CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

MICRO/NANO USINAGE ET STRUCTURATION DE SURFACE PAR LASER FEMTOSECONDE

EPMT
ENVIRONNEMENT PROFESSIONNEL MICROTECHNOLOGIES
SALON INTERNATIONAL

Laboratoire Lasers Plasmas et Procédés Photoniques

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LP3

GIS Photonique et Instrumentation Avancée

Mécanismes d'ablation laser

laser

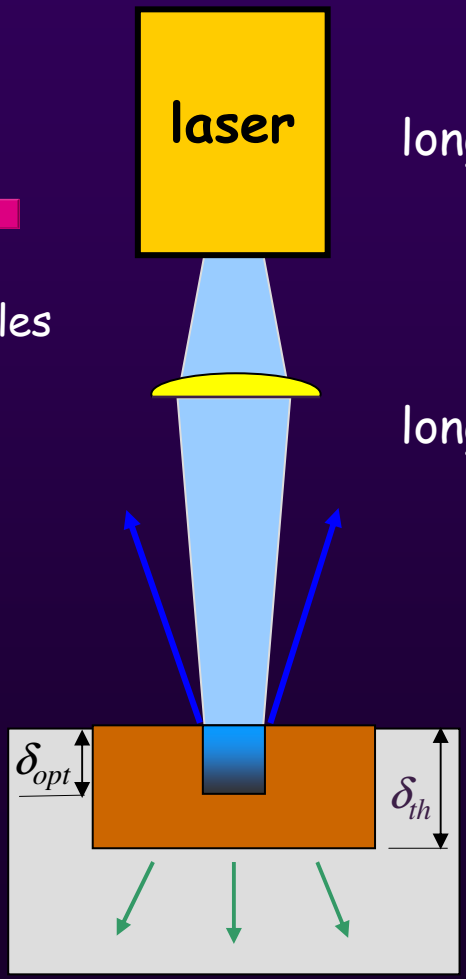
*** longueur d'onde λ_{las}
*** fluence F_{las}
*** durée d'impulsion τ_{las}
** qualité de faisceau
* fluctuations spatio-temporelles

matériau

réflectivité R
coefficient d'absorption, α
conductivité thermique, K_{th}
capacité calorifique, C_p
températures T_{fus}, T_{vap}
chaleurs latentes H_{fus}, H_{vap}

environnement

air, gaz inerte, vide, liquide



longueur de pénétration optique

$$\delta_{opt} = \alpha^{1}$$

longueur de diffusion thermique

$$\delta_{th} = 2\sqrt{\chi \tau_{las}}$$

$$\chi = \frac{k_{th}}{\rho C_p}$$

Quelques grandeurs caractéristiques

Plasma d'ablation :

$T_{initiale}$: 2000 à 10000 °K

Vitesse des particules : ~10^5cm/s

10^{-14}

10^{-13}

10^{-12}

10^{-11}

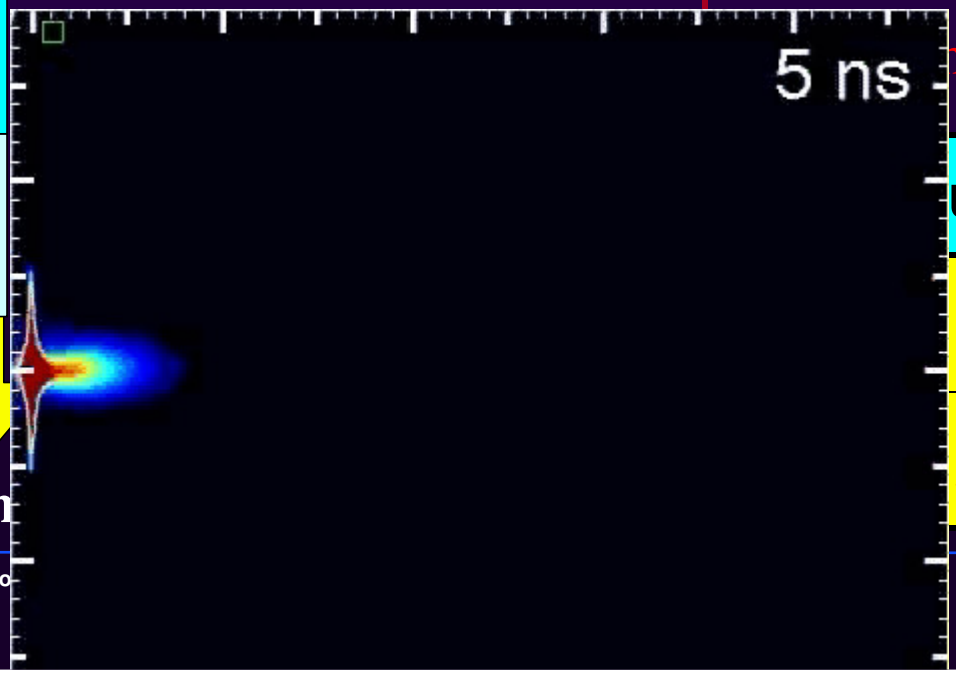
10^{-10}

Thermalisation électronique

Relaxation électron - phonon

non thermique

nique

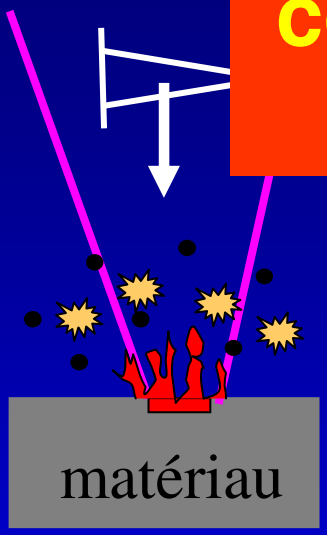


tem

ux	polymères
δ_{ther}	$\delta_{opt} \sim \delta_{ther}$
δ_{ther}	$\delta_{opt} >> \delta_{ther}$

LP3 Laborato

Avantages d'une bonne connaissance de l'interaction laser-matériau



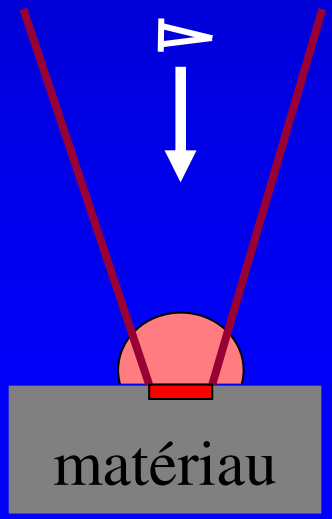
(Nd: YaG, excimères, 10^{-} 1000 W)

Faible efficacité

Faible qualité

Faible précision

Impulsion fs

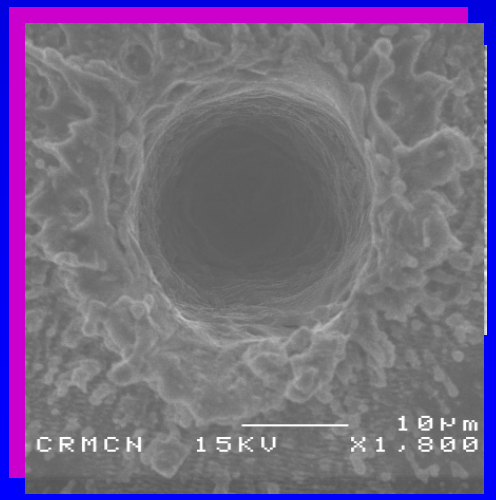


Ablation femtoseconde ($t_{pulse} < t_{diffusion\ chaleur}$, absorption non-linéaire)

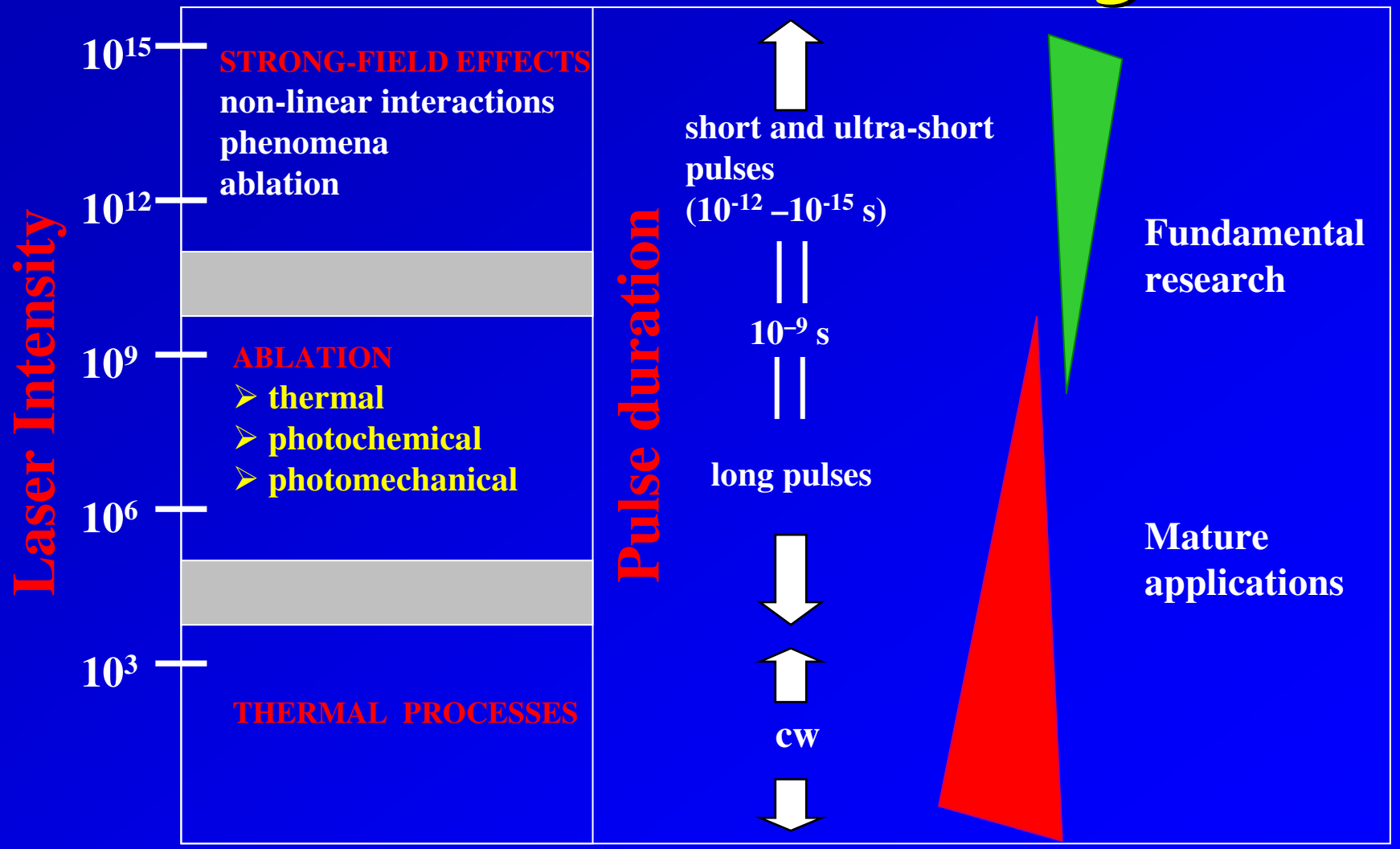
Efficacité, polyvalence

Qualité

Précision, contrôle

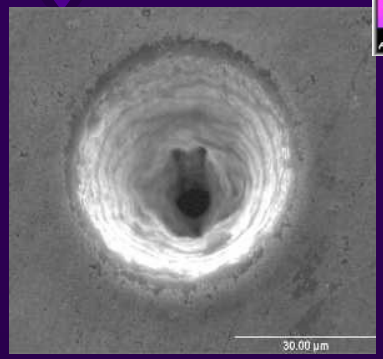


High-Power Laser Applications in Material Processing

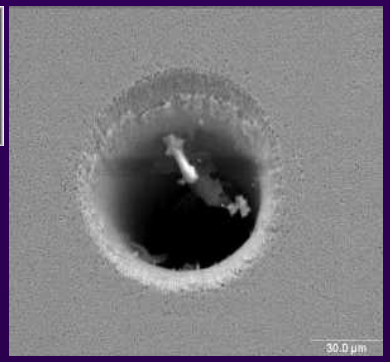


(source : C. Fotakis)

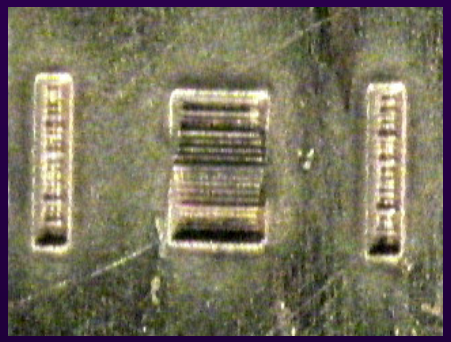
fs Micromachining



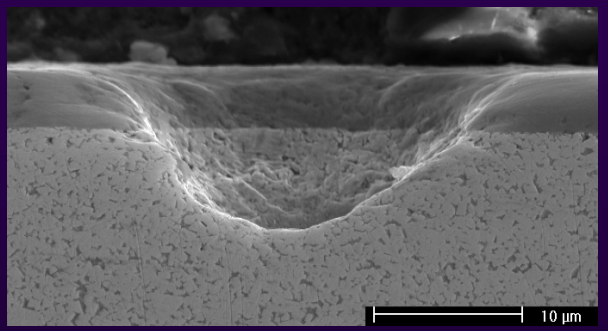
diamond
10^3 shots,
50 µJ, 100 fs



WC / Co
10^4 shots,
50 µJ, 100 fs

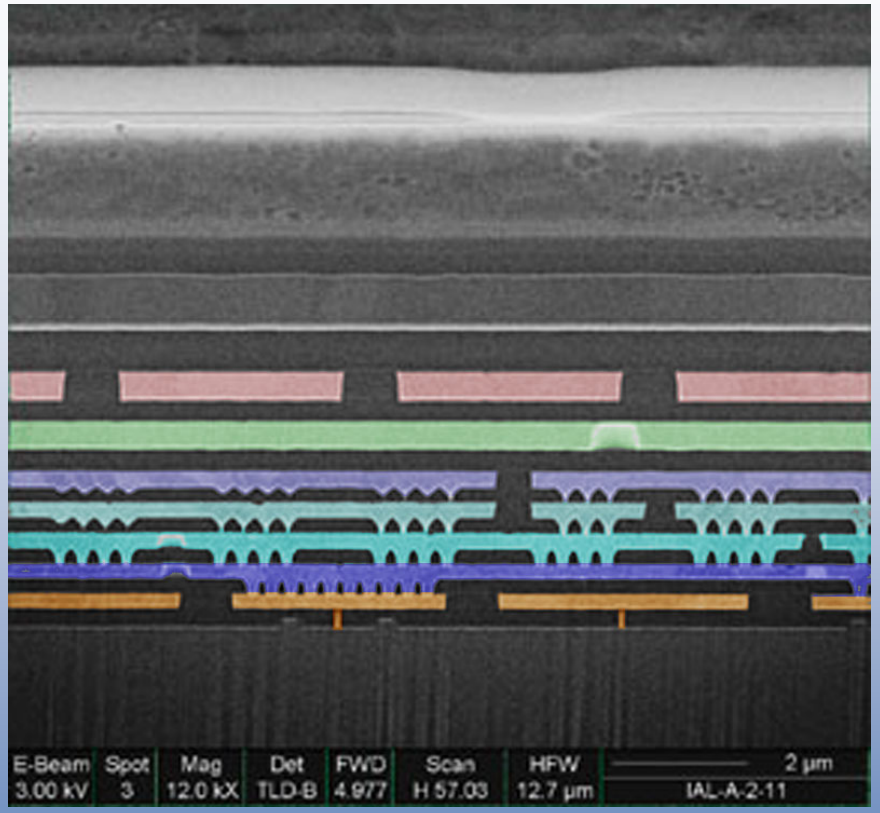


Micro-bridge
in $Bi_2Sr_2CaCu_2O_8$

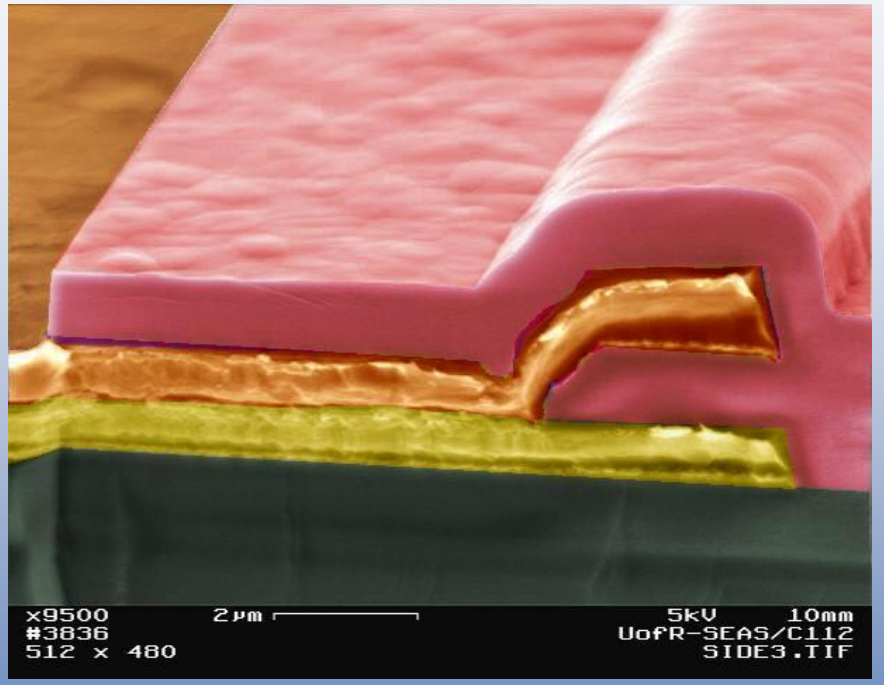


Si wafer cutting

Application pour la microélectronique



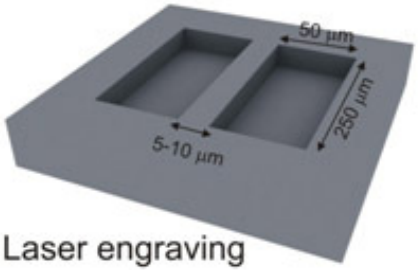
Analyse de défauts



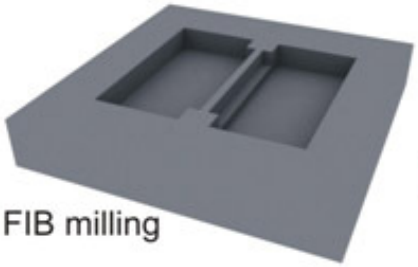
Reverse engineering
(source : optics rochester)

Objectifs : micro-usinage rapide avec effets thermiques très réduits

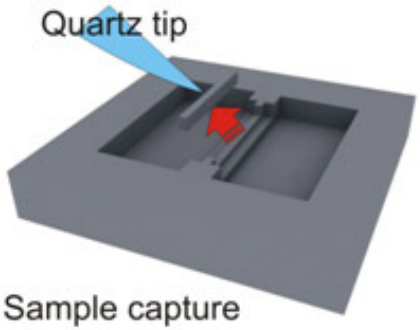
Steps:



Laser engraving



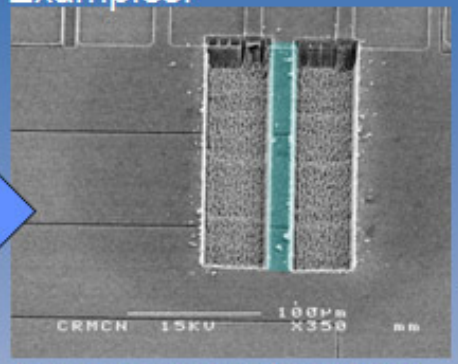
FIB milling



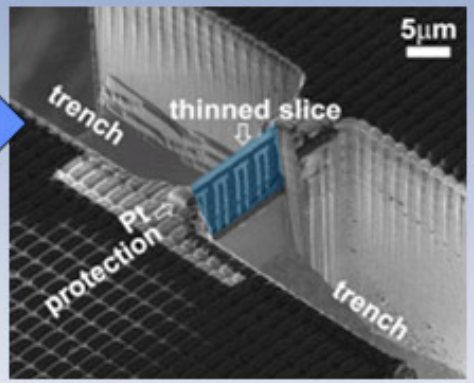
Sample capture

TEM preparation

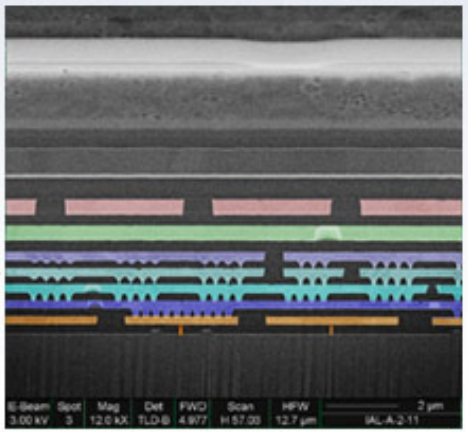
Examples:



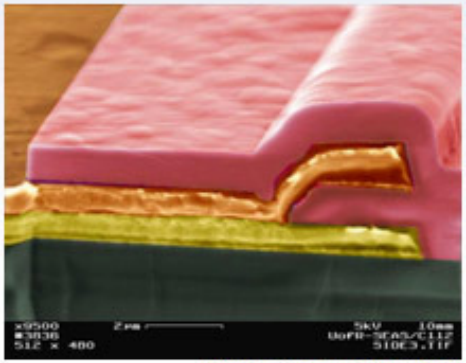
laser engraved cavities



FIB milling / thinning



Defect analysis



Reverse engineering

Why using a fs laser ?

- ✓ fast process
- ✓ maskless, no lithography
- ✓ damage limited
- ✓ accurate
- ✓ works with all materials

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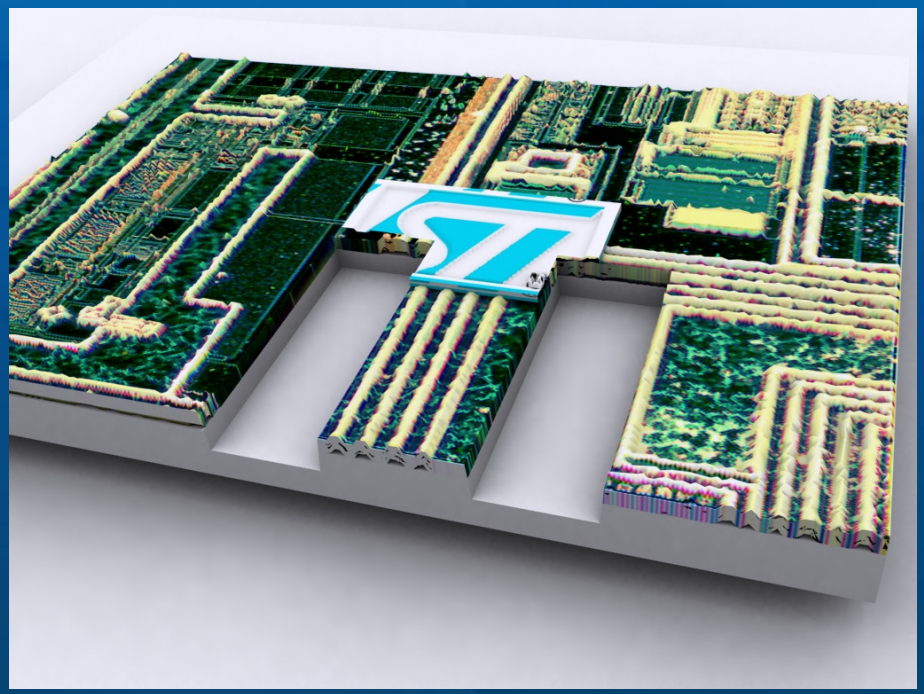
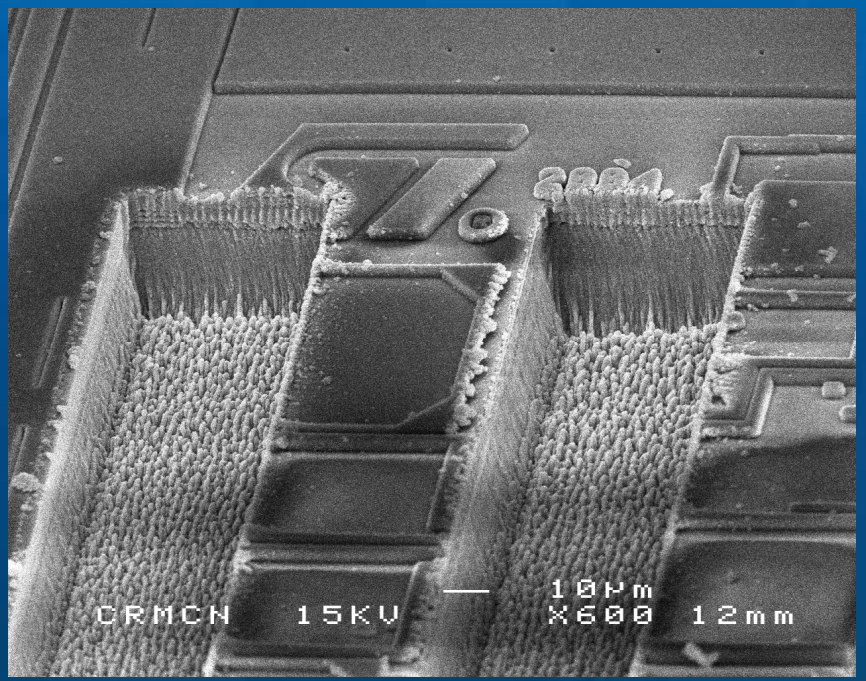
Gravure laser fs pour la réalisation de lames minces

microcavités de 50 x 250 µm

F ~ 6,5 J/cm² (E = 492 nJ)





Micromachining of semiconductor by femtosecond laser for integrated circuit defect analysis

M. Halbwax, T. Sarnet, J. Hermann, Ph. Delaporte, M. Sentis, L. Fares, G. Haller

Appl. Surf. Sci. , Vol 254/4, 2007, pp 911-915

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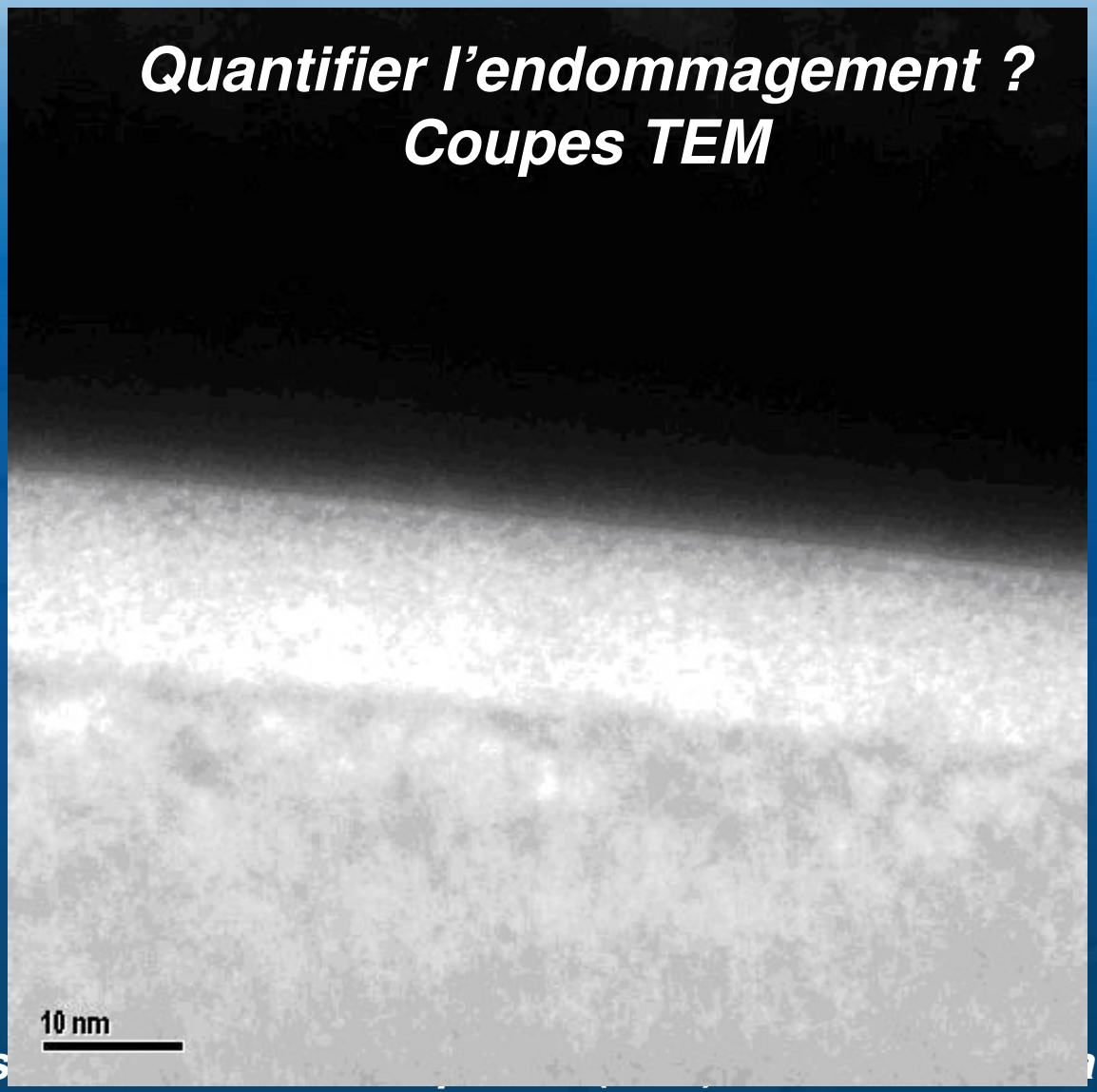
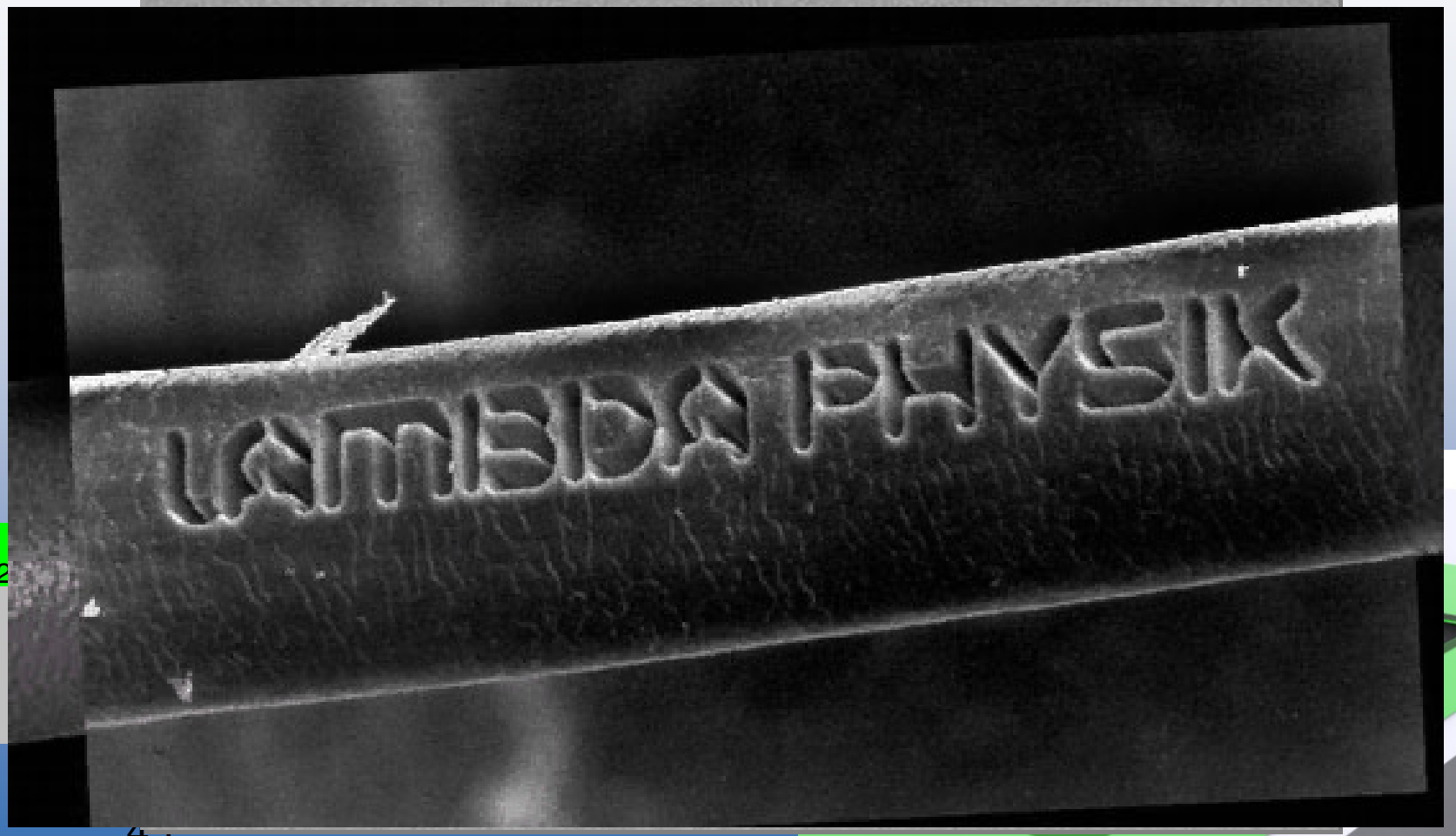
Quantifier l'endommagement ? Coupes TEM



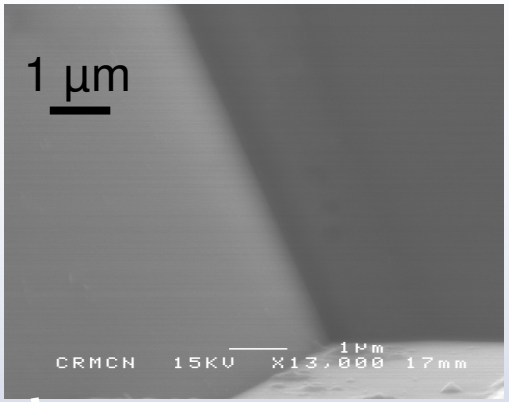
Epaiss… fluence, d'après coupes TEM

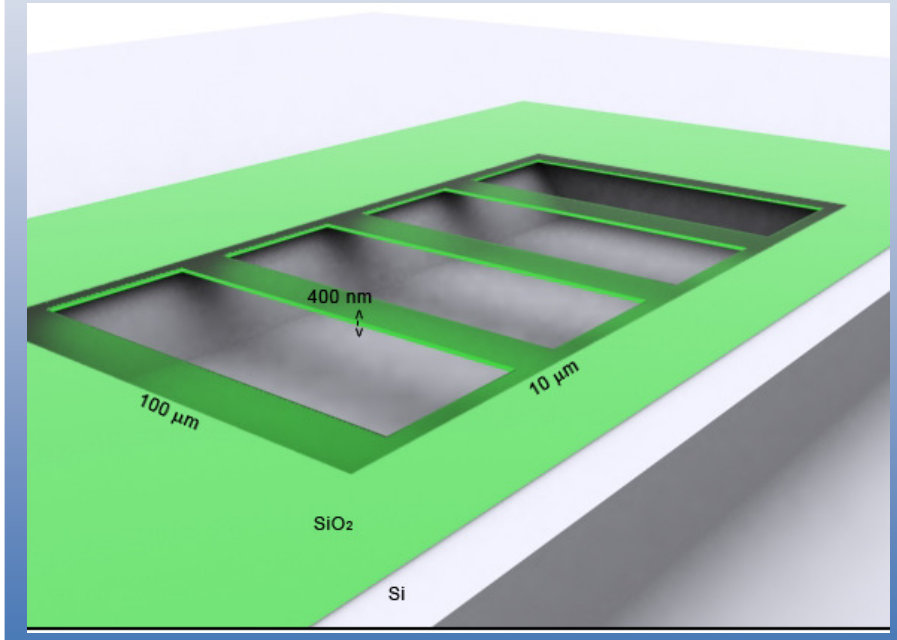
MEMs Applications
Micro cavities – Nano bridges

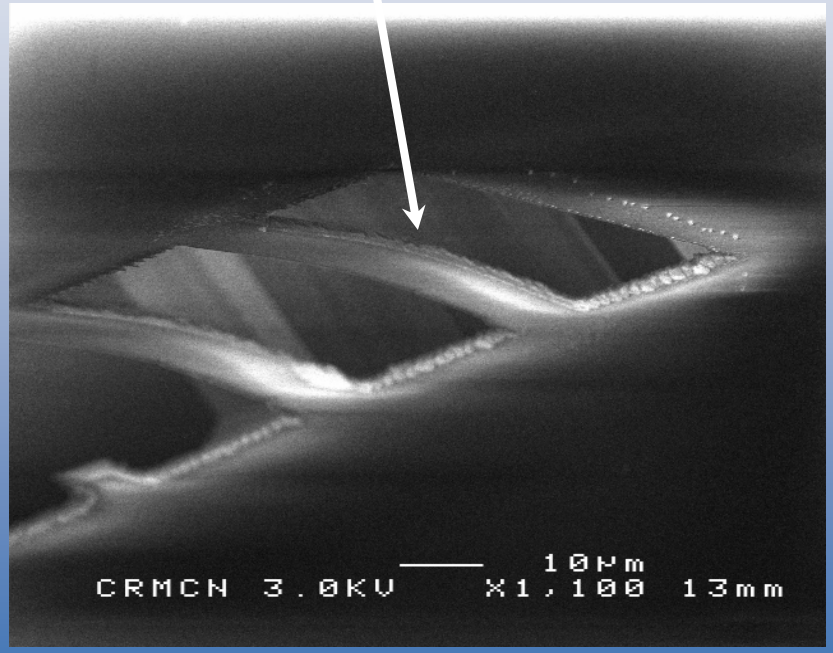


Silicon nano bridges

- 400 nm thickness
- no mask use

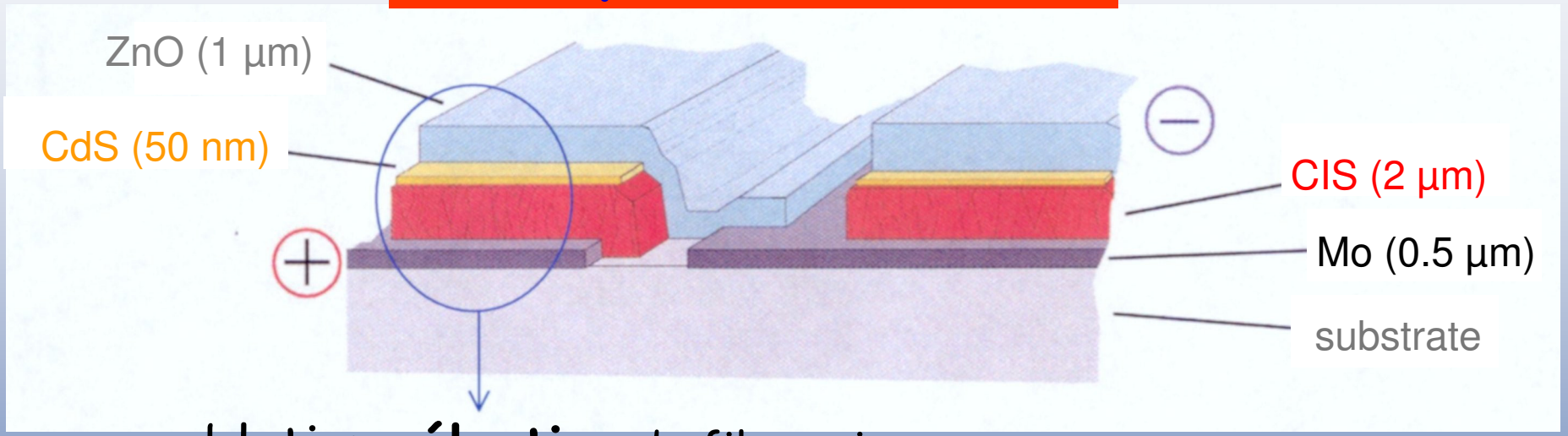






Micro-usinage de cellule solaire à base de $CuInSe_2$ (CIS)

Comparaison ns/fs

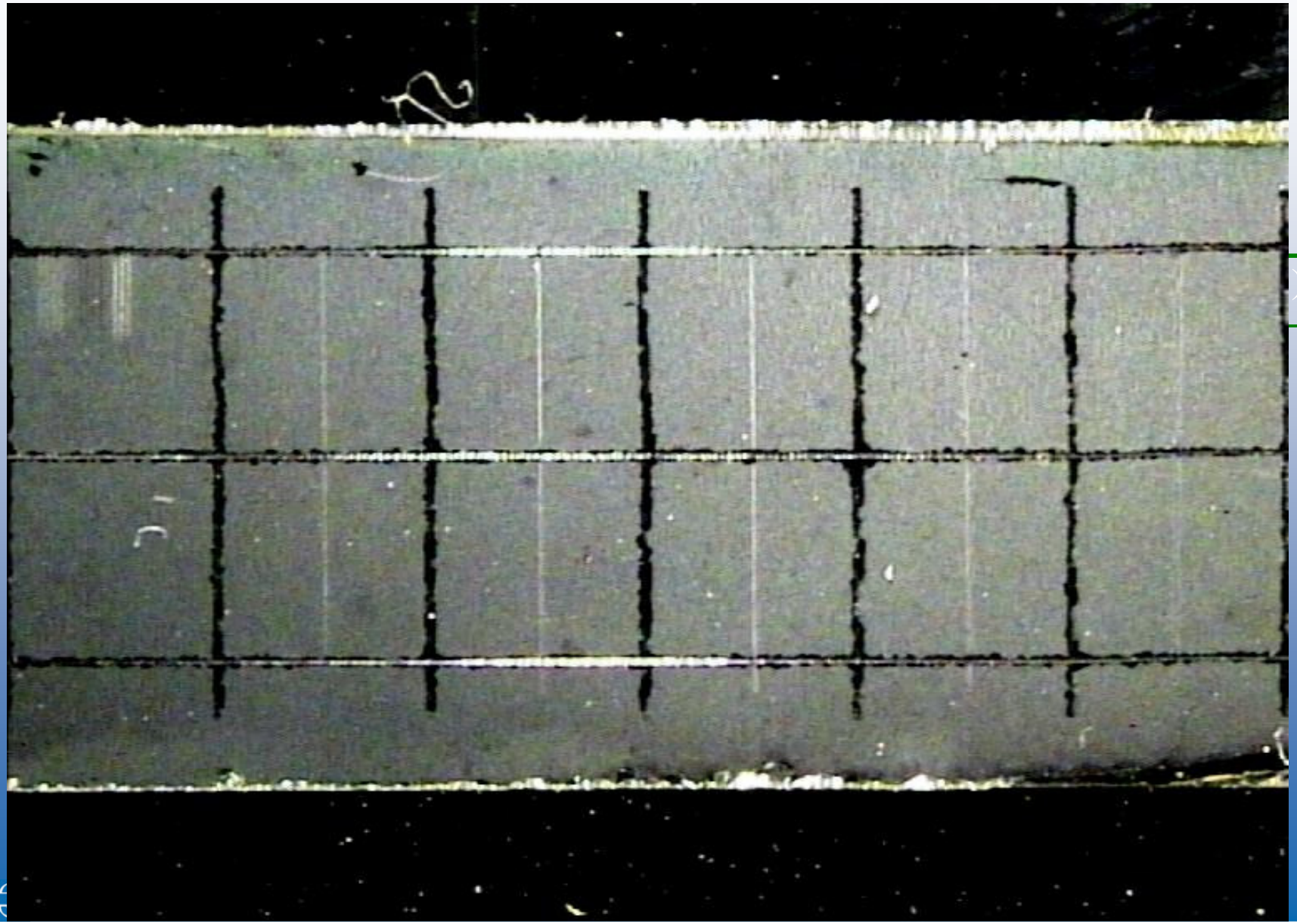


- ablation **sélective** de films minces
- ablation **complète** de tous les films

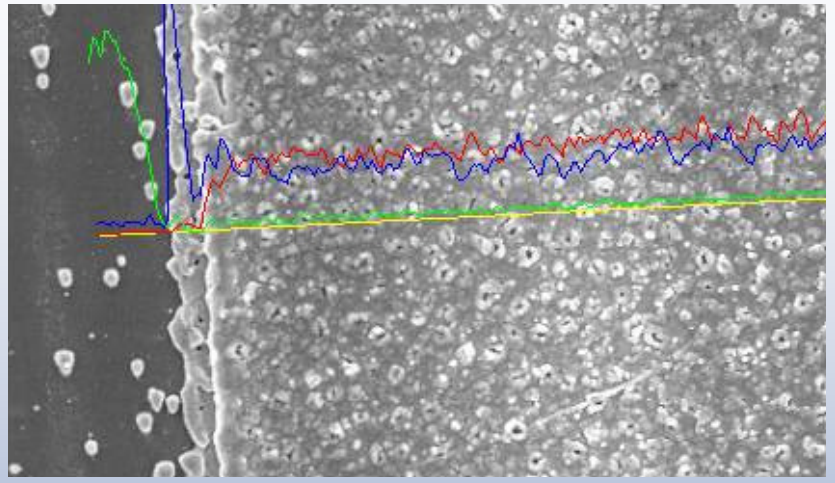
☞ **endommagement minimum du matériau non ablatée**

☞ **largeur de piste réduite**

Caractérisation photoélectrique



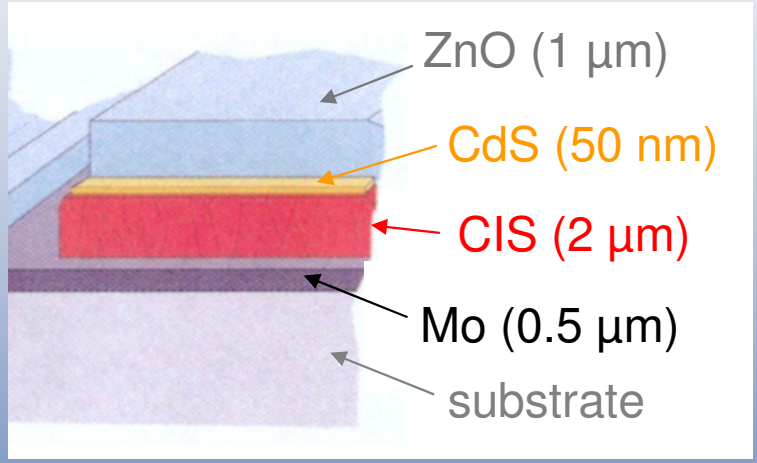
Analyses SEM et EDX

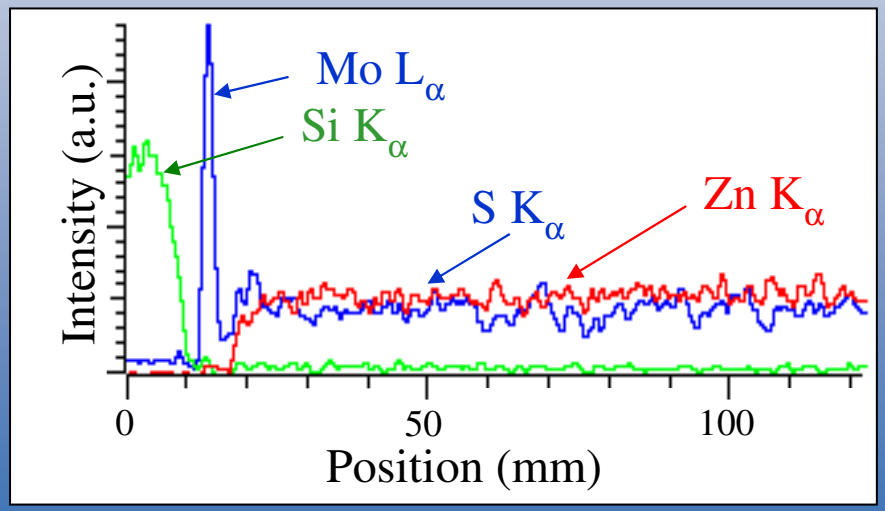


Nd:YAG laser, 532 nm

F_{las} = 2 Jcm^{-2}

n_{las} = 40





Mo sur bords du canal

⇨ **court-circuit**

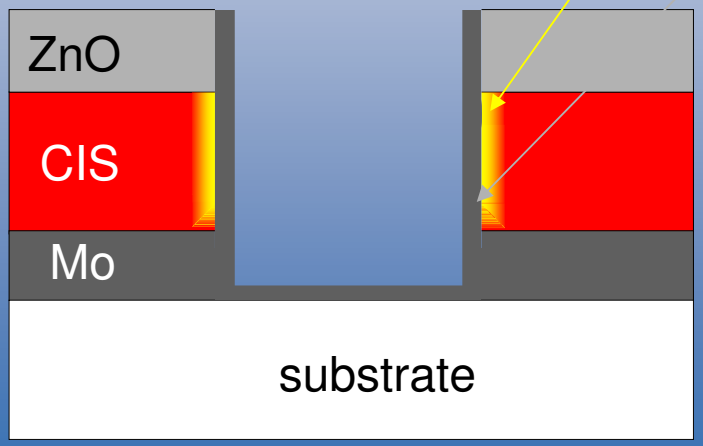
Usinage laser de cellules solaires (CIS)

laser ns

métallisation du CIS

Mo sur bords du canal

⇨ court-circuit



⇨

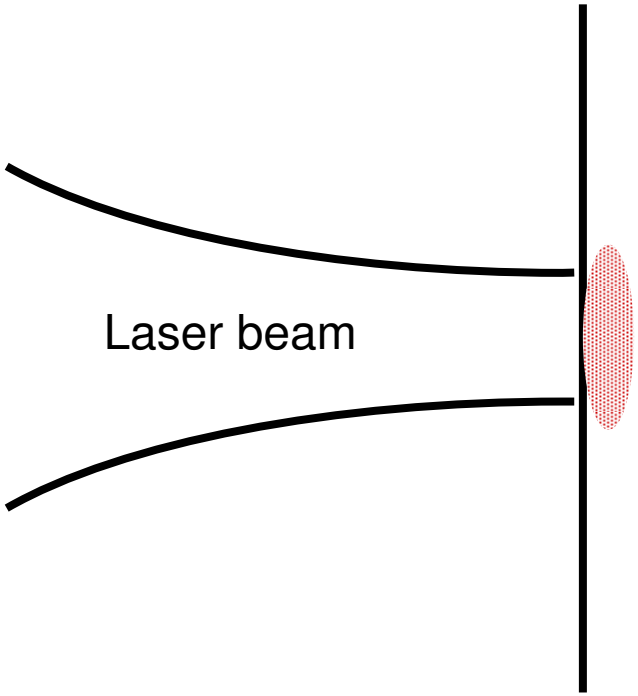
Usinage sans endommagement

~~laser ns~~

laser fs

théorie: laser ps

Claquage dans les diélectriques

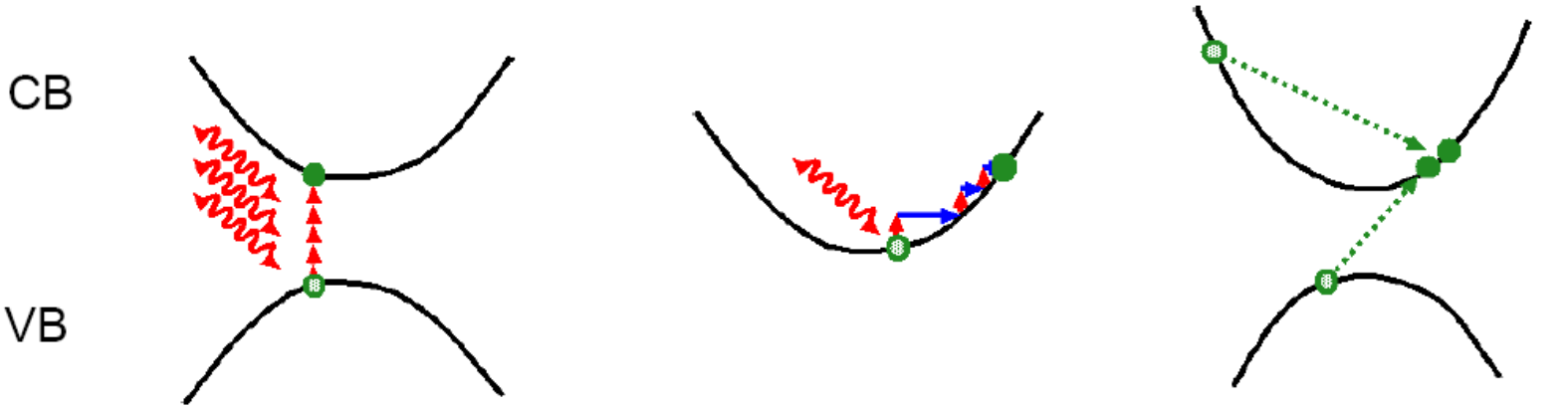


$$n = n_0 \exp(\alpha(E)t)$$

Pour atteindre un claquage il faut que la densité électronique augmente de 10^8 to 10^{21} e/cm^{-3}.

Génération d'électrons libres dans la bande de conduction

Responsible processes



multiphoton-ionization

intrabandabsorption by free electrons

electron-electron impact ionization

standard rate equation:

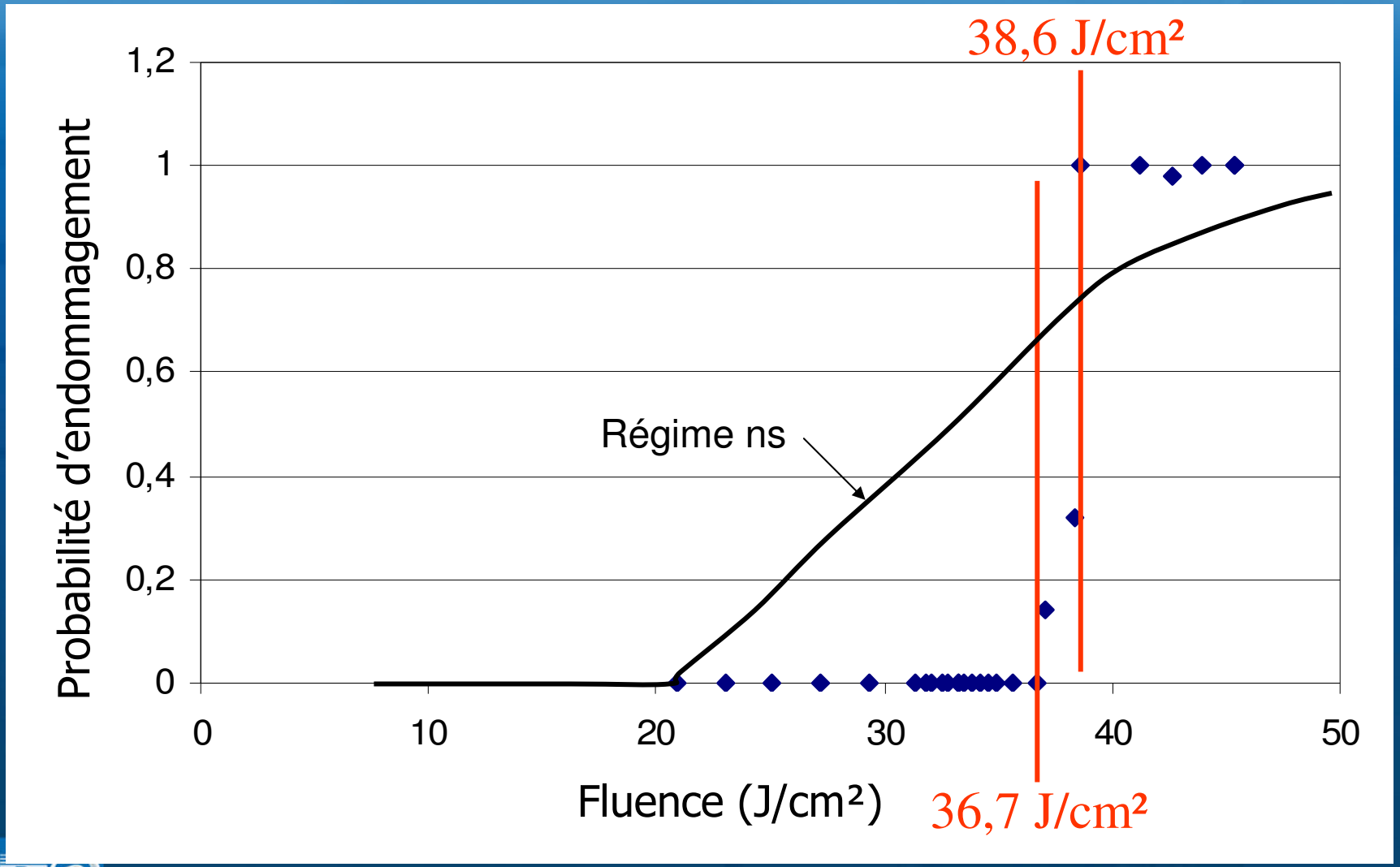
$$\frac{dn_{total}}{dt} = \sigma_l E_L^{2l} + \alpha(E_L)\, n_{total}$$

multiphoton-ionization provides "seed electrons"

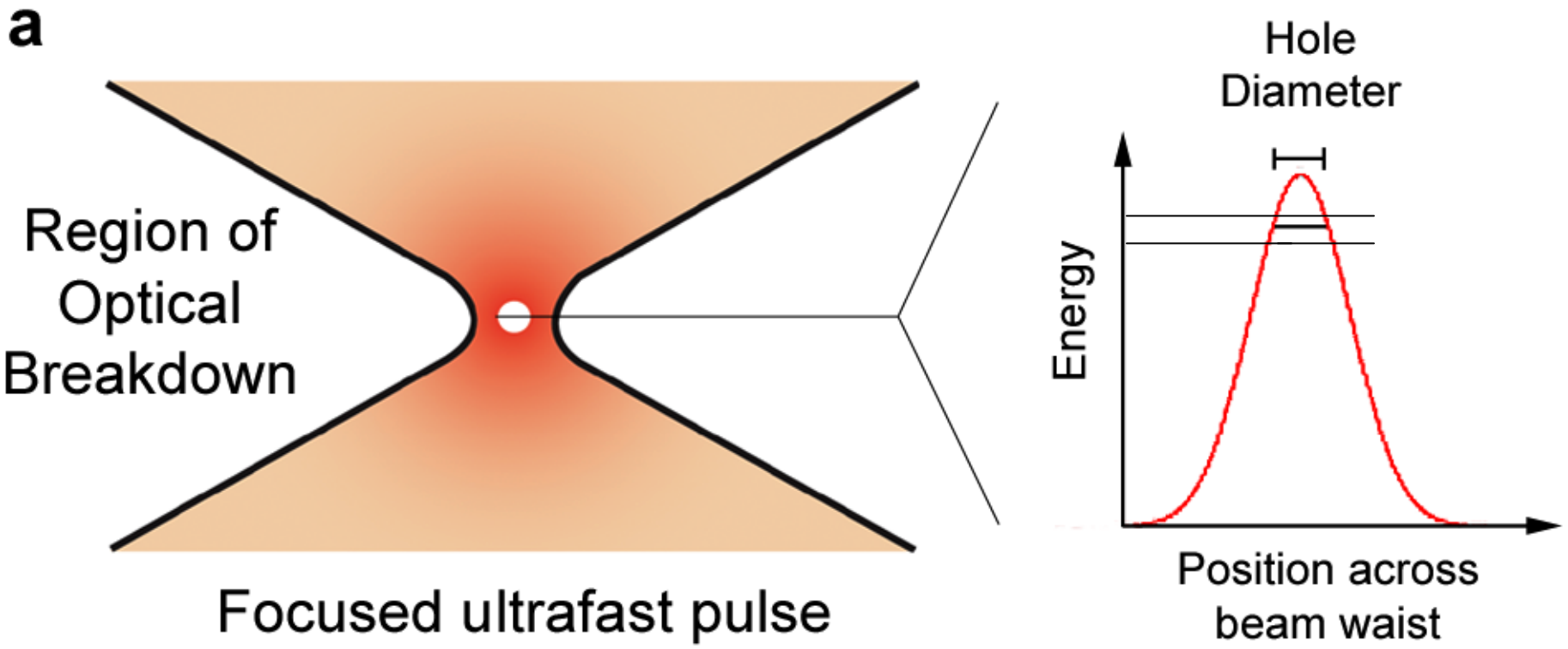
impact ionization leads to avalanche

Seuil d'endommagement déterministe de la silice

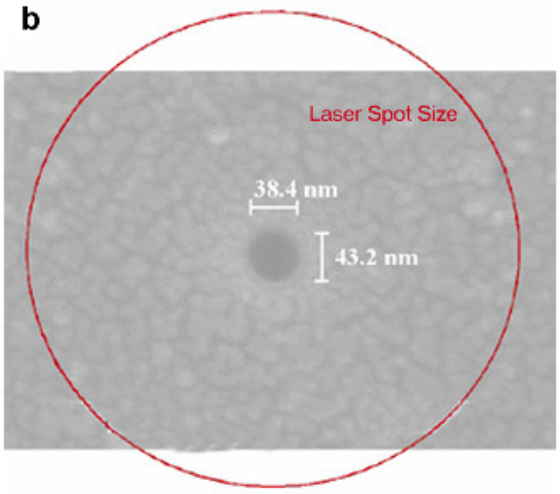
Durée : 450 fs

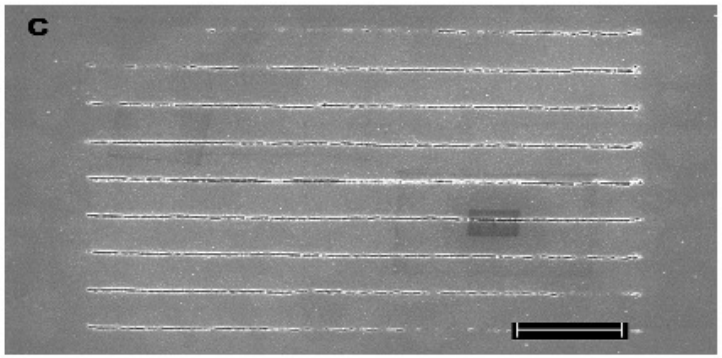


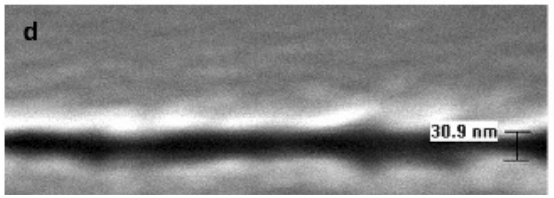
Application du seuil déterministe au nano-usinage



Nano-usinage par laser femtoseconde de verre

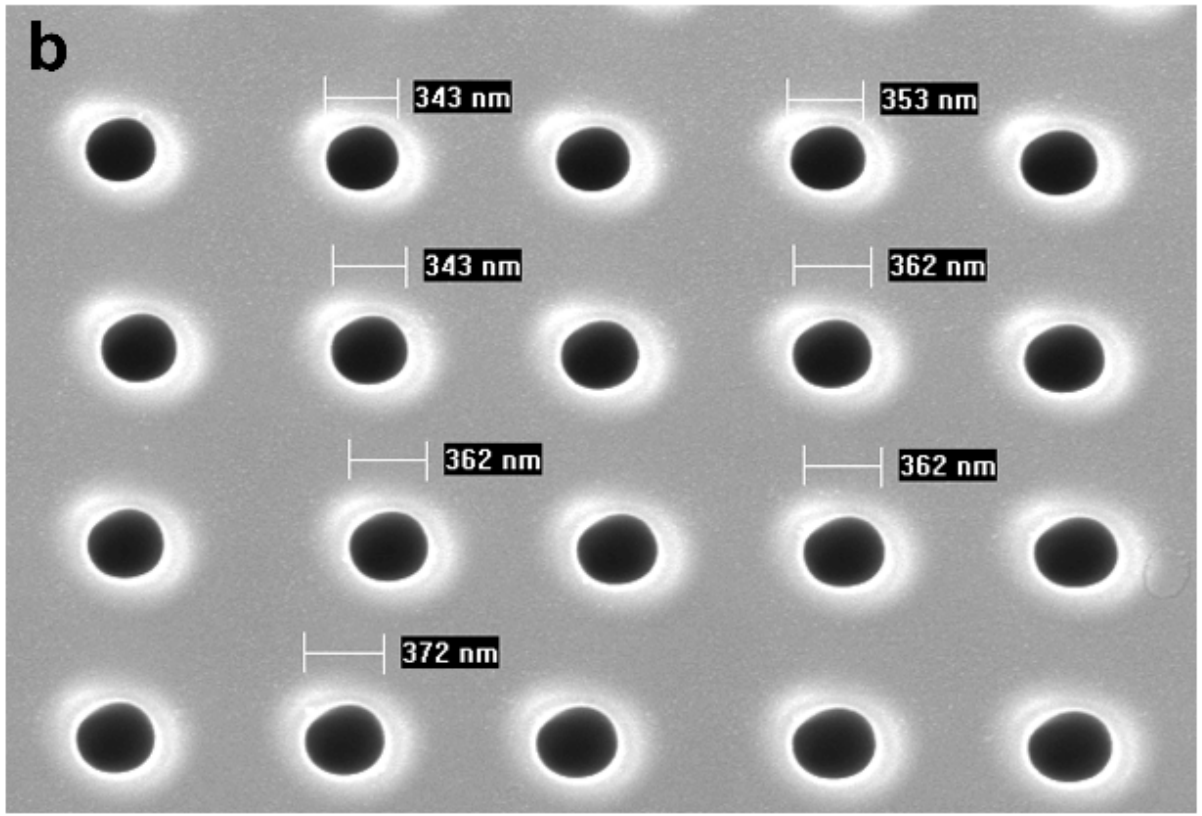






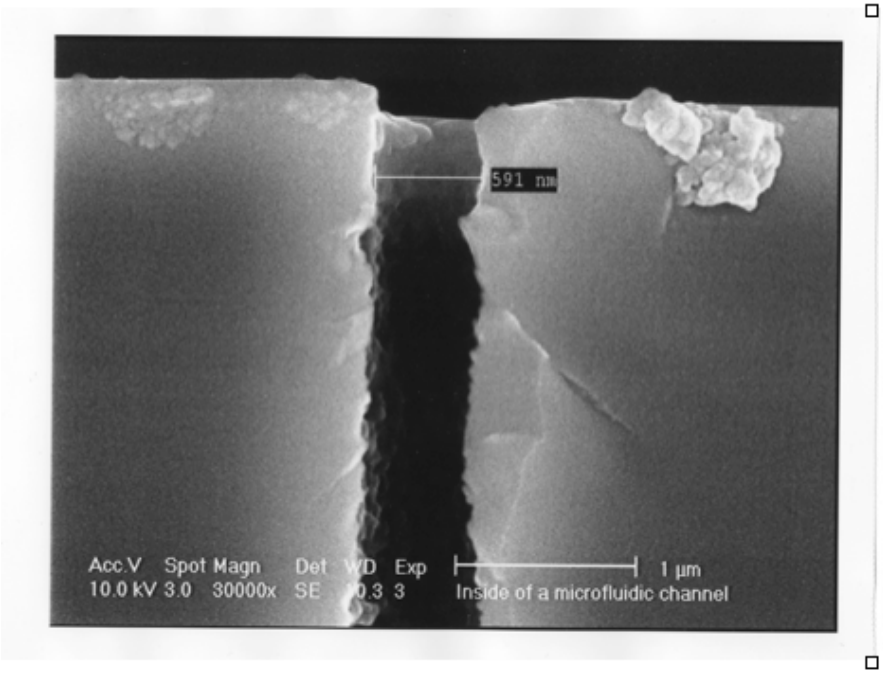
Source : G. Mourou

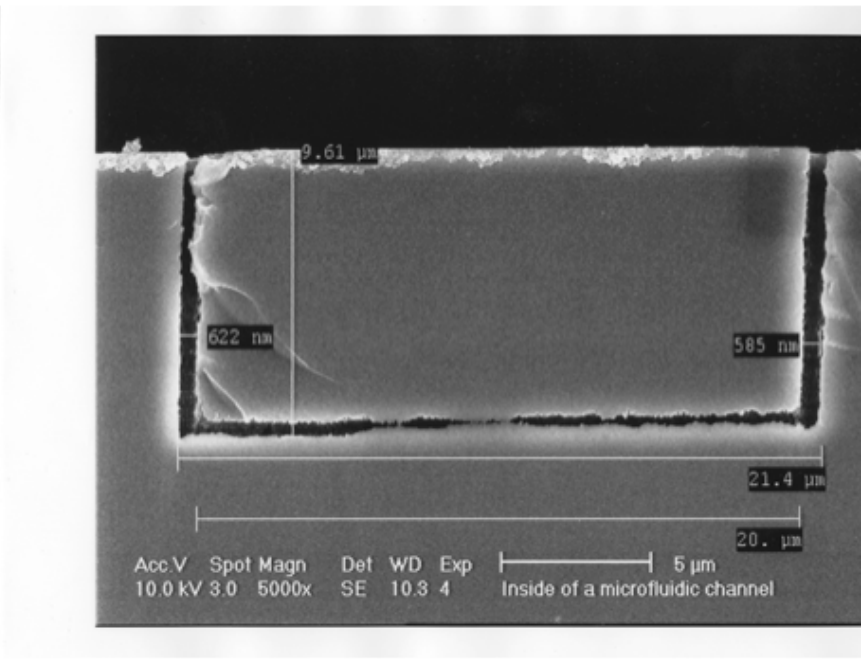
Nano-machining



Source : G. Mourou

Micro-nano Fluidics





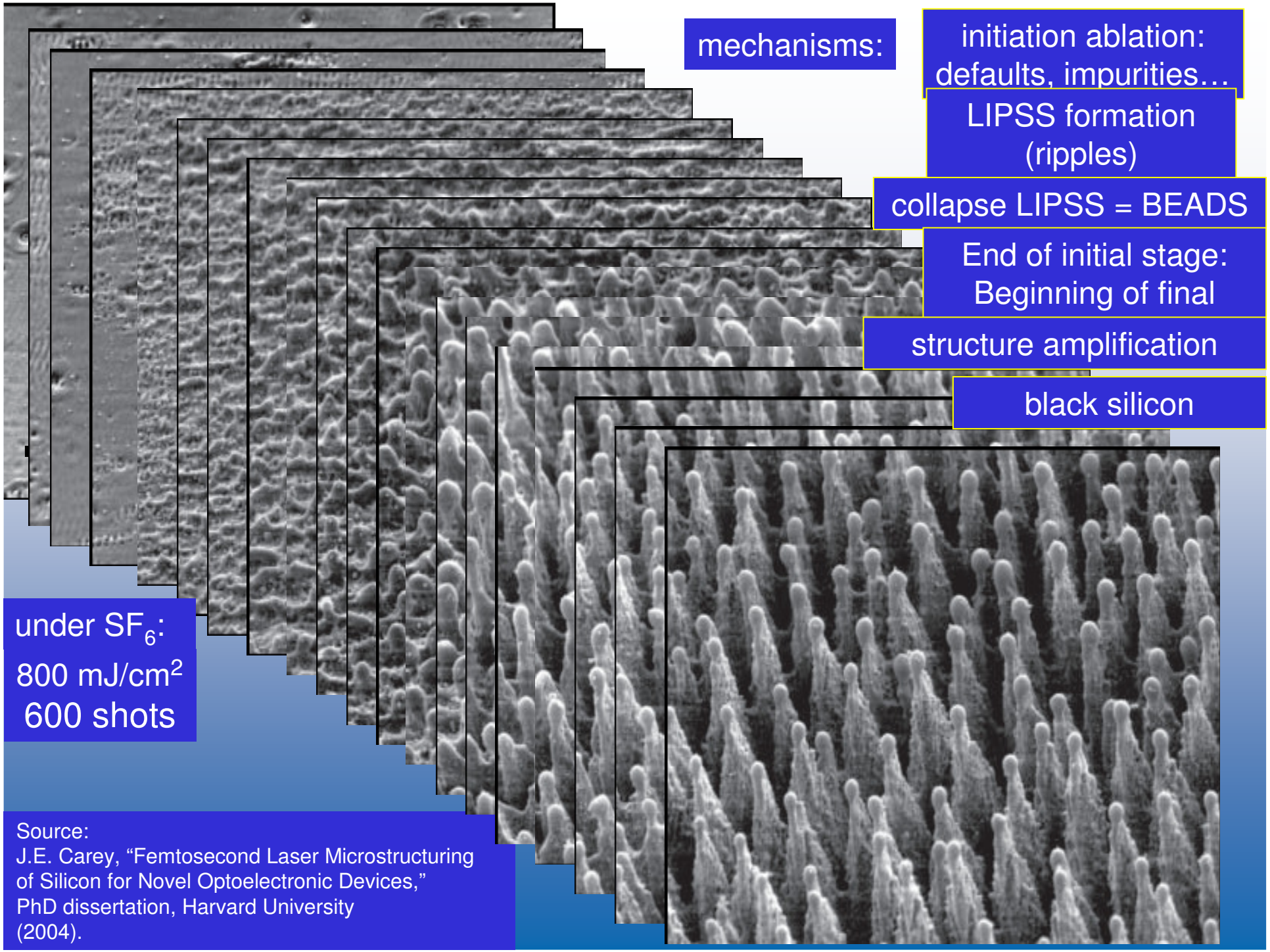
1µm

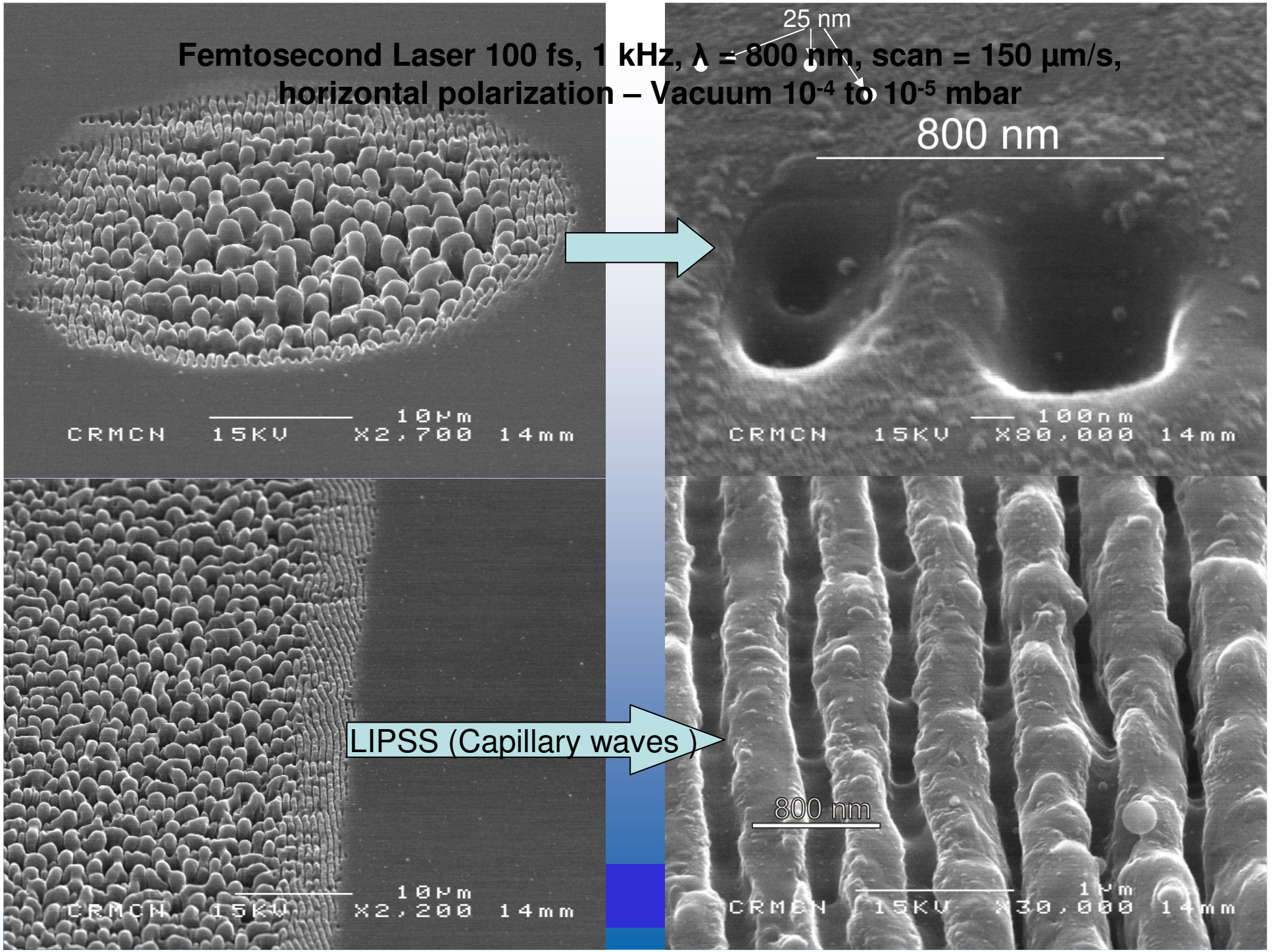
20µm

Self surface nano/micro structuring

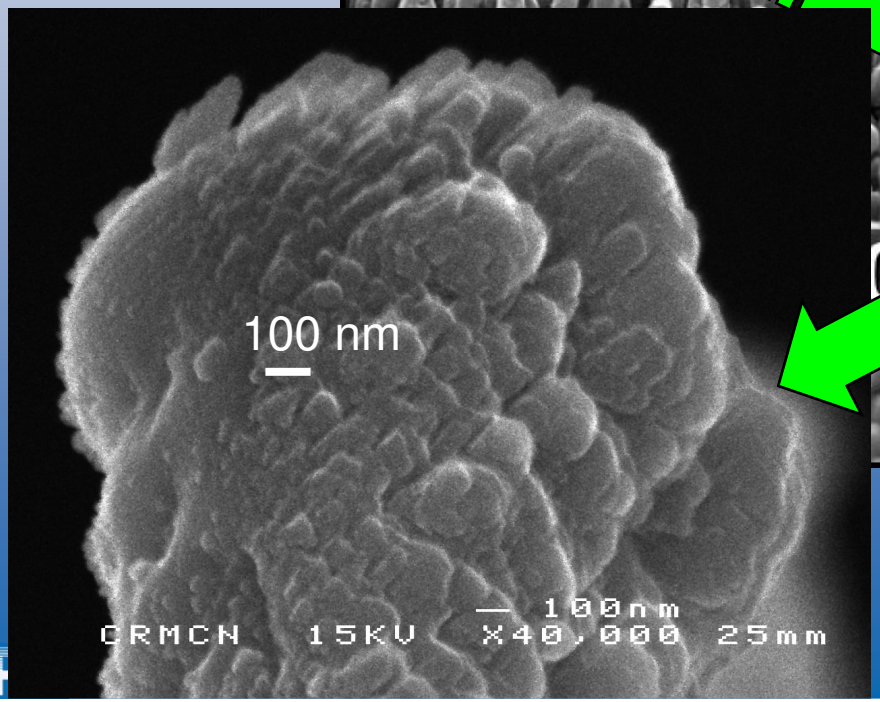
Mazur et al, Harvard University:

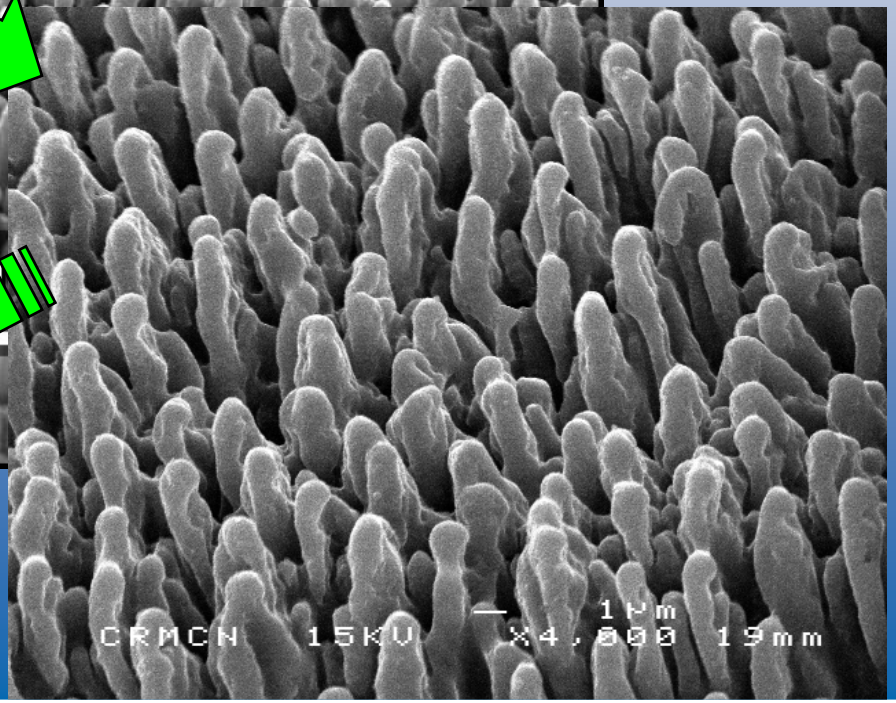
- **laser femtosecond,**
- **monocristallin Si**
- **SF_6**

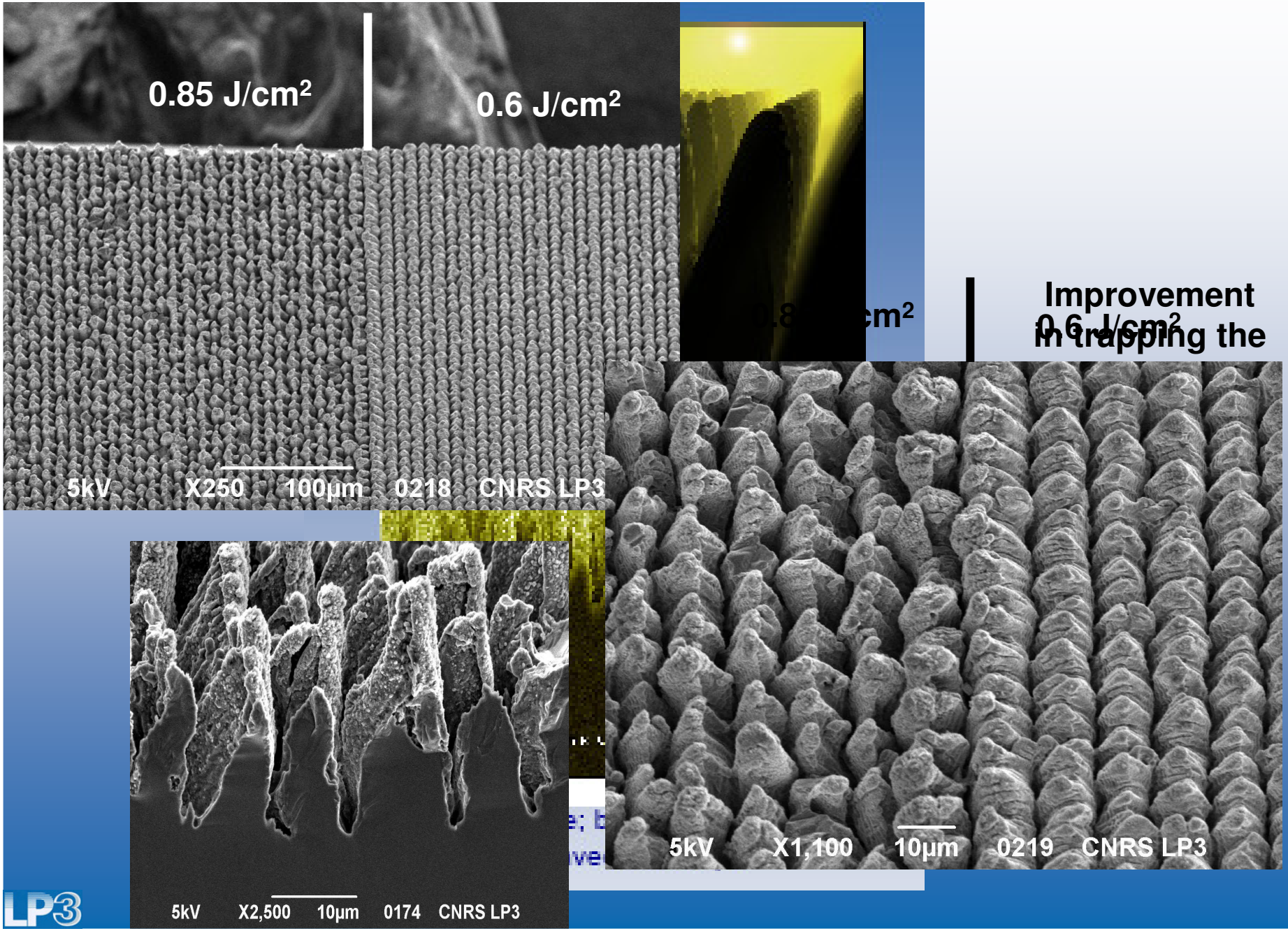

mechanisms:
initiation ablation: defaults, impurities…
LIPSS formation (ripples)
collapse LIPSS = BEADS
End of initial stage: Beginning of final
structure amplification
black silicon
under SF_6:
800 mJ/cm^2
600 shots
Source:
J.E. Carey, “Femtosecond Laser Microstructuring of Silicon for Novel Optoelectronic Devices,” PhD dissertation, Harvard University (2004).

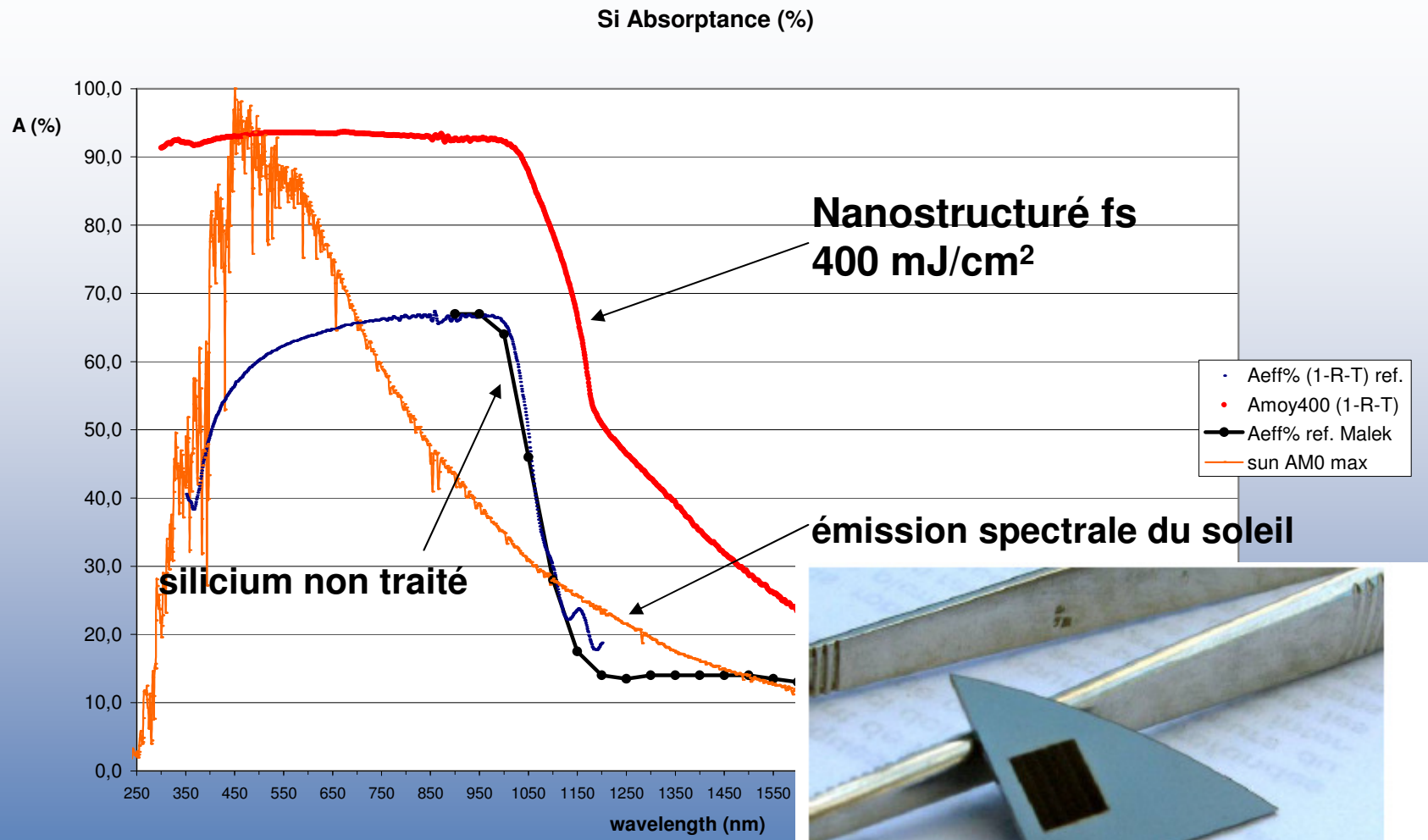

Femtosecond Laser 100 fs, 1 kHz, λ = 800 nm, scan = 150 µm/s,
horizontal polarization – Vacuum 10-4 to 10-5 mbar
25 nm
800 nm
CRMCN 15KV X2,700 10µm 14mm
CRMCN 15KV X80,000 100nm 14mm
LIPSS (Capillary waves)
CRMCN 15KV X2,200 10µm 14mm
800 nm
CRMCN 15KV X30,000 1µm 14mm

Le balayage de la surface avec des multiples tirs lasers permets la génération de micro/nano-structures avec une forme de **pingouins**



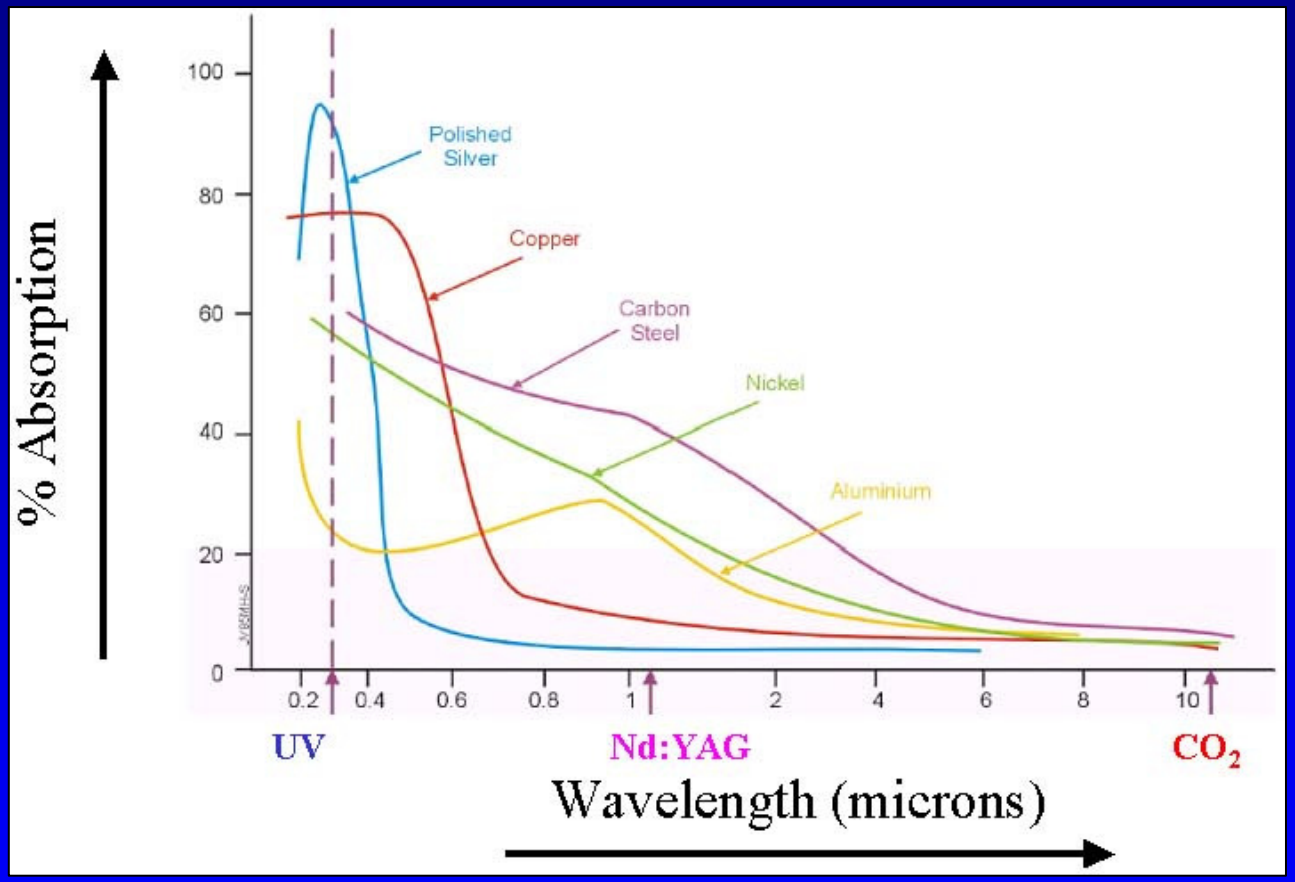



0.85 J/cm2
0.6 J/cm2
5kV X250 100µm 0218 CNRS LP3
Improvement
0.6 J/cm2
in trapping the
5kV X1,100 10µm 0219 CNRS LP3
5kV X2,500 10µm 0174 CNRS LP3



Une augmentation de l'absorptivité et élargissement spectral de l'absorption !

Merci!


% Absorption
100
80
60
40
20
0
Polished Silver
Copper
Carbon Steel
Nickel
Aluminium
0.2
0.4
0.6
0.8
1
2
4
6
8
10
UV
Nd:YAG
CO_2
Wavelength (microns)