Periodic structures self-formed on the surface of Si and SiC upon fs irradiation

Laura Gemini

LaMiNas
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Fyzikální ústav
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INVESTING IN YOUR FUTURE
2007–13
OP Research and Development for Innovation

Outline

Presentation
Kyoto university & Sakabe Lab.

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LIPSS & Parametric decay model

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fs irradiations of Si and SiC

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Kyoto University & Sakabe Lab.

Institute for Chemical Research
Kyoto University

Prof. S. Sakabe

Prof. M. Hashida

4 Int. chambers:
Laser R&D
μ-processing
Rad. sources

CPA Ti:Sa Laser
800 nm, 10 Hz
30÷40 fs
10^{20} W cm^{-2}

Introduction

Tribological systems

Photovoltaic systems

Micro-electronics (MEMS)

Applications

Metals (Ti, Mo, W,…)

Semiconductors (Si, Ge, SiC,…)

Insulators (glass, BaF_2, CaF_2,…)

Materials

LIPSS = **L**aser **I**nduced **P**eriodic **S**urface **S**tructures

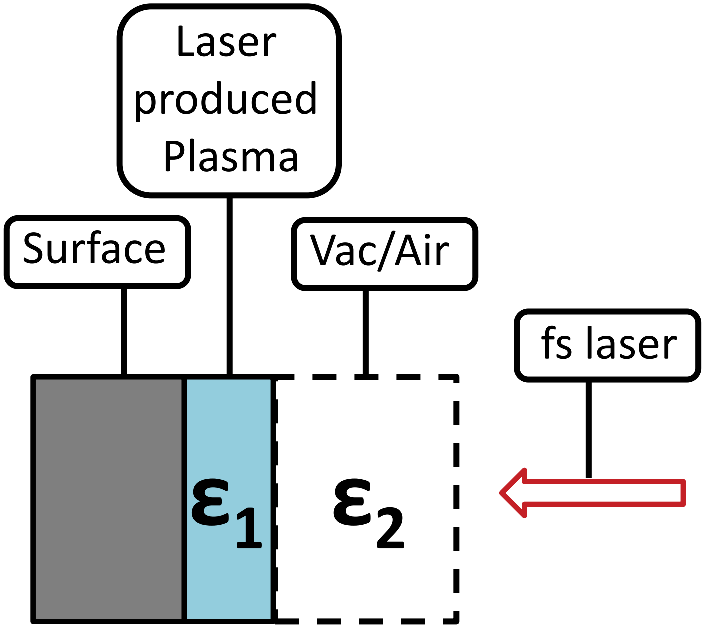
Models

Sipe-Drude Model

Asymmetric excitations

Surface Plasma waves

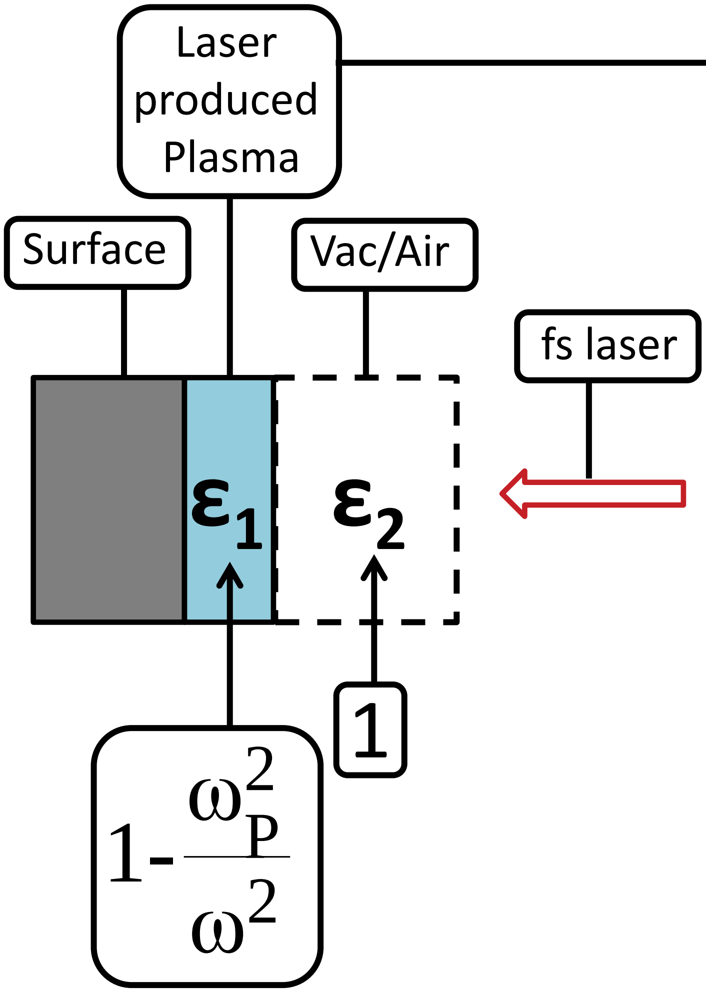
Introduction – Parametric Decay Model



When fs pulse interacts with the material, a surface plasma is formed (the plasma scale length $c_s\tau$ is sufficiently short to form a surface)

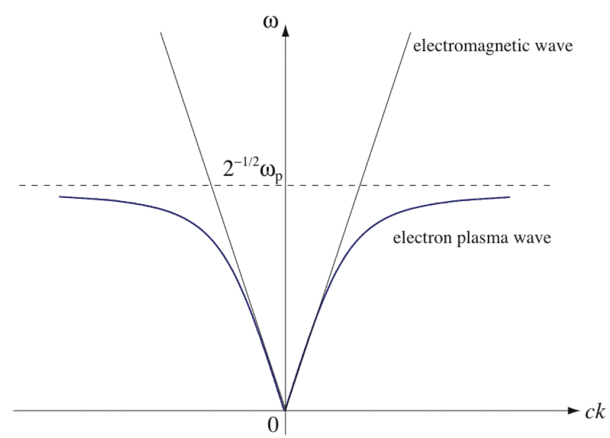
The pulse can interact with the plasma surface rather than the bulk plasma

Introduction – Parametric Decay Model



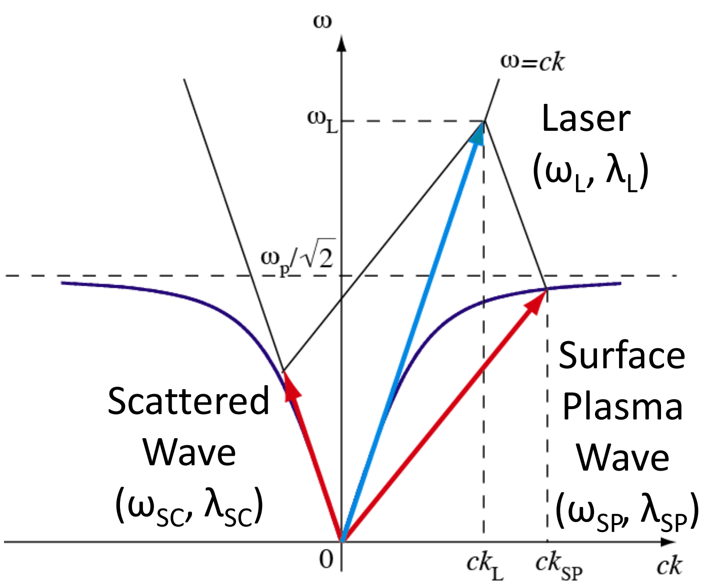
Dispersion relation for the surface plasma wave:

$$(ck)^2=\omega^2\left(\frac{\varepsilon_1\varepsilon_2}{\varepsilon_1+\varepsilon_2}\right)=\omega^2\frac{1-\frac{\omega_P^2}{\omega^2}}{2-\frac{\omega_P^2}{\omega^2}}$$



Introduction – Parametric Decay Model

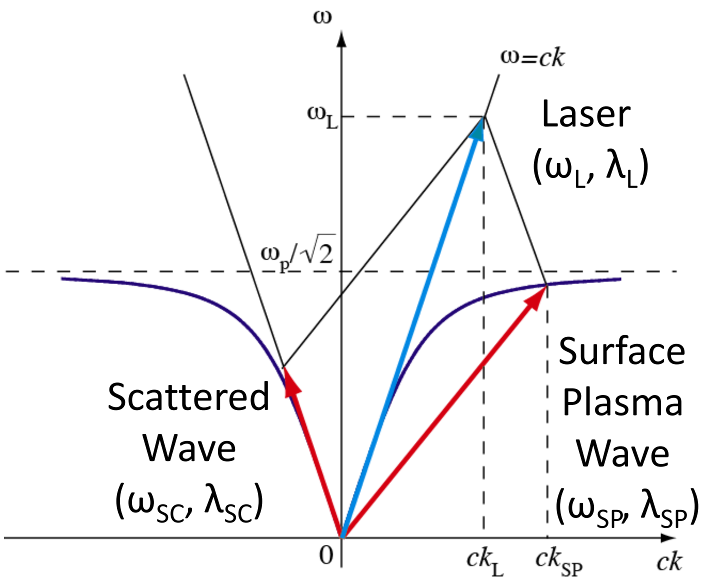
$$\omega_L = \omega_{SC} + \omega_{SP}$$



The incident laser light decays into a surface plasma wave and a scattered electromagnetic wave

Introduction – Parametric Decay Model

$\omega_L = \omega_{SC} + \omega_{SP}$



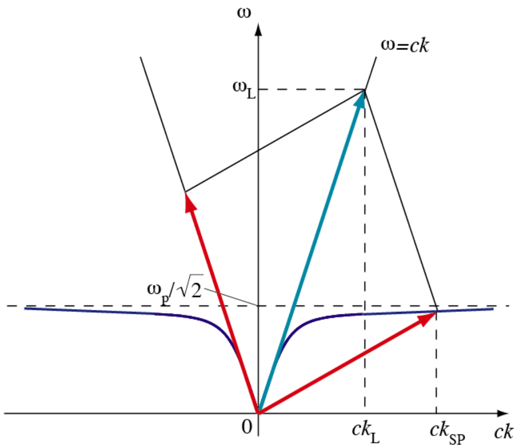
The incident laser light decays into a surface plasma wave and a scattered electromagnetic wave

Locally charged areas are generated on the surface. Positively charged areas are subjected to **Coloumb explosion** towards free-space

A thin layer is ablated forming a grating pattern with a periodicity given by the surface plasma wave wavelength

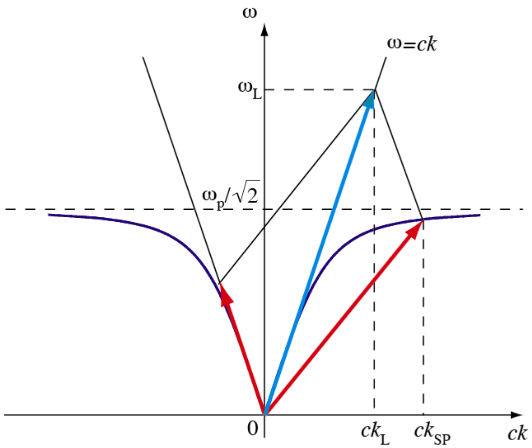
$\lambda_{LIPSS} = \lambda_{SP}$

Introduction – Parametric Decay Model



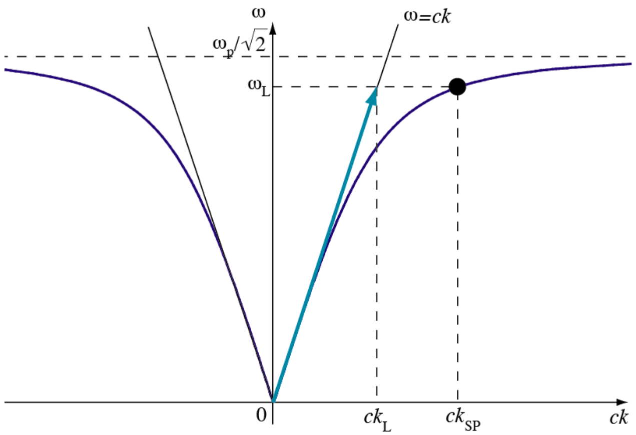
Low density plasma

$\omega_L \gg \omega_P / \sqrt{2}$



High density plasma

$\omega_L > \omega_P / \sqrt{2}$



Very high density plasma

$\omega_L < \omega_P / \sqrt{2}$

- **$\omega_{SP} = f(\omega_P)$** $\Longrightarrow$ $\lambda_{LIPSS} = \lambda_{SP} = f(\omega_P)$
- SP waves can be generated if $\omega_L > \omega_P / \sqrt{2}$, i.e. there is a **fluence upper limit F_M** over which LIPSS cannot be longer generated.

Introduction – Parametric Decay Model

$$\lambda_{LIPSS} = f(\omega_P)$$

$$\omega_p \propto \sqrt{n_{es}}$$

$$n_{es} \propto n_e / c_s \propto n_e / T_e^{1/2} \propto F_L^{1/2}$$

$$c_s = \sqrt{k_B T_e / m} \propto \sqrt{F_L}$$

$$n_e \propto F_L$$

$$\Rightarrow \boxed{\lambda_{LIPSS} \propto F_L^{1/4}}$$

$\lambda_{LIPSS} = f(F_L / F_M)$:

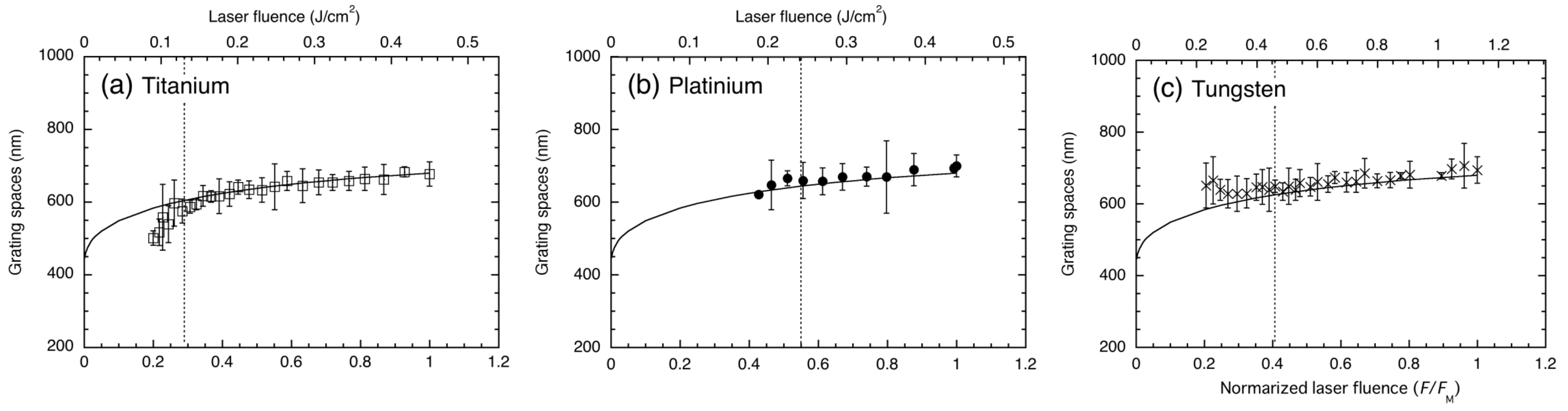
$0 < \omega_P / \sqrt{2} < \omega_L$

400 nm < λ_{LIPSS} < 680 nm

$0 < F_L / F_M < 1$

Introduction – Parametric Decay Model

Experimental data for different metals have been successfully represented by the model



S. Sakabe et Al., Phys. Rev. B 79, 033103 (2009)

K. Okamuro et Al., Phys. Rev. B 82, 165417 (2010)

If LIPSS self formation is closely related to the presence of surface plasmas, such as laser produced plasmas, would semiconductors under intense optical field be classified as metals?

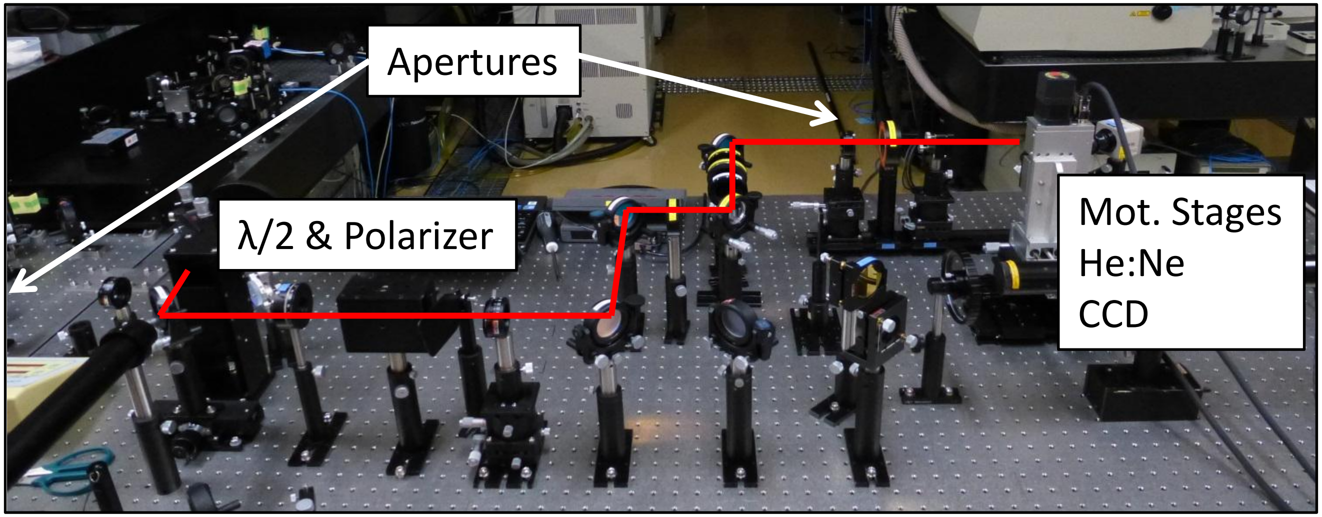
$$\lambda_{LIPSS} = f(F_L/F_M) \text{ for Si and SiC}$$

Experiments – Irradiation parameters

Material	n-type Si (111)	PLD SiC thin film
Laser Fluence	0.1 – 0.75 J cm^{-2}	0.15 – 0.5 J cm^{-2}
Pulse Number	5, 10, 25, 50, 100	

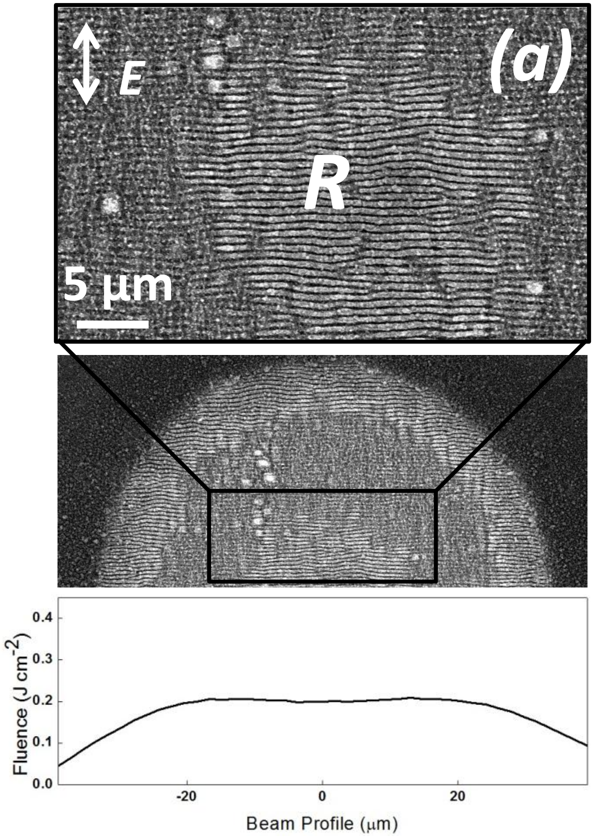
- 800 nm, 10 Hz, 37 fs
- Linear Polarization
- Flat Top Profile
- Normal Incidence in air

Experiments – Setup

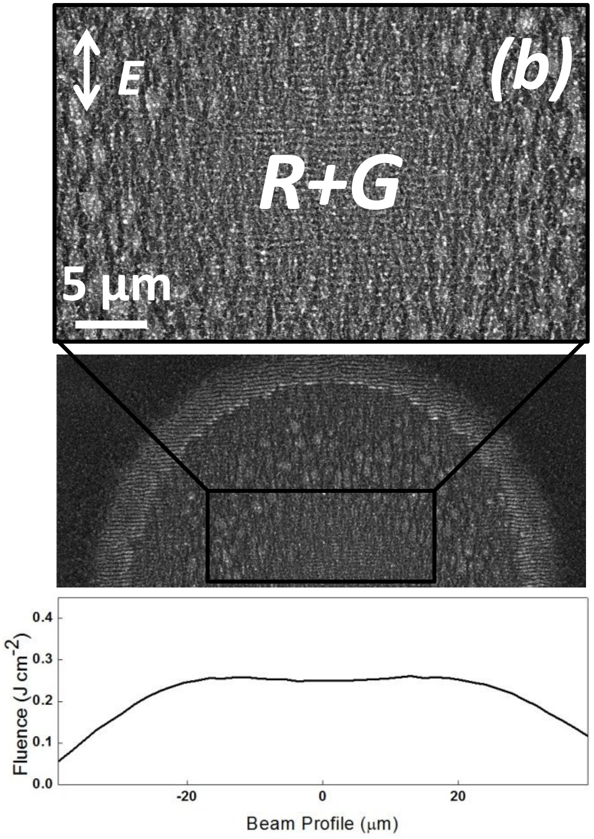


Experiments – Results for Si

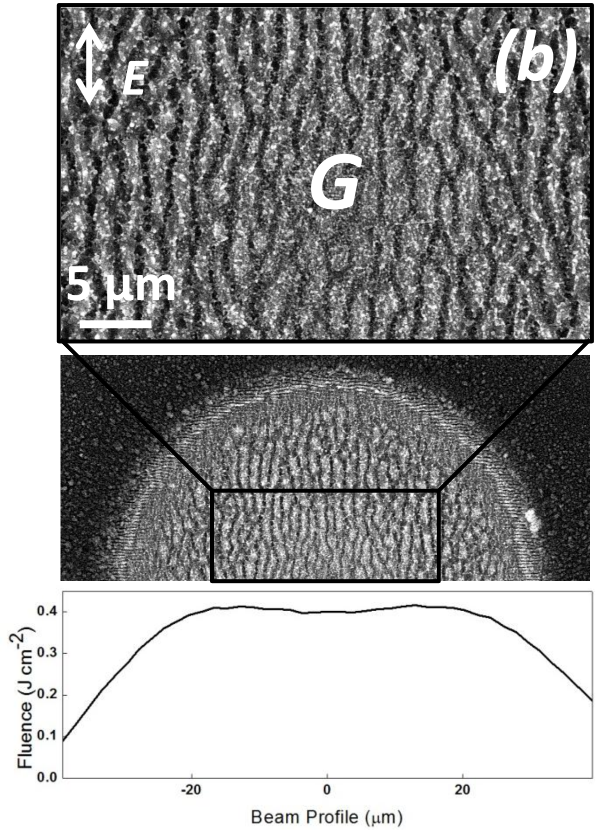
N=100, F_{FT} = 0.2 J cm^{-2}



N=100, F_{FT} = 0.25 J cm^{-2}

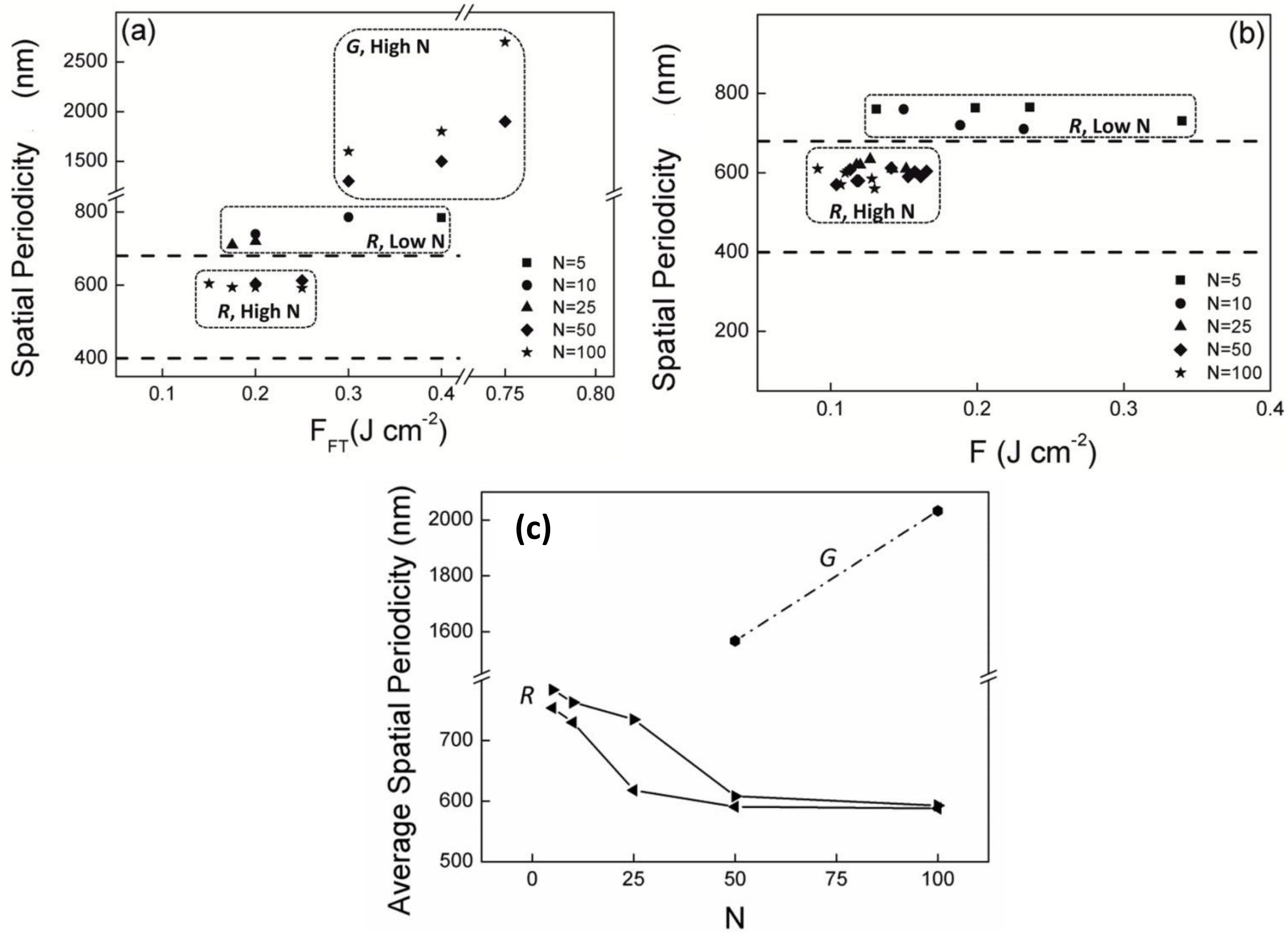


N=100, F_{FT} = 0.4 J cm^{-2}



Experiments – Results for Si

R 600 nm
R 760 nm
G 2 μm



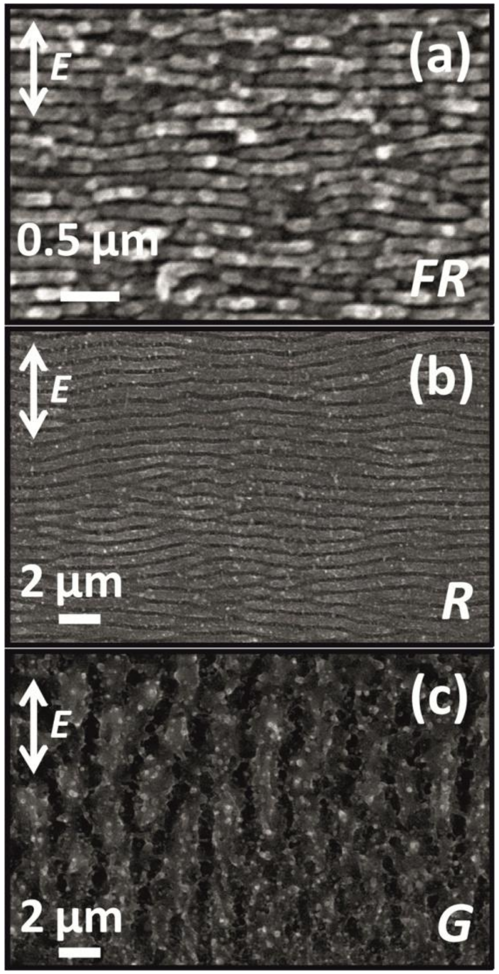
R 600 nm
R 740 nm

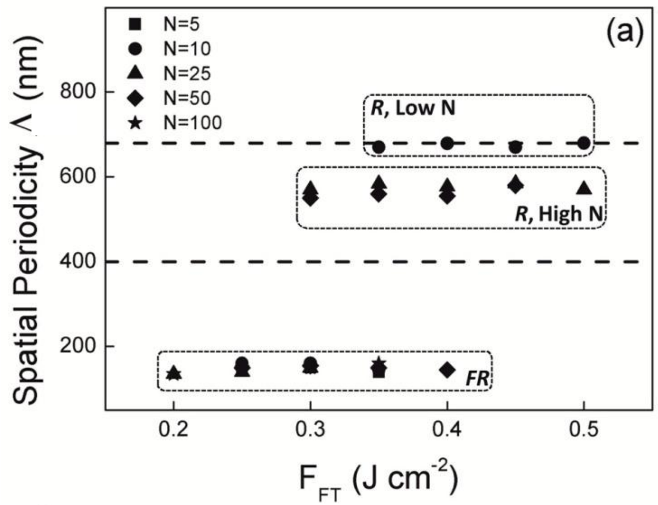
Experiments – Results for SiC

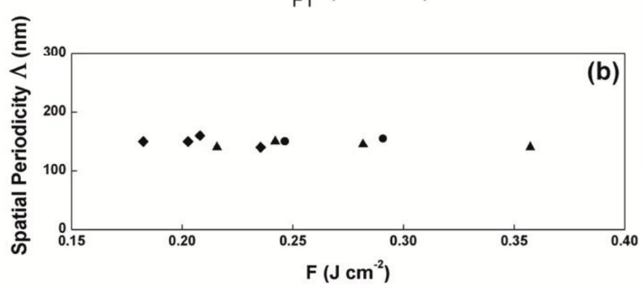
N=25 $F_{FT} = 0.25$ J cm^{-2}

N=25 $F_{FT} = 0.35$ J cm^{-2}

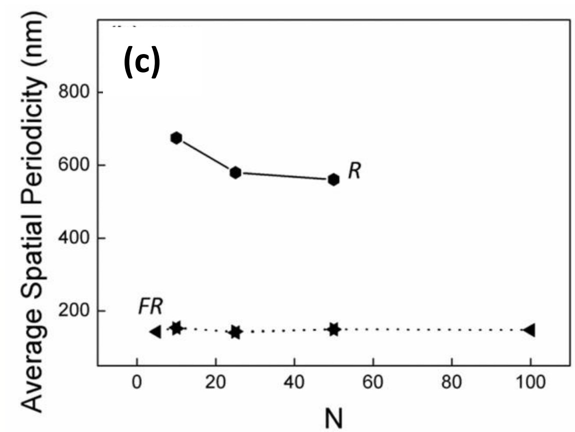
N=100 $F_{FT} = 0.45$ J cm^{-2}





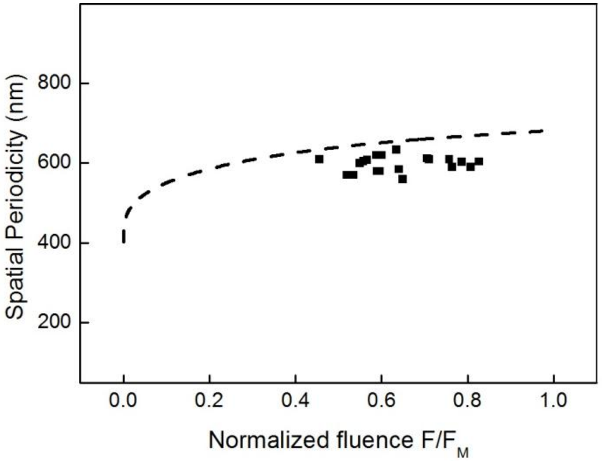


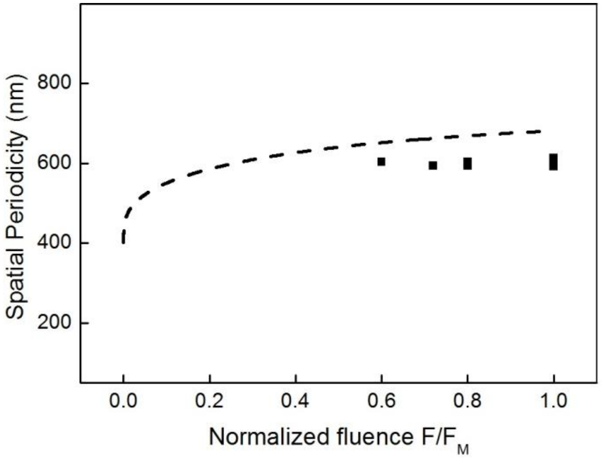
FR 140 nm
R 570 nm
R 670 nm
G 2 µm

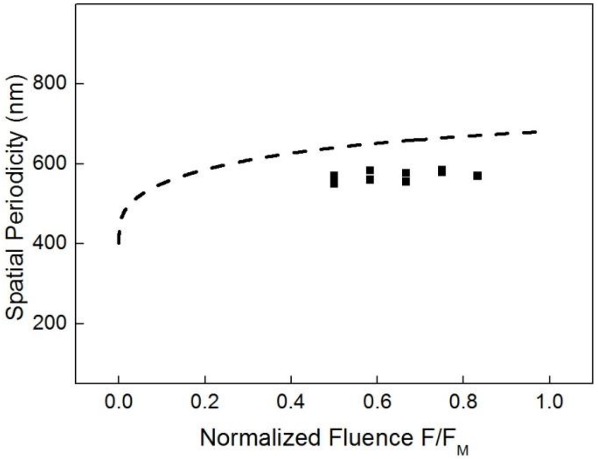


Experiments – Parametric decay model for Si and SiC

Experimental data referred to irradiations with high number of pulses fall into the interval of spatial periodicity predicted by the model







- - - - Parametric decay model

Experiments – Parametric decay model for Si and SiC

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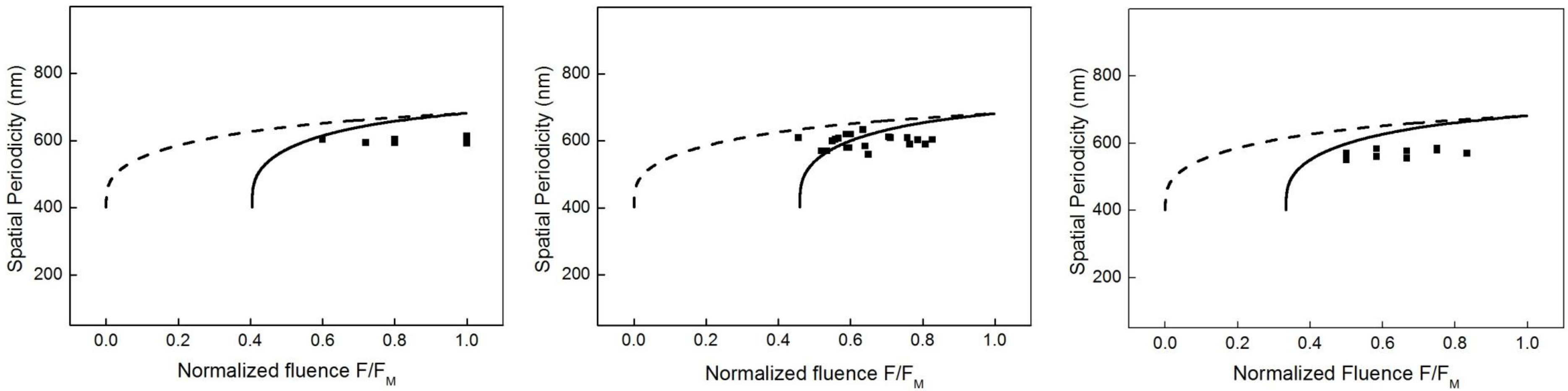
Experimental data referred to irradiations with high number of pulses fall into the interval of spatial periodicity predicted by the model



- - - - Parametric decay model

—— Parametric decay model including normalization to ablation threshold fluence

…although the values of ablation threshold fluence and upper fluence F_M are NOT well defined.

Conclusions & Summary

Increasing the fluence 3 different morhologies are visible:

low N $\Longrightarrow$ Ripples for Si, Fine ripples for SiC

high N $\Longrightarrow$ Ripples and Grooves for Si & SiC (also found for Ti)

[M. Tsukamoto et Al., Vac. 80, 1346 (2006)]

λ_{LIPSS} depends on the number of pulses but not on the laser fluence (except for grooves) $\Longrightarrow$ λ_{LIPSS} (N) already observed for semiconductors and metals

[M. Tsukamoto et Al., Vac. 80, 1346 (2006) & L. Ran er Al., Appl. Surf. Sci. 256, 2315 (2010)]

The model closely approximates the experimental data found for high number of pulses:

Metal like behaviour of semiconductor materials under intense optical field due to multi-shot irradiations.

Future goals

Physical processes at low number of pulses?

Generation of grooves at high fluence?

Generation of fine ripples at low fluence?

Upgrading of the model (Fine ripples? Grooves?)

Thank you for your attention!