Relazione scientifica finale STM Fabio Quaranta (IMM UOS Lecce)

Il programma svolto durante il soggiorno presso la Drexel University di Philadelphia si è concentrato sulla caratterizzazione di dispositivi elettronici basati su effetti plasmonici in strutture con cariche confinate. Sono stati caratterizzati dispositivi, progettati e realizzati in precedenza presso il laboratorio di Microelettronica del IMM Lecce, basati su gas monodimensionali di elettroni e/o lacune (nanowire). Inoltre, durante il soggiorno, in collaborazione con il Dr. Marc Currie del Naval Research Laboratory (NRL) in Washington, sono stati svolti, presso il laboratorio del NRL, esperimenti di campionamento elettro ottico ad alta velocità con relativa analisi dei dati. I risultati principali di tali attività sono stati presentati al European Optical Society Topical on Optical Microsystems Meeting tenutosi a Capri (17 – 19 settembre 2015).

Le attività si sono concentrate sulla caratterizzazione di singoli nanowire con un *core* di GaAs ed una *shell* di AlGaAs (core-shell nanowires, CSNW). Tali nanowire erano stati realizzati precedentemente presso il laboratorio di crescita del IMM di Lecce. La struttura dei nanowire è riportata in Fig.1 mentre da un analisi SEM effettuata, la lunghezza media dei wire è risultata di 2micron.

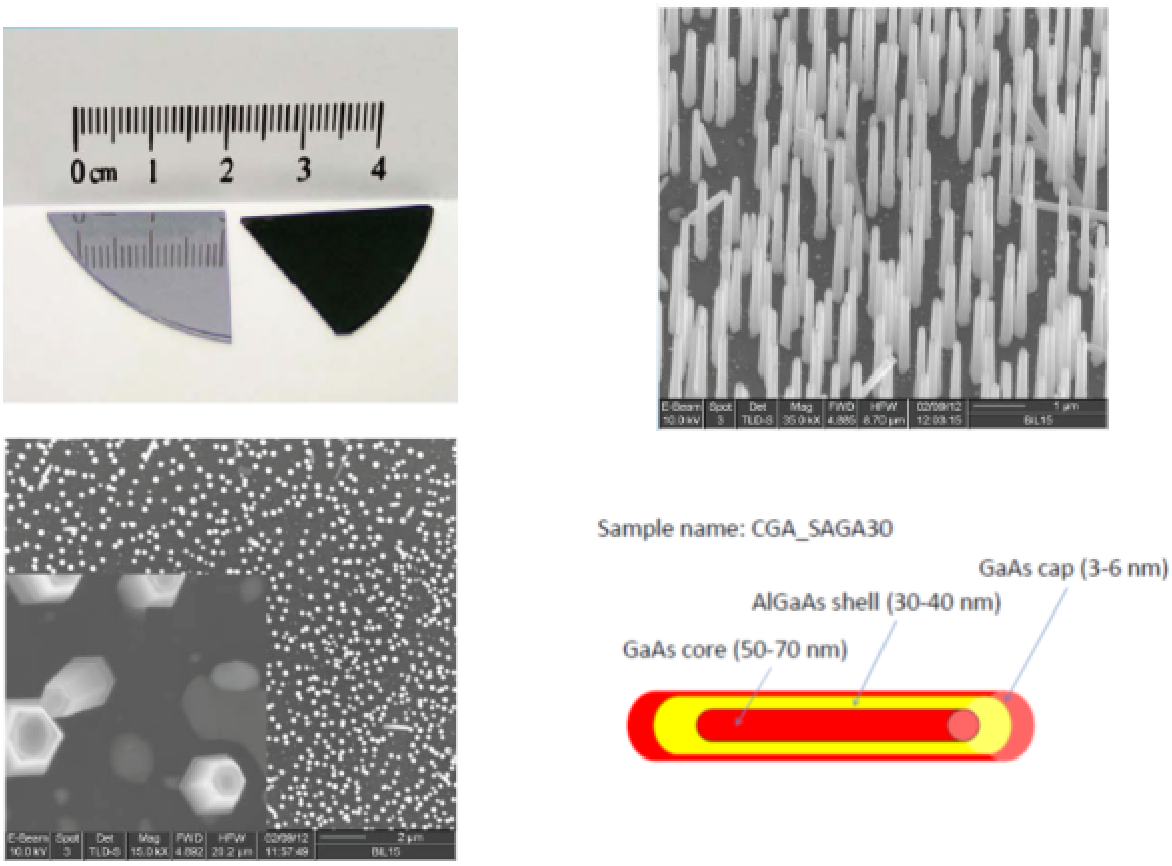


Figura 1

Con un attività svolta sempre preventivamente presso il CNR IMM di Lecce i nanowire sono stati caratterizzati otticamente con differenti tecniche. Sono state effettuate misure di assorbimento ottico e di fotoluminescenza che hanno permesso di evidenziare i contributi dovuti ai wire. Si è riscontrata una estrema variabilità del segnale di fotoluminescenza in funzione della intensità della radiazione incidente che suggerisce l'attivazione di differenti fenomeni di diseccitazione. E' stato inoltre riscontrato un effetto laser a temperatura ambiente che testimonia della ottima struttura cristallina dei nanowire cresciuti sia su substrati di GaAs che su Si.

I nanowire sono stati rimossi dal substrato di crescita con un processo di sonicazione, dispersi in acetone e nuovamente depositati su un substrato di Si ossidato (spessore del ossido 0.5 micron) sul quale erano state in precedenza realizzati dei contatti metallici quali linee di trasmissione di Ti/Au con spessore 3/50 nm. In Fig 2 sono riportate delle osservazioni al SEM effettuate su campioni sui quali i nanowire dispersi sono stati depositati. In Fig.3 è invece riportata una cella elementare dei contatti metallici realizzati con la nomenclatura utilizzata per identificare i nanowire depositati e successivamente contattati tramite EBID (electron beam induced deposition): contatti metallici depositati utilizzando, all'interno di un apparato FIB, un fascio elettronico per frammentare un precursore ed ottenere la deposizione del metallo (platino o tungsteno nel nostro caso).

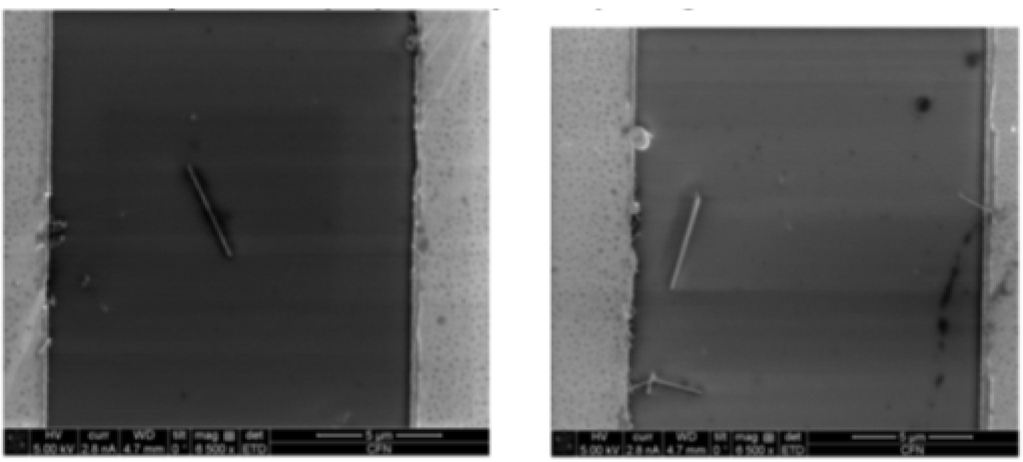


Figura 2

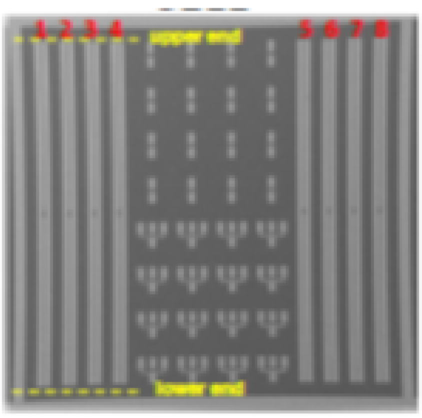


Figura 3

In Fig. 4 è riportata una analisi SEM effettuata su alcuni nanowire contattati con elettrodi di oro realizzati con EBID.

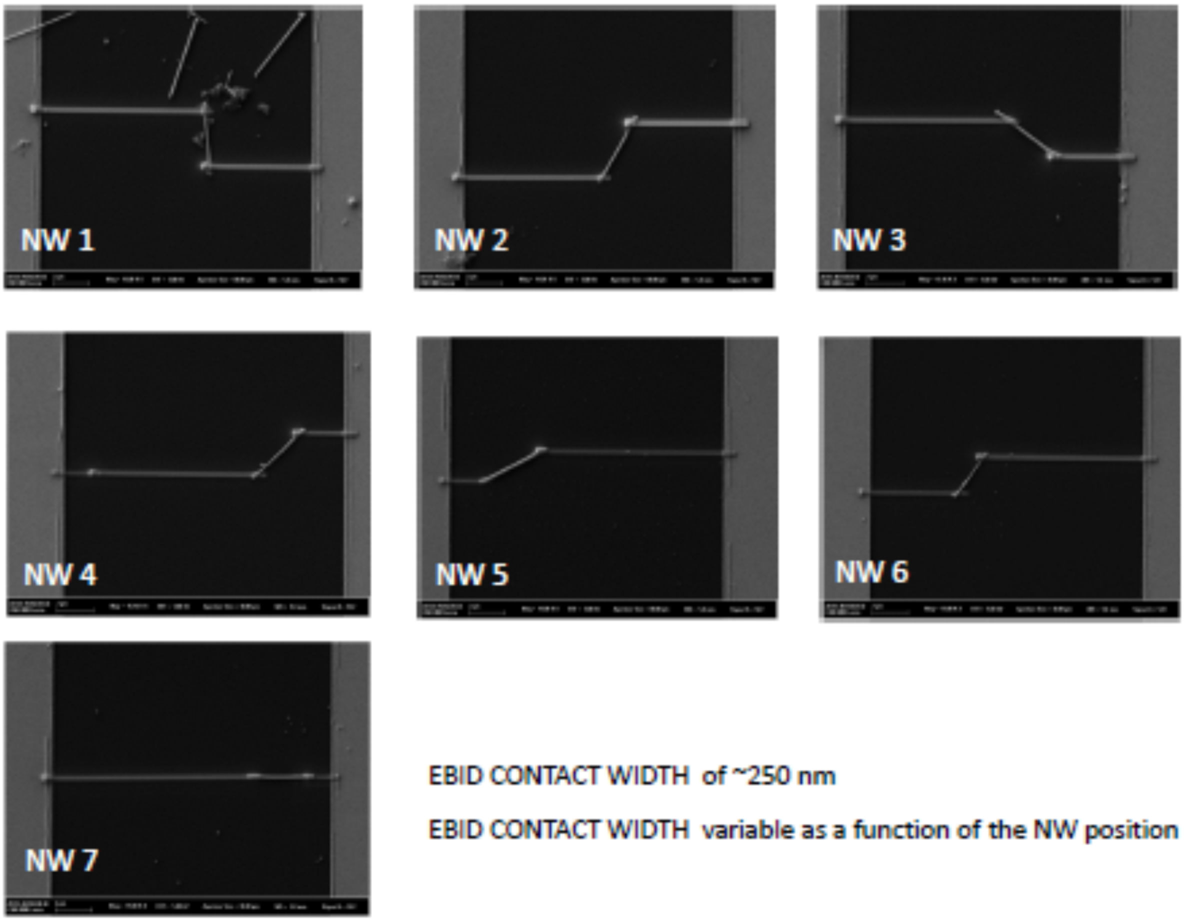


Figura 4

Su alcuni di tali campioni sono state effettuata delle mappe di fotocorrente sia polarizzando che non polarizzando i campioni per evidenziare gli effetti dovuti alla barriera tra contatto e nanowire. I segnali riscontrati non sono simmetrici ma funzione delle proprietà più o meno bloccanti dei contatti così come evidenziato in Fig.5

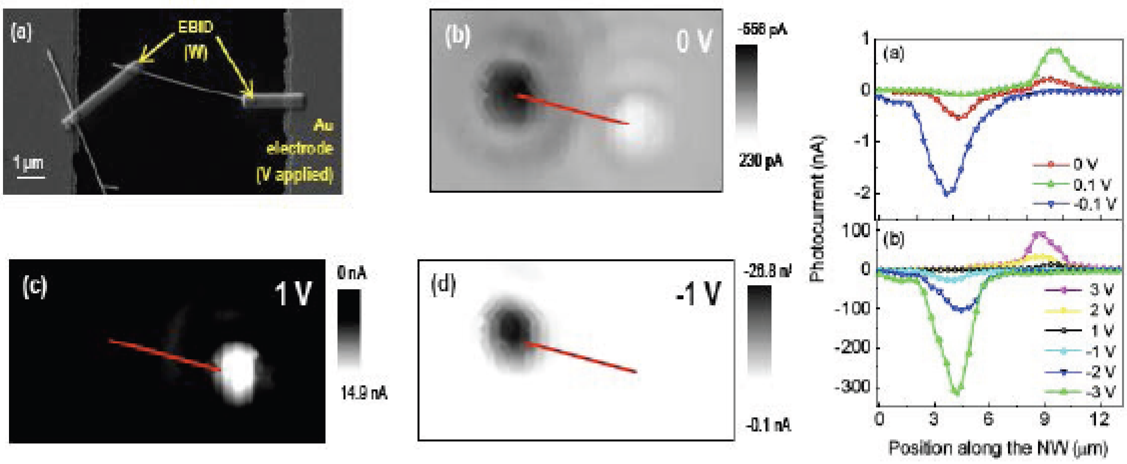


Figura 5

Misure di fotocorrente hanno invece permesso di evidenziare il ruolo della shell di AlGaAs nel ridurre le correnti di buoi del dispositivo infatti sono state riscontrate correnti di buio di

due ordini di grandezza inferiori su campioni con la shell rispetto a campioni nudi. Le correnti sotto illuminazione invece essendo rimasti invariati i volumi di materiale attivo sono risultate sostanzialmente invariate.
Sui campioni, presso il Naval Research Laboratory in Washington sono state effettuate delle osservazioni con un microscopio confocale che evidenziasse eventuali non planarità dei wire o non perfetti contatti metallici. I risultati, riportati in fig.6 mostrano campioni perfettamente planari, evidenziano i contatti e la morfologia dei nanowire che risultano continui e senza restringimenti o fratture

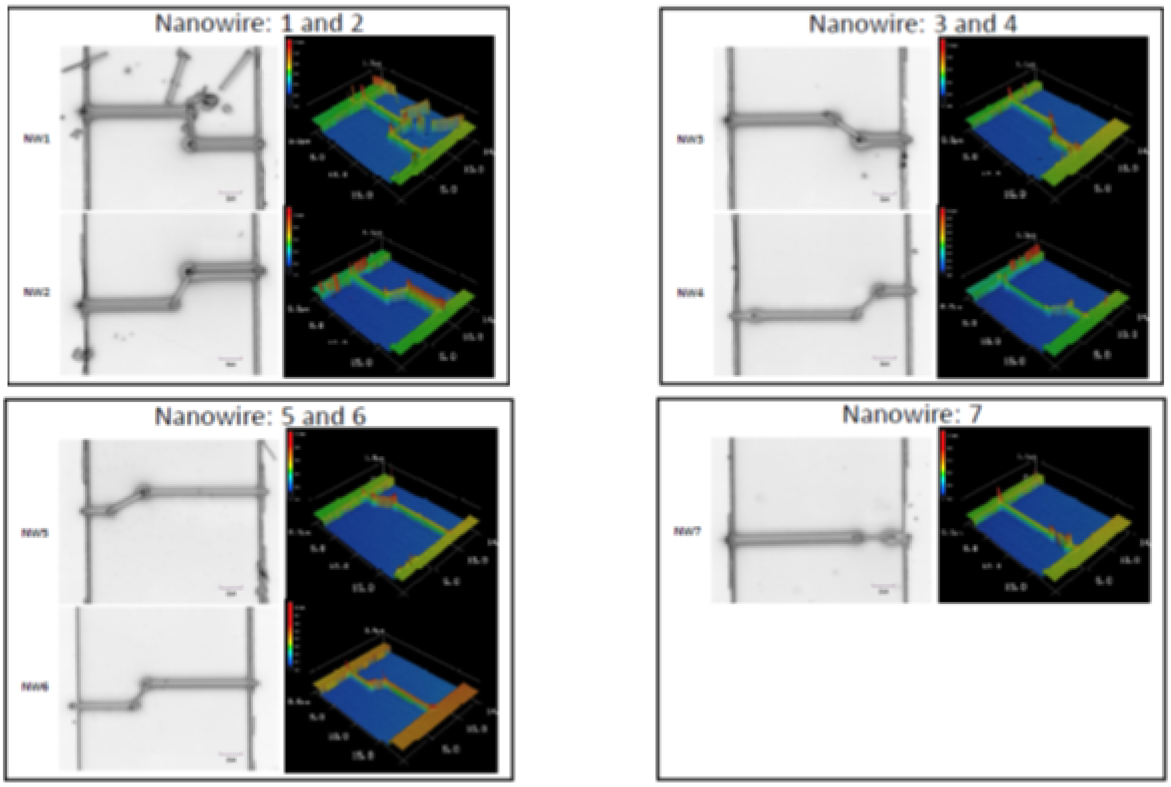


Figura 6

Sui nanowire depositati sono state effettuate delle misure di fotoluminescenza in continua e per evidenziare i possibili contributi di substrato e contatti le misure sono state effettuate in differenti zone e con polarizzazione differenti.
Sono quindi stati realizzati degli esperimenti di campionamento elettro ottico utilizzando un laser al femtosecondo per eccitare e rivelare il segnale di risposta dinamica del wire cioè il tempo di risposta del wire alla radiazione, Sono stati riscontrati dei tempi di risposta estremamente corti (inferiori alla decina di picosecondi) che non sono compatibili con fenomeni di trasporto di carica ma sono invece giustificabili ipotizzando dei fenomeni di plasma connessi ad un forte confinamento di carica in particolari punti del nanowire quali gli spigoli o le singole facce del wire e quindi un assorbimento fortemente localizzato. In particolare si può ipotizzare un confinamento sui sei spigoli del wire. Inoltre la questi effetti di localizzazione portano anche ad una separazione spaziale tra elettroni e lacune e ad una riduzione dello scattering che quindi sono responsabili del forte aumento di assorbimento di luce e della risposta estremamente veloce del dispositivo.

Come già ricordato, durante il soggiorno oltre alla realizzazione delle caratterizzazioni ottiche e alla analisi dei dati è stato preparato un abstratct (allegato 1 alla relazione) che è stato sottoposto ed accettato alla conferenza European Optical Society Topical on Optical Microsystems Meeting tenutasi a Capri (17 – 19 settembre 2015) e in tale sede il prof. Nabet quale co autore ha presentato i risultati di questa attività congiunta (si allegano copia delle slide utilizzate), A questa presentazione farà seguito un articolo pubblicato su rivista internazionale con referaggio.

ALLEGATO 1

On Time Response of Single Nanowires

Summary
We present time response measurements of single nanowires with core of GaAs and shell of AlGaAs using high resolution electrooptic sampling technique. These core-shell nanowires show high quantum efficiency and a speed of response which is faster than comparable devices in bulk.

Introduction
Optoelectronic properties of core-shell nanowires (CSNW) are of great interest since they outperform thin film heterojunctions of the same material in absorption and emission of light, as well as in transport of charge[1-3]. Probing the dynamics of carrier transport in single nanowires using high resolution time response measurements is challenging, but very useful in identifying various relaxation time constants, as well as identifying various mechanisms of current, and signal, transport [4,5]. Here we report on electro-optically sampled (EOS) time response of nanowires with core of ~100nm GaAs and shell of ~40nm AlGaAs and an outer GaAs cap of ~5nm. The length of the CSNW is nearly 3.5 um. We report on quantum efficiency and the time response, both of which are much better than bulk heterojunction of the same material.

Results and Discussion
The electrooptic sampling (EOS) set up is shown in Fig 1a. In our setup the laser is split into two paths: one, the pump beam, is coupled into a fiber to excite the device and the other, probe beam, path that passes through a LiTaO3 crystal to sample the electric field of the propagating response. As shown in Fig. 1a,b the CSNW were placed in the middle of a coplanar transmission line (TL), and connected to the TL by Focused Ion Beam (FIB) lithography. The distance between the two FIB contacts is ~3.5 um.
The CSNW has very low dark current (<0.1pA) which increases to 170nA average photocurrent with 2.6 mW of optical power; quite remarkable for a single wire. This corresponds to a responsivity of 0.03 A/W, while the responsivity for the same volume of GaAs in bulk is 0.02x10-3 A/W. The time response data for the CSNW is shown in Fig. 1c under applied bias of ±10 V, showing as-measured full-width half-max (FWHM) of ~13 ps. The intrinsic speed is faster when the test set up limitations are considered.
Given the length of the wire, this shows higher speed of both electron and hole transport in the wire. In this paper, the absorption process in the CSNW, transport mechanisms, and collection of the optically generated carriers at the contacts will be analyzed, and the effect of polarization, intensity, and spatially varying excitation on the response will be discussed.

References
[1] P. Yang, R. Yan, M. Fardy, Nano Lett. 10, 1529–1536 (2010).
[2] H. J. Dai, E. W. Wong, Y. Z Lu,. S. S. Fan, C. M. Lieber, Nature, 375, 769 (1995).
[3] H. Pettersson,; J. Tragardh, A. I. Persson, L. Landin, D. Hessman, L. Samuelson, Nano Lett. 6, 229 (2006).
[4] E. M. Gallo, G. Chen, M. Currie, T. McGuckin, P. Prete, N. Lovergine, B. Nabet, J. E. Spanier, Appl. Phys. Lett., 98, 241113 (2011).
[5] L. Prechtel, M.Padilla, N. Erhard, H. Karl, G. Abstreiter, A. F. I Morral, A. W. Holleitner, Nano Lett. 12, 2337−2341 (2012)

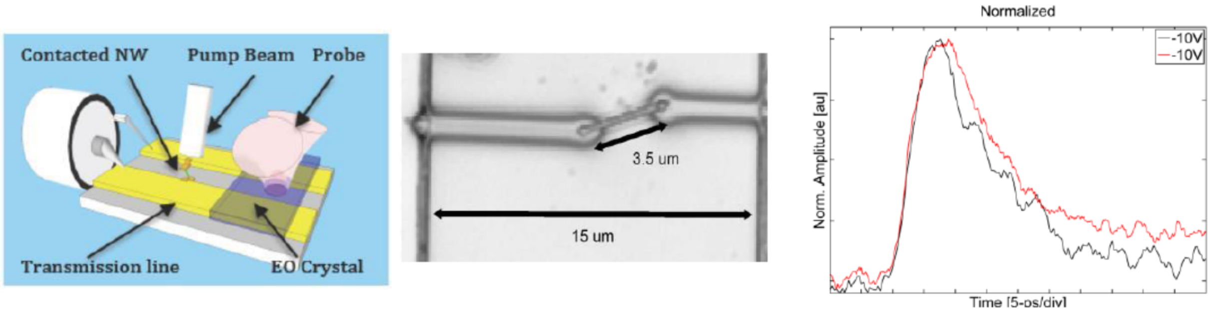


Figure 1 (a) Electrooptic sampling (EOS) time response measurement set up: RF probe is at one end of a transmission line in the middle of which the nanowire (NW) is contacted and is excited by 400 fs pulses of light delivered by fiber; probe beam samples the electric field through the electrooptic crystal. (b) Image of the FIB-contacted NWs (c) Time response data.

On Time Response of Nanowires

Marc Currie[1], Anna Persano[2], AntoniettaTaurino[2], Fabio Quaranta[2], Adriano Cola[2], Paola Prete[2], Nico Lovergine[3], and **Bahram Nabet[4]**

[1]Optical Sciences Division, Naval Research Laboratory,

Washington, DC 20375, USA

[2]IMM-CNR, Institute for Microelectronics and Microsystems-Unit of Lecce,

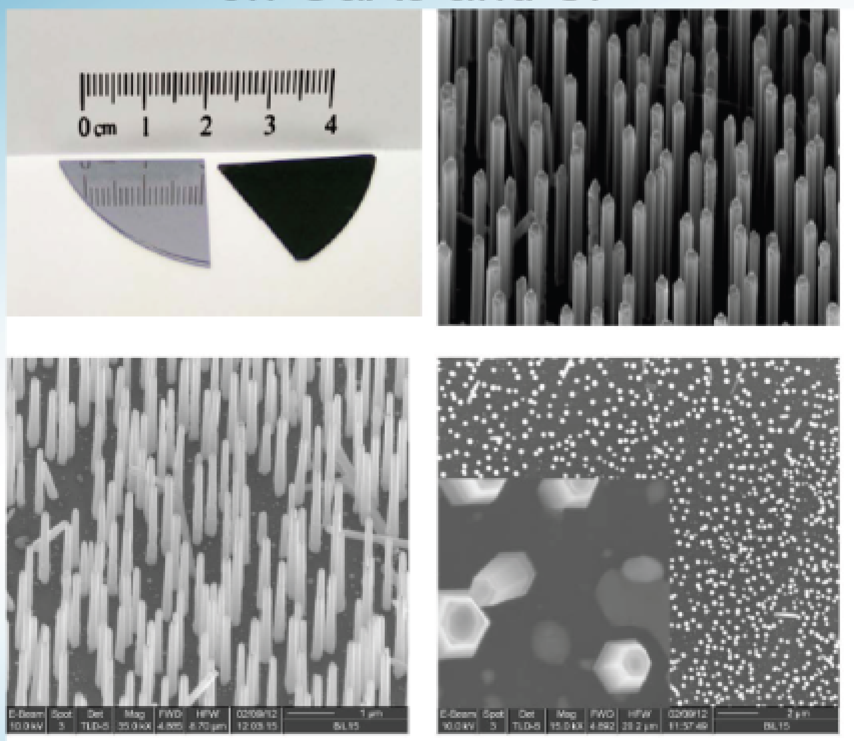
Lecce, Italy

[3]Department of Innovation Engineering, University of Salento, Via Arnesano, I-73100 Lecce, Italy

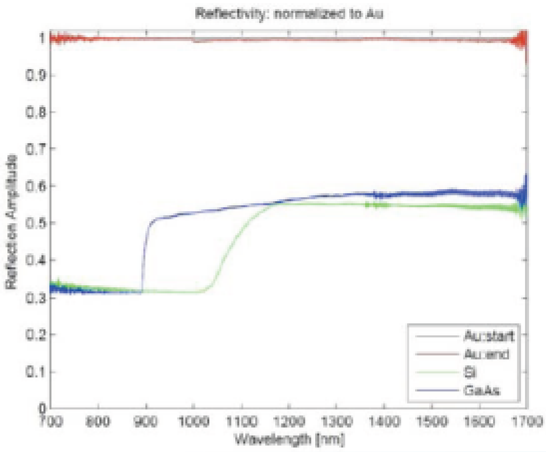
[4]Electrical and Computer Engineering Department, Drexel University,

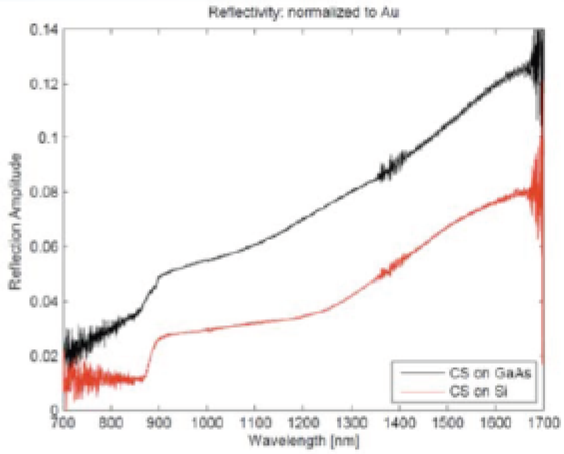
Philadelphia, PA 19104, USA

GaAs/AlGaAs Core-Shells on GaAs and Si

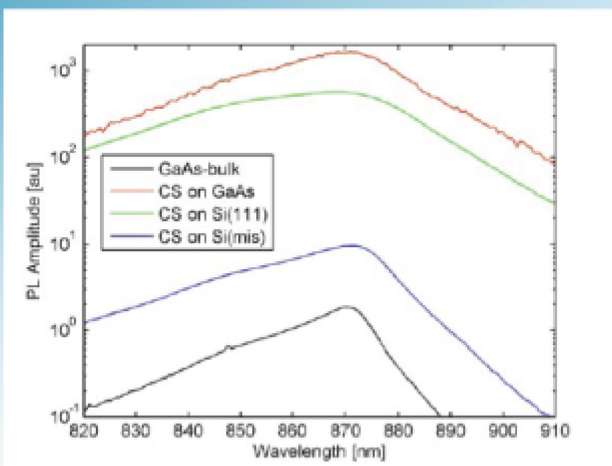


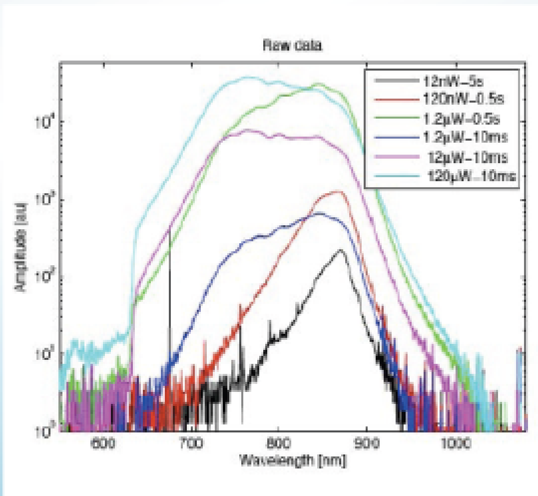
Optical Properties: Absorption





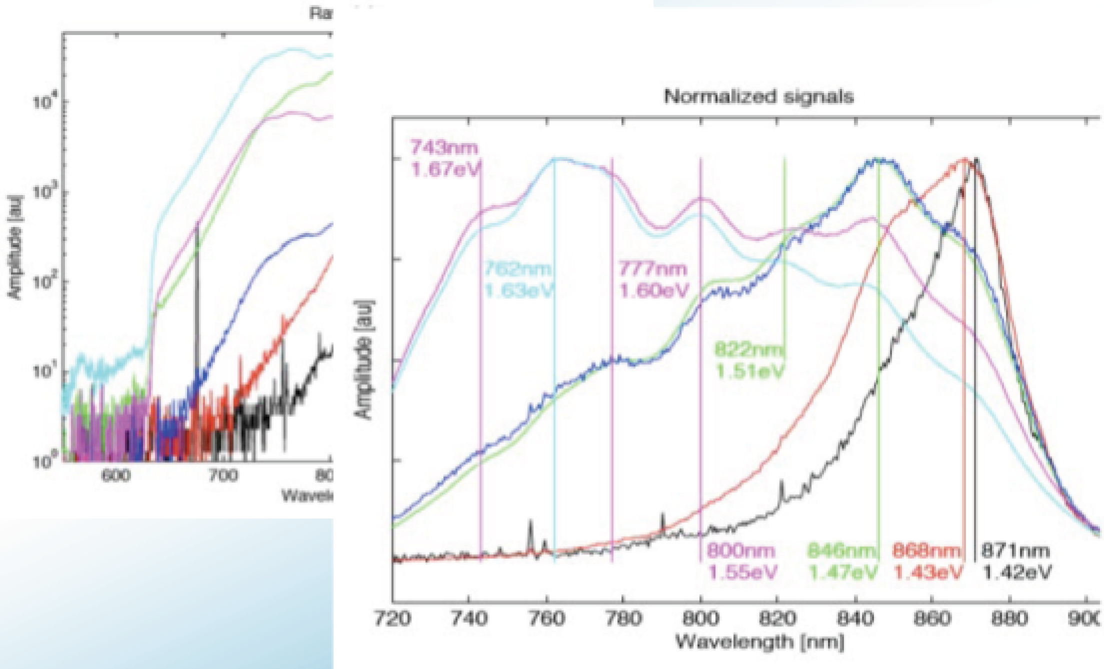
Optical Properties: Emission



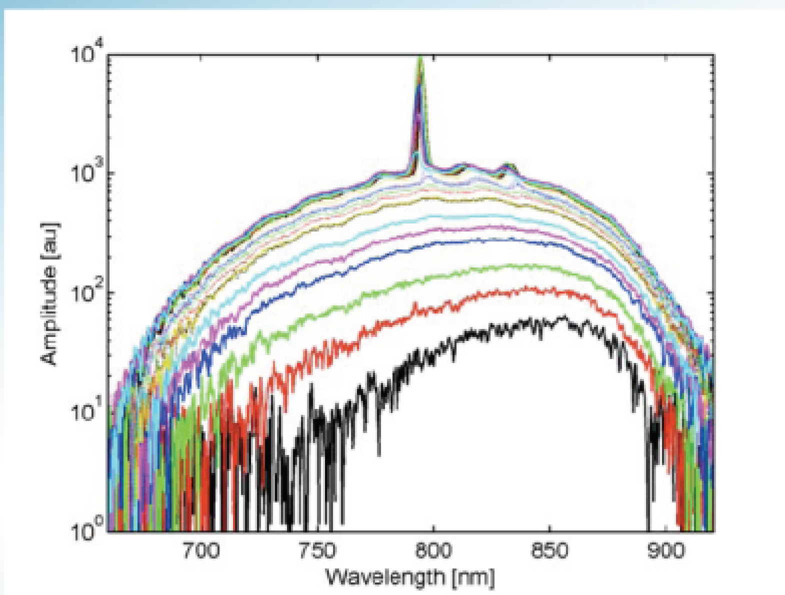


Pulsed PL is Strongly Intensity Dependent

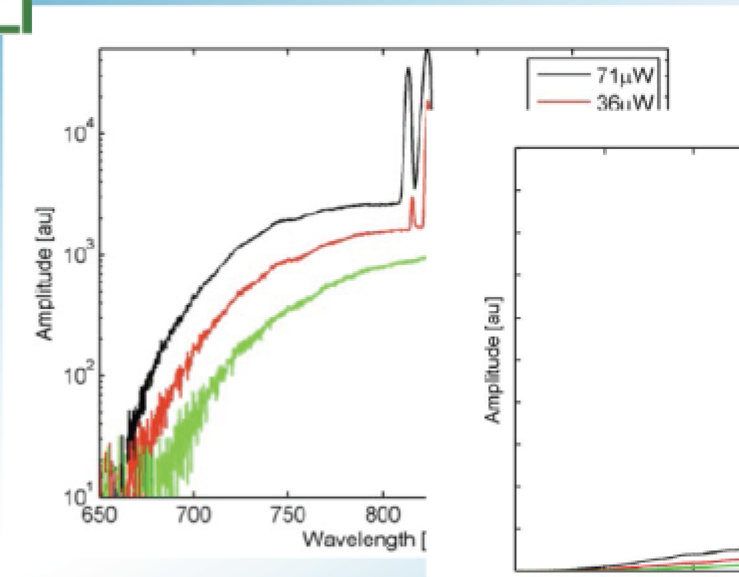
GaAs Core, AlGaAs Shell on GaAs

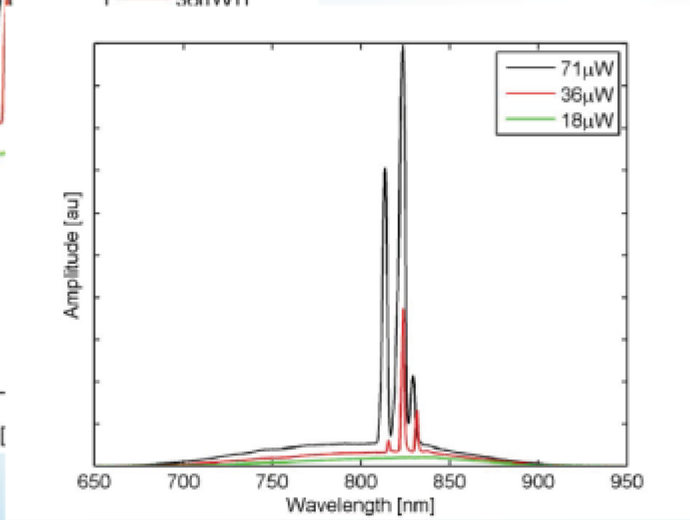


Lasing

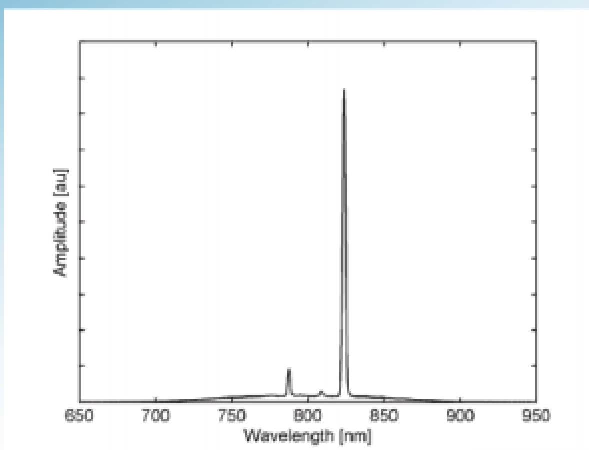


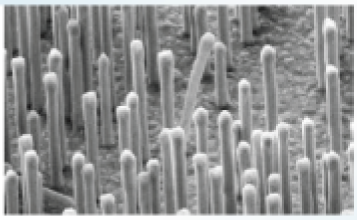
Core-Shell NWs grown on GaAs Lase at Room Temperature
Note: No Vertical Structure

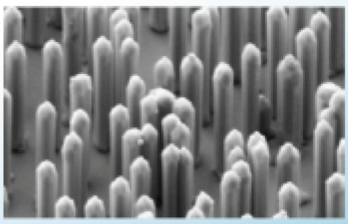




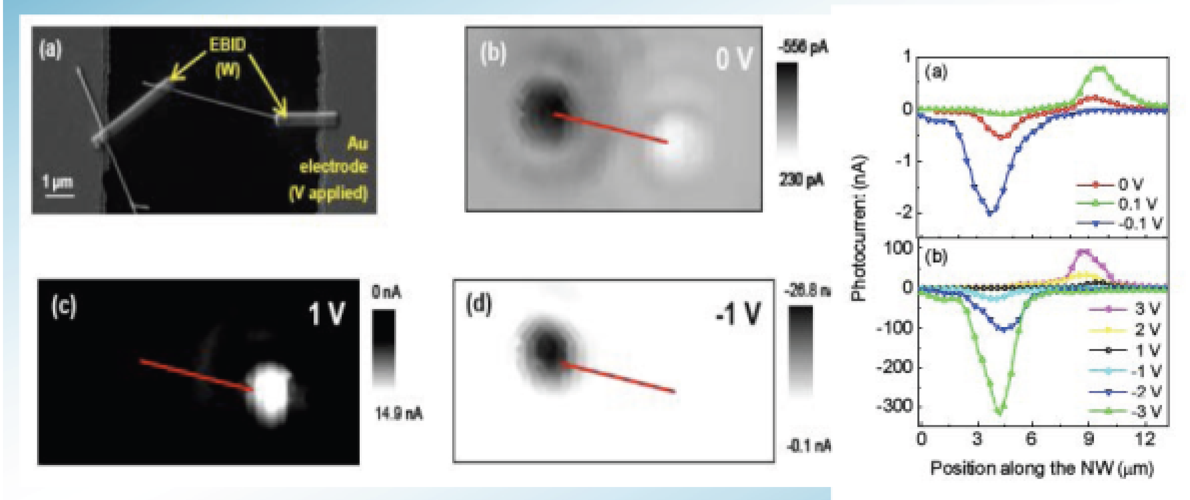
Lasing of CS GaAs/AlGaAs NWs grown on Si



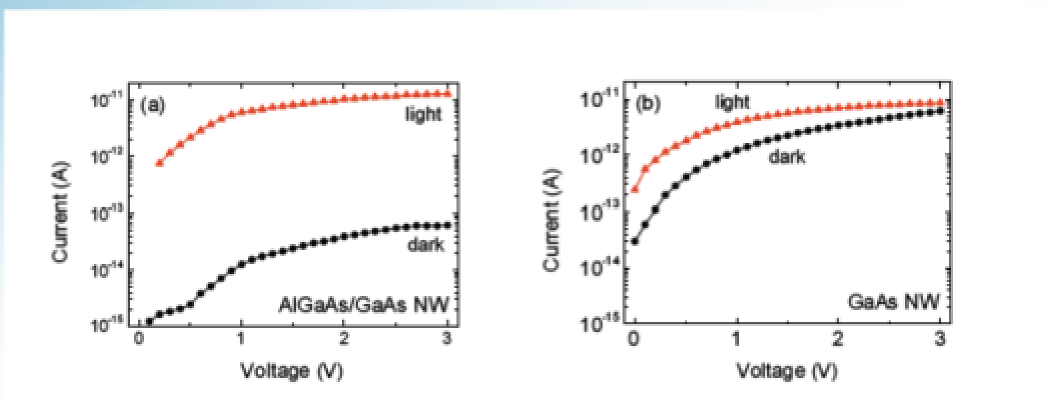


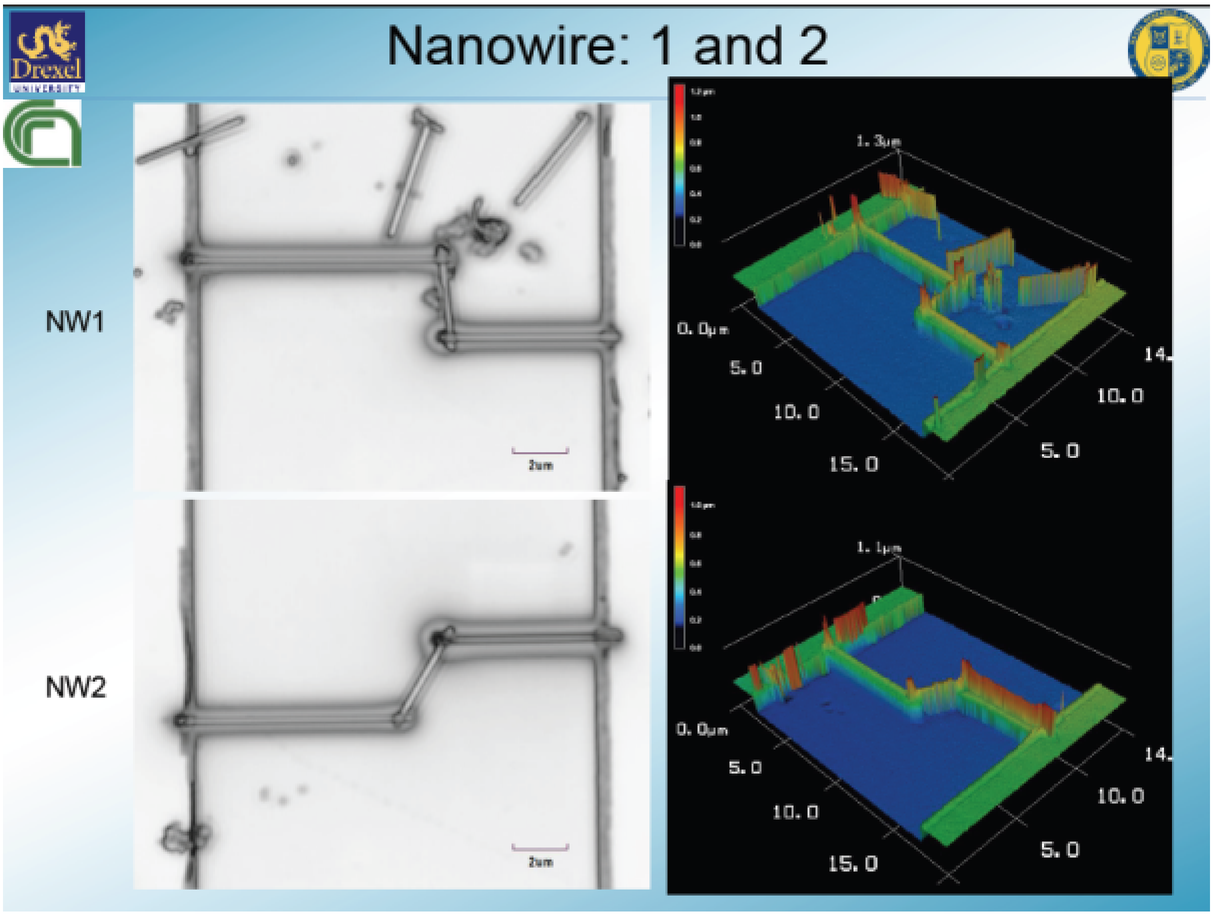


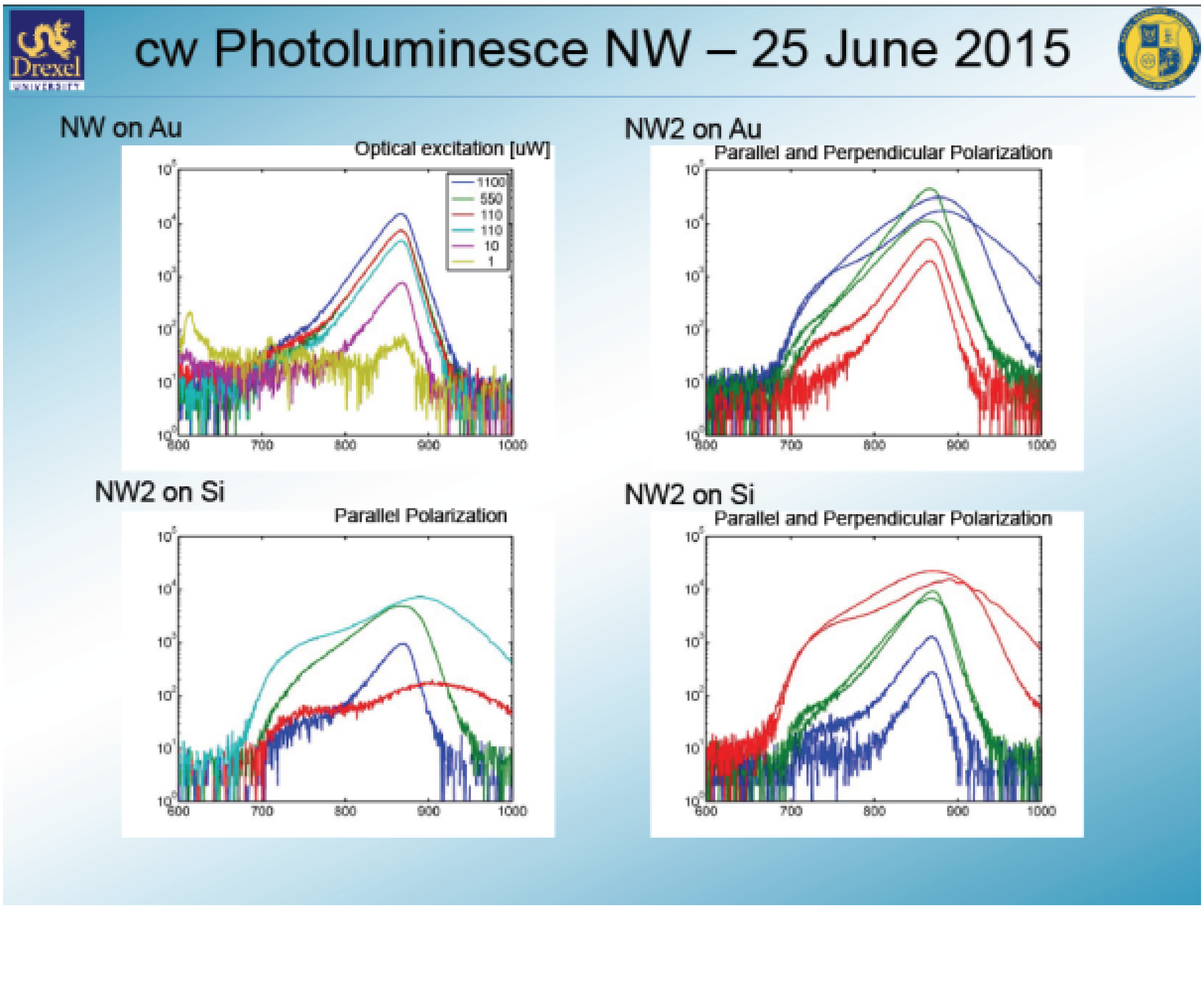
Optical Properties: Photocurrent



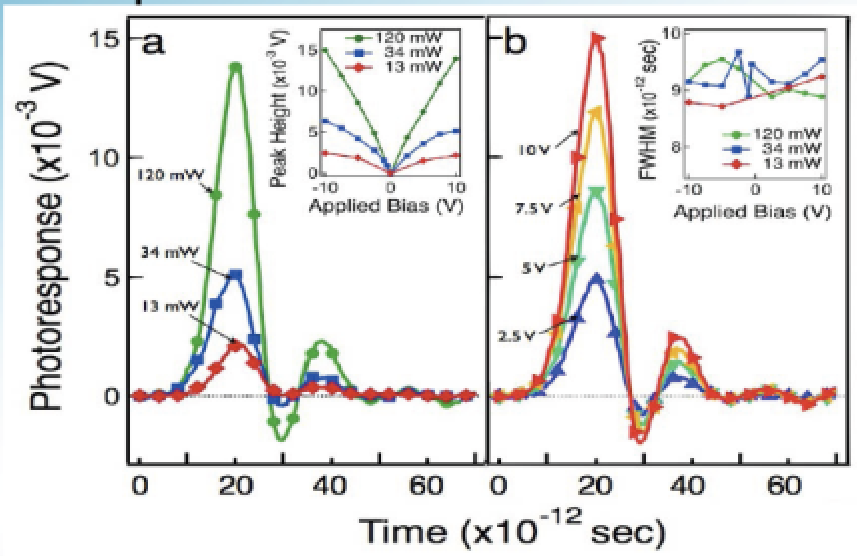
Optical Properties: Photocurrent Core-Shell vs Core only




Nanowire: 1 and 2
NW1
NW2
2um
2um
1.3µm
0.0µm
1.1µm
0.0µm
5.0
10.0
15.0
14.
10.0
5.0


cw Photoluminesce NW – 25 June 2015
NW on Au
Optical excitation [uW]
1100
550
110
110
10
1
NW2 on Au
Parallel and Perpendicular Polarization
NW2 on Si
Parallel Polarization
NW2 on Si
Parallel and Perpendicular Polarization
600
700
800
900
1000

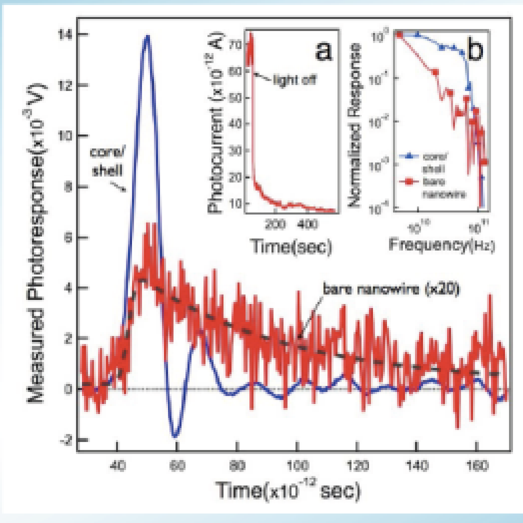
Time Response: Optoelectronic Measurement



Time responses for core/shell detectors at selected (a) incident powers, and (b) biases. Insets: measured peak heights and FWHM values.

.E. M. Gallo, G. Chen, M. Currie, T. McGuckin, P. Prete, N. Lovergine, B. Nabet, and J. E. Spanier
"Picosecond response times in GaAs/AlGaAs core/shell nanowire-based photodetectors"
Applied Physics letters 98, 153106 (2011).

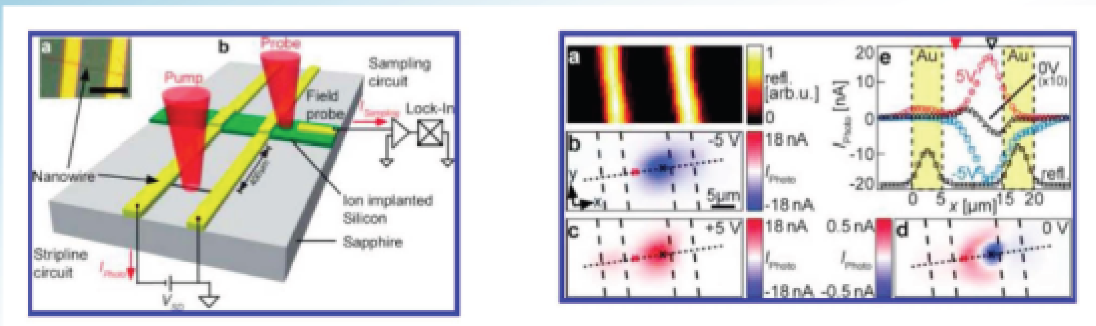
Time Response: Optoelectronic Measurement



Representative time response of a core/shell nanowire and bare GaAs nanowire detectors under 120 W incident illumination and 10 V applied bias.
Inset a: slow time scale response of a bare GaAs nanowire detector; arrow indicates when illumination was removed; Inset b: Normalized frequency
response of the both detectors..

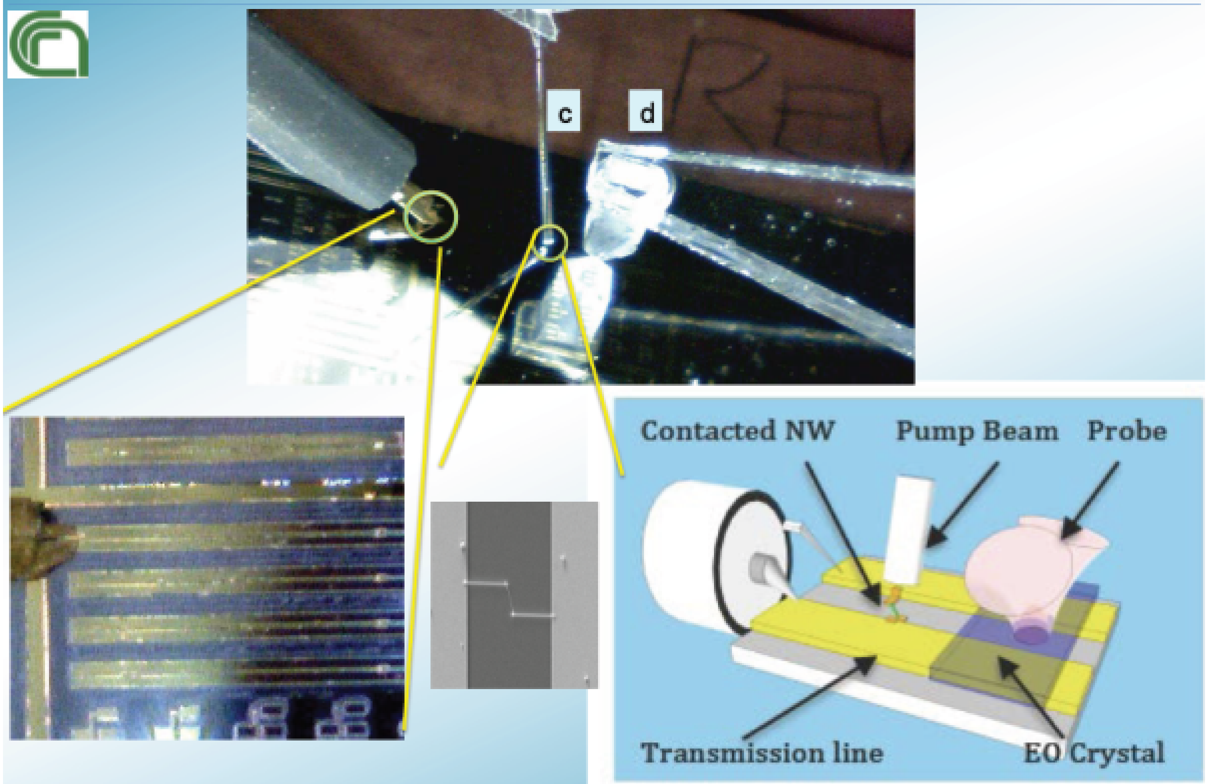
E. M. Gallo, G. Chen, M. Currie, et al. Applied Physics letters 98, 153106 (2011).

Previous Time Resolved Pump-Probe Measurement

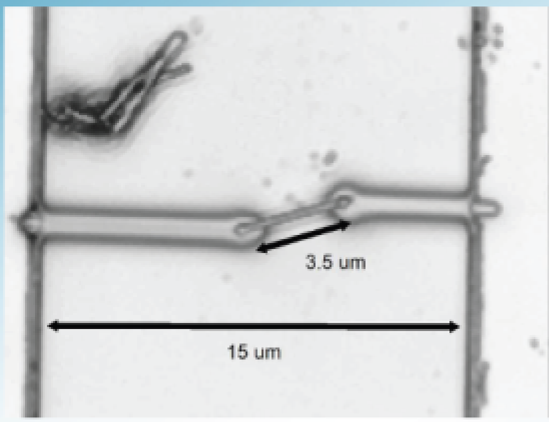


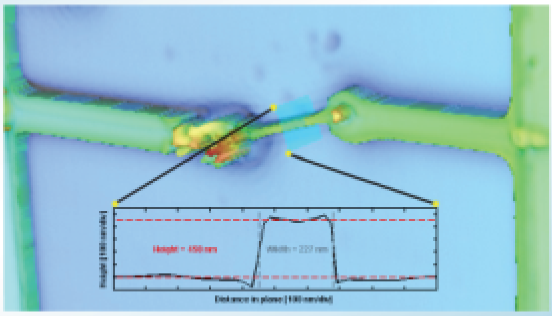
Leonhard Prechtel, Milan Padilla, Nadine Erhard, et al." Time-Resolved Photoinduced Thermoelectric and Transport Currents in GaAs Nanowires" Nano Lett. 2012, 12, 2337−2341

Electro Optic Sampling (EOS)



NW connected to Transmission Line

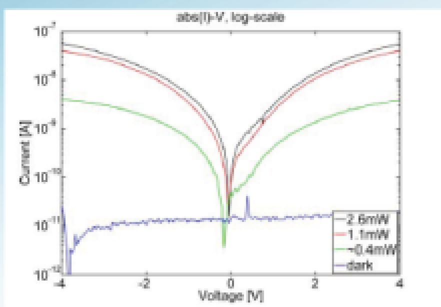


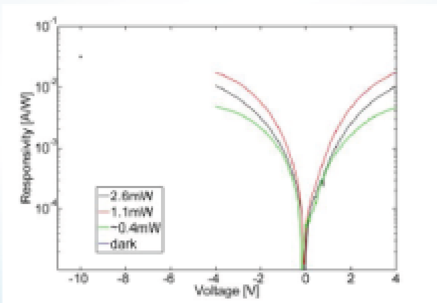


Core-Shell Nanowire dimensions: (50-60nm core / 50-60nm shell / 5-10nm cap)

NW dispersed on substrate with Au transmission lines
NW were connected to T-lines via EBID of Tungsten or Au

NW Optical Response

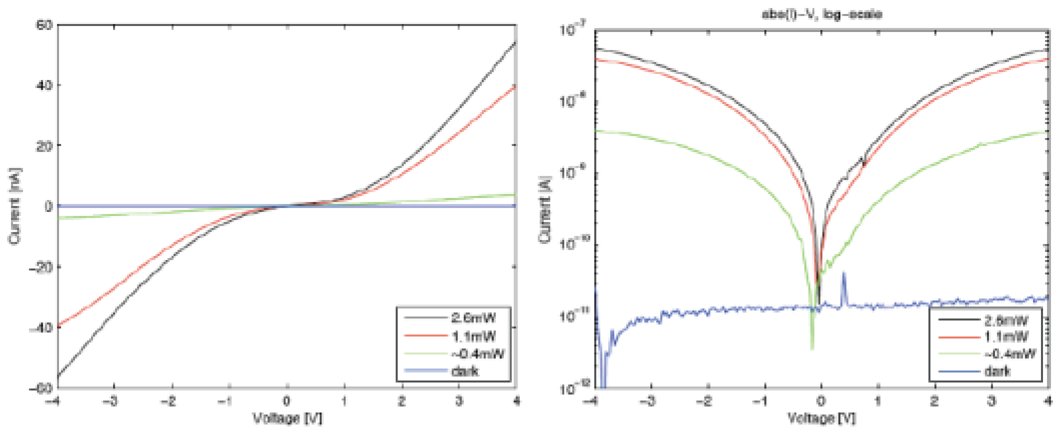




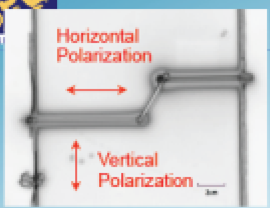
P_{ave} = 2.6mW, max. optical power
I_{ave} = 171nA ave. current
$\Re_{NW}$ = 0.03 A/W

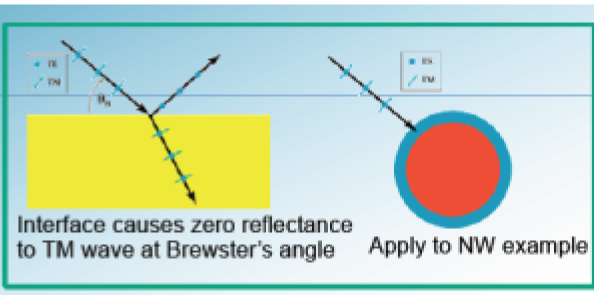
For absorption in the same volume of GaAs, $\Re_{GaAs} = 0.02 \times 10^{-3}$ A/W

NW Optical Response



CS5 on TL, EOS 2.6-mW optical power @ -10V, produces 171 nA!





- Horizontally polarized light is close to TM
- Vertically polarized light is close to TE
- Not the same as TE and TM modes in wire-waveguide
  - *Note: TE optical excitation is along the NW length*

Responsivity assuming:
1) wire dimensions: 0.25-um diameter x 3-um long
2) complete absorption by NW

If we use a simple 3 interface model (air/GaAs/SiO2/Si) to compensate for reflection and incomplete GaAs absorption (.25-um thick), we can claim an additional increase in responsivity of ~5x

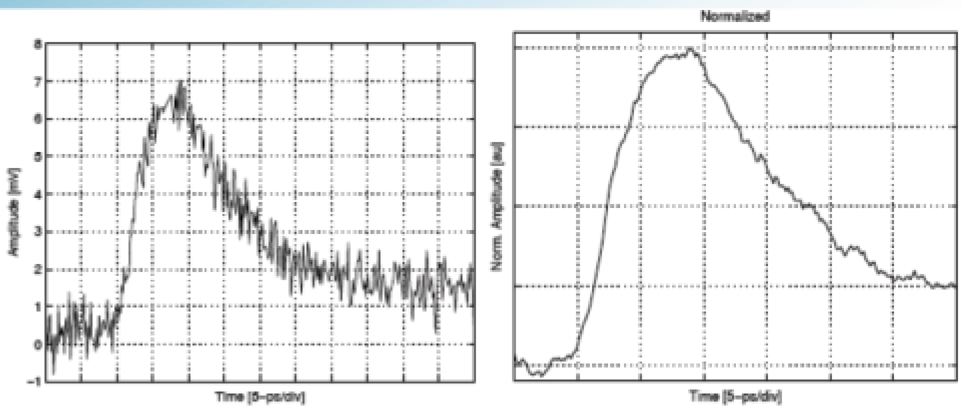
7Vbias

R [A/W]	~300uW	~45uW	~5uW
***cw* horizontal**	0.001	0.001	0.004
***cw* vertical**	0.002	0.003	0.005
***fs* horizontal**	0.002	0.005	0.009
***fs* vertical**	0.002	0.009	0.014

5Vbias

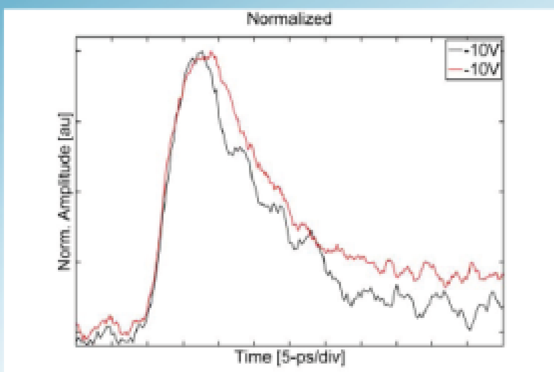
R [A/W]	~300uW	~45uW	~5uW
***cw* horizontal**	0.001	0.001	0.002
***cw* vertical**	0.001	0.002	0.003
***fs* horizontal**	0.001	0.002	0.004
***fs* vertical**	0.001	0.004	0.007

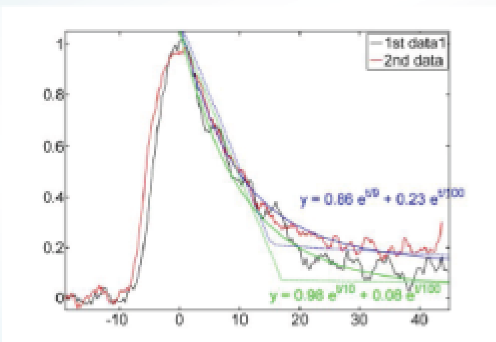
CSNW Dynamic Response



Vbias [V]	Rise Time [ps]	FWHM [ps]
-10	5.2	15.3

Time response

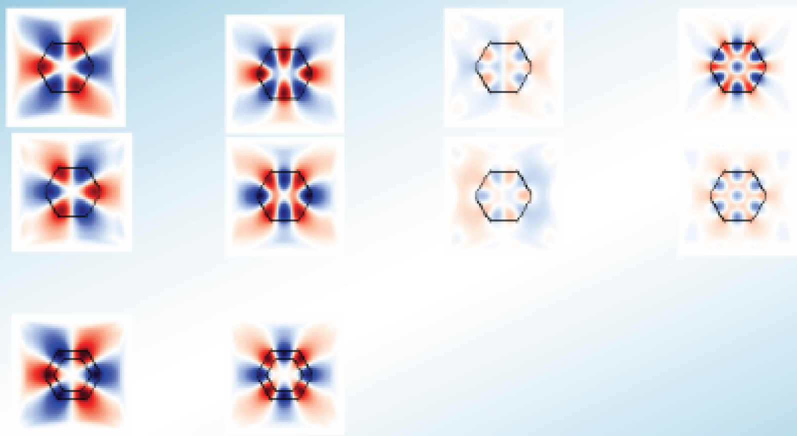




Rise Time = 5ps,
FWHM = 13ps,
Fall Time = bi-exponential, τ_1=10ps, τ_2=100ps,
bi-exponential decay (based on e-h mobilities)

Linear fitting represents Ramo transit times
$I = R_1 + R_2 = A_1*(1-t/(M*T_{a1})) + A_2*(1-t/(M*T_{a2}))$

Analysis: Where are the photons?

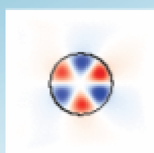


Hexagon
N=3.4

Hexagon
Core-shell
n_core=3.4
n_shell=3.134
9

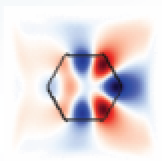
Hexagon
Core-shell
n_core=3.4
n_shell=2.0

Analysis: Where are the photons?



Cylinder
Perpendicular
incident
TE mode

Poynting
Vector in x
direction
Perpendicular
incident

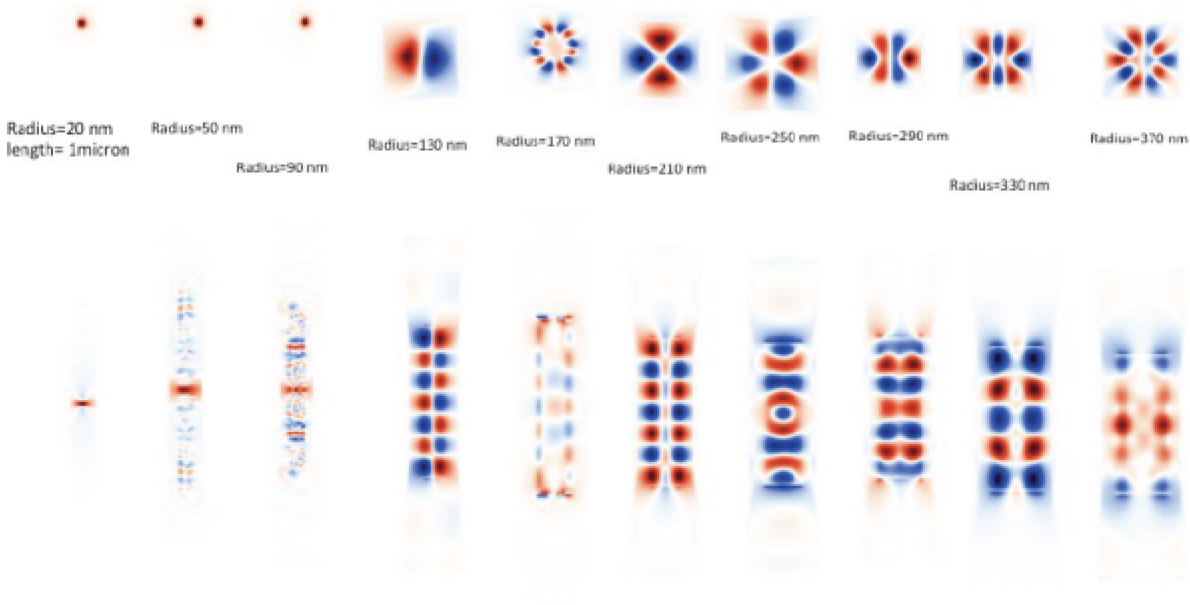


Hexagon
Perpendicular
incident
TE Mode

Poynting
Vector in x
direction
Perpendicular
incident

Analysis: Where are the photons?

TM Excitation varying with radius at same wavelength (532nm) of incident light



Analysis: Where are the electrons?

264103-3 Wolf *et al.* Appl. Phys. Lett. **98**, 264103 (2011)

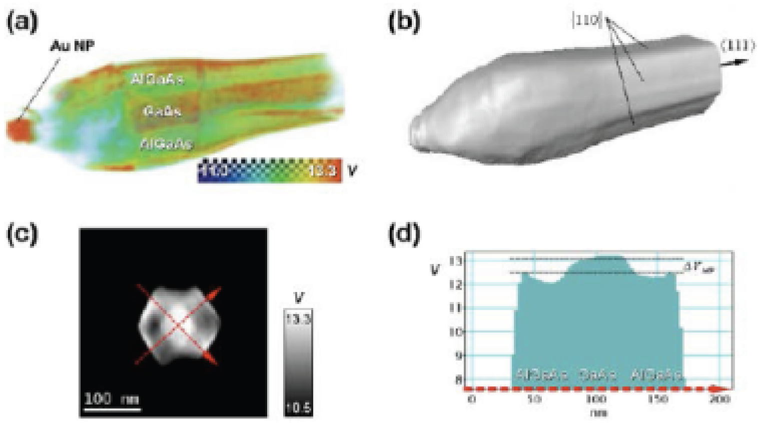
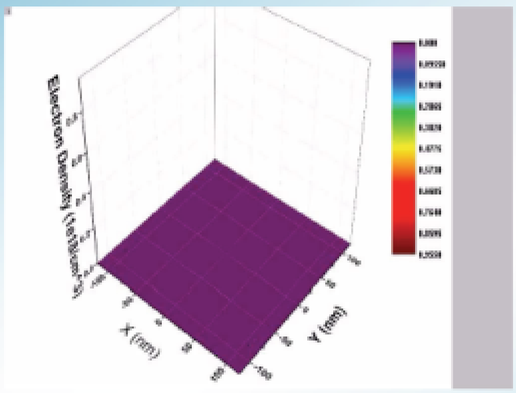
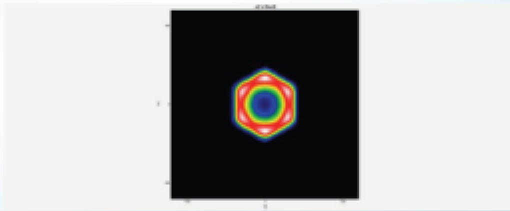


FIG. 3. (Color online) 3D potential of a GaAs-AlGaAs core-shell NW, reconstructed by EHT: (a) volume rendering; (b) surface rendering, of the 9 V-isosurface, showing the {110}-side-wall facets perpendicular to the NW ⟨111⟩ growth direction; (c) cross-sectional map obtained by averaging the potential over a 110-nm long section of the NW, showing its hexagonal cross-section; and (d) line profile obtained as mean of the two line-scans indicated by the arrows in (c).

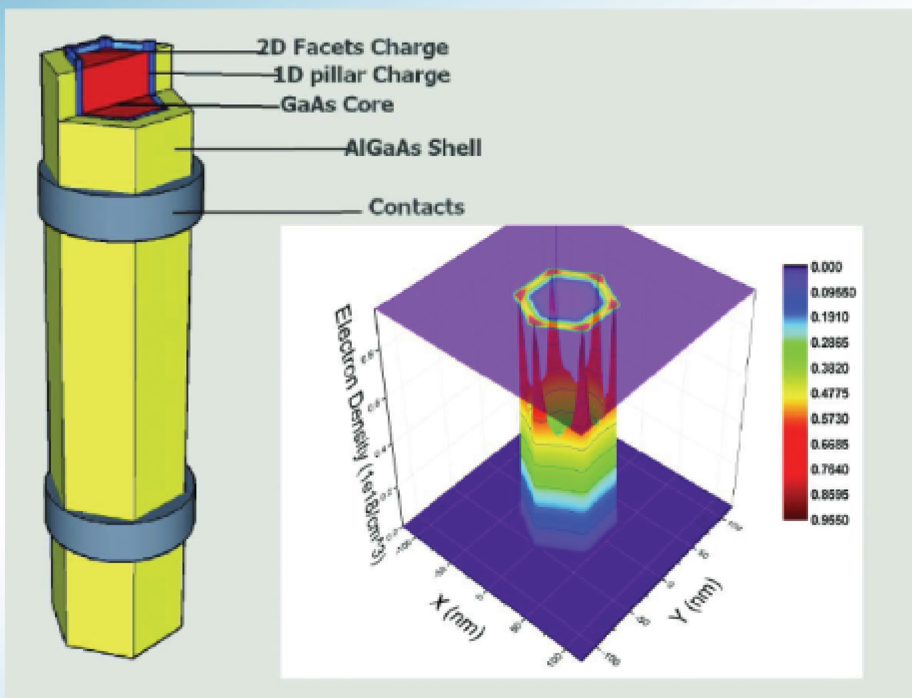
gonal CSNW Electronic Density Varying with Doping Density



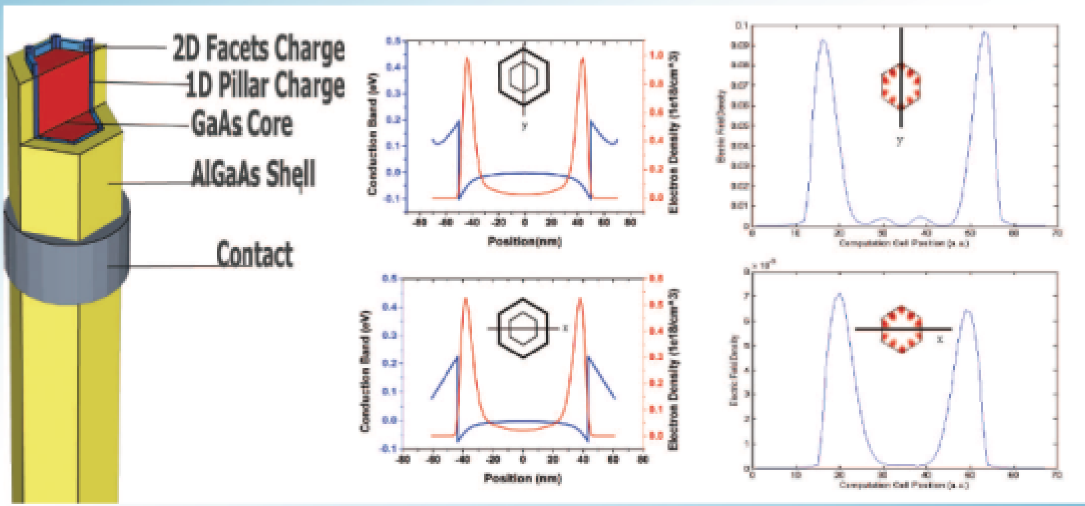


3D view of hexagonal CSNW forming six pillars of charge at corners with increasing doping density.

2D view of hexagonal CSNW forming six pillars of charge at corners with increasing doping density.



Conclusions



Our Device:

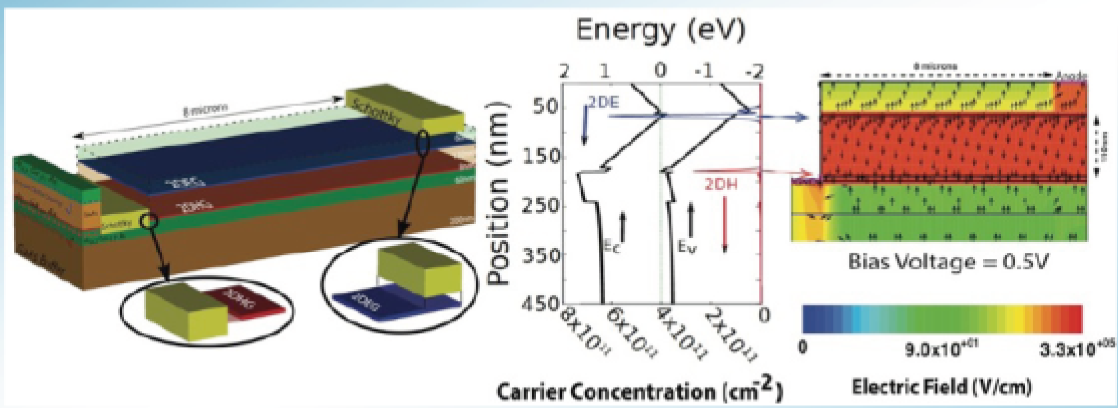
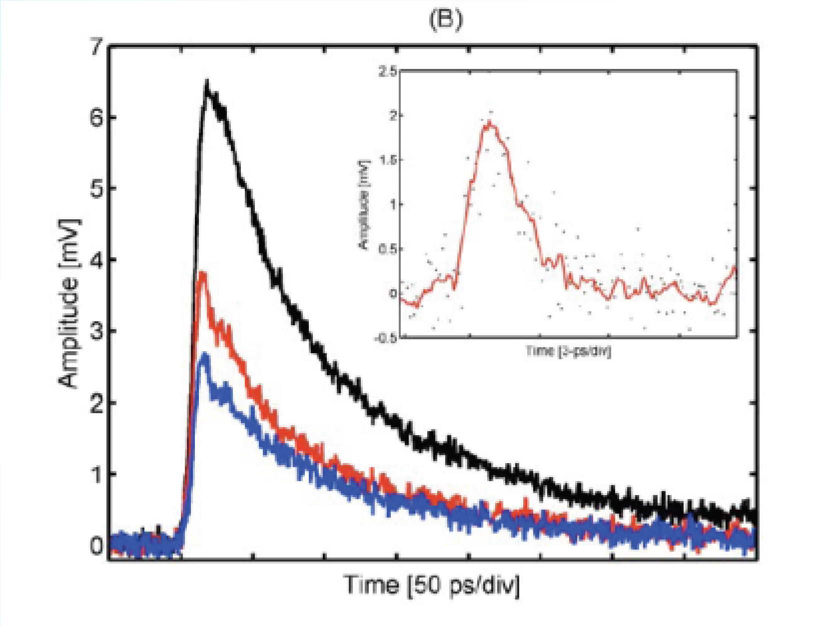


Figure (a) Schematic of the device layer structure with two reservoirs of two-dimensional electron and hole gasses separated by a ~110 nm absorption region. Blocking Schottky contacts form the cathode and anode that are >8 μm apart and separately contact sheets of charge. **(b)** Calculated energy band diagram along the direction of growth in the middle of the device shows existence of large vertical electric field, as well as dense electron and hole gasses which can move only in two dimensions. **(c)** Simulation showing large vertical field in the absorption region between the electron and hole 2D charge reservoirs under 0.5V applied bias. Horizontal and vertical scales are different.

Identical geometries, without 2DEH, and with 2DEH (inset).

~ 2.5 ps vs >75 ps FWHM

~2 ps vs >150 ps Fall time



Analysis includes

- How many ehps are generated
- Electric Field Profile
- Energy Band Diagram
- Effect of Schottky Contacts
- Transport and collection of carriers

Conclusions

- Core-shell Nanowires' optical properties differ from core-only in significant ways.
- There is large absorption enhancement in CSNW
- Time resolved response measurements show speeds that are higher than their thin film counterparts of the same cathode-anode distance. This is partially due to:
  - -- Reduced dimensionality effects such as depletion region extension in 2D and 1D.
  - -- Modification of the EBD
  - -- spatial separation of electrons and holes,
  - -- reduction of scattering,
  - -- some evidence of collective behavior,
- This work has been partially supported by CNR – STM program

Conclusions