SAND2013-7449C

Nanophotonics and Optical Nanomaterials (NPON) Thrust Overview

Igal Brener

Nanophotonics & Optical Nanomaterials










-Igal Brener – Thrust Leader

-Steve Doorn - Partner Scientific Leader

-Anatoly Efimov

-Jennifer Hollingsworth

-Han Htoon

-Sergei Ivanov

-Willie Luk

-Rohit Prasankumar

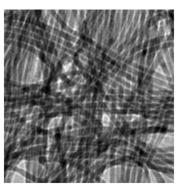
-Hou-Tong Chen

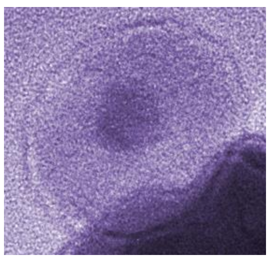
-Ryan Camacho

Vision of Thrust

Thrust Focus: to understand and control fundamental photonic, electronic and magnetic interactions in nanostructured optical materials fabricated using both chemical and physical synthesis

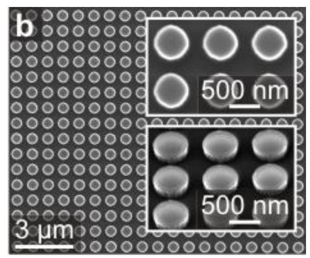
Light-matter interaction at the nanoscale



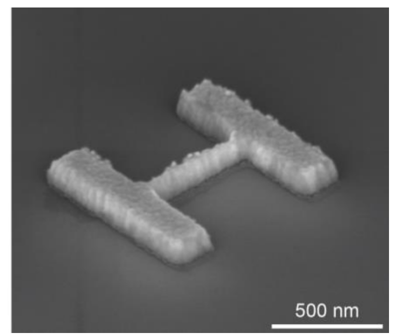


Hybrid nanocrystals

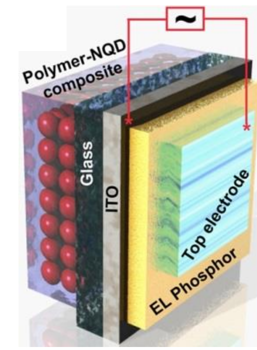
Simple nanowires to superlattice heterostructures



Dielectric Nanoresonators



Metamaterials and Nanoplasmonics



Novel optoelectronic devices

Synthesis

Fabrication
Measurements

Integration

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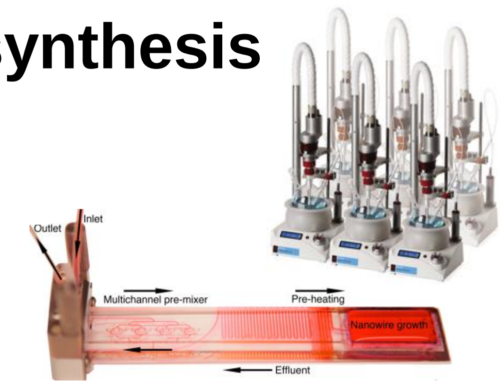
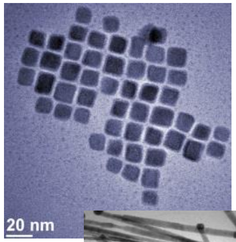
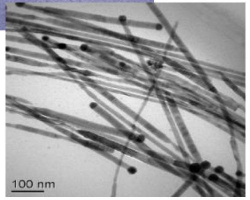
Strengths of NPON thrust at CINT

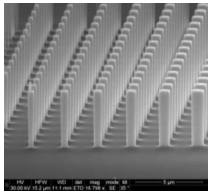
- **Novel optical nanomaterial synthesis**

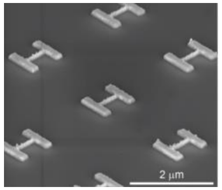




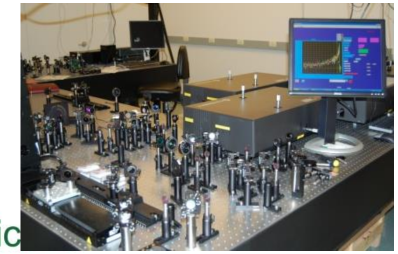


- **World class nanolithography**





- **Cutting edge spatial and temporal optical characterization tools and techniques**



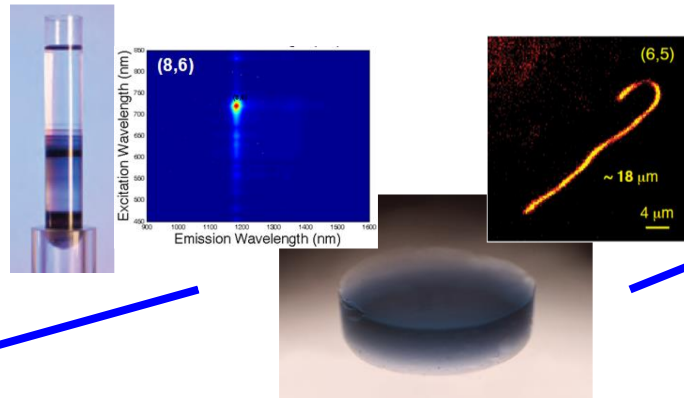
(10 scientists, ~25 postdocs)

Examples of Research Highlights

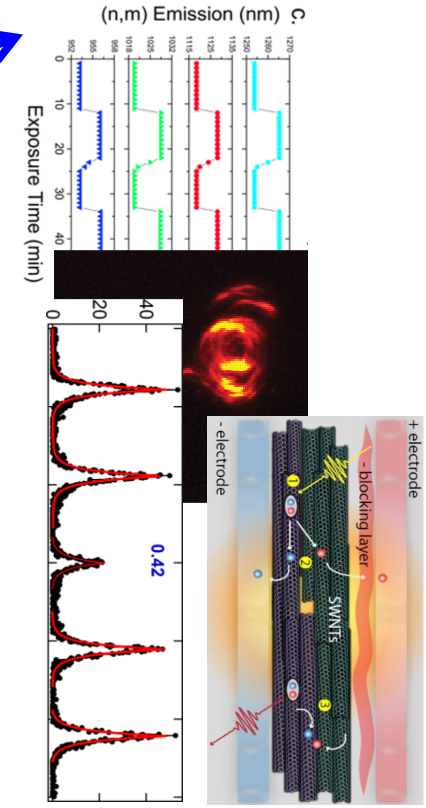
- Carbon Nanotubes
  - Poster: Juan Duque, "Functional Carbon Nanotube Mesocomposites for Sensing & Nanophotonics"
- Ultrafast Dynamics in Nanowires
- Plasmonics and Metamaterials Integration Focused Activity
  - Talk: Burckel, "3D Microfabrication Using Membrane Projection Lithography"
  - Poster: Azad, "Active control of electromagnetically induced transparency analogue in terahertz metamaterials"

Research Highlight: Advances in Carbon Nanotube Spectroscopy and Chemistry

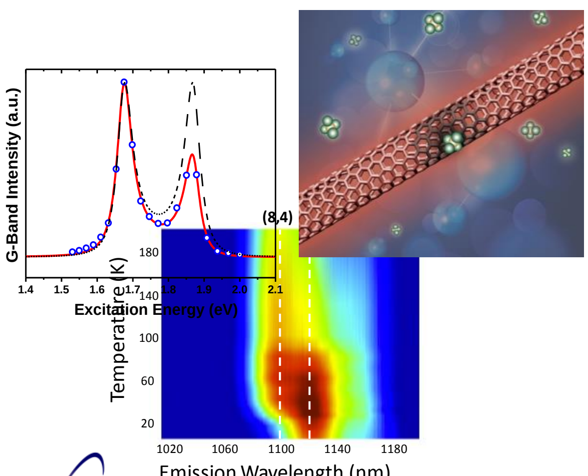
Improved Samples, Novel Matrices, New Probes



Opening
New Applications



Enabling
New Fundamental
Measurements



Nanotube Program

Internationally Recognized Effort

23 user papers since 2010

16 current and former users

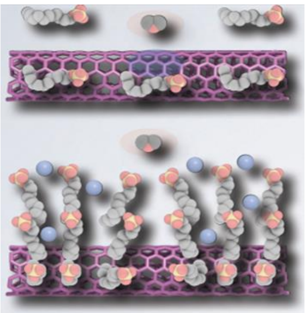
Cross-thrust interactions

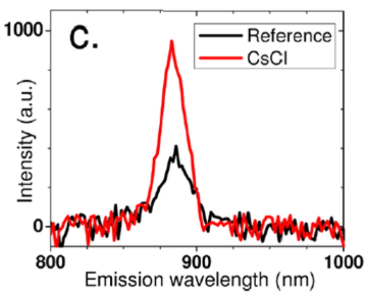
Supporting early-career awards through user projects

Research Highlight: Carbon Nanotube Surface Chemistry in 1-D

Probing Non-Covalent Surface Interactions

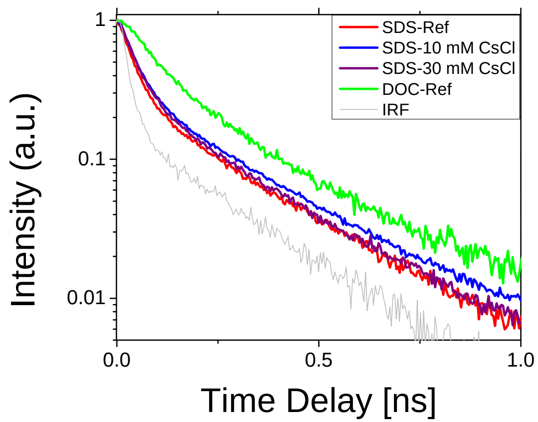
Electrolyte-induced surfactant reorganization.

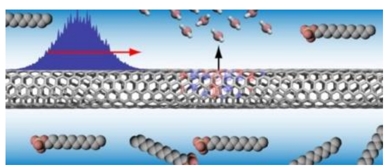




Photoluminescence brightening results.

Exciton dynamics dependent on surface structures.



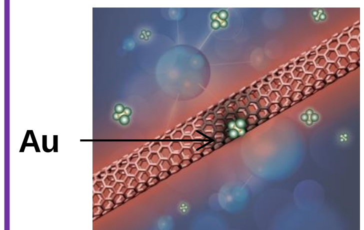


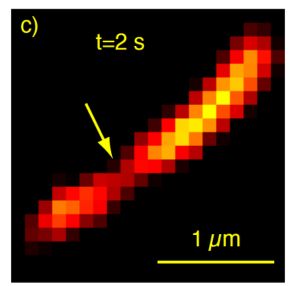
Reveals role of surface water in exciton decay.

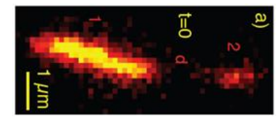
J.G. Duque et al., *J. Am. Chem. Soc.*, **135**, 3379 (2013).
J.G. Duque, et al., *J. Am. Chem. Soc.*, **132**, 16165 (2010).

Single-Tube and Site Imaging/Spectroscopy

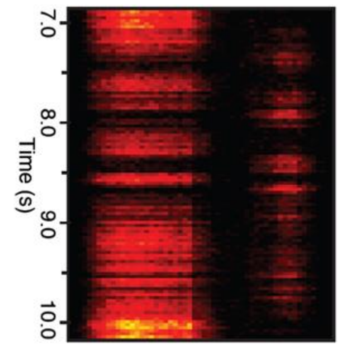
Observing localization and dynamic dopant behaviors via photoluminescence probes.







2 segment CNT



Anti-Correlated blinking

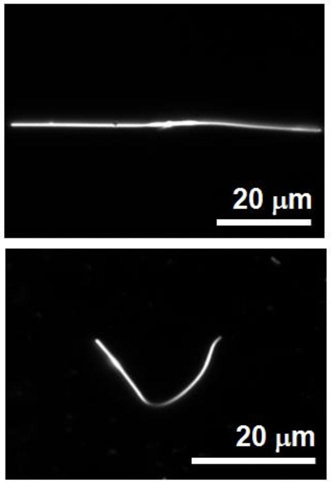
J. Crochet, et. al., *Nature Nanotech*., **7**, 126 (2012).
J. Crochet, et. al., *Nano Letters*, **12**, 5091 (2012).

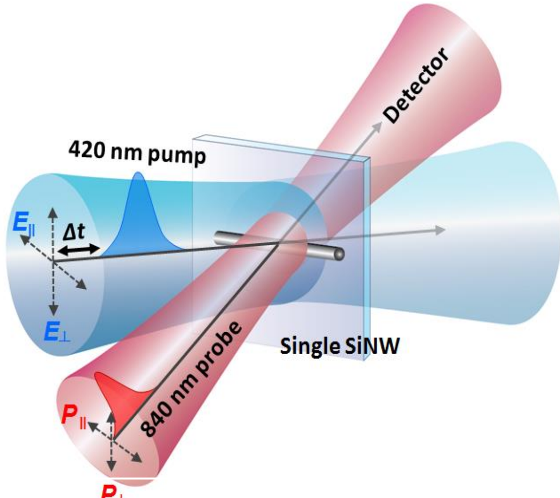
Single dopant sensitivity. Probing new optical states.

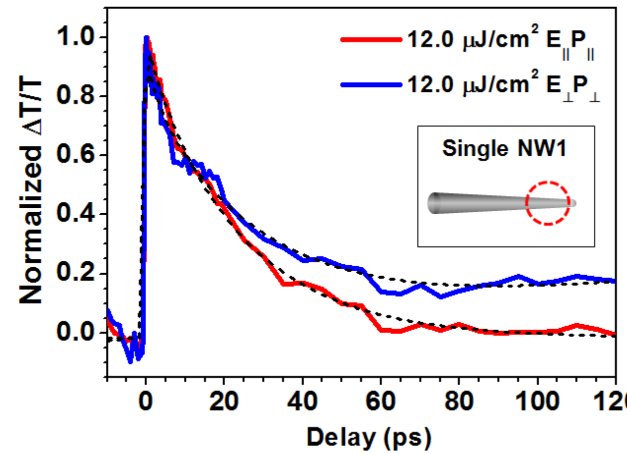
Direct imaging of dopant and exciton diffusion dynamics.

Recent incorporation of single-site spectroscopy.

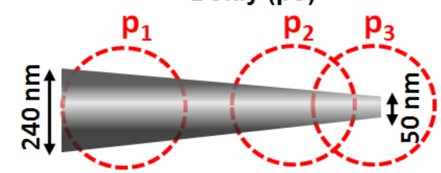
Research Highlight: Understanding Ultrafast Carrier Dynamics in Single Si Nanowires

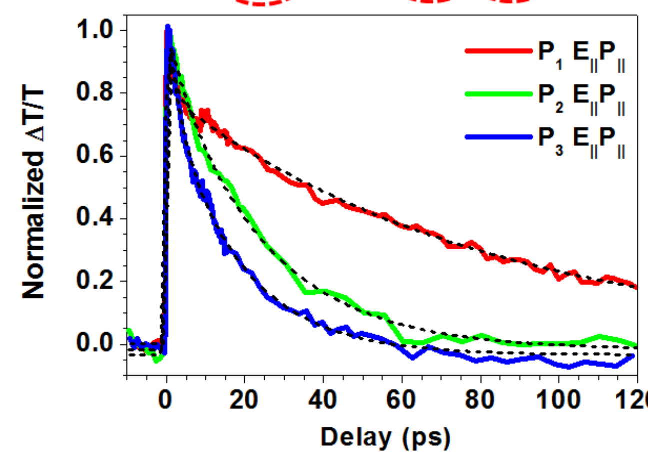






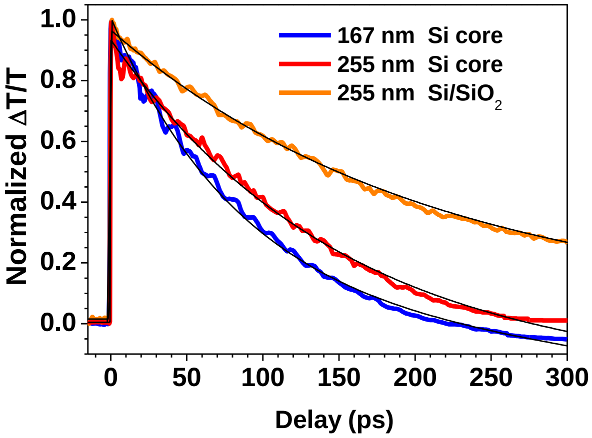
- First ultrafast time-resolved, polarization-dependent experiments on single Si nanowires (NWs)
- Faster decay observed in the single NW as compared to bulk silicon and ensemble NWs
  - Position-dependent experiments show that relaxation time increases with NW diameter
- Polarization-dependent carrier relaxation primarily depends on photoexcited carrier density

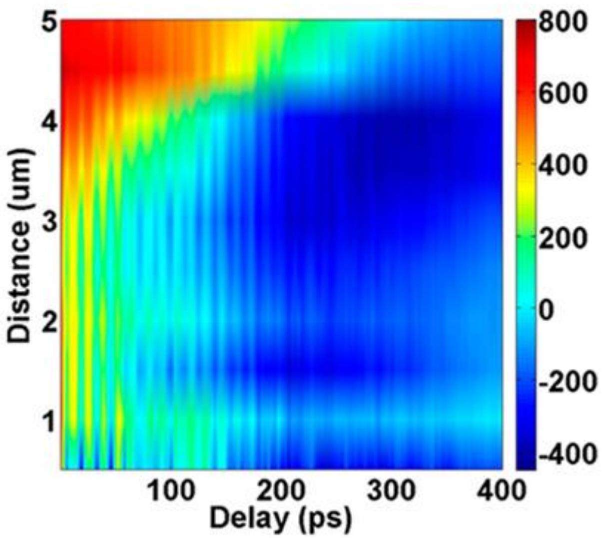




M. A. Seo et al, *Appl. Phys. Lett.* **100**, 071104 (2012).

Research Highlight: Mapping Carrier Diffusion in Single Si NWs Using Ultrafast Microscopy





- Ultrafast optical microscopy was used to map carrier relaxation and diffusion in single Si core-only and core-shell nanowires
  - Observed coherent acoustic phonon oscillations in all NWs for the first time
- Mapped carrier diffusion for electrons and holes in both core-only and core-shell NWs
  - Revealed strong influence of surface passivation on carrier transport in these NWs
  - Can extract fundamental parameters including diffusion constant, diffusion velocities
- These results demonstrate that ultrafast optical microscopy can shed new light on the intrinsic properties of semiconductor NWs

M. A. Seo, et al, *Nano Lett*. **12**, 6334 (2012).

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Integration Focus Activity: Metamaterials and Plasmonics for New Tunable Devices

Artificially structured metamaterials and plasmonics provide novel functionalities which are difficult or impossible to achieve using naturally occurring materials

Integration Science Issues:

- Integration between materials, substrates and metamaterials
- Tunability by hybridizing structures and materials
- Enhanced novel functionalities

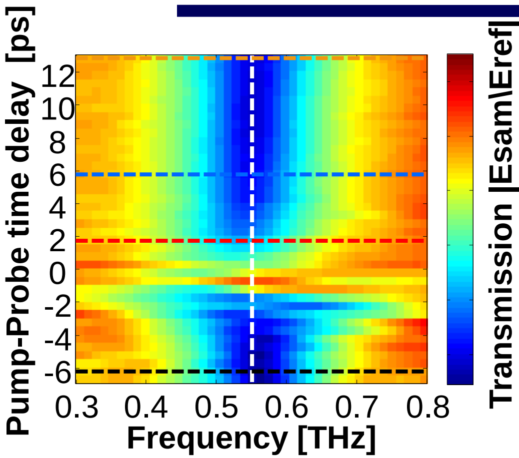
Selected user projects [total user projects, 2010-2012: 65]

1. *Development of non-metallic Fano-resonant infrared metamaterials with exceptionally high quality factors*
   PI: Gennady Shvets, **University of Texas at Austin**; Leading CINT Scientist: Igal Brener
2. *Controllable spatial terahertz modulators*
   PI: Daniel Mittleman, **Rice University**; Leading CINT Scientist: Hou-Tong Chen
3. *Metamaterial Infrared Detectors for Multispectral and Polarimetric Sensitivity*
   PI: Sanjay Krishna, **University of New Mexico**; Leading CINT Scientist: Jennifer Hollingsworth
4. *Strong Exciton-Plasmon Interactions in Semiconductor-Metal Hybrid Nanostructures*
   PI: Xuedan Ma**, Los Alamos National Laboratory**; Leading CINT Scientist: Han Htoon
5. *Tunable THz metamaterial quantum cascade lasers*
   PI: Benjamin Williams, **University of California at Los Angeles**; Leading CINT Scientist: John Reno
6. *Understanding near field enhancement in the metamaterials based quantum dots in a well (DWELL) photodetectors*
   PI: Yagya Sharma**, University of New Mexico**; Leading CINT Scientist: Rohit Prasankumar
7. *Active Nanoplasmonics: Compact, ultrafast, and power-efficient optical devices at the nanoscale*
   PI: Rohan Kekatpure**, Sandia National Laboratory**; Leading CINT Scientist: Willie Luk

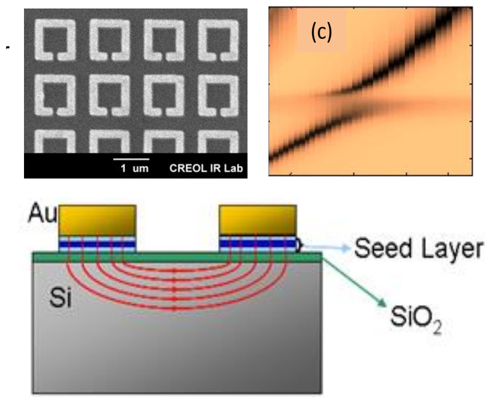
Some of the CINT scientists that participate:

Chen, Brener, Hollingsworth, Htoon, Prasankumar, Reno, Luk, Jia,….

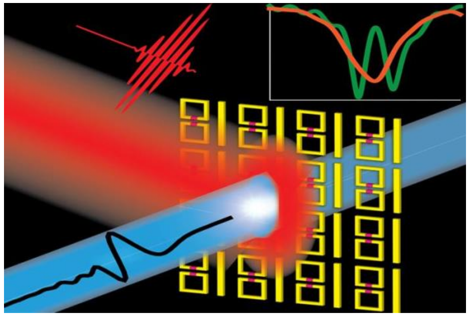
Example Accomplishments in the Metamaterials and Plasmonics IFA



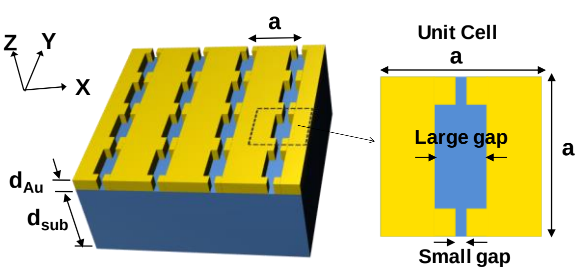
Nonlinear superconducting metamaterials (New J. Phys. 2013, User Project: U2010A989).



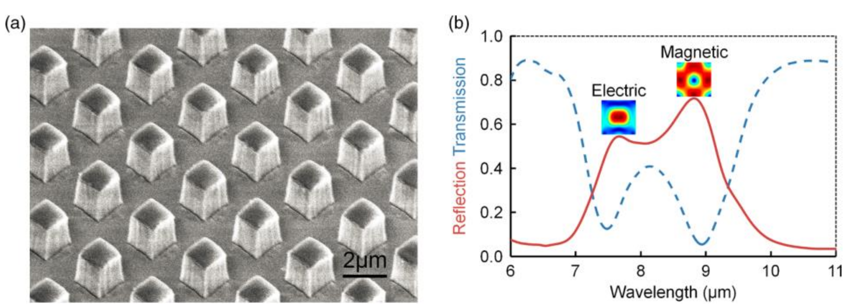
Strong coupling between metamaterials and phonons in SiO2, (Nano Letters 2011, User Project: U2010A1001)



Switchable electromagnetically induced transparency and tunable slow light (Nat. Commun. 2012, User Project C2010A954)



Nonresonant Broadband Funneling of Light via Ultrasubwavelength Channels, (PRL 2011, User Project: U2010B1064).



Dielectric Resonator Metamaterials at Optical Frequencies, (PRL 2012 , User Project: U2010A1001).

Vision and Opportunities

Tuning electromagnetic phenomena using metamaterials & plasmonics

Synthesis and controlled integration

Nanoscale-to-mesoscale excitation and energy-transformation

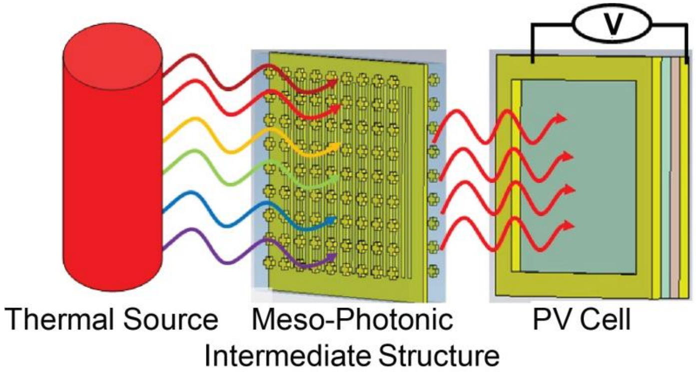
New instrumentation

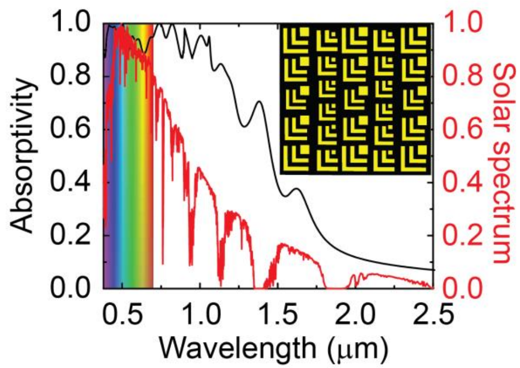
These areas were chosen because of our expertise, capabilities, user base, relevance to applications and synergies

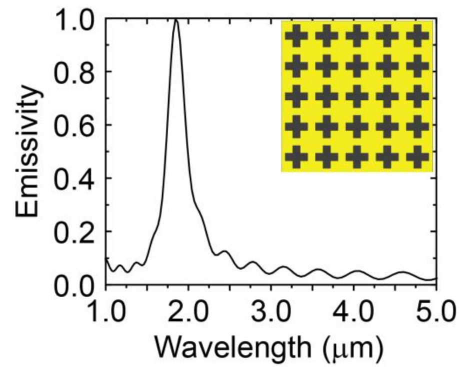
Our research remains at the cutting edge of nanophotonics, as validated at the joint NSRC workshop at CLEO 2013.

Tuning Electromagnetic Phenomena Using Metamaterials & Plasmonics

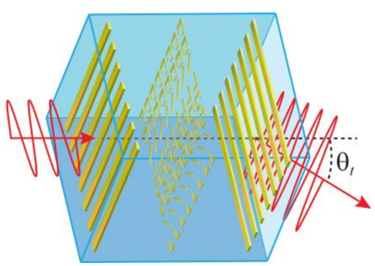
- **Solar thermophotovoltaics through tailored metamaterial absorption/emission**

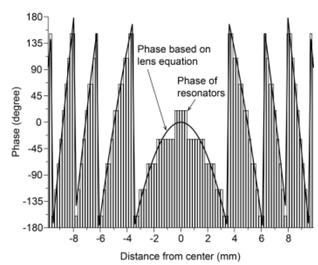


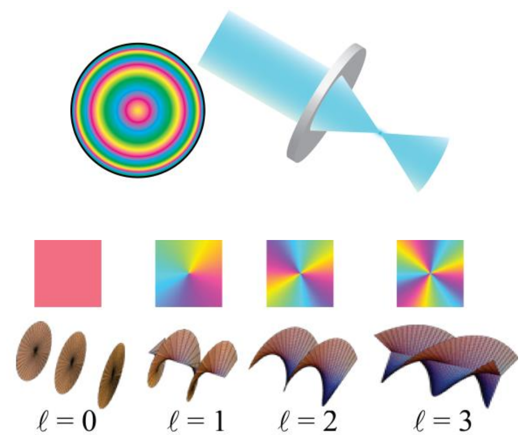




- **Polarization conversion and wavefront shaping: towards flat optics**

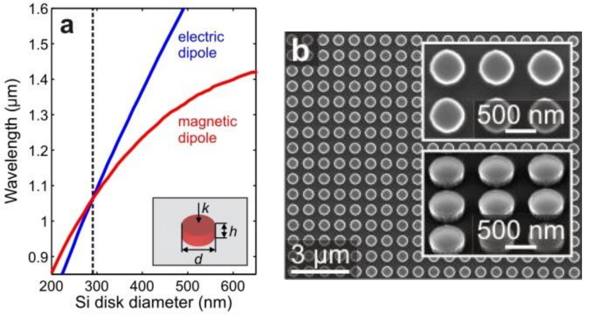




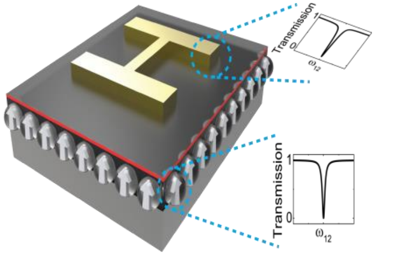


Tuning Electromagnetic Phenomena Using Metamaterials & Plasmonics

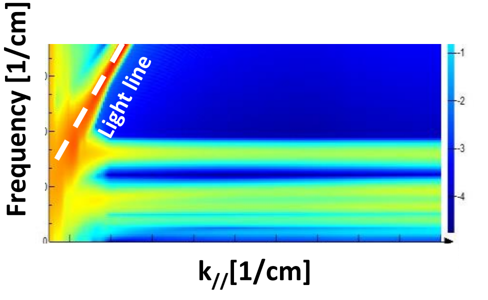
- **Dielectric nanoresonators coupled to QD emitters for improved coupling and directionality**

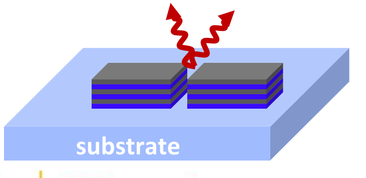


- **Strong coupling between metamaterials + excitations in semiconductor heterostructures (detectors, IR LEDs, etc)**



- **Hyperbolic metamaterial (HM) - deeply subwavelength metallo-dielectric stacks for emission control**



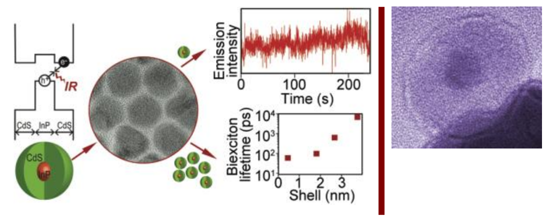


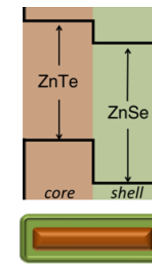
Synthesis and Controlled Integration

1. Next-generation optical nanomaterials

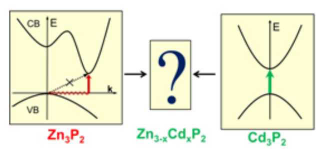
a. New heterostructures for emergent and multi-functionality

- “Giant” shell approach applied to IR
- Hybrid-interfaces: “Inside-out” semiconductor/metal core/shell NCs
- bandgap-engineered NCs, rods and wires (type II)





b. Band structure by composition, anisotropy, etc

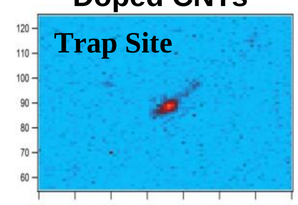


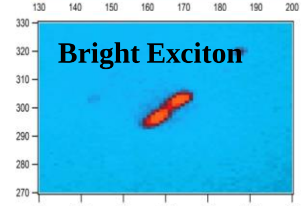
c. Carbon nanotube development

- Novel dopant chemistry for new emitting states
- Tube-aerogel composites: Integrating nano and mesoscale structures
- CVD synthesis for CNT/NW heterostructures

CNT/Aerogel Composites

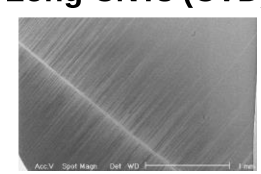
Imaging of Doped CNTs





CVD Growth

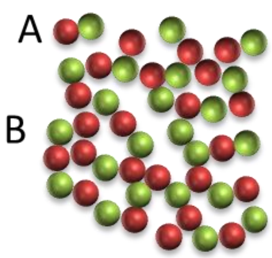
Long CNTs (CVD)



Synthesis and Controlled Integration

2. Integration into hybrid/composite structures through synthetic control

a. Heterocomponent gels



A and/or **B**

- Semiconductor
- Plasmonic metal
- Ferromagnetic
- Core/shell NCs

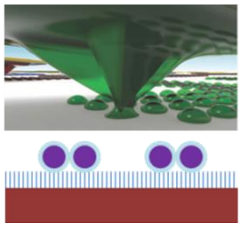
b. Matrices

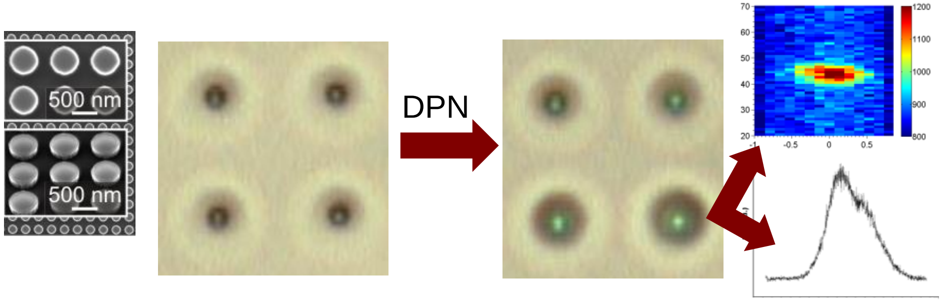
- Charge transport (i.e. solar)
- Stabilization
- Thermally insulating (i.e., thermoelectrics)

3. Precision integration through advanced lithography

- Exciton-plasmon interactions
- Patterning 1D NWs
- Local doping of 2D materials

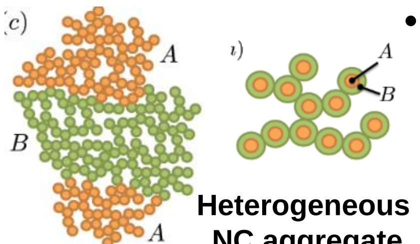
Dip-pen nanolithography





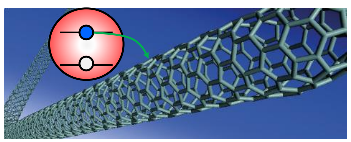
NCs in protective polymer coating selectively deposited onto the tops of Si nanoresonators

Nano-to-Mesoscale Excitation and Energy-Transformation

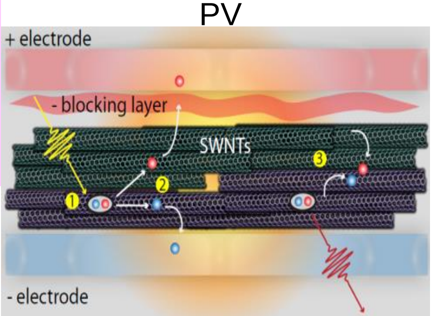


Heterogeneous NC aggregate

NC-SWCNT coupled system



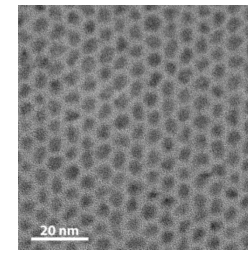
PV



- **Understanding and control of charge and energy transfer processes in mesoscopic assemblies:** Sample systems: NC aerogel, NC-Graphene Flake, NC-SWCNT hybrids, QD Solids
Combine optical spectroscopies with TEM, SEM or AFM
$\Rightarrow$ *effects of dimensionality and coupling on the optical properties*

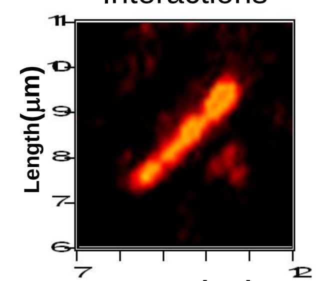
- **Probing and manipulating excitonic and plasmonic behaviors in carbon nanomaterials**

-dopant-induced optical behaviors and dynamic surface chemistry of adsorbed species
-SWNT, Graphene and GO based PV architectures
-microscale optical modulators, switches, detectors, and sensors.

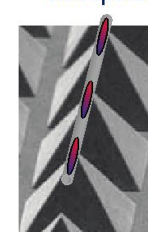


Ordered QD array
(H. Fan)

Exciton/Plasmon Interactions



"hot spots"



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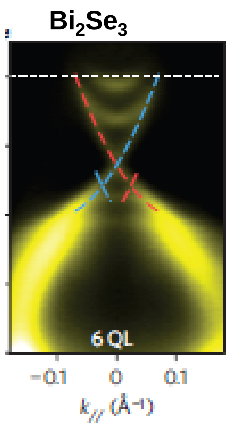
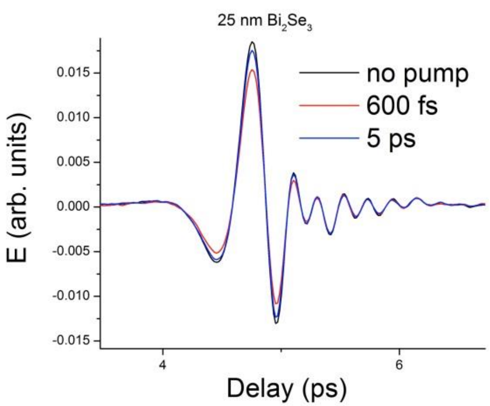
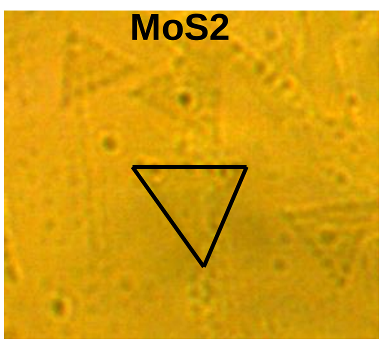
Nano-to-Mesoscale Excitation and Energy-Transformation



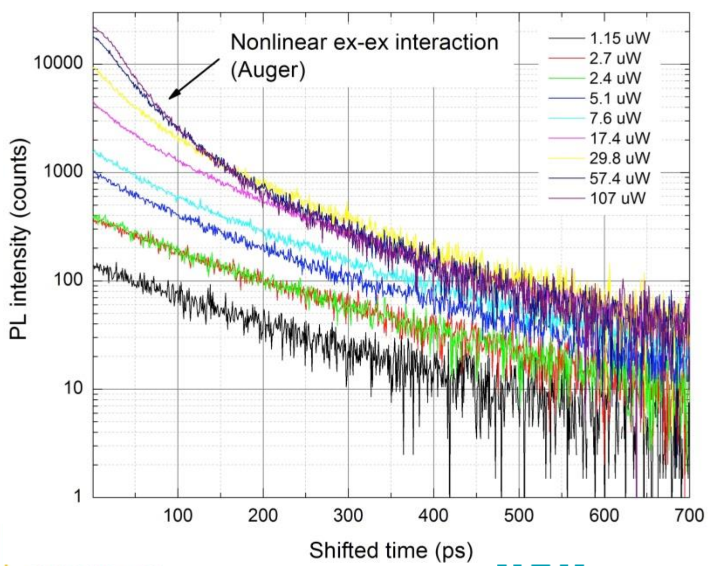
- **Ultrafast carrier dynamics in two-dimensional (2D) nanomaterials, shedding light on phenomena including:**
  - Dynamics of surface states in topological insulators
  - Energy transfer in dissimilar 2D materials separated by a controlled number of BN monolayers
  - Nonlinear exciton dynamics in electrically biased/gated 2D monolayers
  - Spatially-resolved exciton diffusion processes in 2D nanomaterials

Photoinduced changes in the THz E-field through Bi_2Se_3





Time-resolved PL on WSe_2



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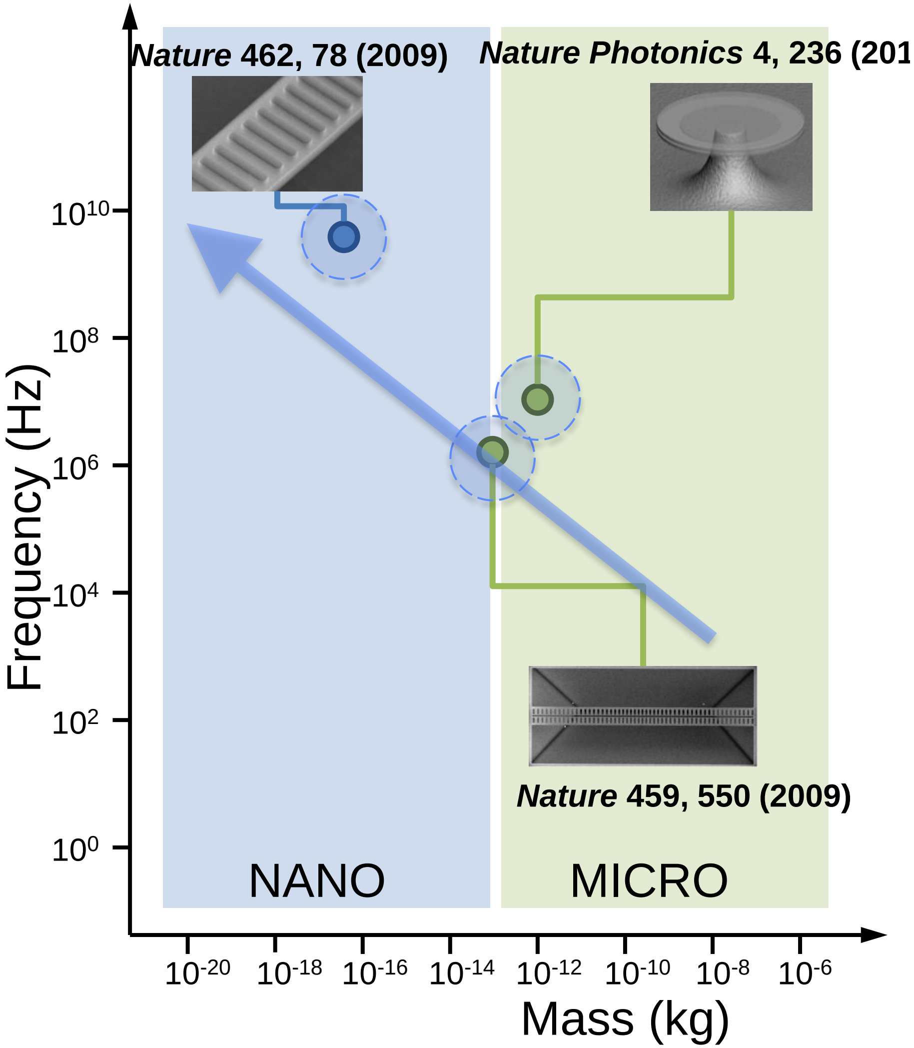
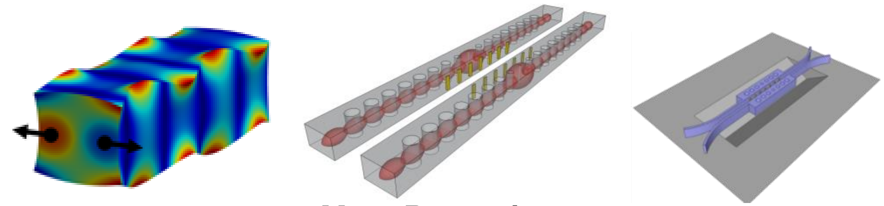
New CINT Science: Optomechanics





Most Recently:

"Giant SBS Enhancement: combination of radiation pressure and electrostriction lead to dramatic nonlinear effects in nano-scale structures."

Phys. Rev. X 2, 011008 (2012)

<u>Next Steps (New CINT Science):</u>

- ***Plasmonic Optomechanics: Coulombic + optical forces lead to even smaller devices, higher optomechanical forces, and novel transduction mechanisms.***
- ***Optomechanics in $\chi^{(2)}$ materials: Novel material systems with non-centrosymmetry will lead to new nonlinear optomechanical effects.***
- ***Exciton transport using optomechanics: Photon-induced electron-hole pairs will be controlled and manipulated using optically generated mechanical waves.***
- ***Optomechanics with intra-cavity light sources: The physics changes dramatically when the optical light source is <u>inside</u> the optomechanical cavity.***

Vision and Opportunities

Tuning electromagnetic phenomena using metamaterials & plasmonics

Synthesis and controlled integration

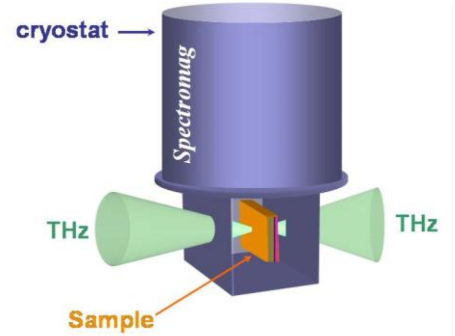
Nanoscale-to-mesoscale excitation and energy-transformation

New instrumentation

New Instrumentation being Developed

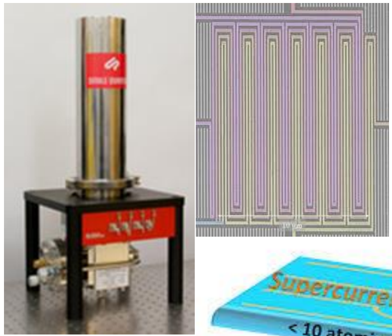
- **THz magneto-optical spectroscopy**
  - THz-TDS measurements can be performed in a B field up to 8 T, at temperatures down to ~1.5 K
  - Explore novel phenomena in 2D nanomaterials including graphene, topological insulators, TMDCs

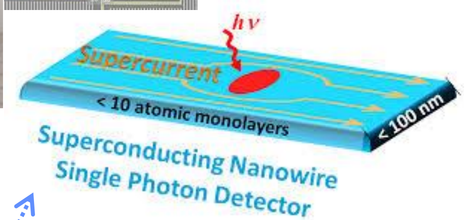
(Prasankumar)



- **Superconducting Nanowire Detector**
  - 50 ps time resolution
  - Detection range 600-1700nm
  - Dark count: <300 Hz at peak QE

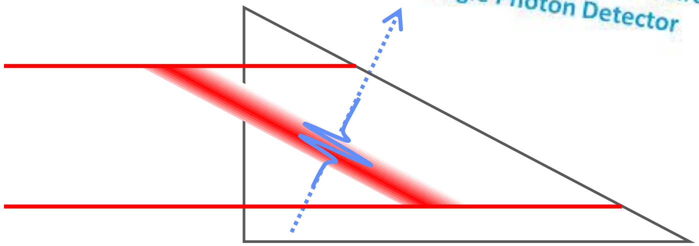
(Htoon)





- **High power THz system**
  - Tilted Pulse Front Optical Rectification
  - >100 kV/cm, 0.5 - 1.5 THz bandwidth
  - Sample in He Cryostat or 8T Magnet

(Chen)



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Outlook

Tuning electromagnetic phenomena using metamaterials & plasmonics

Synthesis and controlled integration

Nanoscale-to-mesoscale excitation and energy-transformation

Nanowires and Metamaterials IFA

New instrumentation

User Talks and Posters

- **User talks:**
  - **Bruce Burckel, (SNL), *"3D Microfabrication Using Membrane Projection Lithography"***
  - **Anton Malko (UT Dallas): *"Colloidal Nanocrystals: From Photoluminescence Blinking to Applications in Energy Transfer"***
- **Posters**
  - **Juan Duque, LANL, *"Functional Carbon Nanotube Mesocomposites for Sensing & Nanophotonics"***
  - **Jun Oh Kim, UNM: *"Polarization-dependent photocurrent enhancement in metamaterial-coupled quantum dot-in-a-well infrared photodetectors"***
  - **Lina He, Skorpios: *"Reducing Losses of Si Photonic Waveguides and Tapers"***
  - **Jeremy Wright, SNL, *"Controlled lasing in GaN nanowires"***
  - **A. Azad, OSU-LANL, *"Active control of electromagnetically induced transparency analogue in terahertz metamaterials"***