Nanotechnology and UV Science: Survey and Opportunities

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Introduction

Nanometer-scale capabilities can encompass:

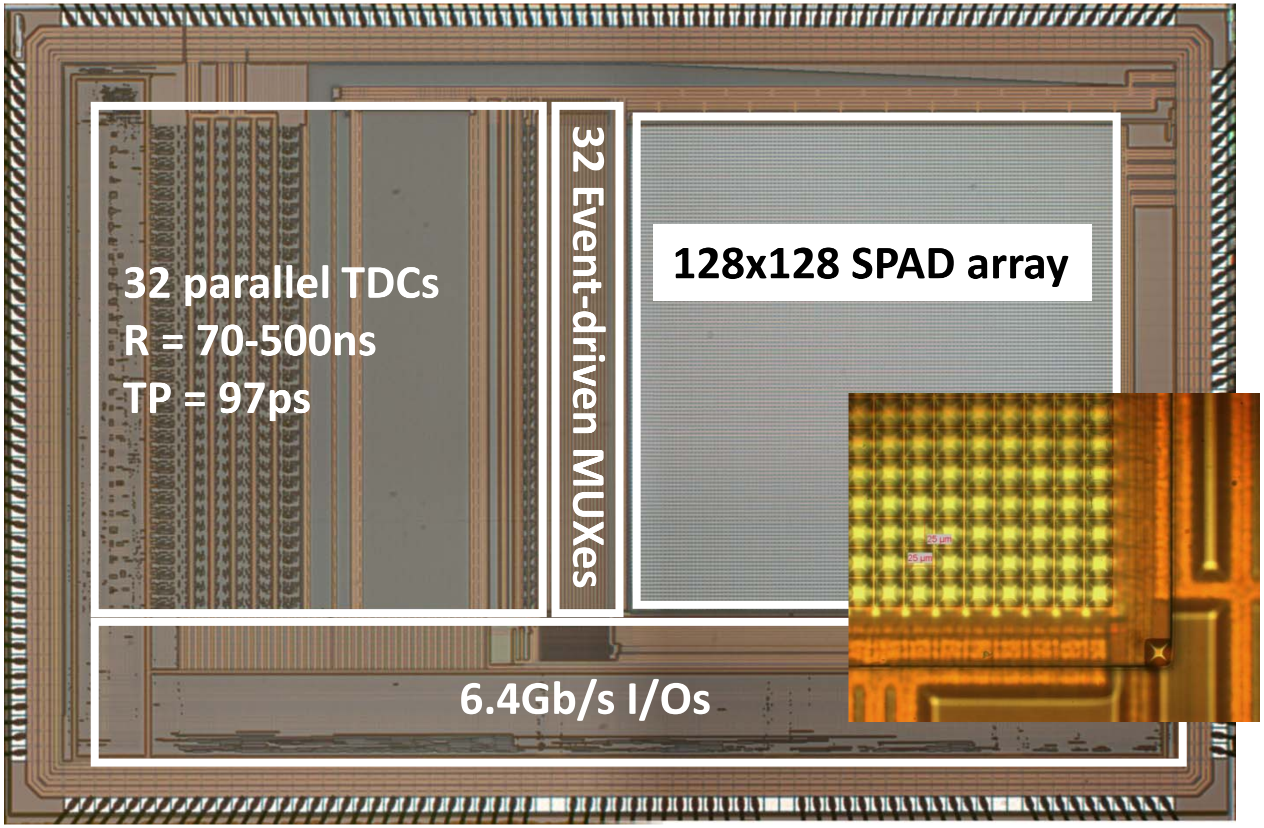
- Manipulation/Fabrication: the ability to construct nanometer-scale features to increase device density, control growth, or enable new functionality
- Characterization: use of nanometer-scale techniques to probe and evaluate operation of small structures
- Functional nanostructures: the incorporation of unique nanoscale properties into the basic device concept

Fabrication

Nanometer-scale (deep submicron) lithography

- Often does not utilize quantum size effects; in many cases the goal is just to reduce size or power, or increase density
- However, new functionality can be enabled by drastic reduction in size

Single-photon avalanche detector (SPAD) array for time-resolved photon detection



Niclass, Favi, Kluter, Gersbach, Charbon, *ISSCC* 2008, *JSSC* 2008

E. Charbon et al., TU-Delft

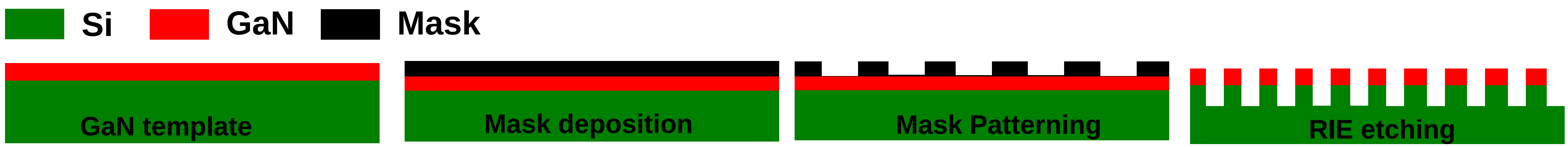
Fabrication

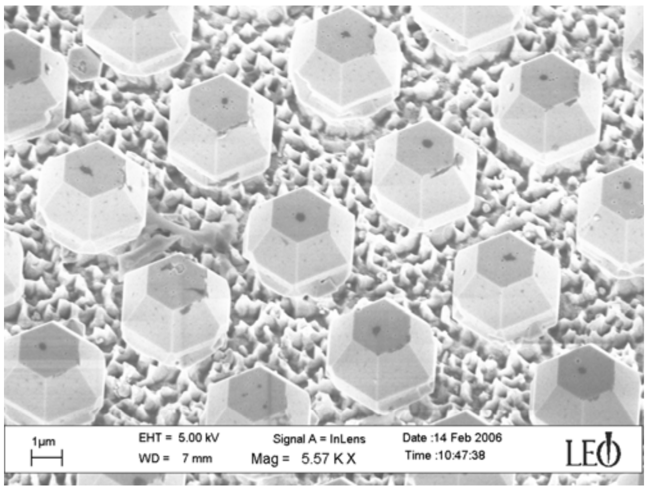
<u>Nanometer-scale features for materials growth control</u>

Nanostructures can be used for improved materials growth, even when the structures themselves are not active elements. Two examples:

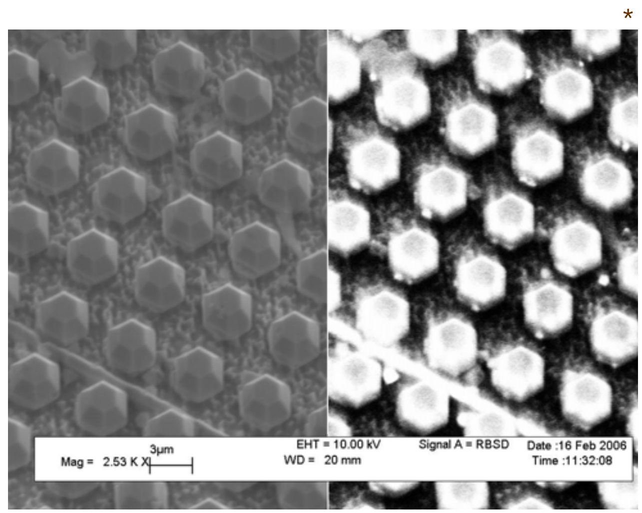
- nanostructures to nucleate defects
- nanostructures to provide reduced constraints on epitaxy

Mesa patterning for high Al% AlGaN nanostructures

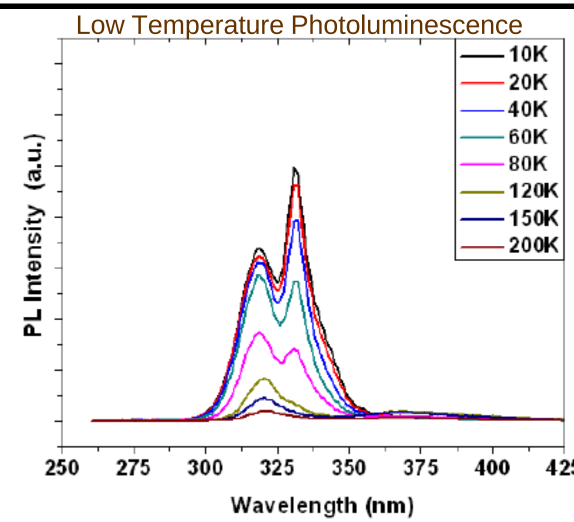




AlGaN nanostructure on patterned GaN/Si



SEM/CL from AlGaN nanostructure on patterned GaN/Si



LTPL from AlGaN nanostructures on patterned GaN/Si

Substrate Patterned SAG

• To avoid interference from polyAlGaN growth on mask and assist in higher percentage of incorporated Al atoms

•Al % incorporation up to 30% in nanostructures

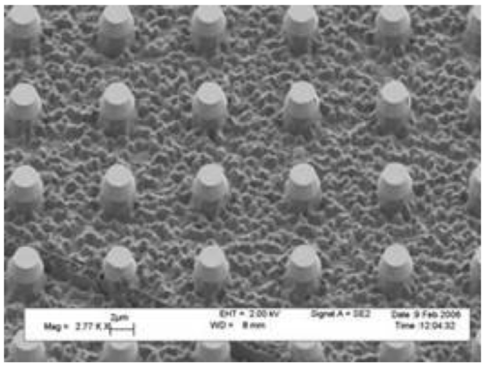
F. Shahedipour-Sandvik et al., SUNY-Albany

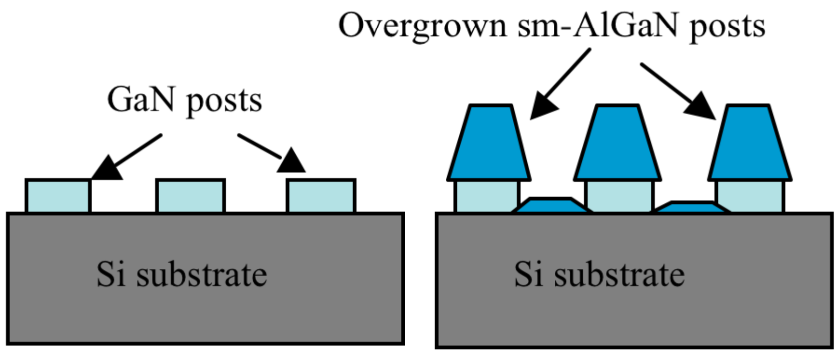
* As measured at GE, GRC

Fabrication

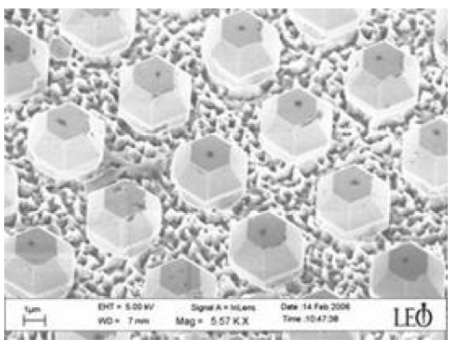
Selective area growth

GaN/Si mesa template

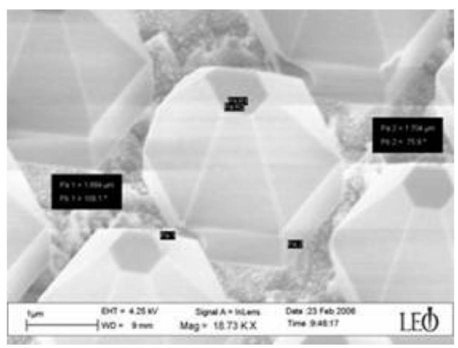




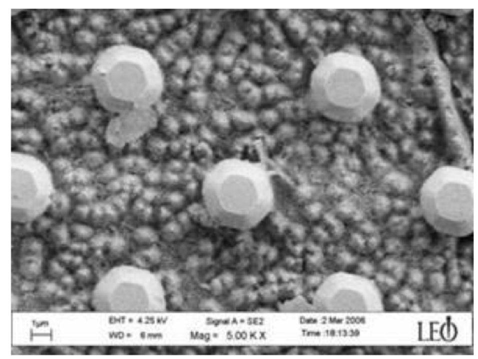
$Al_{0.11}Ga_{0.81}N$ overgrown



$Al_{0.33}Ga_{0.67}N$



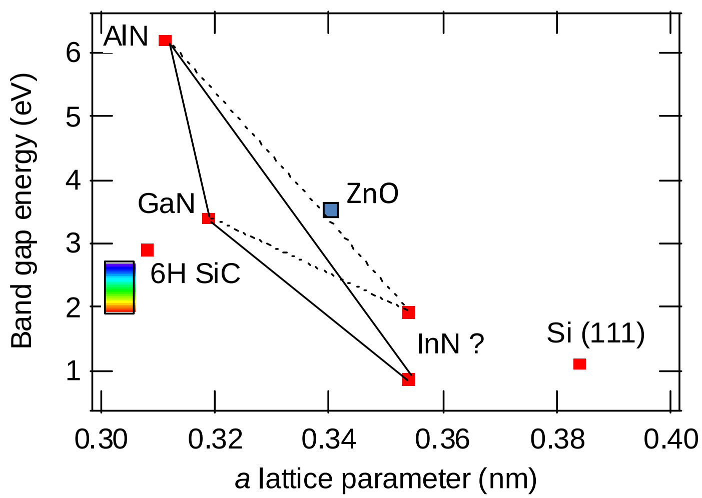
$Al_{0.55}Ga_{0.45}N$

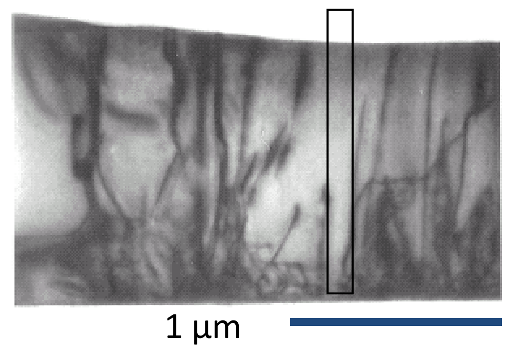


GaN posts patterned on a Si substrate and used for selective area growth of AlGaN truncated pyramids of various Al compositions

F. Shahedipour-Sandvik et al., SUNY-Albany

Fabrication

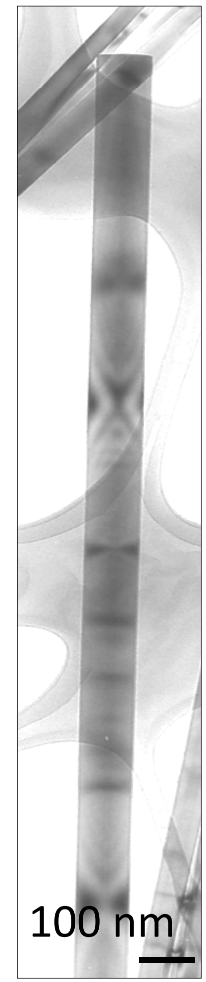




GaN on Sapphire, Weyher, et al. J. Appl, Phys. 90, 6105 (2001). Rectangle represents typical nanowire diameter

- Lack of bulk substrates and large lattice mismatch within alloy system- can't stay on the preferred vertical line of lattice parameter match between film and substrate
- Nanowires are (mostly) free of crystalline defects because of thermodynamic forces driving the crystal nucleation and growth
- Optical characterization of MBE-grown GaN nanowires shows match or exceed best GaN films

Defect-free GaN nanowire
NIST TEM (I. Levin)



K. Bertness et al., NIST

Characterization

<u>Nanometer-scale imaging and active characterization</u>

There are many nanoscale probes of physical, chemical, and electronic structure.

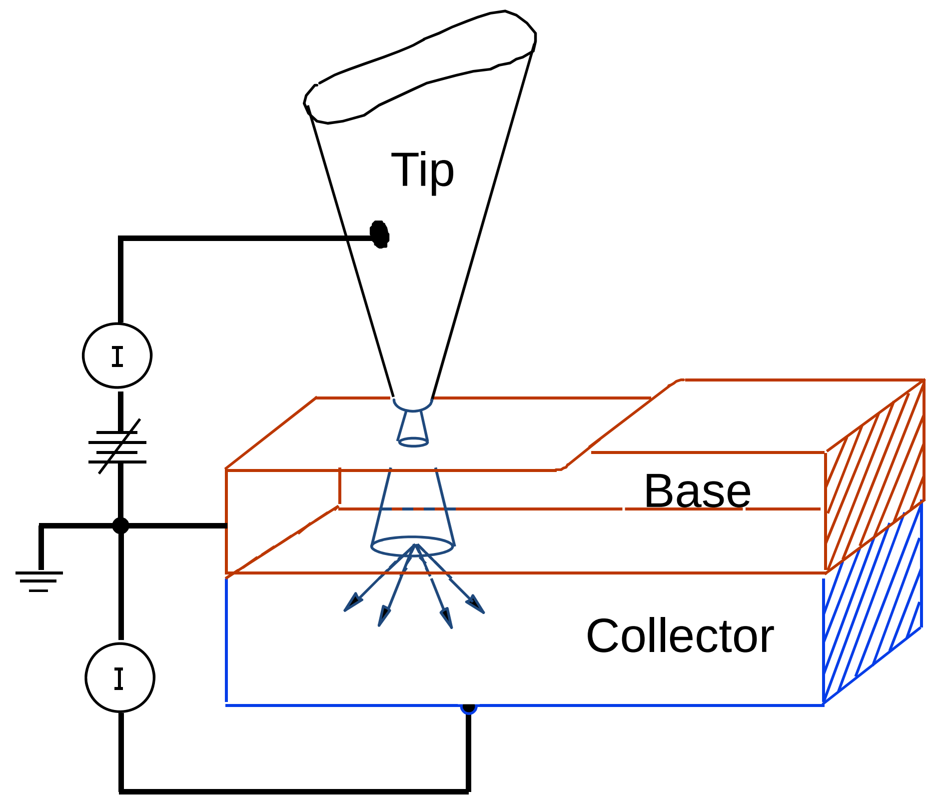
- As device feature sizes shrink, surfaces and interfaces play a larger role in device properties
- An understanding of nanometer-scale properties of materials and devices is essential

One powerful class of techniques is scanned probe microscopy. These techniques allow real-space, non-destructive imaging of materials and device properties.

Characterization

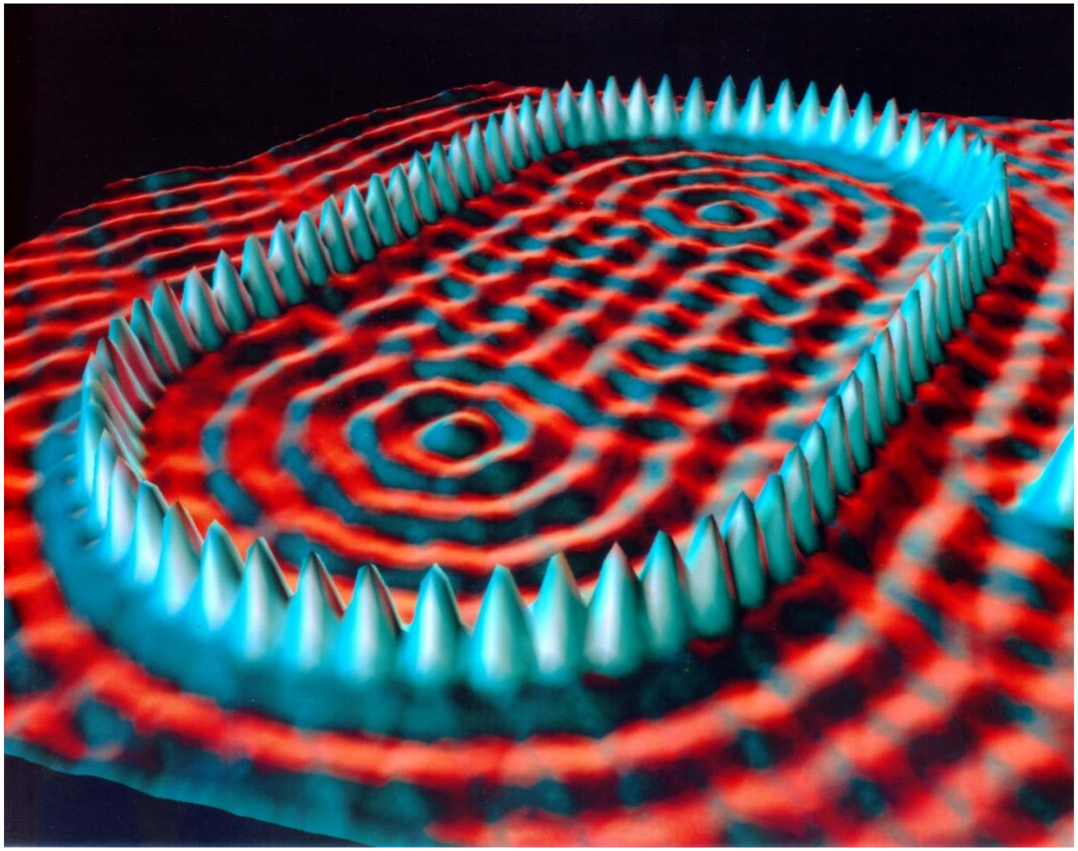
- Scanning tunneling microscopy (STM)
- Ballistic electron emission microscopy (BEEM)
- Scanning tunneling luminescence microscopy (STLM)
- Force microscopy (AFM, MFM)

\- and many others



Schematic configuration of STM and BEEM. The STM tip injects tunneling electrons into a surface area of less than 1 nm^2. Tip position is controlled in order to maintain constant tunnel current. In BEEM, a second current is measured, which gives spatially resolved information about hot-electron transport across interfaces.

Characterization



STM image showing standing-wave patterns in the local density of states of the Cu(111) surface. These spatial oscillations are quantum-mechanical interference patterns caused by scattering of the two-dimensional electron gas off the Fe adatoms.

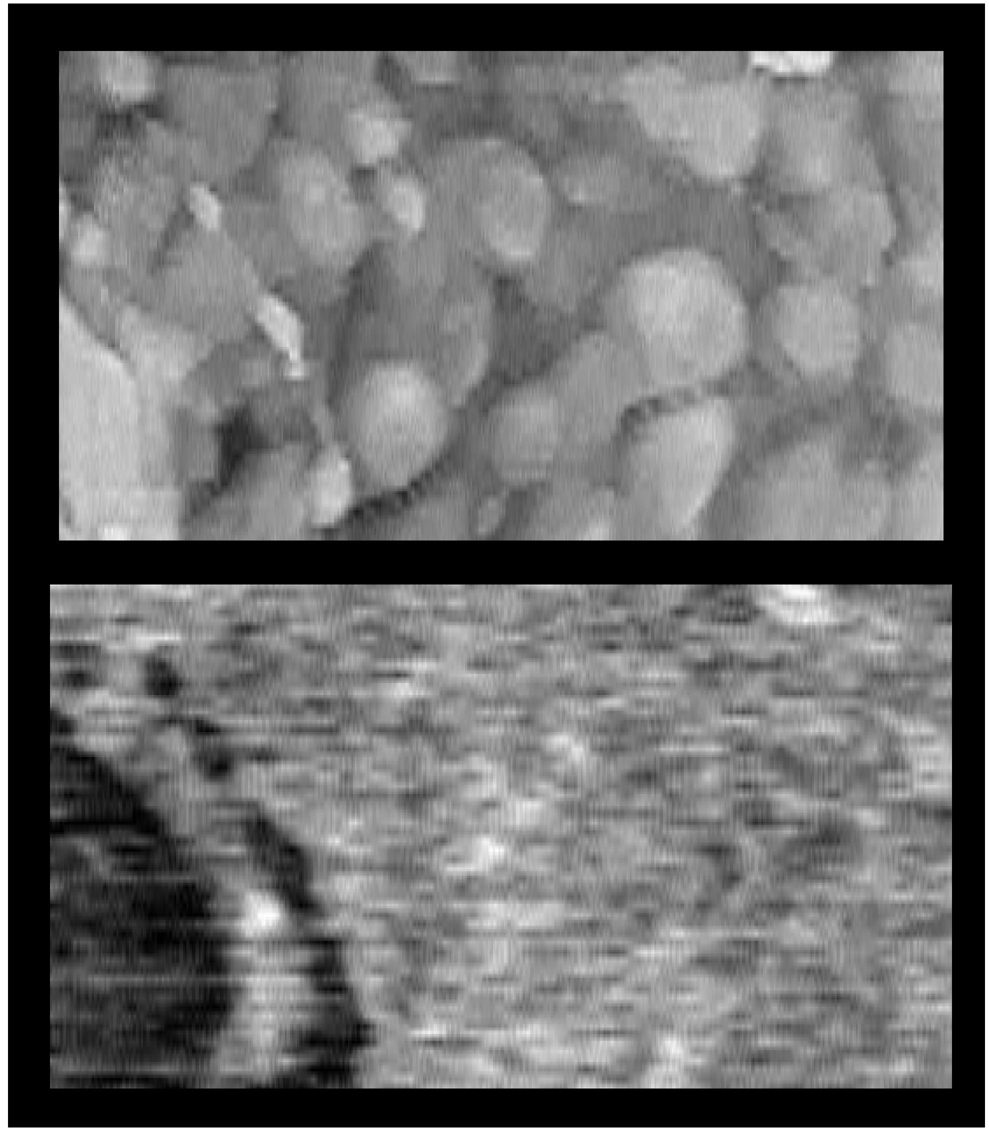
Crommie, Lutz & Eigler, Physics Today 46 (11), 17-19 (1993)

Characterization

<u>Active characterization</u>

spatially localized injection or excitation

addresses electronic properties and electron transport in individual nm-scale functional features



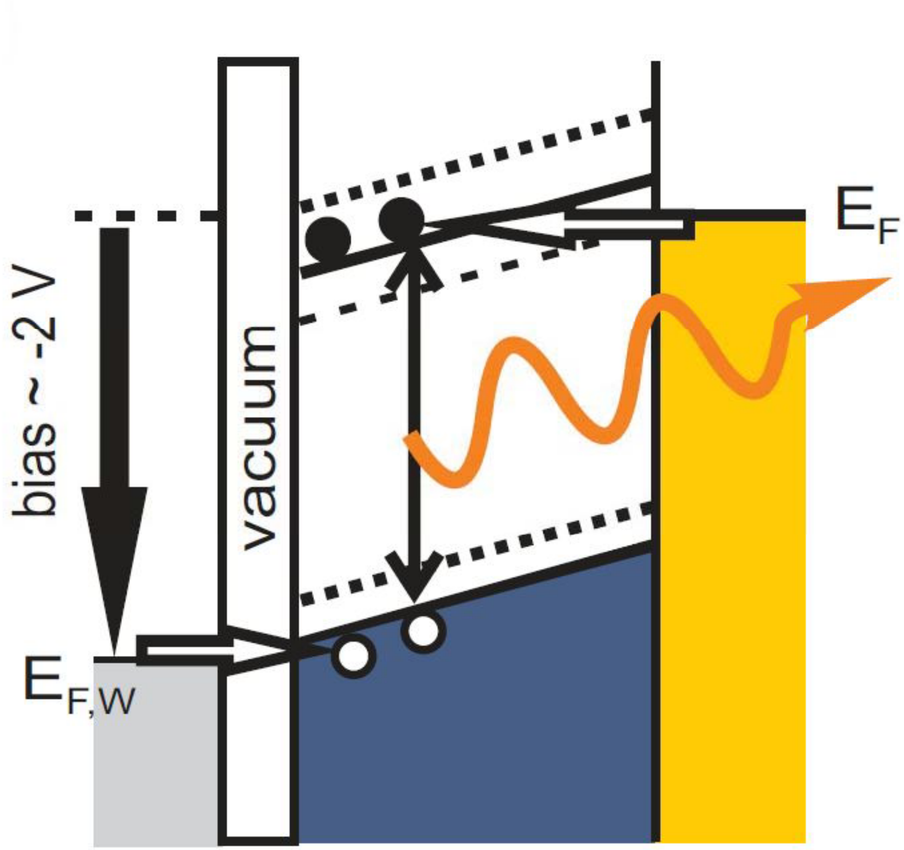
STM/BEEM image pair for Au/GaN annealed at 580°C. Imaged area is 196 x 110 nm.

Characterization

Active characterization:

Scanning tunneling luminescence microscopy

Individual nanostructures can be optically excited and imaged.



Theresa Lutz, EPFL, thesis (2011)

Functional Nanostructures

Nanostructures can be incorporated as active elements in devices to give unique functionality.

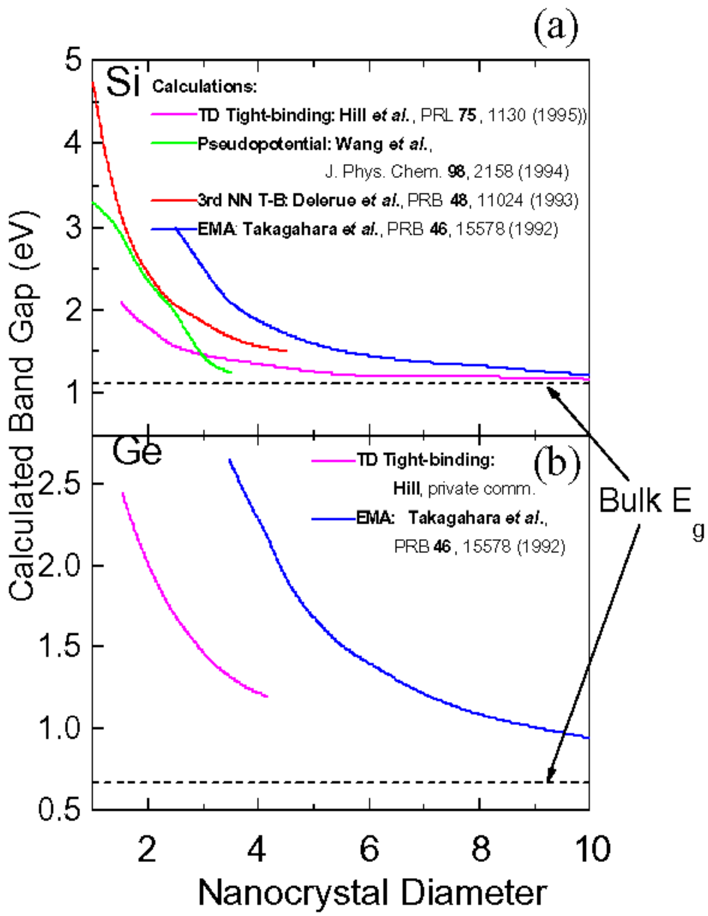
This functionality can be a property of individual elements or of ensembles.

Examples:

- quantum dots
- nanowires
- fullerenes and graphene
- metamaterials

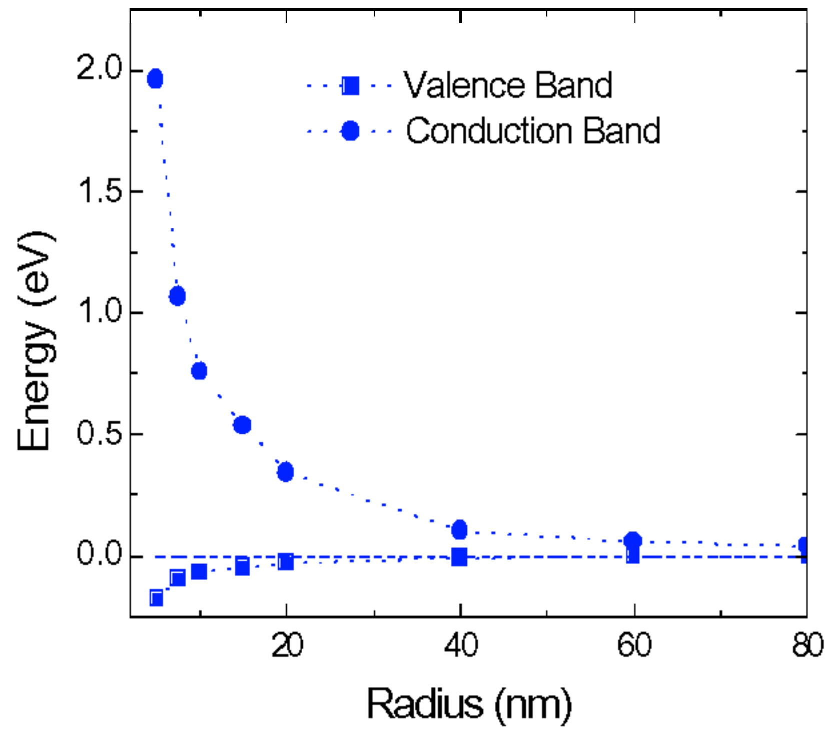
Functional Nanostructures

QDs provide a way to achieve group-IV direct bandgap behavior, through quantum size effects.



Theoretical prediction of band gap energy versus nanocrystal diameter for (a) Si and (b) Ge.

R. Ragan, Ph.D. Dissertation, Caltech, 2001.



Energy of valence and conduction bands versus Sn nanowire radius from semi-empirical tight-binding calculation.

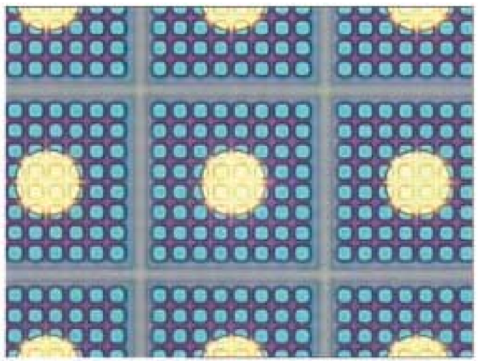
V. Sih, Senior Thesis, Caltech, 2001.

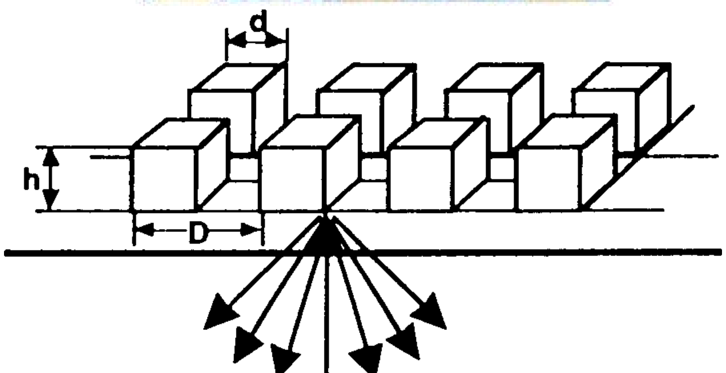
Functional Nanostructures

Quantum dot infrared photodetectors (QDIP) – optical selection rules

In quantum well detectors, intersubband transition can only be excited by IR light polarized in the growth direction (in the effective mass approximation). QDIP allows absorption for normal incidence.

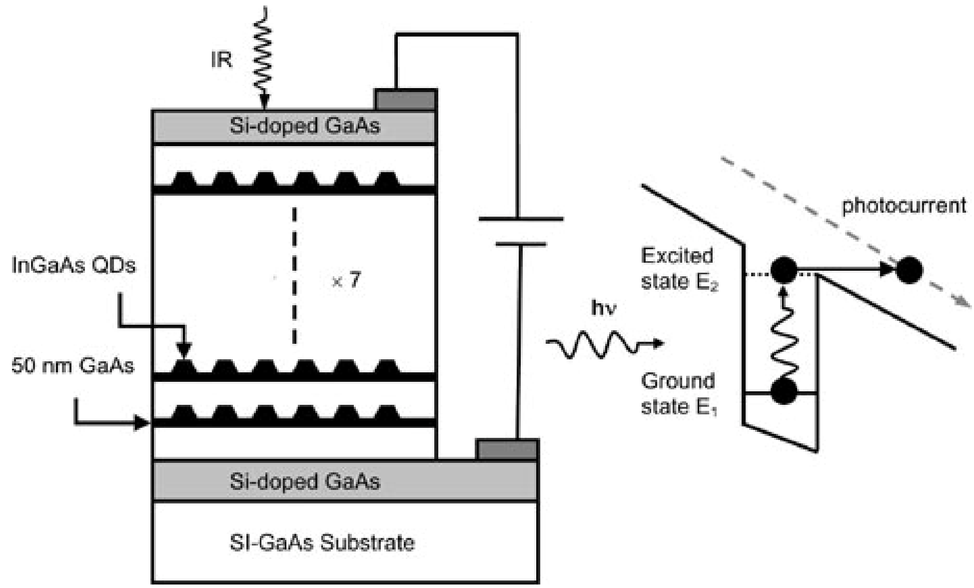
IRnova device





Quantum well infrared photodetector (QWIP) pixel with 2-D periodic grating.

S. Bandara, S. Gunapala, J. Liu, W. Hong & J. Park, JPL



Schematic of a 10-layer InGaAs/GaAs quantum dot infrared photodetector (QDIP) structure. The quantum dot layers alternate with GaAs barrier layers. At the right is the conduction band diagram of a QDIP operating under an electric field.

Lan Fu, P. Kuffner, H. Hoe Tan, & Chennupati Jagadish, Australian National University

Functional Nanostructures

Nanopillars in PV – geometric effects

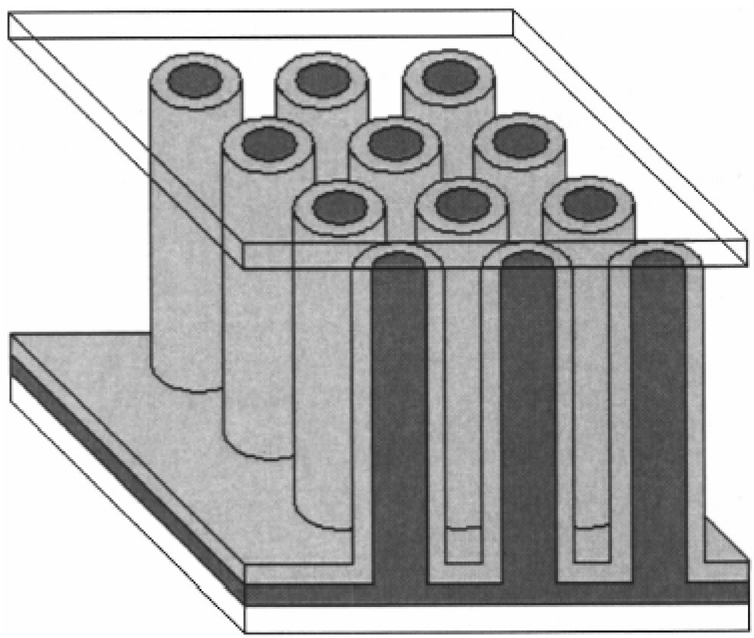


FIG. 3. Schematic cross-section of the radial p-n junction nanorod cell. Light is incident on the top surface. The light grey area is n type, the dark grey area p type.

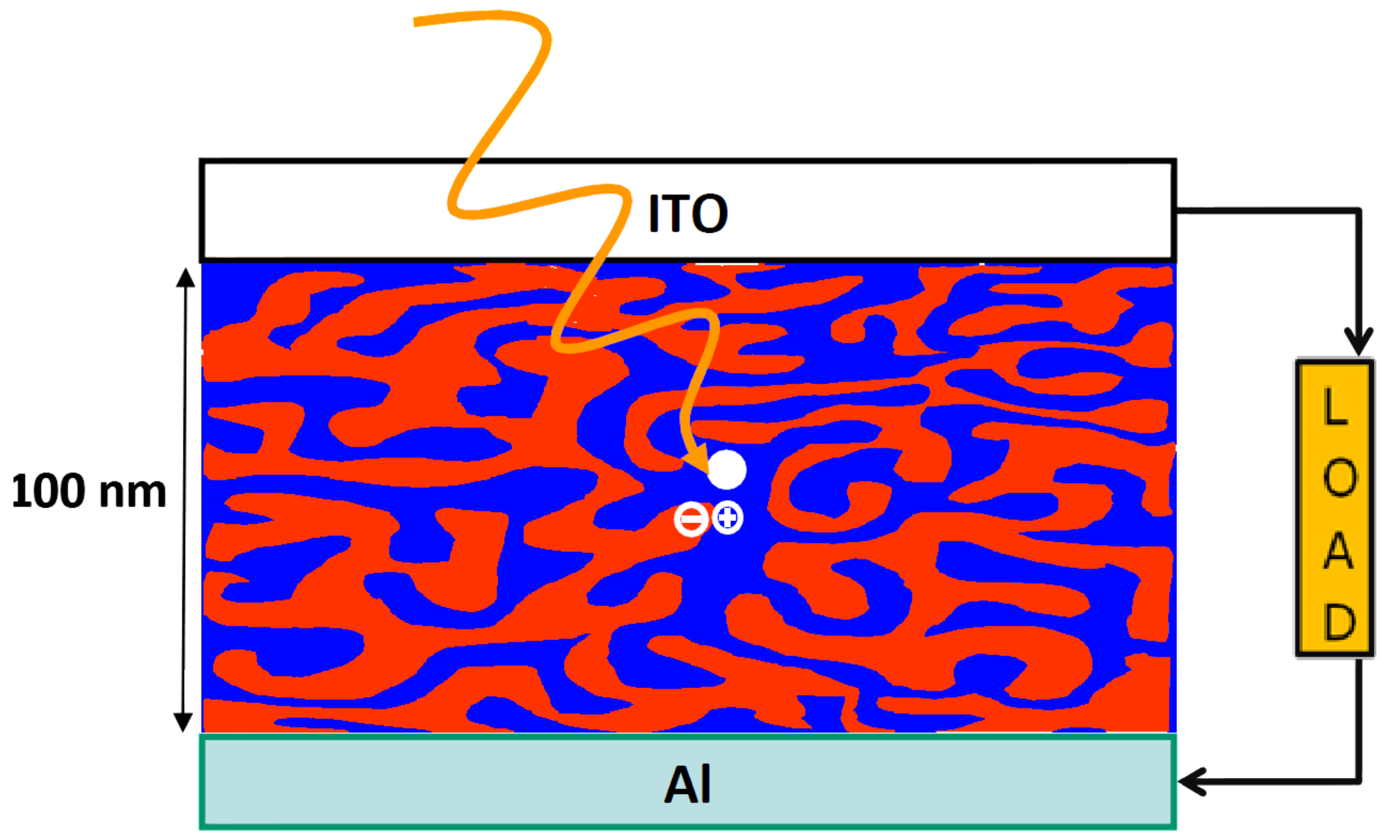
Orthogonalize absorption and minority carrier diffusion

B. M. Kayes, H. A. Atwater, & N. S. Lewis
Comparison of the device physics principles of planar and radial p-n junction nanorod solar cells
Journal of Applied Physics **97**, 114302 (2005)

Fabrication

<u>Growth of interconnected photodetector networks</u>

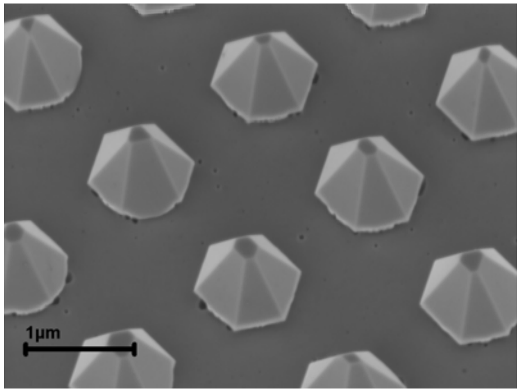
Idea from organic photovoltaics



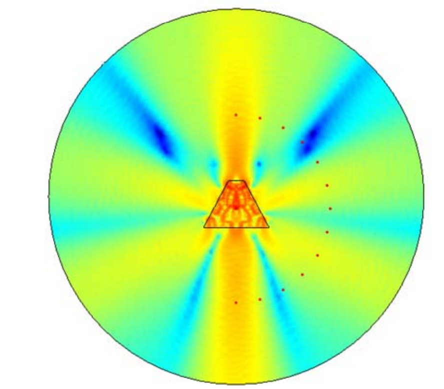
Shannon Yee, Segalman group, UCB

Functional Nanostructures

GaN nanostructures: Emitters

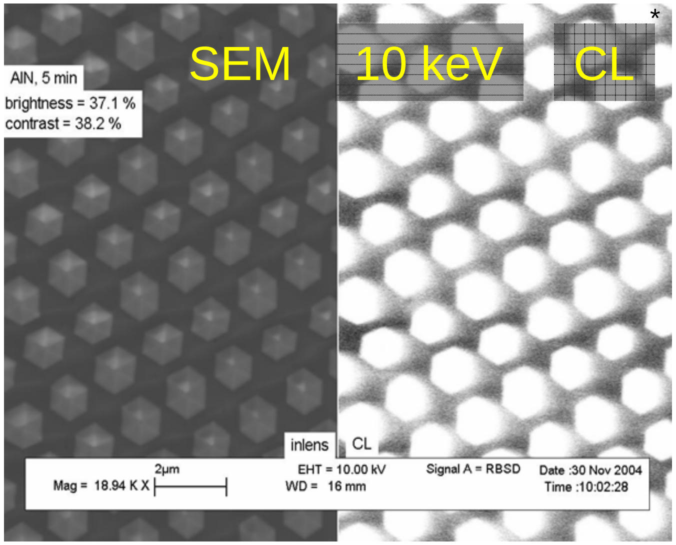


GaN nanostructures grown by SAG on GaN



Optical confinement in GaN microcavity *

* As measured at GE, GRC



*

Lasing action achieved on GaN pyramids by CL and PL

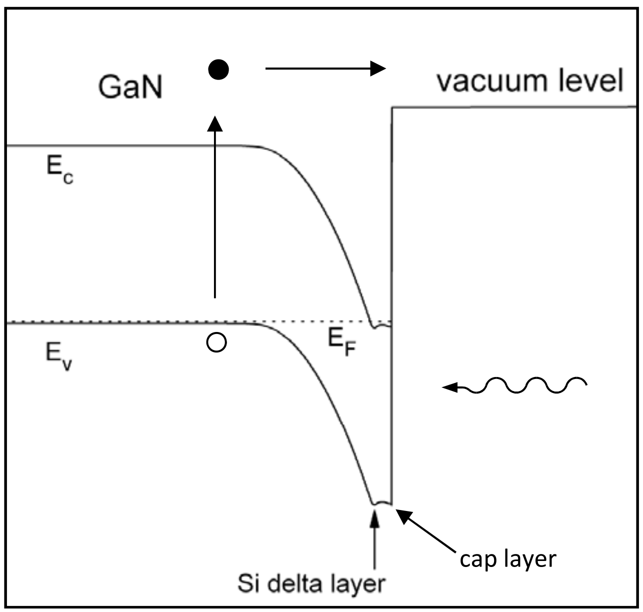
Bright pyramids suggest that the lasing CL signal is coming from pyramids only

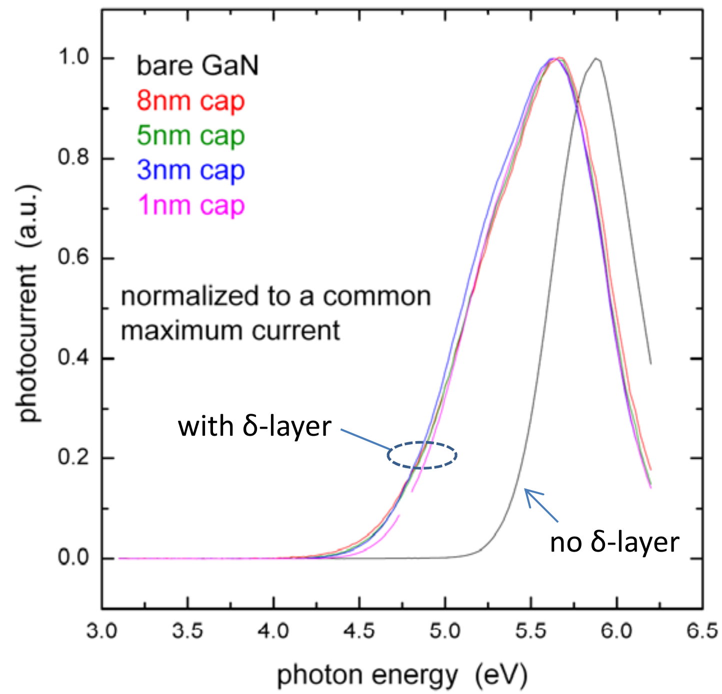
F. Shahedipour-Sandvik et al., SUNY-Albany

Functional Nanostructures

Delta-doping: precise placement of extremely high dopant distributions within devices.

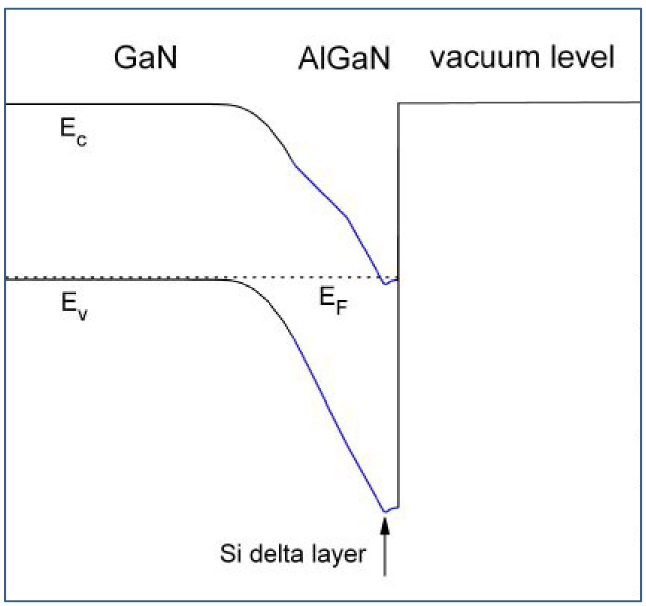
AlGaN photocathodes: Si δ-doping can be used to control band positions to achieve negative electron affinity.

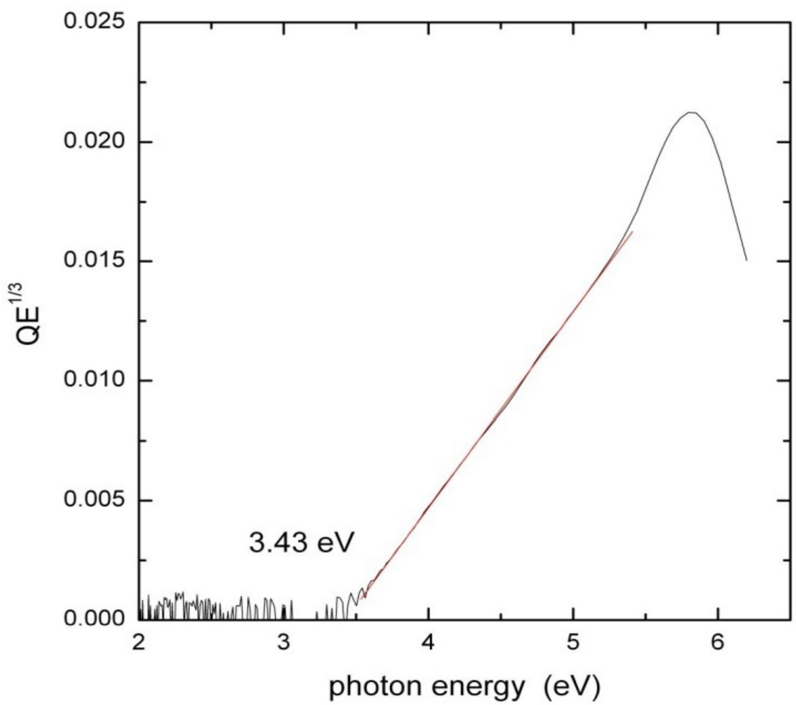




Functional Nanostructures

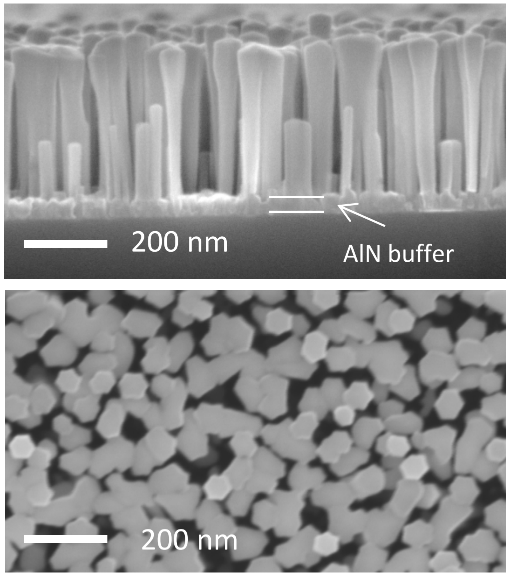
Using delta-doping techniques combined with polarization charge engineering, we can achieve negative electron affinity without surface cesiation.

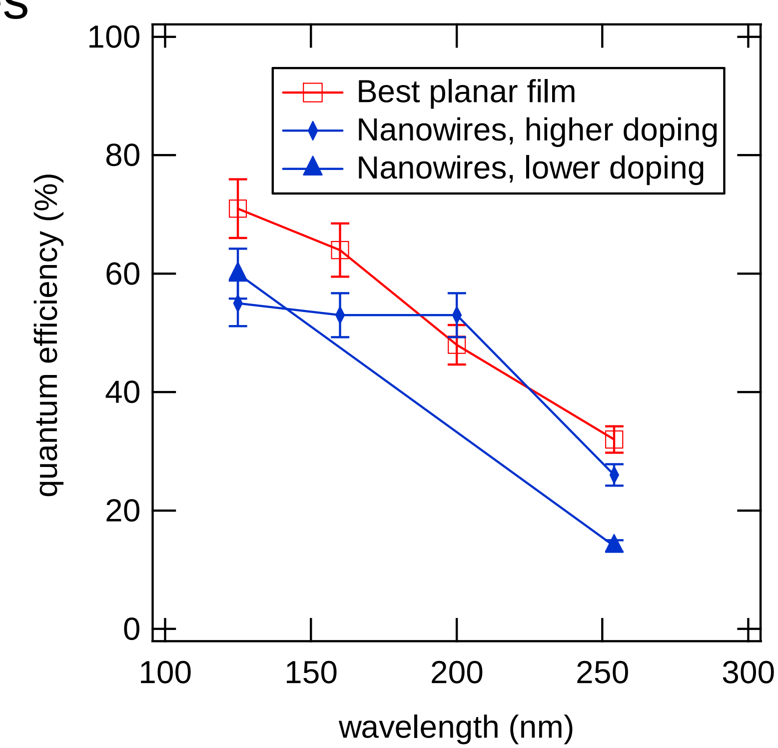




Functional Nanostructures

GaN nanowires for photocathodes





Area Coverage ≈ 0.74

- GaN nanowires grown with heavy Mg doping near tip
- Cesiated and quantum efficiency measured at NASA Goddard
- Initial results poor due to insufficient cleaning
- Performance now similar to best planar GaN

K. Bertness et al., NIST

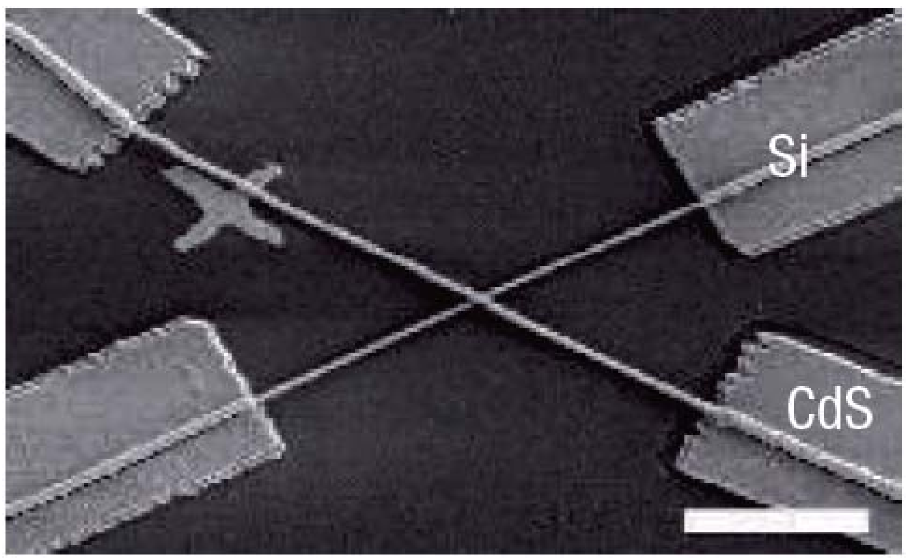
Functional Nanostructures

Nanowire APDs: avalanche multiplication of the photocurrent in nanoscale p–n diodes consisting of crossed silicon–cadmium sulphide nanowires.

LETTERS

Nanoscale avalanche photodiodes for highly sensitive and spatially resolved photon detection

OLIVER HAYDEN[1*†], RITESH AGARWAL[1†‡] AND CHARLES M. LIEBER[1,2§]



Nature Materials **5**, 352–356 (1 May 2006)

Functional Nanostructures

Metamaterials: artificially structured materials designed for novel electromagnetic properties.

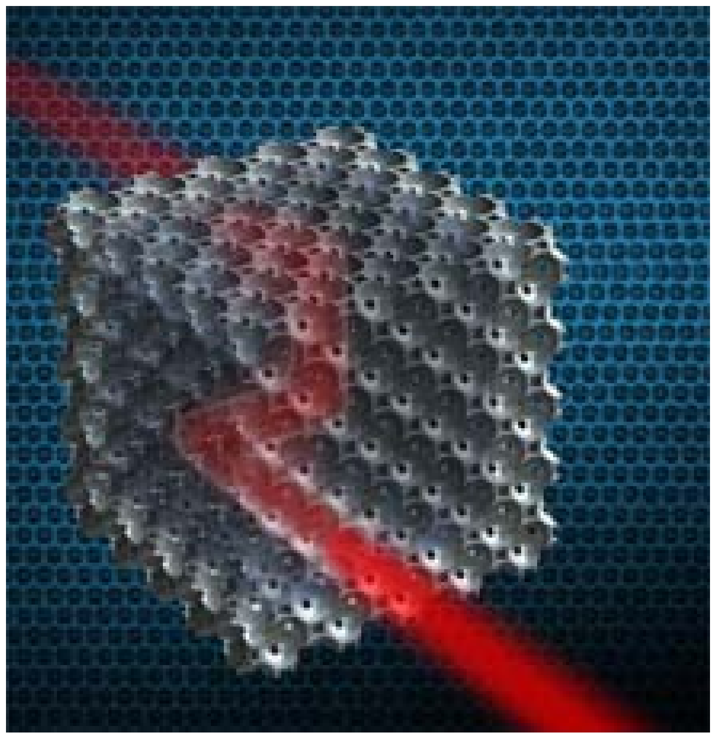
Photonic structures have lagged behind electronic structures, mainly due to a lack of naturally occurring, self-organizing building-blocks.

Several main classes of such materials have attracted interest. Two of the most familiar are:

- photonic crystals
- left-handed (negative index) materials

Functional Nanostructures

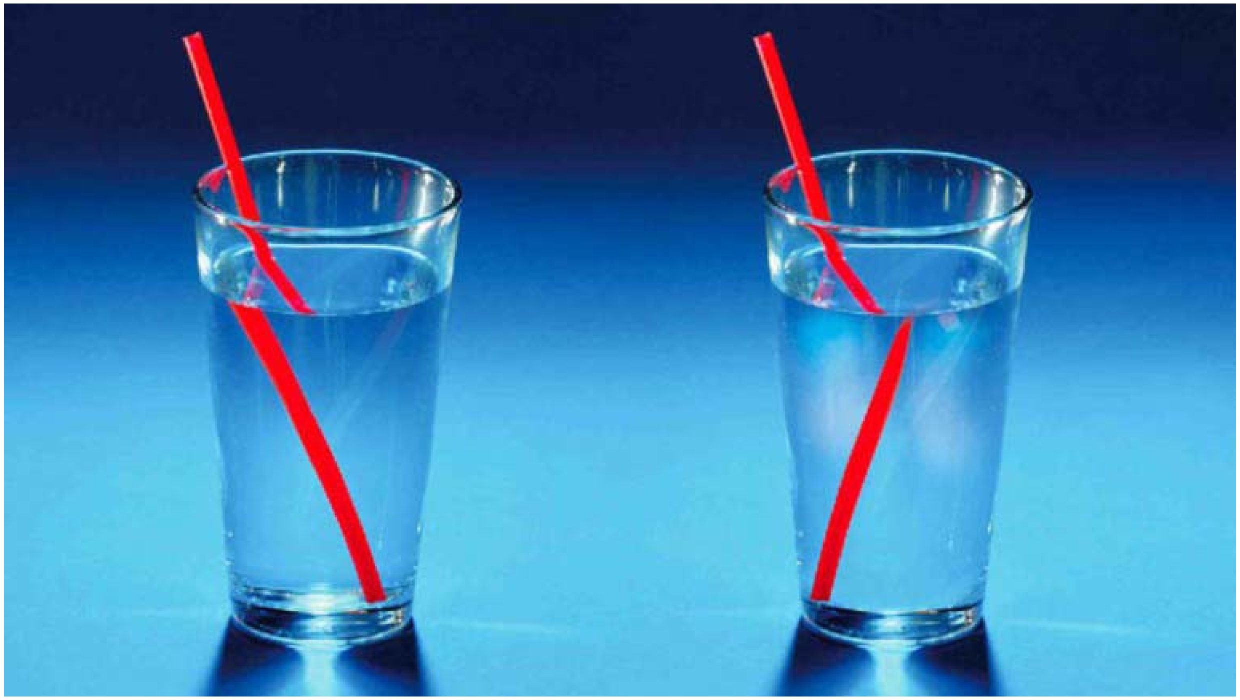
Photonic crystals are artificial structures with periodicity on the order of the wavelength of the electromagnetic radiation of interest. Using the concept of a photonic band gap, these materials offer the hope of designing materials with a high degree of control over opacity, transparency, and directionality for specific wavelength ranges.



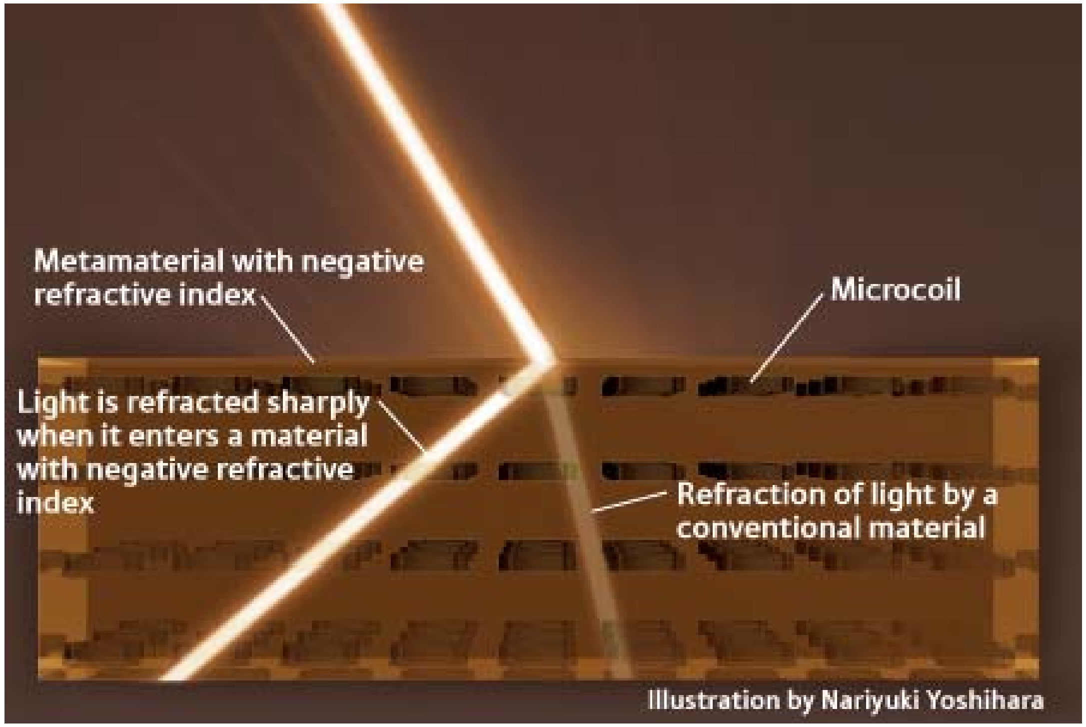
S. A. Rinne, F. Garcia-Santamaria, and P. V. Braun
“Embedded cavities and waveguides in three-dimensional silicon photonic crystals”
Nature Photonics **2**, 52 (2008).

Functional Nanostructures

Negative index materials can be constructed using periodic structures that produce an effective negative permittivity and permeability. Such materials do not occur naturally, but can produce “left-handed” refraction.



Functional Nanostructures



Metamaterial with negative refractive index. Microcoils in a metamaterial interact with the magnetic component of the light wave to refract the beam at a sharper angle, and in an opposite direction to the normal of a normal material.

Takuo Tanaka, RIKEN

Functional Nanostructures

PRL **100,** 207402 (2008) PHYSICAL REVIEW LETTERS week ending 23 MAY 2008

Perfect Metamaterial Absorber

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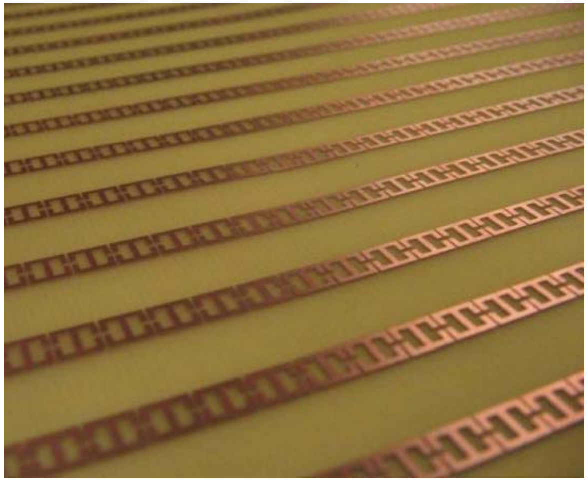
[2]*Department of Electrical and Computer Engineering, Duke University, Durham, North Carolina 27708, USA*

(Received 6 November 2007; revised manuscript received 10 March 2008; published 21 May 2008)

We present the design for an absorbing metamaterial (MM) with near unity absorbance $A(\omega)$. Our structure consists of two MM resonators that couple separately to electric and magnetic fields so as to absorb all incident radiation within a single unit cell layer. We fabricate, characterize, and analyze a MM absorber with a slightly lower predicted $A(\omega)$ of 96%. Unlike conventional absorbers, our MM consists solely of metallic elements. The substrate can therefore be optimized for other parameters of interest. We experimentally demonstrate a peak $A(\omega)$ greater than 88% at 11.5 GHz.



Functional Nanostructures

PRL **99,** 113903 (2007) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2007

Ideal Cylindrical Cloak: Perfect but Sensitive to Tiny Perturbations

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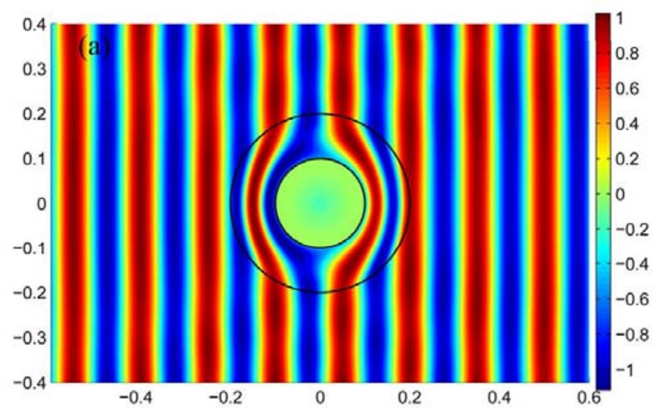
[2]*Joint Research Center of Photonics of the Royal Institute of Technology (Sweden) and Zhejiang University, Zhejiang University, Yu-Quan, 310027 Hangzhou, People's Republic of China*

(Received 8 May 2007; published 14 September 2007)

A cylindrical wave expansion method is developed to obtain the scattering field for an ideal two-dimensional cylindrical invisibility cloak. A near-ideal model of the invisibility cloak is set up to solve the boundary problem at the inner boundary of the cloak shell. We confirm that a cloak with the ideal material parameters is a perfect invisibility cloak by systematically studying the change of the scattering coefficients from the near-ideal case to the ideal one. However, because of the slow convergence of the zeroth-order scattering coefficients, a tiny perturbation on the cloak would induce a noticeable field scattering and penetration.



Conclusions

- Nanotechnology has a vast array of features that will contribute new capability and functionality to the field of UV detection.
- The ability to fabricate small structures with greater precision allows the properties to nanostructures to be used in new device designs.
- Characterization techniques now exist to evaluate the structure and optical/electronic properties of nanostructures, and to actively probe their operation.
- Nanostructures are now being developed with spectacular and unique properties which will enable completely new functionality for UV science instruments.