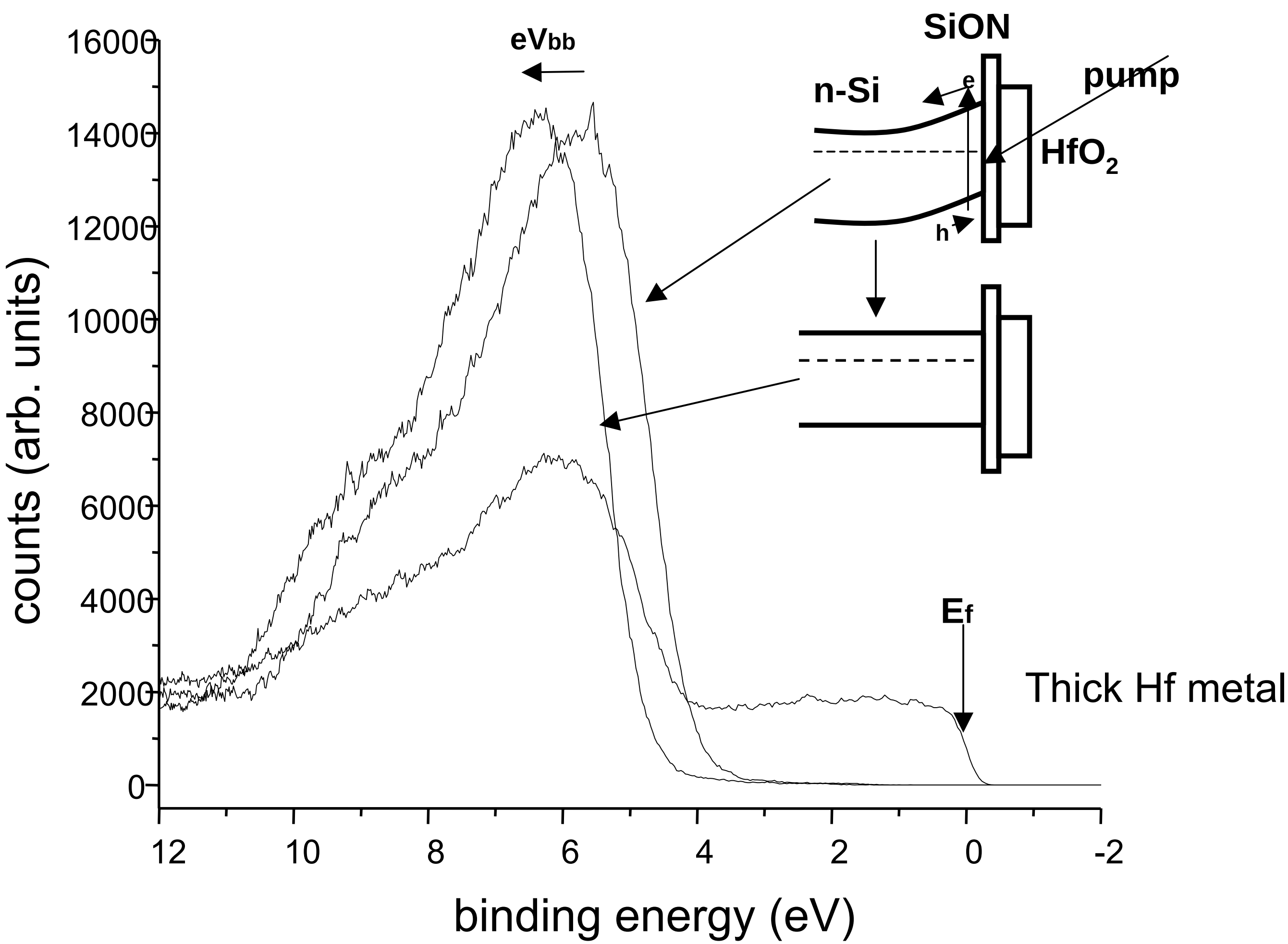
- Fs ablation provides significant improvement in quality and placement of repair
- Both ablative and additive repair
- High throughput, spatial control big win
- Machine presently operating in IBM's BTV Mask House
- >10^8 $$ in mask value repaired

PHOTOVOLTAGE MEASUREMENTS OF METAL OXIDE SEMICONDUCTOR STRUCTURES USING PUMP-PROBE FS PHOTOELECTRON SPECTROSCOPY



P-FET

HfO_2/SiON/Si(100)- n



Photon energy 26.35 eV

Band Bending and Charge Transfer In HfO_2/Si(100)

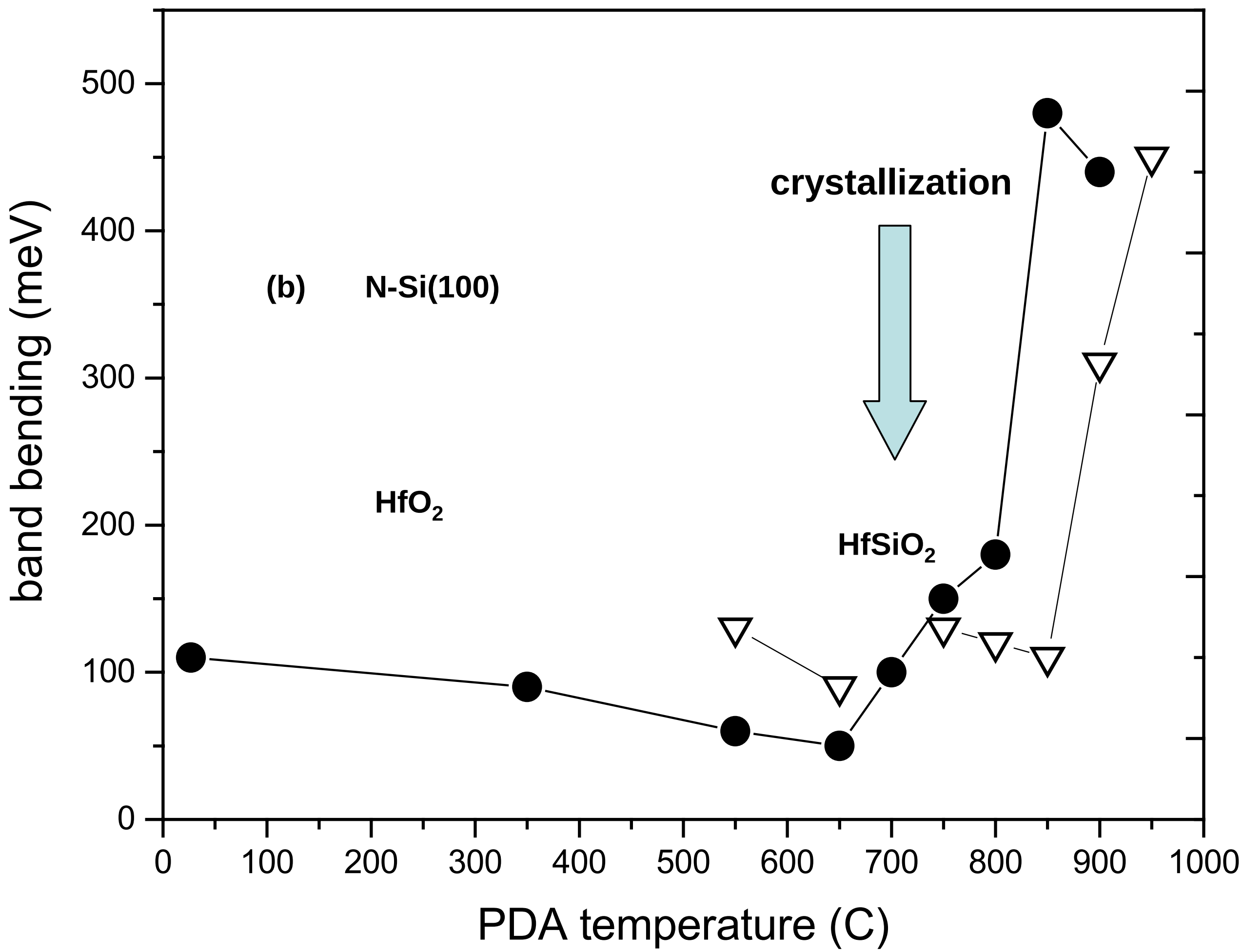


Fig. 4

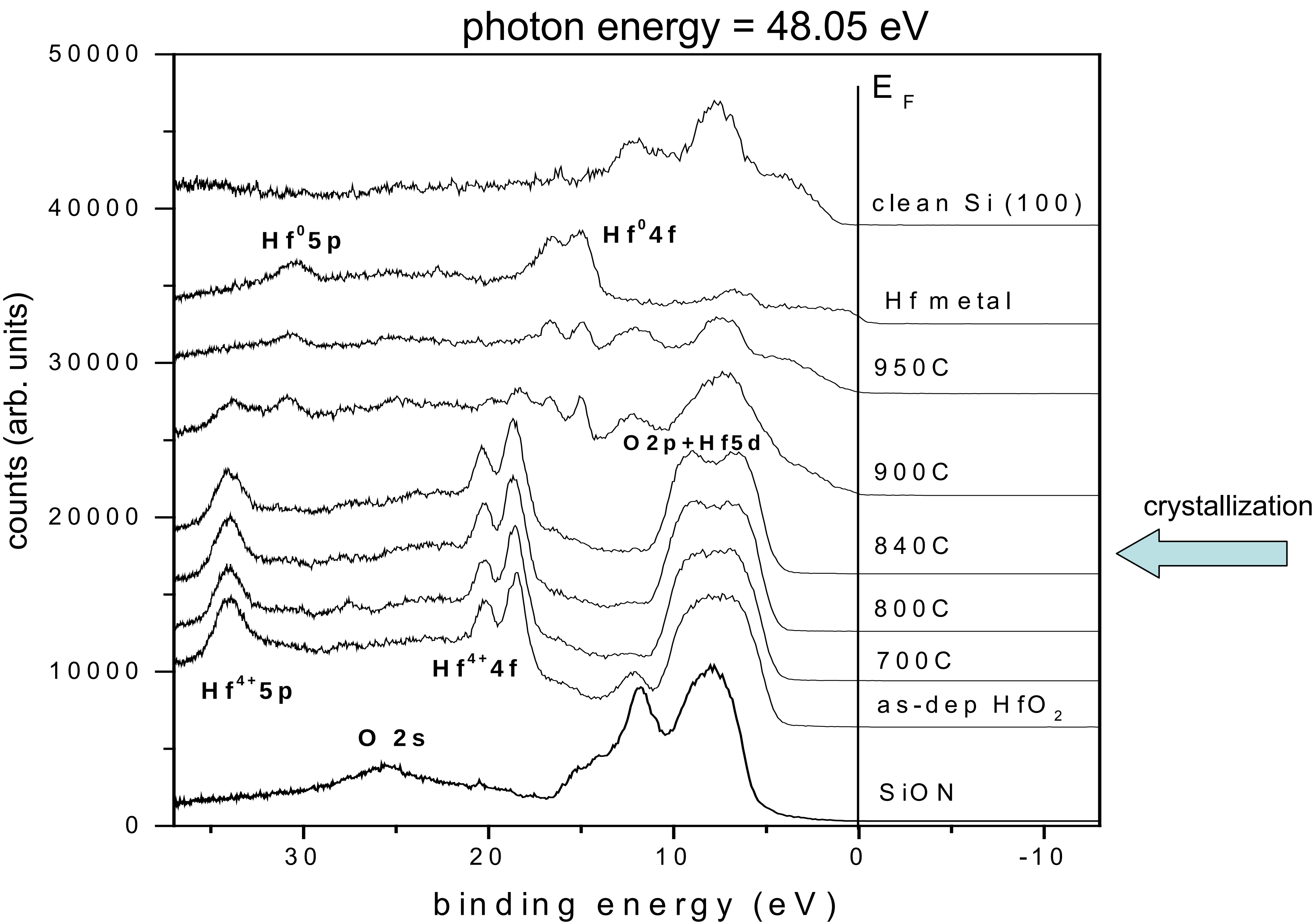

photon energy = 48.05 eV
counts (arb. units)
binding energy (eV)
50000
40000
30000
20000
10000
0
30
20
10
0
-10
E F
clean Si (100)
Hf metal
950C
900C
840C
800C
700C
as-dep HfO 2
SiON
Hf 0 5p
Hf 0 4f
O2p+Hf5d
Hf 4+ 5p
Hf 4+ 4f
O 2s
crystallization

Fig. 6

IN A NUTSHELL:

High temp anneal→ oxygen vacancy formation

Electrons tunnel into defects and become trapped

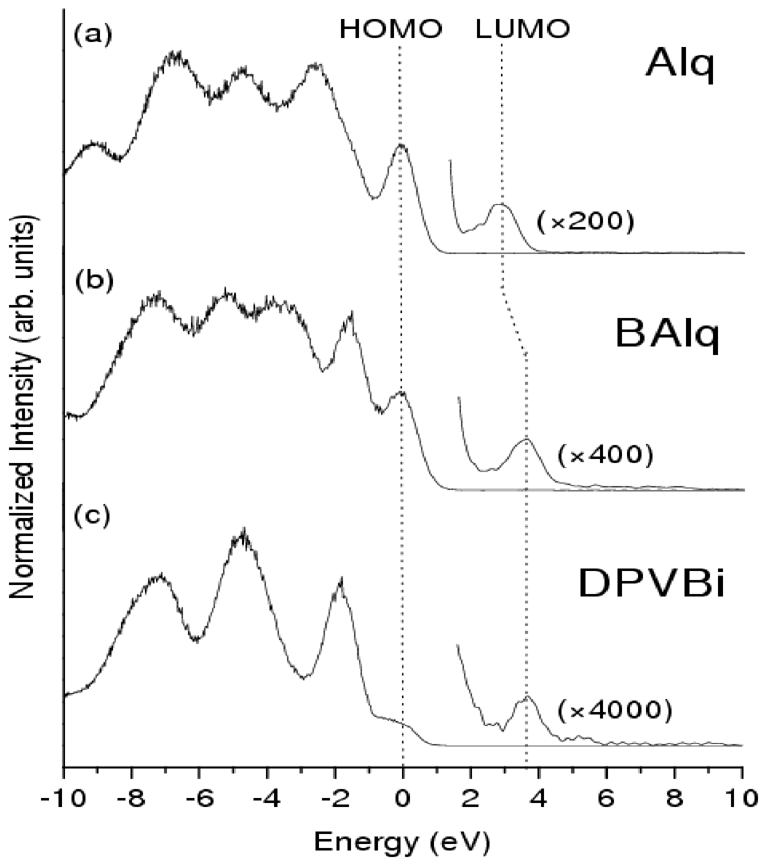
Possible Experiments on the FEL

- **Can we generate high harmonics on the FEL?**

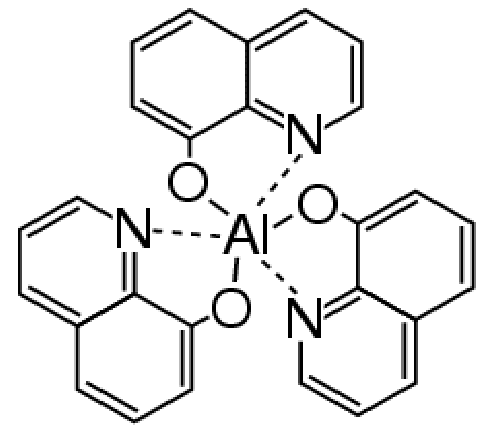
$E_{max} = E_i + 3.2\ U_p$: need temporally short IR pulse
$U_p = (e^2E^2)/(4m\omega^2)$ high intensity (100's μJ→ mJ)

- **FEL could provide big advantage in repetition rate (10^3 – 10^4) to look at weak signals, small structures**

ORGANIC LIGHT EMITTERS



Alq



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**