Research at the Center for Nanophotonics

Yong-Hang Zhang
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ASU

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		
Names	**Unit**	**Main Research Areas**
Rudy Diaz	EE	Electro-magnetics
Jeff Drucker	Physics	SiGe MBE
Shane Johnson	IAFSE	OE Devices and MBE
Jose Menendez	Physics	Optical spectroscopy
Cun-Zheng Ning	EE	Modeling and nanowires
Fernando Ponce	Physics	Nitride LED and materials physics
Don Seo	Chemistry	Nanostructure synthesis & characterization
Brian Skromme	EE	Optical spectroscopy & SiC device
Bruce Towe	BE	OE device for biosensing
Kong-Thon (Frank) Tsen	Physics	Bio-photonics
Shuiqing Yu	EE	OE devices and packaging
Dragica Vasileska	EE	Transport & TE effect
Yong-Hang Zhang	EE	Optoelectronic materials and devices

http://www.asu.edu/aine/nanop/nanop_main.html

Center for Nanophotonics

Affiliate Members

David Allee	Electrical Engineering/FDC
Yung Chang	School of Life Sciences
Junseok Chae	Electrical Engineering
Stephen Goodnick	Electrical Engineering
Jiping He	Bio Engineering
Joseph Hui	Electrical Engineering
Ghassan Jabbour	School of Materials/FDC
Nate Newman	School of Materials
David Smith	Physics
Nongjian Tao	Electrical Engineering
Ignatius Tsong	Physics
Hao Yan	Chemistry & Biochemistry
Hongbin Yu	Electrical Engineering
Frederic Zenhausern	Bio Design Institute/FDC

Major on-going programs

Programs	Funding Agency	PI &Co-PIs
Semiconductor optical refrigeration	MURI (ASU is the lead) (2004-2009)	Y.-H. Zhang and J. Menendez
Self Assembly at Photonic and Electronic Scales	NSF GOALI NIRT (2006- 11)	R. Diaz, A. Panaretos, H. Yan et al.
Si based lasers	MURI (ASU is the lead) (2006-2011)	J. Menendez, J. Kouvetakis, A. Chizmeshya, Y.-H. Zhang, F. Ponce
Ultra high efficiency multijunction solar cells	AFRL (2008-12)	Y.-H. Zhang , S. Yu, S. Johnson
Micro laser made of nanowires	DARPA (2007-12)	C.-Z. Ning
Novel high efficiency solar cells	SRG Award (SFAz) (2007-08)	Y.-H. Zhang, F. Ponce, C.-Z. Ning, A. Kost, S. Yu, S. Johnson
Green Lasers	DARPA (2007-11)	F. Ponce
Modeling of quantum dot photodetectors	NSF (2007-10)	D. Vasileska and D. Mamaluy

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**

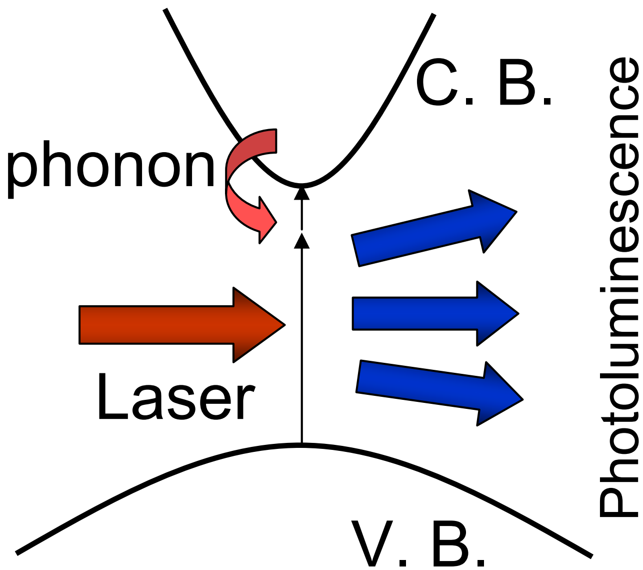
  J. Chae, M. Kozicki and Y.- H. Zhang

- **Modeling heating effects in SOI devices**

  D. Vasileska and S. Yu

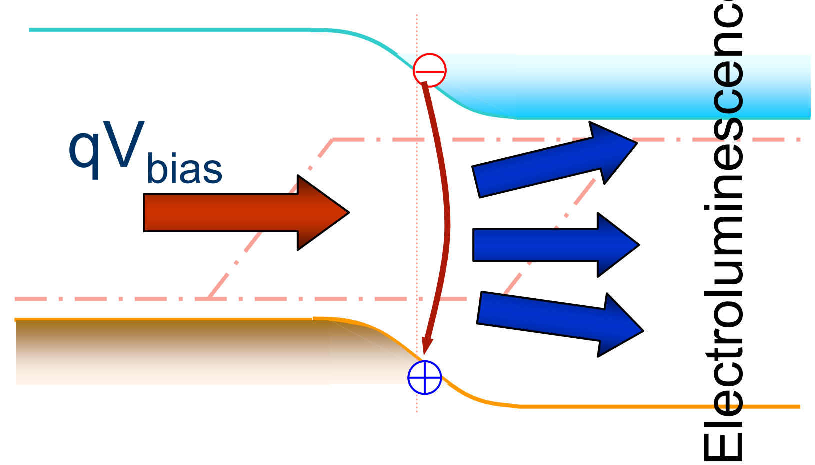
Highlights of External Sponsored Research Programs

Semiconductor optical refrigeration (MURI)



$$h\nu_{out} > h\nu_{in}$$

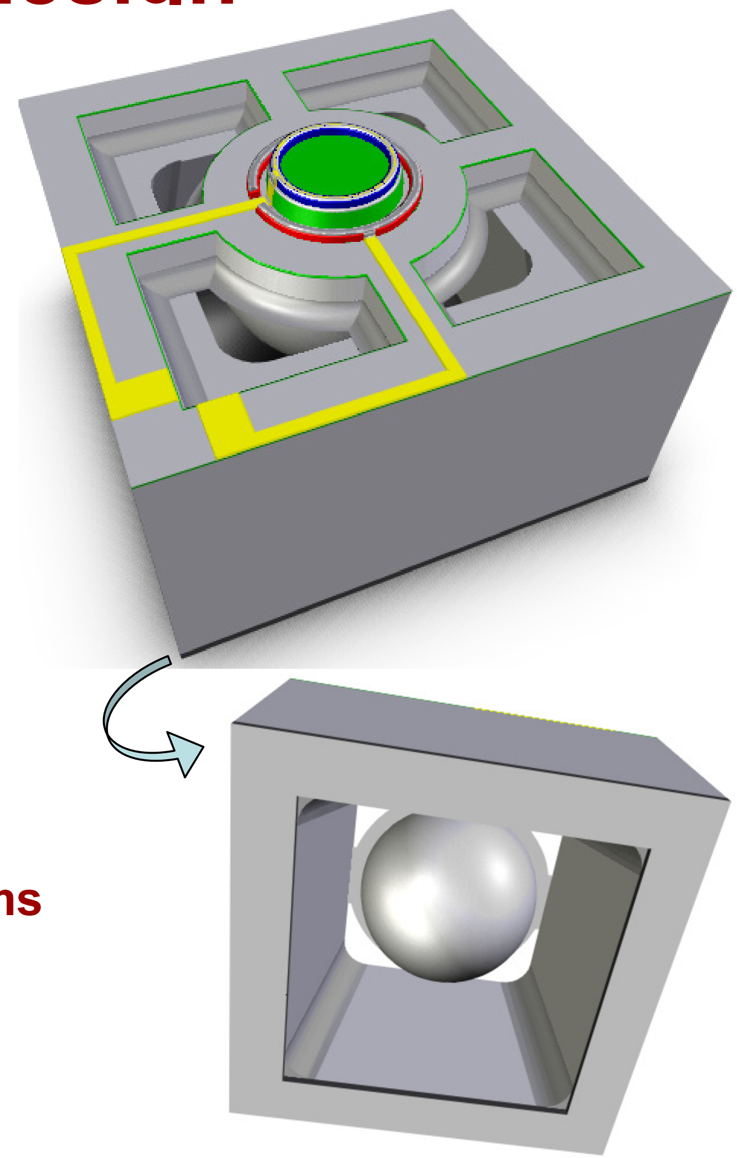
Photoluminescence refrigeration



$$h\nu_{out} > qV_{bias}$$

Electroluminescence refrigeration

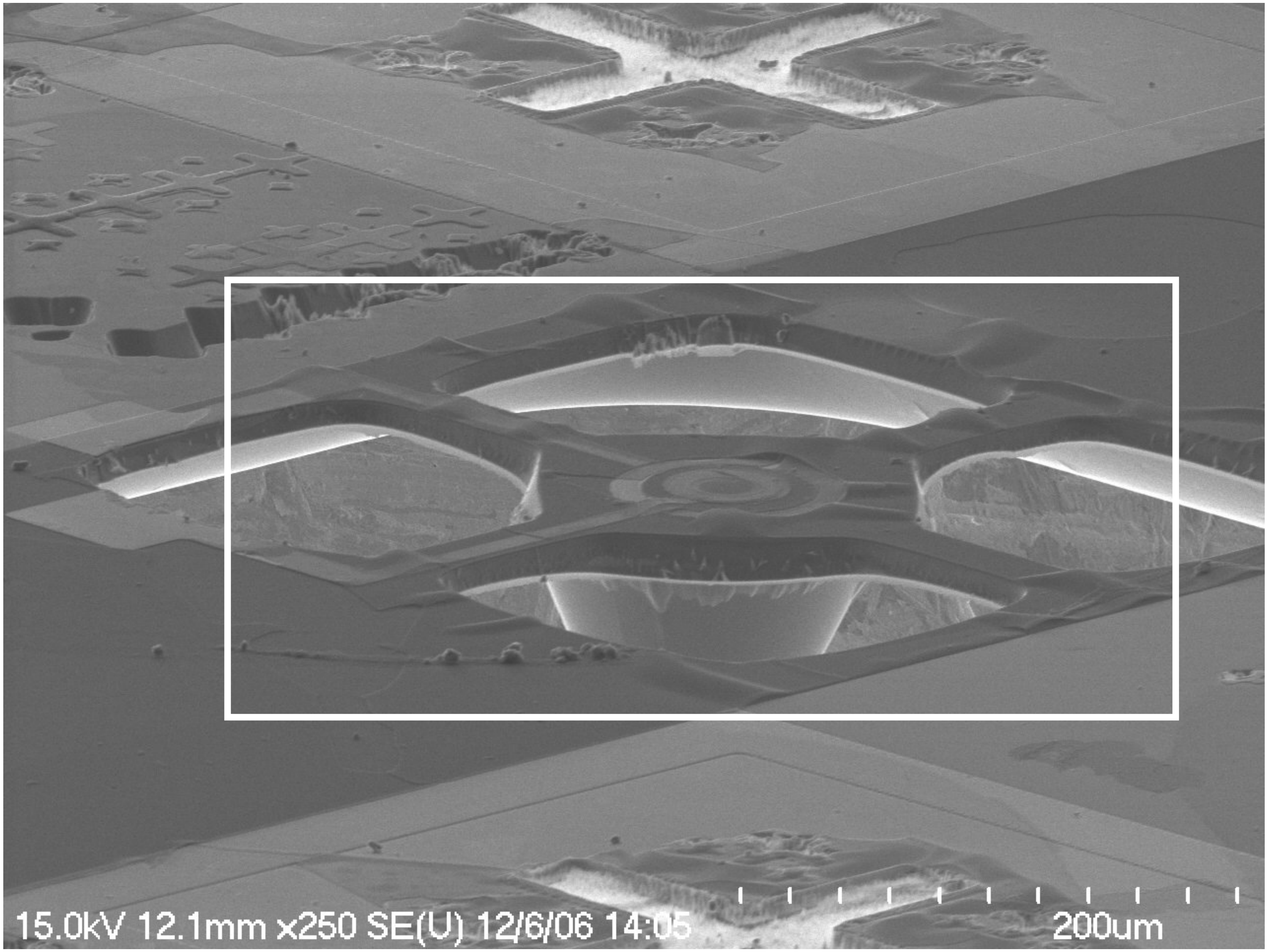
Summary of the design



- ❑ **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**

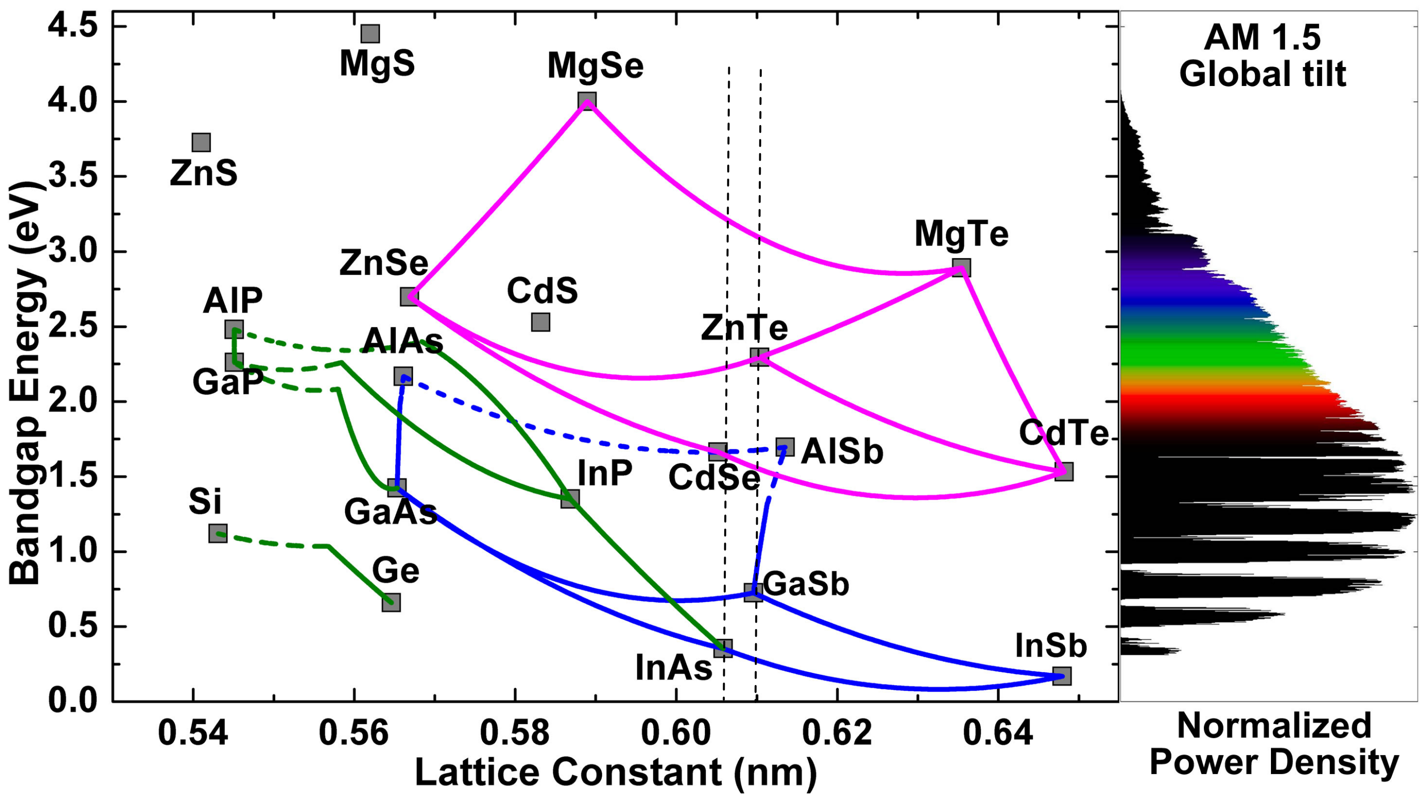
Grand Challenges
Up to 10 photolithography steps
and a 15-day (8 hour/day) job!!

Devices pictures (Lapping and polishing)

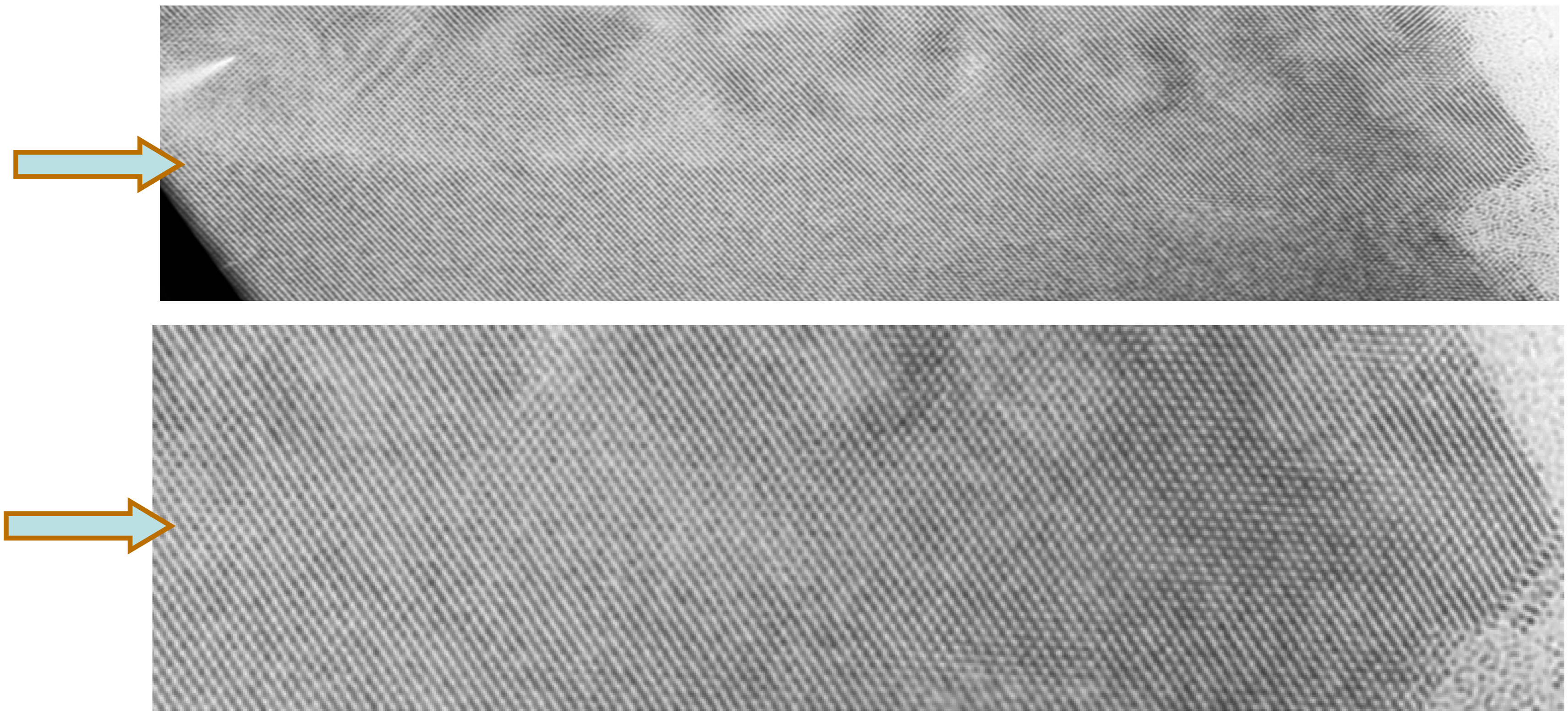


Ultrahigh efficiency multijunction solar cells

- 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

AlGaN

GaN

Green Lasers (DARPA-VIGIL)
Electron Holography
Cathodoluminescence

Physics Of Nitride Compound Electronics

High Efficiency Phosphors (Durel Grant)
ZnS
GaN

InGaN

InN

Epitaxy on Silicon substrates
(With Germany)
Microstructure and light emission

Materials for Green Lasers (Nichia Grant)
InGaN, Defects

Solid State Lighting Initiative (DOE)
Applications to Interior Lighting

Nanostructures in III-V Nitride Films

Prof. Fernando Ponce
Current research activities

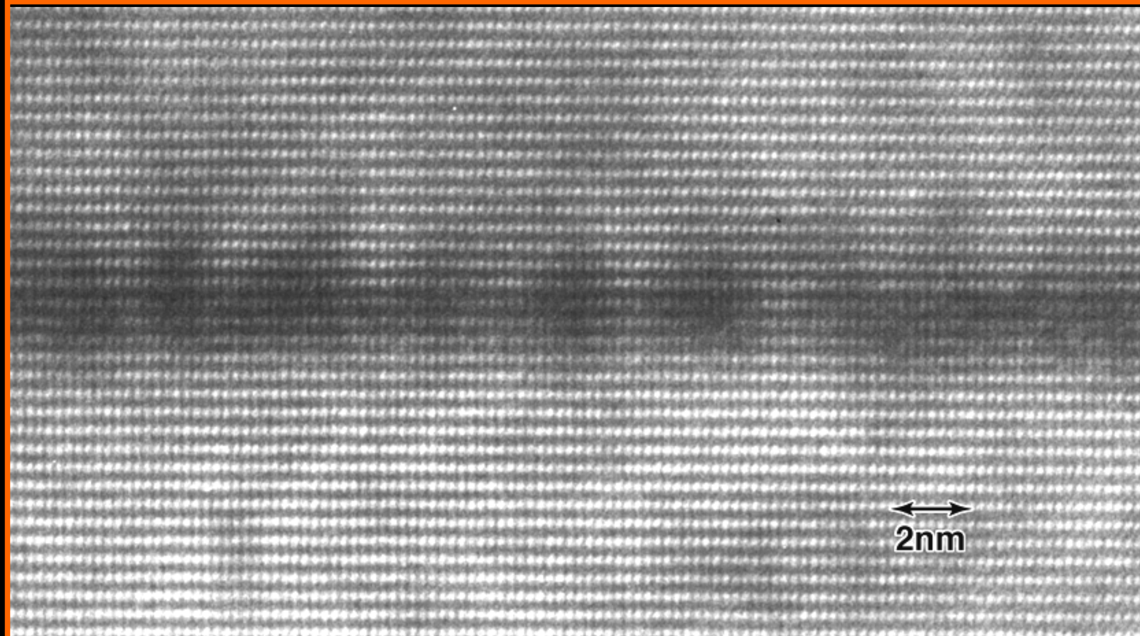
Wide-gap semiconductors for high efficiency light emitting devices
- Nichia Project
- DOE Project

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

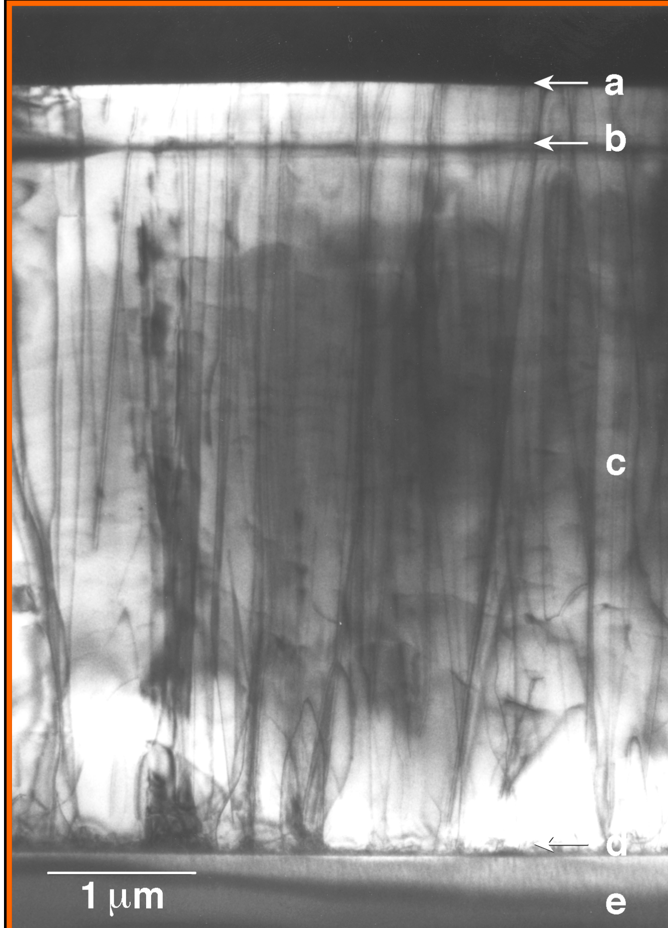
Ultraviolet LEDs and Lasers based on AlGaN
- DARPA UV Program



InGaN Quantum wells for green lasers
Fluctuations in thickness and composition are important in increasing the light emitting efficiency
F. A. Ponce et al, Phys. Stat. Sol, ***22****, 51 (2004)*

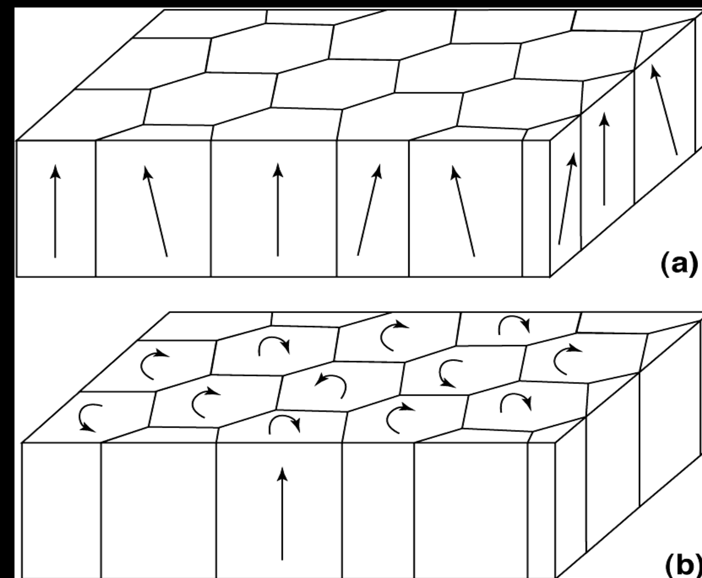
Ponce Group

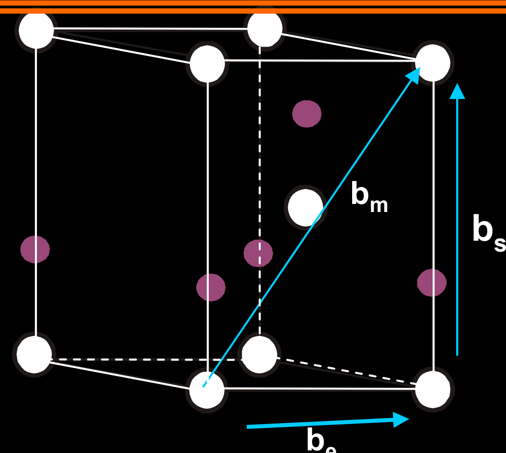
Nitride Films for Solid State Lighting



Cross-section view -- Nichia blue LED
GaN/GaInN/GaN/Sapphire
Using GaN buffer layers
10^{10} Dislocations/cm^2
*F. A. Ponce, D. P. Bour, Nature **386**, 351 (1997)*

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





Three types of DLs:
Edge type, $\mathbf{b_e}$ = **1/3 $\langle 11\bar{2}0\rangle$**

Screw type, $\mathbf{b_s}$ = $\langle 0001\rangle$

Mixed type, $\mathbf{b_m}$ = 1/3 $\langle 11\bar{2}3\rangle$

*F. A. Ponce et al, APL **69**, 770 (1996).*

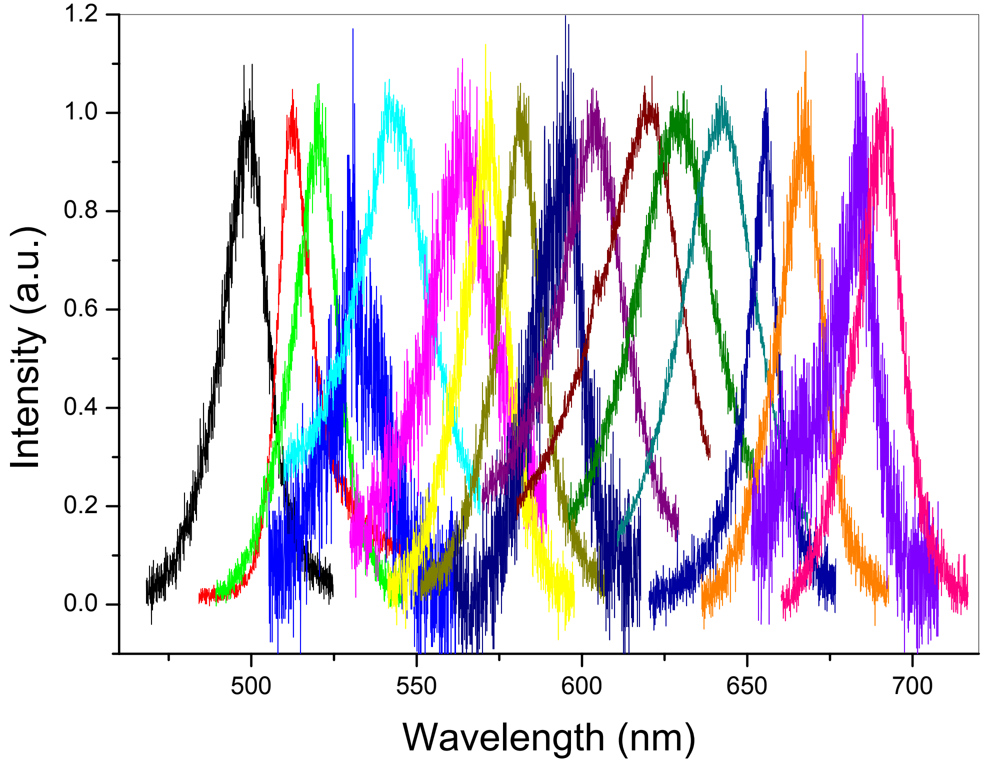
Threading dislocations limit the electrical and optical performance of devices. Need to know the electronic charge states at different types of threading DLs.

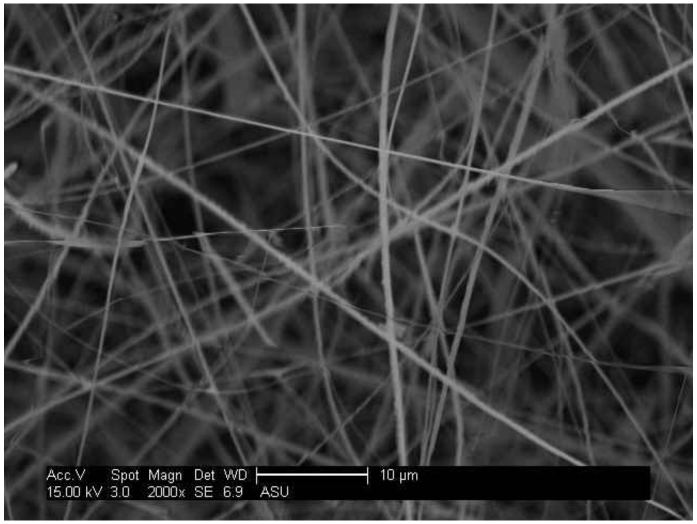
Ponce Group

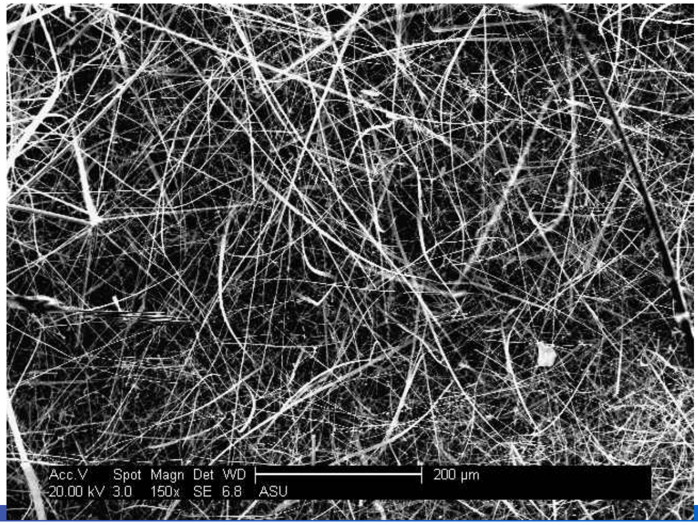
Alloy Semiconductor Nanowires as PV Materials

Ning Group

- **Growth and characterization of semiconductor alloy nanowires**



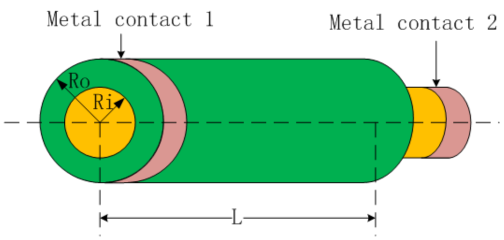


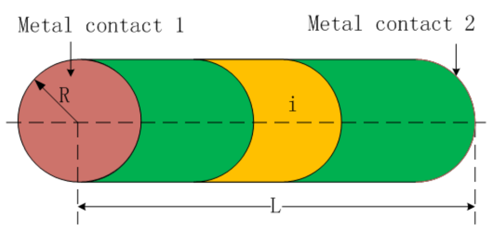


(Part of the SFAz SRG Program)

Electrical Injection Plasmonic Nanolasers

Ning Group





To understand, design, optimize, and fabricate

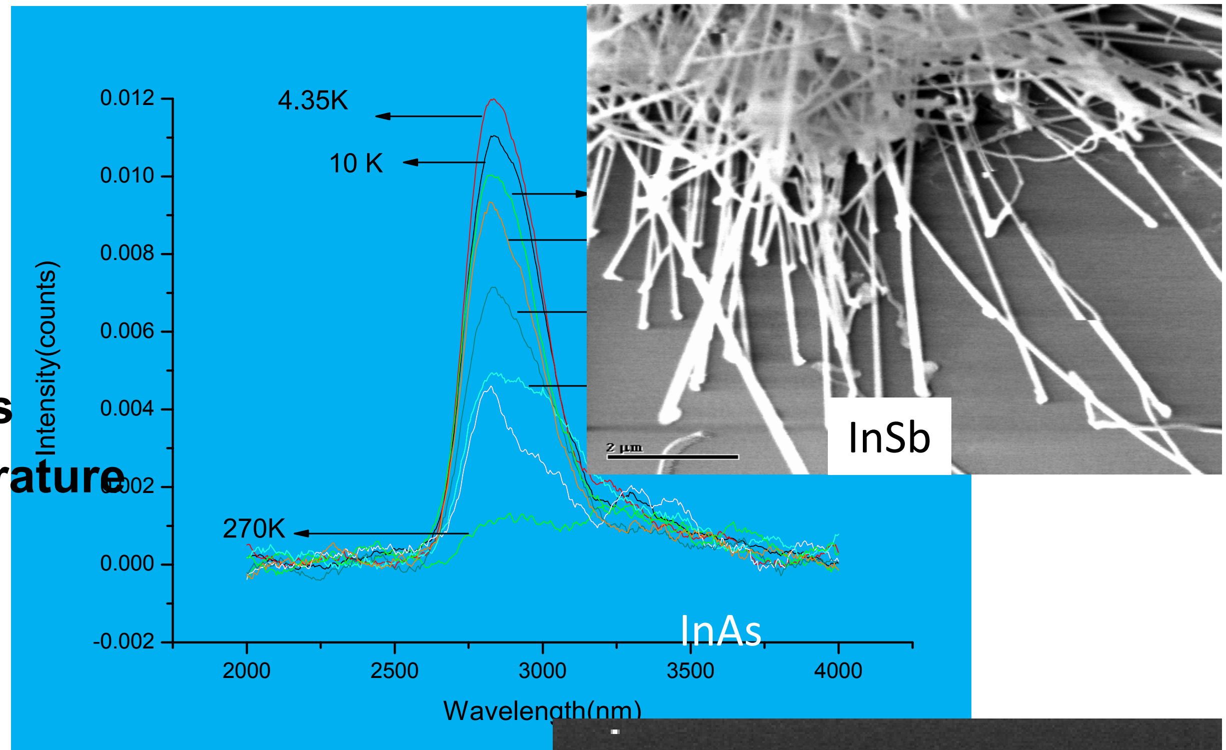
- Nanoscale semiconductor-metal contacts
- p-n, or p-i-n junction configuration for carrier injection
- Interaction between nanoscale metal structures (bowtie) and semiconductors (QDs, NWs)
- Nanoscale plasmonic lasers

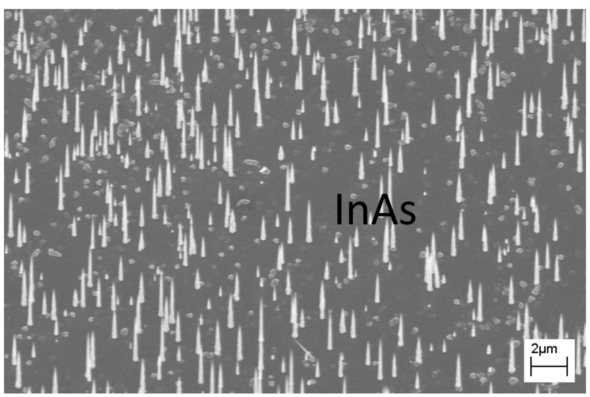
- Dependence of contact resistance on contact size and geometry studied
- Dependence of depletion width on diameter of wires
- Carrier injection in longitudinal junction and core-shell junction studied
- Injection levels as function of doping, metal choice, and bias investigated
- Threshold of bowtie-antenna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

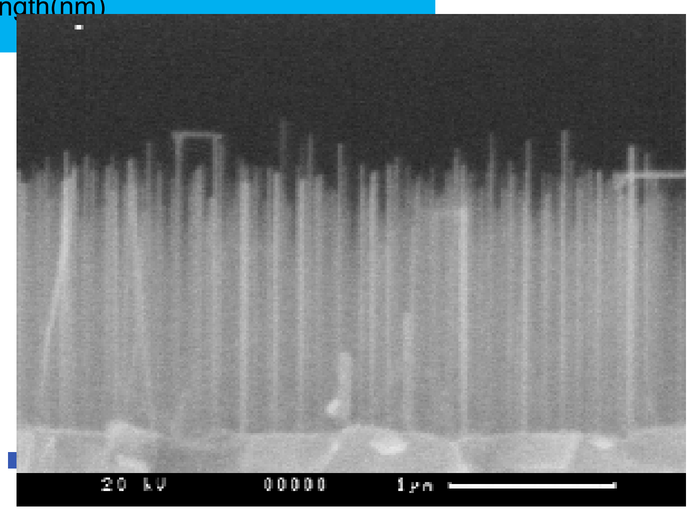
(Part of DARPA NACHOS Program, in collaboration with Berkeley, LBNL, UIUC)

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)

NSF GOALI NIRT Self Assembly at Photonic and Electronic Scales

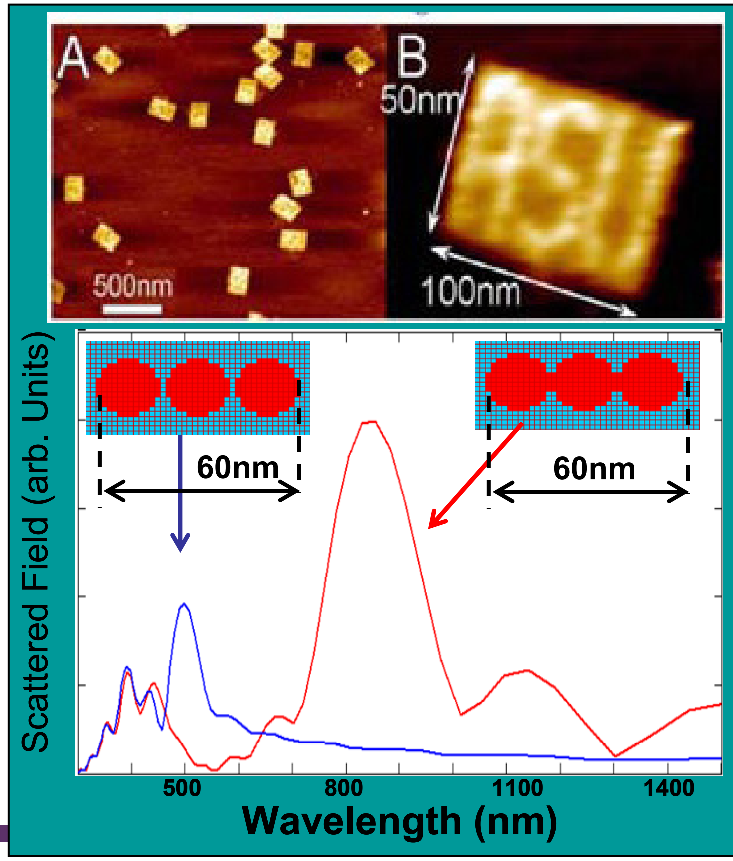
Bio-Design, Chemistry + AINE (Diaz, Panaretos)

OBJECTIVE

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

APPROACH

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



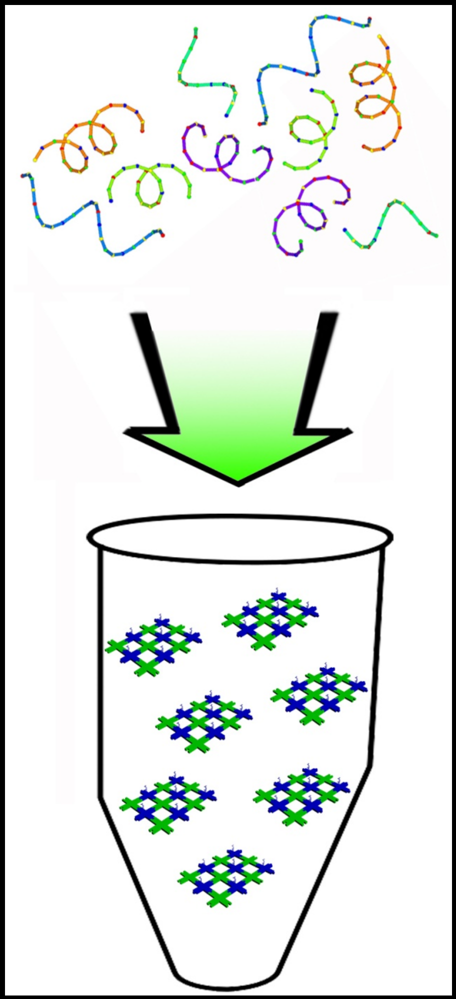
ACCOMPLISHMENTS

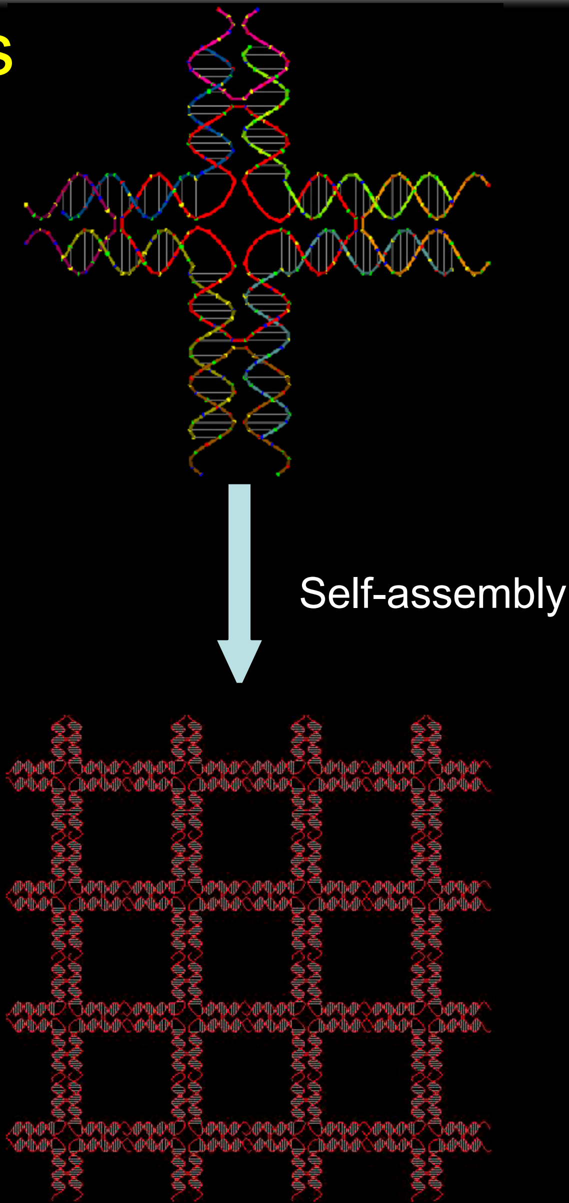
- Computational demonstration of true antenna mode resonance of connected spheres.
- Simulation of polydisperse chains.
- Computational demonstration of Transition rate enhancement.

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

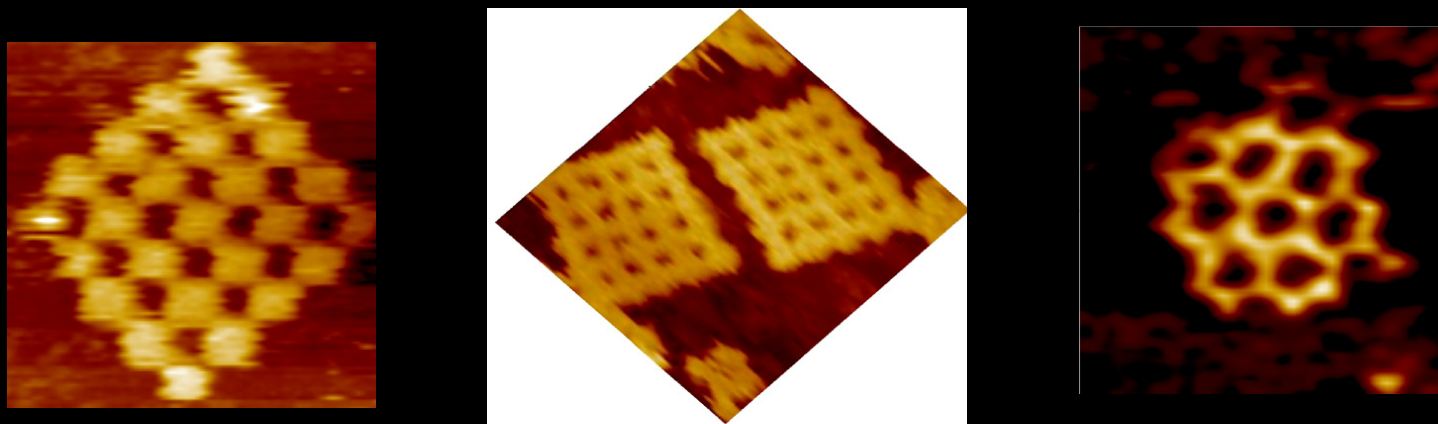




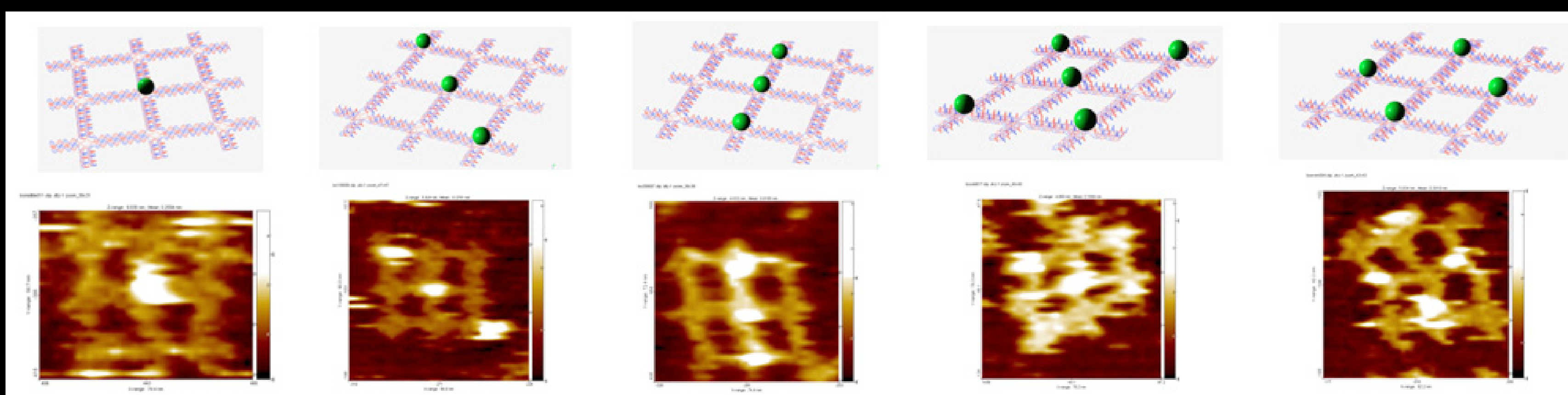
H. Yan *et al.* ***Science*** 301, 1882-1884 (2003).

ASU BIODESIGN INSTITUTE
ARIZONA STATE UNIVERSITY

Arrays of finite dimension and addressability



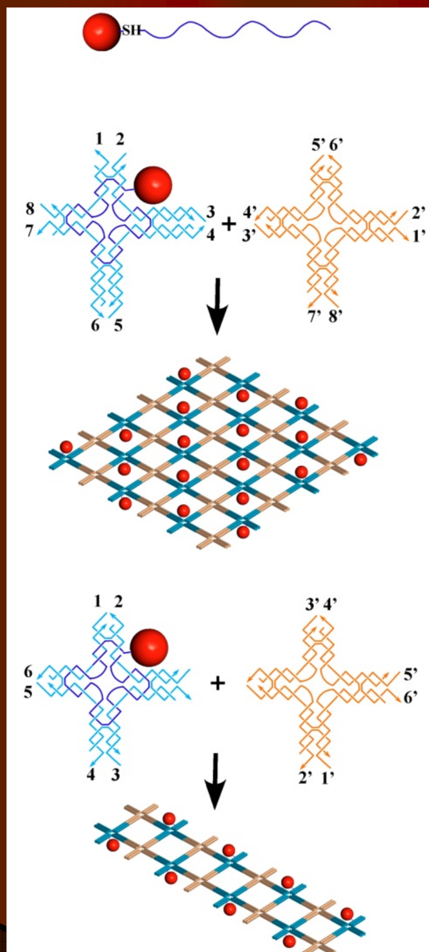
Y. Liu, Y. Ke, H. Yan, *J. Am. Chem. Soc.* 127, 17140-17141 (2005)

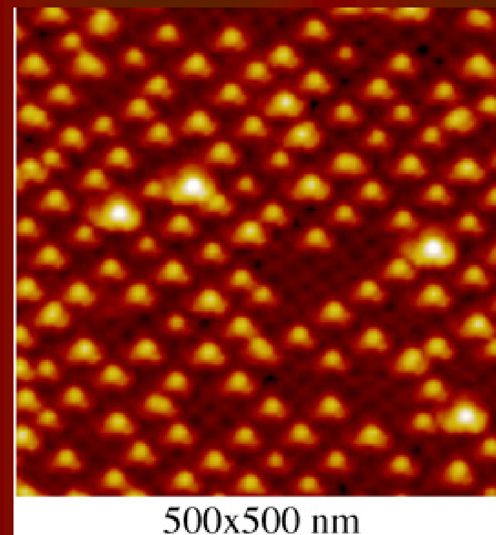


K. Lund, Y. Liu, S. Lindsay, H. Yan, *J. Am. Chem. Soc.* 127, 17606-17607 (2005).

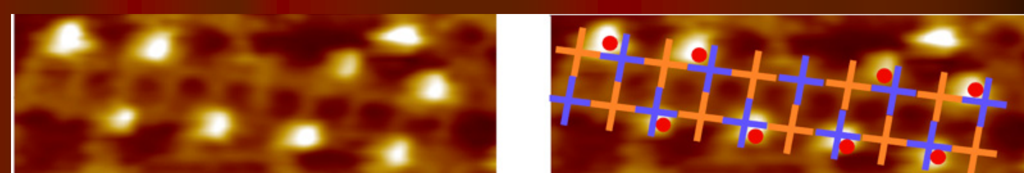
Yan Group

DNA Nanoarrays directed Self-assembly of Metallic Nanoparticle Arrays





J. Zhang, Y. Liu, Y. Ke, H. Yan, *Nano Letters.* 6, 248-251 (2006).



J. Sharma, R. Chhabra, Y. Liu, H. Yan, *Angew Chem Int Ed.* 45, 730-735 (2006).

Yan Group

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,
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

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.

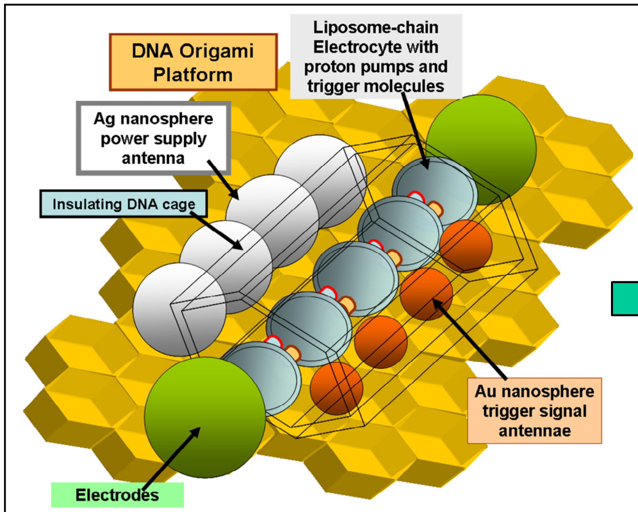
ACCOMPLISHMENTS

• Baseline model of the molecule implemented.

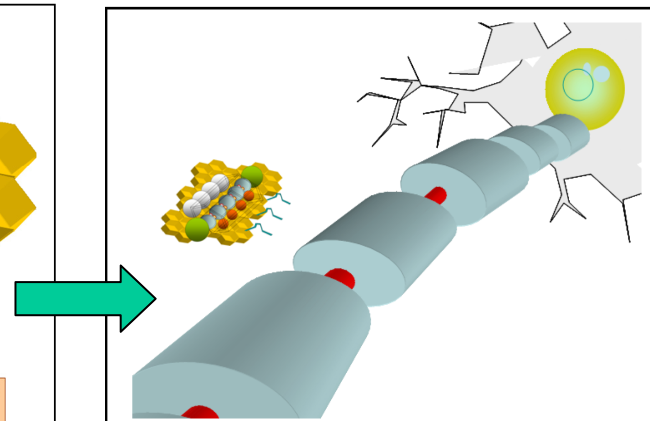
• General scalable model being developed.

PAY-OFF: NIH Eureka proposal

• Molecule model will enable the design of an artificial electrocyte for the creation of neuro-stimulation nanomachines



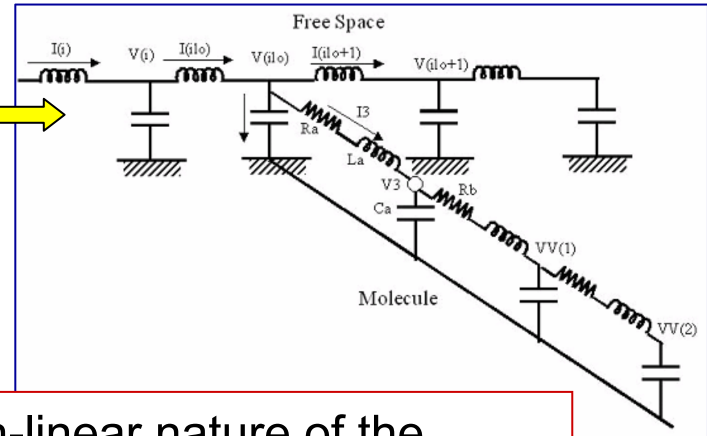
Conceptual drawing of DNA self-assembled nano-machine for delivery and sensing of cellular electrical stimuli.

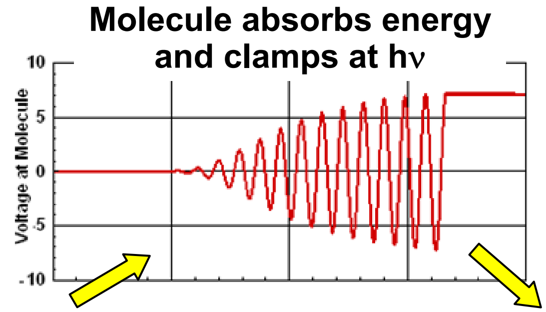


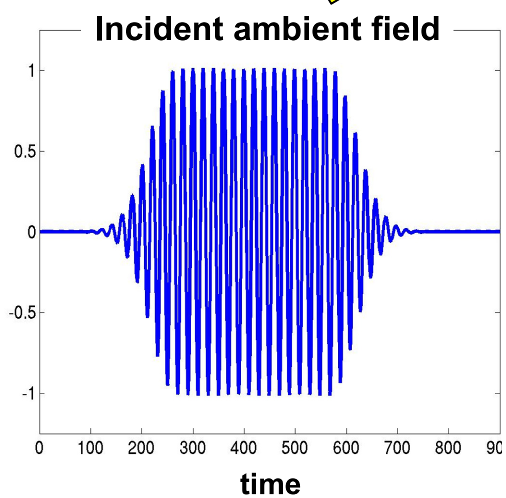
The ultimate application of these nano-machines is to the real-time in vivo interaction with neurons.

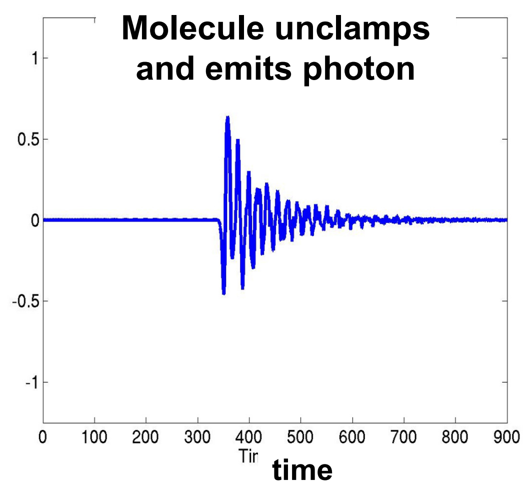
Ongoing work and challenges

- 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.

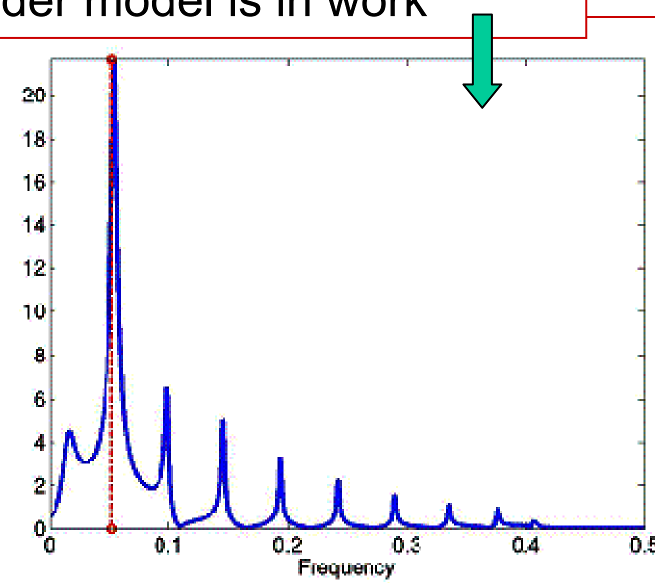




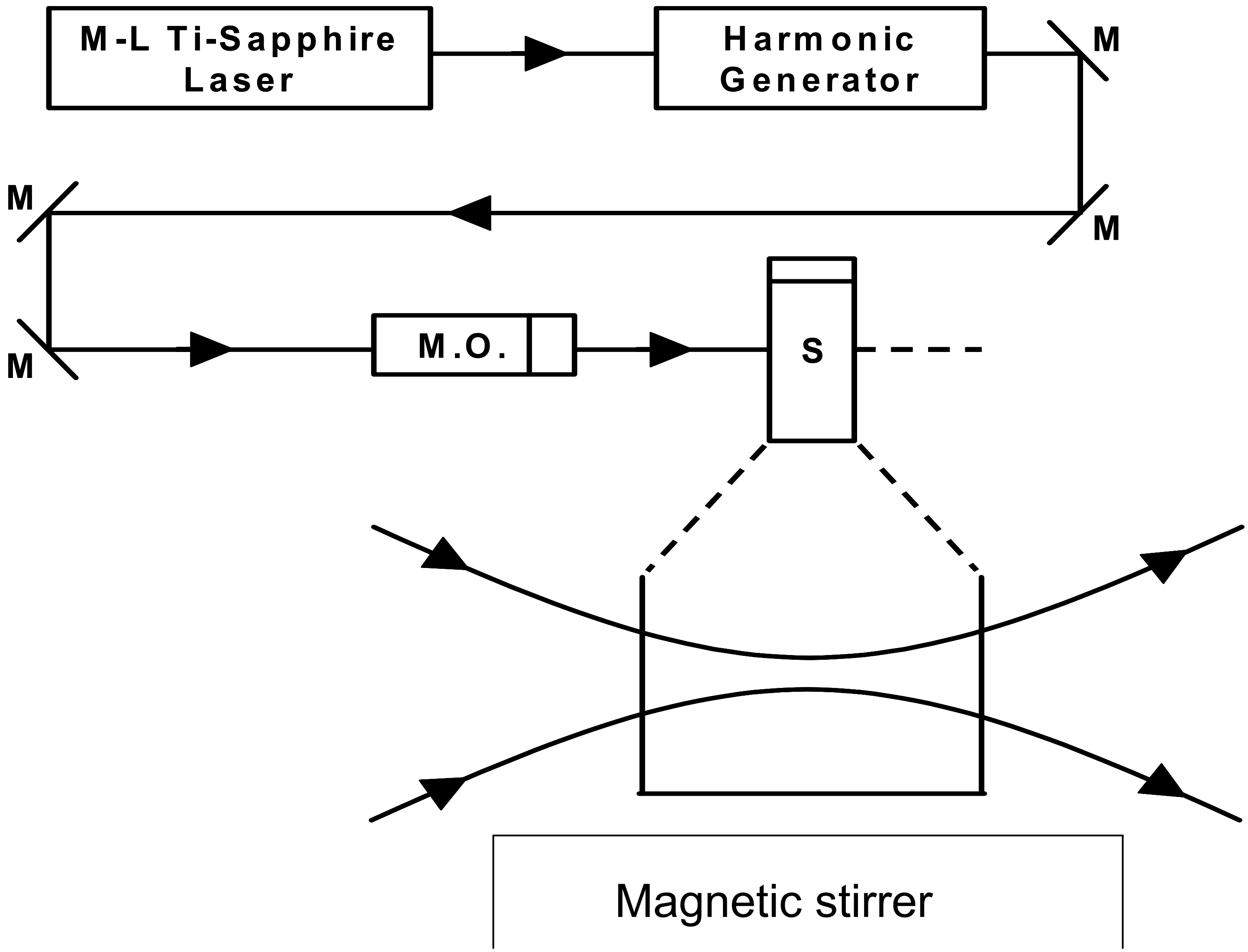




- The non-linear nature of the switching mechanism creates non-physical harmonics.
- Next order model is in work

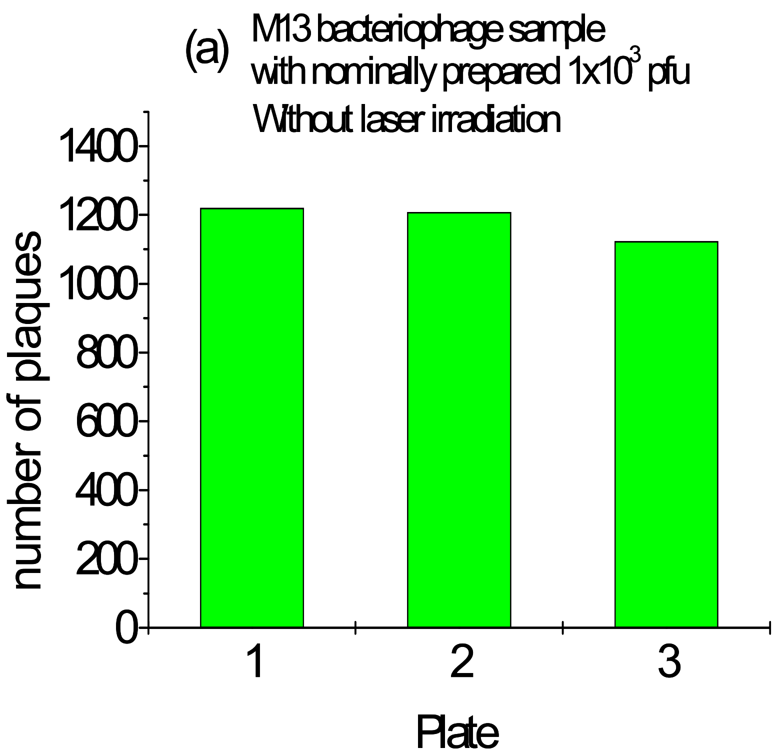


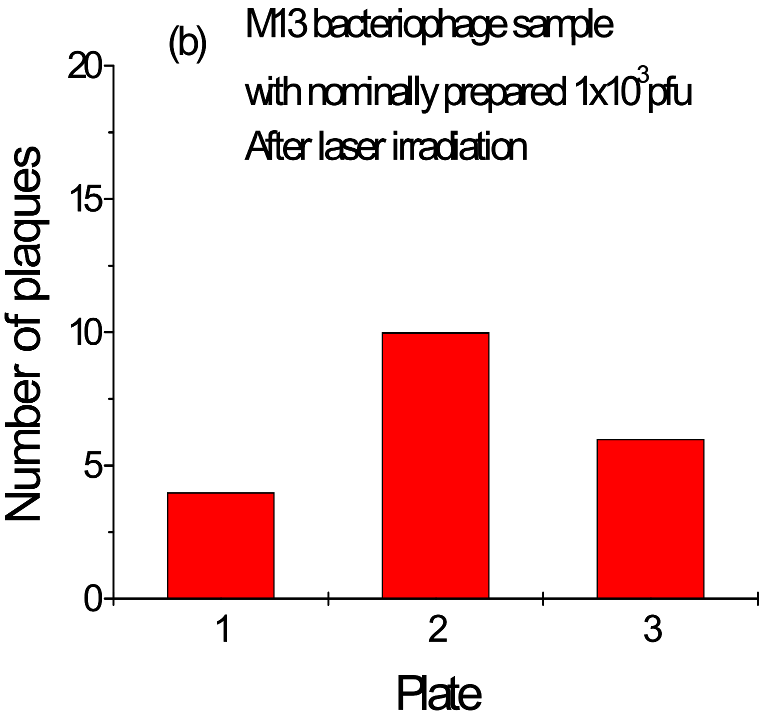
Experimental setup for the inactivation of viruses



Tsen Group

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

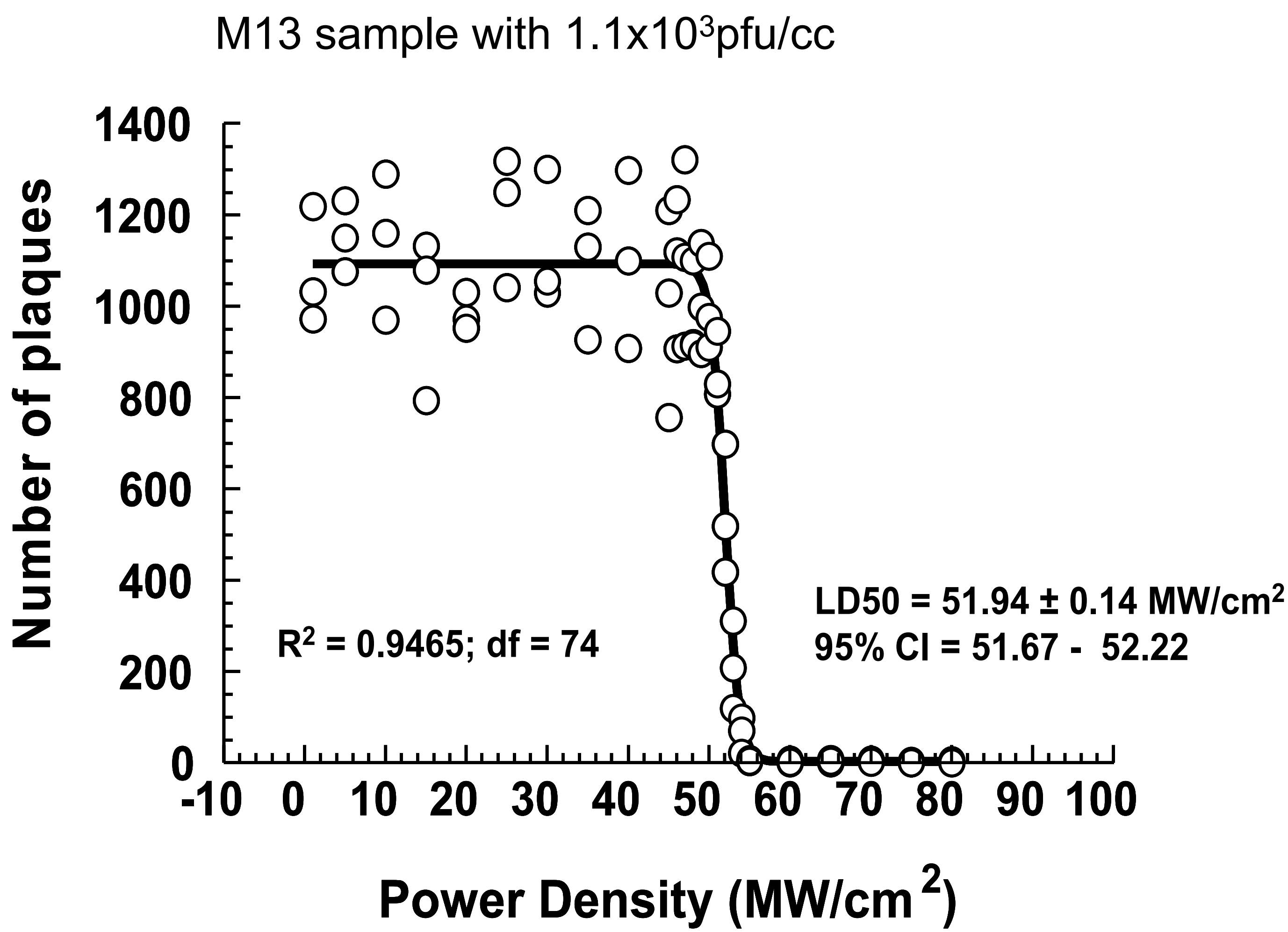




Laser power density – dependence of the inactivation of M13 phages

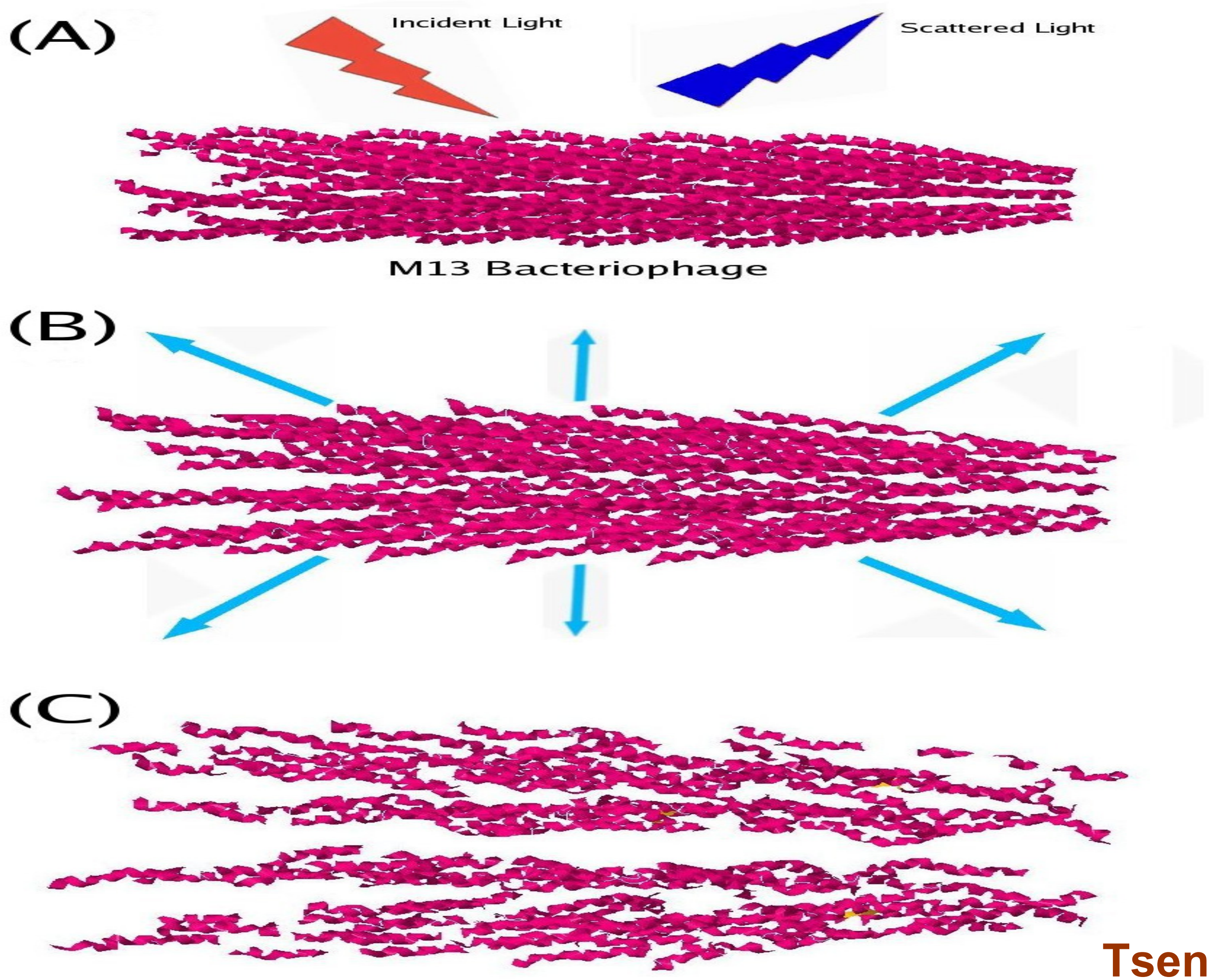
Excitation laser with wavelength at 425 nm, pulse width of 100 fs

focused spot = 100 microns



Tsen Group

How does ISRS technique inactivate the viruses?



Tsen Group

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.**

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

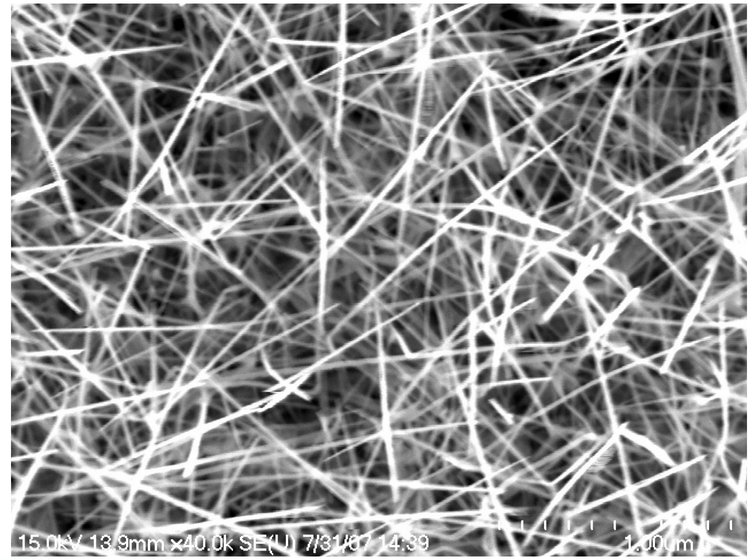
•Novel scanning technology for nano-photonics application, H. Yu and S. Yu

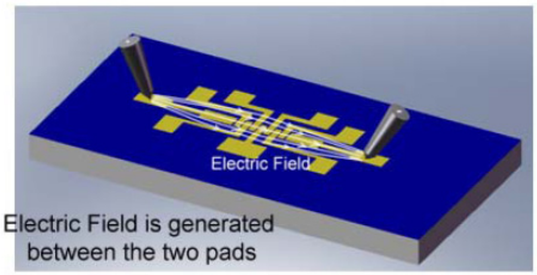
•Chip-scale directional microphones using photonic devices and nano-dendrimers, J. Chae, M. Kozicki and Y.- H. Zhang

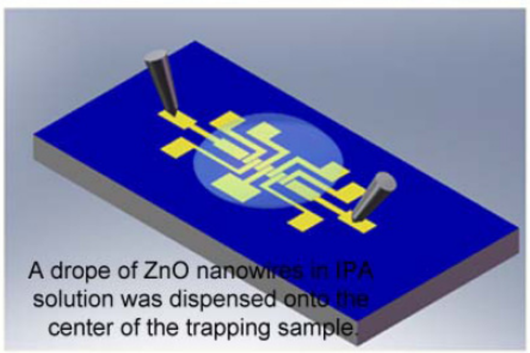
•Modeling heating effects in SOI devices, D. Vasileska and S. Yu

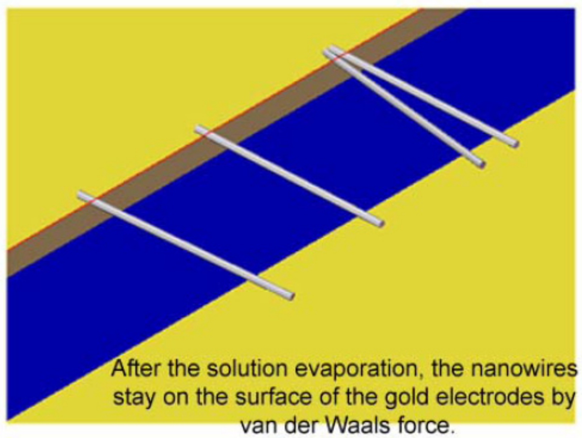
ZnO Nanostructure Synthesis and Device Fabrication

SEM image of ZnO nanowires

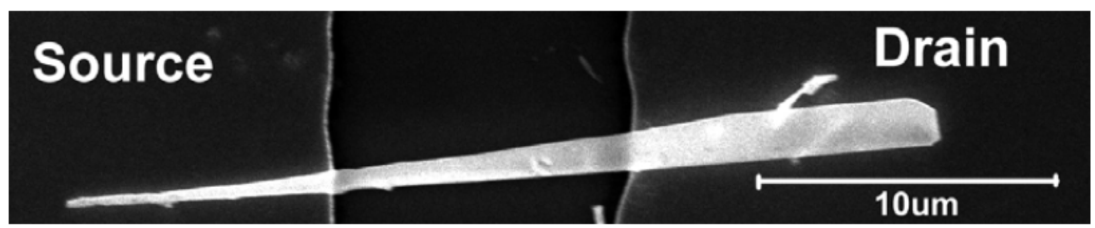








ZnO Device Fabrication



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