Photo Credit: I. Tsukerman, Seefeld, Austria, January, 2009

Nanoplasmonics and Spaser

Mark I. Stockman

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- **Introduction: Plasmonics and Nano-confinement of Optical Energy**
- **Nanoplasmonic Resonances and their Frequencies (Colors)**
- **Localized Surface Plasmons and Plasmonic Hot Spots**
- **Theory of Spaser: Spaser as an Ultrafast Quantum Generator and Nanoamplifier**
- **Experiments on Spasers**
- **New Theoretical Predictions Regarding Spasers**

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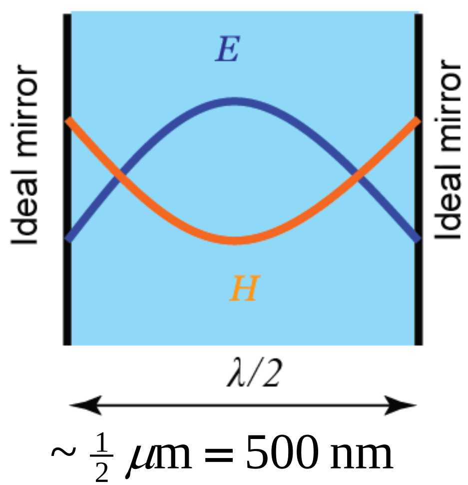
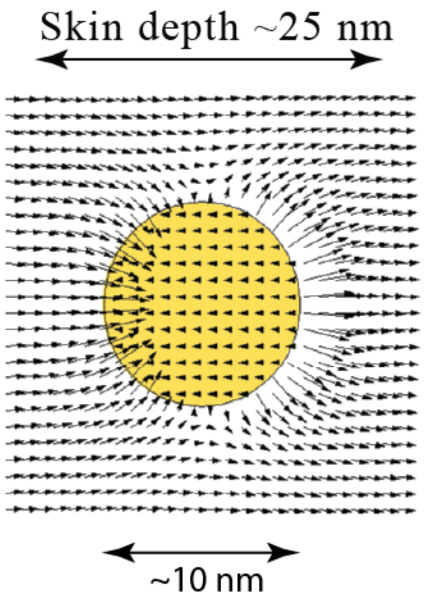
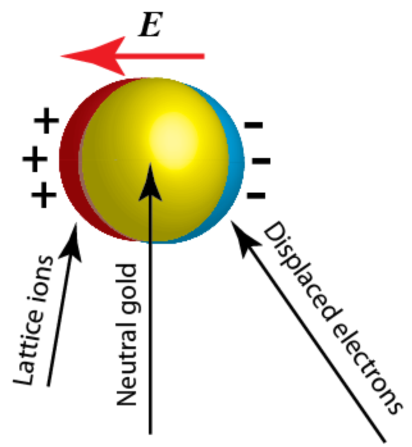
M. I. Stockman, *Nanoplasmonics: The Physics Behind the Applications*, Phys. Today **64**, 39-44 (2011).

Nanoplasmonics in a nano-nutshell

Concentration of optical energy on the nanoscale







Photon: Quantum of electromagnetic field

Surface Plasmon: Quantum of electromechanical oscillator

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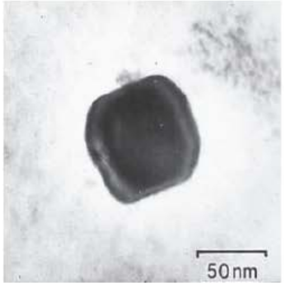
Lycurgus Cup (4th Century AD): Roman Nanotechnology

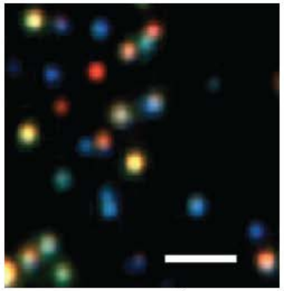


I. Freestone, N. Meeks, M. Sax, and C. Higgitt, *The Lycurgus Cup - a Roman Nanotechnology*, Gold Bull. **40**, 270-277 (2007

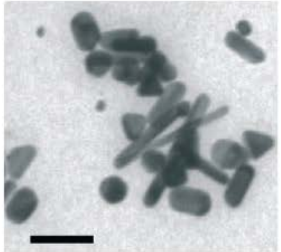
Nanoplasmonic colors are very bright. Scattering and absorption of light by them are very strong. This is due to the fact that all of the millions of electrons move in unison in plasmonic oscillations

Nanoplasmonic colors are also eternal: metal nanoparticles are stable in glass: they do not bleach and do not blink. Gold is stable under biological conditions and is not toxic *in vivo*

Colors of Silver Nanocrystals and Gold Nanoshapes

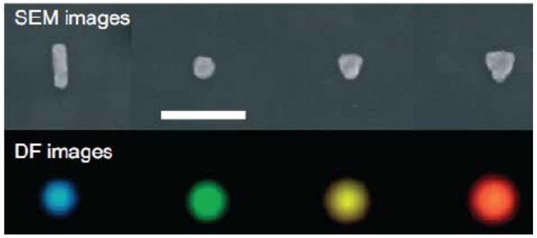


2 µm



100 nm

C. Orendorff, T. Sau, and C. Murphy, *Shape-Dependent* …, Small **2**, 636-639 (2006)

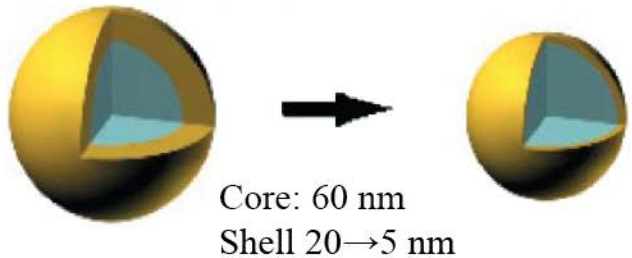


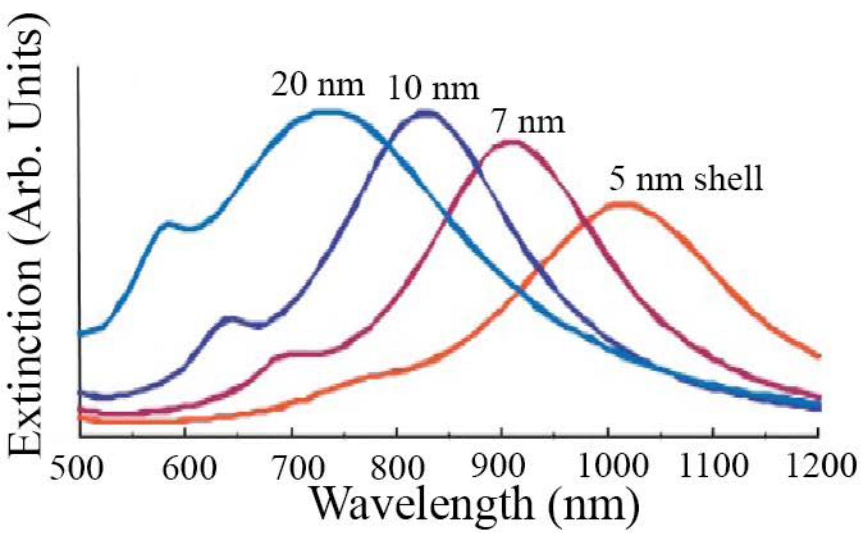
Scanning electron microscopy

Dark field optical microscopy

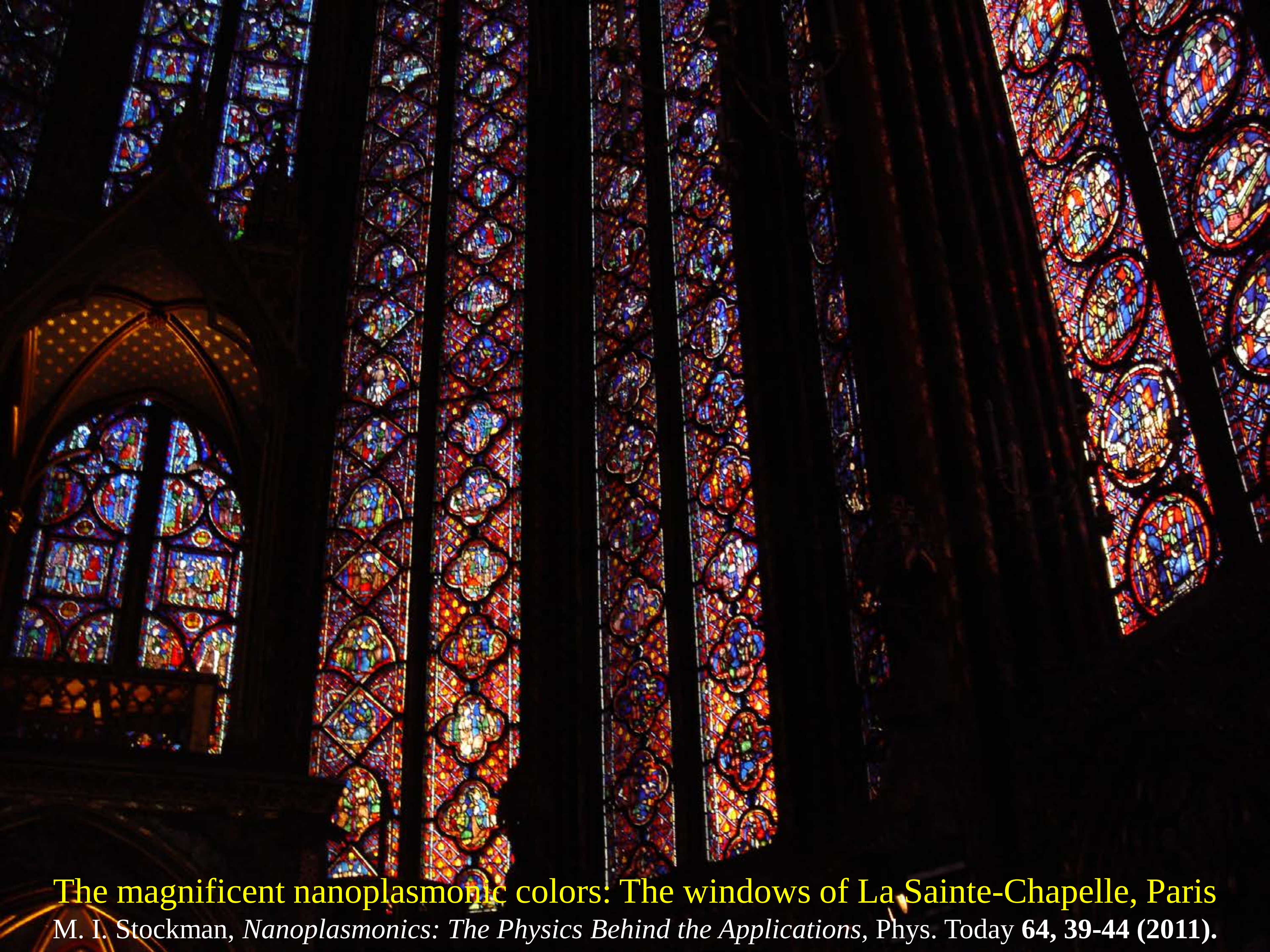
W. A. Murray and W. L. Barnes, *Plasmonic Materials*, Adv. Mater. **19**, 3771-3782 (2007) [Scale bar: 300 nm]

When shell becomes progressively thinner comparing to the core, the spectrum of the nanoshell shifts to the red and then to the near-infrared where biological tissues do not absorb





J. L. West and N. J. Halas, *Engineered Nanomaterials for Biophotonics Applications: Improving Sensing, Imaging, and Therapeutics*, Annu. Rev. Biomed. Eng. **5**, 285-292 (2003).



The magnificent nanoplasmonic colors: The windows of La Sainte-Chapelle, Paris

M. I. Stockman, *Nanoplasmonics: The Physics Behind the Applications*, Phys. Today **64, 39-44 (2011).**

Enhancement factors for small nanoparticles (size $R < l_s$~25 nm)

Plasmonic quality factor: $Q = \frac{\omega}{2\gamma} \approx \frac{-\operatorname{Re}\varepsilon_m}{\operatorname{Im}\varepsilon_m} \sim 10-100$

Radiative rate enhancement for dipole mode frequency: $\sim Q^2$

Excitation rate enhancement : $\sim Q^2$

SERS enhancement: $\sim Q^4$

The above-listed enhancement factors do not depend on size *R*

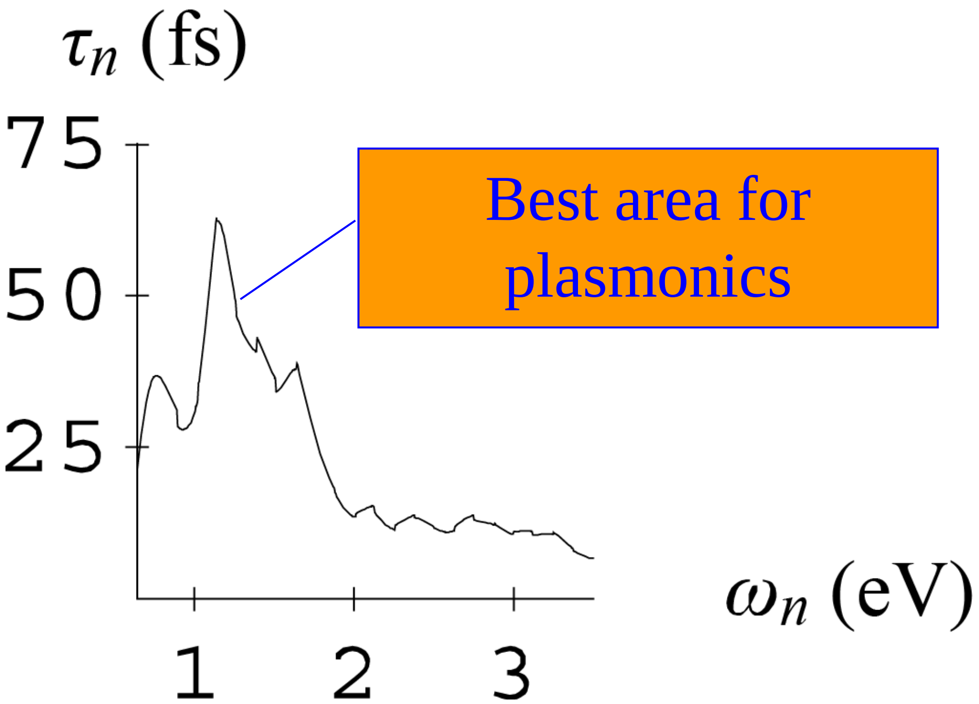
Emission rate of SPs into a mode: $\propto \frac{Q}{R^3}$

This with respect to free photons: $\sim \frac{\lambda^3 Q}{R^3}$ (Purcell factor)

This enhancement factor is *inversely* proportional to R^3

This is of fundamental importance for spasers (plasmonic nanolasers)

Nanoplasmonics is intrinsically ultrafast:



Spectrally, surface plasmon resonances in complex systems occupy a very wide frequency band; for gold and silver:

$$\Delta\omega \approx \omega_p / \sqrt{2} \approx 4\,\text{eV}$$

Including aluminum with plasmon responses in the ultraviolet, this spectral width increases to ~10 eV.

Corresponding rise time of plasmonic responses ~ 100 as

Surface plasmon relaxation times are in ~10-100 fs range

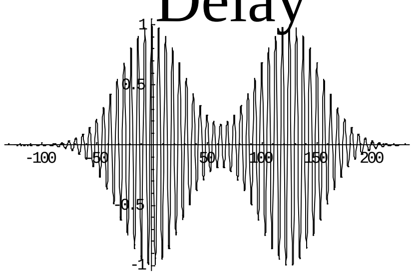
Localized SP hot spots and SPPs coexist in space and time on nanostructured surfaces

A. Kubo, K. Onda, H. Petek, Z. Sun, Y. S. Jung, and H. K. Kim, *Femtosecond Imaging of Surface Plasmon Dynamics in a Nanostructured Silver Film*, Nano Lett. 5, 1123 (2005).

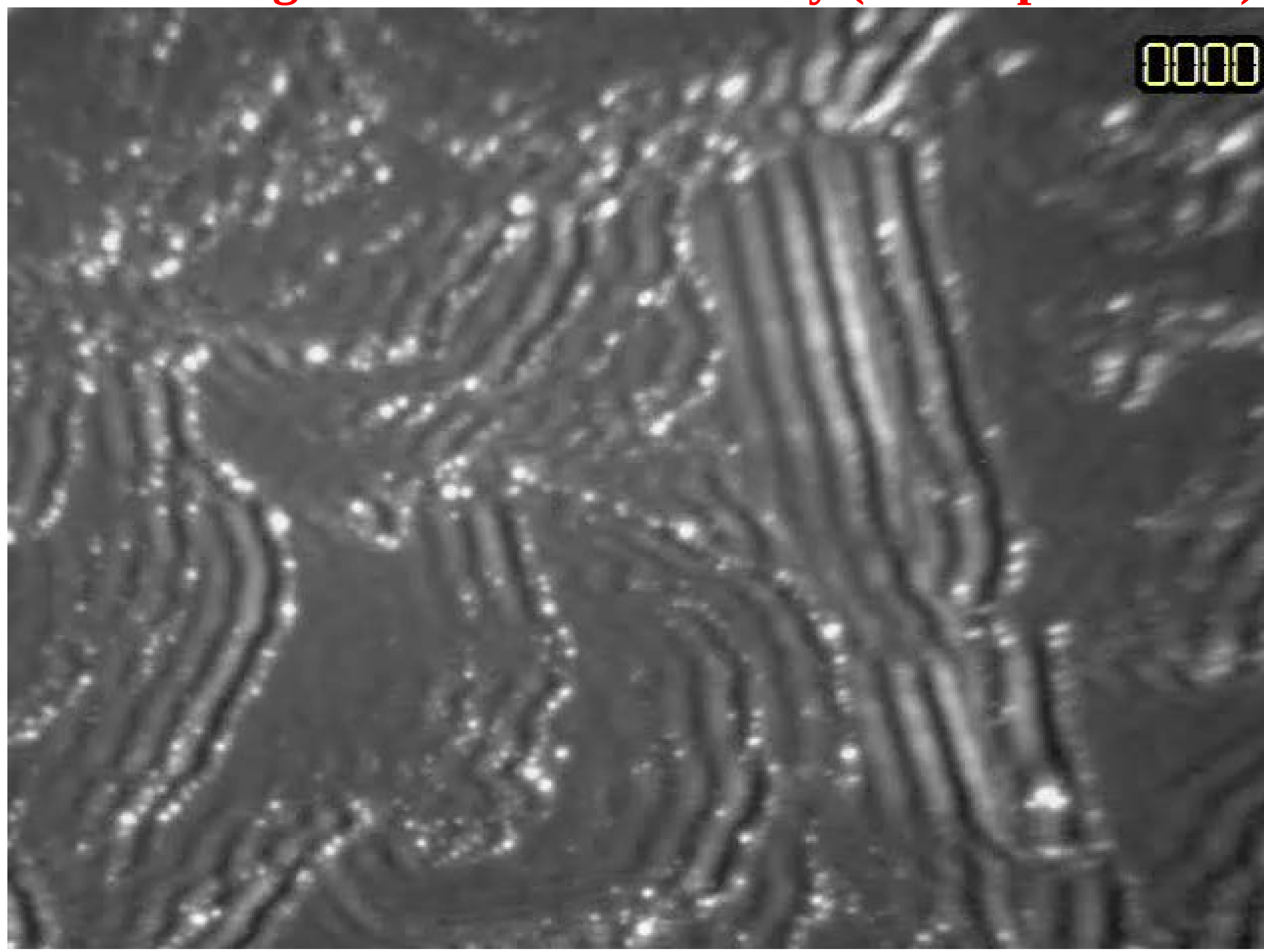
200 nm

30 femtoseconds from life of a nanoplasmonic systems

Localized SP hot spots are deeply subwavelength as seen in PEEM (photoemission electron microscope)



PEEM Image as a Function of Delay (250 as per frame)



Spasers explained

nature photonics | VOL 2 | JUNE 2008 |

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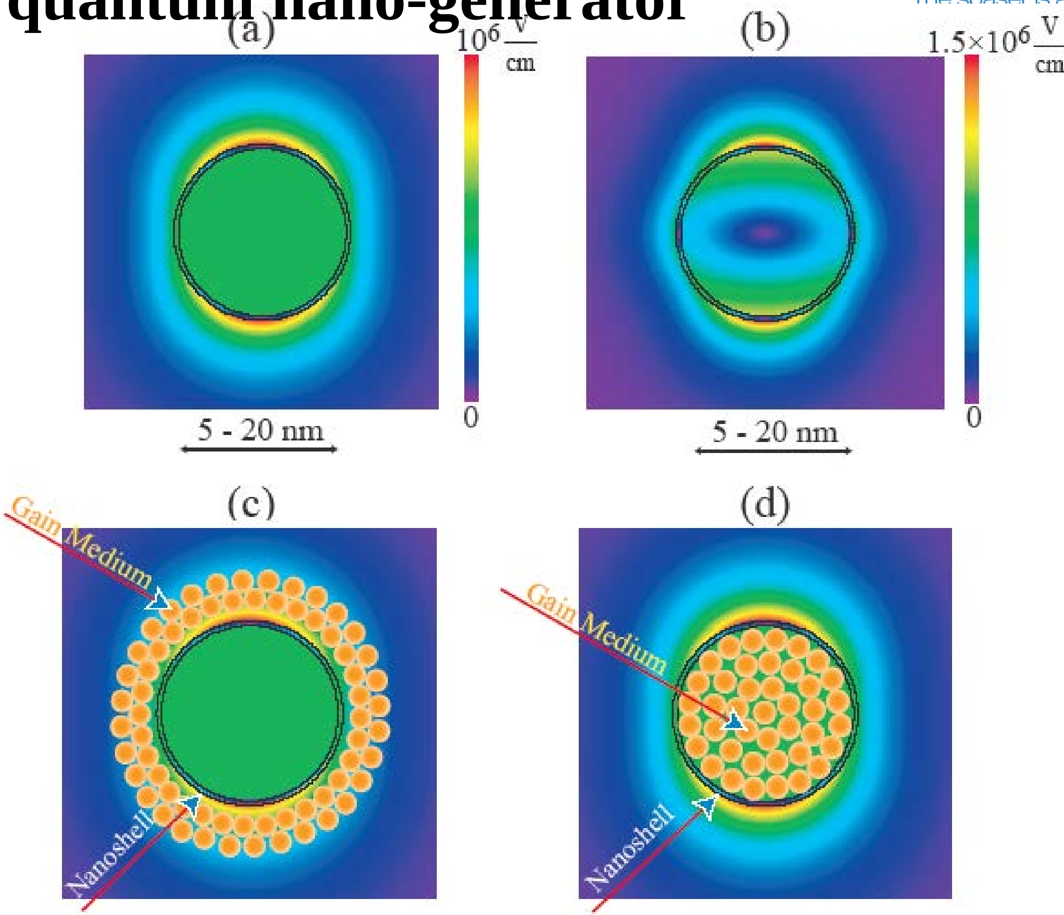
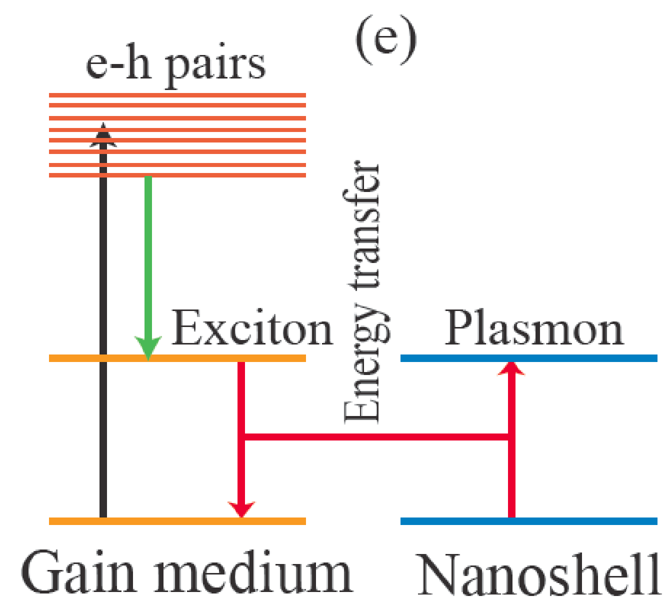
The spaser is a propos

Spaser is the ultimately smallest quantum nano-generator

For small nanoparticles, radiative loss is negligible.

Spaser is fully scalable





D. J. Bergman and M. I. Stockman, *Surface Plasmon Amplification by Stimulated Emission of Radiation: Quantum Generation of Coherent Surface Plasmons in Nanosystems*, Phys. Rev. Lett. **90**, 027402-1-4 (2003).

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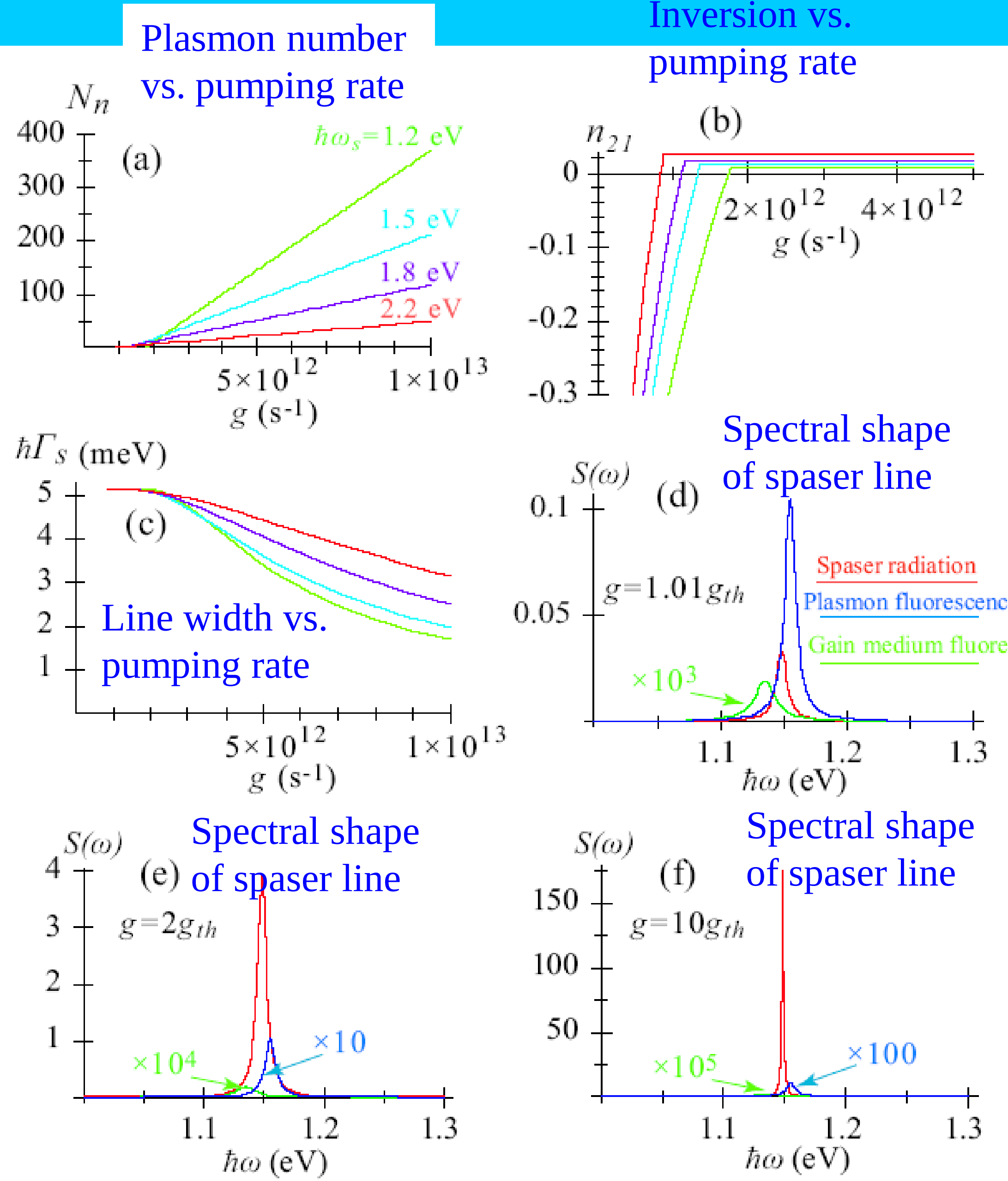
Stationary (CW) spaser regime

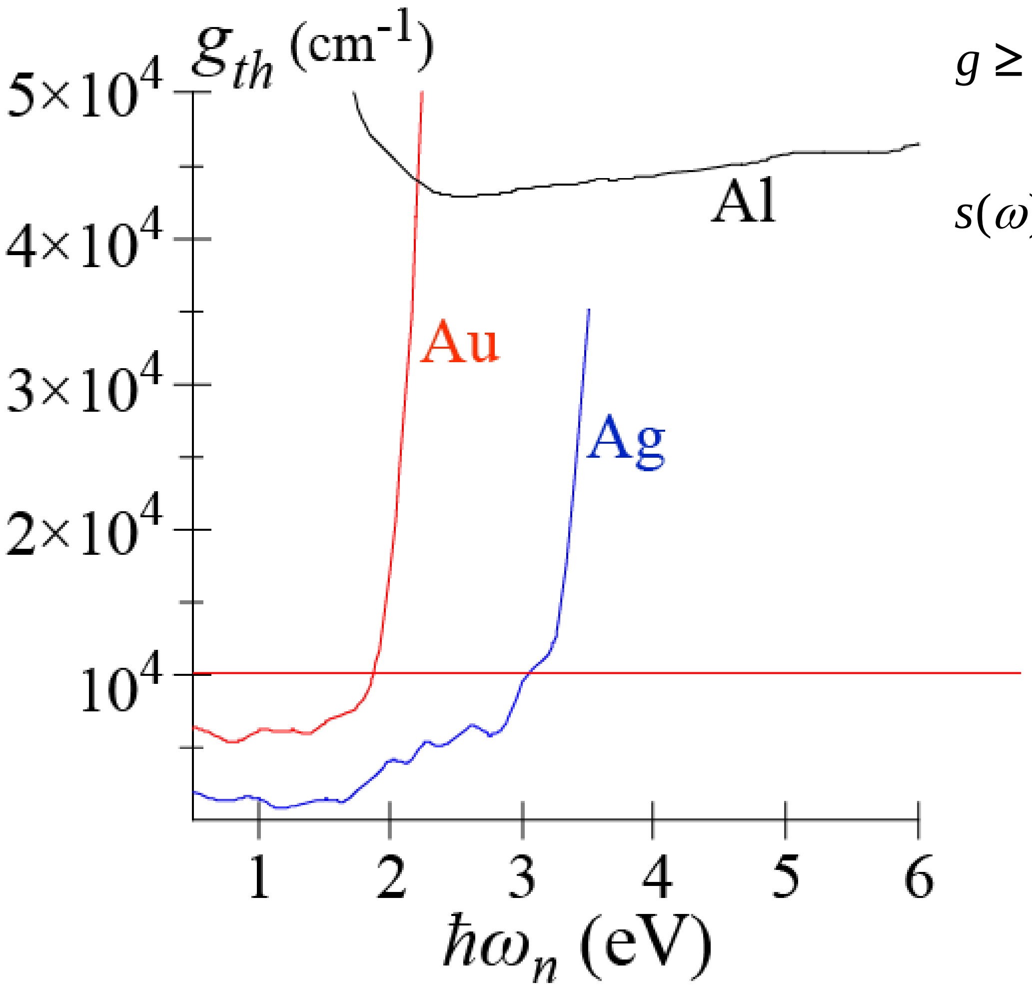
This quasilinear dependence of the number of plasmons per mode $N_n(g)$ is a result of the very strong feedback in spaser due to the small modal volume

$$\Gamma_s \propto g^{-1}$$



arXiv:0908.3559
Journal of Optics, **12**, 024004-1-13 (2010).

Gain of bulk medium required for spasing and for loss compensation by gain: M. I. Stockman, *Spaser Action, Loss Compensation, and Stability in Plasmonic Systems with Gain*, Phys. Rev. Lett. **106**, 156802-1-4 (2011); Phil. Trans. R. Soc. A **369**, 3510 (2011).



$$g \geq g_{th}, \quad g_{th} = \frac{\omega}{c\sqrt{\varepsilon_d}} \frac{\operatorname{Re} s(\omega) \operatorname{Im} \varepsilon_m(\omega)}{1 - \operatorname{Re} s(\omega)}$$

$$s(\omega) = \frac{\varepsilon_d}{\varepsilon_d - \varepsilon_m(\omega)}; \quad 1 > \operatorname{Re} s(\omega) > 0$$

Realistic gain for direct band-gap semiconductors

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Scaling of Spaser

Local optical field: $E \sim \frac{\sqrt{\hbar\omega}}{R^{3/2}}\sqrt{N_p} \sim \left(\frac{R}{10\ \text{nm}}\right)^{-3/2}\sqrt{N_p}\ \frac{\text{MV}}{\text{cm}}$

Heat per flop: $H = \hbar\omega\, N_p$

Threshold: $g \geq g_{th},\ g_{th} = \frac{\omega}{c\sqrt{\varepsilon_d}}\frac{\operatorname{Re} s(\omega)\operatorname{Im}\varepsilon_m(\omega)}{1-\operatorname{Re} s(\omega)},\quad s(\omega) = \frac{\varepsilon_d}{\varepsilon_d - \varepsilon_m(\omega)}$

Switching time: $\tau \sim \frac{1}{\omega_R} \sim \left(\frac{R}{10\ \text{nm}}\right)^{3/2}\frac{100}{\sqrt{N_p}}\ \text{fs}$

Number of quanta for pumping intensity I: $N_p \sim \frac{\rho}{10^{19}\ \text{cm}^{-3}}\frac{\sigma_a}{10^{-16}\ \text{cm}^2}\left(\frac{R}{10\ \text{nm}}\right)^3\frac{I}{1\ \frac{\text{GW}}{\text{cm}^2}}\frac{1\ \text{eV}}{\hbar\omega}\frac{\tau_p}{20\ \text{fs}}$

Conclusion: Spaser is orders of magnitude more efficient (less heat per flop) and much faster than transistor. It can operate close to the quantum limit ($\omega_R \sim \omega$).

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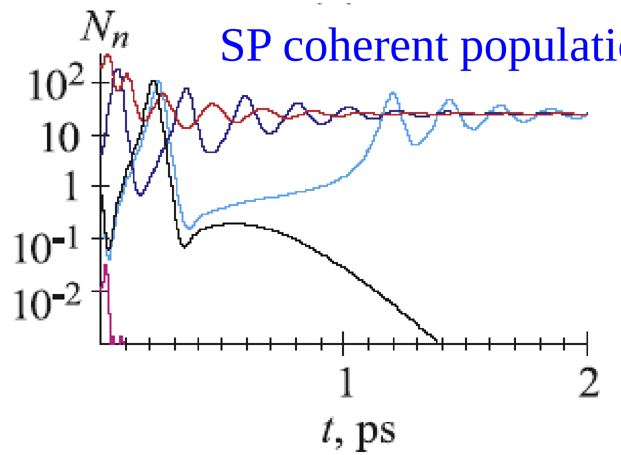
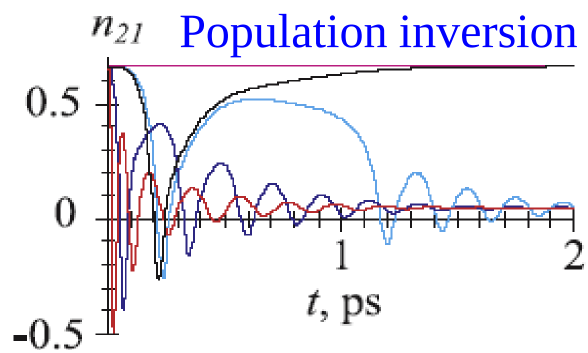
Bandwidth ~ 10-100 THz
Very high resistance to ionizing radiation

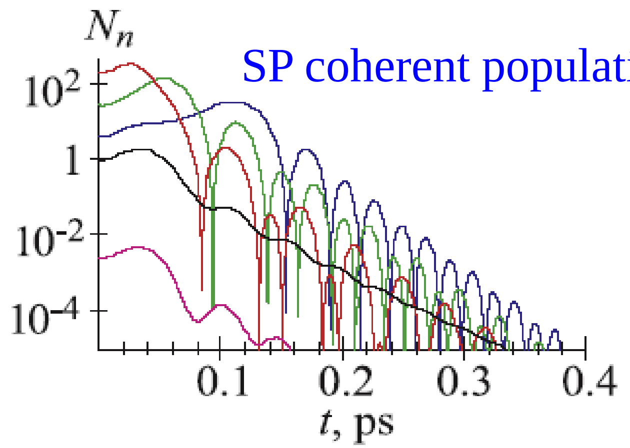
Amplification in Spaser with a Saturable Absorber (1/3 of the gain chromophores)

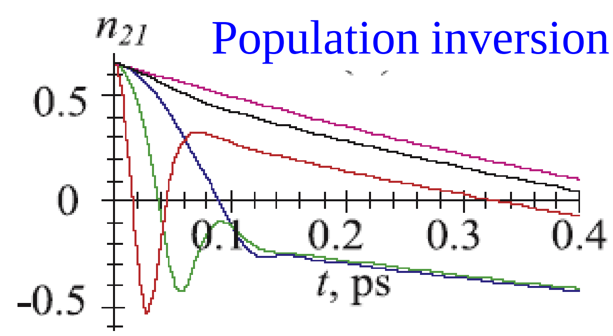
Stationary pumping





Pulse pumping





Experimental Observations of Spaser

doi:10.1038/nature08318 nature

LETTERS

Demonstration of a spaser-based nanolaser

M. A. Noginov[1], G. Zhu[1], A. M. Belgrave[1], R. Bakker[2], V. M. Shalaev[2], E. E. Narimanov[2], S. Stout[1,3], E. Herz[3], T. Suteewong[3] & U. Wiesner[3]

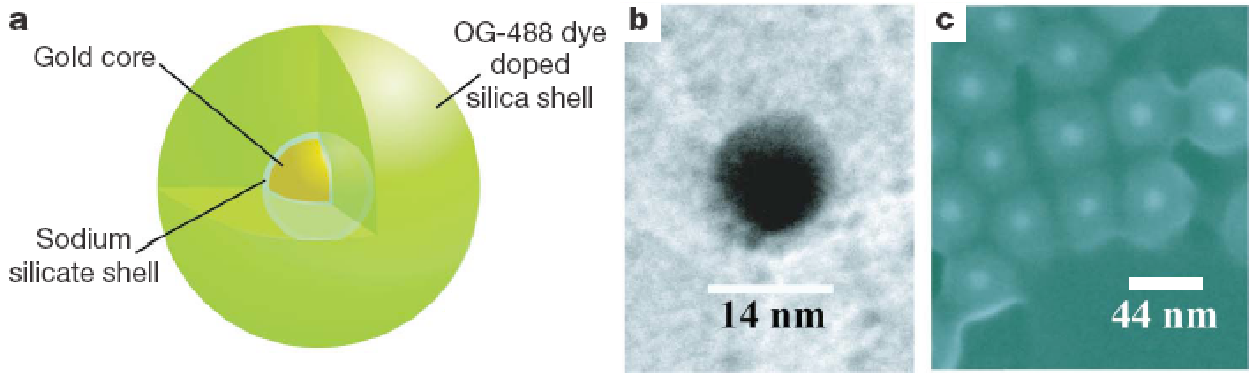


Figure 1 | Spaser design. a, Diagram of the hybrid nanoparticle architecture (not to scale), indicating dye molecules throughout the silica shell. **b**, Transmission electron microscope image of Au core. **c**, Scanning electron microscope image of Au/silica/dye core–shell nanoparticles. **d**, Spaser mode (in false colour), with $\lambda = 5$ circles represent the 14-nm strength colour scheme is sh

[1]Center for Materials Research, Norfolk State University, Norfolk, Virginia 23504, USA. [2]School of Electrical & Computer Eng University, West Lafayette, Indiana 47907, USA. [3]Materials Science and Engineering Department, Cornell University, Ithaca

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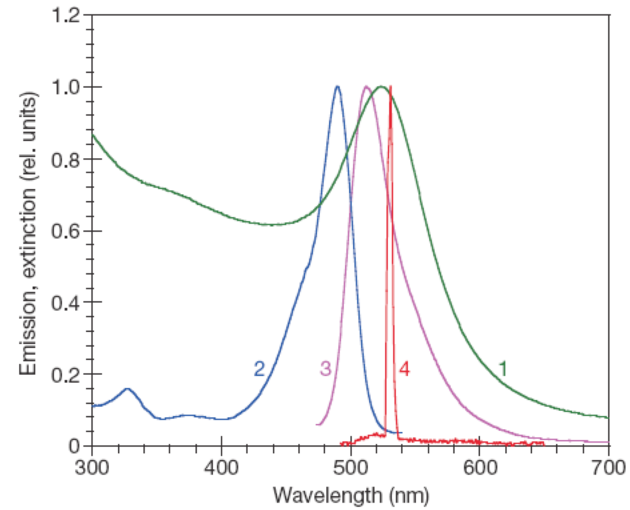

Figure 2 | Spectroscopic results. Normalized extinction (1), excitation (2), spontaneous emission (3), and stimulated emission (4) spectra of Au/silica/dye nanoparticles. The peak extinction cross-section of the nanoparticles is 1.1×10^{-12} cm^2. The emission and excitation spectra were measured in a spectrofluorometer at low fluence.

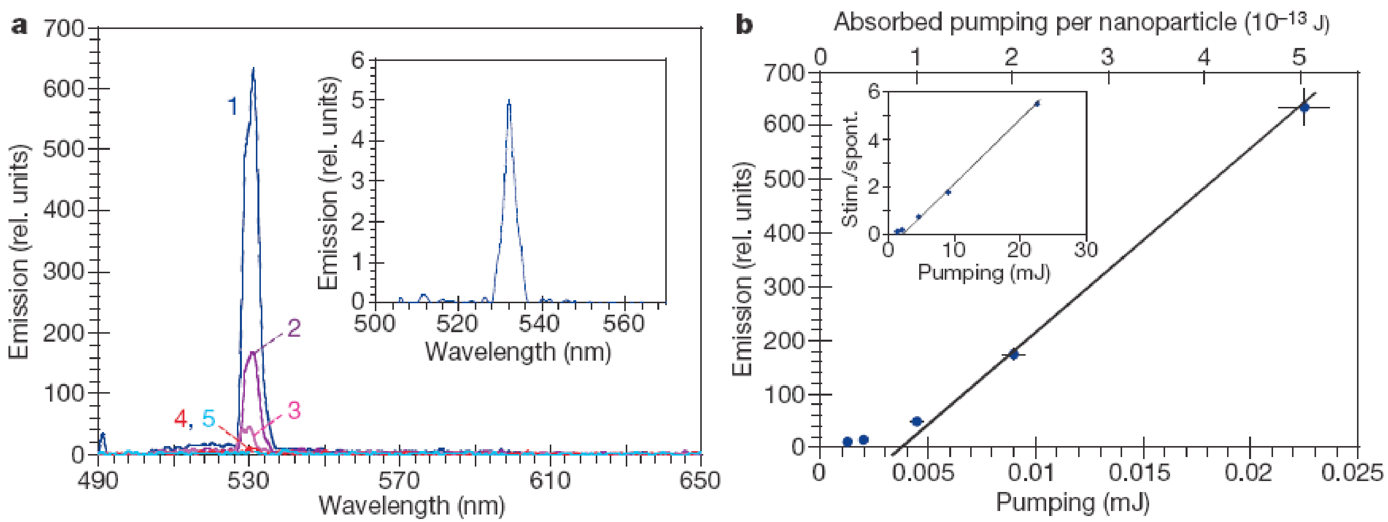

Figure 4 | Stimulated emission. a, Main panel, stimulated emission spectra of the nanoparticle sample pumped with 22.5 mJ (1), 9 mJ (2), 4.5 mJ (3), 2 mJ (4) and 1.25 mJ (5) 5-ns optical parametric oscillator pulses at $\lambda = 488$ nm. **b**, Main panel, corresponding input–output curve (lower axis, total launched pumping energy; upper axis, absorbed pumping energy per

by the noise of the photodetector and the instability of the pumping laser) do not exceed the size of the symbol. Inset of **a**, stimulated emission spectrum at more than 100-fold dilution of the sample. Inset of **b**, the ratio of the stimulated emission intensity (integrated between 526 nm and 537 nm) to the spontaneous emission background (integrated at <526 nm and

Lasing in metal-insulator-metal sub-wavelength plasmonic waveguides

Martin T. Hill[1*], Milan Marell[1], Eunice S. P. Leong[2], Barry Smalbrugge[1], Youcai Zhu[1], Minghua Sun[2], Peter J. van Veldhoven[1], Erik Jan Geluk[1], Fouad Karouta[1], Yok-Siang Oei[1], Richard Nötzel[1], Cun-Zheng Ning[2], and Meint K. Smit[1]

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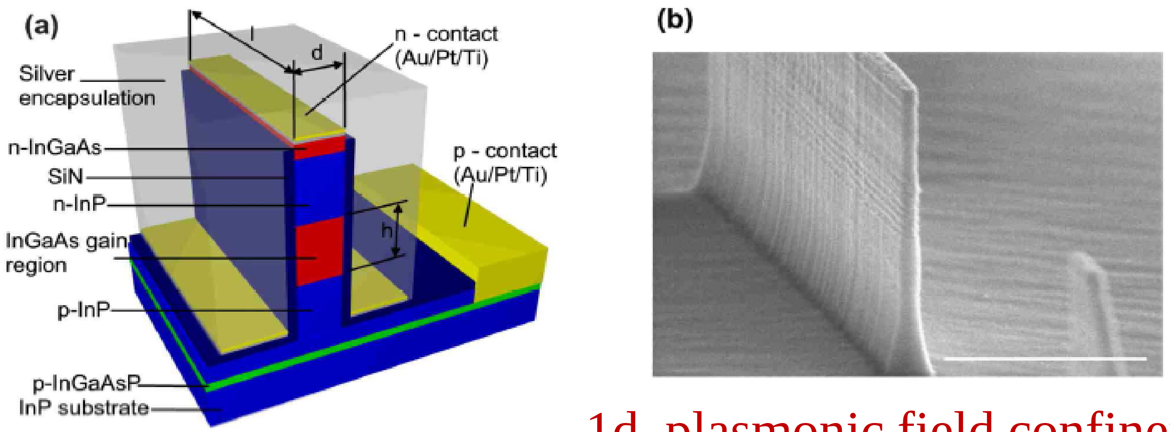


1d plasmonic field confinement

Fig. 1. Structure of cavity formed by a rectangular semiconductor pillar encapsulated in Silver. (a) Schematic showing the device layer structure. (b) Scanning electron microscope image showing the semiconductor core of one of the devices. The scale bar is 1 micron.

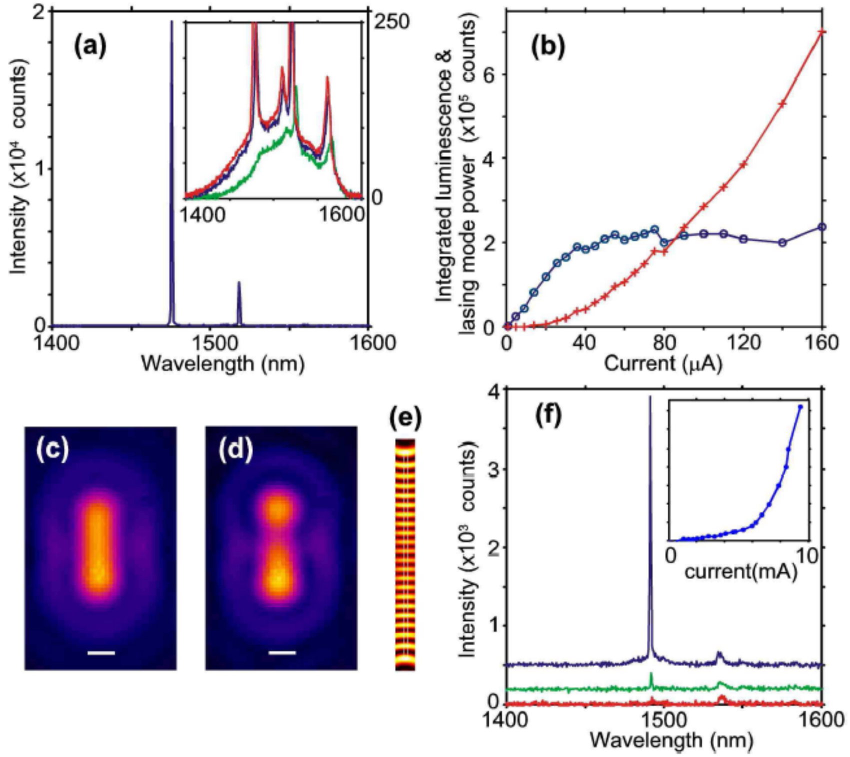


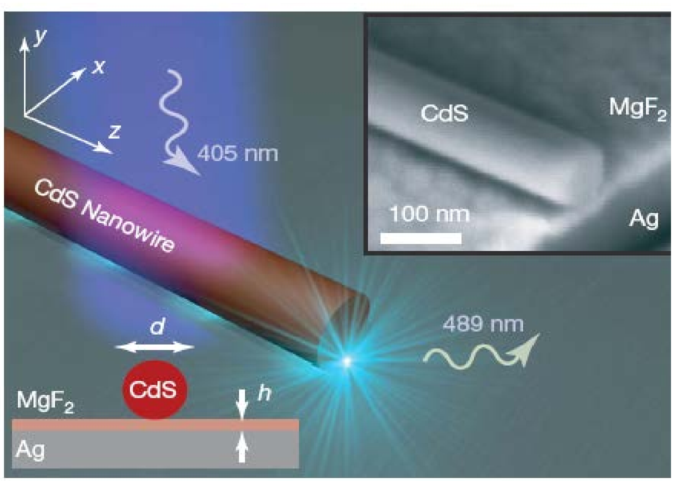
Fig. 2. Spectra and near field patterns showing lasing in devices. (a) Above threshold emission spectrum for 3 micron long device with semiconductor core width d~130nm (± 20nm), with pump current 180 μA at 78K. Inset: emission spectra for 20 (green), 40 (blue) and 60 (red) μA, all at 78K. (b) Lasing mode light output (red crosses), integrated luminescence (blue circles), versus pump current for 78K. (c) Actual near field pattern (in x-y plane) for 6 micron (d = 130nm) device captured with 100x, 0.7 NA long working distance microscope objective and infrared camera, the scale bar is 2 micron, for below threshold 30 μA, and (d) above threshold 320 μA. (e) Simulated vertical (z) component of the Poynting vector taken at 0.7 microns below the pillar base, shows most emitted light at ends of device. (f) Spectra for a 6 micron long device with d~310nm at 298K, pulsed operation (28 ns wide pulses, 1MHz repetition). Spectra for peak currents of 5.2mA (red), 5.9mA (green) and 7.4mA (blue), (currents were estimated from the applied voltage pulse amplitude). The spectra for 5.9 and 7.4 mA are offset from 0 for clarity. Inset shows the total light collected by the spectrometer from the device for currents ranging from 0 to 10mA.

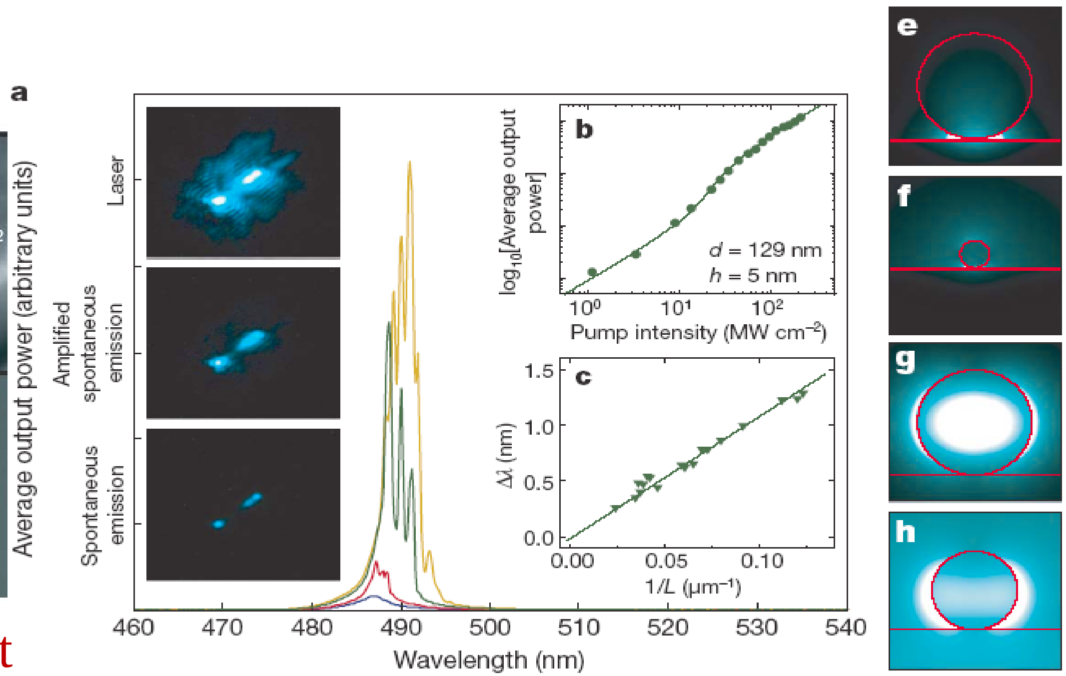
doi:10.1038/nature08364 nature

LETTERS

Plasmon lasers at deep subwavelength scale

Rupert F. Oulton[1]*, Volker J. Sorger[1]*, Thomas Zentgraf[1]*, Ren-Min Ma[3], Christopher Gladden[1], Lun Dai[3], Guy Bartal[1] & Xiang Zhang[1,2]





2d plasmonic field confinement

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Geor
Atlan

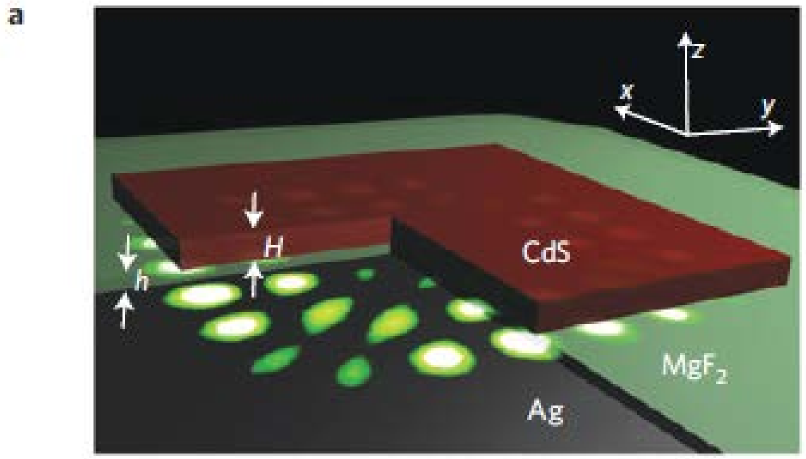
nature materials

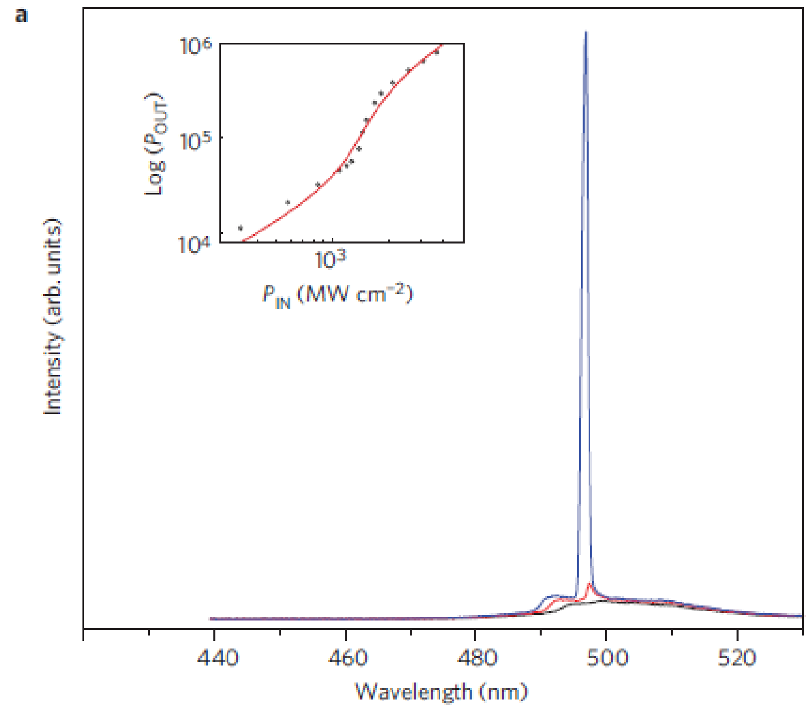
LETTERS

PUBLISHED ONLINE: 19 DECEMBER 2010 | DOI: 10.1038/NMAT2919

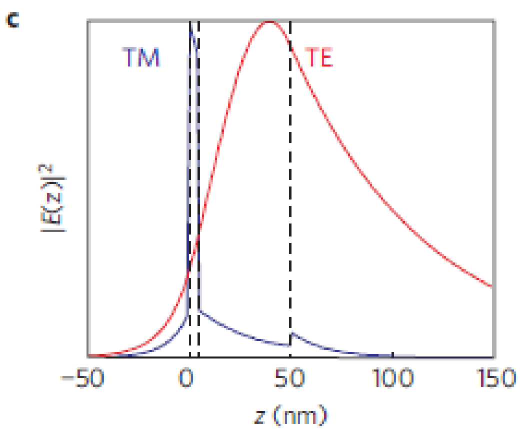
Room-temperature sub-diffraction-limited plasmon laser by total internal reflection

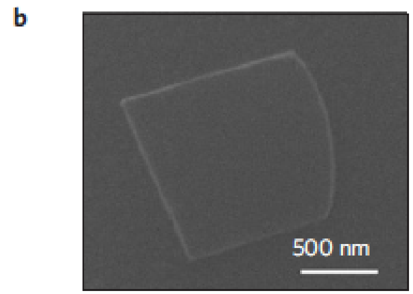
Ren-Min Ma[1†], Rupert F. Oulton[1†], Volker J. Sorger[1], Guy Bartal[1] and Xiang Zhang[1,2★]

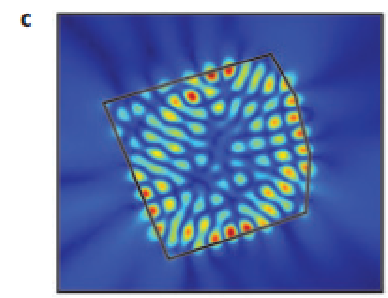




1d +2d plasmonic field confinement



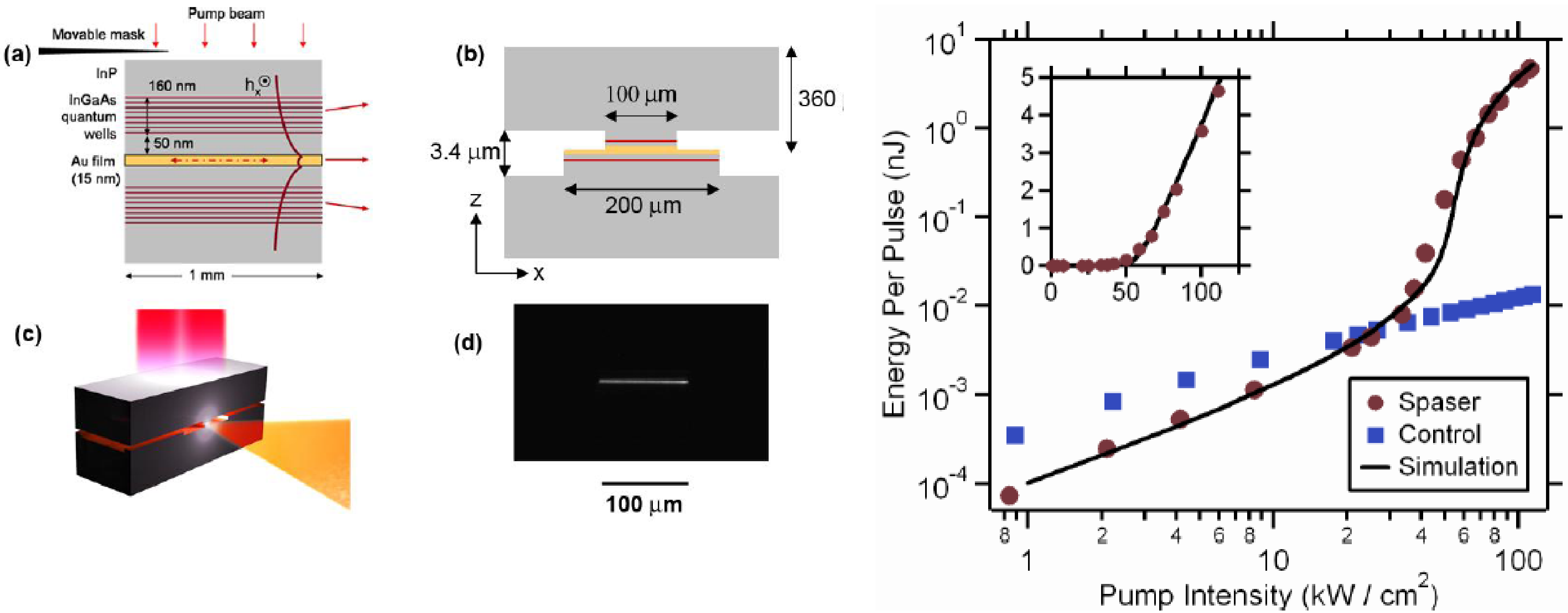




A room-temperature semiconductor spaser operating near 1.5 μm

R. A. Flynn,[1] C. S. Kim,[1] I. Vurgaftman,[1] M. Kim,[1] J. R. Meyer,[1] A. J. Mäkinen,[1] K. Bussmann,[2] L. Cheng,[3] F.-S. Choa,[3] and J. P. Long[4,*]

25 April 2011 / Vol. 19, No. 9 / OPTICS EXPRESS 8954

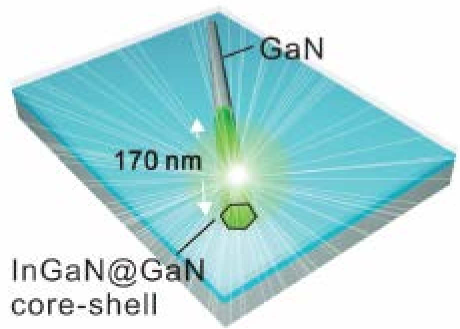


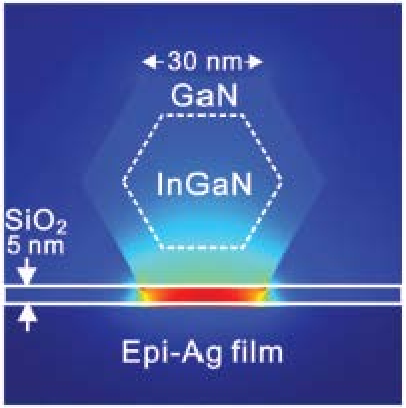
Plasmonic Nanolaser Using Epitaxially Grown Silver Film

Yu-Jung Lu,[1*] Jisun Kim,[2*] Hung-Ying Chen,[1] Chihhui Wu,[2] Nima Dabidian,[2] Charlotte E. Sanders,[2] Chun-Yuan Wang,[1] Ming-Yen Lu,[3] Bo-Hong Li,[4] Xianggang Qiu,[4] Wen-Hao Chang,[5] Lih-Juann Chen,[3] Gennady Shvets,[2] Chih-Kang Shih,[2]† Shangjr Gwo[1]†

Science AAAS

Having developed epitaxially grown, atomically smooth Ag films as a scalable plasmonic platform, we report a SPASER under CW operation with an ultralow lasing threshold at liquid nitrogen temperature and a mode volume well below the 3D diffraction limit. The device has





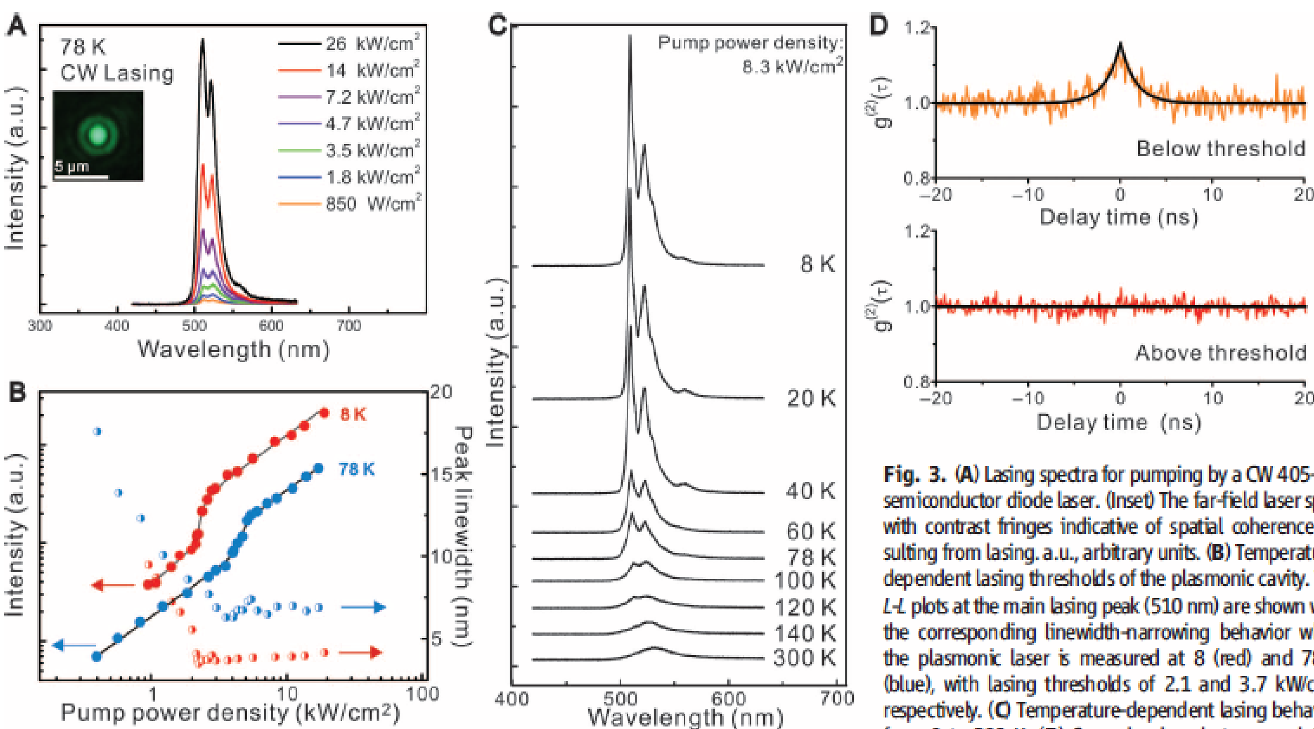


Fig. 3. (**A**) Lasing spectra for pumping by a CW 405-nm semiconductor diode laser. (Inset) The far-field laser spot, with contrast fringes indicative of spatial coherence resulting from lasing. a.u., arbitrary units. (**B**) Temperature-dependent lasing thresholds of the plasmonic cavity. The *L-L* plots at the main lasing peak (510 nm) are shown with the corresponding linewidth-narrowing behavior when the plasmonic laser is measured at 8 (red) and 78 K (blue), with lasing thresholds of 2.1 and 3.7 kW/cm^2, respectively. (**C**) Temperature-dependent lasing behavior from 8 to 300 K. (**D**) Second-order photon correlation function measurements at 8 K.

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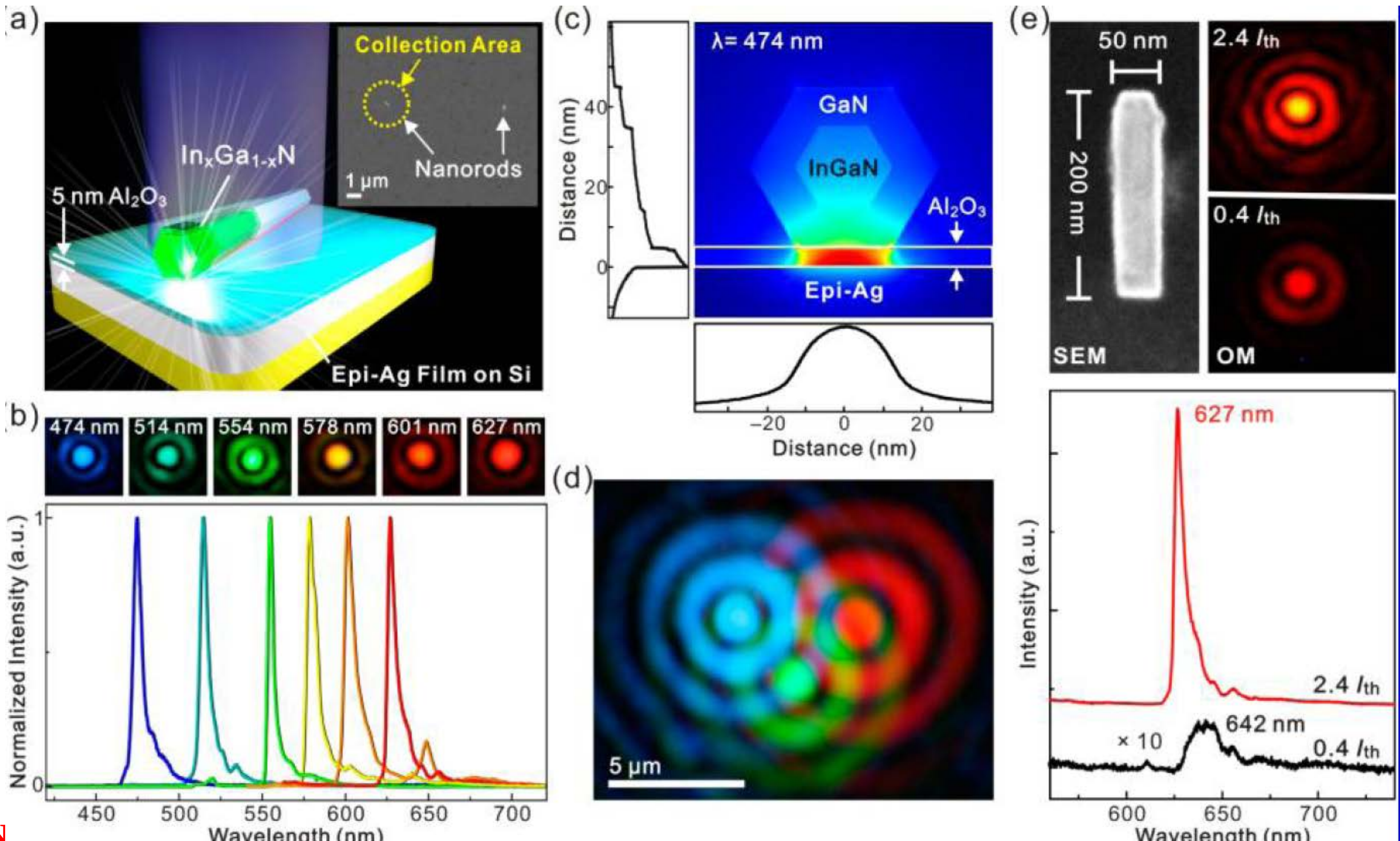
NANO LETTERS
Letter
pubs.acs.org/NanoLett
dx.doi.org/10.1021/nl501273u
Y.-J. Lu *et al.*, Nano Lett. **14**, 4381 (2014)

All-Color Plasmonic Nanolasers with Ultralow Thresholds: Autotuning Mechanism for Single-Mode Lasing

Yu-Jung Lu,[†] Chun-Yuan Wang,[†] Jisun Kim,[‡] Hung-Ying Chen,[†] Ming-Yen Lu,[∥] Yen-Chun Chen,[⊥] Wen-Hao Chang,[⊥] Lih-Juann Chen,[∥] Mark I. Stockman,[§,#,¶] Chih-Kang Shih,[*,‡] and Shangjr Gwo[*,†]



IOP PUBLISHING JOURNAL OF OPTICS
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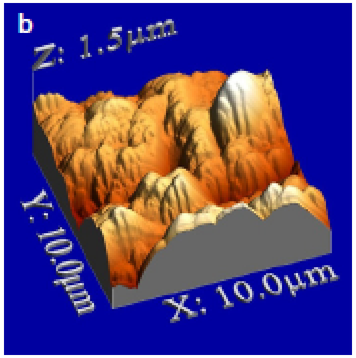
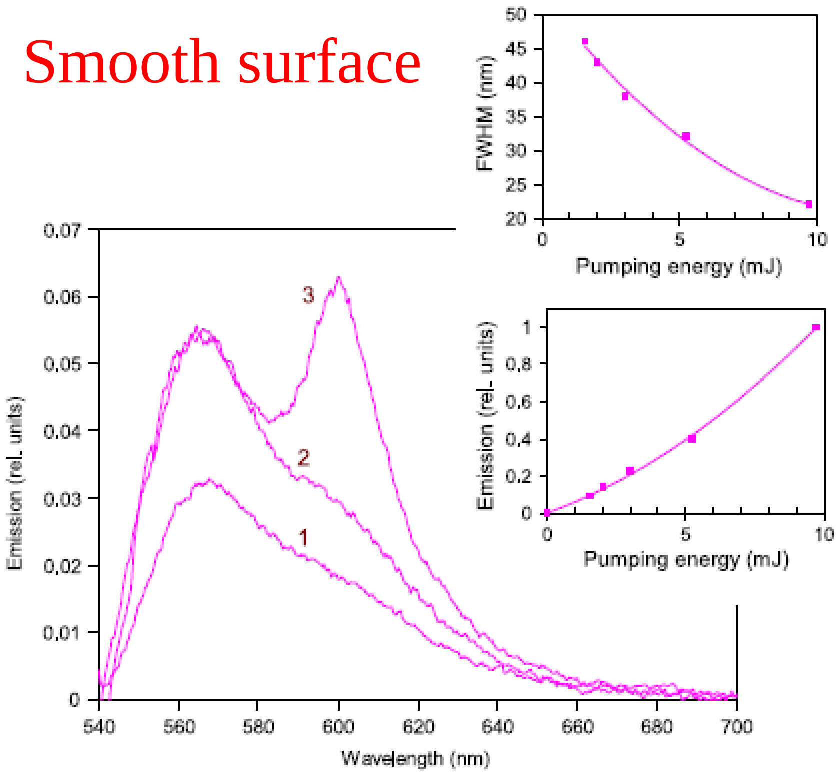
Stimulated emission of surface plasmon polaritons on smooth and corrugated silver surfaces

J K Kitur, G Zhu, Yu A Barnakov and M A Noginov



Random Spaser

Smooth surface



Rough surface

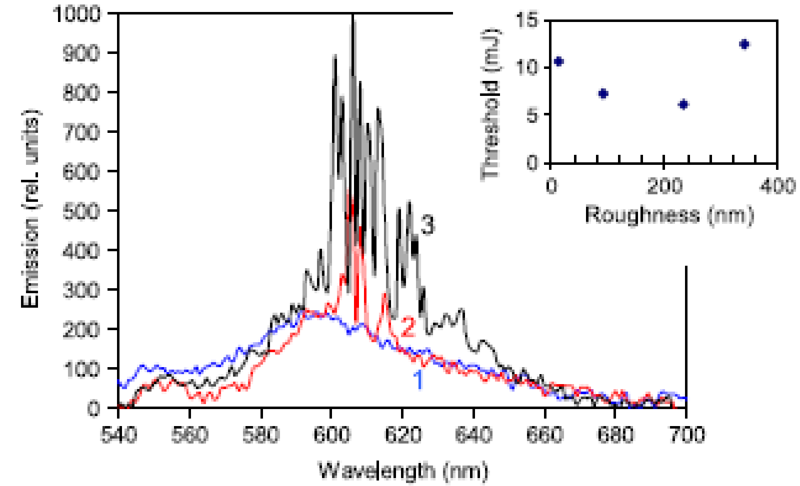


Figure 5. Emission spectra in the RB:PMMA film deposited on a roughened silver with surface roughness equal to 234 nm, pumped with 7 mJ (1), 13 mJ (2) and 20 mJ (3) laser pulses. Inset: stimulated emission threshold as a function of the surface roughness.

Surface plasmon lasing observed in metal hole arrays

Phys. Rev. Lett. **110**, 206802-1-5 (2013)

Frerik van Beijnum,[1] Peter J. van Veldhoven,[2] Erik Jan Geluk,[2] Michiel J.A. de Dood,[1] Gert W. 't Hooft,[1,3] and Martin P. van Exter[1]

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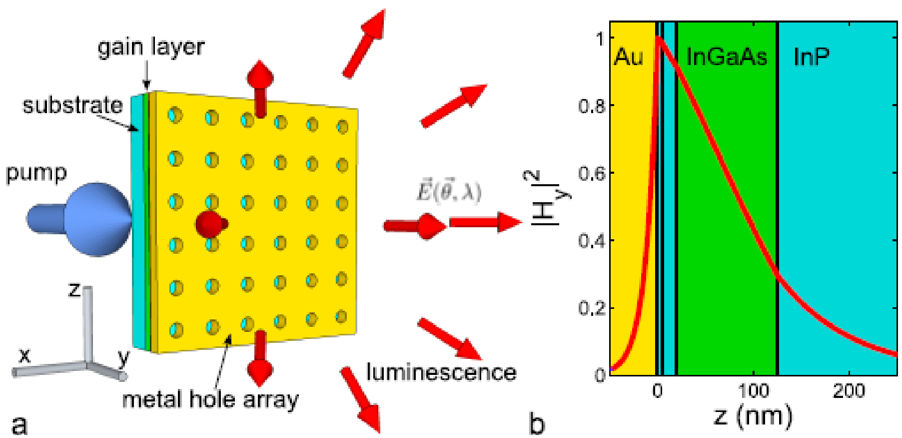
See also: W. Zhou, M. Dridi, J. Y. Suh, C. H. Kim, D. T. Co, M. R. Wasielewski, G. C. Schatz, and T. W. Odom, *Lasing Action in Strongly Coupled Plasmonic Nanocavity Arrays*, Nature Nanotechnology **8**, 506-511 (2013)



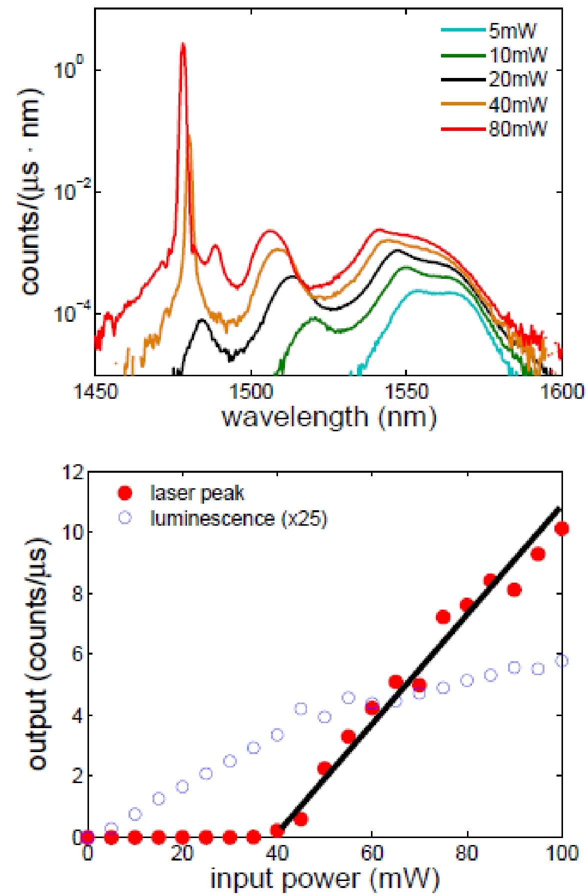


FIG. 2. (a) Luminescence spectra as a function of pump power, plotted on a semilog scale. For increasing pump power the bandwidth of the luminescence increases until the device starts lasing. Above threshold, the emission of the non-lasing resonances starts to saturate at a maximum intensity. 80 mW corresponds to ∼ 11 kW/cm^2 (b) The output in the lasing peak and in the luminescence in the range of 1485 – 1600 nm. The power in the lasing peak shows a clear threshold (red). The black line is a guide to the eye. The luminescence outside the lasing peak starts to level off, as expected for lasing in semiconductor devices (blue).

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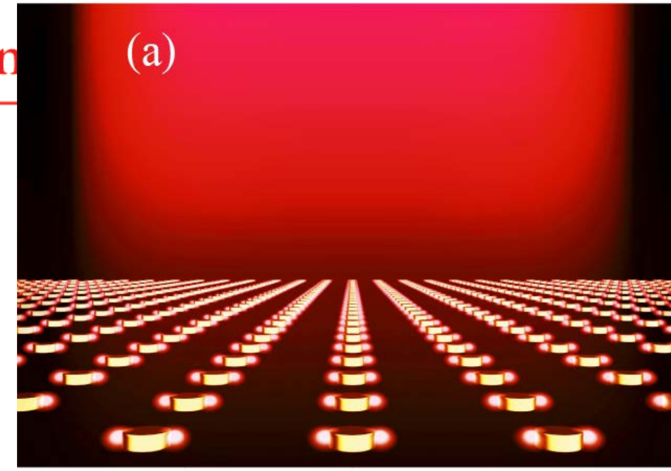
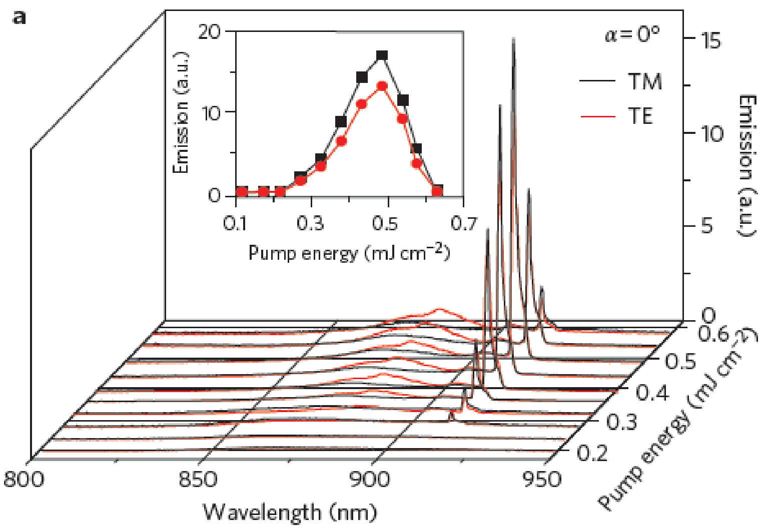
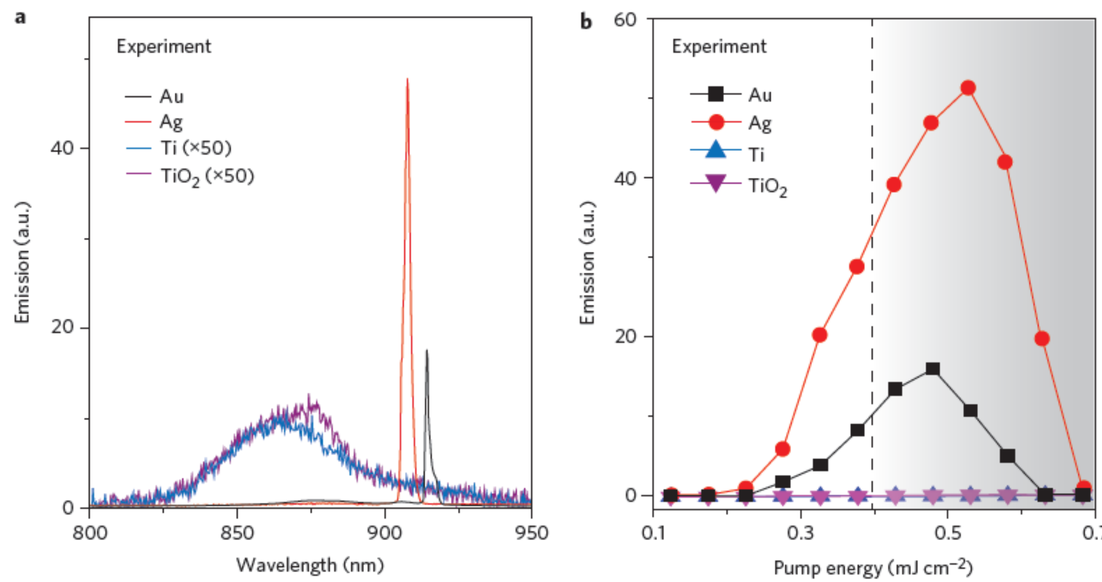
PUBLISHED ONLINE: 16 JUNE 2013 | DOI: 10.1038/NNANO.2013.99
nature nanotechn

Lasing action in strongly coupled plasmonic nanocavity arrays

Wei Zhou[1†], Montacer Dridi[2], Jae Yong Suh[2], Chul Hoon Kim[2,3†], Dick T. Co[2,3], Michael R. Wasielewski[2,3], George C. Schatz[2] and Teri W. Odom[1,2,3]*







SCIENTIFIC REPORTS

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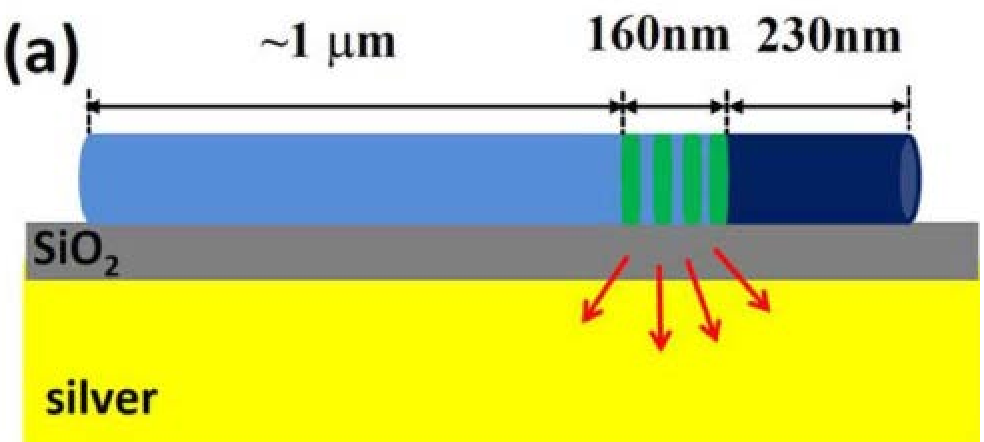
Room temperature plasmonic lasing in a continuous wave operation mode from an InGaN/GaN single nanorod with a low threshold

Y. Hou, P. Renwick, B. Liu, J. Bai & T. Wang

SCIENTIFIC REPORTS | 4 : 5014 | DOI: 10.1038/srep0501



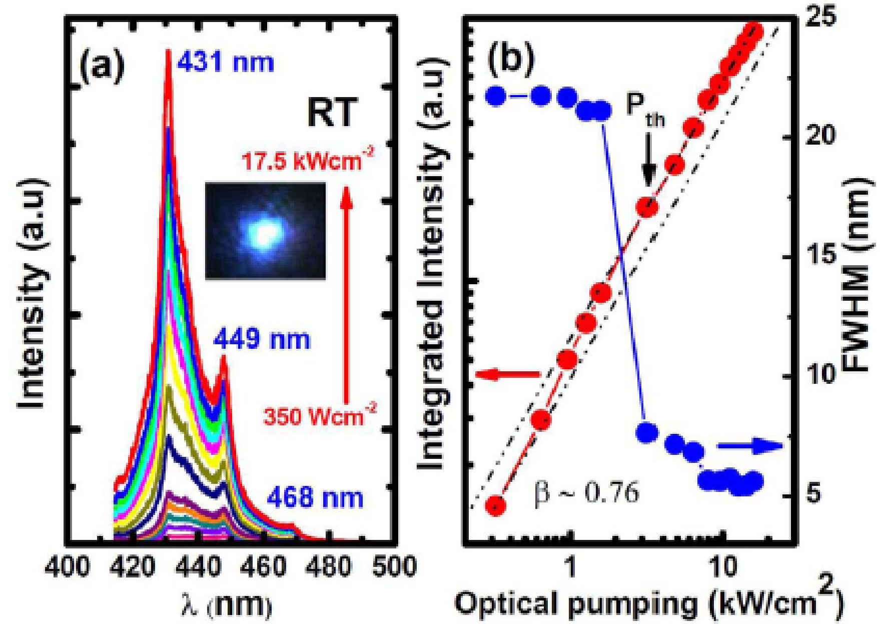


Figure 2 | (a) Lasing spectra from our nano-SPASER recorded as a function of optical pumping at room temperature. Inset showing the far-field laser spot; (b) L-L curve plotted in a log-log scale and FWHM as a function of optical pumping, respectively. The dash-lines are guides to eyes.

Nanoplasmonics and Spaser

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nature nanotechnology
LETTERS
PUBLISHED ONLINE: 20 JULY 2014 | DOI: 10.1038/NNANO.2014.135

Explosives detection in a lasing plasmon nanocavity

Ren-Min Ma[1†], Sadao Ota[1†], Yimin Li[1], Sui Yang[1] and Xiang Zhang[1,2*]

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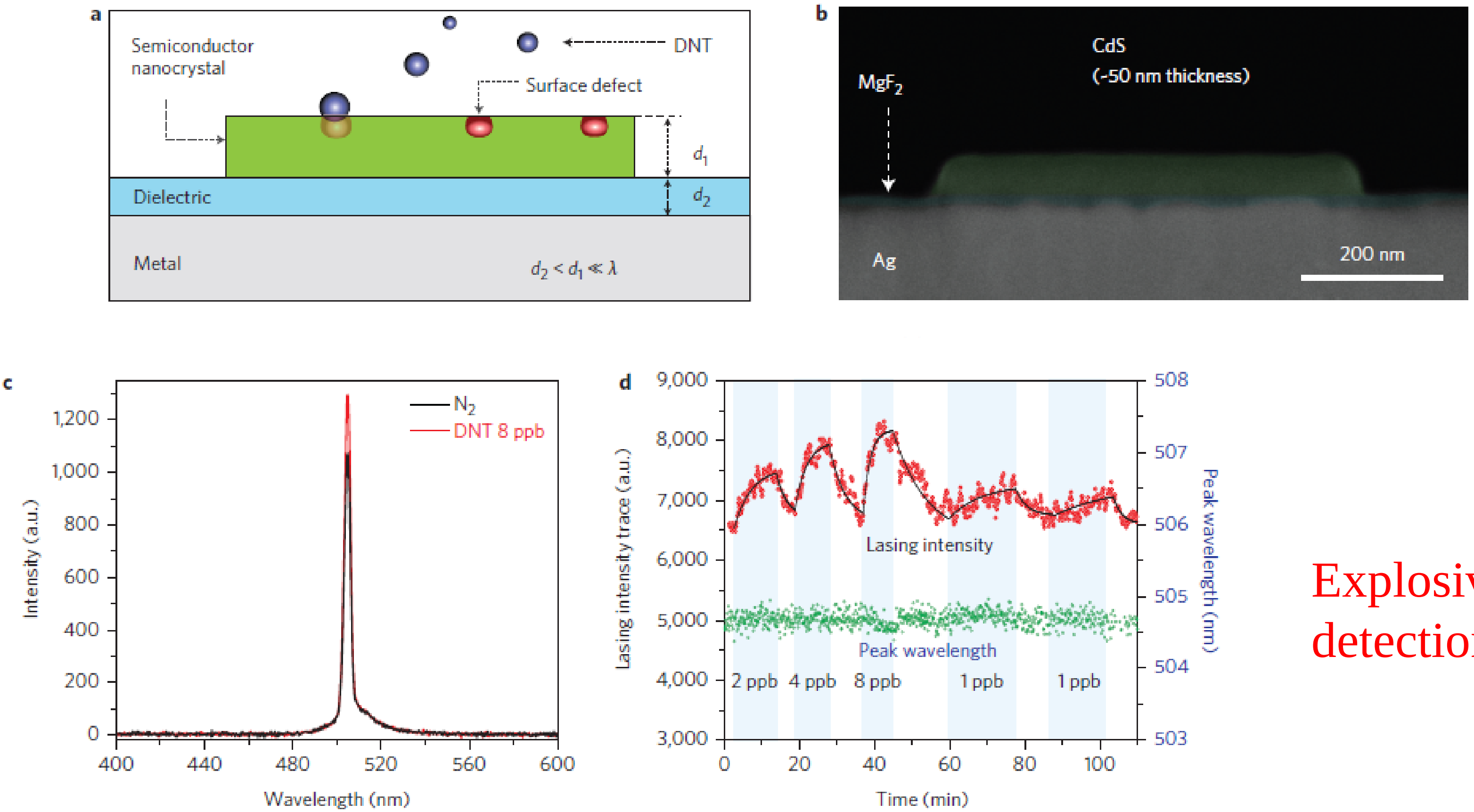

Explosive (DNT) detection

Georgia State University

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NATURE PHYSICS | **ARTICLE**

Ultrafast plasmonic nanowire lasers near the surface plasmon frequency

Themistoklis P. H. Sidiropoulos, Robert Röder, Sebastian Geburt, Ortwin Hess, Stefan A. Maier, Carsten Ronning & Rupert F. Oulton

Nature Physics (2014) doi:10.1038/nphys3103
Received 14 April 2014 Accepted 19 August 2014 Published online 28 September 2014

Abstract

Light–matter interactions are inherently slow as the wavelengths of optical and electronic states differ greatly. Surface plasmon polaritons — electromagnetic excitations at metal–dielectric interfaces — have generated significant interest because their spatial scale is decoupled from the vacuum wavelength, promising accelerated light–matter interactions. Although recent reports suggest the possibility of accelerated dynamics in surface plasmon lasers, this remains to be verified. Here, we report the observation of pulses shorter than 800 fs from hybrid plasmonic zinc oxide (ZnO) nanowire lasers. Operating at room temperature, ZnO excitons lie near the surface plasmon frequency in such silver-based plasmonic lasers, leading to accelerated spontaneous recombination, gain switching and gain recovery compared with conventional ZnO nanowire lasers. Surprisingly, the laser dynamics can be as fast as gain thermalization in ZnO, which precludes lasing in the thinnest nanowires (diameter less than 120 nm). The capability to combine surface plasmon localization with ultrafast amplification provides the means for generating extremely intense optical fields, with applications in sensing, nonlinear optical switching, as well as in the physics of strong-field phenomena.

References

1. Bergman, D. & Stockman, M. Surface plasmon amplification by stimulated emission of radiation: Quantum generation of coherent surface plasmons in nanosystems. *Phys. Rev. Lett.* **90**, 1–4 (2003).
2. Ma, R., Oulton, R. F., Sorger, V. J. & Zhang, X. Plasmon lasers: Coherent light source at molecular scales. *Laser Photon. Rev.* **7**, 1–21 (2012).
3. Lu, Y-J. *et al.* Plasmonic nanolaser using epitaxially grown silver film. *Science* **337**, 450–453 (2012).
4. Oulton, R. F. Surface plasmon lasers: Sources of nanoscopic light. *Mater. Today* **15**, 592–600 (2012).

Graphene spaser

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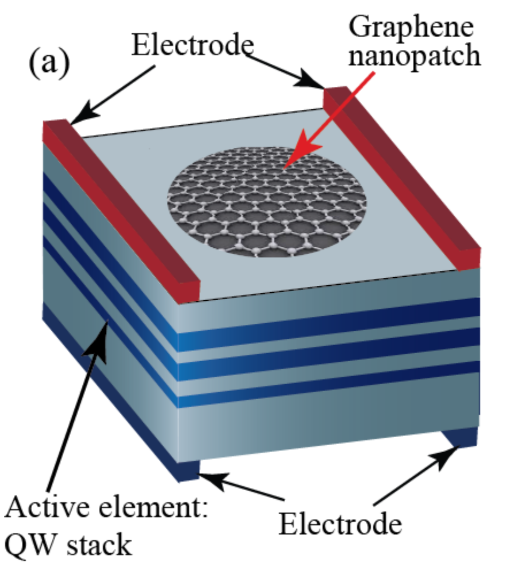
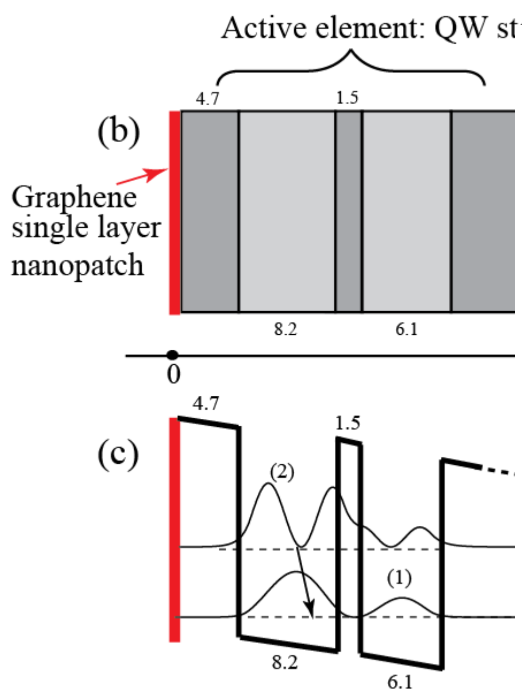
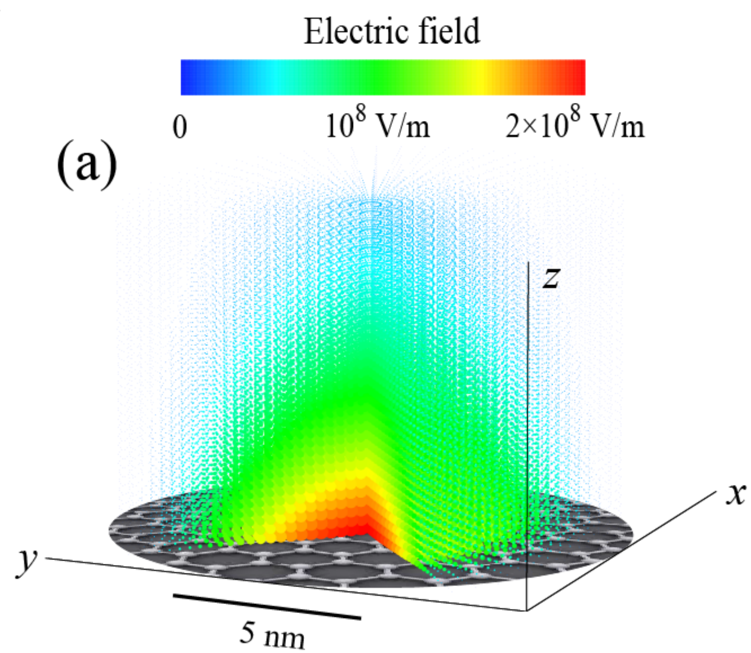
(Dated: May 10, 2013)

We propose a graphene spaser, which is a coherent quantum generator of surface plasmons in nanostructured graphene. The plasmonic core of this spaser is a graphene monolayer nanopatch and its active (gain) element is a multi-quantum well system with a design similar to the design of an active element of quantum cascade laser. For realistic parameters of the multi-quantum well system, the spasing in graphene monolayer can be achieved at a finite doping of graphene and at a plasmon frequency, ≈ 0.15 eV, close to the typical frequency of intersubband transitions in multi-quantum well systems. The proposed graphene spaser will be an efficient source of intense and coherent nanolocalized fields in the mid-infrared spectral region with wide perspective applications in mid-infrared nanoscopy, nano-spectroscopy, and nano-lithography.

V. Apalkov and M. I. Stockman, *Proposed Graphene Nanospaser*, NPG: Light Sci. Appl. **3,** e191 (2014).







PRL 110, 106803 (2013) PHYSICAL REVIEW LETTERS week ending 8 MARCH 2013

Electric Spaser in the Extreme Quantum Limit

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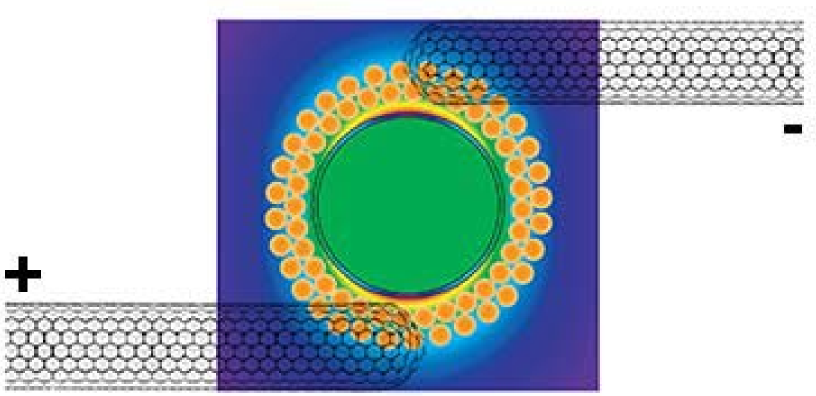
(Received 29 October 2012; published 7 March 2013)

We consider theoretically the spaser that is excited electrically via a nanowire with ballistic quantum conductance. We show that, in the extreme quantum regime, i.e., for a single conductance-quantum nanowire, the spaser with a core made of common plasmonic metals, such as silver and gold, is fundamentally possible. For ballistic nanowires with multiple-quanta or nonquantized conductance, the performance of the spaser is enhanced in comparison with the extreme quantum limit. The electrically pumped spaser is promising as an optical source, nanoamplifier, and digital logic device for optoelectronic information processing with a speed of ~100 GHz to ~100 THz.



Geometry of the spaser: metal nanoshell surrounded by gain medium and two ballistic nanowires (carbon nanotubes) attached to it to supply the current

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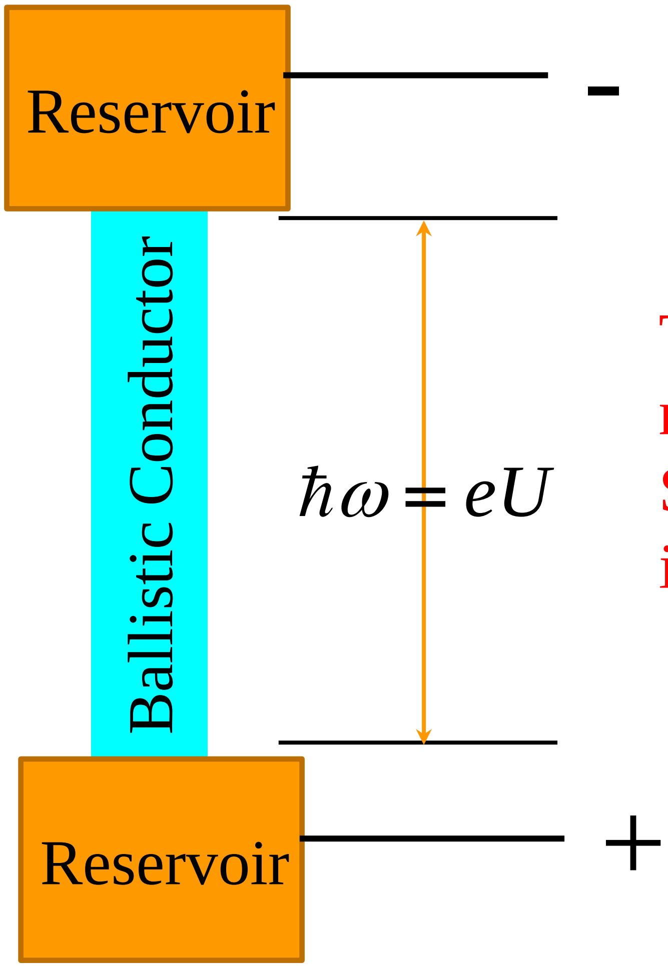
Ballistic conductance and Landauer quantum of resistance (per single conduction channel):

$$J = 2e\frac{\omega}{2\pi} = \frac{e^2}{\pi\hbar}U = G_0 U \ , \quad G_0 = \frac{e^2}{\pi\hbar}$$



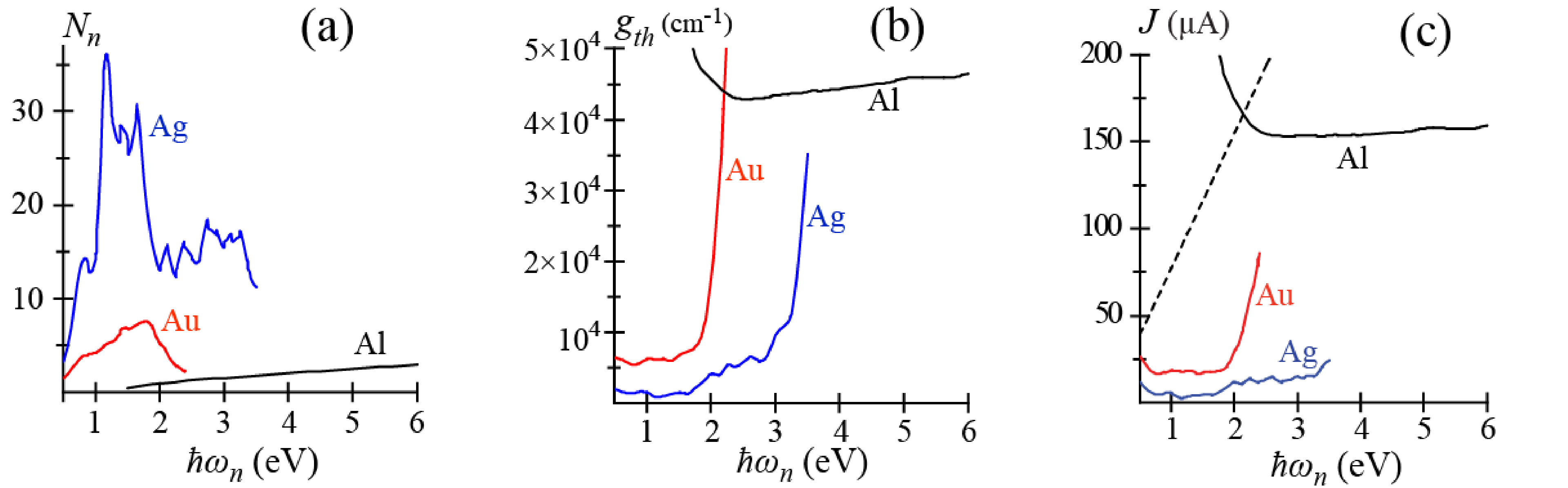
To excite a plasmon in the extreme quantum regime, we need to have $U = \hbar\omega_n / e$. Substituting *U*, we obtain universal current in the quantum wire:

$$J = \frac{e\omega_n}{\pi}$$

Number of plasmons per spasing mode in the *developed spasing regime*

$$N_n = \frac{J}{e\gamma_n} \ , \quad \gamma_n = \frac{\operatorname{Im}\varepsilon(\omega_n)}{\partial \operatorname{Re}\varepsilon(\omega_n)/\partial\omega_n}$$

No dependence on gain medium!



Number of plasmons per spasing mode as a function of frequency. The spaser is pumped electrically via ballistic wire with single quantum conductance channel. Developed spasing is assumed

Spasing condition: Threshold gain of bulk gain media necessary for spasing

The spasing condition is fundamentally different from a condition $N_n \gg 1$.

Current required per one plasmon in spasing mode for three plasmonic metals in the developed spasing regime. Dashed line is the current supplied by a single quantum-conductance channel.

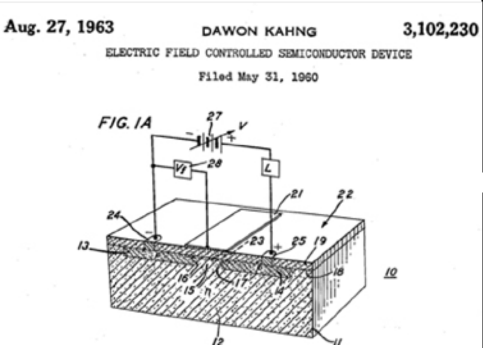
The most important technological application: Information processing

P. Packan et al., in 2009 IEEE International Electron Devices Meeting (IEDM), *High Performance 32nm Logic Technology Featuring Second Generation High-K + Metal Gate Transistors (Baltimore, MD, 2009), Vol. IEDM09-662, p. 28.4.1-28.4.4*

Abstract:

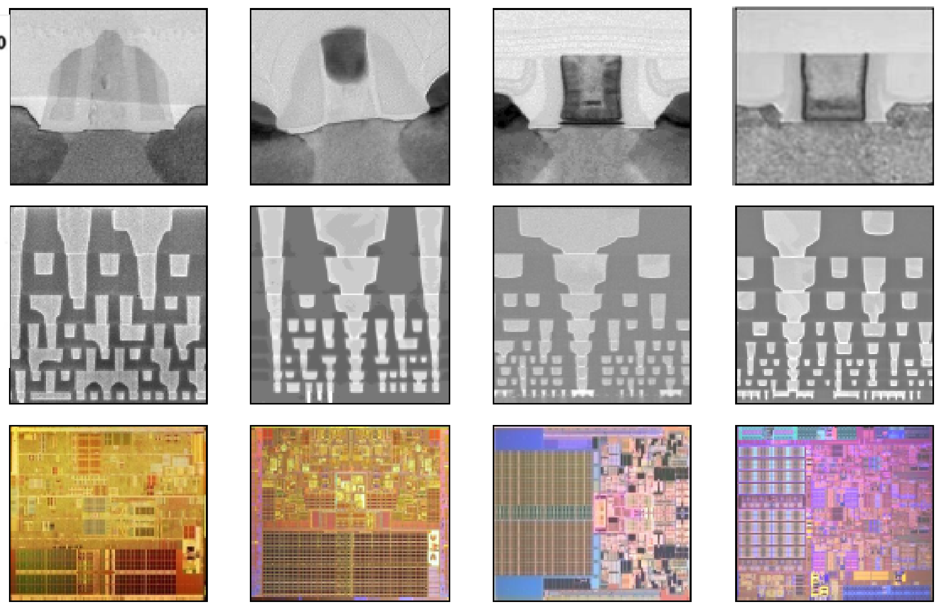
A 32nm logic technology for high performance microprocessors is described. 2nd generation high-k + metal gate transistors provide record drive currents at the tightest gate pitch reported for any 32 nm or 28nm logic technology. NMOS drive currents are 1.62mA/um Idsat and 0.231mA/um Idlin at 1.0V and 100nA/um Ioff. PMOS drive currents are 1.37mA/um Idsat and 0.240mA/um Idlin at 1.0V and 100nA/um Ioff. The impact of SRAM cell and array size on Vccmin is reported.

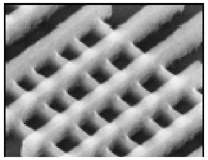
MOSFET US Patent



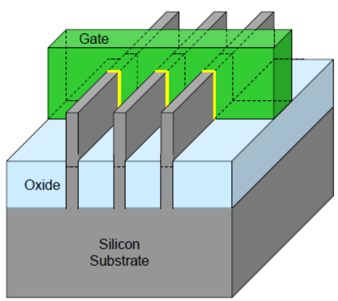
Speed ~ 100-300 GHz
Low resistance to ionizing radiation

90 nm	65 nm	45 nm	32 nm	22 nm
2003	2005	2007	2009	2011





22 nm Tri-Gate Transistor



Tri-Gate transistors can have multiple fins connected together to increase total drive strength for higher performance

Processor speed :

$$f_{max} = I_{drive} / \left(C_{Intercon} \Delta U \right) \sim 3 \text{ GHz}$$

Transistor speed is not a limiting factor!
Charging the interconnects is.

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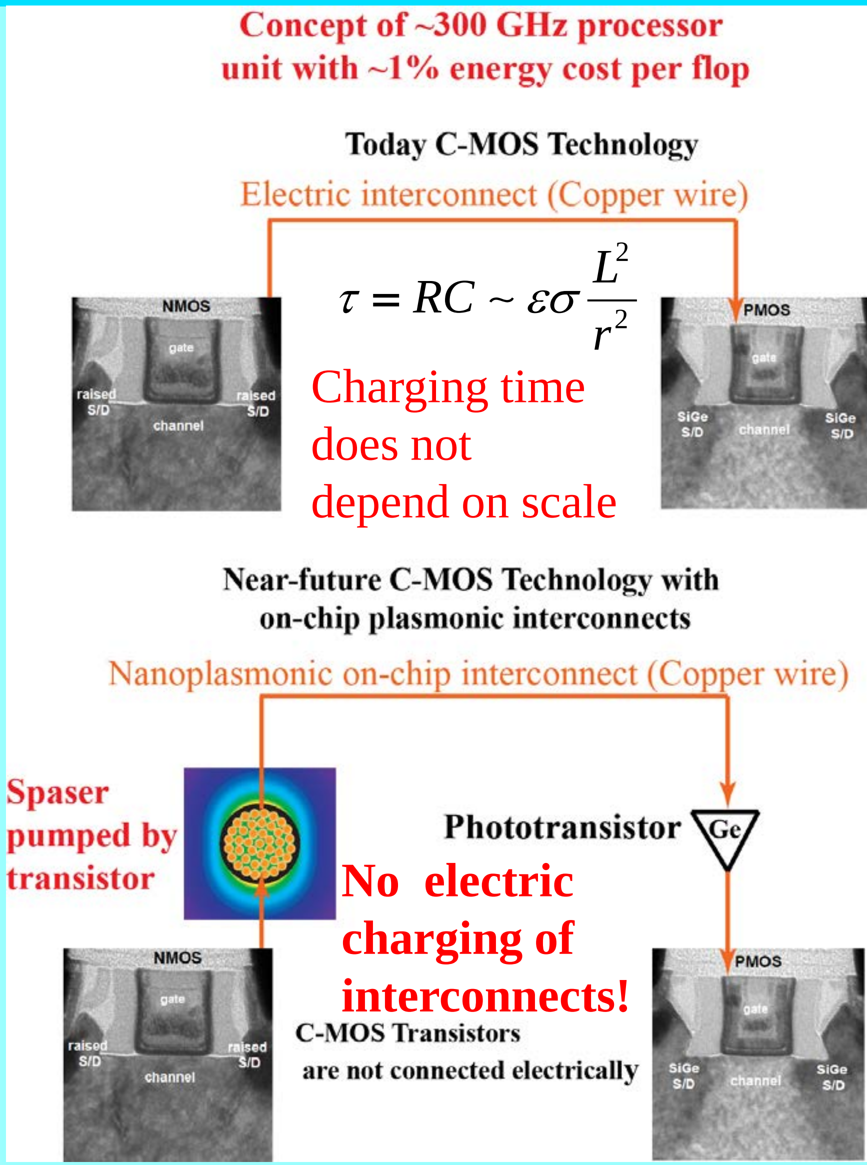
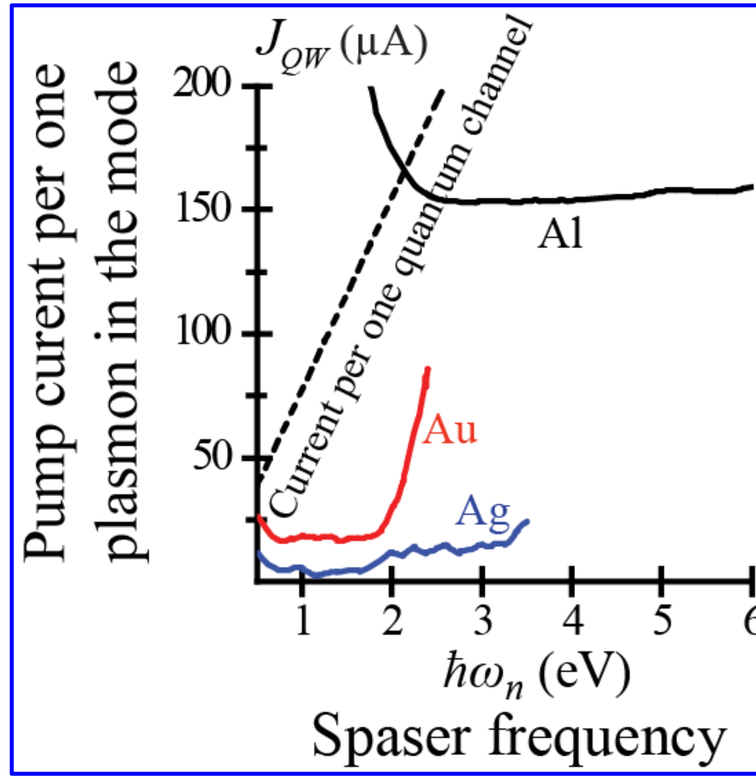
Nanospaser with electric excitation ("pumping") does not exist as of today *yet*, but fundamentally it is entirely possible





http://www.phy-astr.gsu.edu/stockman
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The End