One-Dimensional Nanostructures as Subwavelength Optical Elements for Photonics Integration

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Pushing the Size Limits of Photonics

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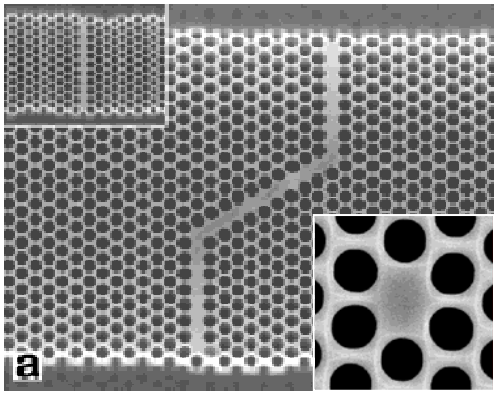
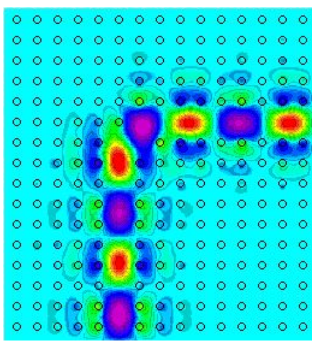
• Controlling the flow of light in small volumes – optical memory, logic, switching, etc.

Photonic Crystals (>1 μm)

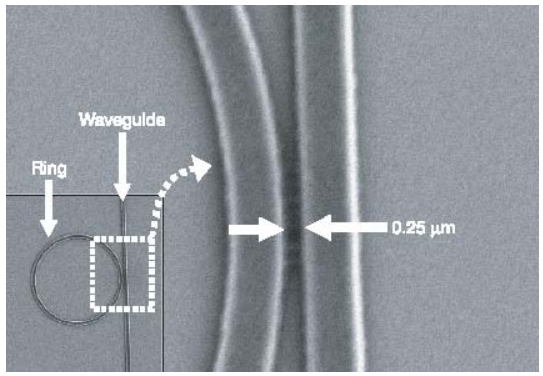


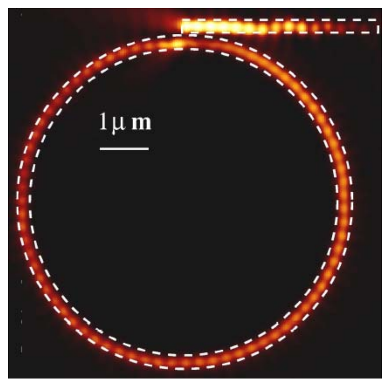


S.Y. Lin *et.al. Science* **282**, 274 (1998).

A. Birner *et. al. Adv. Mat.* **13**, 377 (2001).

Slab/Slot Waveguides (<1 μm)

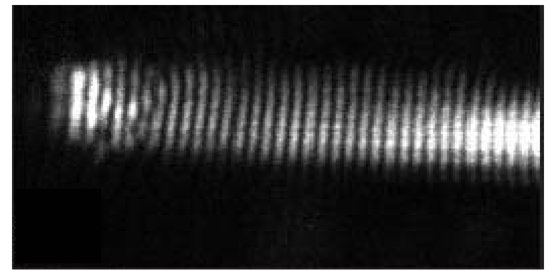


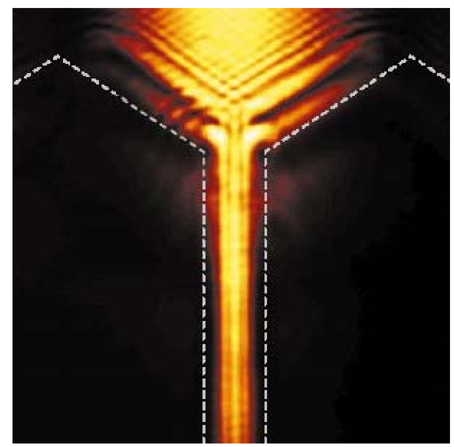


V.L. Almeida *et. al. Nature* **431**, 1081 (2004).

R. Quidant *et. al. Phys. Rev. B* **69**, 81402R (2004).

Plasmonics (< 100 nm)

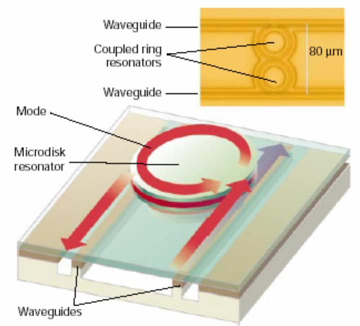


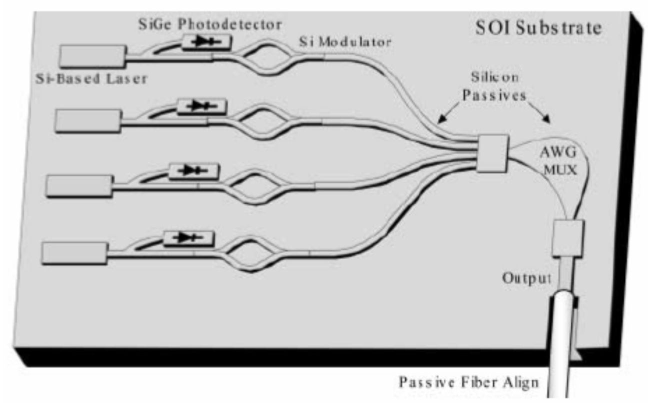


J.C. Krenn *et. al. Phil. Trans. R. Soc. Lond*. A ***362**, 739 (2004)*

Barnes *et. al. Nature* **424**, 824 (2003).

On-Chip Photonic Integration



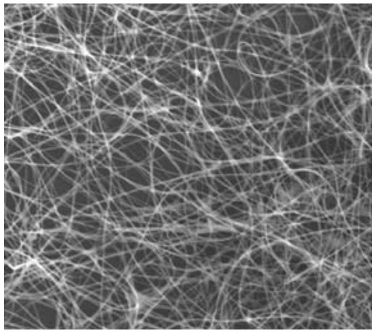


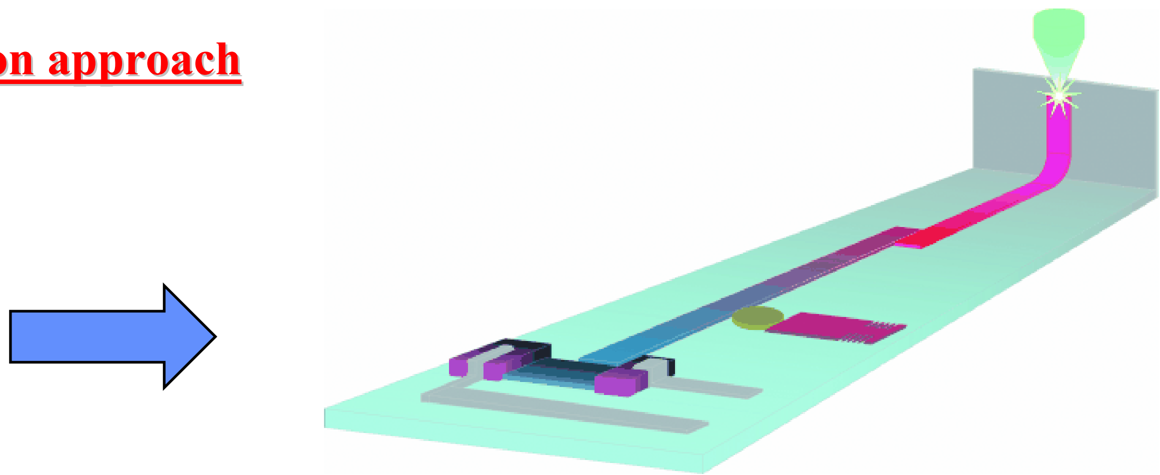
K. Djordjev *et. al. IEEE Phot. Technol. Lett.*, **14**, 828 (2002).
K.J. Vahala *Nature (Insight Review)*, **424**, 839 (2003).

M. Paniccia *et. al. Topics Appl. Phys.*, **94**, 51 (2004).

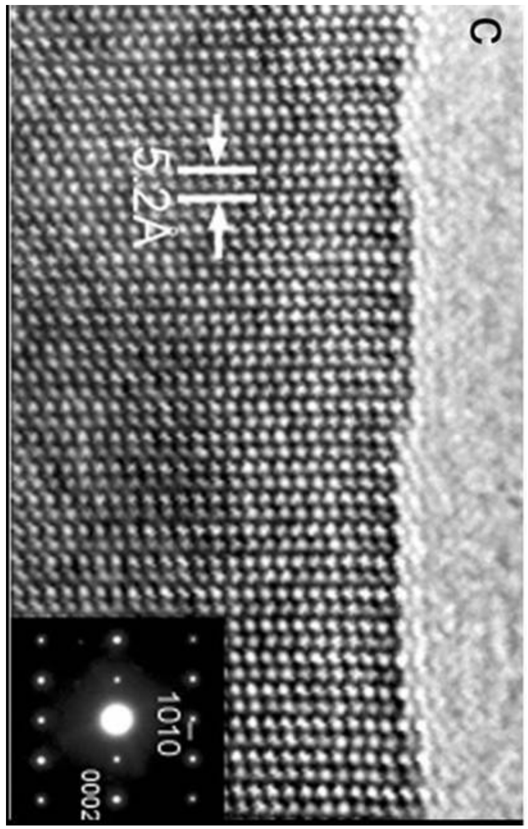
SOI fabrication approach

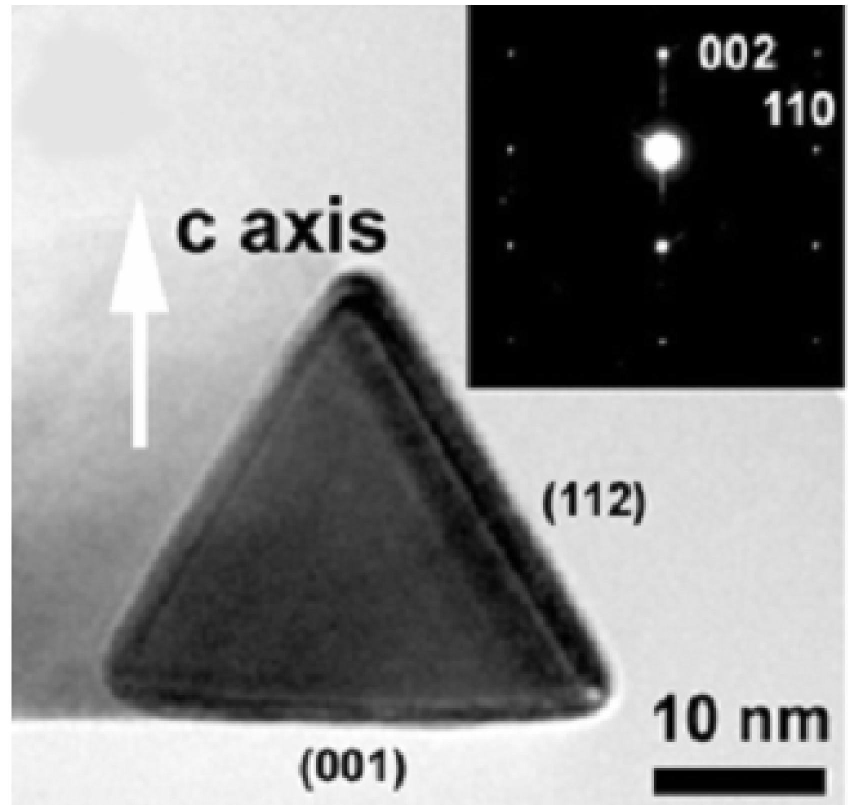
Heterogeneous Integration approach





Single Crystalline, Single Domain, Facetting



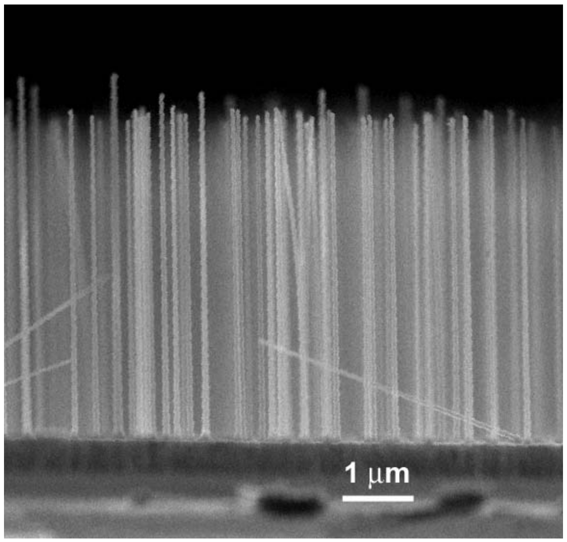


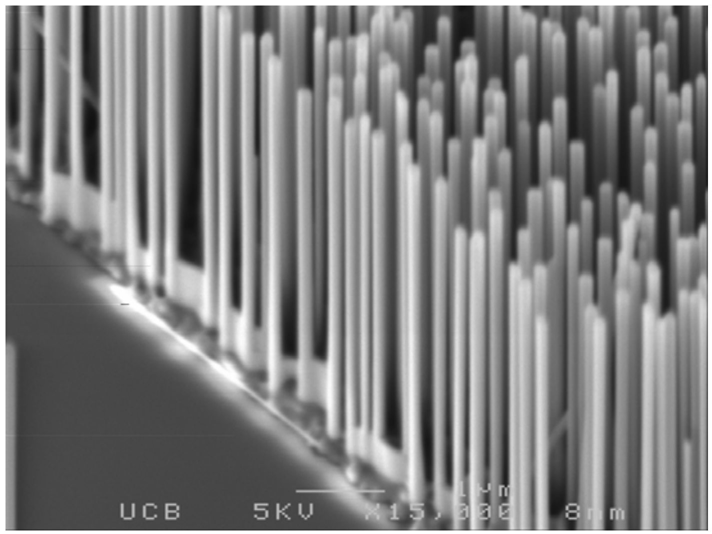
H. Yan et al. *Adv. Func. Mater*. 12, 323,2002
T. Kuykendall, P. Pauzauskie, et al. Nano. Lett. 3, 1063, 2003.

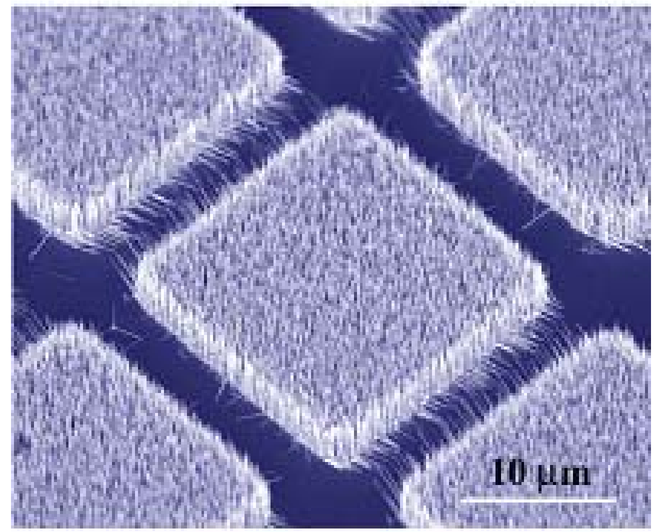
Vapor-Liquid-Solid Epitaxy

Si Nanowire Arrays

GaN Nanowire Arrays







ZnO Nanowire Arrays

P. Yang, Adv. Mater. 15, 353, 2003.
Y. Wu et al. Chemistry, Euro. J. 8, 1260, 2002
M. Law et al. Annu. Rev. Mater. Sci. . 34, 83, 2004

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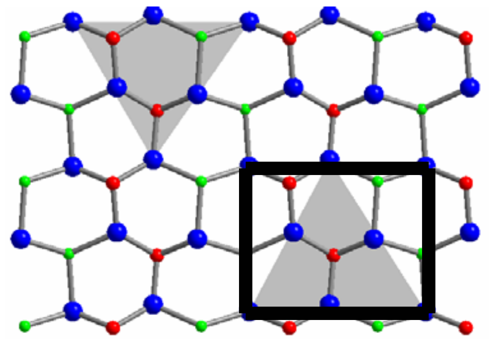
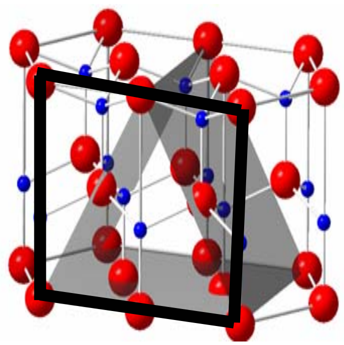
University of California, Berkeley

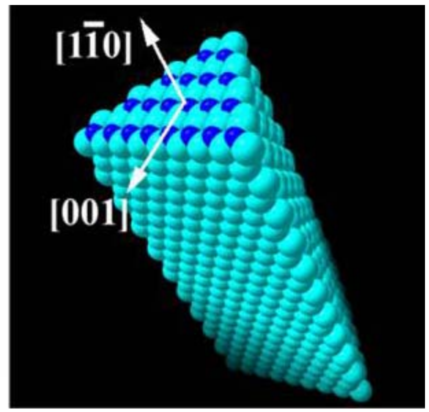
Growth Direction Control

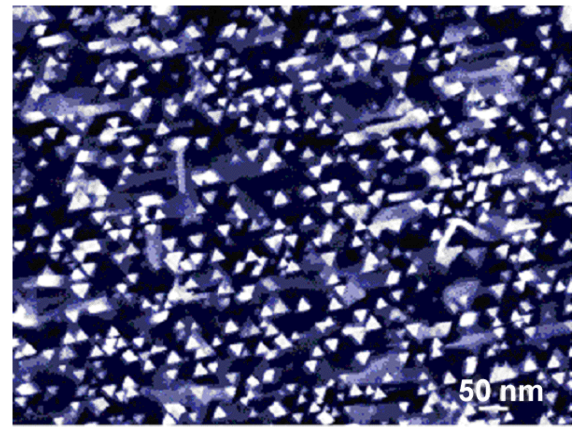
< 1 $\bar{1}$ 0 > Alignment: GaN

γ-$LiAlO_2$ (100)



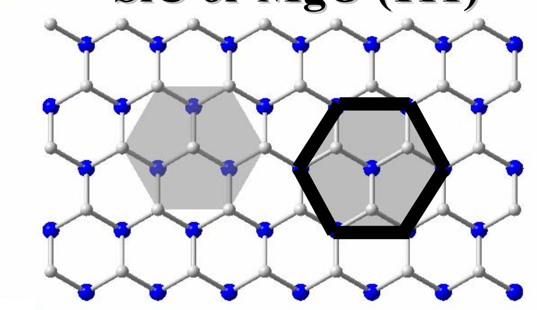


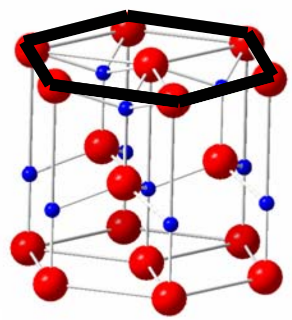


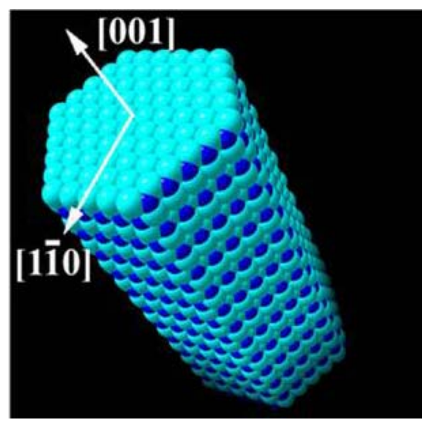


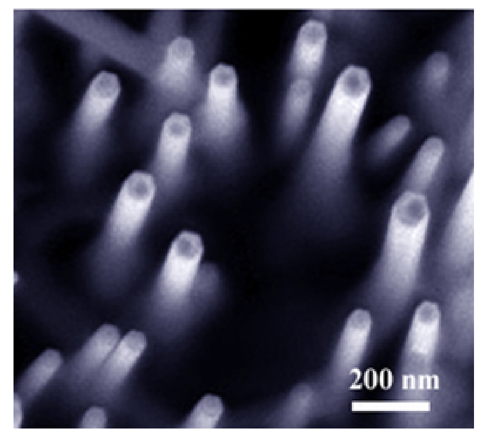
< 0 0 1 > Alignment: GaN

SiC or MgO (111)









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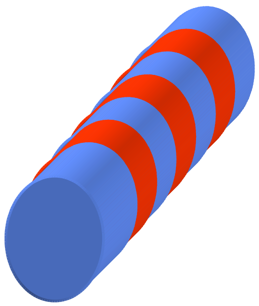
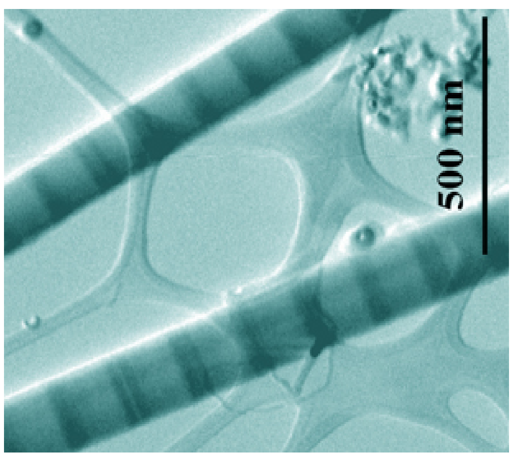
T. Kuykendall, P. Pauzauskie et al. Nature Mater. 3, 528,2004

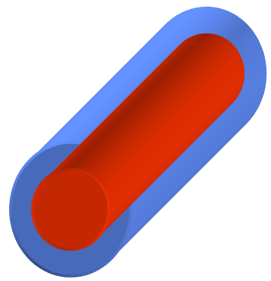
Interface within Nanowires

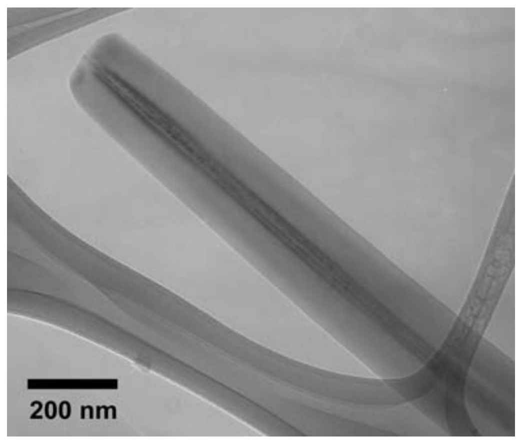
Superlattice



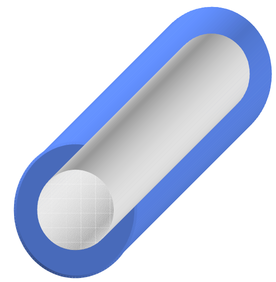


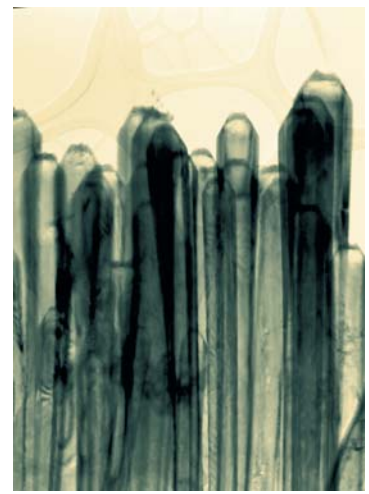
Core-Sheath





Nanotube



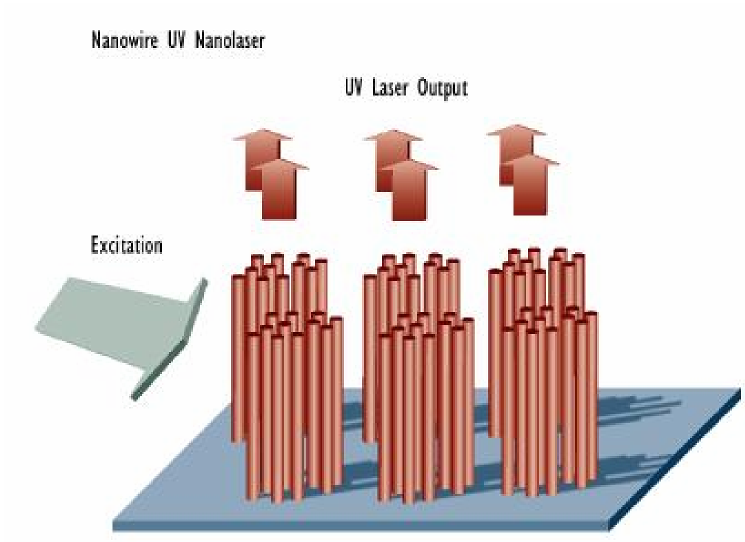


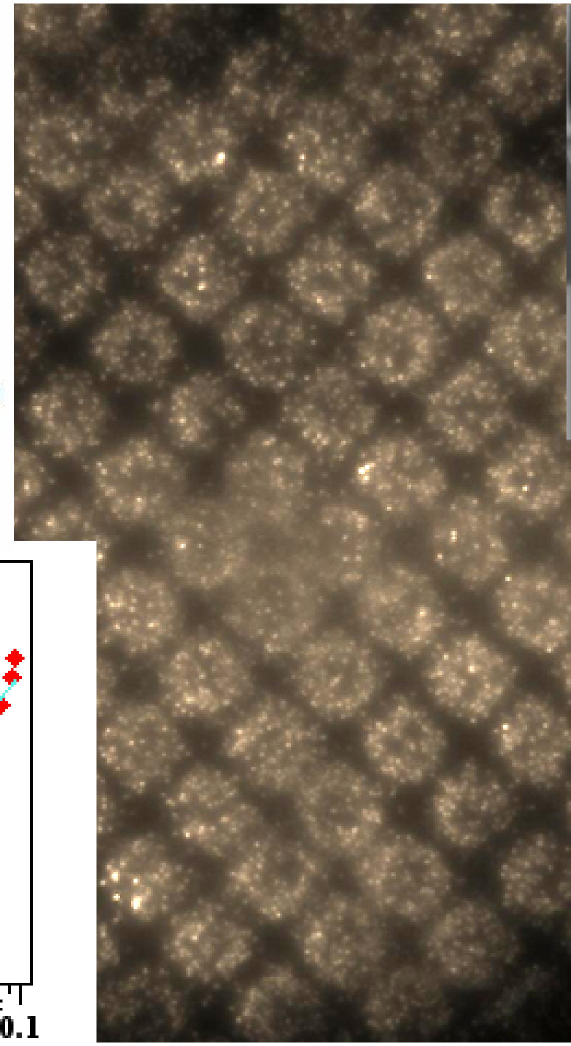
Y. Wu et al.Nanolett, 2, 83, 2002.

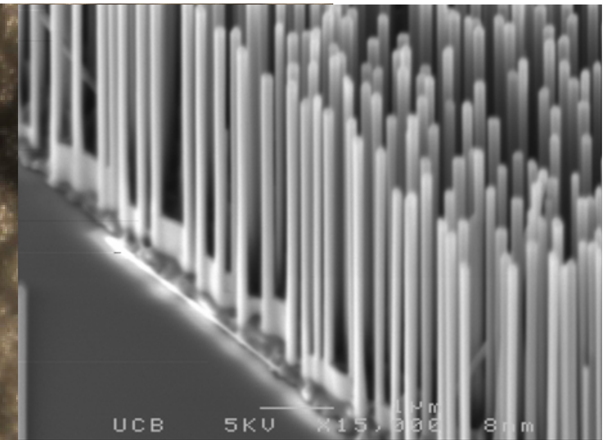
J. Goldberger et al. Nature, 422, 599, 2003 .

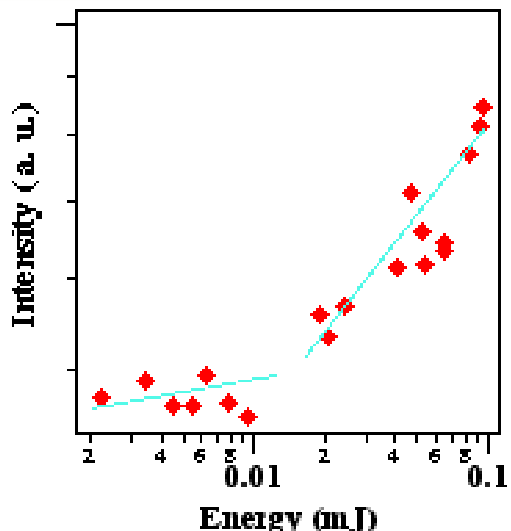
H. Choi et al. J. Phys. Chem. B 107, 8721, 2003.

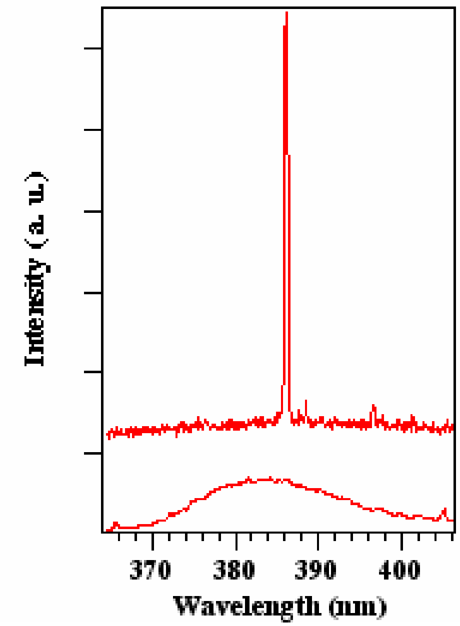
Semiconductor Nanowire Microcavities











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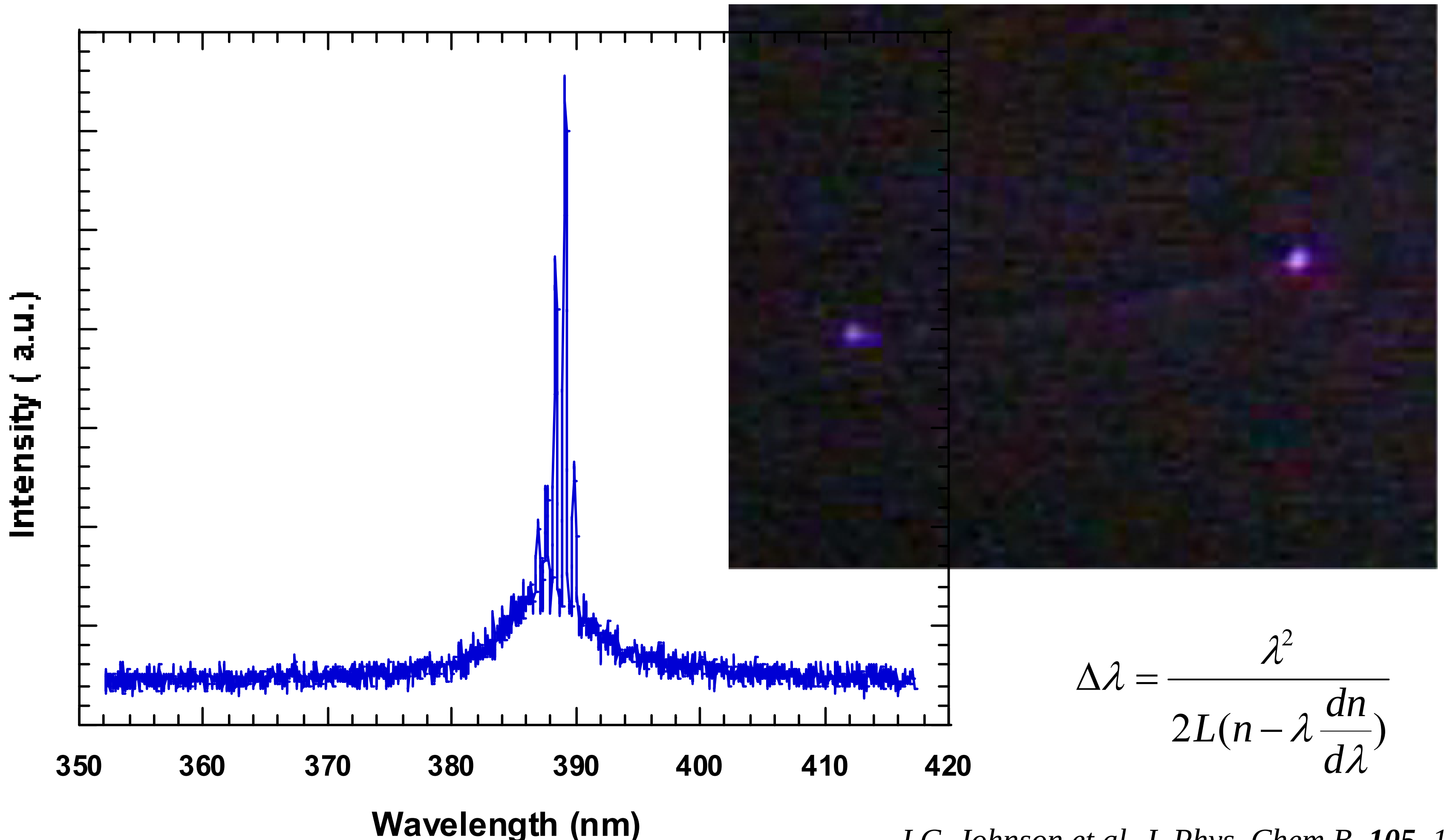
M. Huang et al. Science, 292, 1897, 2001.

Lasing Single ZnO Nanowire



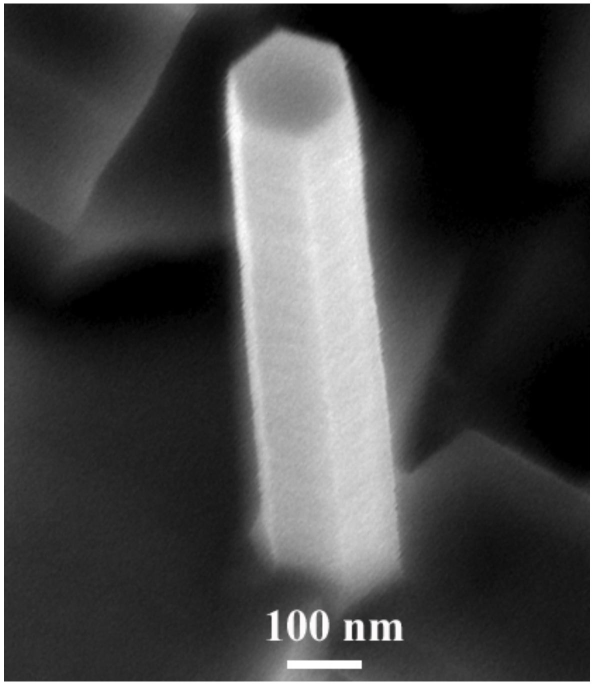
$$\Delta\lambda = \frac{\lambda^2}{2L(n - \lambda \frac{dn}{d\lambda})}$$

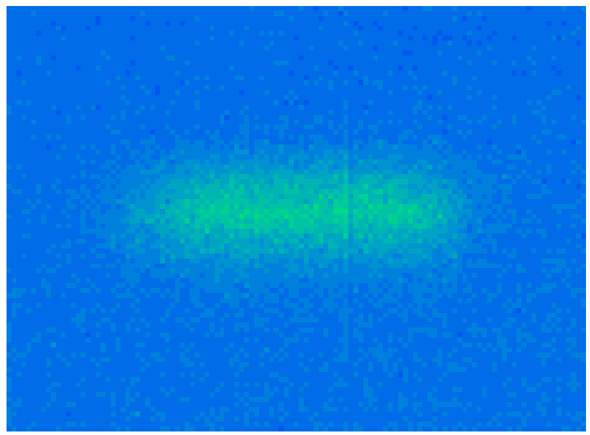
J.C. Johnson et al. J. Phys. Chem B ***105****, 11387 (2001).*

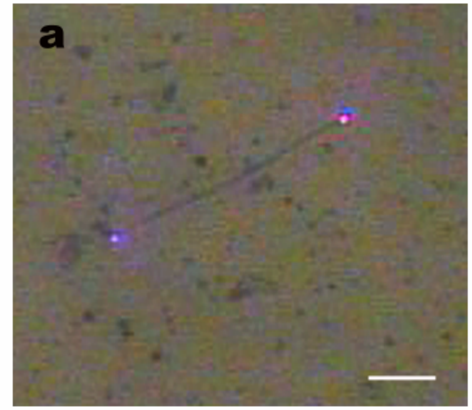
J. C. Johnson et al. J. Phys. Chem. B, 107, 8816, 2003.

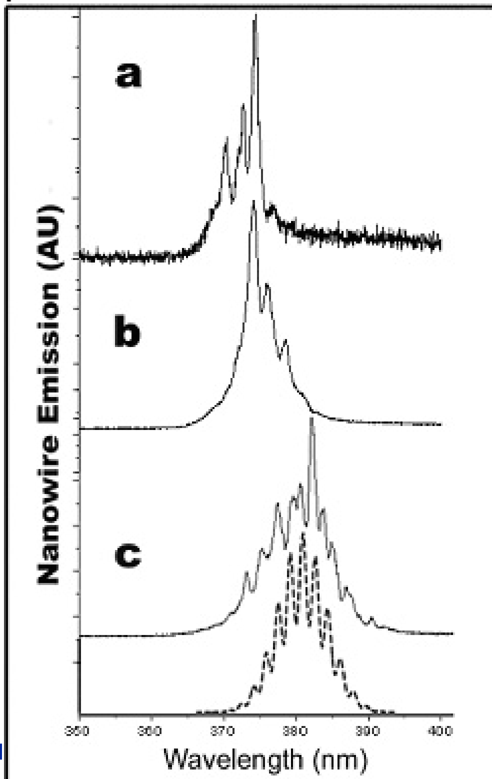
H. Yan et al. Adv. Mater. 2004

GaN Nanowire Nanolaser







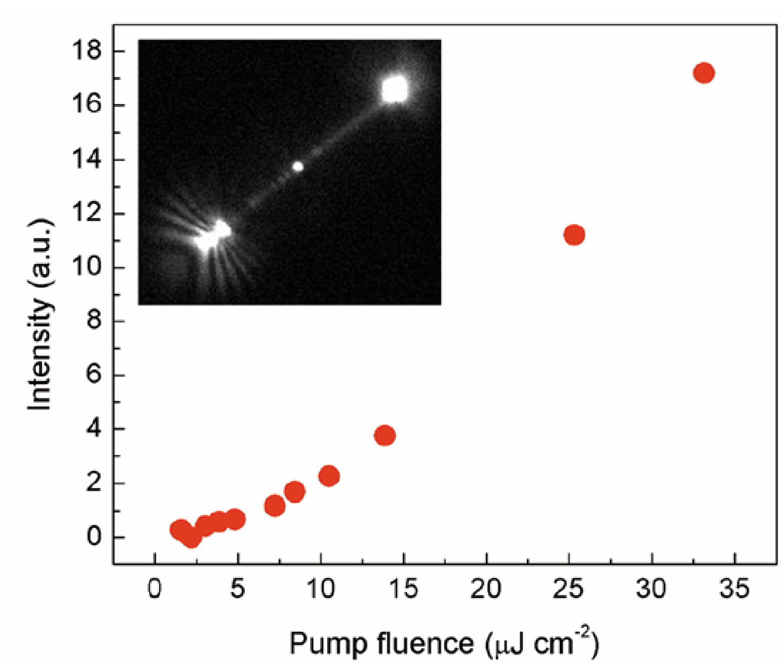


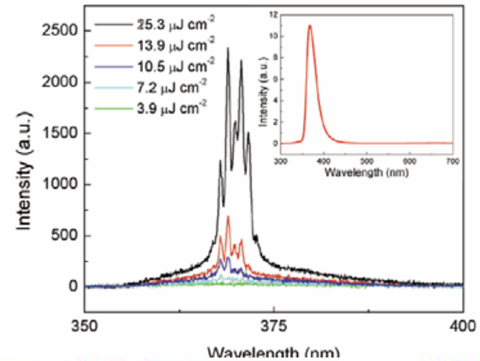
$$\Delta\lambda = \frac{\lambda^2}{2L(n - \lambda \frac{dn}{d\lambda})}$$

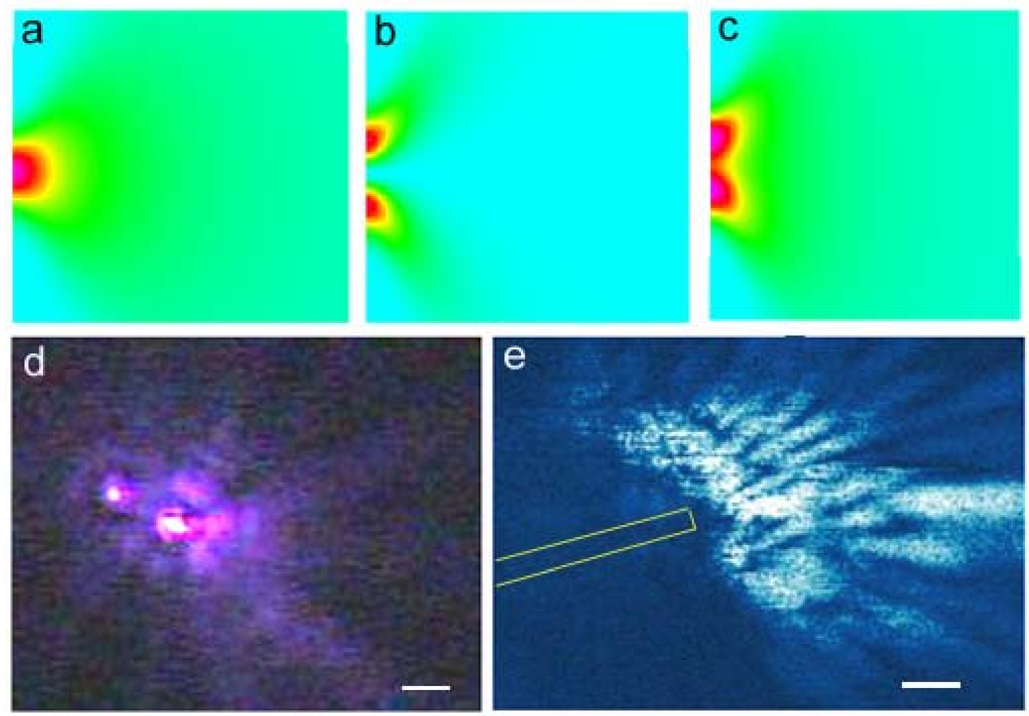
Nature Materials 1, 101,2002

Complex far-field emission pattern

- Evidence for coherent laser pulses (GaN and ZnO)

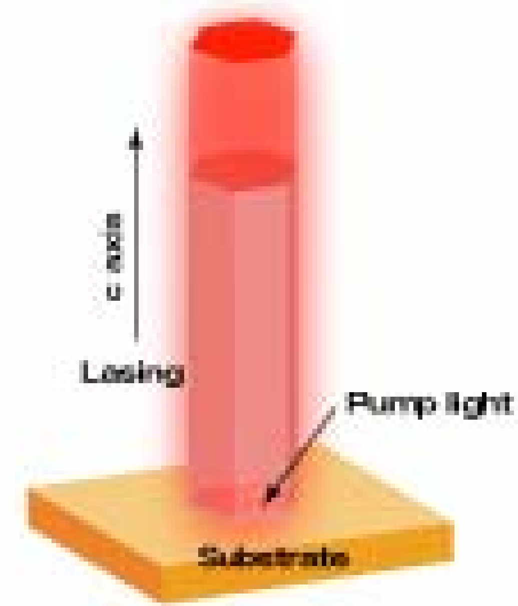






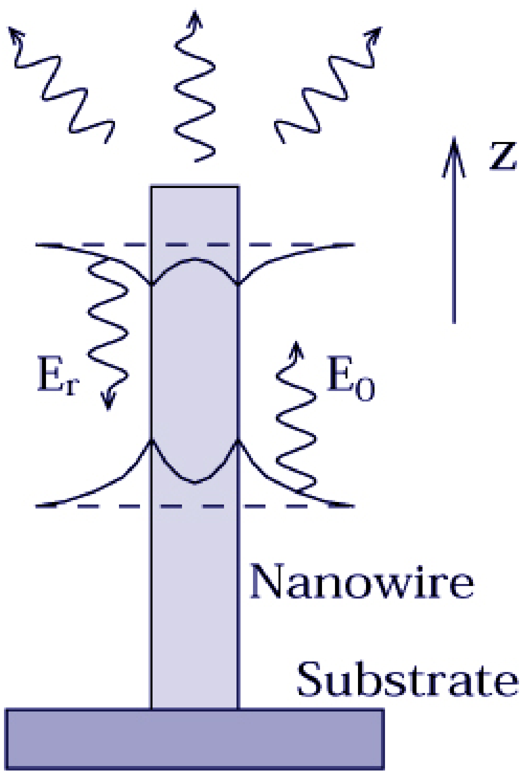
Nanowire microcavity/laser

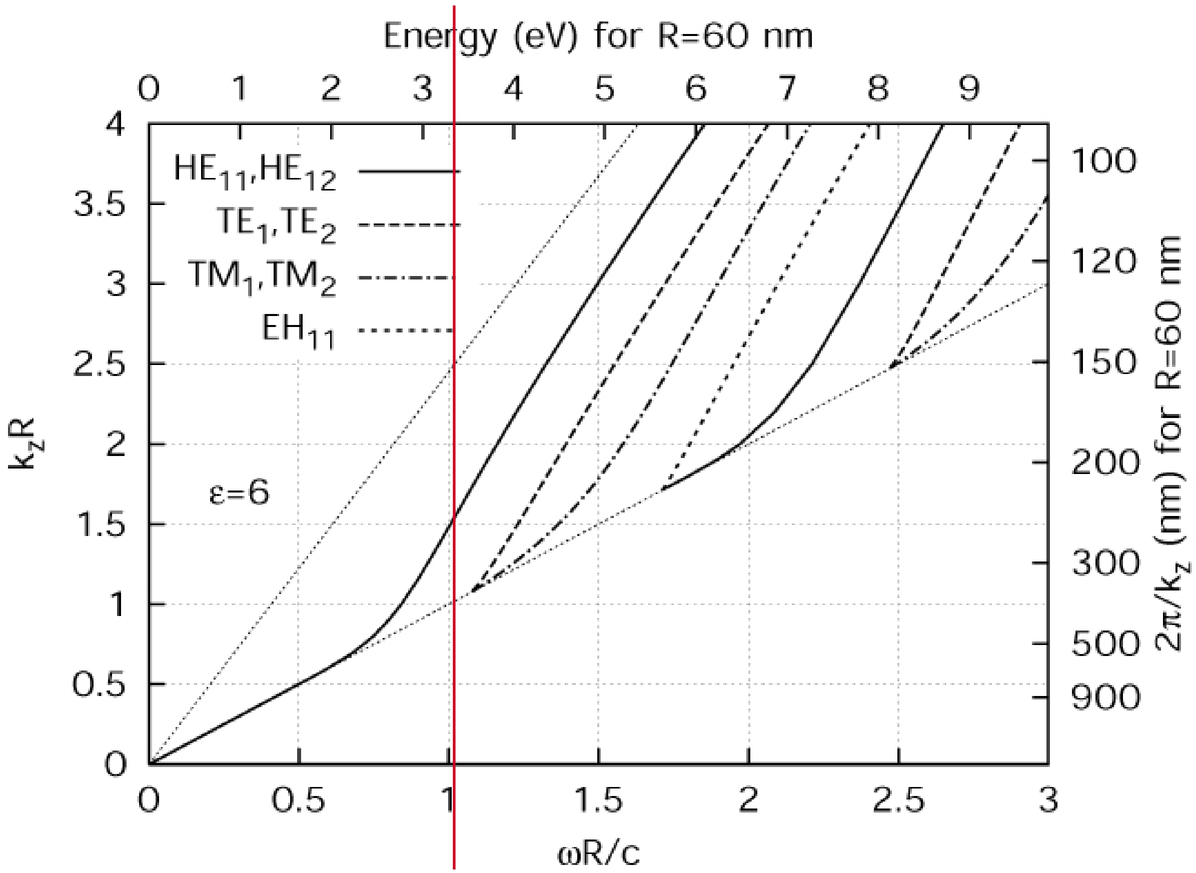
- Highly Facetting/Single Crystalline
- Lower limit $\lambda/2n$: r > 60 nm
- G_{th}: ***400 – 3000 cm^{-1}***
- High-Q: ***500-1500***
- Lower lasing threshold: ~ 70 nJ/cm^2 (sub-ps pulses)



J. Phys. Chem. B, 107, 8816, 2003

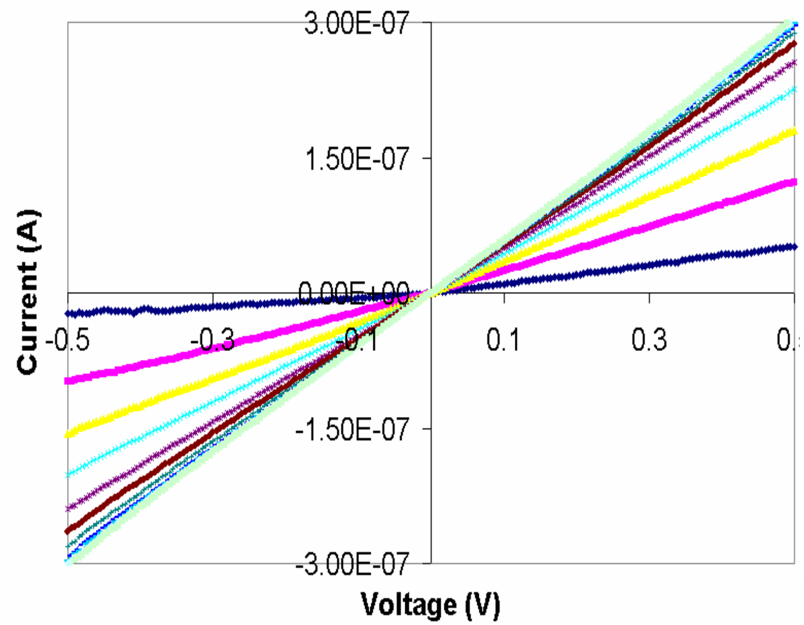
Theoretical Simulation: Nanowire Lasers

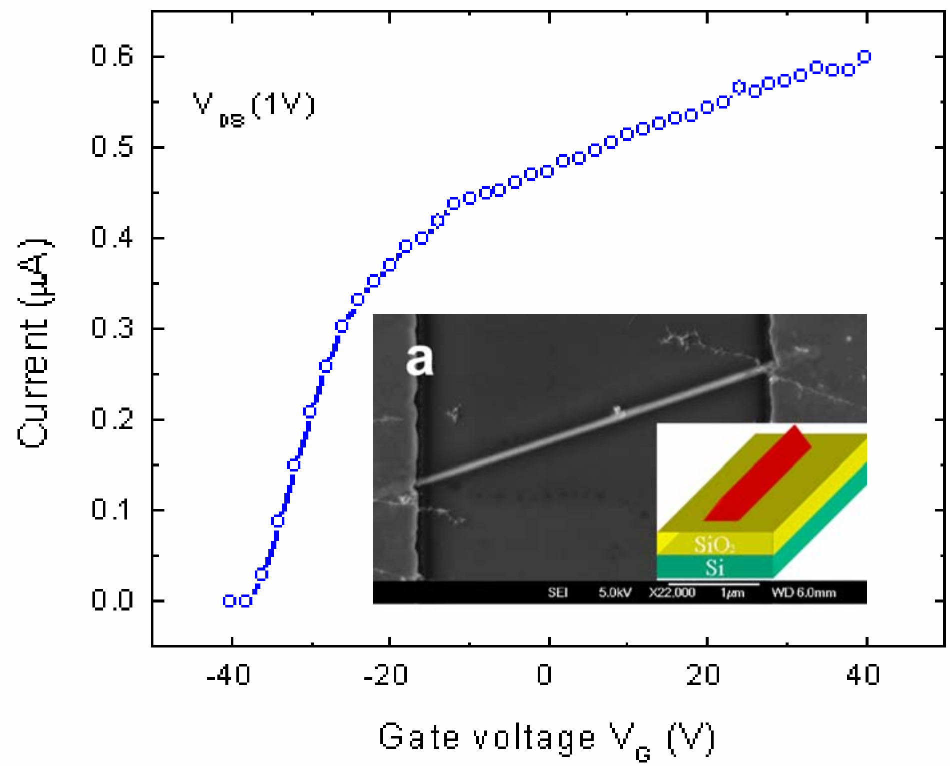




C. Ning et al. APL, 83, 1237, 2003

GaN Nanowire Transistor: n-type





$$\frac{dI}{dV_G} = \mu \cdot \left(\frac{C}{L^2}\right) \cdot V_{DS}$$

~ 50-200 cm²/V.s

$$n_e = \frac{Q}{e \times \pi r^2 \times L}, \qquad Q = C \cdot V_{th}$$

$$1 - 3 \times 10^{18}\, cm^{-3}$$

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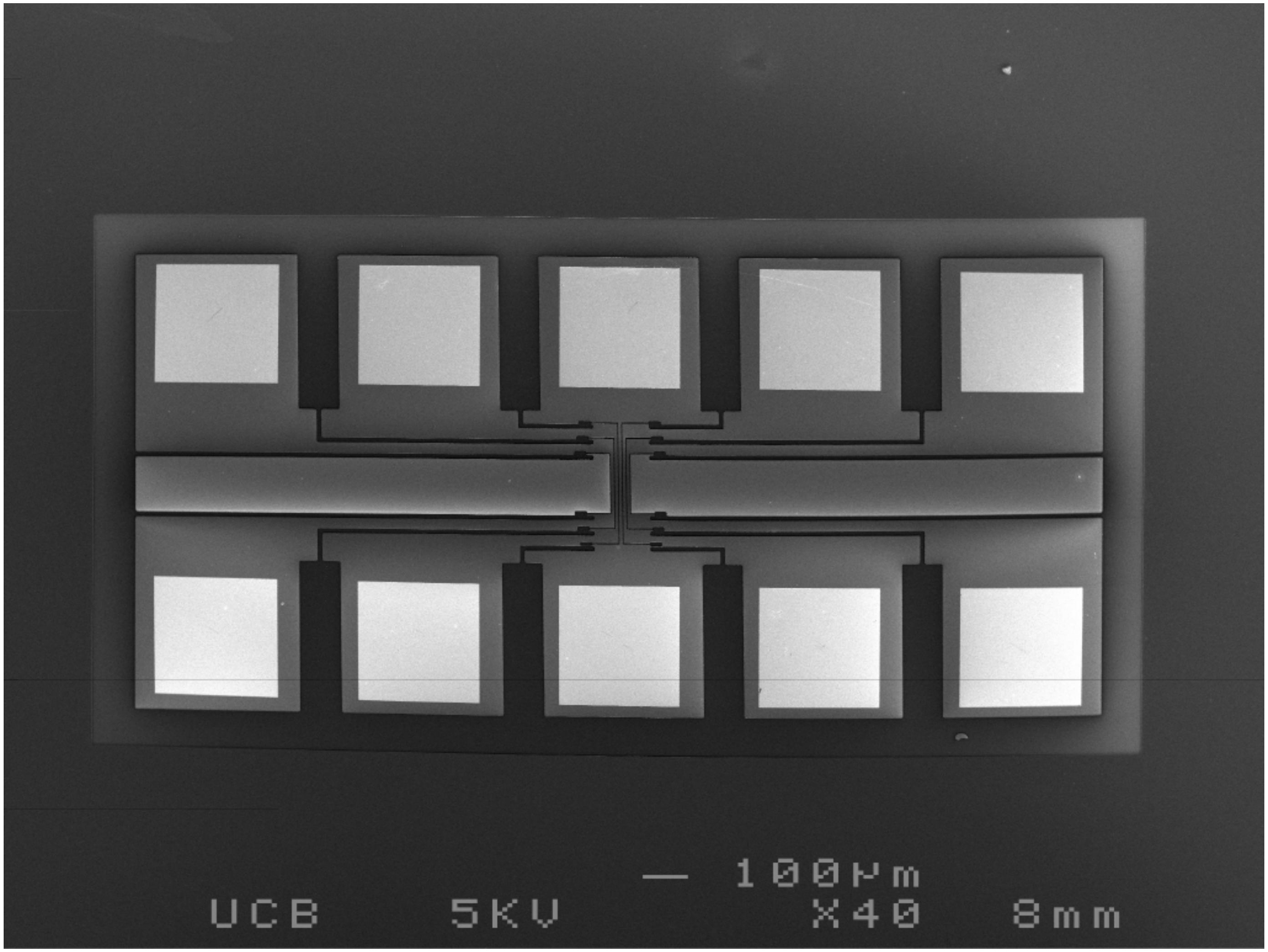
Nano. Lett. 3, 1063, 2003.

p-SOI/ n-GaN Nanowire Matrix LED



H. Yan, J. Goldberger, Unpublished Results

p-SOI/ n-GaN Nanowire Matrix LED

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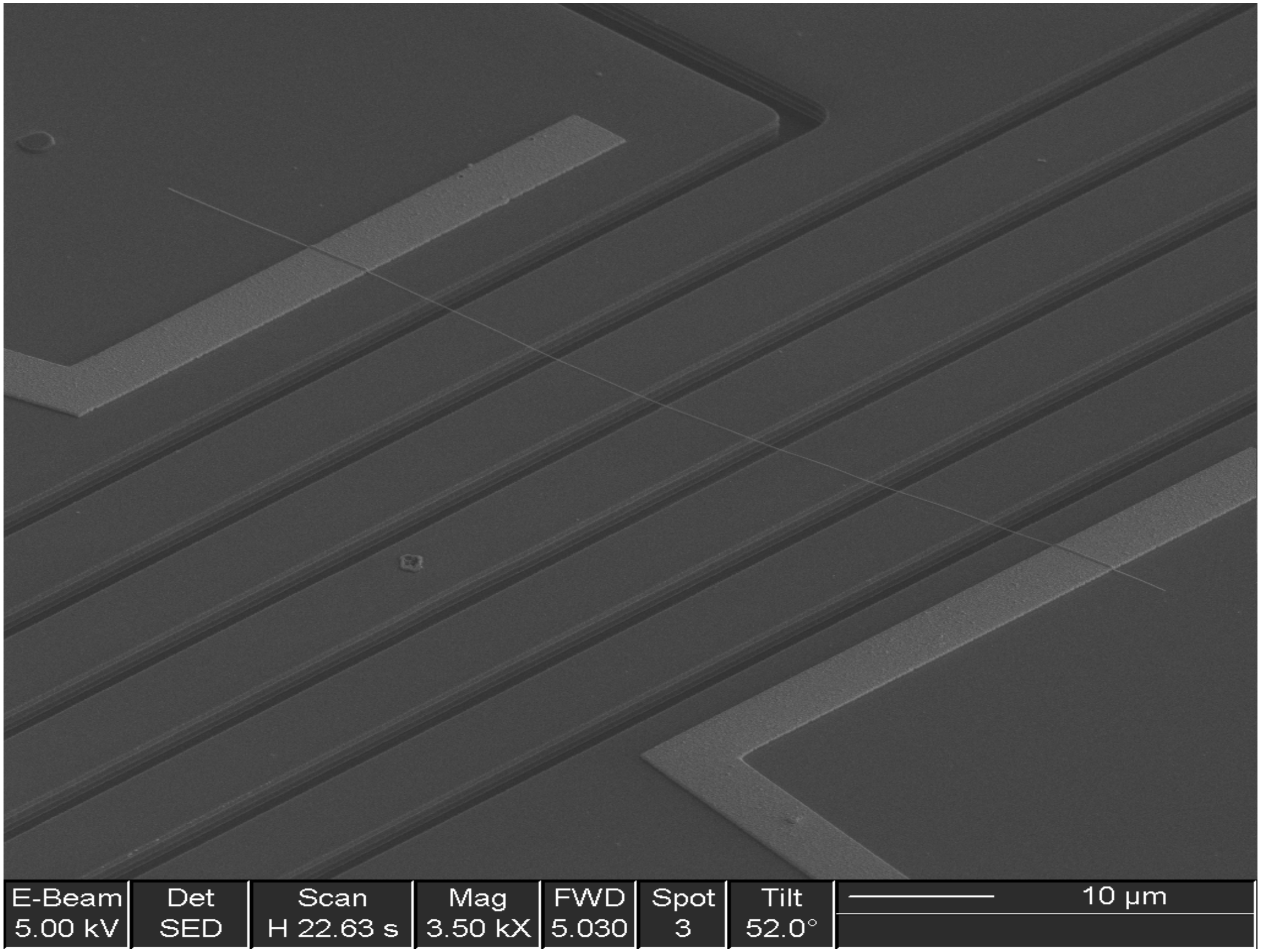

H. Yan, J. Goldberger, Unpublished Results

Addressable UV LED Array

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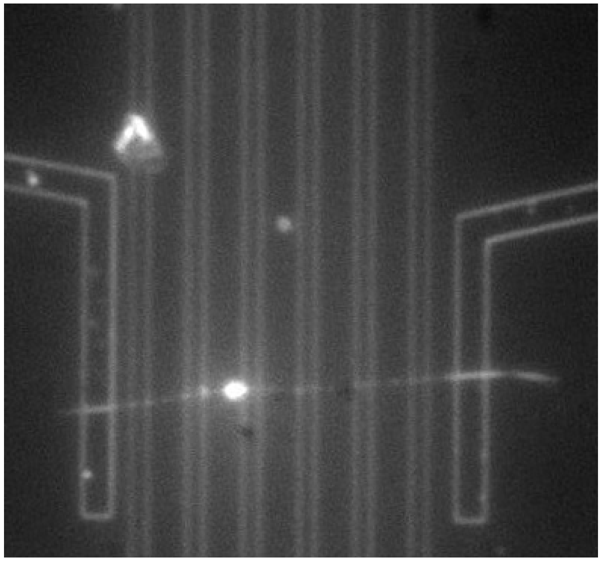

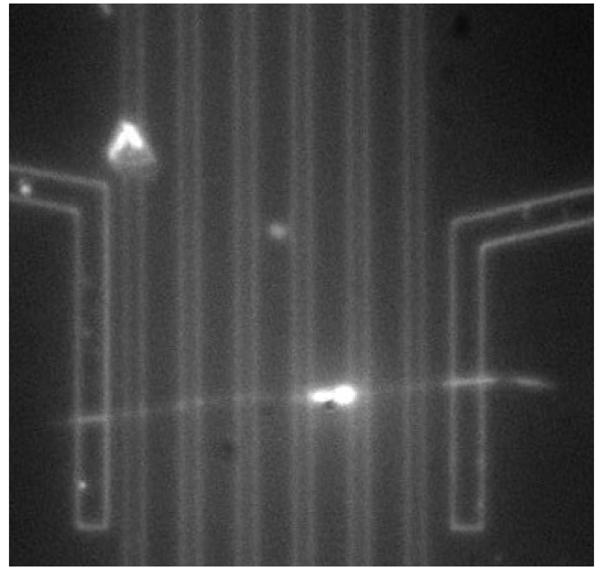

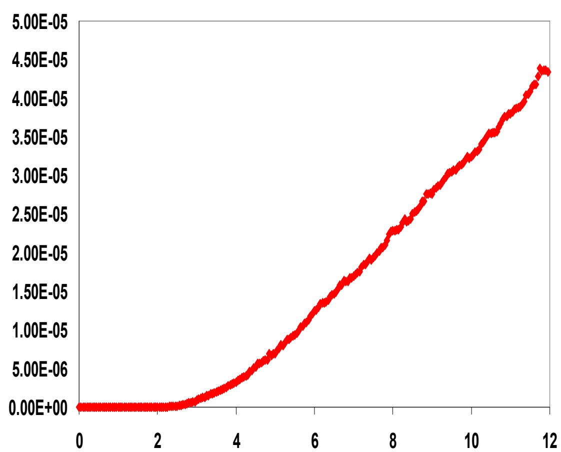

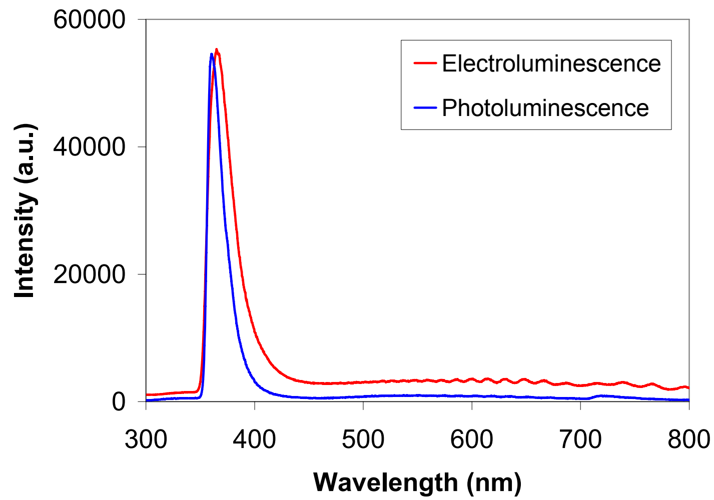

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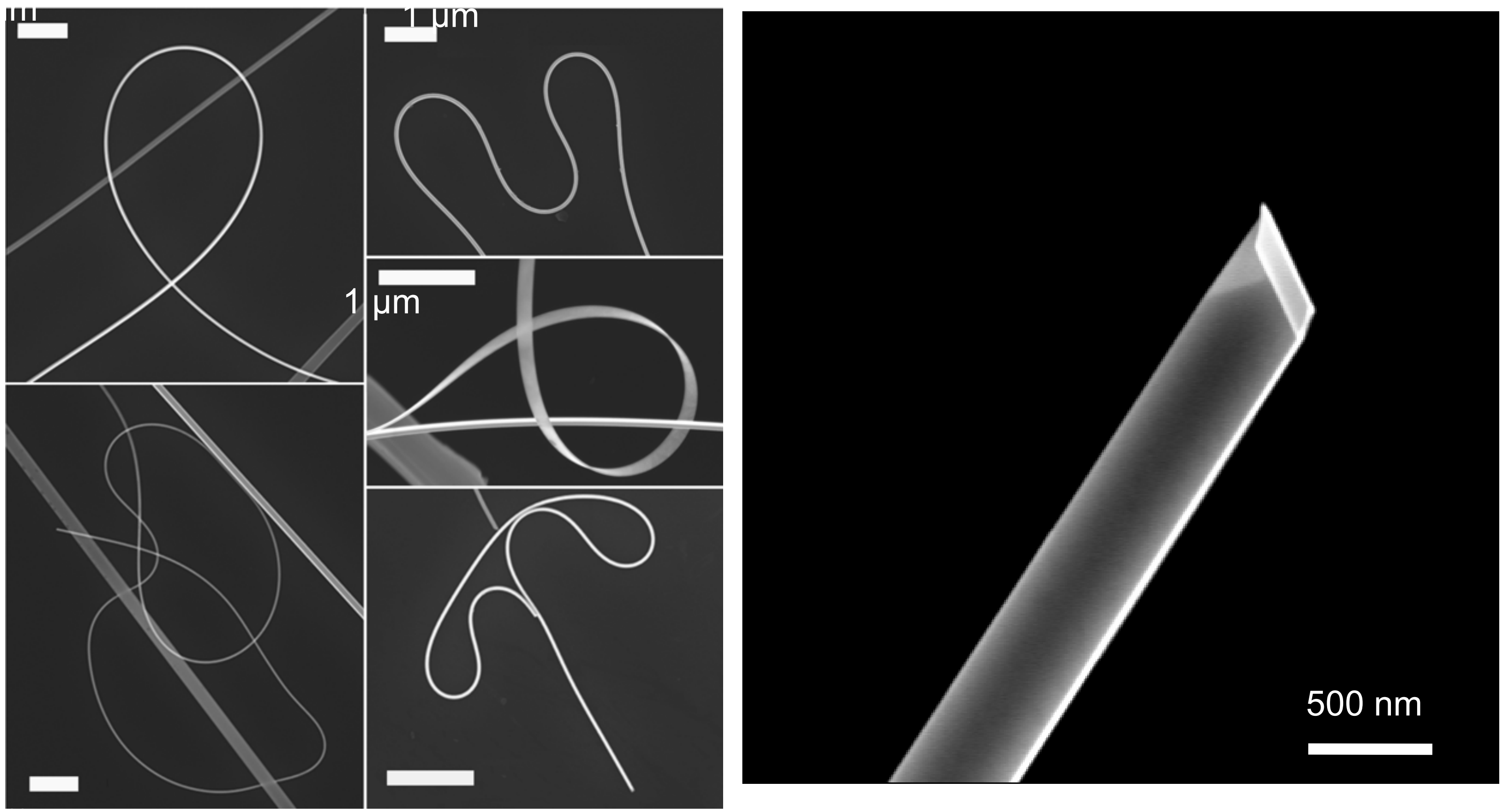
Subwavelength oxide Nanoribbon Waveguides and Optical Elements



Dimensions: **Length > 1.5 mm** **Width 200 – 500 nm** **Thickness 100 – 300 nm**

Aspect ratios > 1000

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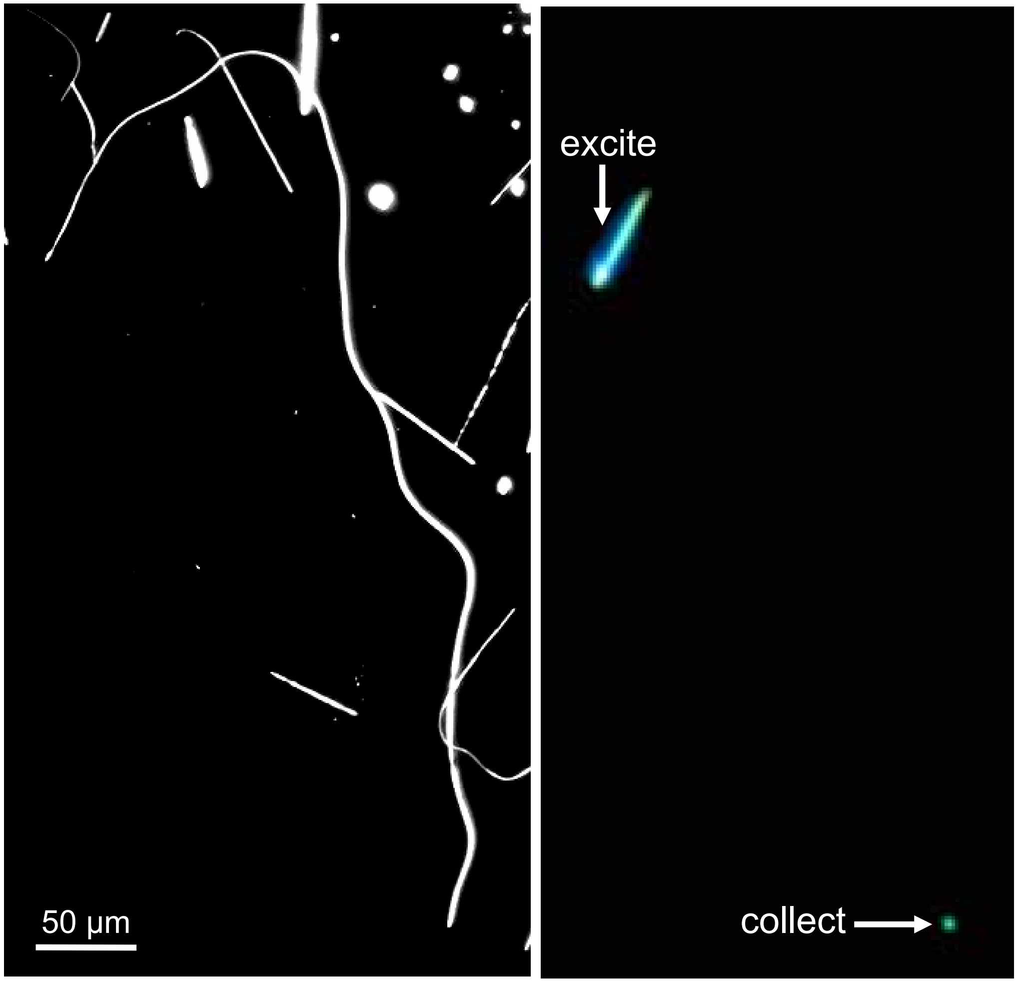
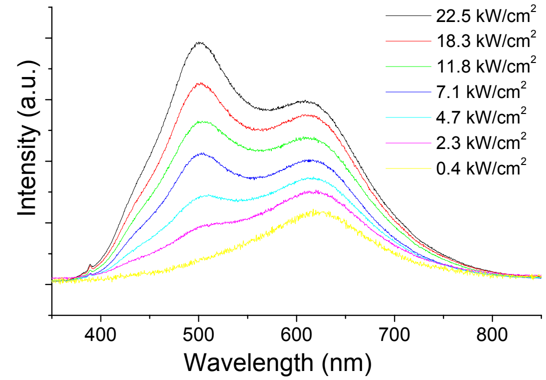
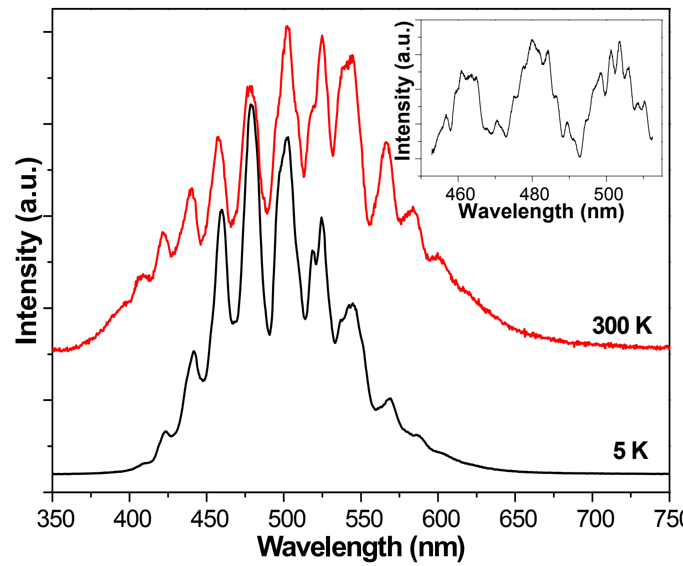
Low-Loss Optical Waveguiding







Dimensions: 715 µm x 350 nm x 245 nm

Propagation losses: 1 – 8 db/mm (NSOM)

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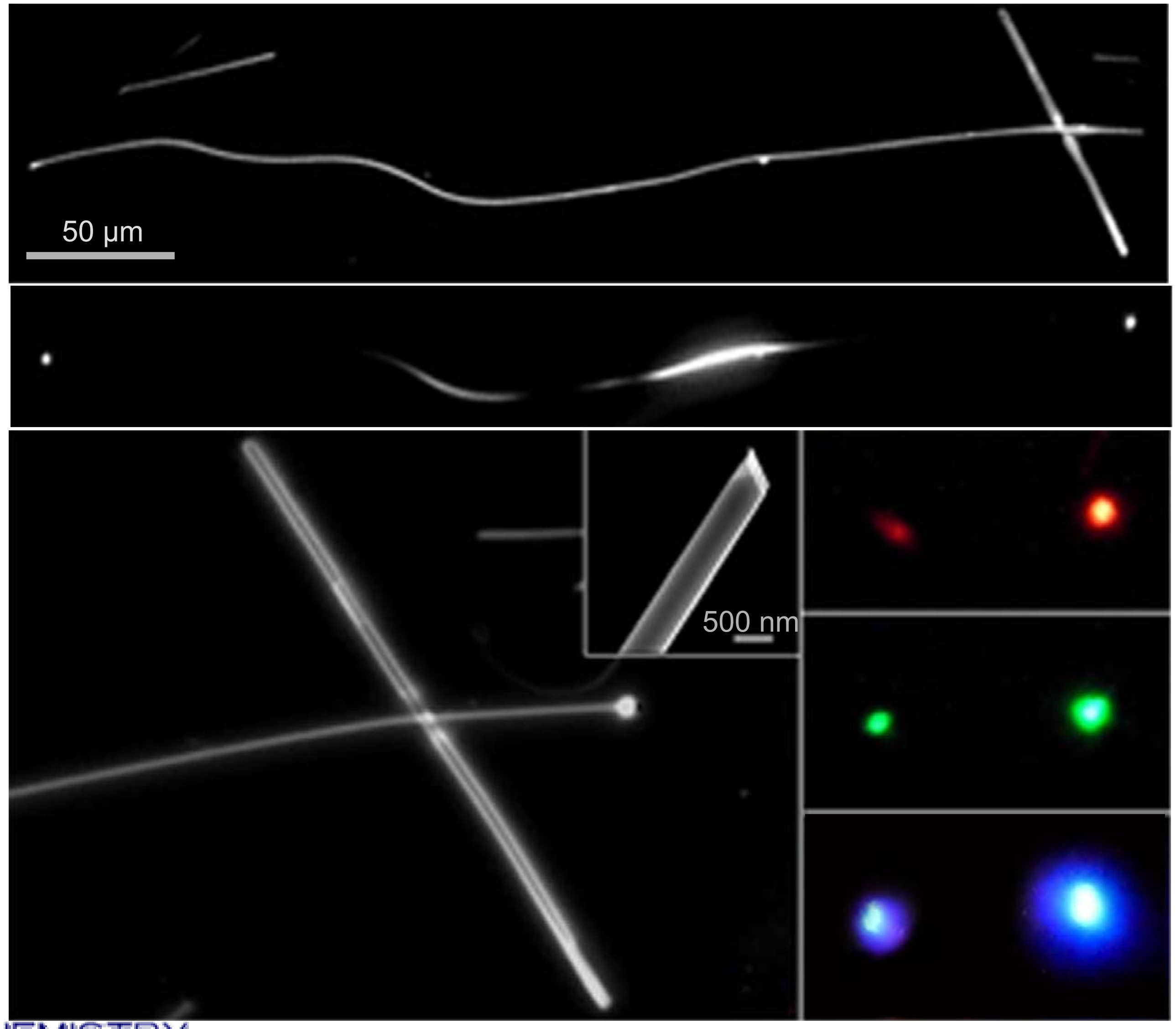
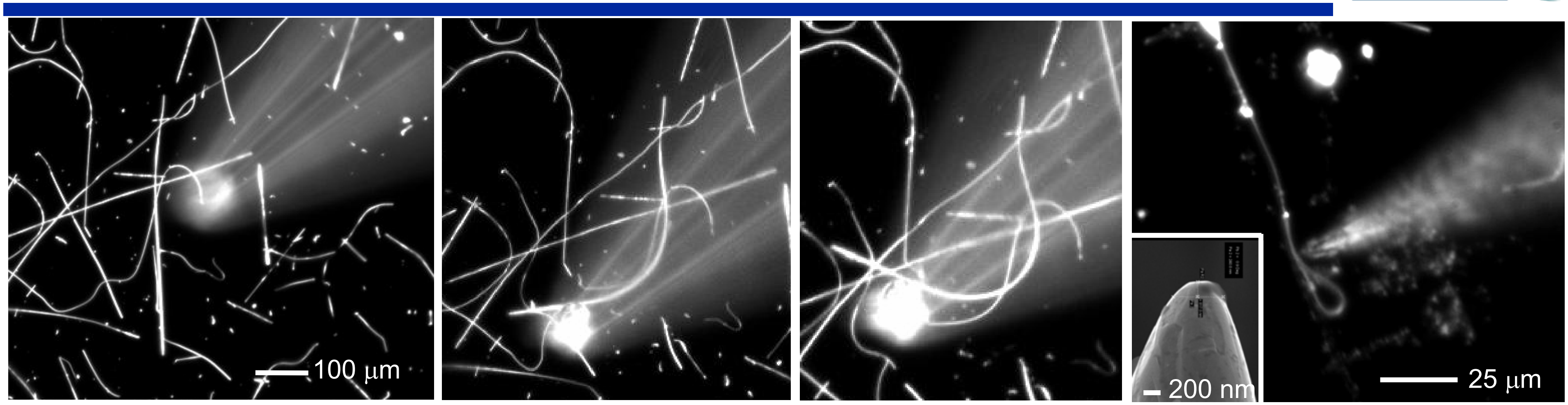
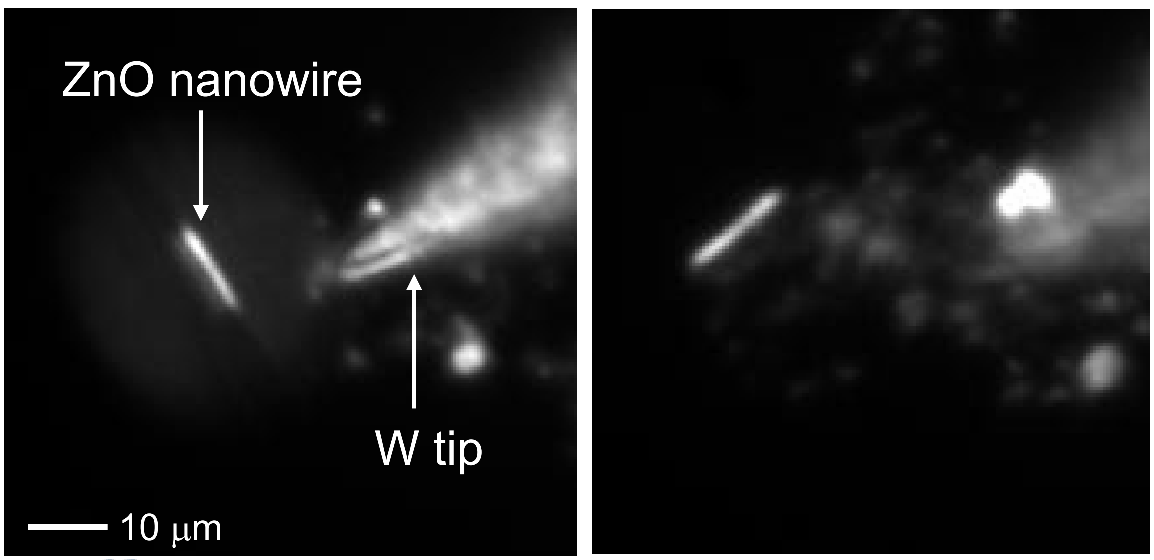
Non-Resonant Waveguiding



M. Law and D.J. Sirbuly *et al.* *Science* **305**, 1269 (2004).

Cavity Manipulation





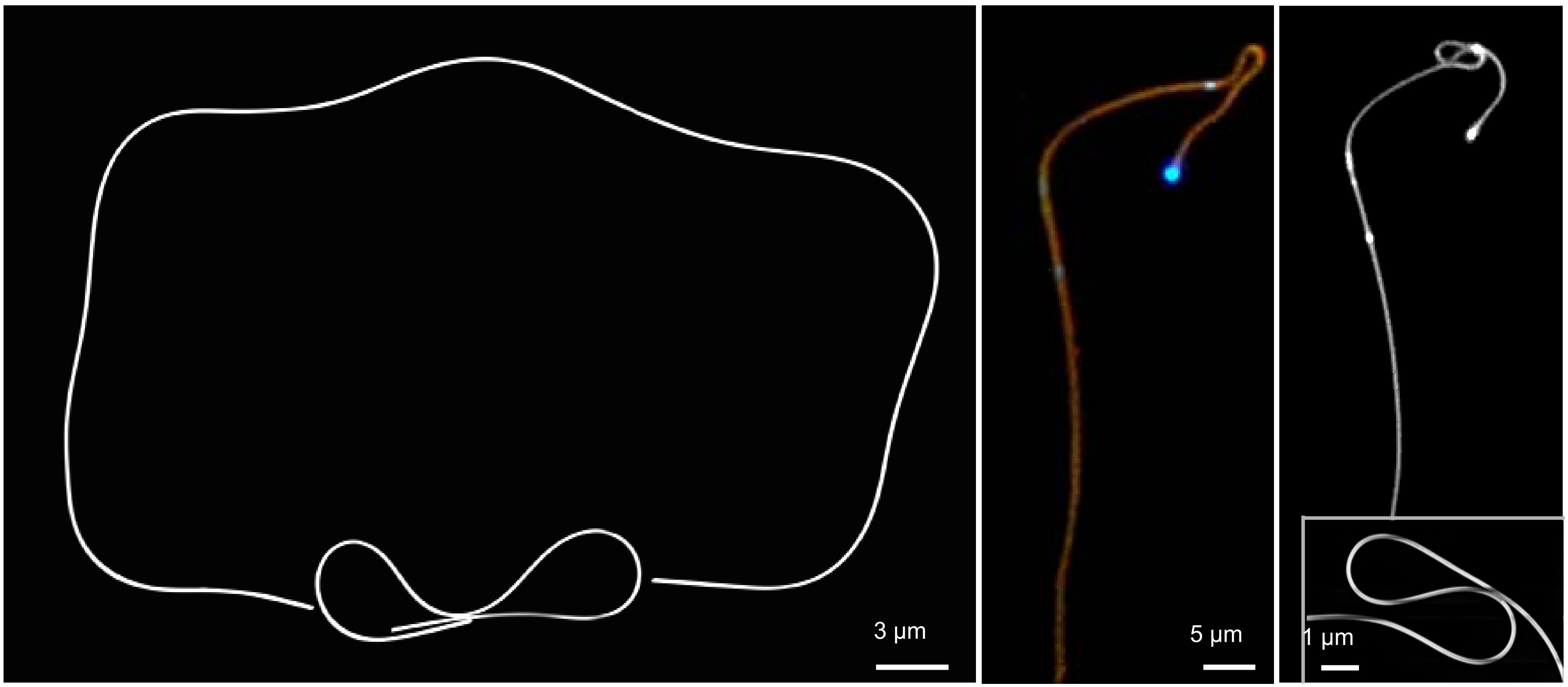
Manipulation size limits:

Wires: < 3 µm length
< 50 nm dia.

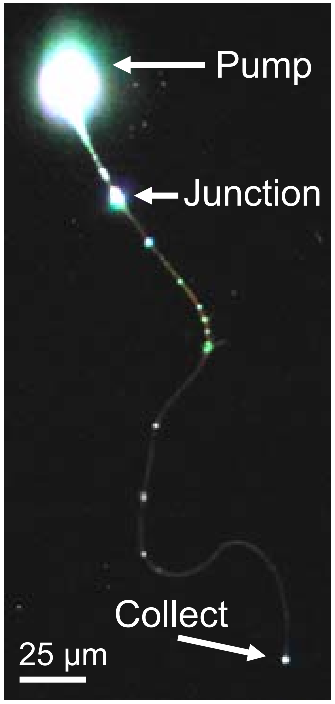
Particles < 50 nm dia.

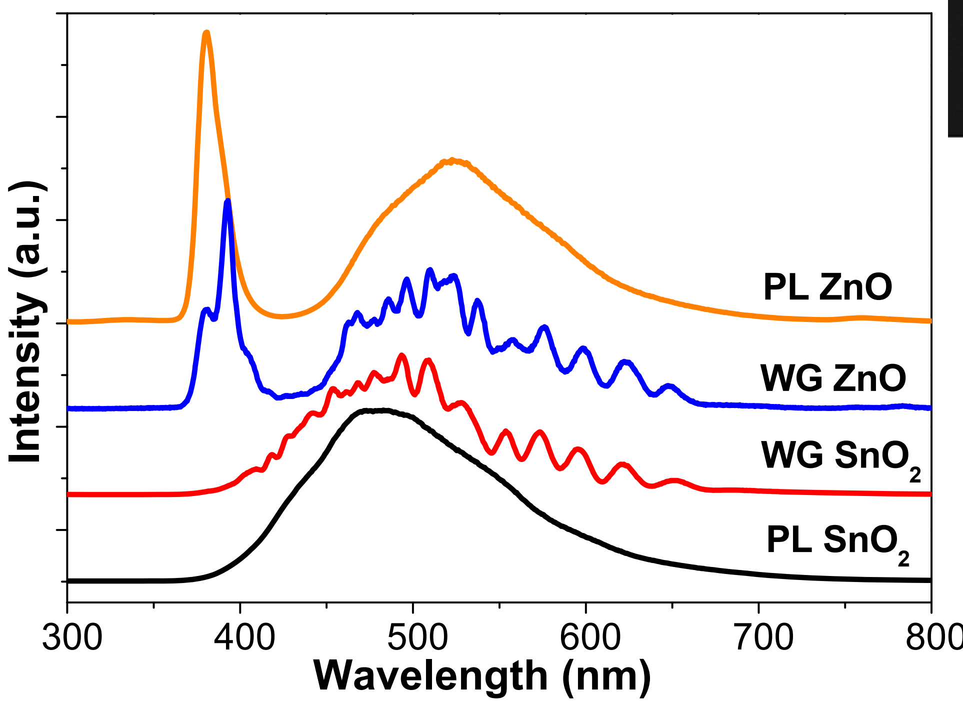
Used to cut, flip, bend, rotate, position, etc.

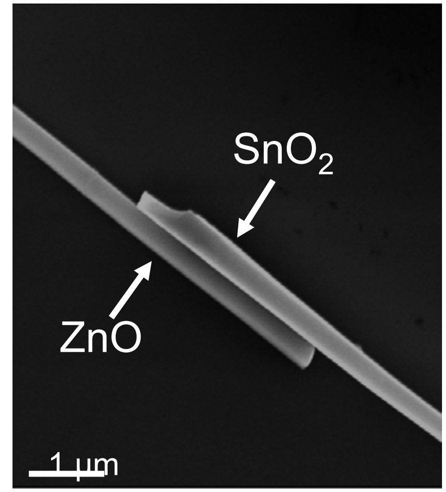
Shape Manipulation



Optical Heterojunctions: ***Evanescent wave coupling***

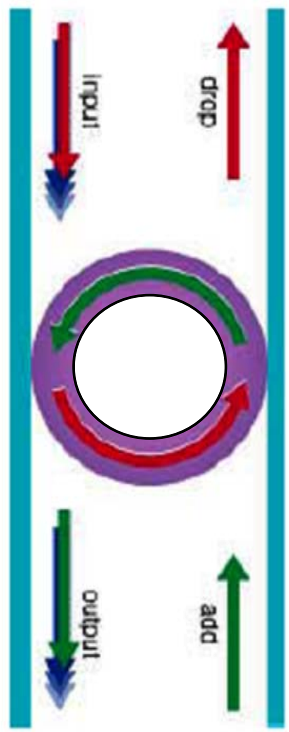


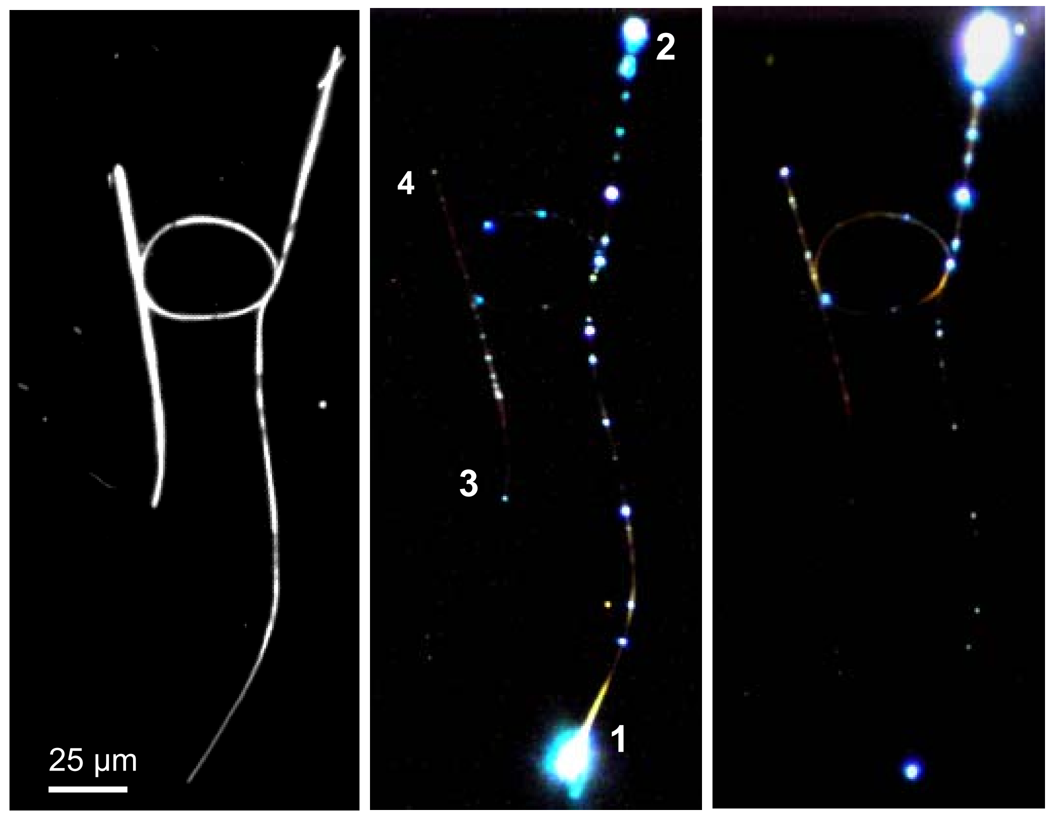




The nanoribbon imprints its mode spectrum on the ZnO PL.

Subwavelength Optical Junctions and Networks

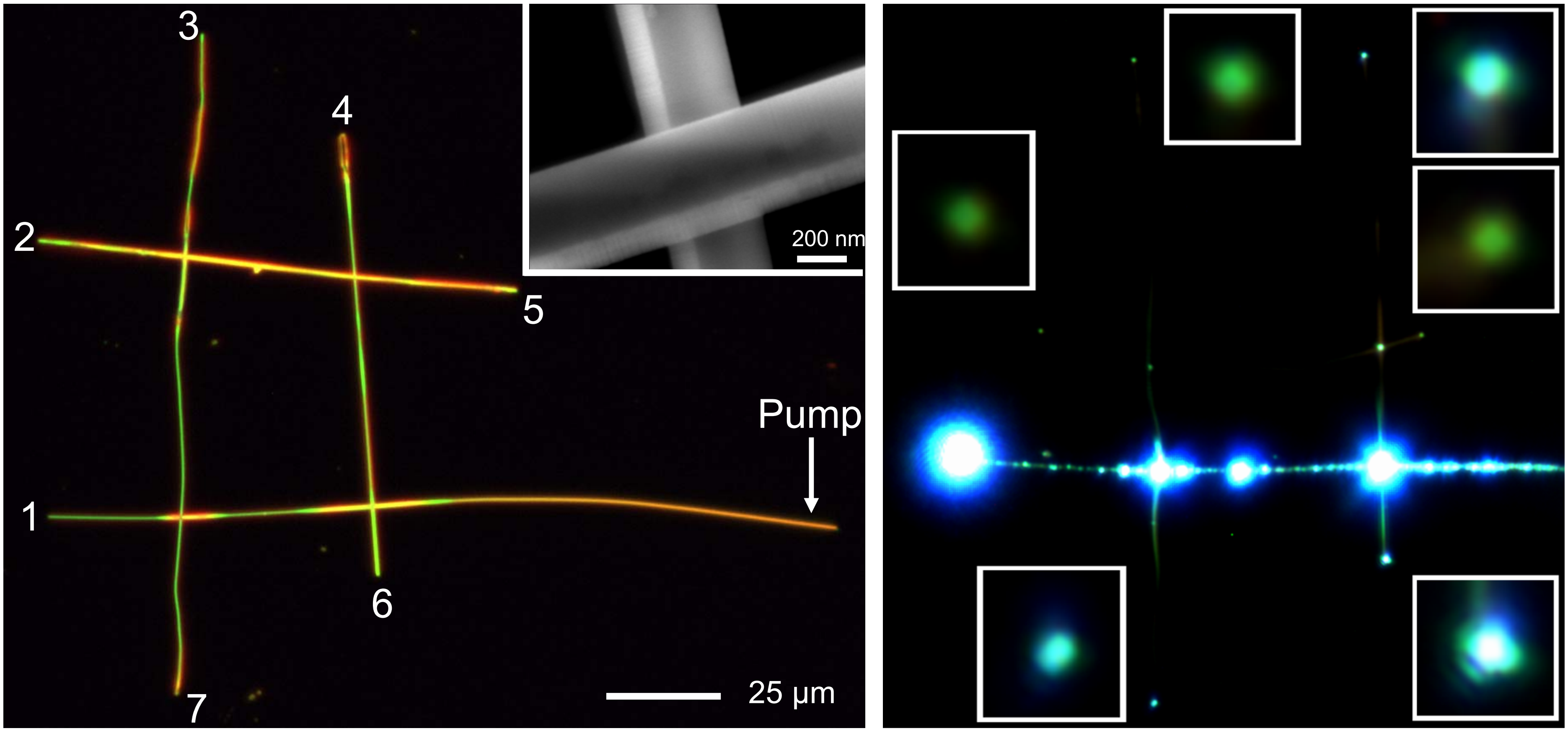




1 ⟶ 2 & 3 2 ⟶ 1 & 4

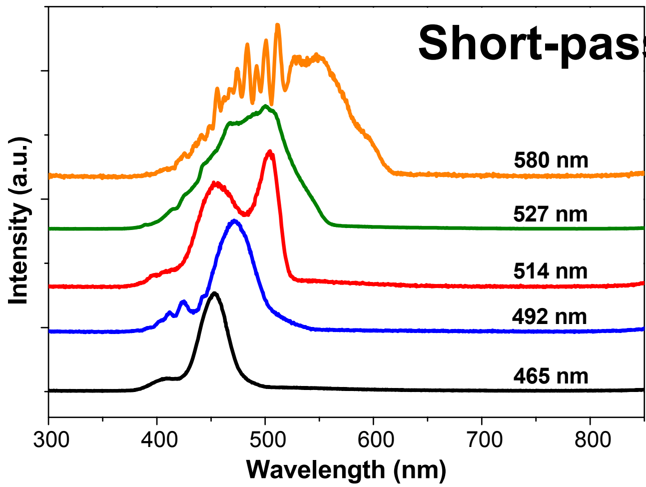
~ 50% of light energy couples through junction – evanescent waves

Cross-Bar Assembly – Coupling Scattered Light



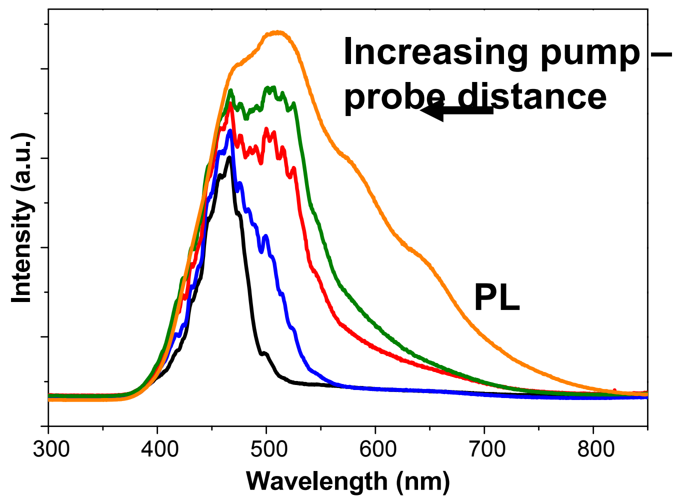
Intensity Variations: 1 >> 6 > 4 ≈ 7 > 3 > 5 >2

Size Effect on Waveguiding



Short-pass filters:

$\lambda_{\text{cut-off}}$	Dimensions
580 nm	375 x 140 nm (0.052 μm²)
527 nm	250 x 225 nm (0.056 μm²)
514 nm	350 x 115 nm (0.040 μm²)
492 nm	280 x 120 nm (0.034 μm²)
465 nm	310 x 100 nm (0.03 μm²)



V-parameter: $$V = \frac{\pi d}{\lambda}(n_{co}^2 - n_{cl}^2)^{1/2}$$

Single-mode operation: $$0 < V < 2.405$$

$$d_{cut-off} = \frac{2.405}{\pi}\lambda(n_{co}^2 - n_{cl}^2)^{-1/2}$$

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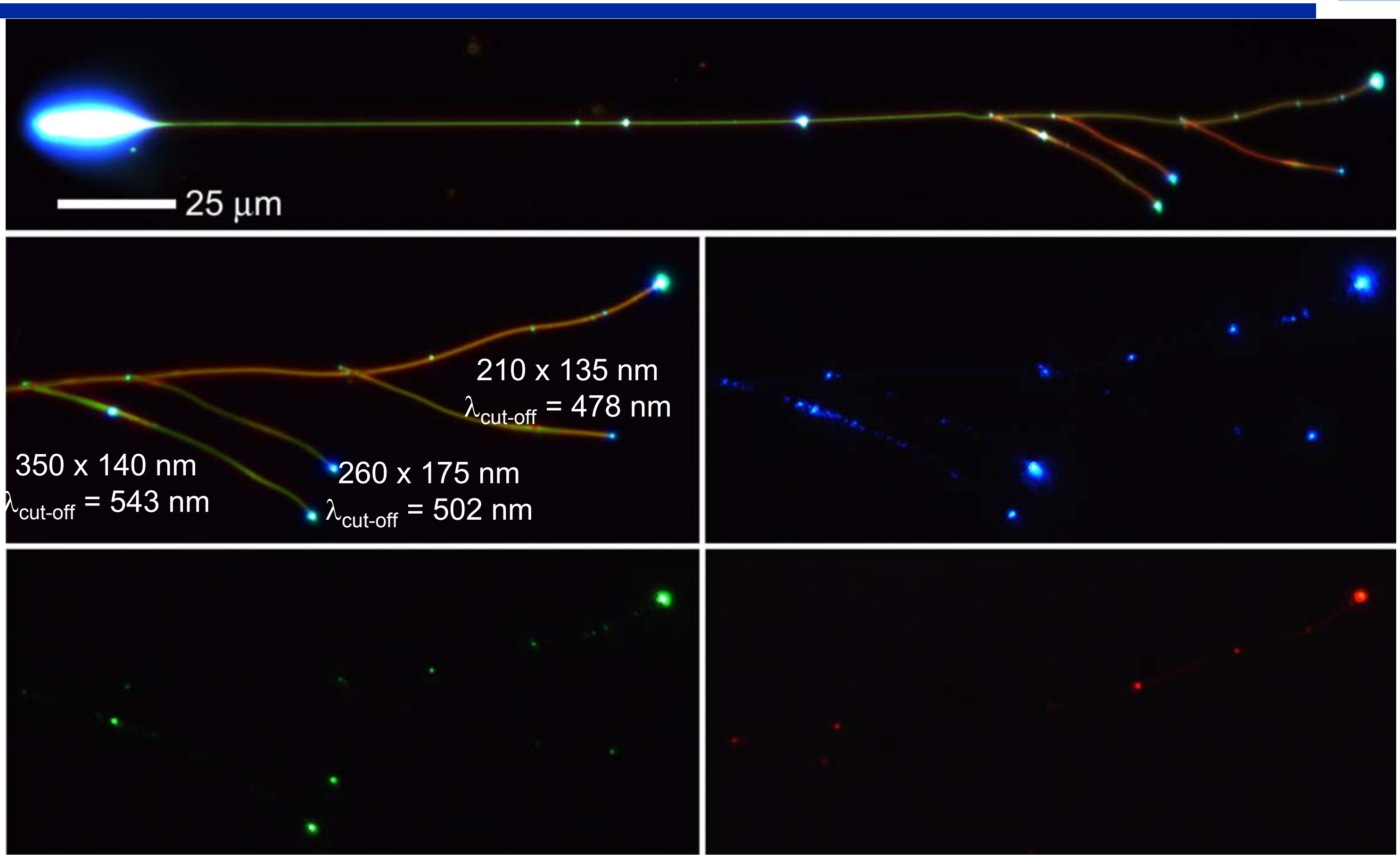
Filtering White Light (Multi-Channel)



single mode cut-off (cylindrical step-index fiber)	Diameter (nm)	Area (um^2)	Exp. Area (um^2)
543 nm	274 nm	**0.05896**	**0.04900**
502 nm	253 nm	**0.05027**	**0.04550**
478 nm	241 nm	**0.045617**	**0.02835**

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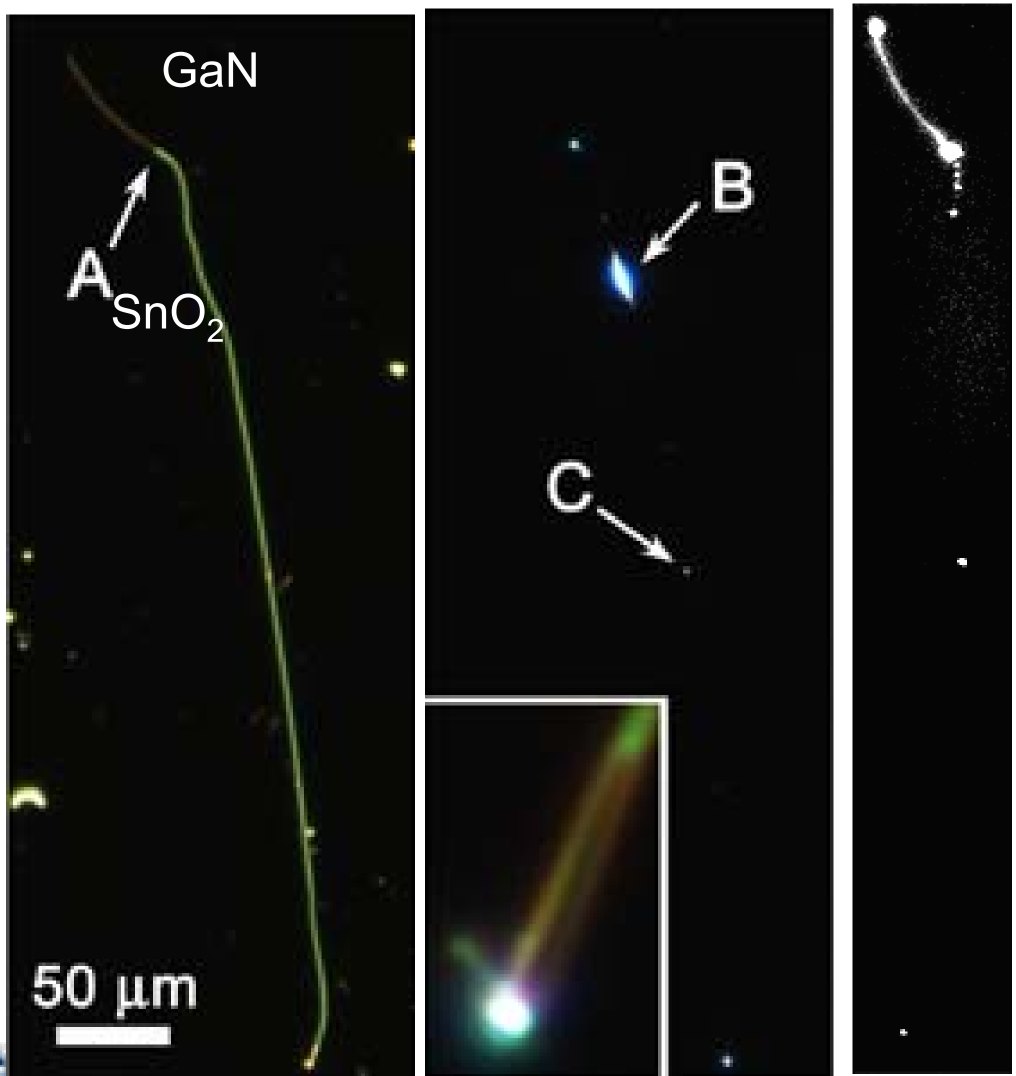
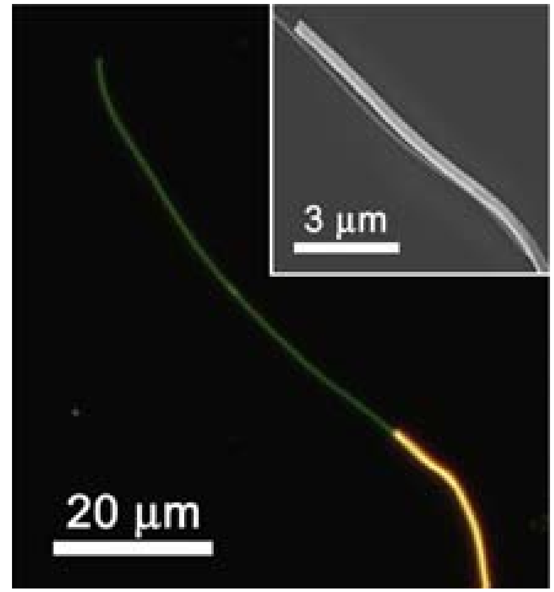
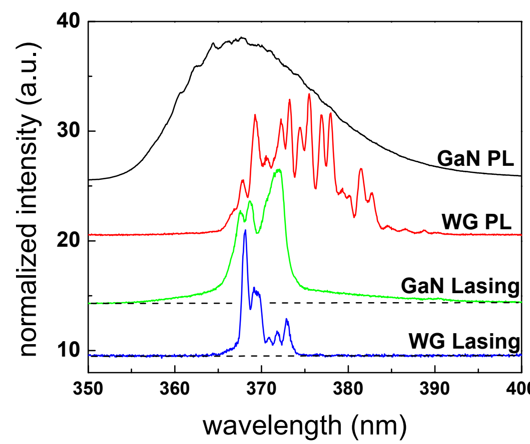
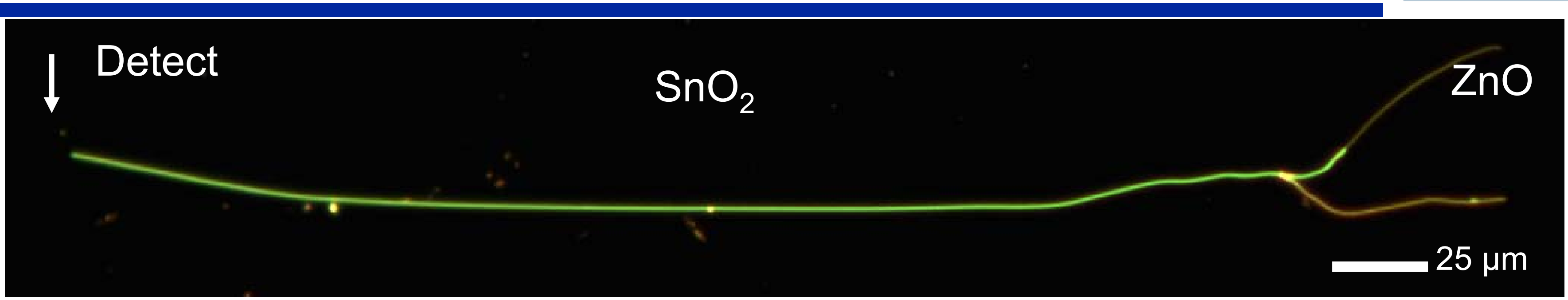
Waveguiding Nanowire Laser Pulses - GaN



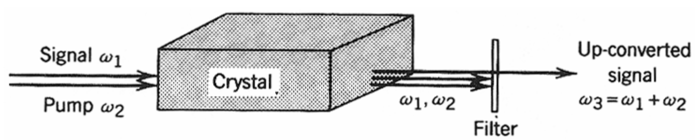




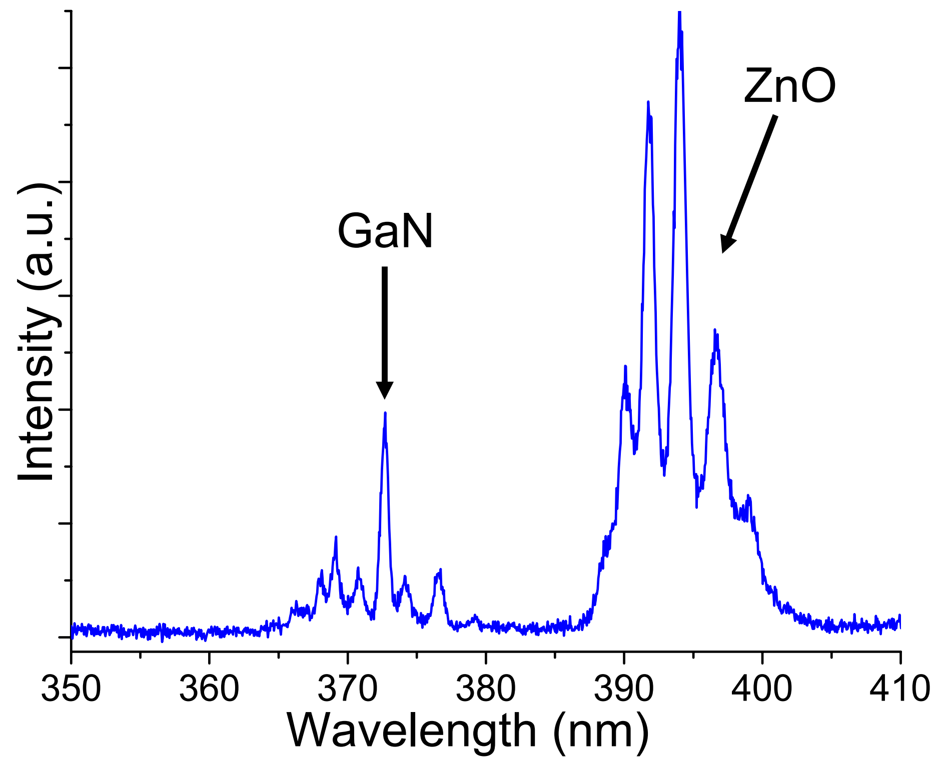
Dual Nanowire Laser Injection



Wave Mixing?



$$\omega_3 = \omega_1 + \omega_2 \qquad \omega_2 = \omega_3 - \omega_1$$



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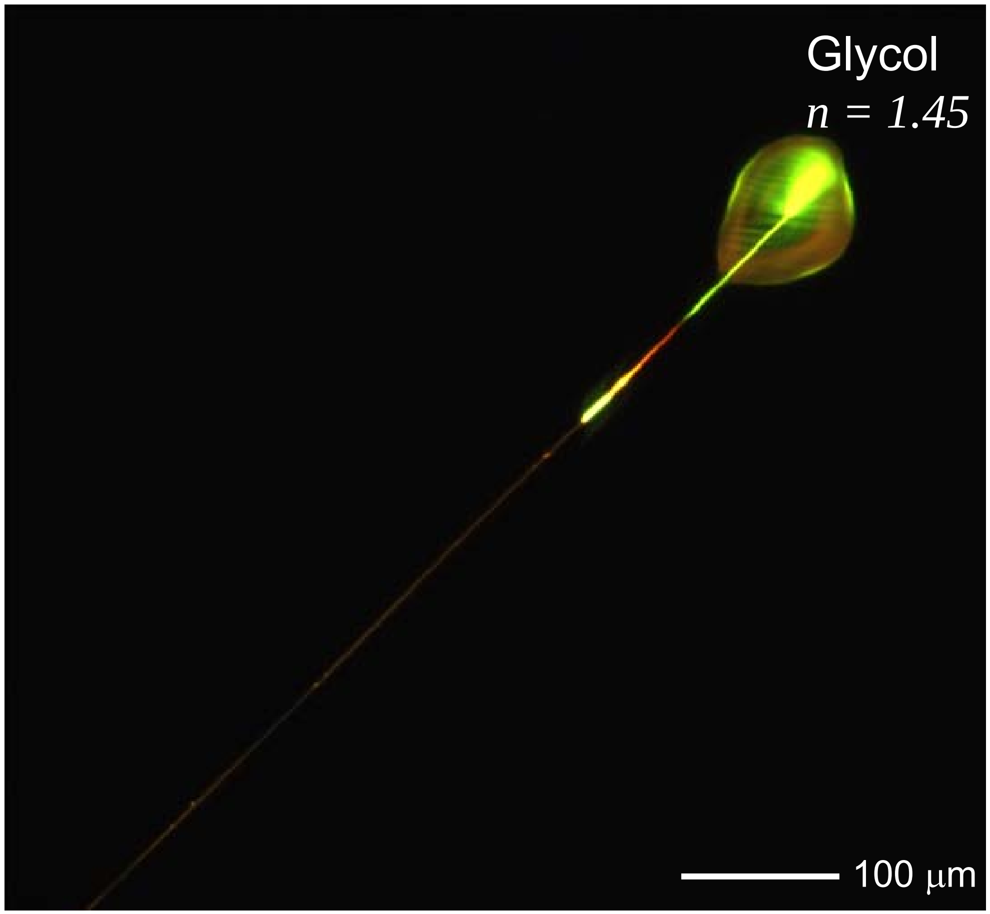
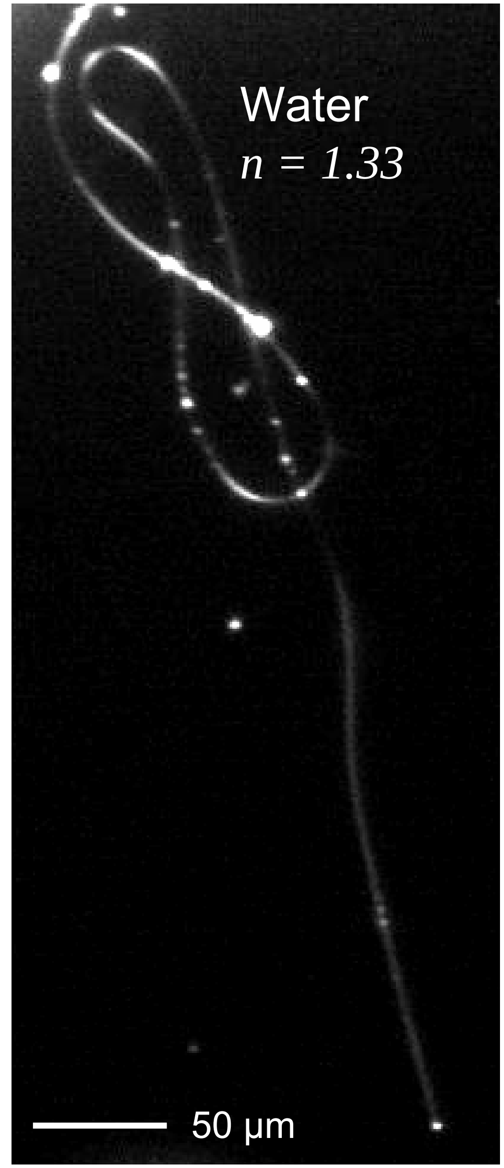
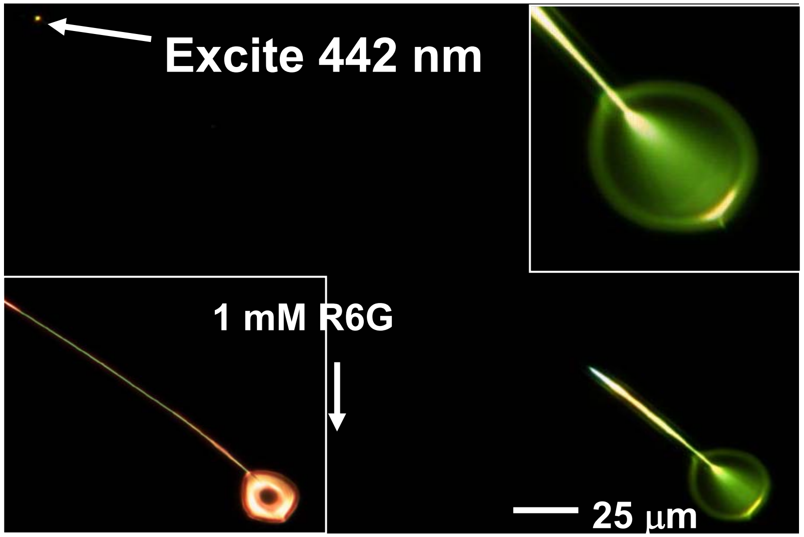
Waveguiding in Liquids – High Index Nanowires

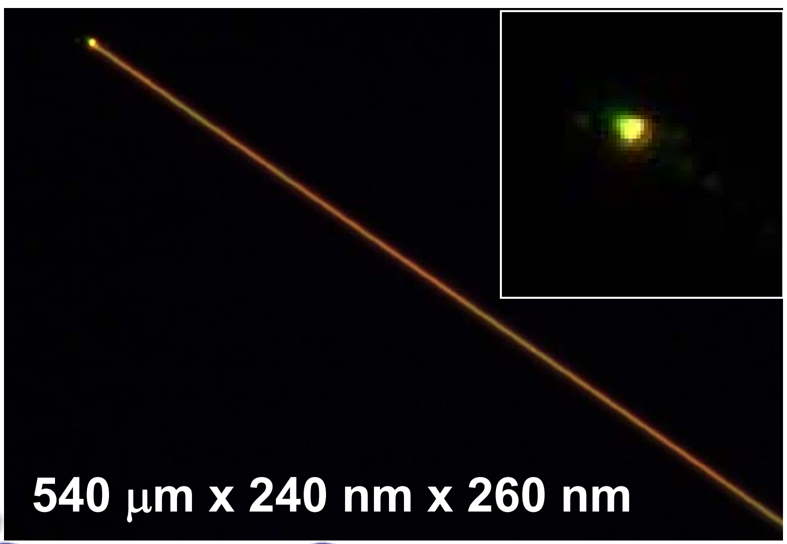
- Local bio-medicinal probe/spectroscopy (*in vivo)*
- Micro/nanofluidics, PDT, chemical photo-release, integrated bio-chip, etc.





Nanowire Evanescent Subwavelength Spectrometry

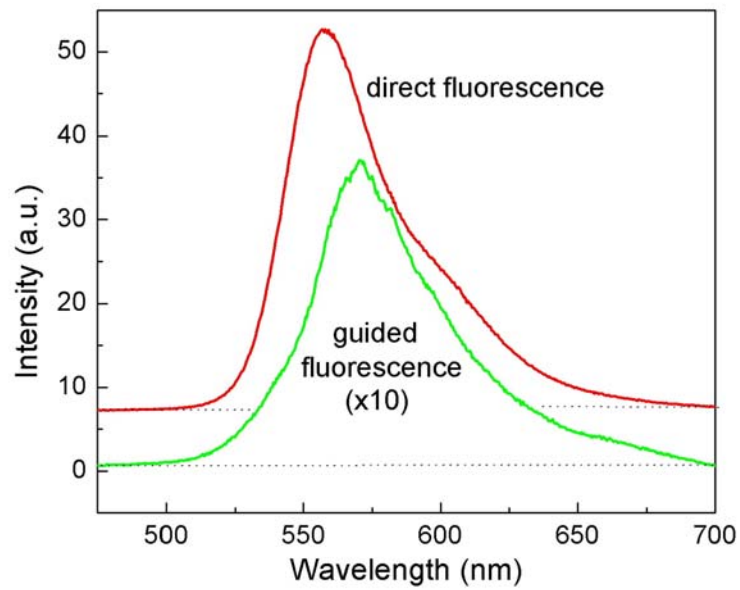




Local Fluorescence Scheme

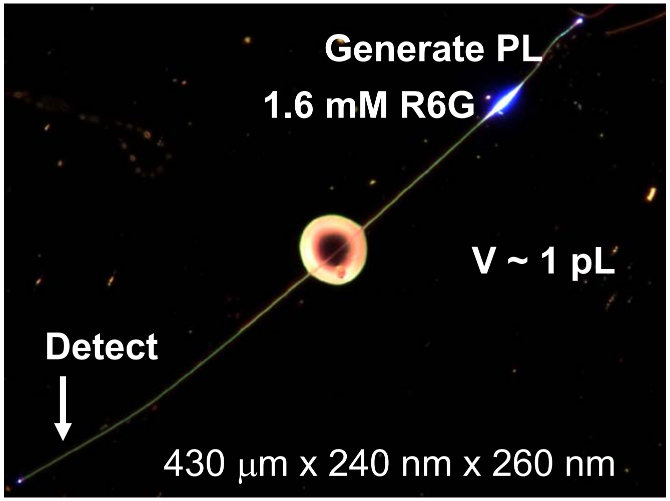
- Inject resonant light to induce local fluorescence at the end or along the length of the ribbon.

- Probe direct or back-guided fluorescence.



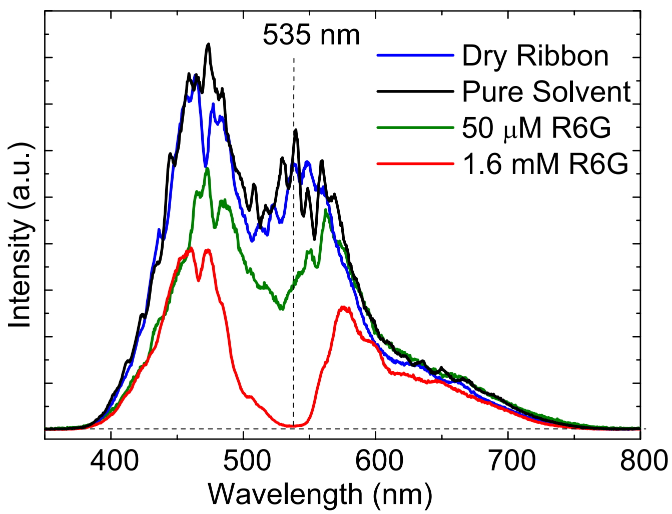
D.J. Sirbuly and M. Law *et al. PNAS* (2005).

Nanowire Evanescent Subwavelength Spectrometry



Local Absorption Scheme

- Inject broad light source and probe waveguided photons.
- Utilize evanescent field to detect molecules.



- sub-picoliter probe volumes
- path lengths of 1-50 microns
- detection of 10^3 molecules is achievable

Semiconductor Nanowires as Subwavelength Photonics Integration

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On-Chip Heterogeneous Photonic Integration
Pushing the Size Limits of Photonics

- ✓ **Precise 1-dimensional nanostructure synthesis and assembly**
  → ***Self-Organized Optical Cavity***

- ✓ **Nanowire based optical cavity, UV coherent light sources**
- ✓ **From Fabry-Perot cavity to ring laser**
- ✓ **From optical pumping to light emitting diodes, and laser diodes**
- ✓ **Subwavelength optical waveguides**
- ✓ **Optical waveguiding in solution, interface with microfluidics**
- ✓ **Subwavelength optical spectroscopy (absorption, PL…)**

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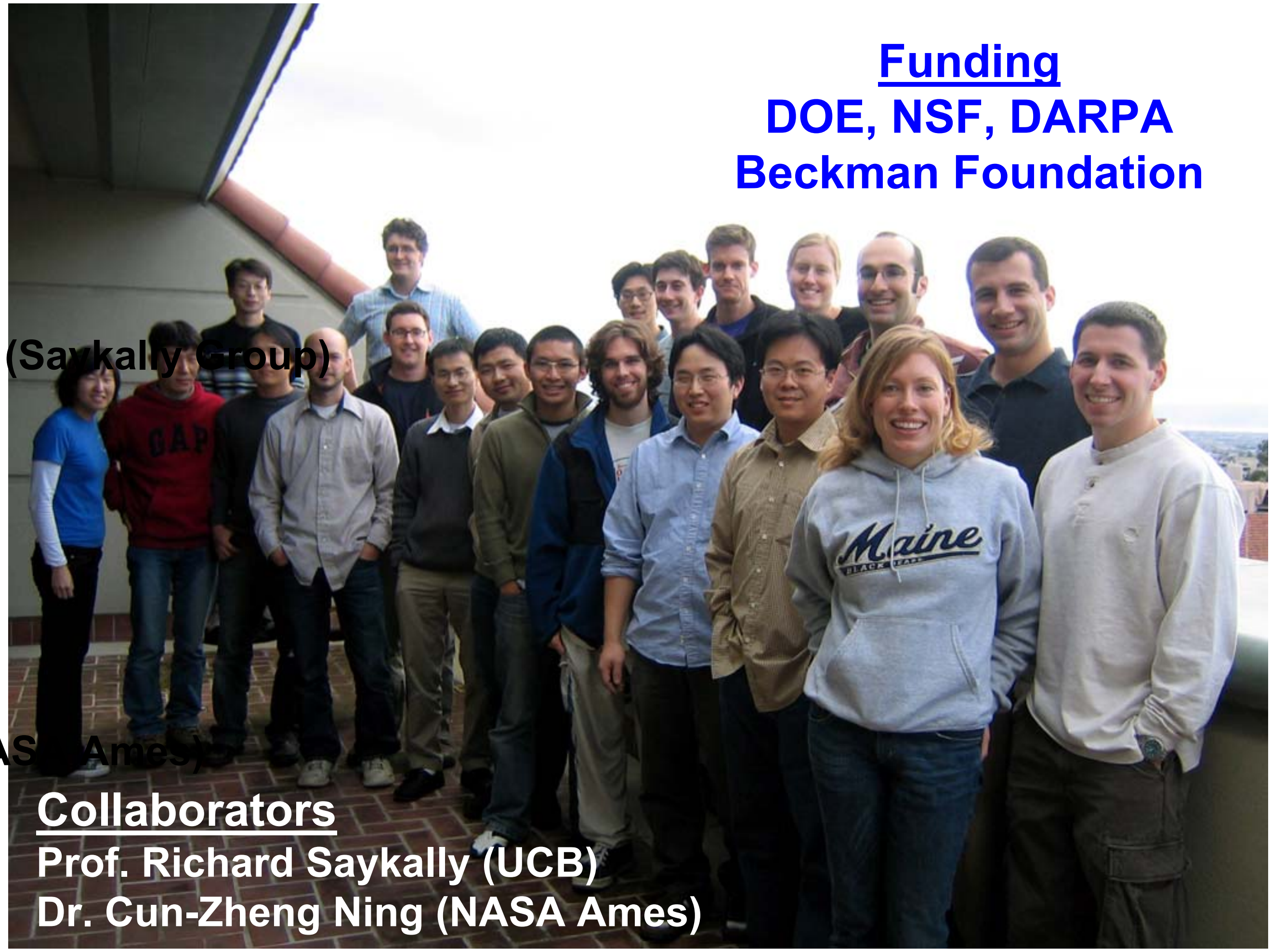

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