Nanolasers:

Current Status of Trailblazer of Synergetics

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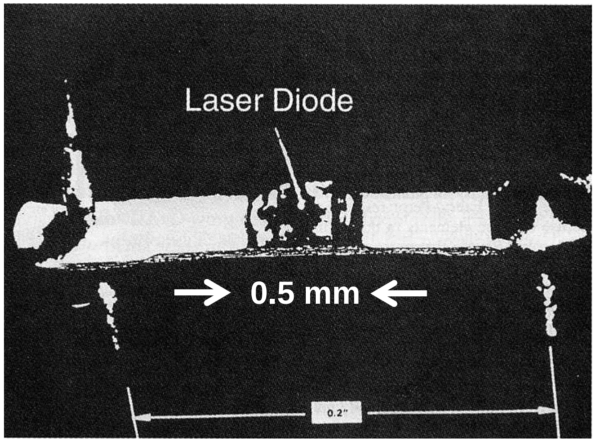
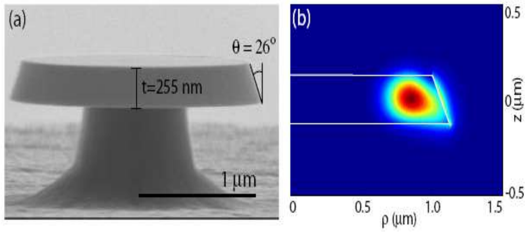
Support: ARO, AFOSR, DARPA, NASA, SFAz

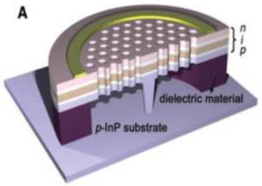
Miniaturization of Semiconductor Lasers

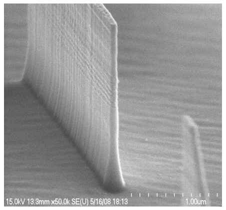


First laser diode (GaAs) Lincoln Lab

mm ~ cm scale
(1962)







100 nm ~ μm scale
(2012)

Engineering Photon-Semiconductor Interaction

Radiative coupling between light and semiconductor

$$r_{cv} \propto \boxed{\rho_{ph}(\omega)} \bullet \boxed{\rho_e(E)}$$

Density of Photonic States

Density of Electronic States

Free space: $\rho_{ph}^{3D}(\omega_0) = \frac{\omega_0^2}{\pi^2 c^3}$

3D cavity:

$$\rho_{ph}^{cav}(\omega) = \frac{1}{V_c}\frac{1}{\pi}\frac{\kappa}{(\omega-\omega_0)^2+\kappa^2}$$

Decreasing V_c

Purcell Enhancement

$$F_P = \frac{\rho_{ph}^{cav}(\omega_0)}{\rho_{ph}^{3D}(\omega_0)} = \frac{3}{4\pi^2}\left(\frac{\lambda^3}{V_c}\right)Q$$

Cavity Size Reduction

Size Quantization

Bulk $\rho_e^{3D}(E) = \frac{1}{2\pi^2}\left(\frac{2m^*}{\hbar^2}\right)^{\frac{3}{2}}\sqrt{E-E_g}$

QW: $\rho_e^{2D}(E) = \frac{m^*}{\pi\hbar^2}$

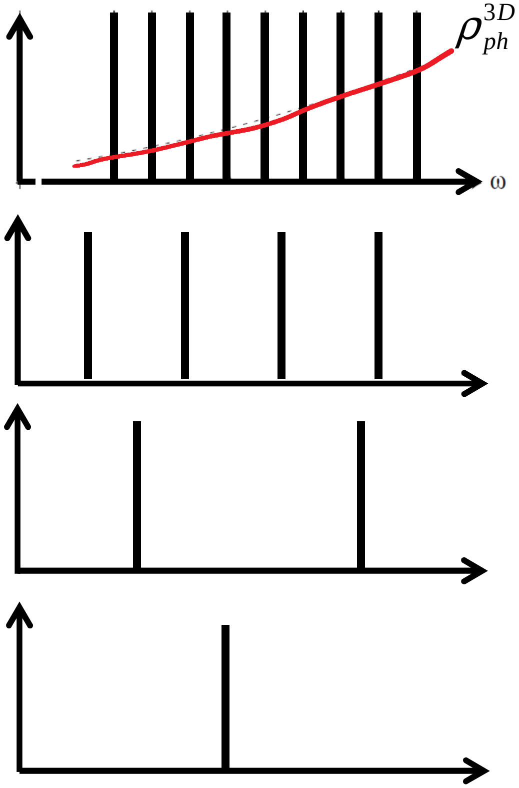
QWR: $\rho_e^{1D}(E) = \frac{\sqrt{2m^*}}{\pi\hbar}\frac{1}{\sqrt{E-E_n}}$

QD: $\rho_e^{0D} = 2\delta(E-E_n)$

Engineering the Densities of States

Density of Photonic States

$\rho_{ph}^{cav}(\omega_0)$

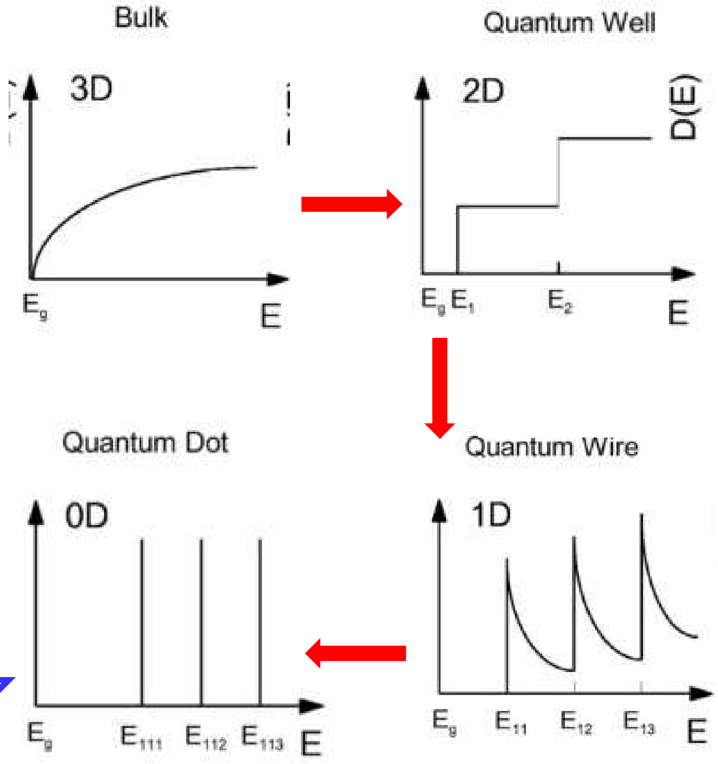


$$\rho_{ph}^{3D}(\omega_0) = \frac{\omega_0^2}{\pi^2 c^3}$$

Cavity Size Reduction

Density of Electronic States

Size Quantization



More efficiently use of photons

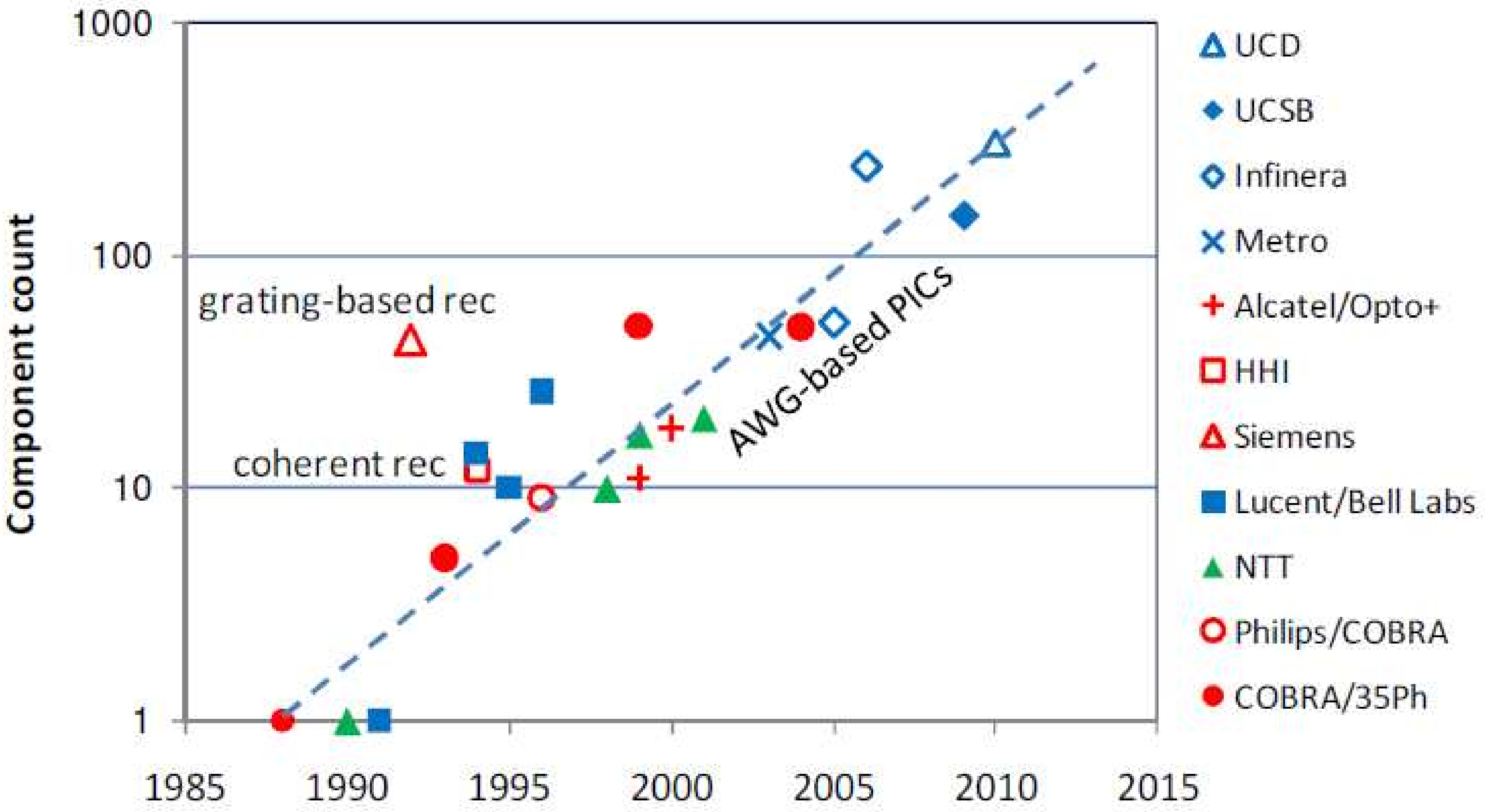
More efficiently use of electrons/holes

More efficiently coupling photons and semiconductors

Why Nanolasers?
From Application Point of View

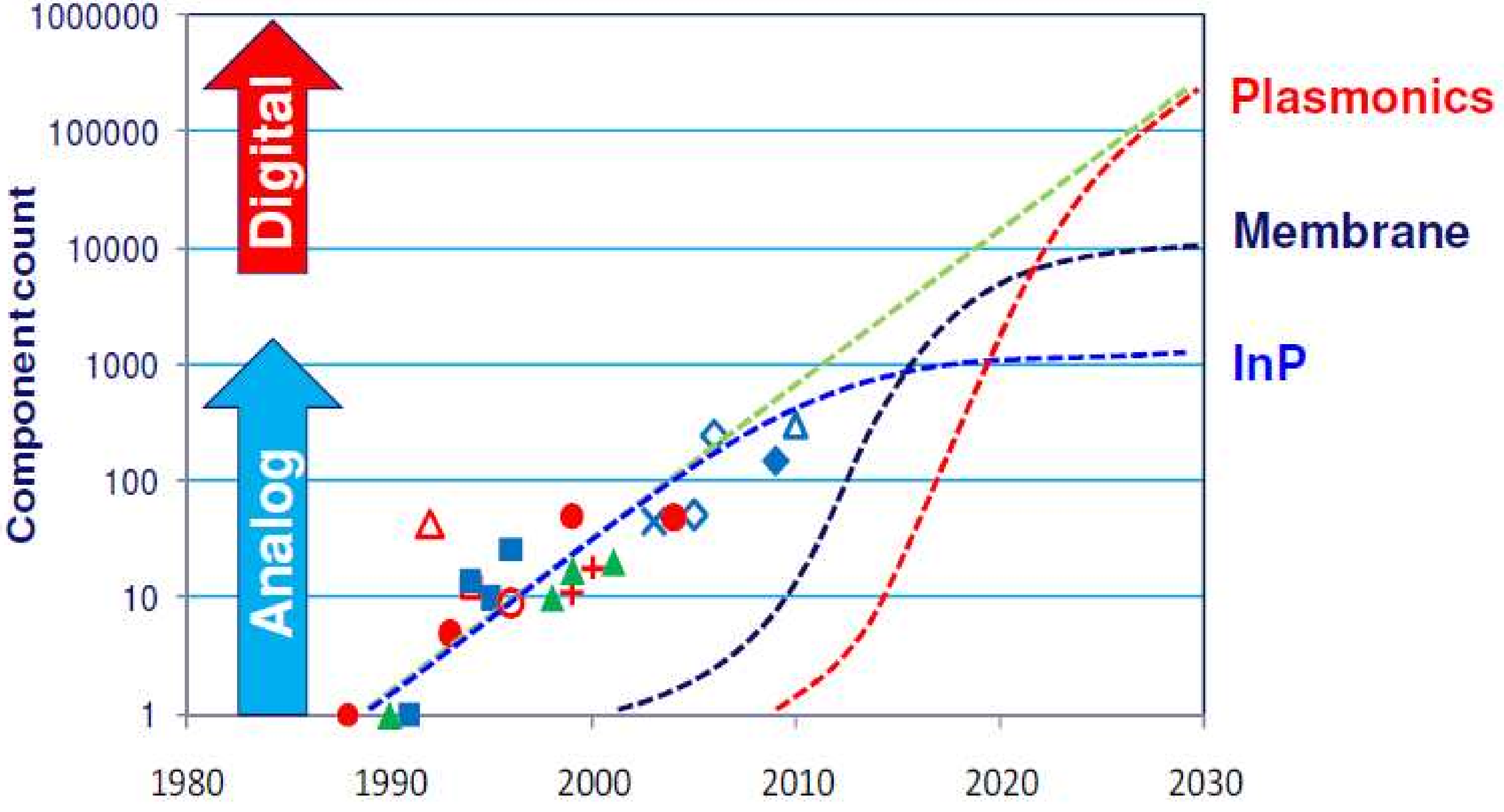
- Optical and electronic integration, size compatibility with electronic devices
- VLSI photonics: more functions in smaller volume
- On-chip light sources (e.g., micro and nano-fluidic)
- General trends in nanotechnology development: the smaller the better
- Other new applications not envisioned yet, but will be enabled once smaller and smaller lasers are available

Moore’s Law in Photonics



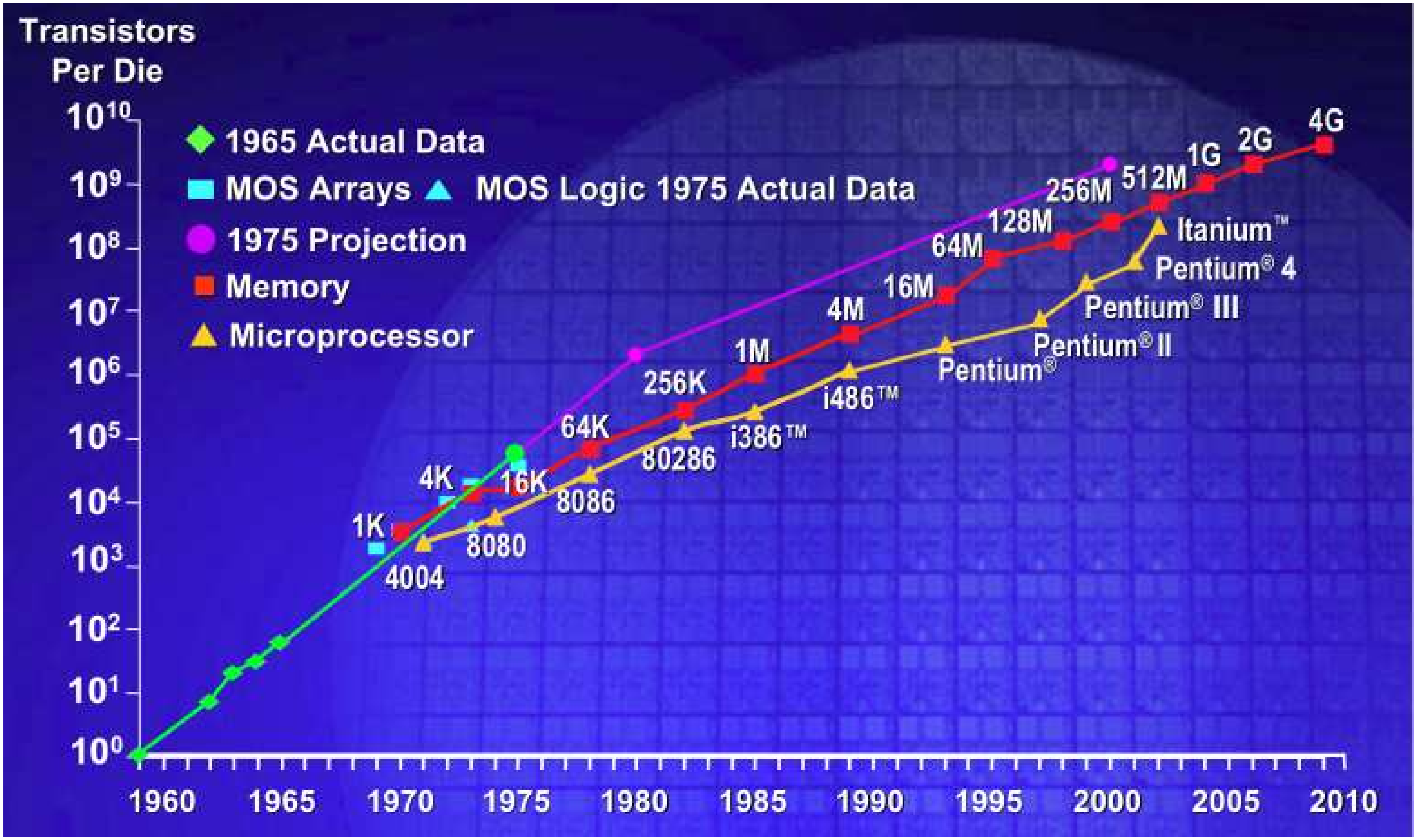
M.K. Smit, Moore’s law in photonics

Moore's Law in Photonics
Technology Breakup



M.K. Smit, Moore's law in photonics

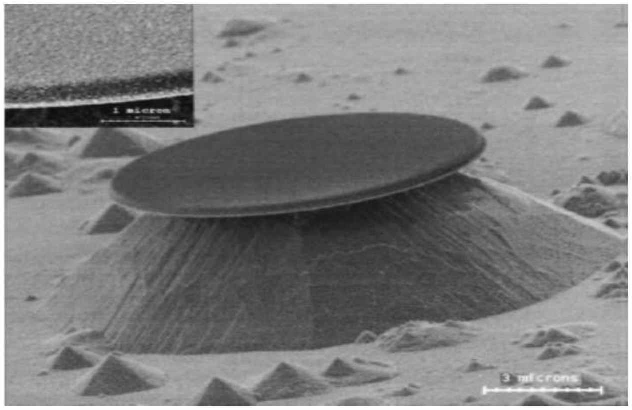
Moore’s Law for Microelectronics



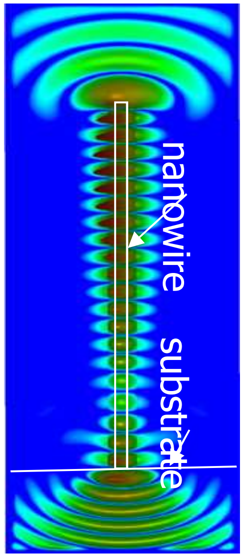
Challenges for Nanophotonics

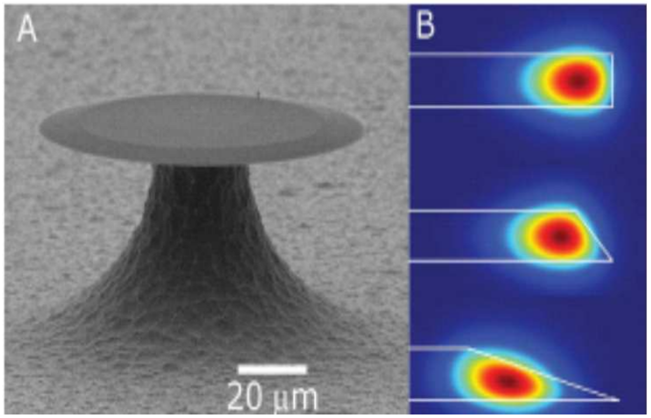
- **Size, Size, and Size**
  - a) Passive devices (waveguides): $> \lambda / 2n$, single mode fiber: 5 μm; silicon wire or other semiconductor nanowire: 100-200 nm
  - b) Active devices: (lasers): gain length required to achieve threshold: 1-100 μm, large footprint, difficult for integrate
- **Complexity, diversity, and cost: diversity of devices and materials, small market share of each device, expensive manufacturing**
- **Compatibility with silicon for integration with electronics light emitting materials: non-silicon (III-V, II-VI) such as GaAs, InP**
- **No silicon light source (external to CMOS)**
- **…**

Examples of Smallest Lasers…(before 2007)
(what is in common: pure dielectric waveguide structures)

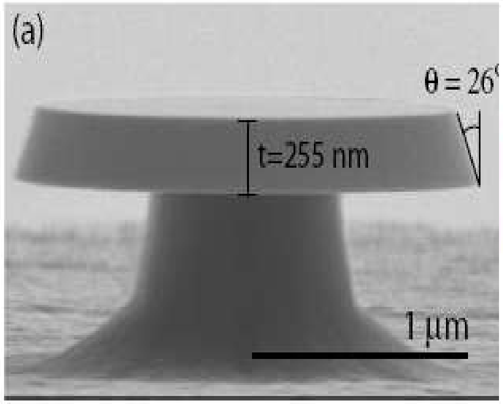


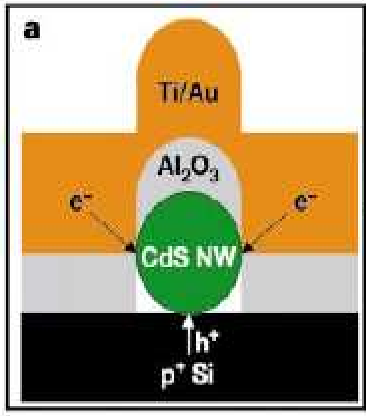
55 nm-think ZnO nanocrystal layer is dispersed on a SiO_2 disk of 10 microns in diameter, Liu et al, APL (2004)



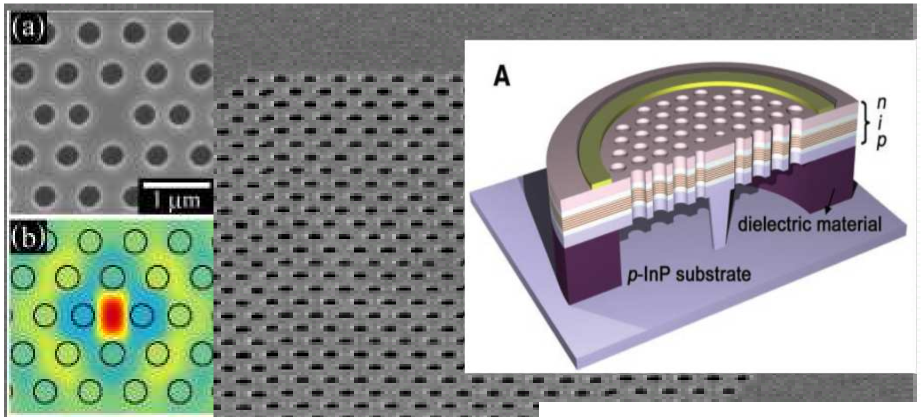


Erbium doped silica disk of 60 microns in diameter on a silicon stem (Kippenberg, PRA 2006) (optically pumped)





InAs/AlGaAs single layer of QD, 60 nW output (Painter group, Opt. Exp. 2006)



(Optically pumped, RT-CW, smallest, PC laser, Baba's group, InGaAsP/InP, Opt. Exp.2007)

Park et al. Science **305**, 1444 (2004).

Questions

- Can lasers be made even smaller?
- What is the ultimate size limit?
- How about electrical injection, rather than optical?
- Can you make a laser that is smaller than vacuum wavelength *in all three dimensions* (DARPA NACHOS program)?

NACHOS (Nanoscale Architectures for Coherent Hyper-Optic Sources)

Goals: Electrical injection, room temperature, subwavelength in all 3-dimensions

How to Make Smaller Cavities?

- **Pure dielectric cavities are not adequate**
- **Metallic, especially plasmonic structures offer potential hope**

Plasmonics, Spasers, Before 2007….

- Bergman and Stockman, PRL 2003
- Stockman and Bergman, Laser Phys, 2004
- Nezhad, Tedz, and Fainman, Opt. Exp. 2004
- Maier, Opt. Comm. 2006
- Miyazaki and Kurokawa, PRL 2006

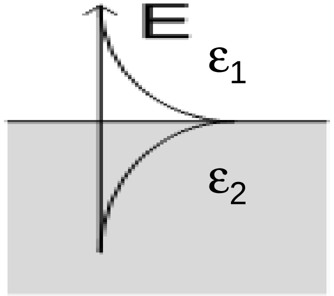
Plasmon Photon Coupling

Plasma/Plasmon: **Longitudinal excitation of electron motion (in metals or doped semiconductors)**

Drude model:

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \qquad \omega_p = \left(\frac{Ne^2}{\varepsilon_0 m}\right)^{1/2}$$

Surface Plasmon or Surface Plasmon Polariton: **Coupled EM wave and plasmon excitation at the interface of a dielectric layer and a metallic layer.**

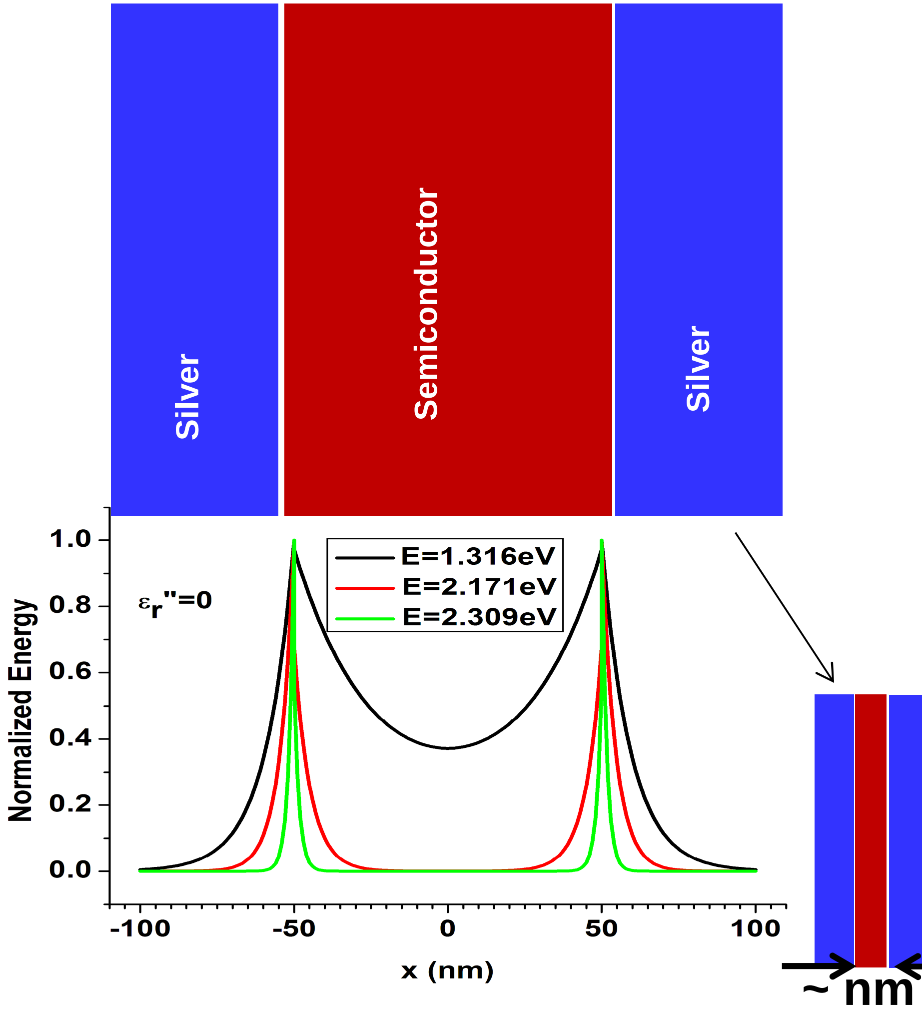


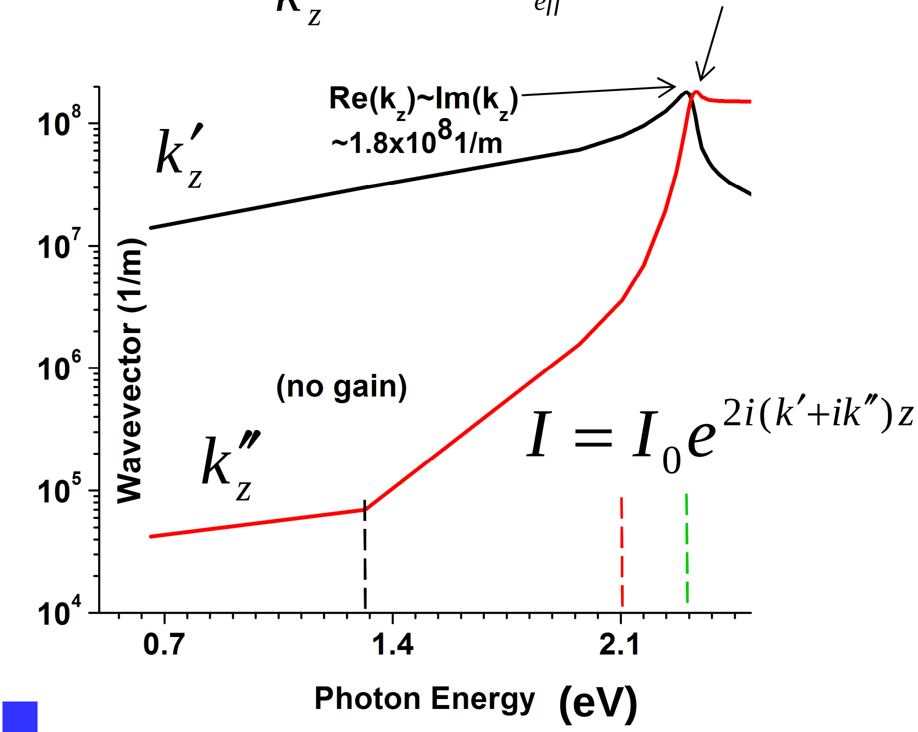
$$k_z = \frac{\omega}{c}\sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}}$$

Surface Plasmon Polariton (SPP)

SPP wave along the interface

$$\lambda_{eff} = \frac{2\pi}{k'_z} \Rightarrow \frac{\lambda_0}{\lambda_{eff}} = \frac{540\,nm}{35\,nm} = 15.4$$



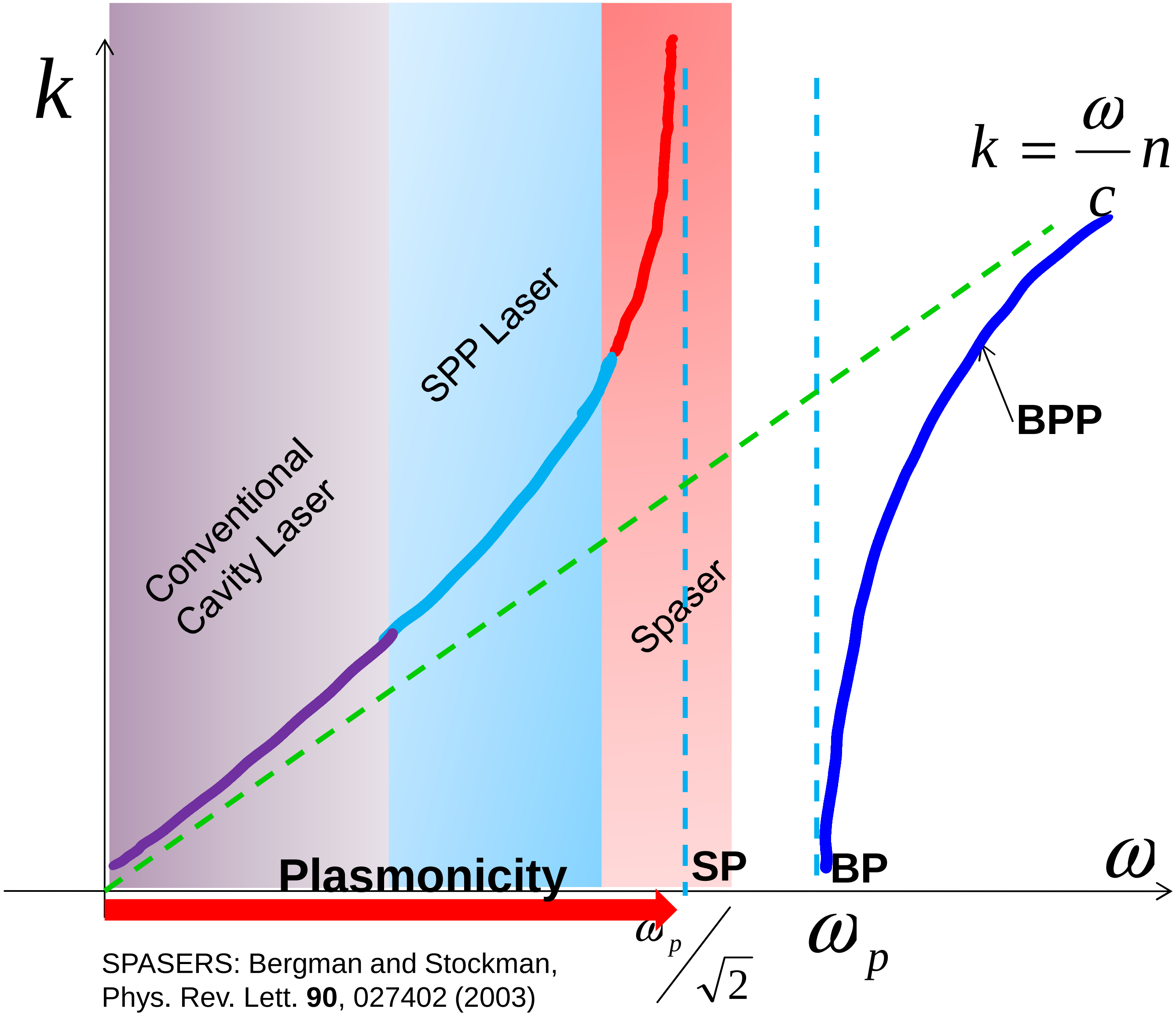


$$I = I_0 e^{2i(k'+ik'')z}$$

Near SPP Resonance:

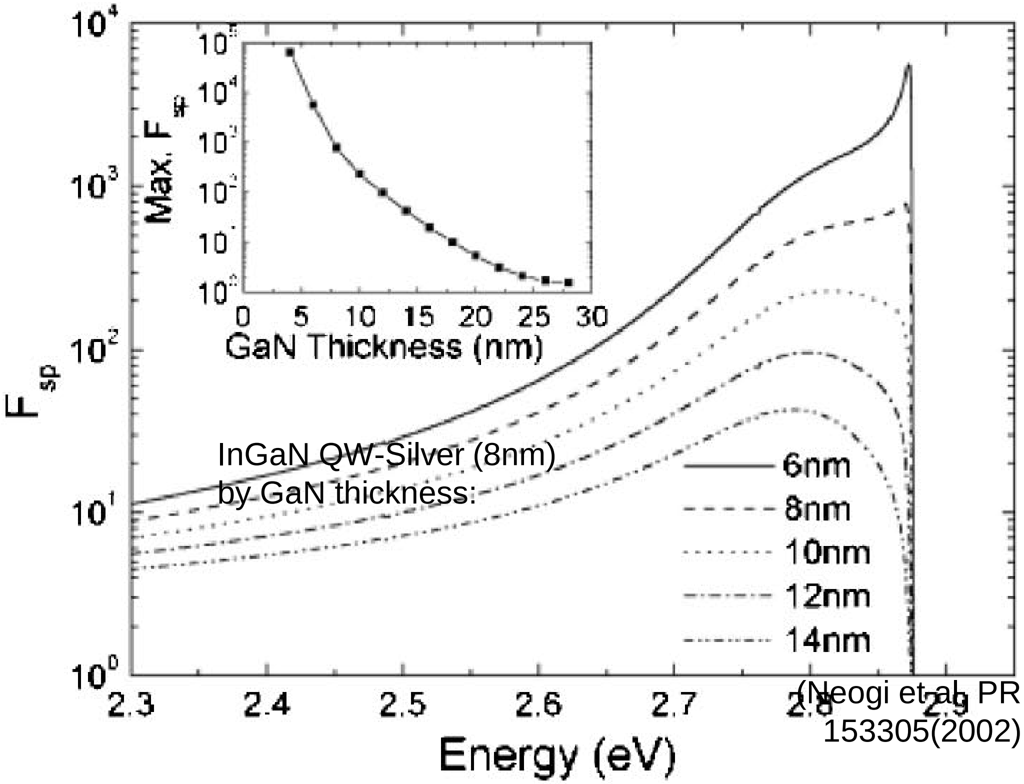
1) Huge wave compression (35 nm)
2) Strong localization (few nm)
3) Huge loss (3.6 million 1/cm)

Lasers, Spasers, and Photon-Plasmon Coupling



SPASERS: Bergman and Stockman, Phys. Rev. Lett. **90**, 027402 (2003)

Light Coupling to SPP Mode: Dramatic Purcell Enhancement

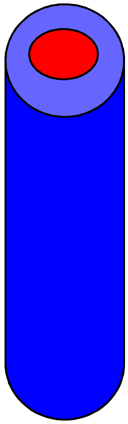


InGaN QW-Silver (8nm)
by GaN thickness:

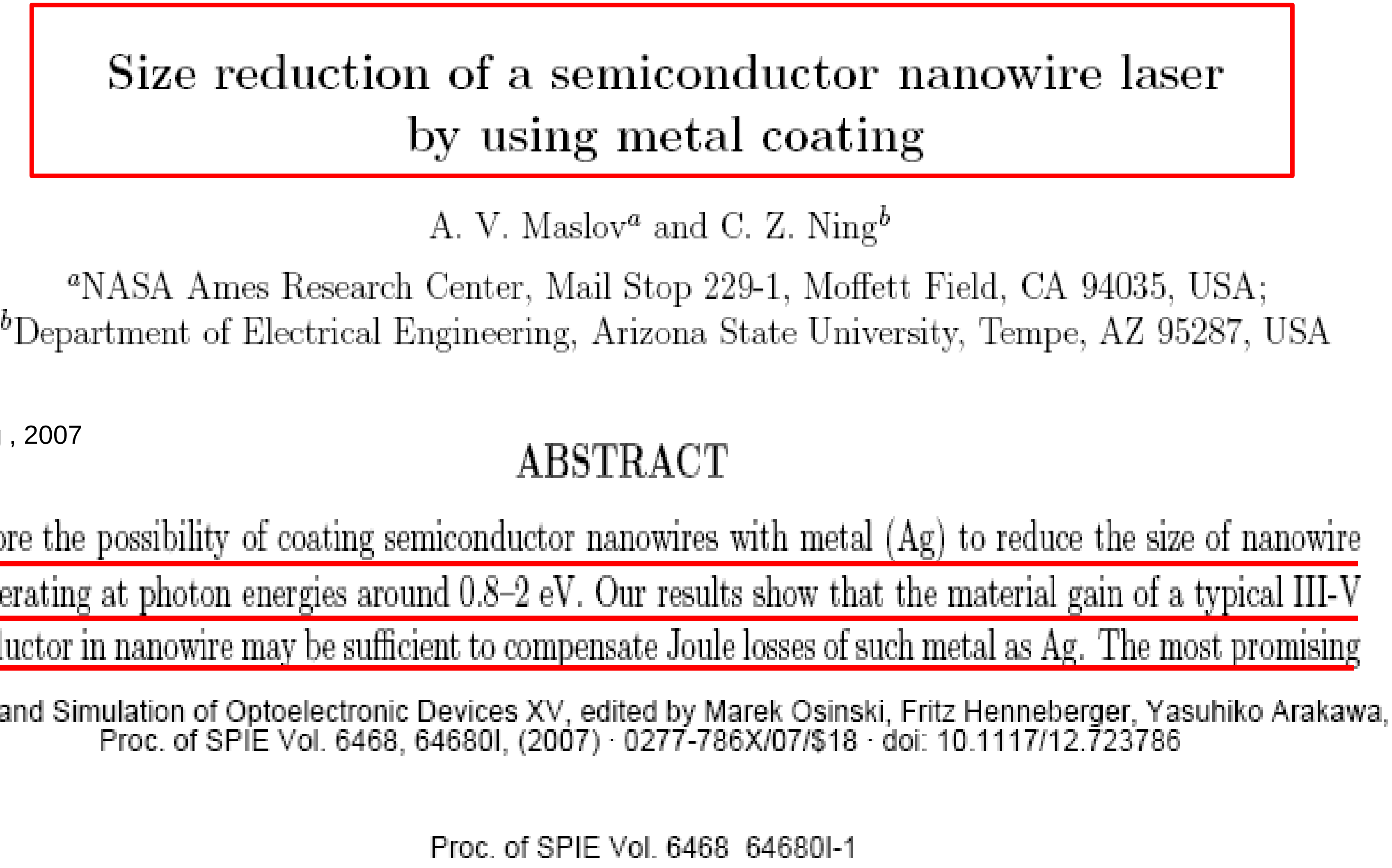
(Neogi et al, PRB66, 153305(2002)

Neogi et al, PRB, 2002

Feasibility of a Semiconductor-Core Metal-Shell (Jan 2007 SPIE Paper)



Maslov-Ning , 2007



Size reduction of a semiconductor nanowire laser by using metal coating

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[a]NASA Ames Research Center, Mail Stop 229-1, Moffett Field, CA 94035, USA;
[b]Department of Electrical Engineering, Arizona State University, Tempe, AZ 95287, USA

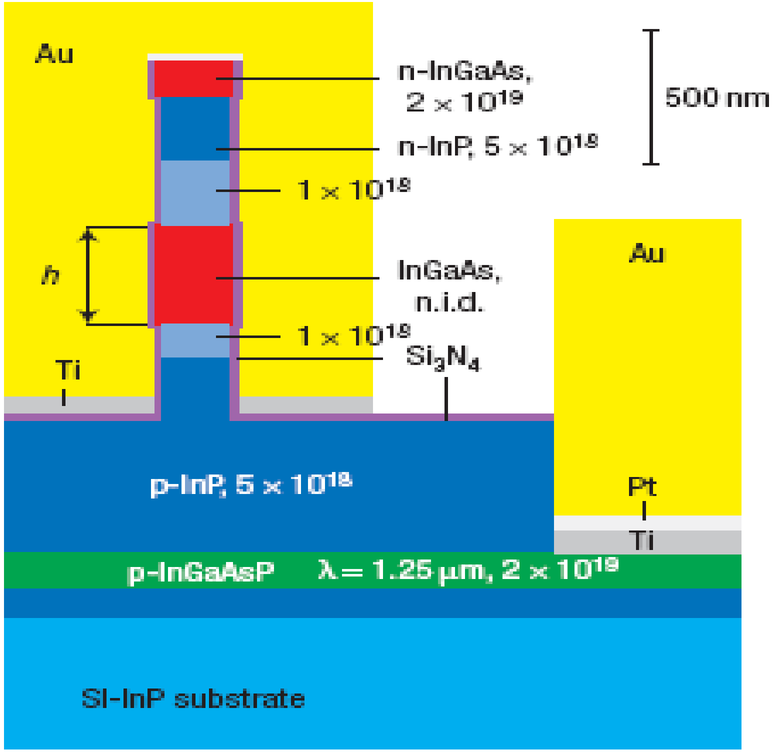
ABSTRACT

We explore the possibility of coating semiconductor nanowires with metal (Ag) to reduce the size of nanowire lasers operating at photon energies around 0.8–2 eV. Our results show that the material gain of a typical III-V semiconductor in nanowire may be sufficient to compensate Joule losses of such metal as Ag. The most promising

Physics and Simulation of Optoelectronic Devices XV, edited by Marek Osinski, Fritz Henneberger, Yasuhiko Arakawa,
Proc. of SPIE Vol. 6468, 64680I, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.723786

Proc. of SPIE Vol. 6468 64680I-1

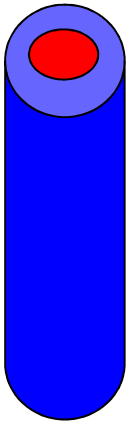
First Experimental Demonstration of the Semiconductor-Metal Core-Shell Laser



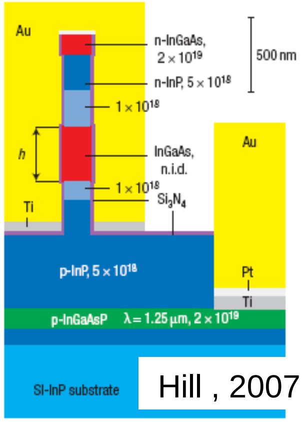
M. Hill et al. Nat. Photonics, 1, (2007),589

A Zoo of Nanolaser Designs… after 2007

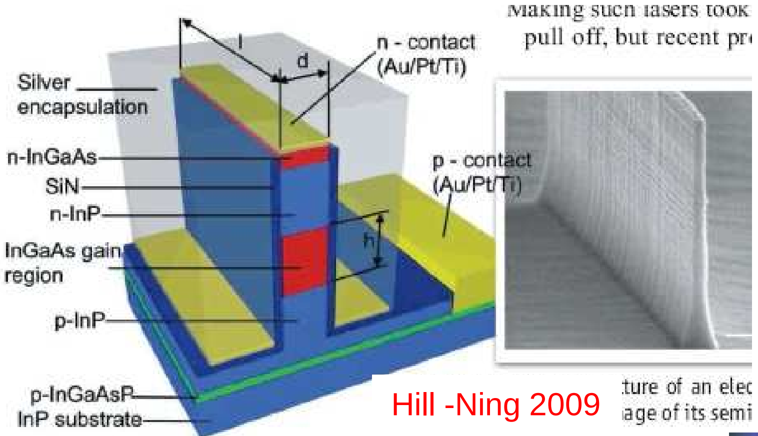
(What is in Common? Everyone Likes Metals)



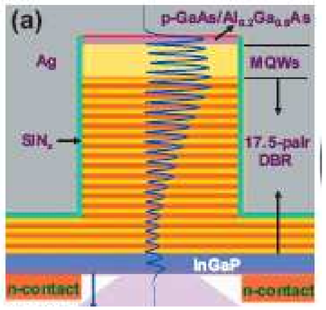
Maslov-Ning , 2007



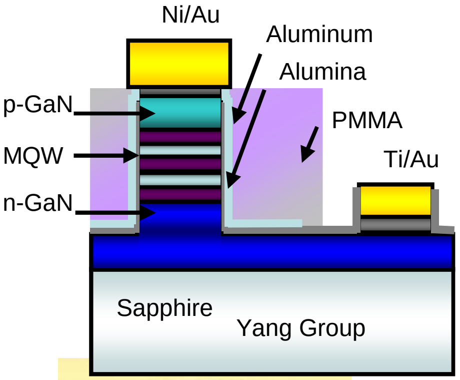
Hill , 2007



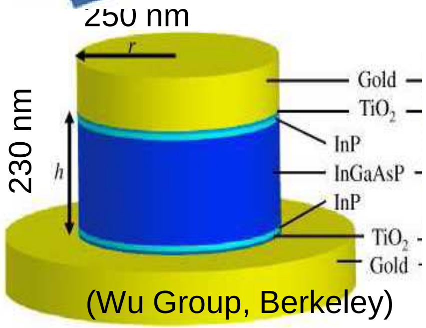
Hill -Ning 2009



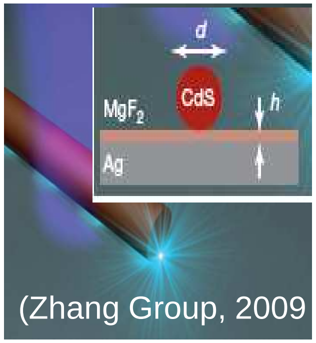
Chuang-Bimberg Group



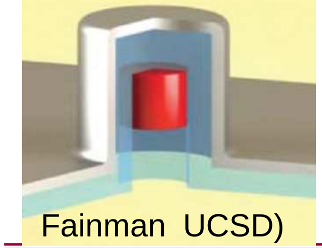
Yang Group



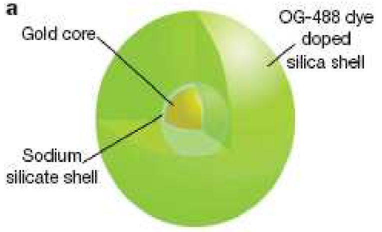
(Wu Group, Berkeley)

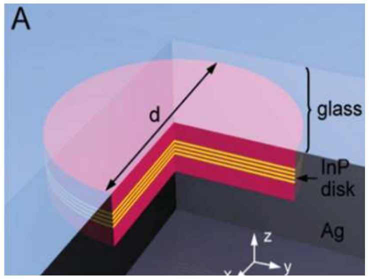


(Zhang Group, 2009

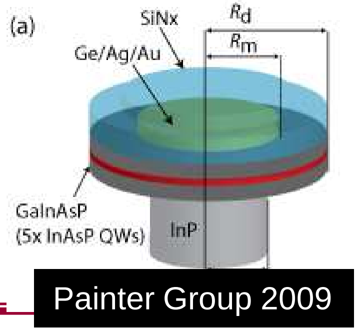


Fainman UCSD)





(Lieber, Harvard, Park, Korea)



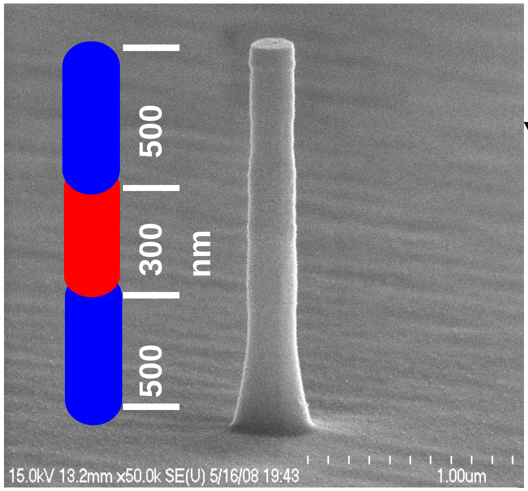
Painter Group 2009

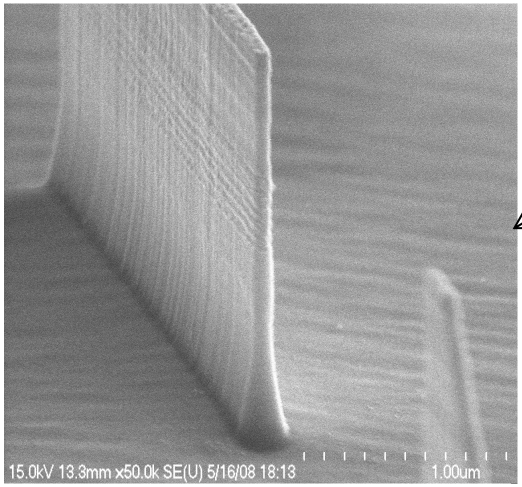
Summary of Short History and Status

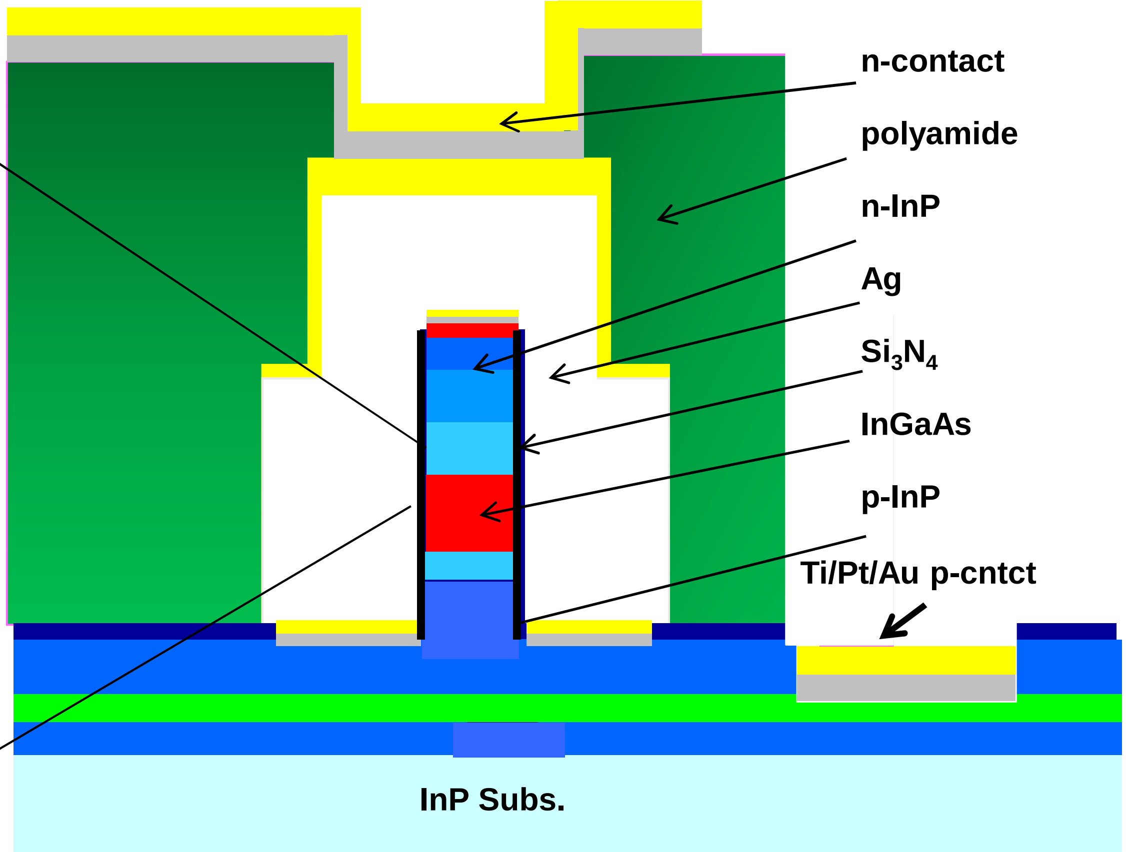
- **Design and theoretical study: Maslov and Ning, Proc. SPIE 6468, (2007)64680I**
- **1st experimental demonstration: M. Hill et al. Nat. Photonics, 1, (2007),589**
- **Electrical injection sub-half-wavelength laser: Hill et al, Opt. Exp., 2009**
- **Metal encased in a doped shell: Noginov et al., 2009**
- **Wire on a metal surface: Oulton et al., 2009**
- **Metal-semiconductor disk laser, Parahia et al, APL, 95 (2009) 201114**
- **Optically pumped lasing at RT: Nezhad et al, Nat. Phontonics, 4, (2010),395**
- **Nano patch laser: Yu et al., Opt. Exp. , 18 (2010) 8790**
- **Nano pan laser: Kwon et al. (2010), Nano. Lett, 10, (2010),3679**
- **Metallic cavity VCSEL, RT operation, Lu et al, Appl. Phys. Lett, 96, 251101 (2010)**
-

Goals: Sub-wavelength, CW RT operation, electrical injection

Semiconductor-Metal Core-Shell Nanolaser



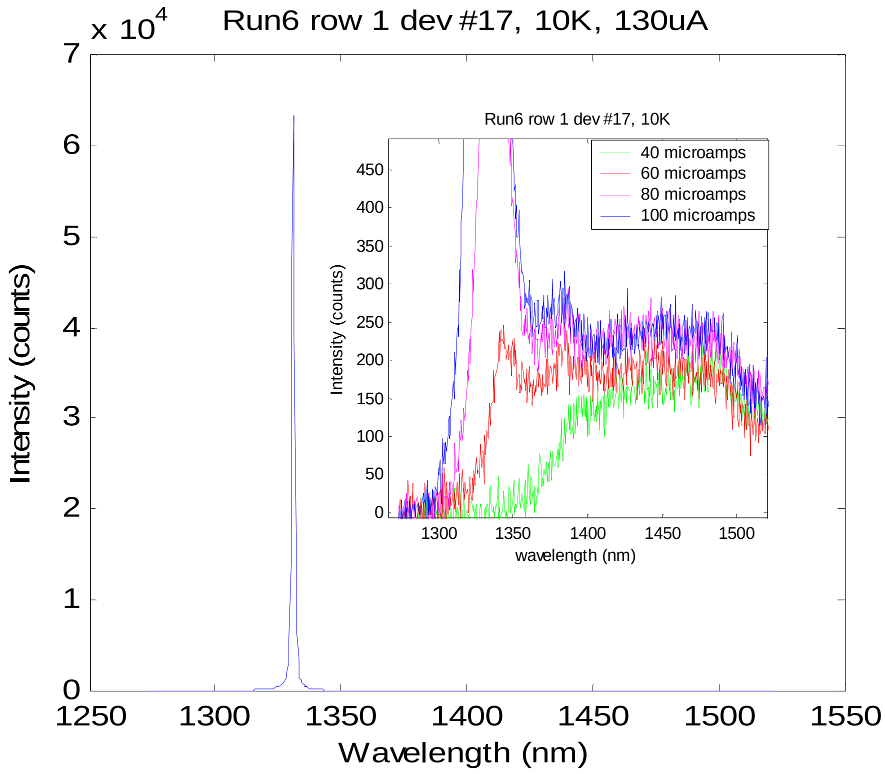


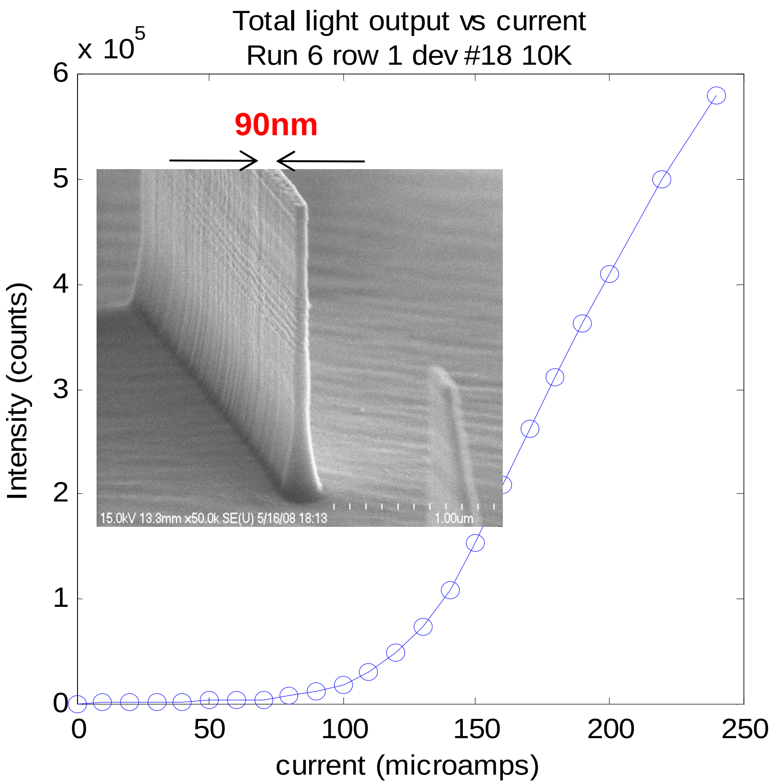


- **Circular pillars: diameters ~280nm to 500nm**
- **Rectangular pillars: 6 and 3 micron long; core width ~80nm +/- 20nm to ~340nm**

Hill, Marell, Leong, Smalbrugge, Zhu, Sun, Veldhoven, Geluk, Karouta, Oei, Nötzel, Ning, Smit, Opt. Exp.,17, 11107 (2009)

Lasing in a Silver-Coated 90+40 nm-Thick Pillar:
(thickness below half-wavelength limit)





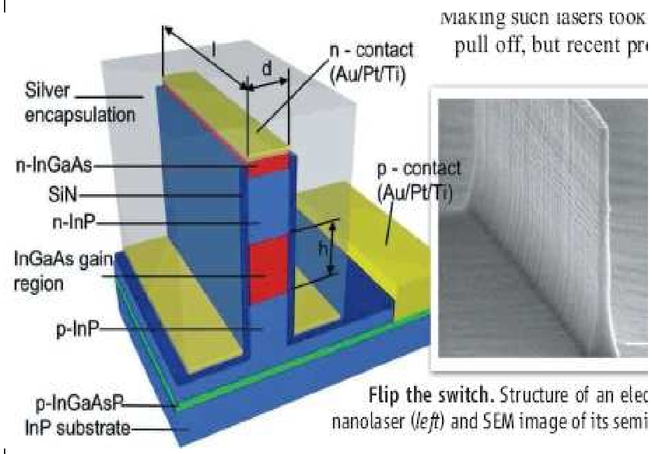
Optical thickness = 3.1X90 + 2X20X2 + 2X10X2 = 400 nm < DL $=\lambda/2=670\,nm$

(Semicond.) (Dielectric) (Metal)

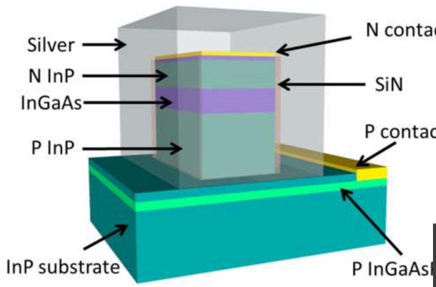
The thinnest electrical injection laser ever demonstrated !

Hill, Marell, Leong, Smalbrugge, Zhu, Sun, Veldhoven, Geluk, Karouta, Oei, Nötzel, Ning, Smit, Opt. Exp.,17, 11107 (2009)

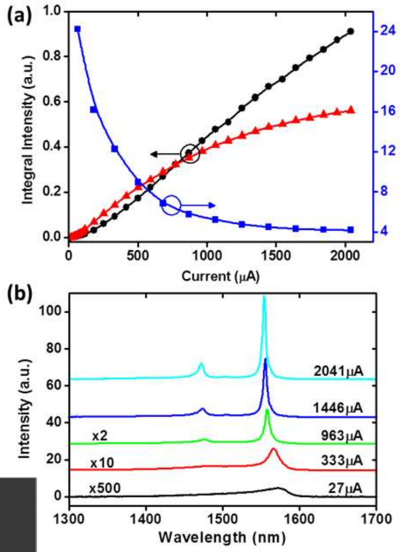
More Recent Progress on Nanolasers with $V < \lambda^3$

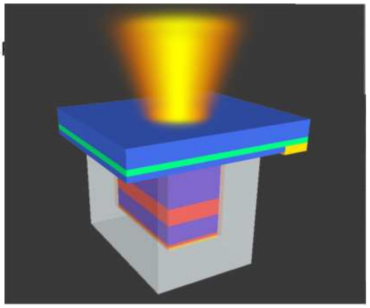


2009, pulse, LT



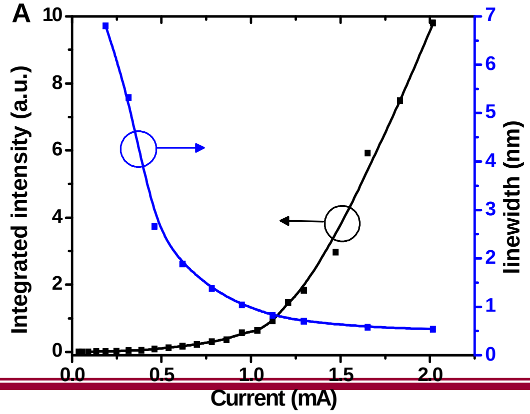
2011, CW 260K

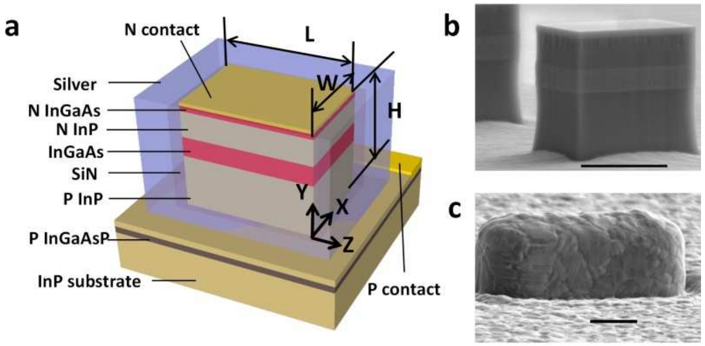


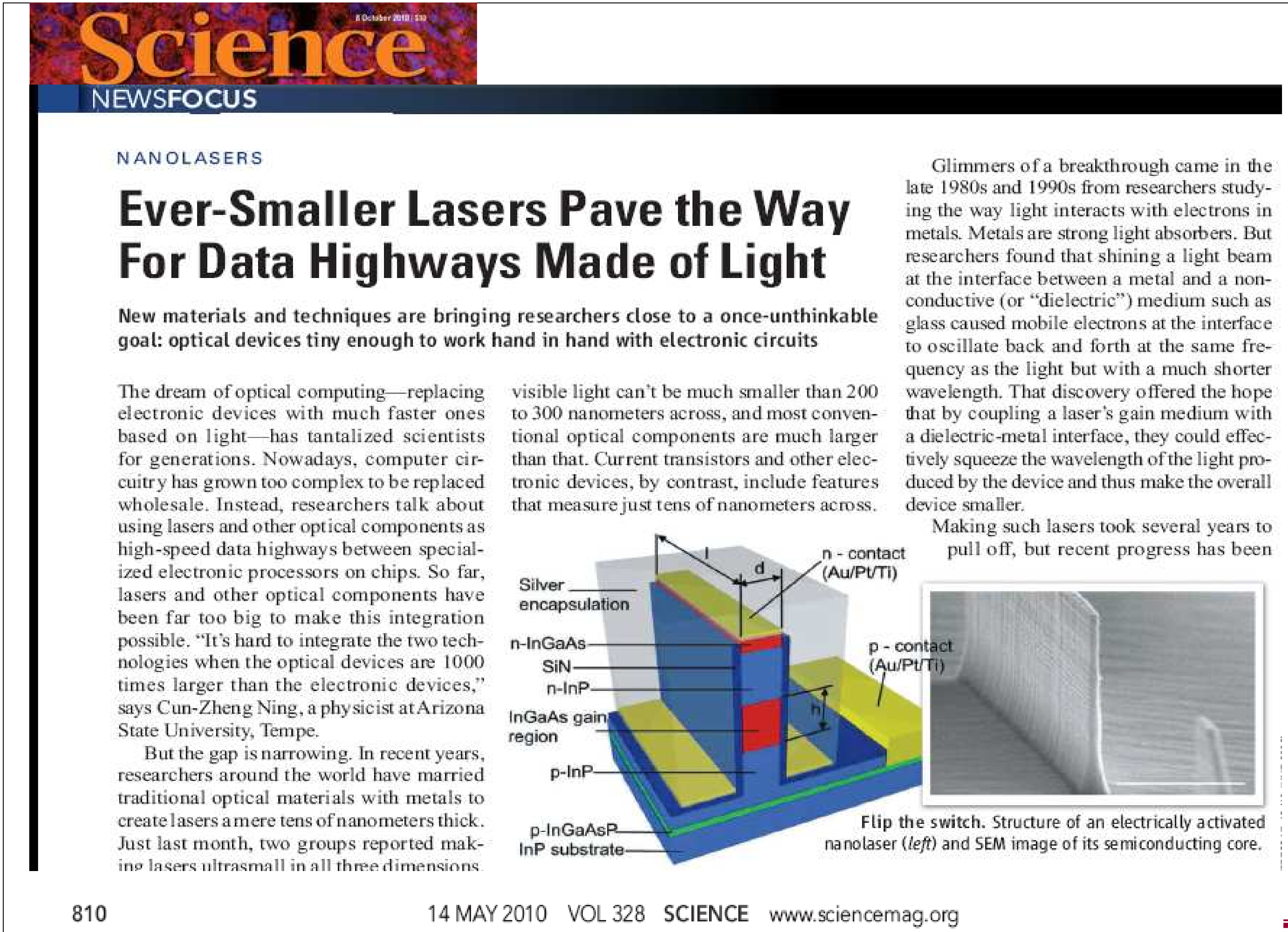


2012, CW, RT wide linewidth

2012, CW, RT final goal!







Science
8 October 2010 | $10
NEWSFOCUS

NANOLASERS

Ever-Smaller Lasers Pave the Way For Data Highways Made of Light

New materials and techniques are bringing researchers close to a once-unthinkable goal: optical devices tiny enough to work hand in hand with electronic circuits

The dream of optical computing—replacing electronic devices with much faster ones based on light—has tantalized scientists for generations. Nowadays, computer circuitry has grown too complex to be replaced wholesale. Instead, researchers talk about using lasers and other optical components as high-speed data highways between specialized electronic processors on chips. So far, lasers and other optical components have been far too big to make this integration possible. "It's hard to integrate the two technologies when the optical devices are 1000 times larger than the electronic devices," says Cun-Zheng Ning, a physicist at Arizona State University, Tempe.

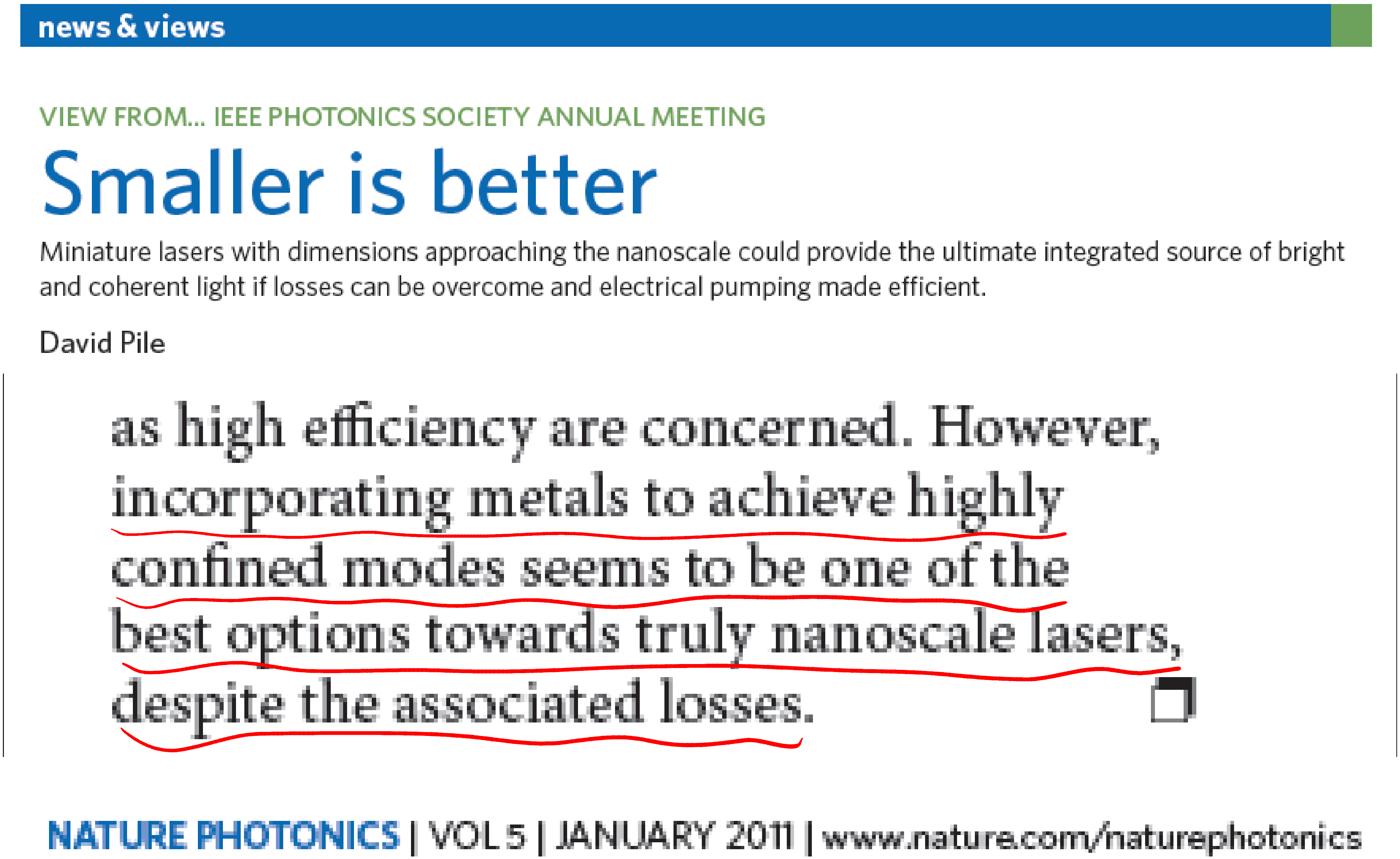
But the gap is narrowing. In recent years, researchers around the world have married traditional optical materials with metals to create lasers a mere tens of nanometers thick. Just last month, two groups reported making lasers ultrasmall in all three dimensions.

visible light can't be much smaller than 200 to 300 nanometers across, and most conventional optical components are much larger than that. Current transistors and other electronic devices, by contrast, include features that measure just tens of nanometers across.

Glimmers of a breakthrough came in the late 1980s and 1990s from researchers studying the way light interacts with electrons in metals. Metals are strong light absorbers. But researchers found that shining a light beam at the interface between a metal and a nonconductive (or "dielectric") medium such as glass caused mobile electrons at the interface to oscillate back and forth at the same frequency as the light but with a much shorter wavelength. That discovery offered the hope that by coupling a laser's gain medium with a dielectric-metal interface, they could effectively squeeze the wavelength of the light produced by the device and thus make the overall device smaller.

Making such lasers took several years to pull off, but recent progress has been

Flip the switch. Structure of an electrically activated nanolaser (*left*) and SEM image of its semiconducting core.



news & views

VIEW FROM... IEEE PHOTONICS SOCIETY ANNUAL MEETING

Smaller is better

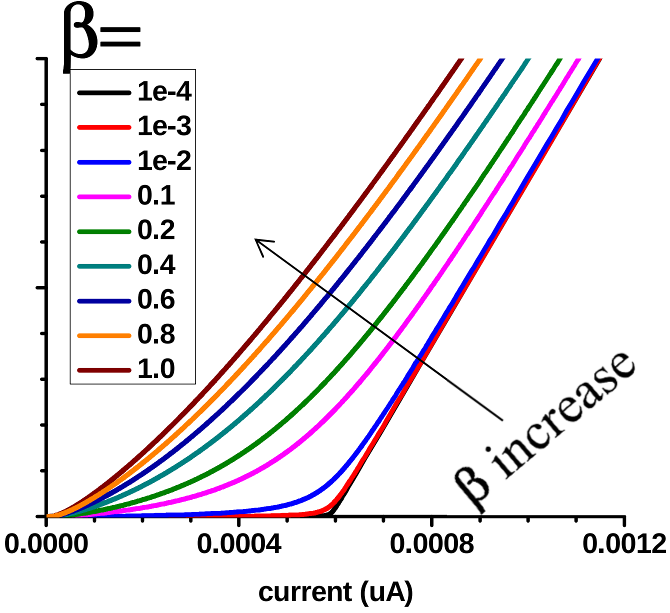
Miniature lasers with dimensions approaching the nanoscale could provide the ultimate integrated source of bright and coherent light if losses can be overcome and electrical pumping made efficient.

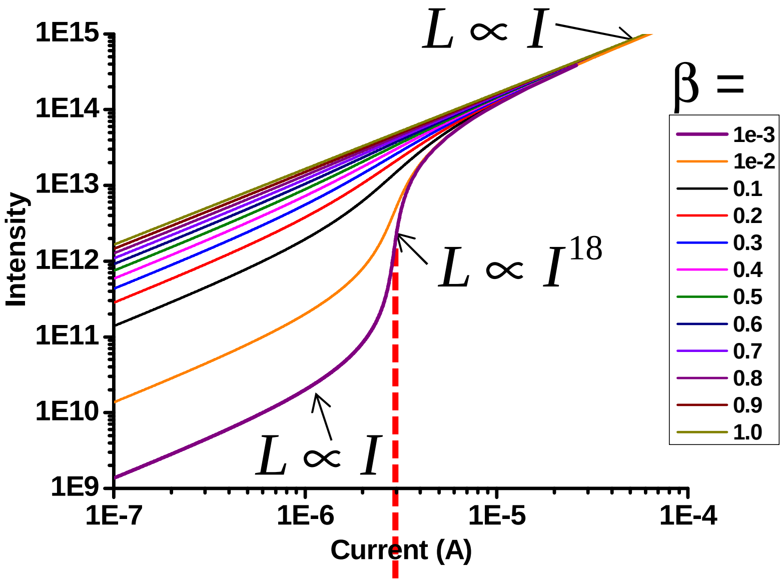
David Pile

as high efficiency are concerned. However, incorporating metals to achieve highly confined modes seems to be one of the best options towards truly nanoscale lasers, despite the associated losses. ☐

NATURE PHOTONICS | VOL 5 | JANUARY 2011 | www.nature.com/naturephotonics

Disappearance of Threshold in Nanolasers





$$\frac{1}{\beta} \propto V$$

Similar to disappearance of phase transitions in finite or lower dimensional systems, threshold becomes increasingly soft and disappears eventually in nanolasers as size decreases

Thresholdless? Yes.

But approaching zero (lasers)? or infinity (LED)?

Photon Statistics Near Threshold

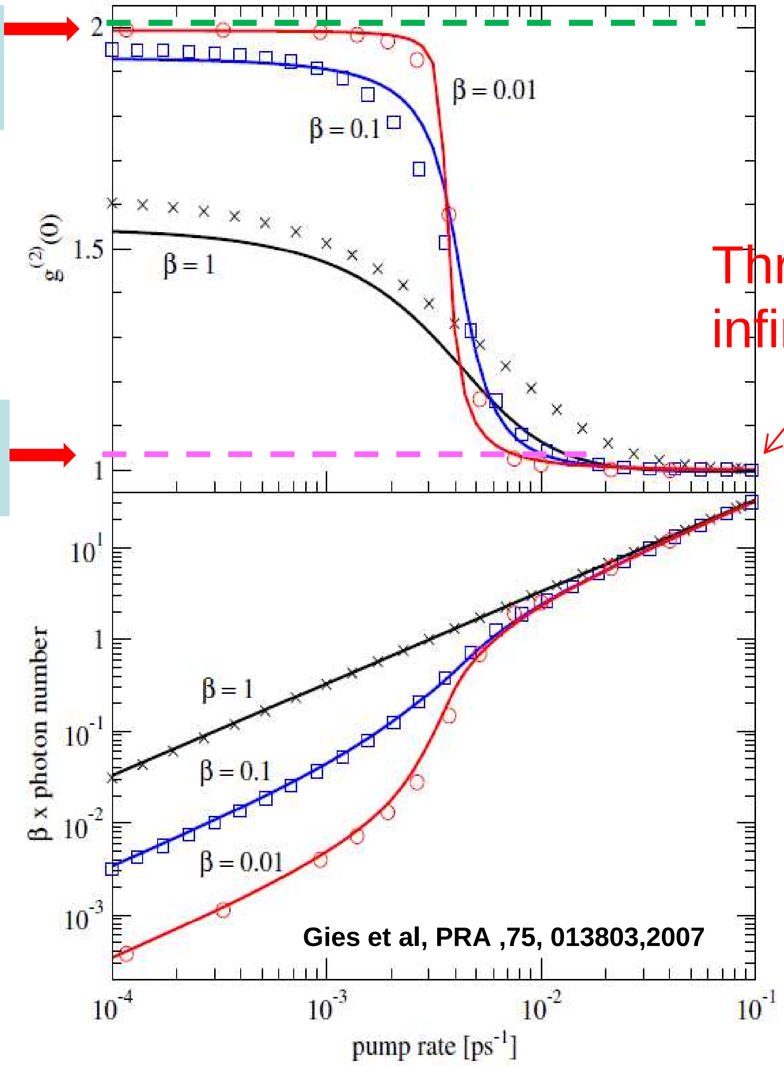
$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

thermal light

$$g^{(2)}(0) = 2$$

laser light

$$g^{(2)}(0) = 1$$

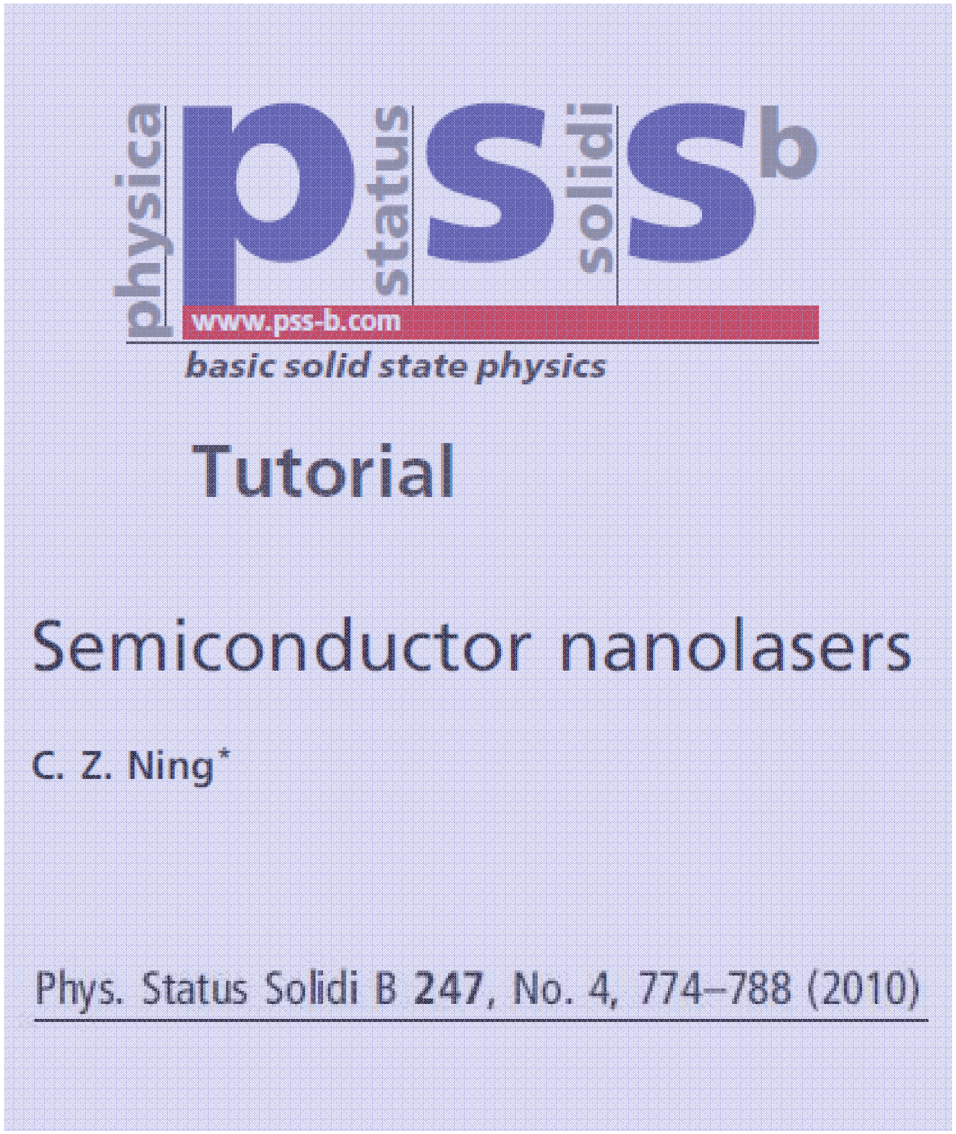


Gies et al, PRA ,75, 013803,2007

Threshold infinity?

There seems to be a more fundamental limitation (beyond gain requirement and cavity mode etc) to how small laser can be made: When size becomes too small, we cannot make a laser with the coherent state emission

Further on Nanolasers…



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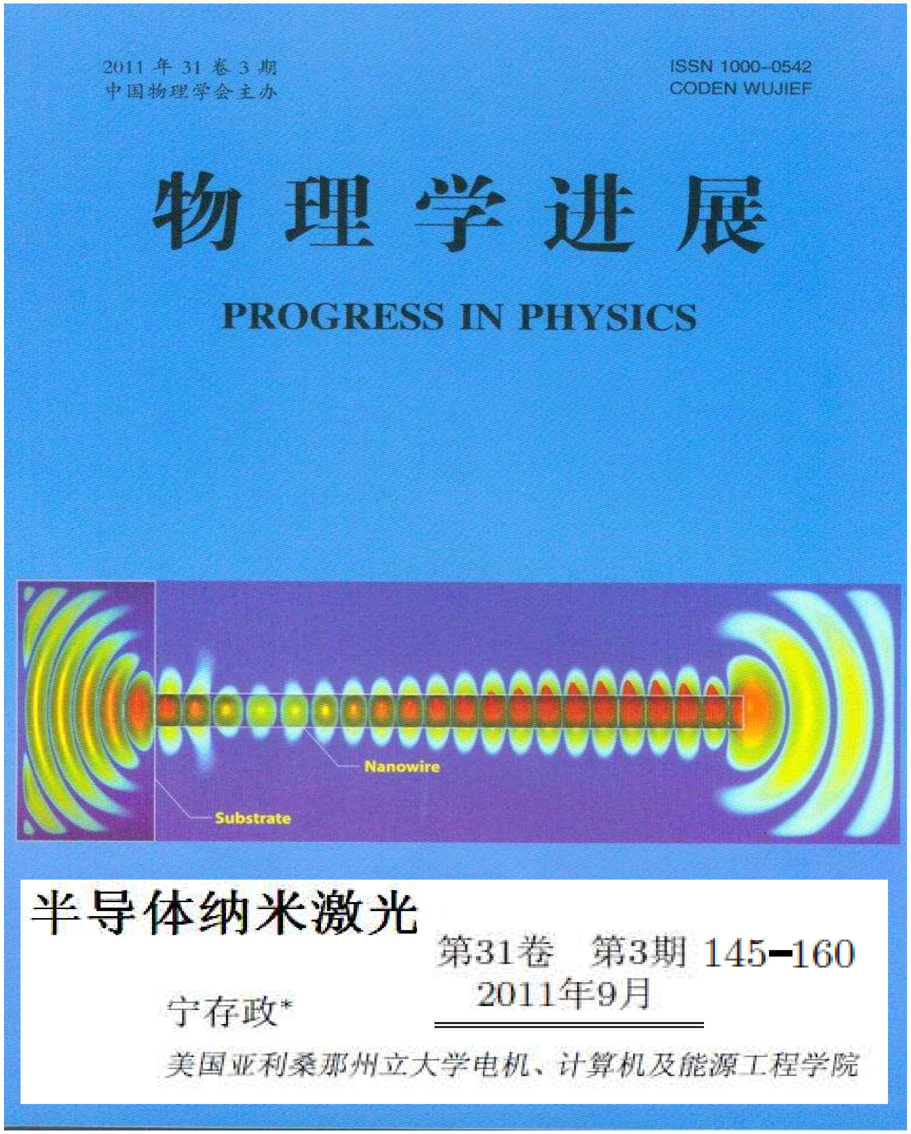
basic solid state physics

Tutorial

Semiconductor nanolasers

C. Z. Ning*

Phys. Status Solidi B **247**, No. 4, 774–788 (2010)



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Summary

- Nanolsaer research is driven both by the engineering of photonic and electronic densities of states and by future applications in nanophotonic integrated systems
- Plasmonic structures provide an interesting means for the cavity miniaturization to reach nanoscale
- There seems to be a fundamental limit in terms of how small a laser cavity can be: when the cavity is so small that spontaneous emission coupling to the lasing mode is approaching 100%, the threshold becomes increasingly high!

Thank You!