Semiconductor metasurfaces in strong optical fields

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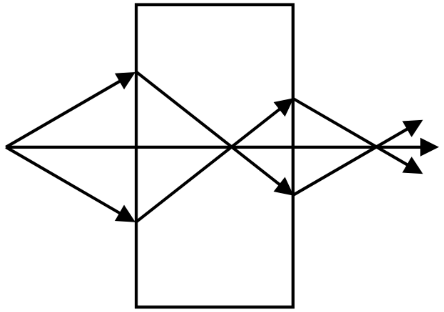
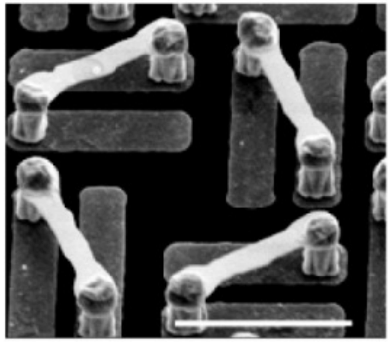
Department of Electrical Engineering and Computer Science
University of California, Irvine

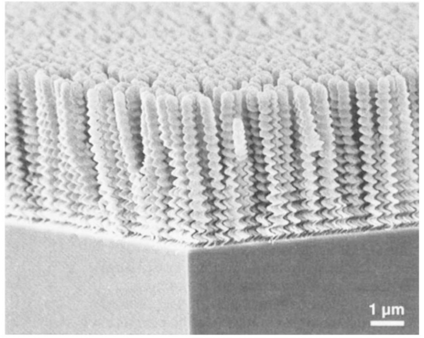
Sponsors and collaborators:
SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY
Agency for Science, Technology and Research SINGAPORE
THE AUSTRALIAN NATIONAL UNIVERSITY
Sandia National Laboratories



Negative refraction and LHM

Veselago, Pendry, Shelby, Smith, Schultz, Lezec, Shalaev, X Zhang, Soukoulis, Sihvola, Tretyakov, Fan

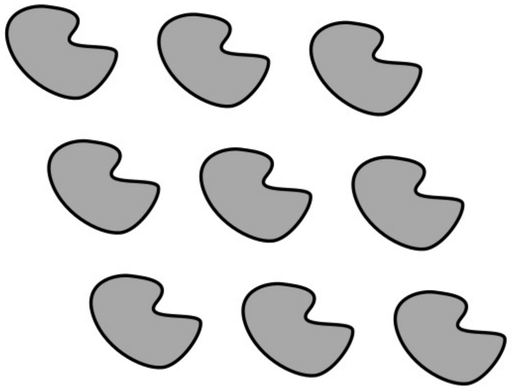




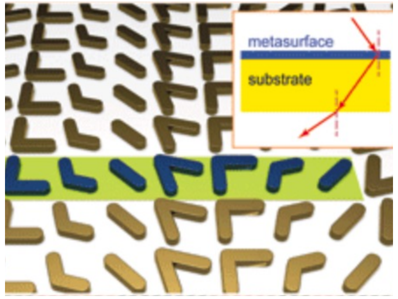
Polarization and chirality

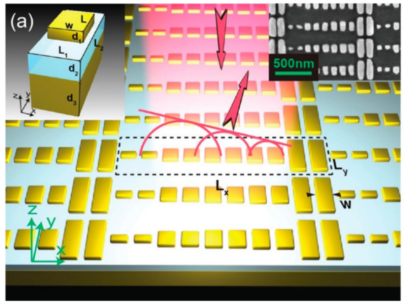
Pendry, Lakhtakia, X Zhang, Zheludev, He, Wegener, Pertsch, Soukoulis, Ozbay, HT Chen, S Zhang

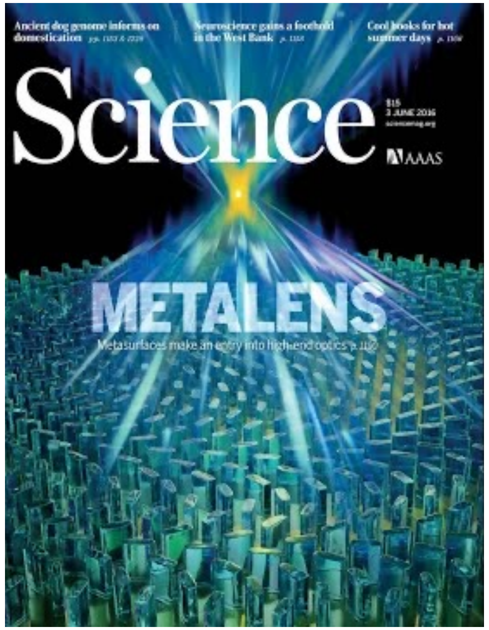
$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \chi(\mathbf{r}) \mathbf{E}(\mathbf{r})$$



$\chi(\mathbf{r})$ defines it all







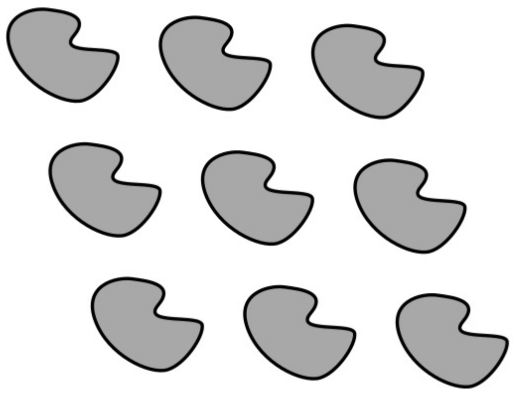
Metasurface-based devices

Capasso, Alu, Yu, Kivshar, Shalaev, Boltasseva, Brongersma, Fan, Maier, Belov, Simovski, Zentgraf, Tsai, Bozhevolnyi, Neshev, Cai, Faraon, Staude, Brener, many others

Metamaterials: tailored nonlinear and spatio-temporal response

UCI Samueli School of Engineering

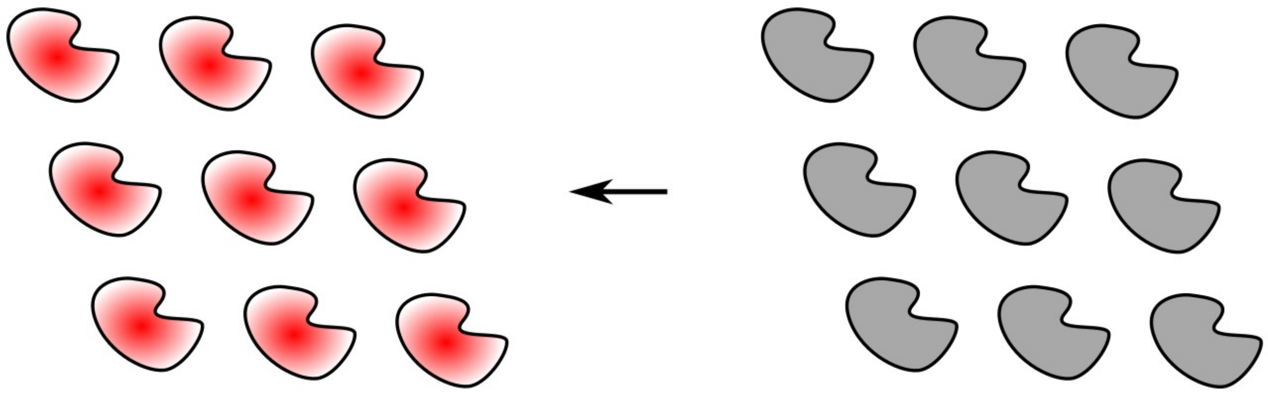
$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \chi(\mathbf{r}) \mathbf{E}(\mathbf{r})$$



Metamaterials: tailored nonlinear and spatio-temporal response

$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \sum \chi^{(n)}(\mathbf{r})\mathbf{E}^{\mathrm{n}}(\mathbf{r})$$

$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \chi(\mathbf{r})\mathbf{E}(\mathbf{r})$$



Nonlinear metamaterials

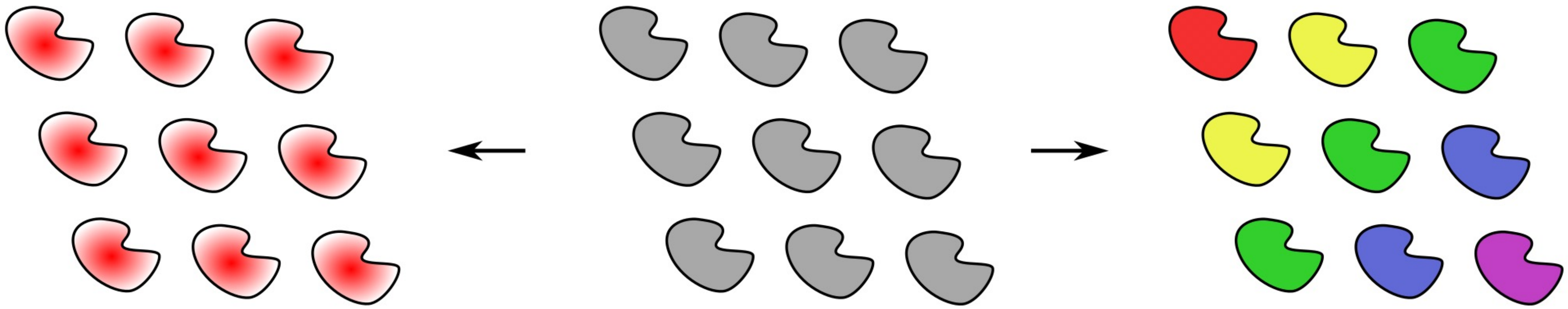
Nano Letters **14**, 6488 (2014)
ACS Photonics **2**, 578 (2015)
Nano Letters **15**, 6985 (2015)
Nano Letters **16**, 4857 (2016)
Nature Communications **8**, 17 (2017)
Nature Communications **10**, 1345 (2019)

Metamaterials: tailored nonlinear and spatio-temporal response

$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \sum \chi^{(n)}(\mathbf{r})\mathbf{E}^{\mathrm{n}}(\mathbf{r})$$

$$\mathbf{P}(\mathbf{r}) = \varepsilon_0 \chi(\mathbf{r})\mathbf{E}(\mathbf{r})$$

$$\mathbf{P}(\mathbf{r},t) = \varepsilon_0 \int d\mathbf{r}' \int dt' \, \chi(\mathbf{r},t,\mathbf{r}',t')\mathbf{E}(\mathbf{r}-\mathbf{r}',t-t')$$



Nonlinear metamaterials

Nano Letters **14**, 6488 (2014)
ACS Photonics **2**, 578 (2015)
Nano Letters **15**, 6985 (2015)
Nano Letters **16**, 4857 (2016)
Nature Communications **8**, 17 (2017)
Nature Communications **10**, 1345 (2019)

Time-variant metamaterials

Nature Communications **10**, 1345 (2019)
Optica (Memorandum) **6**, 1441 (2019)
Physical Review A **100**, 063847 (2019)
Nano Letters **20**, 7052 (2020)
APL Materials **9**, 060701 (2021)

Time-variant metasurfaces

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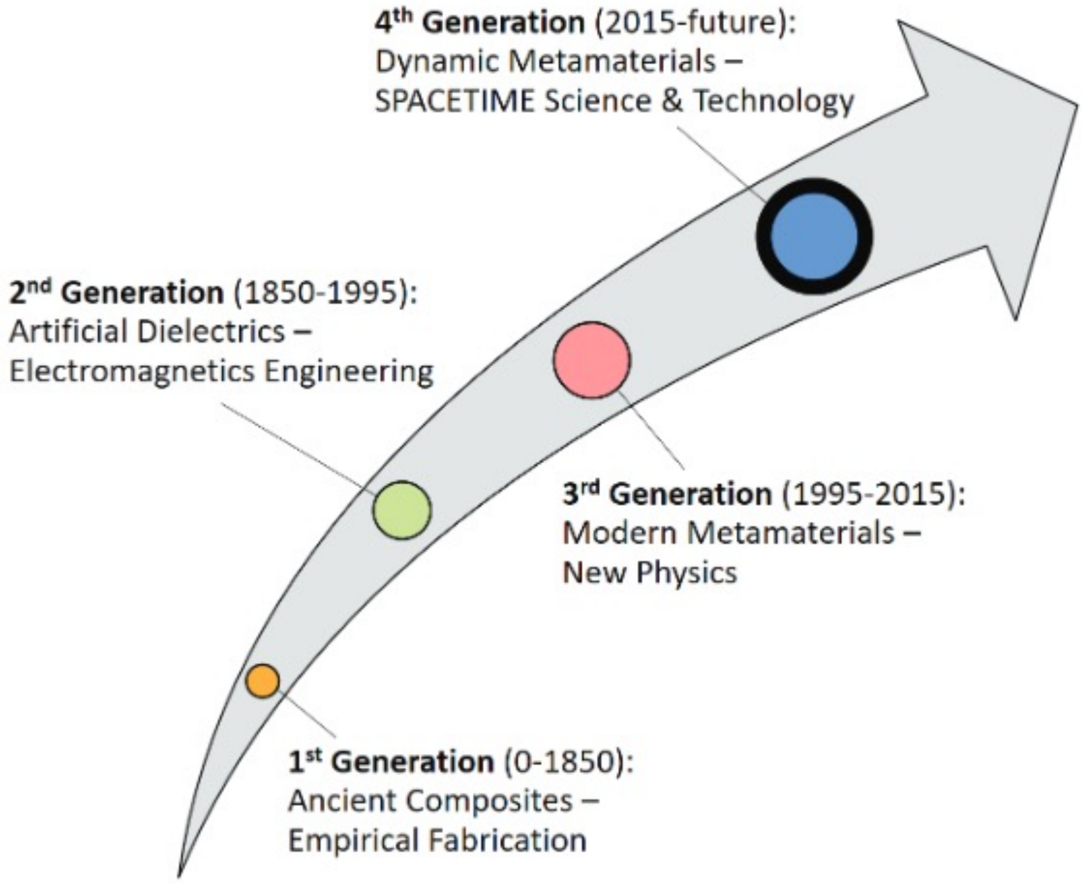
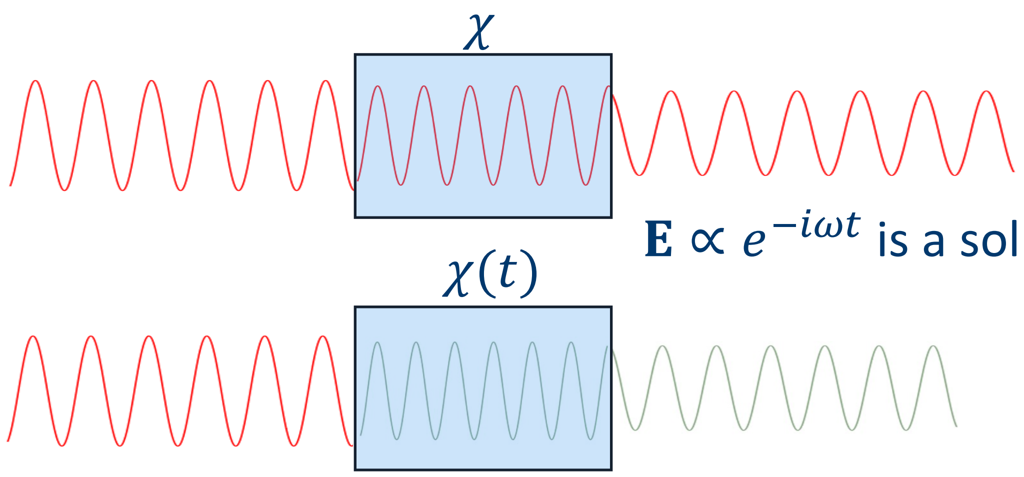


Caloz and Deck-Leger, *IEEE Trans Ant Propag* **68**, 1569 (2020)



$\mathbf{E} \propto e^{-i\omega t}$ is a solution

$\mathbf{E} \propto e^{-i\omega t}$ is not a solution

Tretyakov, Boyd, Pendry, Engheta, Alu, Segev, Shadrivov, Shvets, Huidobro, Boltasseva, Shalaev, Brongersma, Kinsey, Halevi, Khurgin, Caglayan, Faccio, Nassar, Narimanov, Monticone, Sapienza, Fleury, Rodriguez, Lurie, Ramezani, Ramaccia many others

Experiments in time-variant metasurfaces

Nano Letters **20**, 7052 (2020)
Nature Communications **10**, 1345 (2019)

Nonlinear optics in nanostructures

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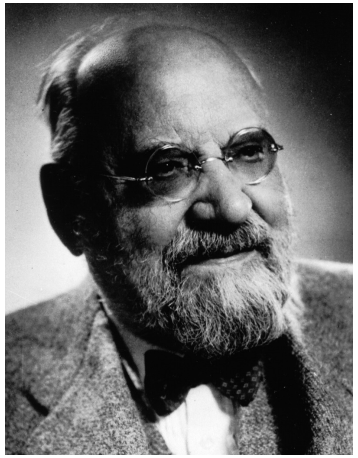
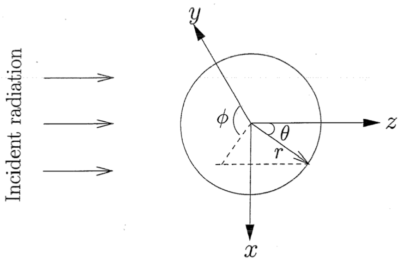


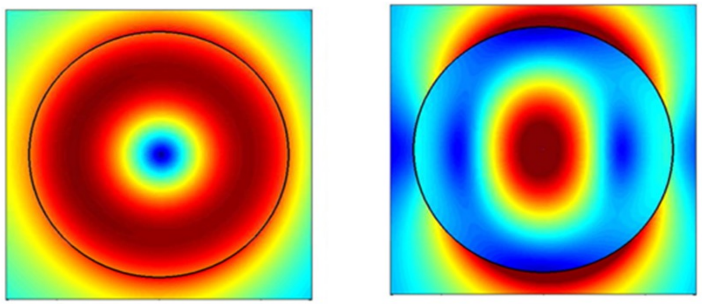
Gustav Mie
(1869 – 1957)

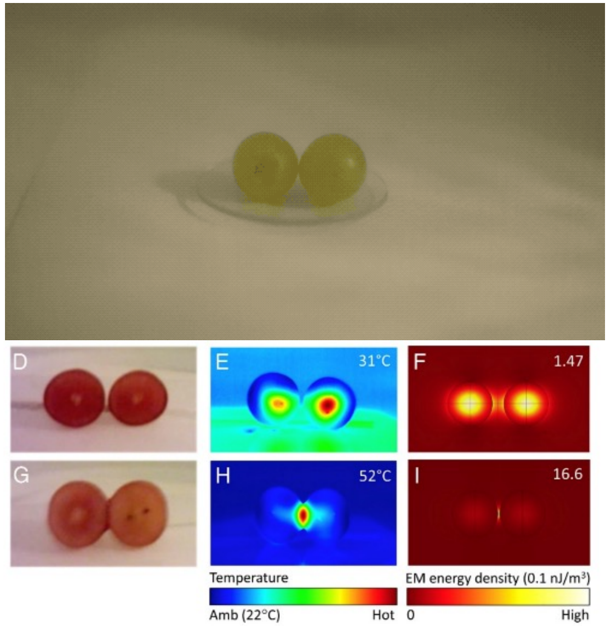


Bohren, C. F. & Huffman, D. R. *Absorption and Scattering of Light by Small Particles* Wiley Inter-Science, 1998.

$|\mathbf{E}|^2$ maps

(1) Magnetic dipolar **(2) Electric dipolar**

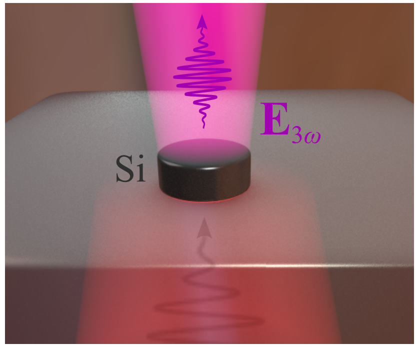


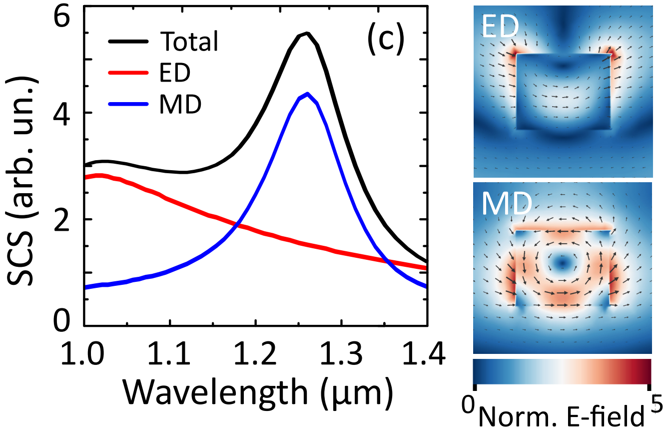


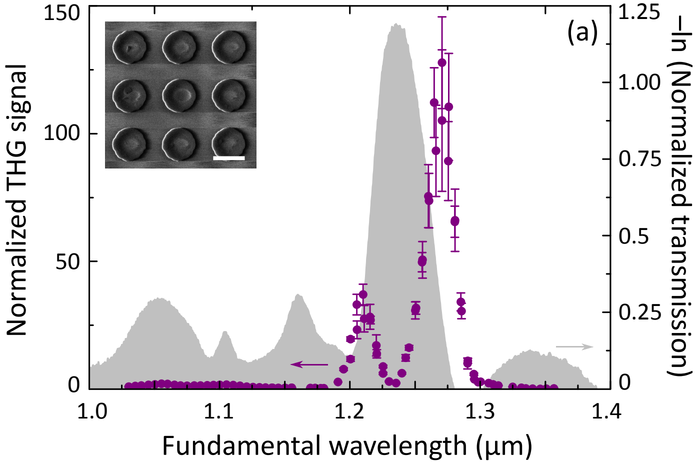
Khattak et al., *PNAS* **116**, 4000 (2019)

$$\tilde{P} = \chi^{(1)}\tilde{E}(t) + \chi^{(2)}\tilde{E}^2(t) + \chi^{(3)}\tilde{E}^3(t) + \dots$$

$$\tilde{E}(t) \propto e^{i\omega t} \qquad \propto e^{2i\omega t} \qquad \propto e^{3i\omega t}$$





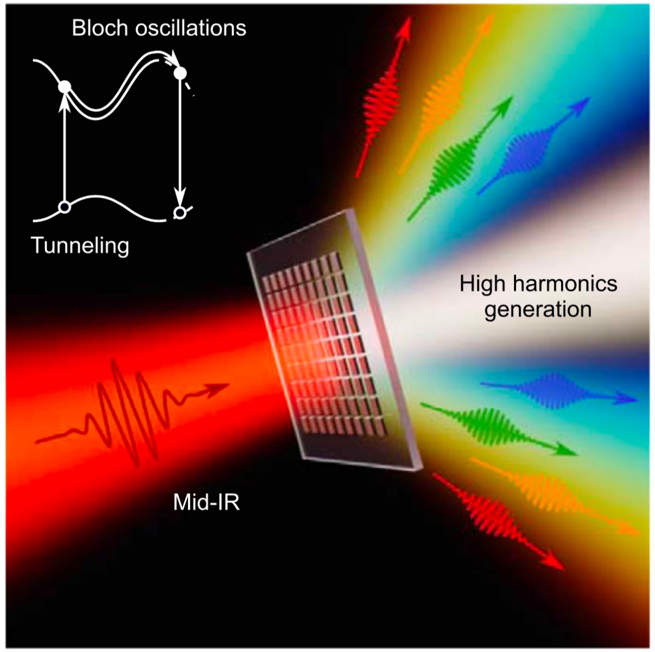


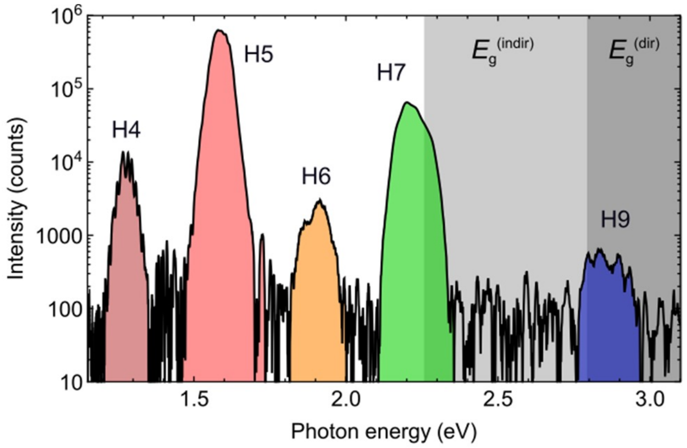
10^2 enhancement vs bulk silicon

Shcherbakov et al., *Nano Lett.* **14**, 6488 (2014)

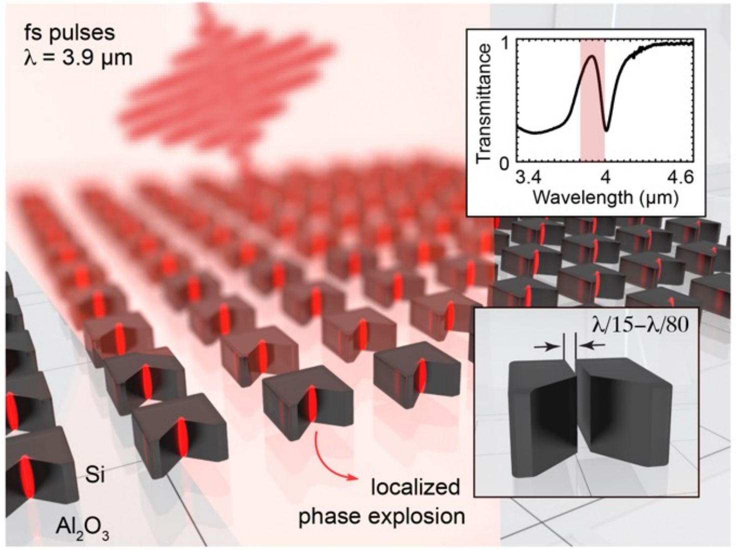
Outline

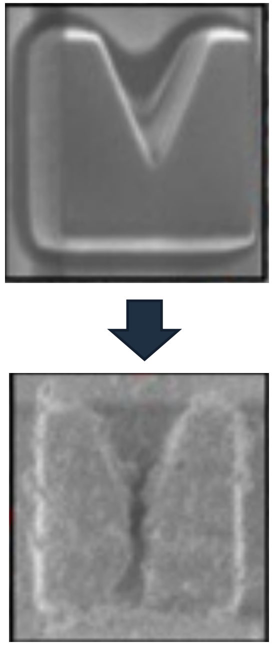
- Strong fields:
  high harmonics generation





- Very strong fields:
  laser damage and nanomachining





High harmonic generation

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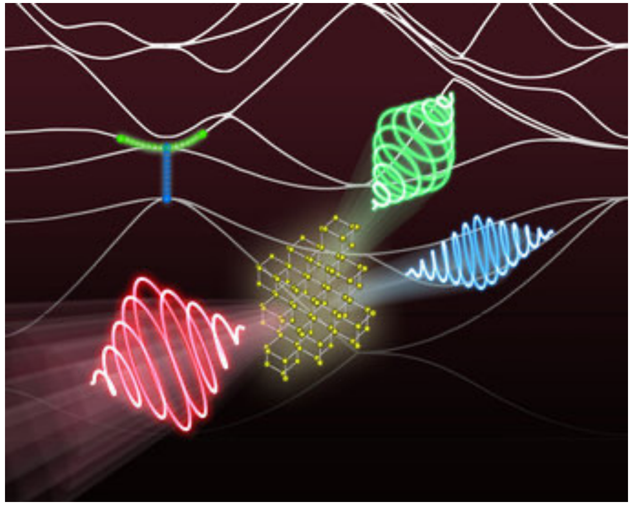

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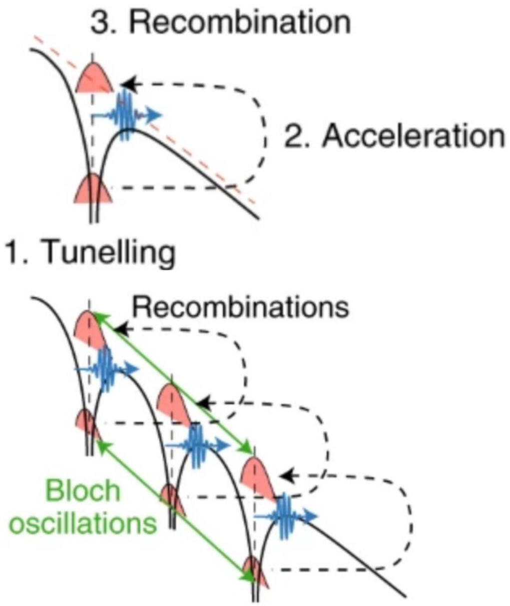
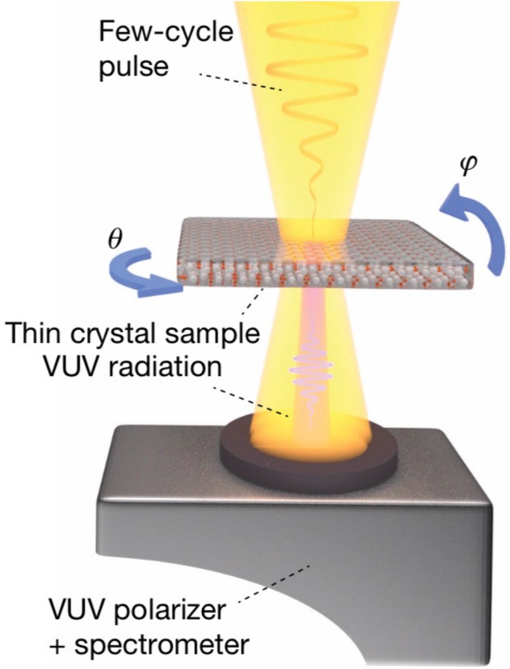
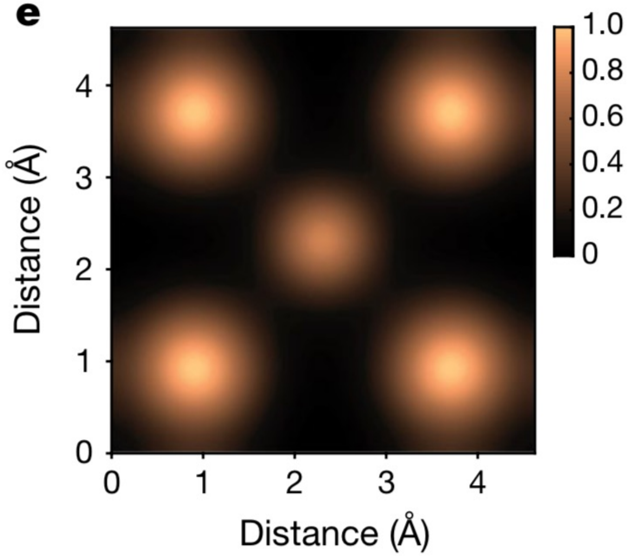
+ Joerg M. Harms, MPSD



Ghimire & Reis,
Nature Physics **15**, 10–16 (2019)

Pushing the resolution limits





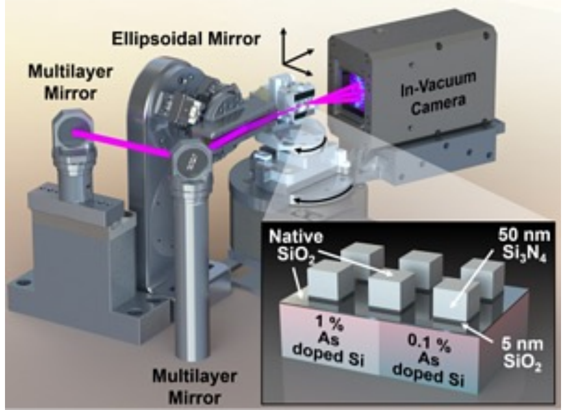
Article

Laser picoscopy of valence electrons in solids

https://doi.org/10.1038/s41586-020-2429-z

H. Lakhotia[1,2,4], H. Y. Kim[1,2,4], M. Zhan[1,2], S. Hu[3], S. Meng[3] & E. Goulielmakis[1,2]✉

XUV sources for photolithography



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HHG in nanostructures

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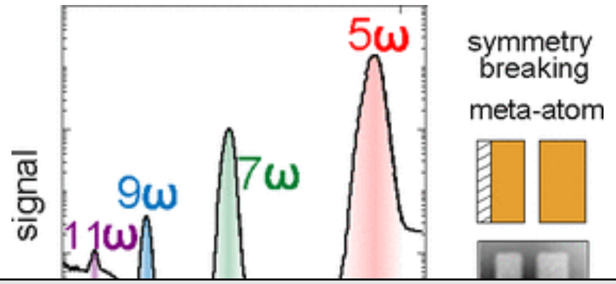
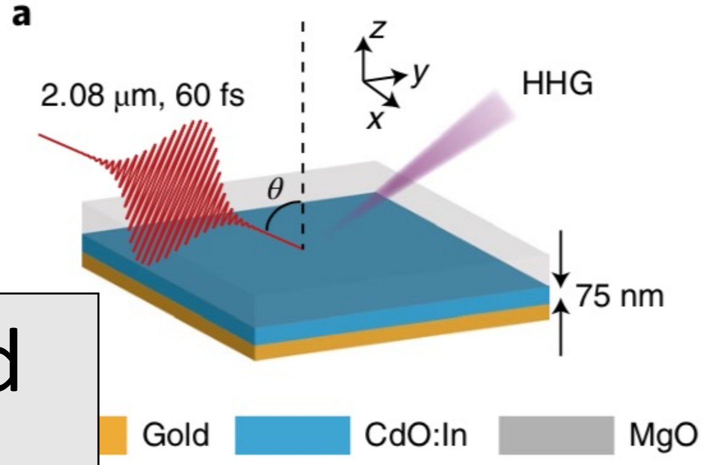
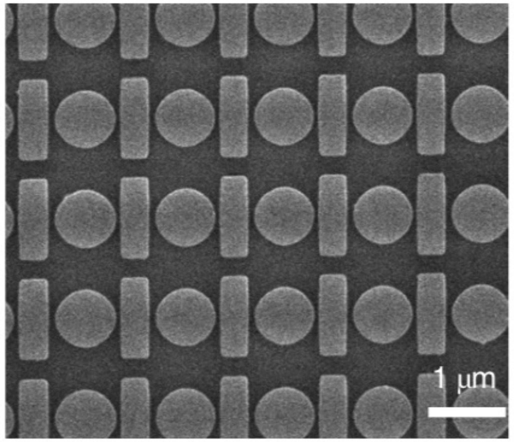
Nanostructured solids are natural candidates for HHG

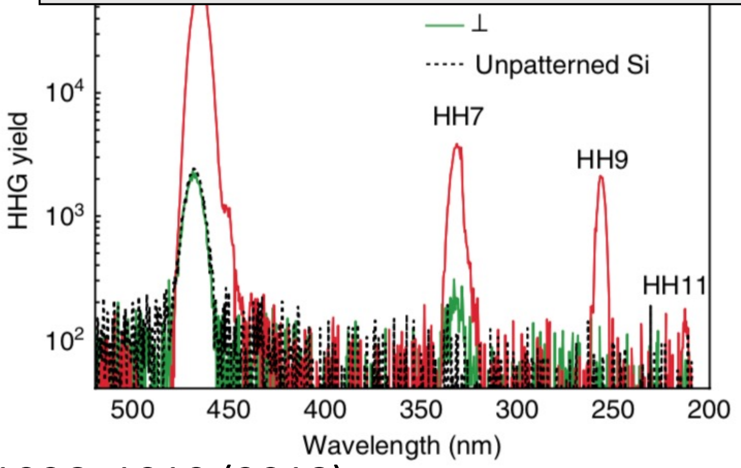
- No phase matching issues
- Enhanced local fie

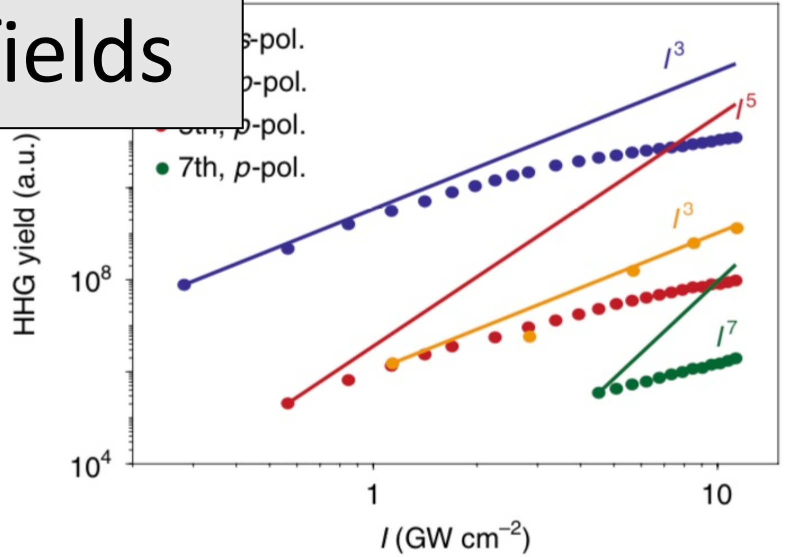


- Even harmonics are limited
- High reabsorption
- Hard to access strong fields





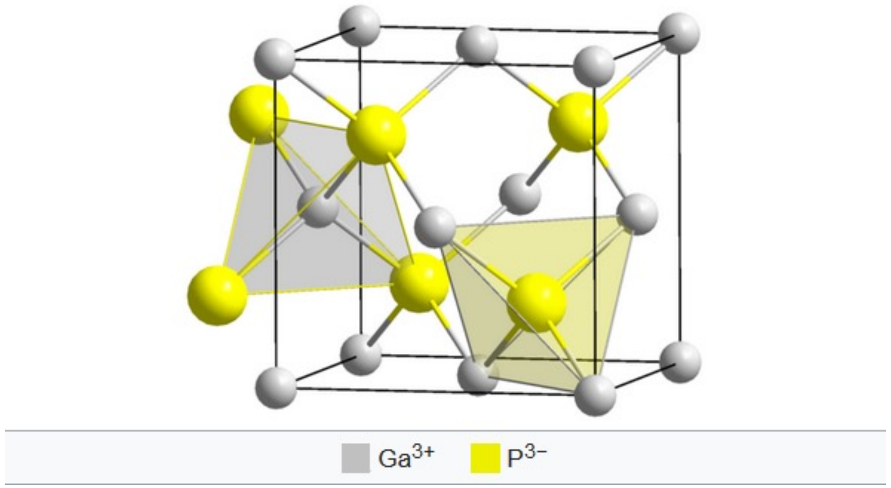


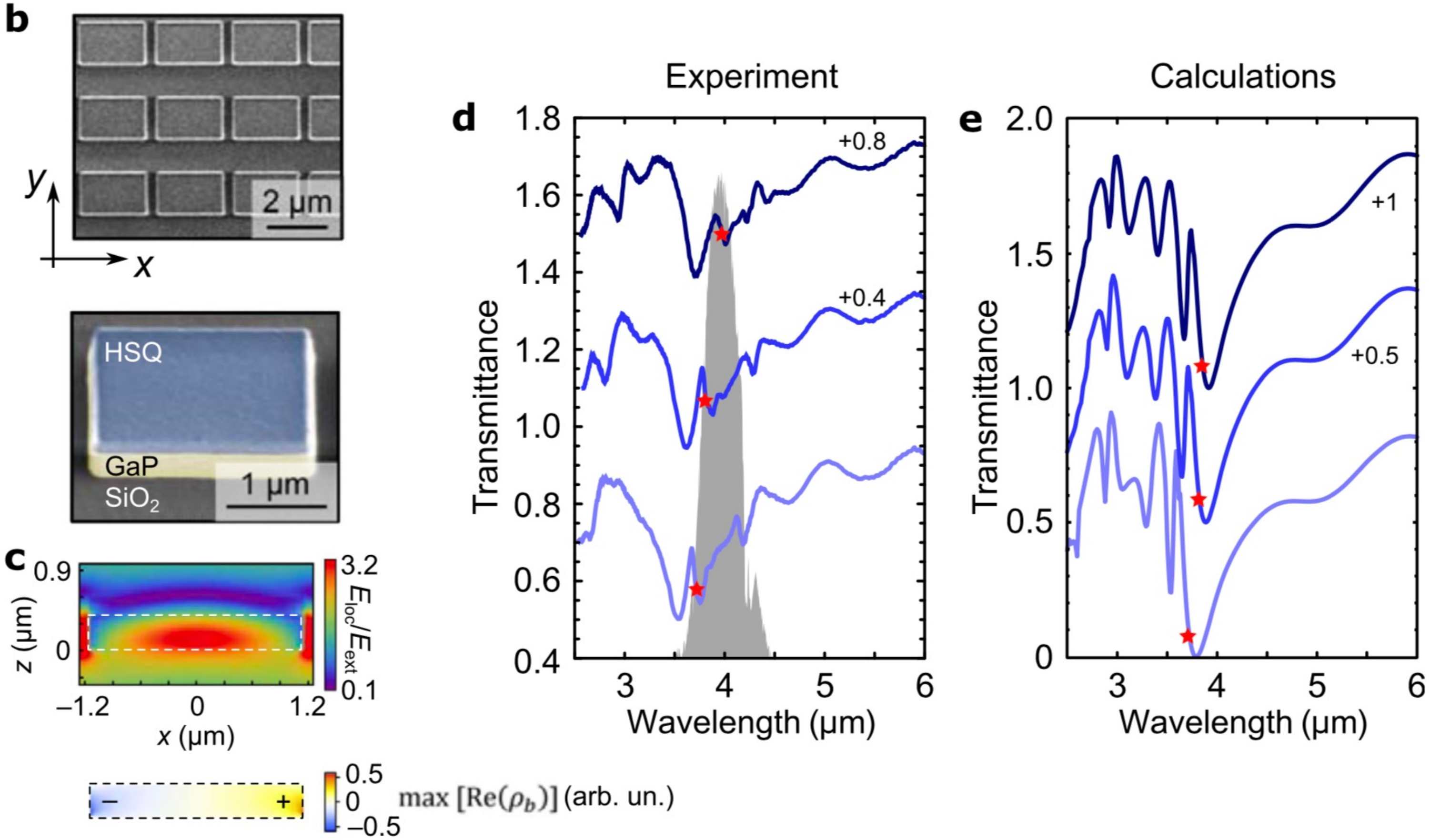


Liu et al., *Nature Physics* **14**, 1006–1010 (2018)

Yang et al., *Nature Physics* **15**, 1022–1026 (2019)

GaP — material of choice





- Noncenstrosymmetric
- Good tradeoff between E_{bg} and refractive index

Fabrication — Arseniy Kuznetsov’s group, A*Star (Singapore)

HHG measurements

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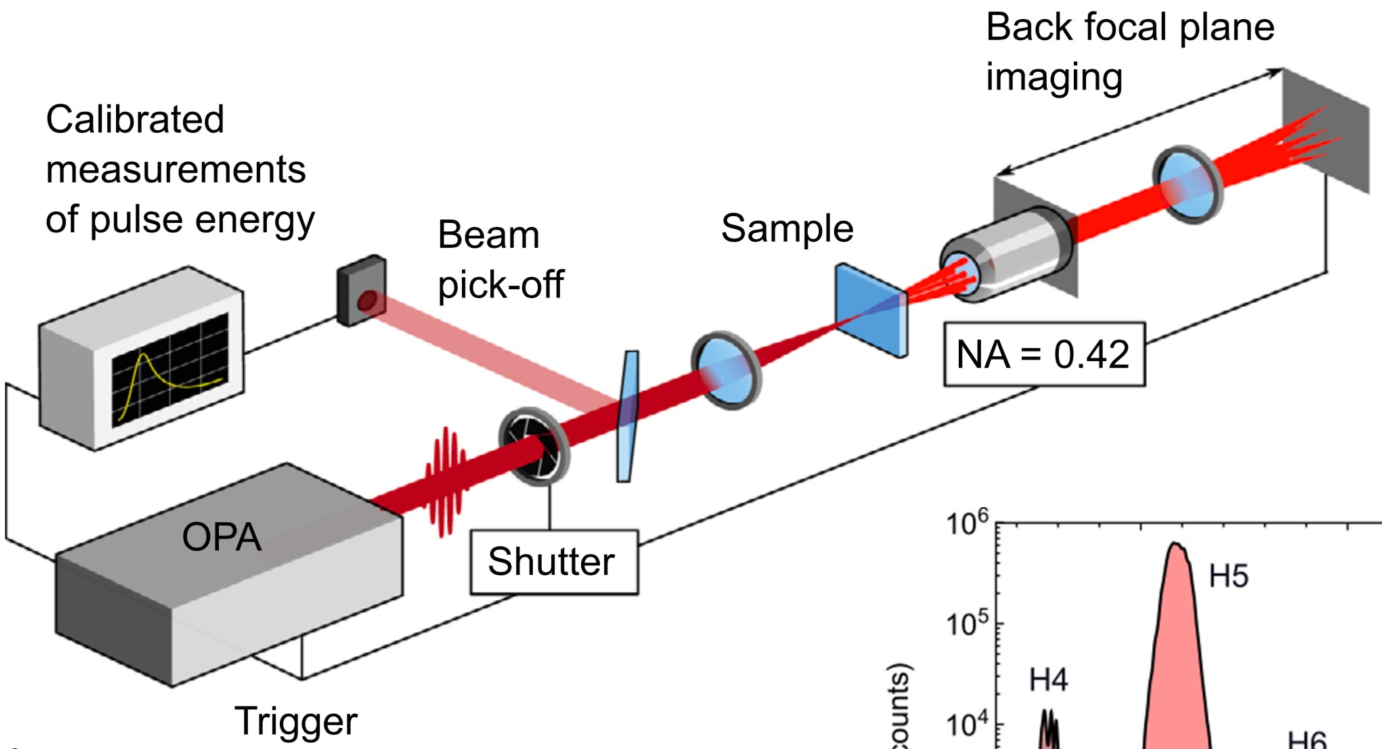
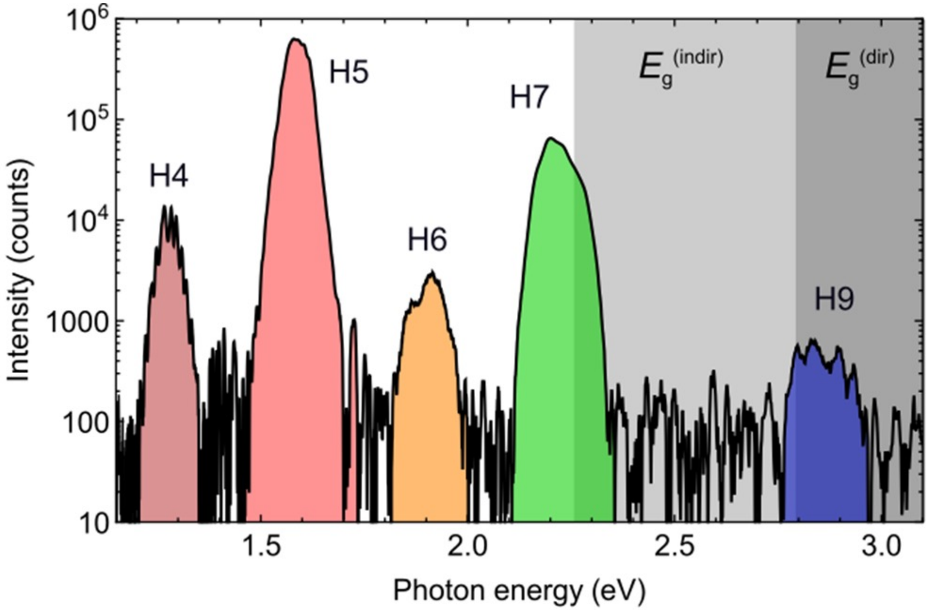
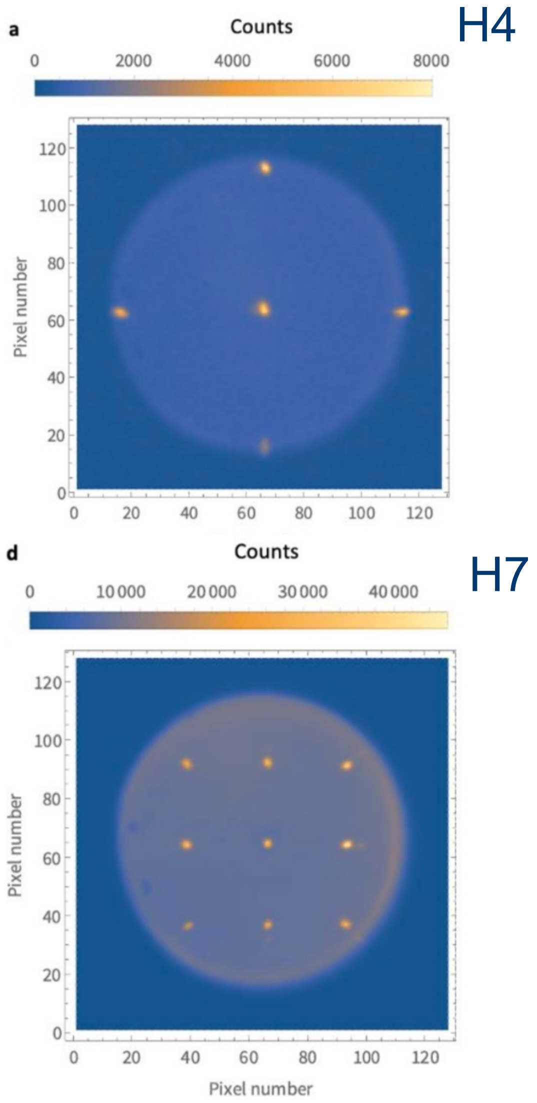


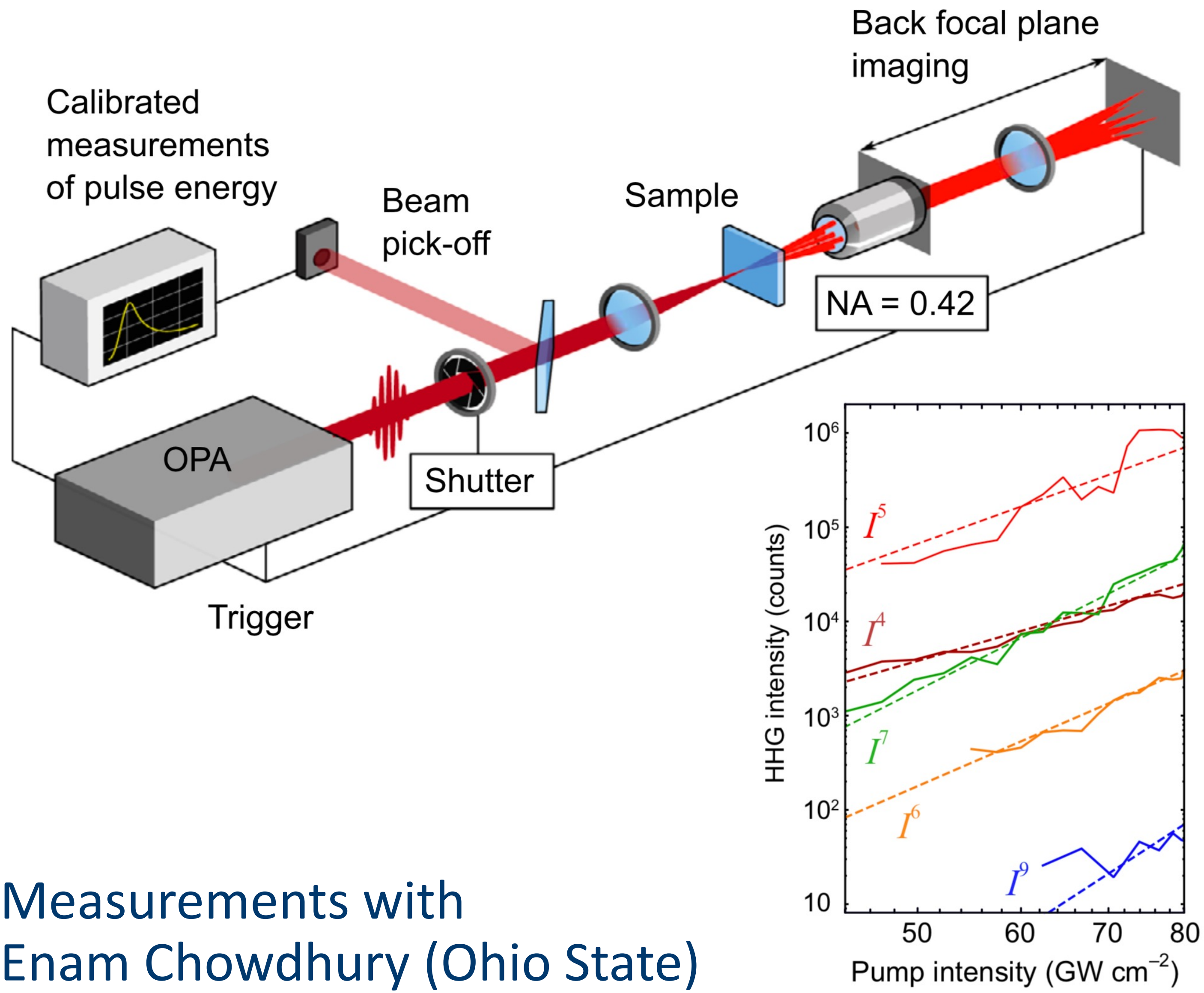
$\lambda = 4\ \mu m$





Measurements with
Enam Chowdhury (Ohio State)

Single-shot HHG



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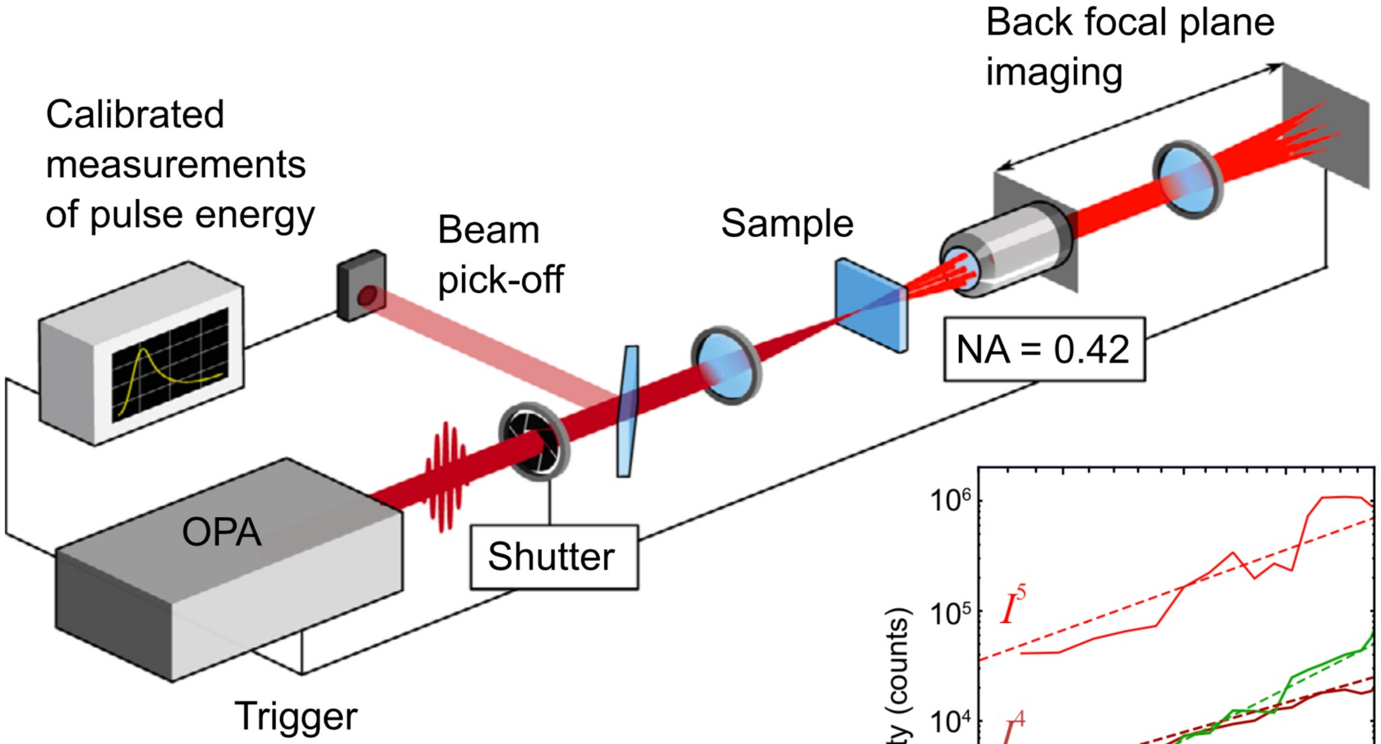
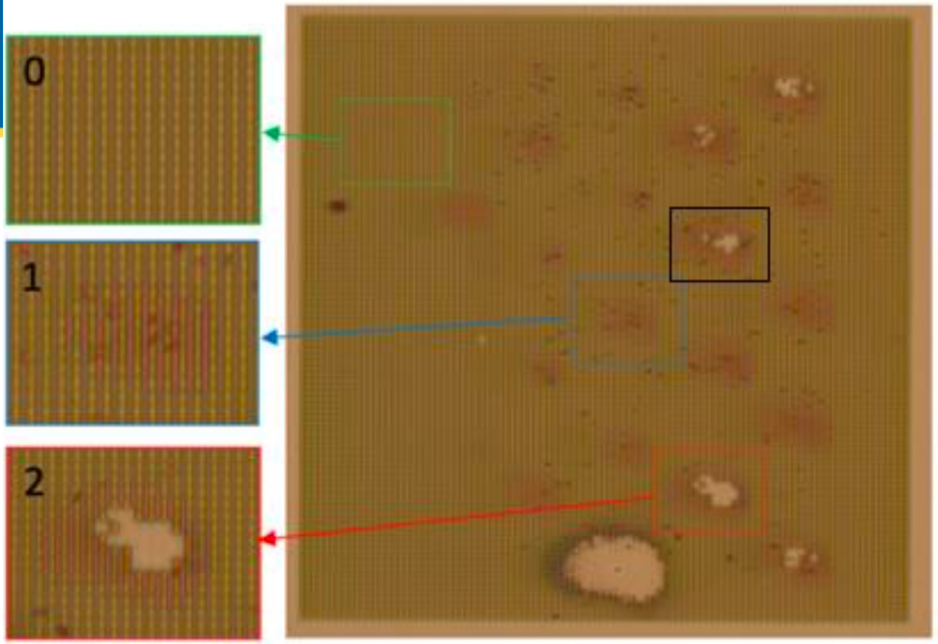
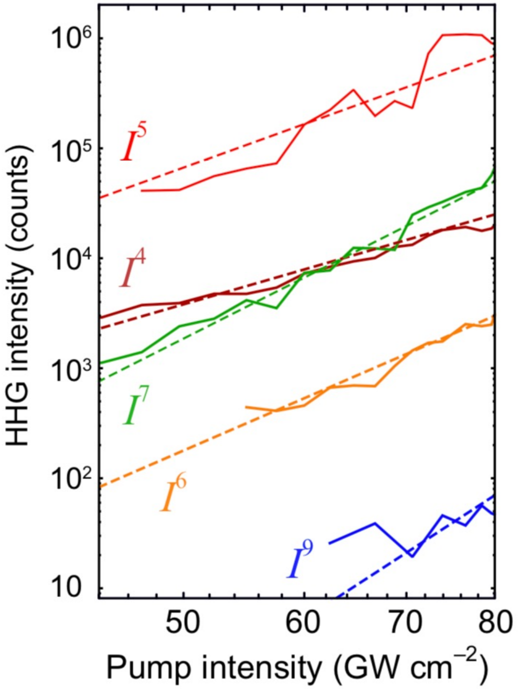
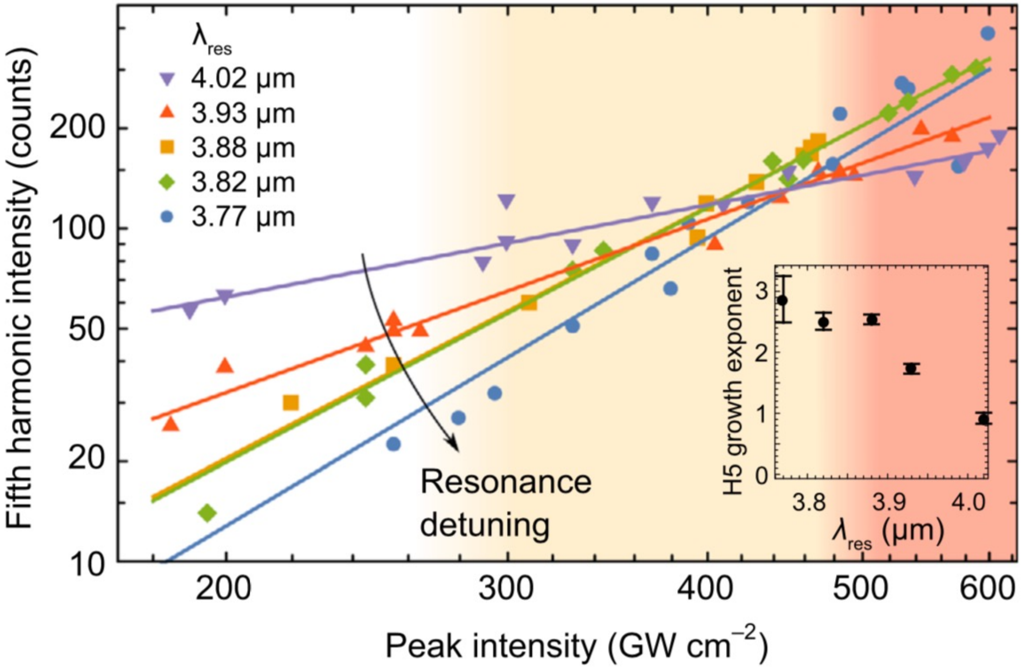




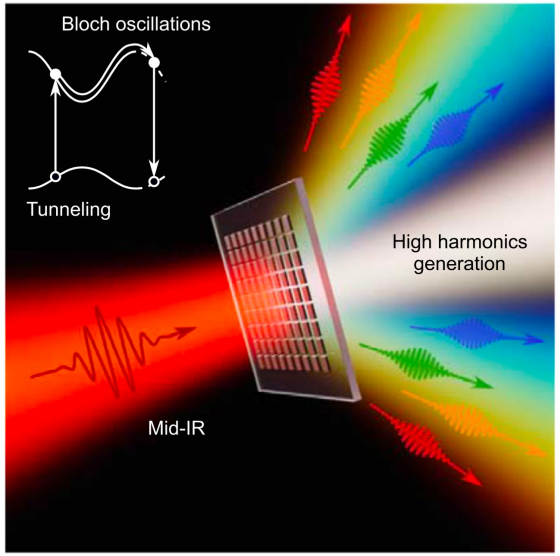


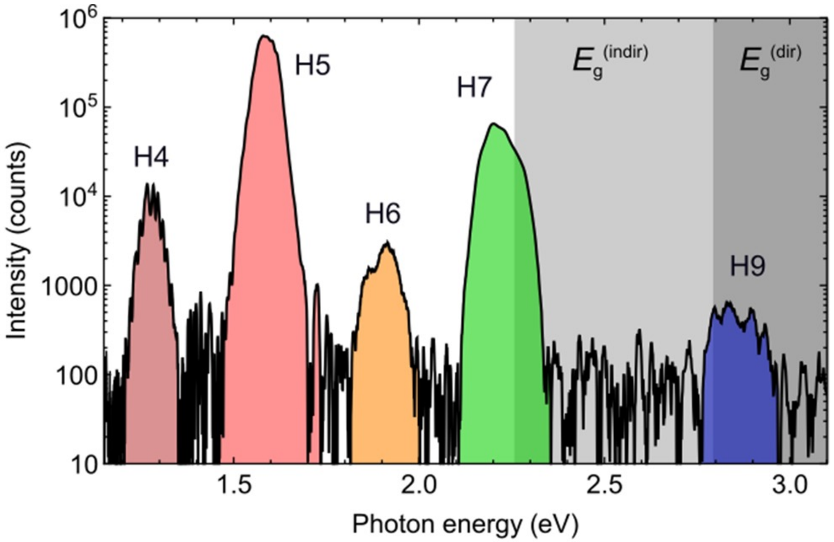


Measurements with
Enam Chowdhury (Ohio State)

Conversion efficiencies

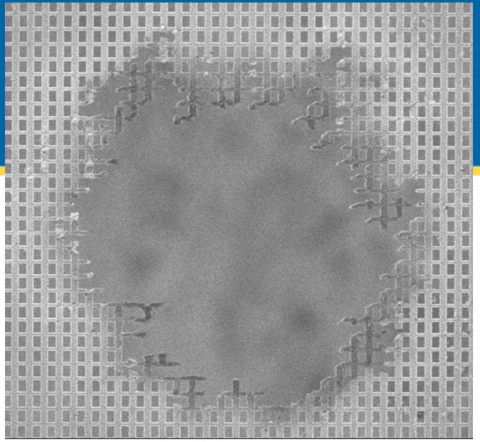
Material	Harmonic order	Conversion efficiency	Efficiency per 1 μm thickness
GaP metasurface [this work]	5 (SP)	1.4×10^{-6}	3.5×10^{-6}
	7 (MP)	2×10^{-9}	5×10^{-9}
ZnO [8]	5	3×10^{-5}	10^{-7}
	7	6×10^{-6}	2×10^{-8}
Periodically poled $LiNbO_3$ [9]	5	10^{-2}	4×10^{-7}
	7	10^{-2}	4×10^{-7}
Si metasurface [10]	5	5×10^{-9}	2.2×10^{-8}
ENZ material [11]	5	10^{-8}	1.3×10^{-7}
	7	10^{-10}	1.3×10^{-9}





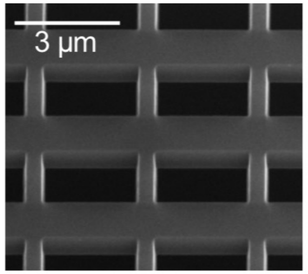
Shcherbakov et al.,
Nature communications **12**, 4185 (2021)

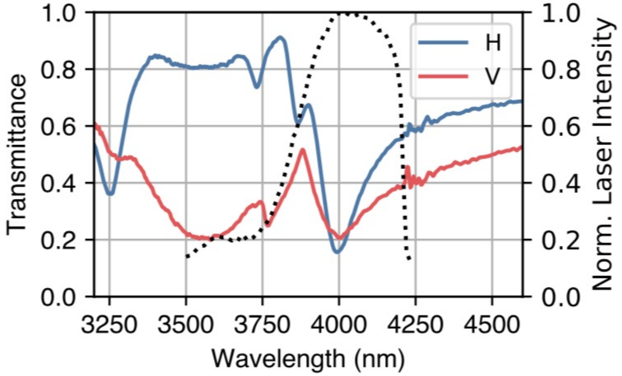
SiC free-standing membranes

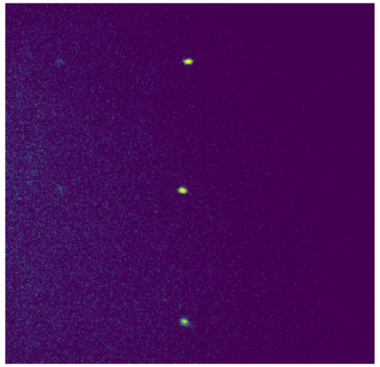


Samples: Free-standing membrane SiC metasurface
Daniil Lukin, Jelena Vuckovic

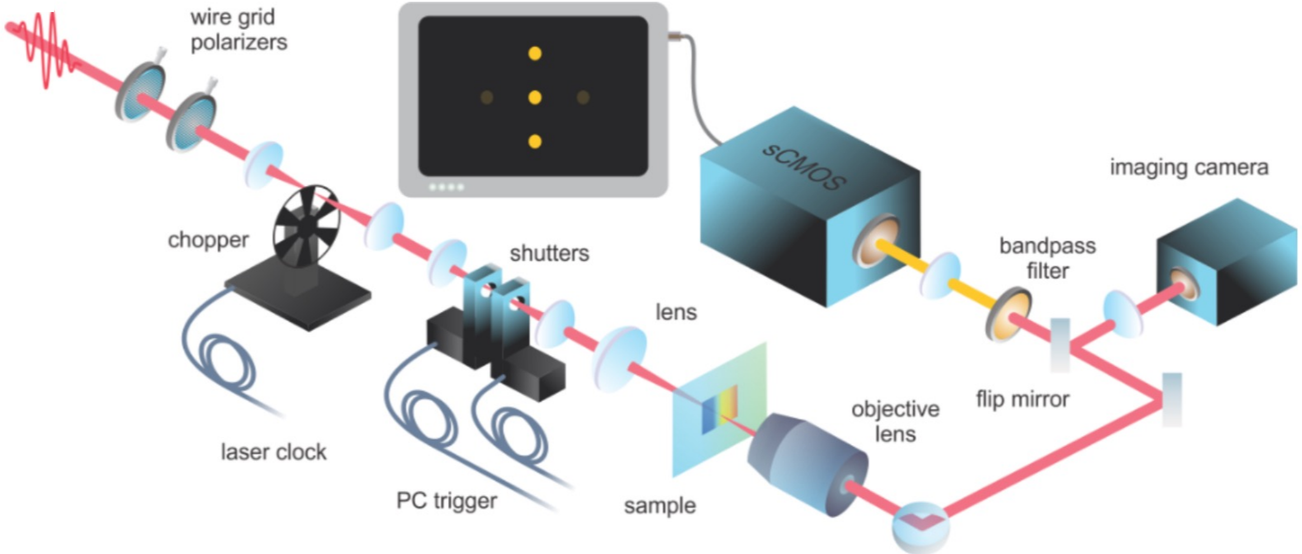
Pulse train = damage!

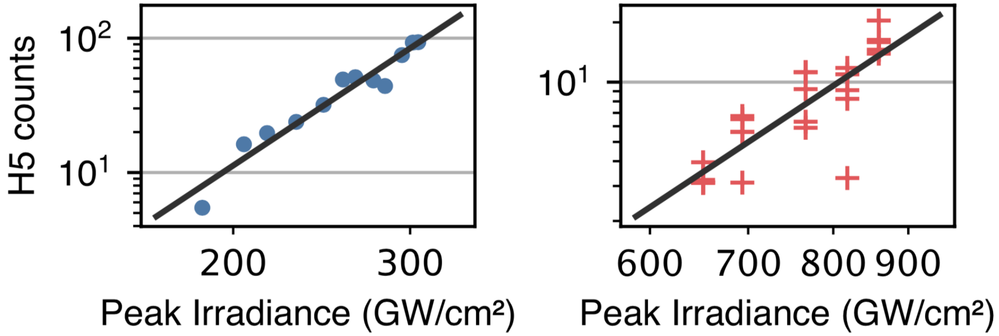






Single shot
back focal plane H5



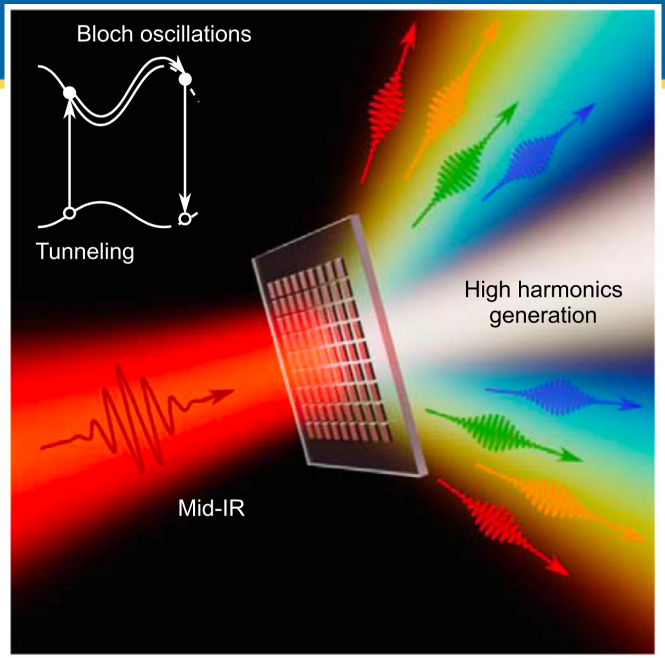


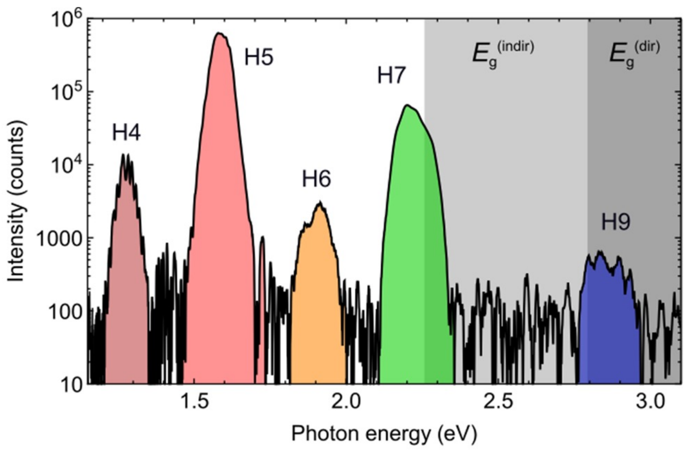
$$I(5\omega) \sim I^5(\omega)$$

Measurements: Shvets group, Fishman group, Shcherbakov group

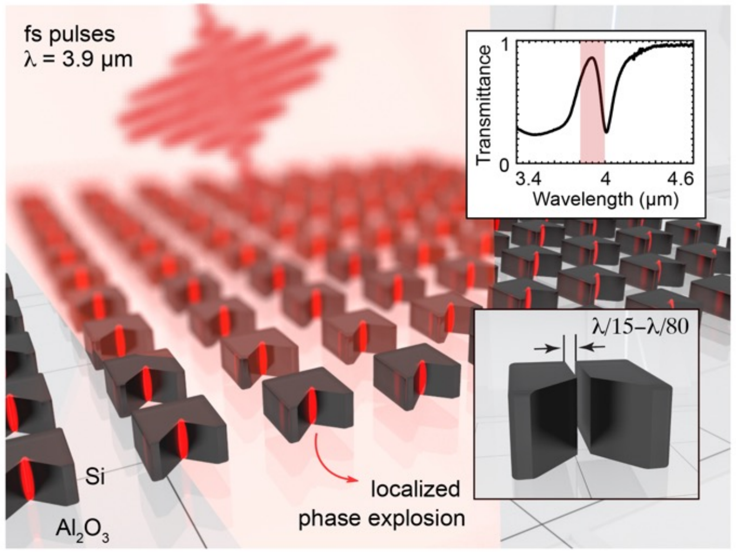
Outline

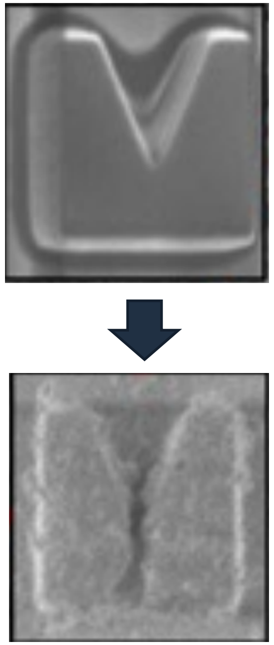
- Strong fields:
  high harmonics generation





- Very strong fields:
  laser damage and nanomachining





Laser Nanomachining

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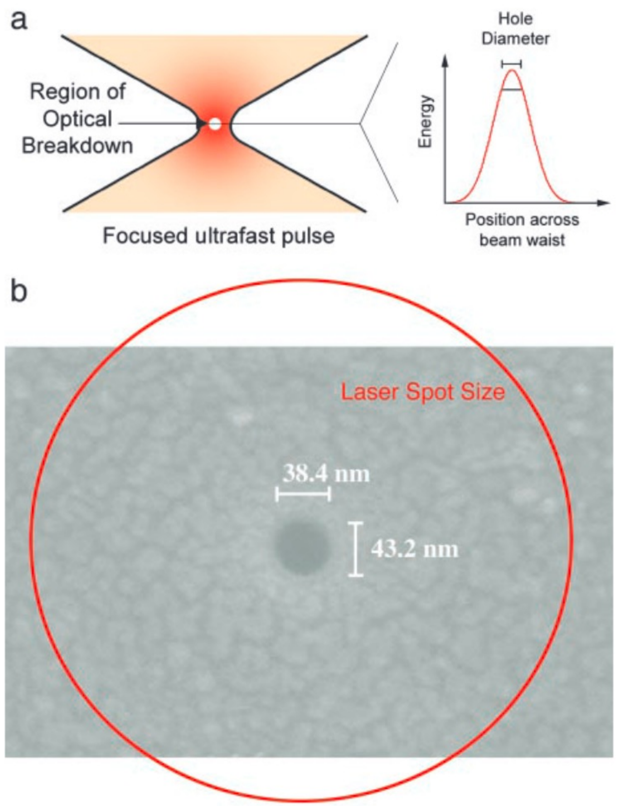
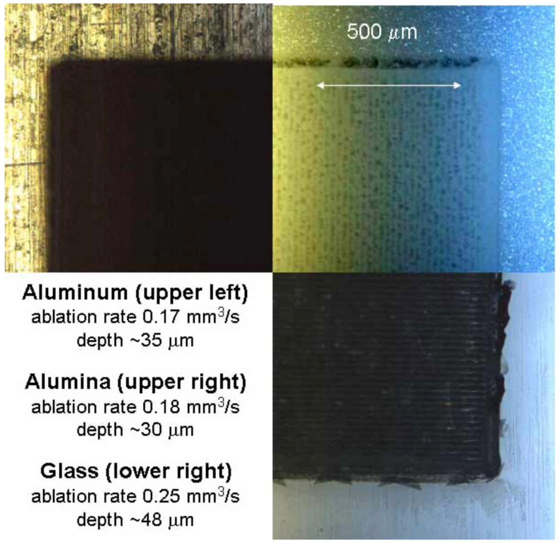
Single-pulse

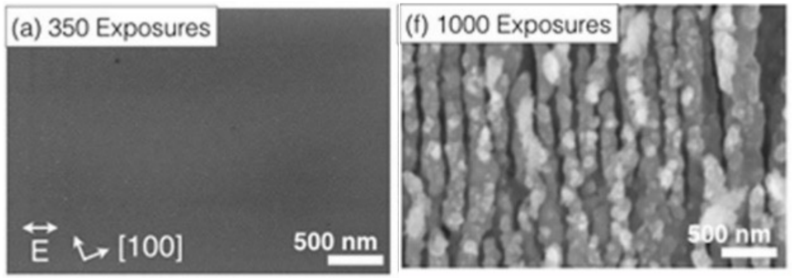


Joglekar et al., *PNAS* **101** 5856 (2003)

Multi-pulse



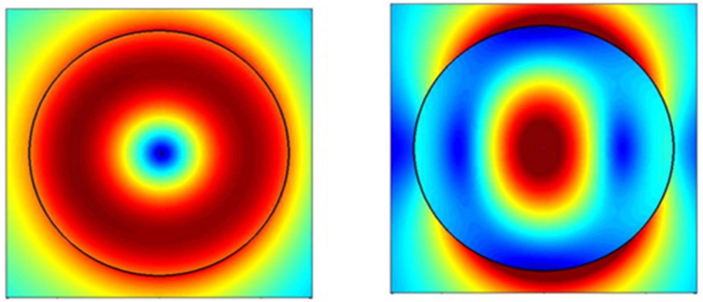
Shah et al., *Optics Express* **14**, 12546 (2006)

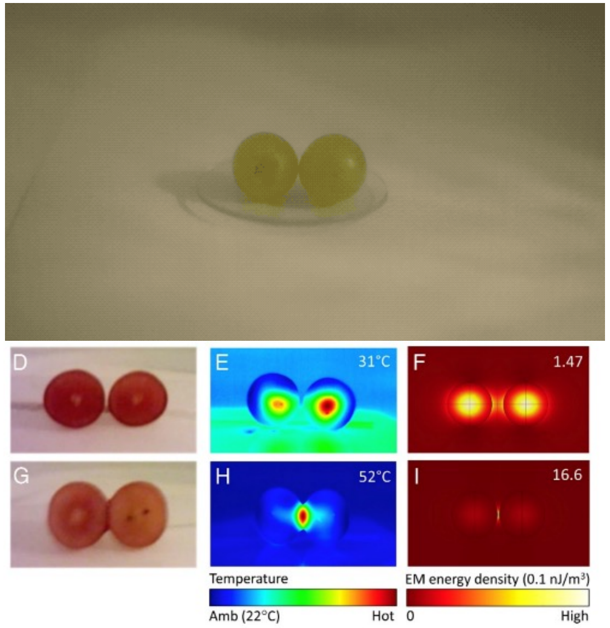


Abere et al., *Journal of Applied Physics* **126**, 143102 (2019)

$|\mathbf{E}|^2$ maps

(1) Magnetic dipolar **(2) Electric dipolar**





Khattak et al., *PNAS* **116**, 4000 (2019)

Resonators for deep-subwavelength machining

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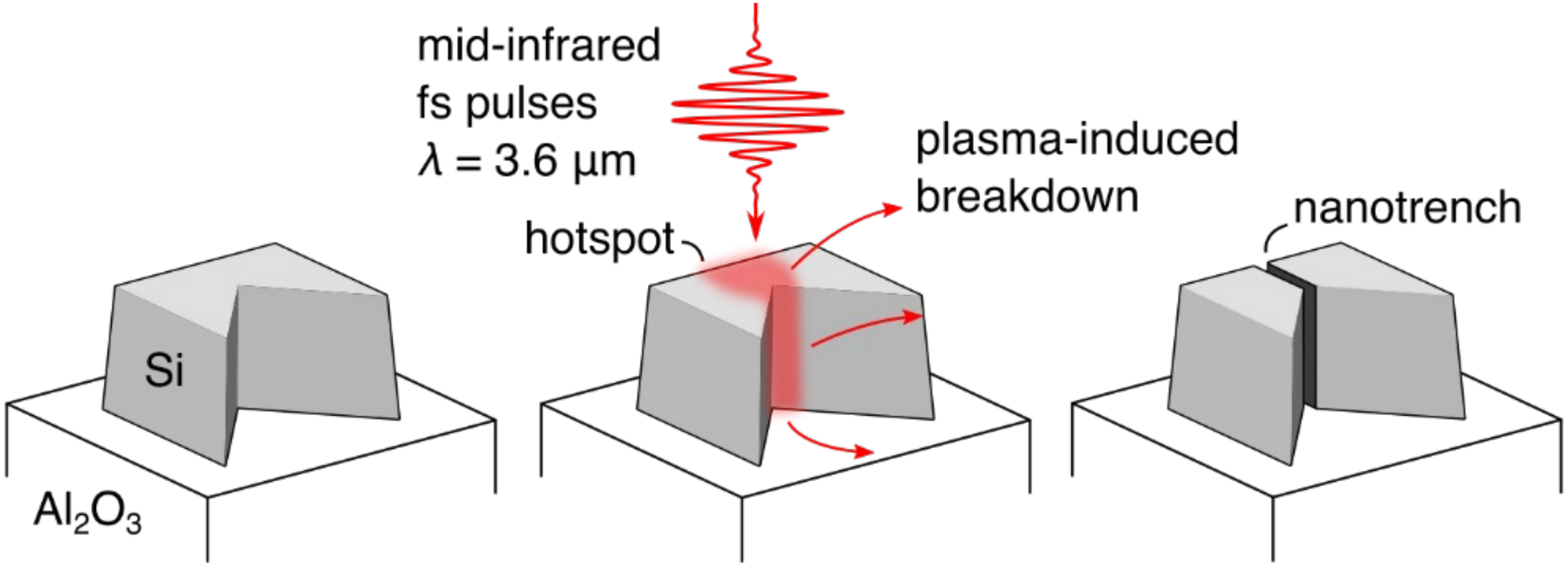
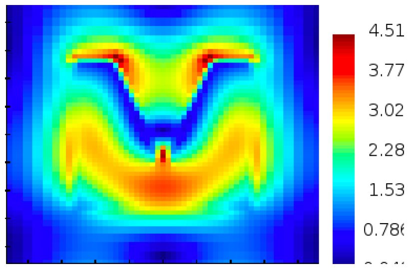
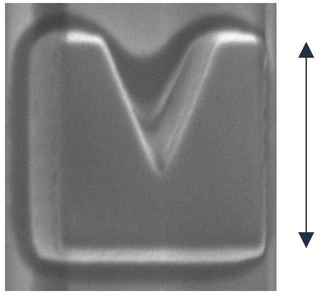
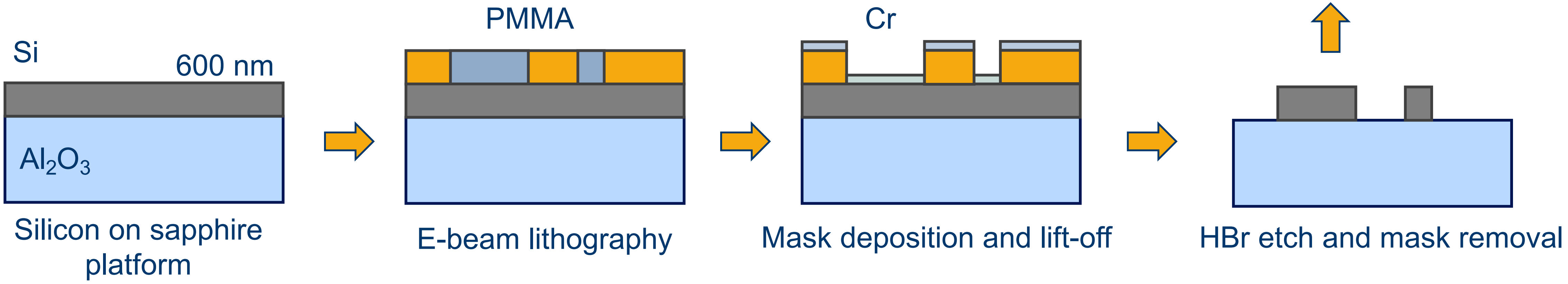




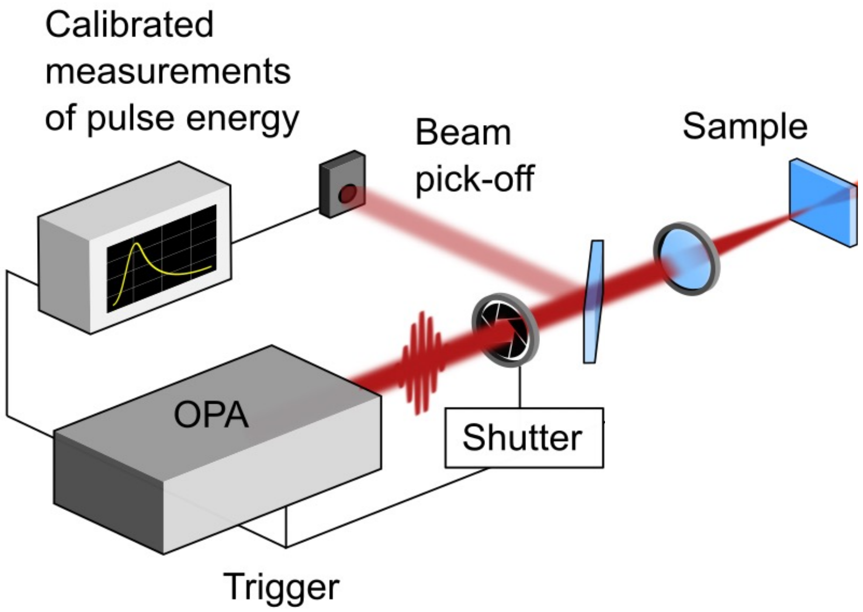
E-field map

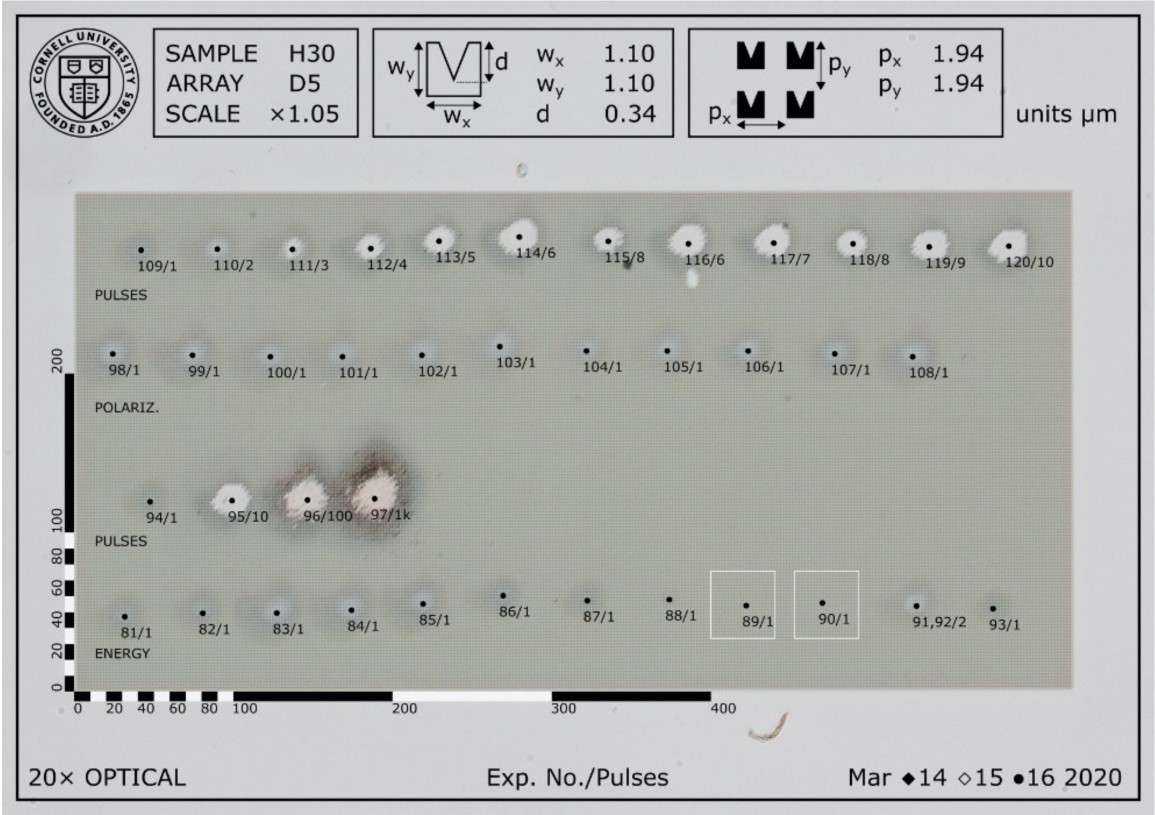


~ 1 micron



Methodology

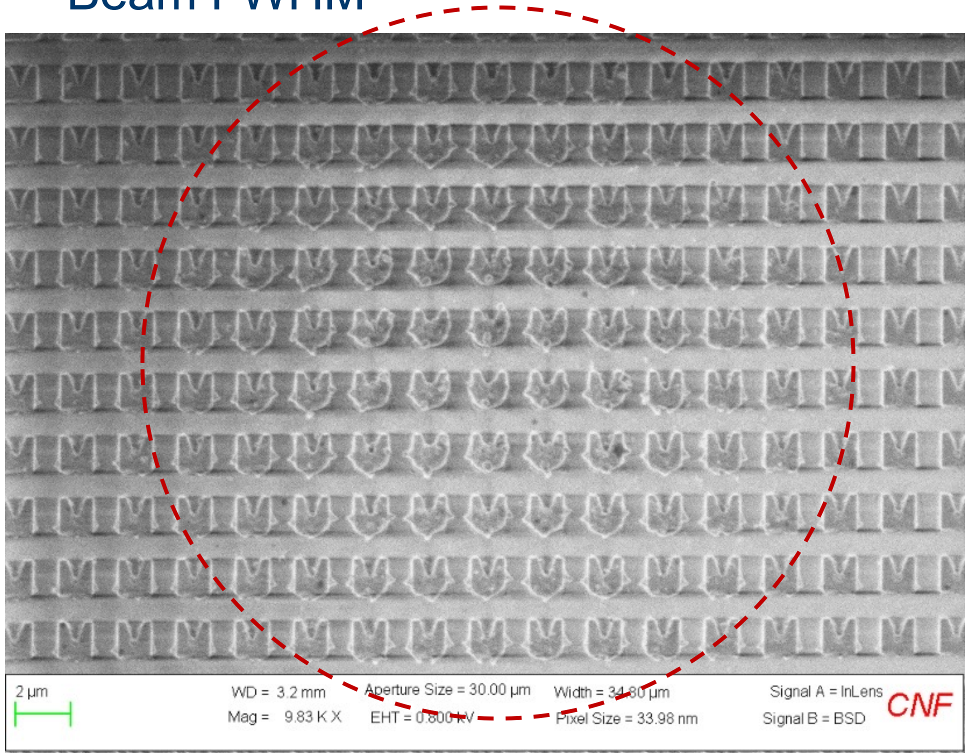


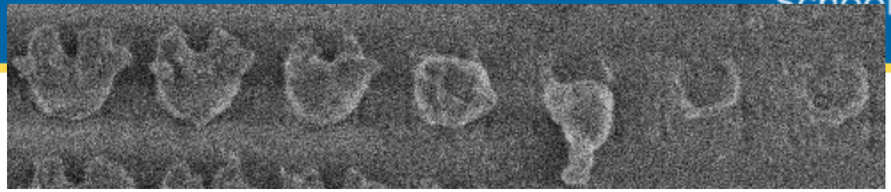


Variations in pulse energy, number and polarization

Damage Type 1: Single-pulse Above Threshold

Beam FWHM



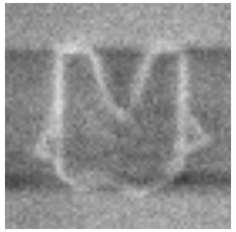


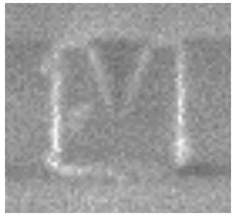
Outside → Beam center

"Wings" "Blob" Detachment

E-field

Beam center





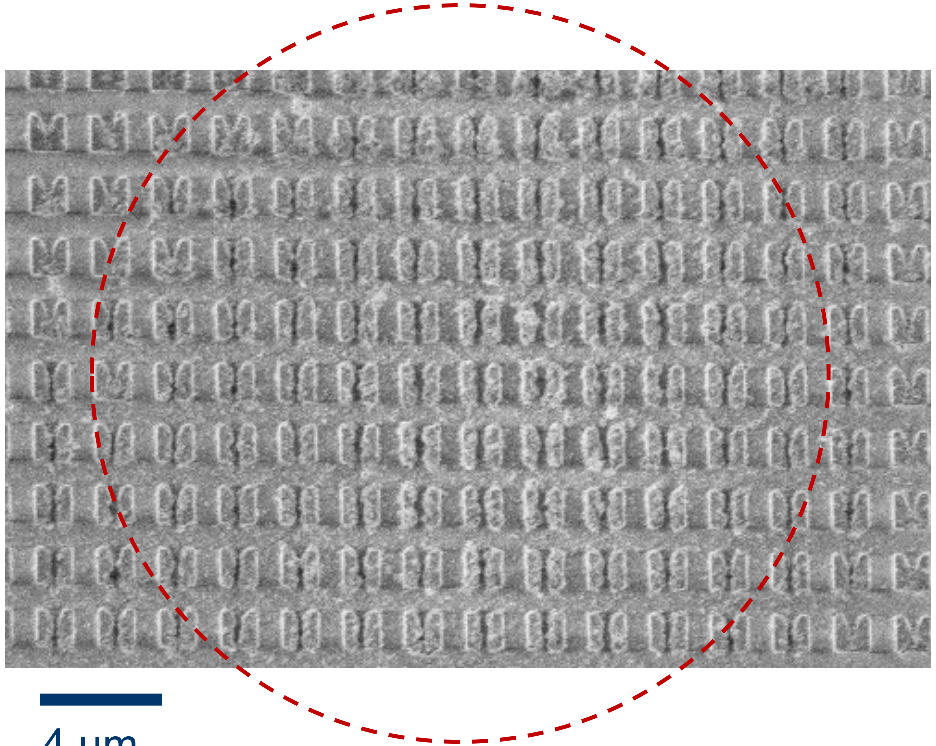
Outside

Damage threshold: **< 0.05 J/cm²**

Typical mid-IR Si single-pulse damage threshold: **~ 0.25 J/cm²**

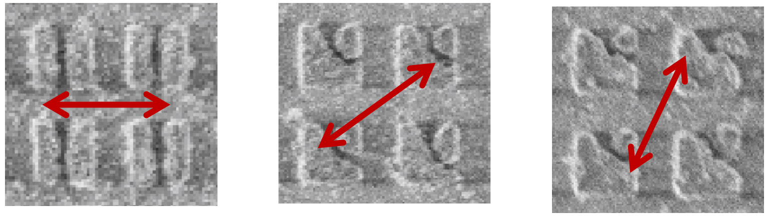
Werner et al., *Scientific Reports* **9**, 19993 (2019)

Damage Type 2: Sub-threshold “Trenching”

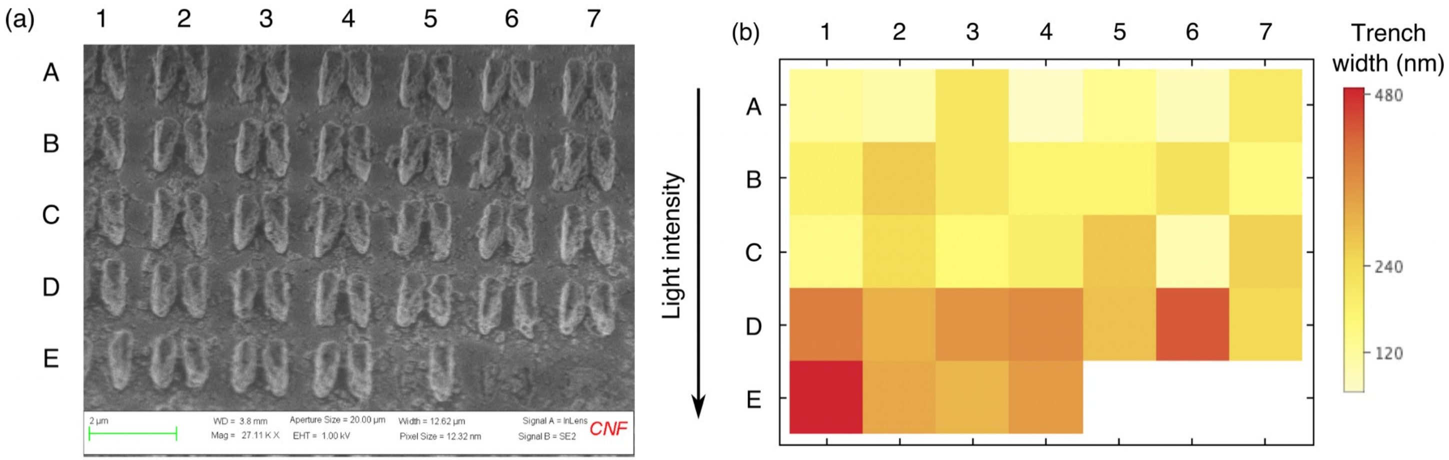


4 µm

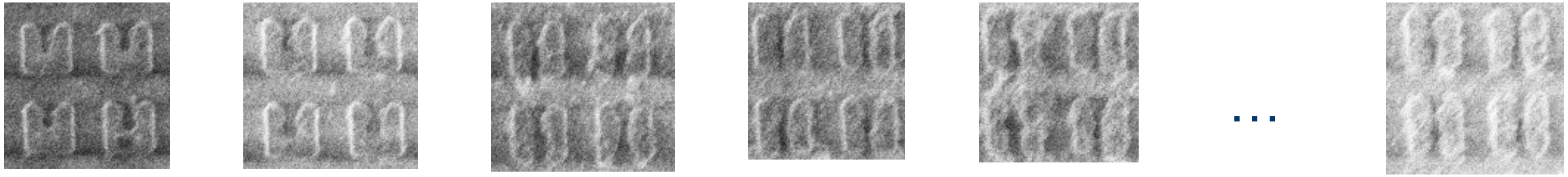
Trench control by polarization



Trench control by intensity



Trench control by number of shots



10 shots 20 shots 30 shots 40 shots 50 shots … 100 shots

Dense plasma formation and machining

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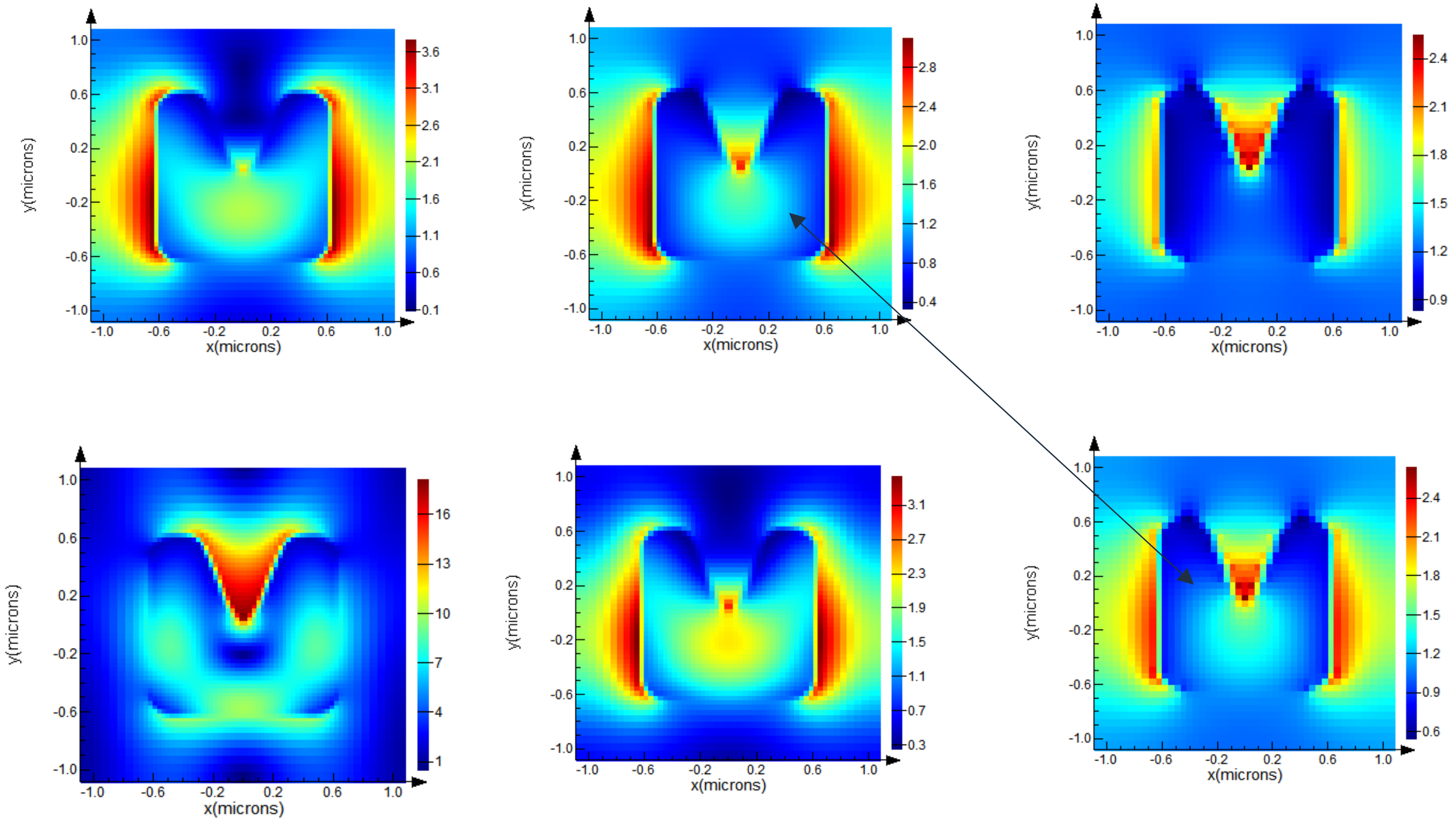
$$\varepsilon = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}, \qquad \varepsilon_\infty = 12, \qquad \gamma^{-1} = 10\ \text{fs}, \qquad \omega_{p,crit} = \omega\sqrt{\varepsilon_\infty} = 1.6 \cdot 10^{15}\ \text{s}^{-1}$$

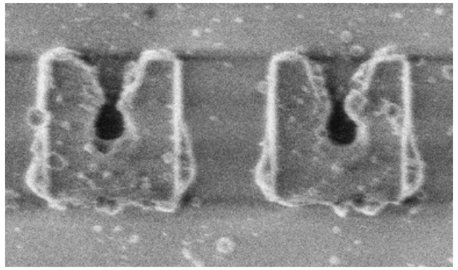
$\omega_p = 10^{14}\ \text{s}^{-1}$ | $\omega_p = 10^{15}\ \text{s}^{-1}$ | $\omega_p = 1.5 \cdot 10^{15}\ \text{s}^{-1}$

Off resonance

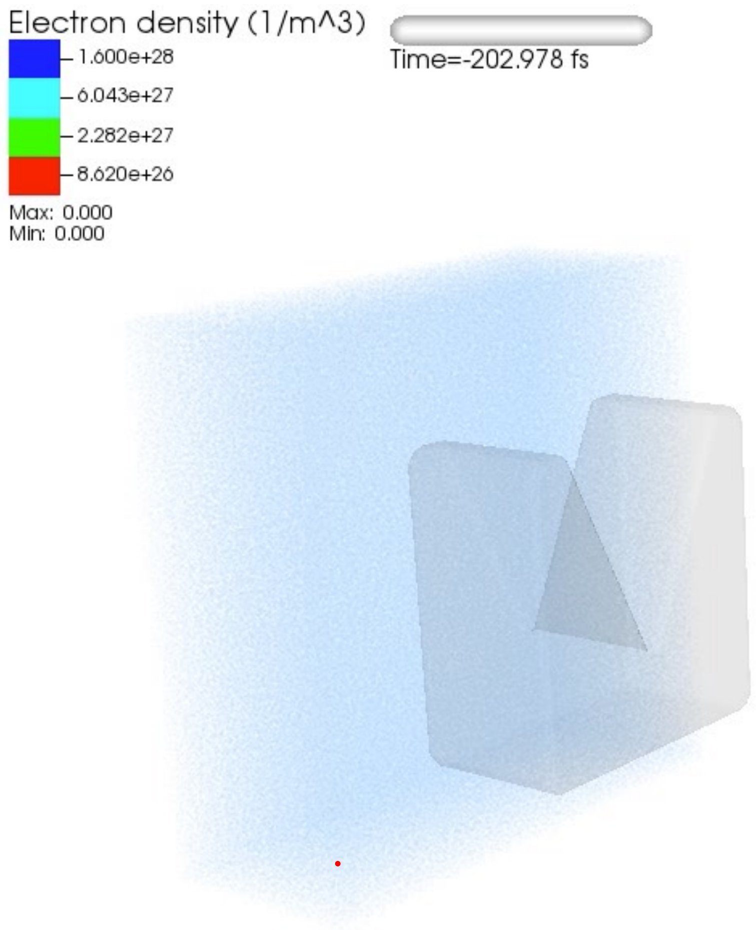
On resonance

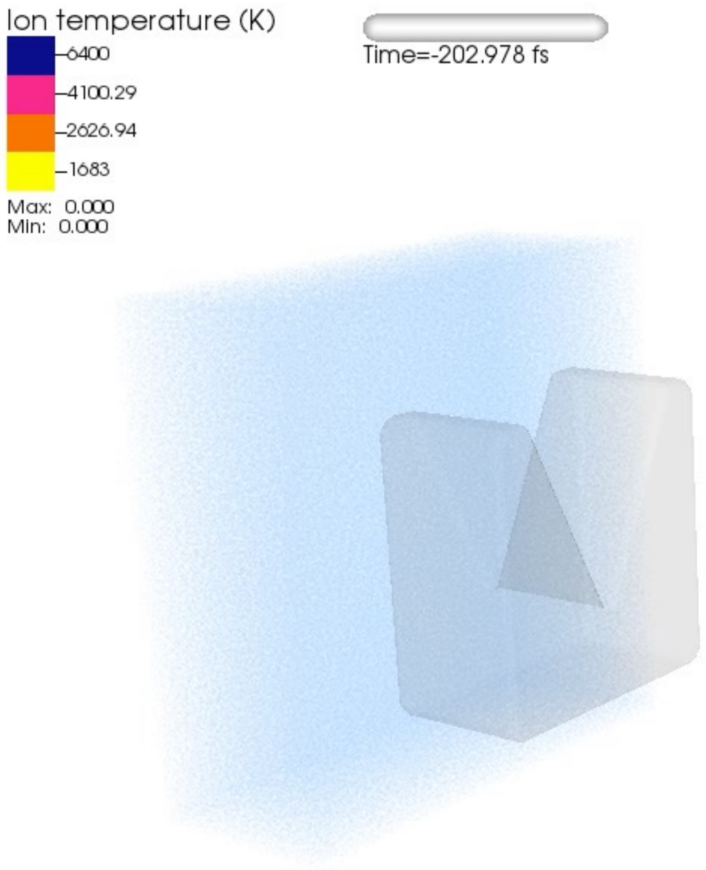


Near-threshold



Particle-in-cell simulations





Particle-in-cell simulations

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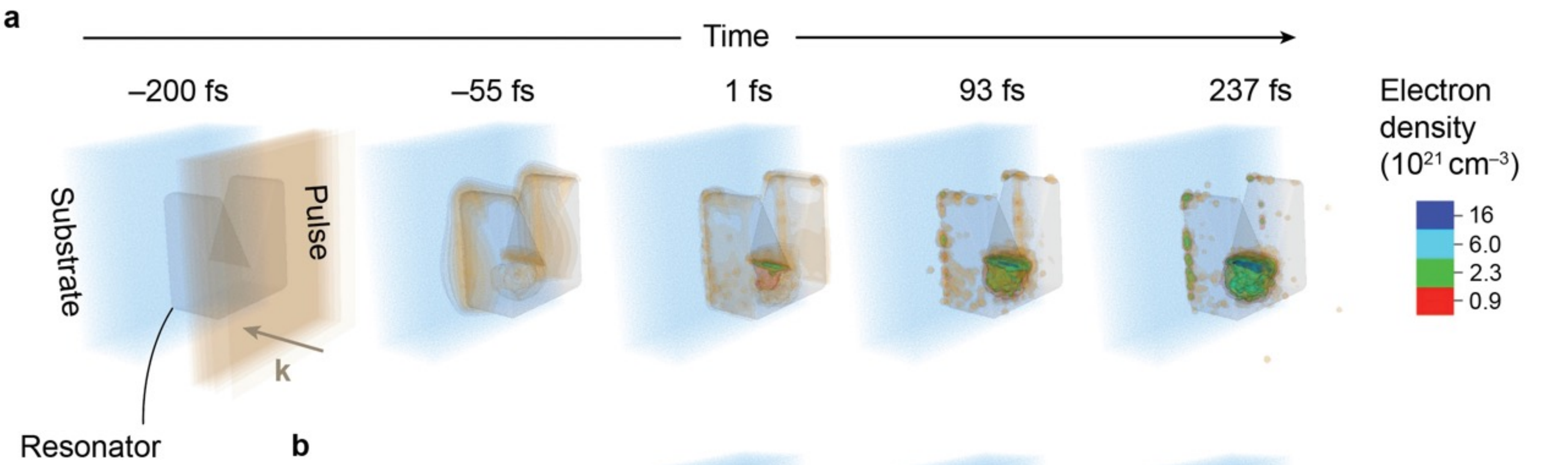
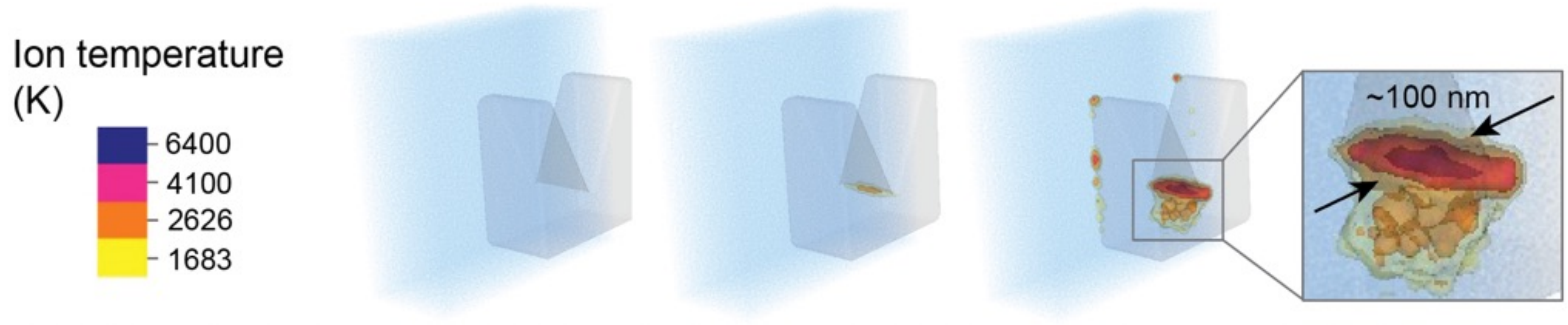
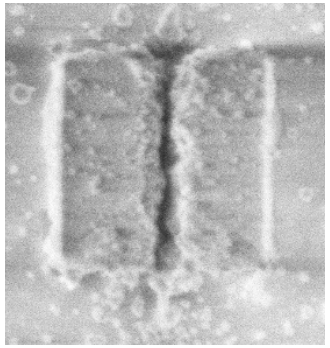
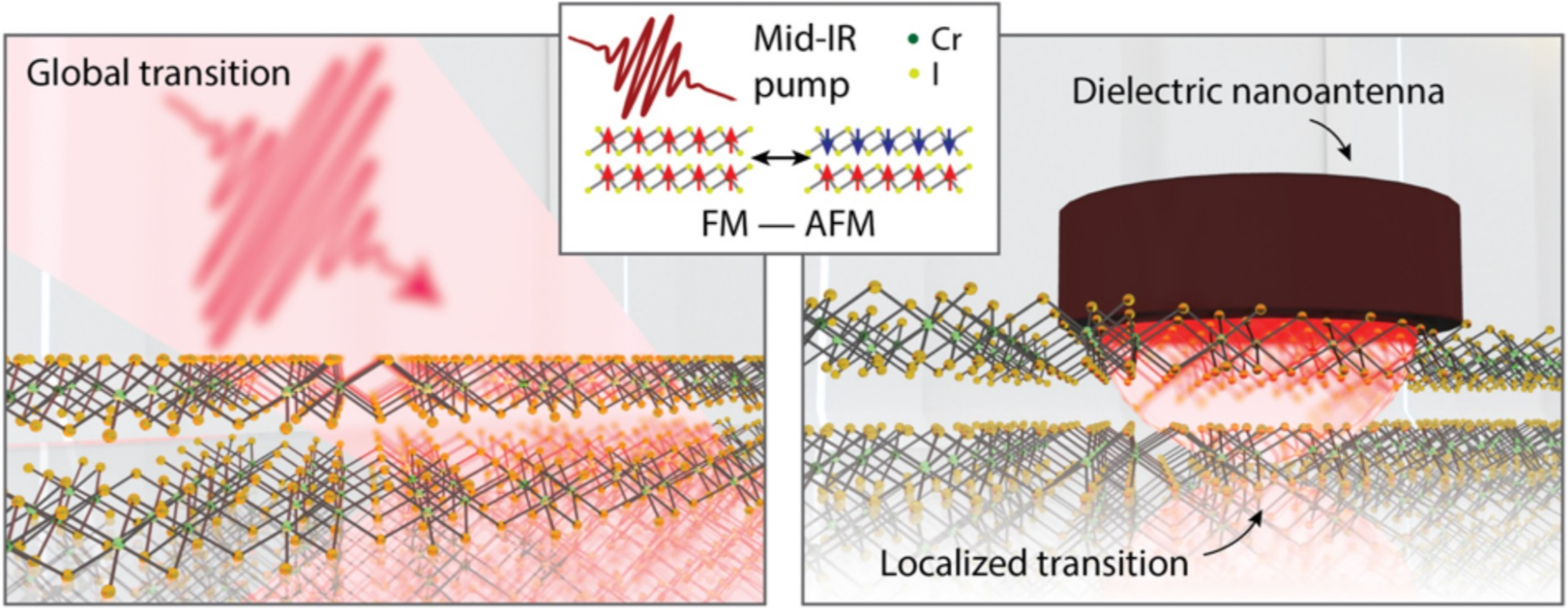






Trench parameters: Length ~1.5 µm, Width at bottom ~50 nm, Depth = 600 nm

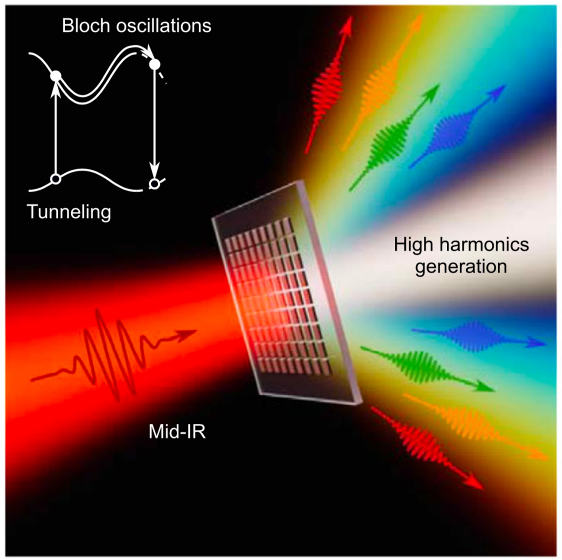
Strong fields + 2D materials

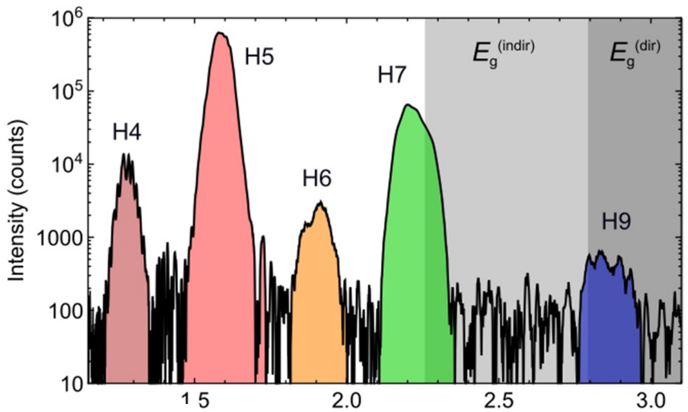


Great outlook to control elementary excitations in low-dimensional materials

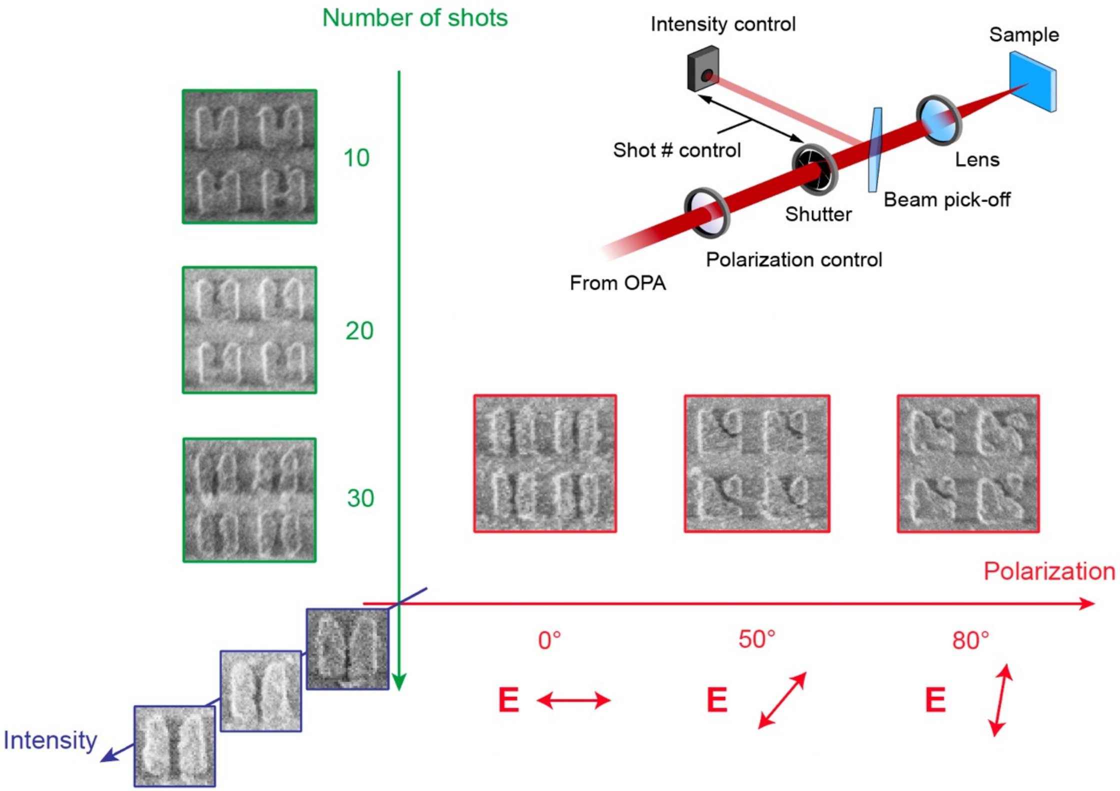
Outline

- Strong fields:
  high harmonics generation





- Very strong fields:
  laser damage and nanomachining



Nature Communications **12**, 4185 (2021)
APL Materials **9**, 060701 (2021)
Advanced Optical Materials **9**, 2100240 (2021)

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Cornell University

Agency for Science, Technology and Research SINGAPORE

CNF Cornell NanoScale Science and Technology Facility

Ohio State

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Vuckovic group (Stanford), Kuznetsov group (A*Star Singapore)