Research at the Center for Nanophotonics

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Areas of Research Interest

• Optical properties of compound semiconductor nanostructures and devices (quantum wells, quantum dots, nanowires, photonic crystals, lasers, and photodetectors)

• Si-based nanophotonic structures and devices (Si-based low-dimensional optoelectronic materials, structures, and devices)

• Energy conversion materials and devices (optical refrigeration, solid state lighting, solar cells, thermophotovoltaics etc.)

• Bio-photonics (optical biomedical imaging, optical inactivation viruses and bacteria, biosensing etc.)
## Center for Nanophotonics

### Members

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<th>Names</th>
<th>Unit</th>
<th>Main Research Areas</th>
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<td>Rudy Diaz</td>
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<td>Electro-magnetics</td>
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<td>Jeff Drucker</td>
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<td>Shane Johnson</td>
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<td>Jose Menendez</td>
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<td>Cun-Zheng Ning</td>
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<td>Fernando Ponce</td>
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<td>Nitride LED and materials physics</td>
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<td>Don Seo</td>
<td>Chemistry</td>
<td>Nanostructure synthesis &amp; characterization</td>
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<td>Brian Skromme</td>
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<td>Bruce Towe</td>
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<td>Kong-Thon (Frank) Tsen</td>
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<td>Shuiqing Yu</td>
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<td>Dragica Vasileska</td>
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<td>Yong-Hang Zhang</td>
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<td>Optoelectronic materials and devices</td>
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[http://www.asu.edu/aine/nanop/nanop_main.html](http://www.asu.edu/aine/nanop/nanop_main.html)
## Center for Nanophotonics

### Affiliate Members

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<td>David Allee</td>
<td>Electrical Engineering/FDC</td>
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<td>Yung Chang</td>
<td>School of Life Sciences</td>
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<tr>
<td>Junseok Chae</td>
<td>Electrical Engineering</td>
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<td>Stephen Goodnick</td>
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<td>Jiping He</td>
<td>Bio Engineering</td>
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<td>Joseph Hui</td>
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<tr>
<td>Ghassan Jabbour</td>
<td>School of Materials/FDC</td>
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<tr>
<td>Nate Newman</td>
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<td>David Smith</td>
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<td>Nongjian Tao</td>
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<td>Ignatius Tsong</td>
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<td>Hao Yan</td>
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<td>Hongbin Yu</td>
<td>Electrical Engineering</td>
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<td>Frederic Zenhausern</td>
<td>Bio Design Institute/FDC</td>
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# Major on-going programs

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<td>MURI (ASU is the lead) (2004-2009)</td>
<td>Y.-H. Zhang and J. Menendez</td>
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<td>Si based lasers</td>
<td>MURI (ASU is the lead) (2006-2011)</td>
<td>J. Menendez, J. Kouvetakis, A. Chizmeshya, Y.-H. Zhang, F. Ponce</td>
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<td>Micro laser made of nanowires</td>
<td>DARPA (2007-12)</td>
<td>C.-Z. Ning</td>
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<td>Green Lasers</td>
<td>DARPA (2007-11)</td>
<td>F. Ponce</td>
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<td>Modeling of quantum dot photodetectors</td>
<td>NSF (2007-10)</td>
<td>D. Vasileska and D. Mamaluy</td>
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The expertise of the center

• **Novel Optoelectronics Devices**
  • Fixed wavelength and tunable lasers in NIR/MWIR range for sensing applications (Zhang, S. Yu, Johnson)
  • Micro laser with low power consumption (Ning)
  • Ultrahigh efficiency solar cells (Zhang, Ponce, Ning, S. Yu, Johnson, Seo)
  • Device packaging (S. Yu, Zhang)

• **Growth Capabilities**
  • III/V semiconductors (In, Ga, Al)(N, As, P, Sb) with Si, Te, Be, C dopant (Zhang, Johnson)
  • Si/Ge MBE (Drucker)
  • CVD growth capabilities for nanowires (Ning, Ponce)

• **State of the art Materials and Device Characterization Facility**
  • PL, micro-PL and time-resolved optical system covering UV – far IR (Zhang, Ning)
  • TEM and cathode luminescence and Raman scattering (Ponce and Menendez)
  • High speed device test lab (Zhang)

• **Modeling**
  • Solar cell modeling (Vasileska, Zhang)
  • FDTD modeling (Dias)
  • Microscopic modeling of OE devices (Ning)
Center Funded Projects

CNP Research Projects

• Design of Multi-functional DNA-assembled Nanophotonic Devices
  PI: Rudy Diaz, Co-PI: Hao Yan
• Semiconductor nanostructures with extremely wide bandgap coverage on a single substrate
  PI: Cun-Zheng Ning, Co-PI: Shane Johnson
• Inactivation of viruses and bacteria using novel optical methods
  K.-T. (Frank) Tsen, S. Yu, B. Towe, Y.-H. Zhang

Seed Projects

• Novel scanning technology for nano-photonics application
  H. Yu and S. Yu
• Chip-scale directional microphones using photonic devices and nano-dendrimers
  J. Chae, M. Kozicki and Y.-H. Zhang
• Modeling heating effects in SOI devices
  D. Vasileska and S. Yu
Highlights of External Sponsored Research Programs
Semiconductor optical refrigeration (MURI)

\[ h \nu_{\text{out}} > h \nu_{\text{in}} \]

Photoluminescence refrigeration

\[ h \nu_{\text{out}} > qV_{\text{bias}} \]

Electroluminescence refrigeration
Summary of the design

- Electroluminescence refrigeration
  - LED (p-n junction) structure
  - Thin film with optimized doping profile
- High internal quantum efficiency
  - Choice of right active material
  - Optimized barrier layer materials
- High extraction efficiency
  - Hemisphere “lens” design
  - Low loss material
  - Anti-reflection coating
- Thermal isolation design
  - Suspended structures
  - Thin cross-section of the suspension arms

Grand Challenges
Up to 10 photolithography steps and a 15-day (8 hour/day) job!!
Devices pictures (Lapping and polishing)
Ultrahigh efficiency multijunction solar cells

- Integrated lattice matched II/VI and III/V semiconductors on 6.1A substrates cover the entire solar spectrum
- Multijunction (up to 5 and more) solar cells can reach more 50% conversion efficiency under a concentration ratio of 500
- Both II/VI and III/V materials are well studied and the integration is demonstrated feasible at ASU very recently
- Substantial large sponsored research programs have offered strong leverage for industrial partners
TEM Images

HR-TEM images of a 120 nm ZnTe layer grown on a GaSb substrate, with a lower resolution image on the top and a higher resolution image at the bottom. Clear and smooth interfacial configuration (where the arrows point to) between ZnTe and GaSb can be seen in the images, which confirms the very coherent interface and excellent crystalline quality of the samples.

Taken by X. Zhang and D. Smith
The PONCE Group at Arizona State University

**Physics Of Nitride Compound Electronics**

- **AlGaN Alloys**
  - (Air Force Grant)
  - Properties and microstructure
- **Materials for UV Lasers**
  - (NEDO Grant)
  - Akasaki/Amano, Meijo Cherns, Bristol
- **Nitride Semiconductor Powder**
  - (DOE Grant)
  - Synthesis by combustion
- **Green Lasers**
  - (DARPA-VIGIL)
  - Electron Holography Cathodoluminescence
- **Physics Of Nitride Compound Electronics**
- **Epitaxy on Silicon substrates**
  - (With Germany)
  - Microstructure and light emission
- **Materials for Green Lasers**
  - (Nichia Grant)
  - InGaN, Defects
- **High Efficiency Phosphors**
  - (Durel Grant)
  - ZnS GaN
- **Solid State Lighting Initiative**
  - (DOE)
  - Applications to Interior Lighting
Nanostructures in III-V Nitride Films

Prof. Fernando Ponce
Current research activities

Wide-gap semiconductors for high efficiency light emitting devices
- Nichia Project
- DOE Project

Development of Green Lasers
-DARPA Project – VIGIL

Nanostructured InGaN Solar Cells
-Science Foundation of Arizona Project

GaN Powders and Thin Films for Electroluminescent Displays
-Rogers/Durel Project

Ultraviolet LEDs and Lasers based on AlGaN
- DARPA UV Program

InGaN Quantum wells for green lasers
Fluctuations in thickness and composition are important in increasing the light emitting efficiency
Nitride Films for Solid State Lighting

Low-angle domain boundaries
By x-ray rocking curves
C-axis tilt: ~5 arc min
C-axis rotation: ~8 arc min
(assymmetric reflexions)
F. A. Ponce, MRS Bull, 22, 51 (1997)

Three types of DLs:
- Edge type, \( \mathbf{b}_e = 1/3 \langle 1120 \rangle \)
- Screw type, \( \mathbf{b}_s = \langle 0001 \rangle \)
- Mixed type, \( \mathbf{b}_m = 1/3 \langle 1123 \rangle \)

Cross-section view -- Nichia blue LED
GaN/GaInN/GaN/Sapphire
Using GaN buffer layers
10^{10} Dislocations/cm^2

Threading dislocations limit the electrical and optical performance of devices.
Need to know the electronic charge states at different types of threading DLs.
Alloy Semiconductor Nanowires as PV Materials
Ning Group

• Growth and characterization of semiconductor alloy nanowires

(Part of the SFAz SRG Program)
Electrical Injection Plasmonic Nanolasers
Ning Group

To understand, design, optimize, and fabricate

• Nanoscale semiconductor-metal contacts
• p-n, or p-i-n junction configuration for carrier injection
• Interaction between nanoscale metal structures (bowtie) and semiconductors (QDs, NWs)
• Nanoscale plasmonic lasers

• Dependence of contact resistance on contact size and geometry studied
• Dependence of depletion width on diameter of wires
• Carrier injection in longitudinal junction and core-shell junction studied
• Injection levels as function of doping, metal choice, and bias investigated
• Threshold of bowtie-antenna laser studied using a model system
• Various metal-semiconductor structures fabricated and PL studied

(Part of DARPA NACHOS Program, in collaboration with Berkeley, LBNL, UIUC)
Microscope Photoluminescence Study of Semiconductor Nanowires
(Ning Group)

- InAs (MBE and MOCVD)
- GaN (CVD and MOCVD)
- GaSb and InSb (CVD)
- II-VI nanowires (CVD)
- Metal oxides
- Micro-PL on single wires
- Cryostat to room temperature

Collaboration with Connie Chang (UC Berkeley)
Vladmir Dubroski (Ioffe Institute)
Mahendra Sunkara (U of Louisville)
OBJECTIVE

• Create nanoscale devices for higher efficiency solar energy and photonics applications: specifically demonstrate the feasibility of a “monolayer” solar cell.

ACCOMPLISHMENTS

• Computational demonstration of true antenna mode resonance of connected spheres.
• Simulation of polydisperse chains.

APPROACH

• DNA self-assembly of Ag-nanosphere antenna arrays.
• AINE Tasks:
  • Computational design of antennas to maximize receiving cross section between 600 nm to 900 nm (solar peak)
  • Goal: >90% absorption in a monolayer.

PAY-OFF

• Proposal submitted to DOE rated highly.
• Other proposals on photonic devices requiring first principles simulation of photonic antennas
Designer DNA architectures that self-assemble

Arrays of finite dimension and addressability


Yan Group
DNA Nanoarrays directed Self-assembly of Metallic Nanoparticle Arrays


Highlights of CNP Sponsored Programs

• Design of Multi-functional DNA-assembled Nanophotonic Devices
  PI: Rudy Diaz, Co-PI: Hao Yan

• Semiconductor nanostructures with extremely wide bandgap coverage on a single substrate,
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• Inactivation of viruses and bacteria using novel optical methods
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Non-Maxwellian Boundary Conditions for the modeling of the interaction of molecules and photonic devices

Diaz, Yan, Panaretos

OBJECTIVE
• Implement realistic (non-Maxwellian) boundary conditions presented by molecules and the biological environment to electromagnetic fields, to enable accurate design of plasmonic antenna systems for nano-bio-electronics.

APPROACH
• Model the molecule in the full-physics solver as an electrically small antenna with internal non-linear structure that resonantly absorbs one quantum of energy from an ambient field.
• Bohr correspondence between the probability of radiative transitions and the radiation resistance.

ACCOMPLISHMENTS
• Baseline model of the molecule implemented.
• General scalable model being developed.

PAY-OFF: NIH Eureka proposal
• Molecule model will enable the design of an artificial electrocyte for the creation of neuro-stimulation nanomachines.

The ultimate application of these nano-machines is to the real-time in vivo interaction with neurons.
Ongoing work and challenges

• The internal structure of the molecule is a resonant length of transmission line with non-linear resistors (fuses) that switch open when one quantum of energy has been absorbed.
• Upon reconnection, the emission (radiative transition) rate is governed by the Radiation resistance.

• The non-linear nature of the switching mechanism creates non-physical harmonics.
• Next order model is in work
Experimental setup for the inactivation of viruses

M-L Ti-Sapphire Laser ➔ Harmonic Generator ➔ M.O. ➔ S ➔ Magnetic stirrer

Tseng Group
Excitation laser with wavelength at 425 nm, pulse width of 100 fs
$P_{av} = 40$ mW; focused spot = 100 microns

(a) M13 bacteriophage sample with nominally prepared $1 \times 10^3$ pfu
Without laser irradiation

(b) M13 bacteriophage sample with nominally prepared $1 \times 10^3$ pfu
After laser irradiation

Tsen Group
Laser power density – dependence of the inactivation of M13 phages

Excitation laser with wavelength at 425 nm, pulse width of 100 fs
focused spot = 100 microns

M13 sample with $1.1 \times 10^3$ pfu/cc

- $R^2 = 0.9465$; df = 74
- LD$_{50} = 51.94 \pm 0.14$ MW/cm$^2$
- 95% CI = 51.67 - 52.22

Tsen Group
How does ISRS technique inactivate the viruses?
Important Findings

• Very low power femtosecond visible lasers can efficiently inactivate viruses.

• Selectivity of inactivation of microorganisms can be obtained by proper manipulation of femtosecond lasers.

• The technique targets the mechanical vibrations of the capsid with a visible laser beam, as a result it is very unlikely to produce mutated strains of unwanted microorganisms, i.e., it is environmentally friendly.

• The method can be a general way of inactivating unwanted microorganisms while leaving the sensitive materials such as mammalian cells unharmed. In particular, it can be used for effective treatments/load reduction of blood-borne diseases such as AIDS and Hepatitis C, as well as the disinfection of blood bank.

Tsen Group
News coverage of Tsen’s work

• BBC News: Laser treatment could kill HIV
• U.S. News: New Laser Technique Kills Bacteria and Viruses
• Washington Post: New Laser Technique Kills Bacteria and Viruses [03/2008].
• http://spie.org/x18231.xml?highlight=x2416
• http://www.osa-opn.org/OpenContent/Feature2.aspx
Highlights of CNP Seed Projects

• Novel scanning technology for nano-photonics application, H. Yu and S. Yu

• Chip-scale directional microphones using photonic devices and nano-dendrimers, J. Chae, M. Kozicki and Y.-H. Zhang

• Modeling heating effects in SOI devices, D. Vasileska and S. Yu
ZnO Nanostructure Synthesis and Device Fabrication

SEM image of ZnO nanowires

Electric Field is generated between the two pads.

A drope of ZnO nanowires in IPA solution was dispensed onto the center of the trapping sample.

After the solution evaporation, the nanowires stay on the surface of the gold electrodes by van der Waals force.

Yu Group
Thermoelectric and Electrothermal Effects in Nanoscale Devices
D. Vasileska, K. Raleva, S. M. Goodnick and S. Yu

Objective:
1. Develop state of the art simulator for modeling heating effects in nanoscale devices
2. Use the simulator to investigate heating effects in conventional FD SOI devices with different channel lengths (different device technologies)
3. Use the simulator to examine whether Silicon on Diamond has advantages over conventional SOI devices
4. Extend the simulator to 3 spatial dimensions to be able to model FinFET device structures

Work Accomplished:
1. Developed the most sophisticated simulator in the world for modeling heating effects in FD SOI devices. Within our model we solve BTE for the electrons and the acoustic and optical phonons energy balance equations in a self-consistent manner
2. We observe that in the smallest nanoscale devices the presence of non-stationary transport and velocity overshoot leads to smallest degradation of the device characteristics as most of the energy is converted to heat in the drain contact
3. SOD technology is better then SOI