Progress in nanophotonics & nanobiotechnology

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DEPARTMENT OF PHYSICS, NANO LASER LAB

극미세 나노선 광소자 창의연구단 (2009 ~ 현재)

- **Goal**: We study strong light-matter interaction, and develop novel nanophotonic devices such as photonic/plasmonic nanolasers, waveguides, nanowire solar cells for ultracompact photonic integrated circuits.

- 단장: 박홍규 교수
- 연구교수: 김경호, 이정민, 김정길, 최재혁 박사
- 연구원: 서효영
- 박사과정: 장세환, 박진성, 소재필, 김하림, 이순재, 이후철, 이성원, 이호성, 김진산

1. Nanolasers
2. Nanowires
3. 2D materials
4. Neuroscience

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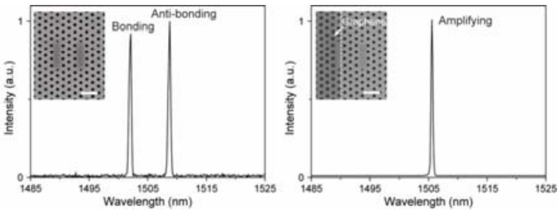
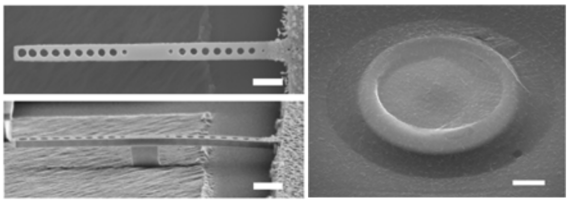
Nanolasers

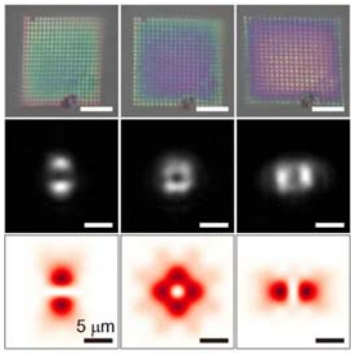
Nanolaser using parity-time symmetry breaking
Nature Communications (2016)

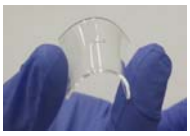


Electrically driven nanolasers
Nature Communications (2013) &
Nature Communications (2012)



Strain-gauge nanolaser
Nature Communications (2016)





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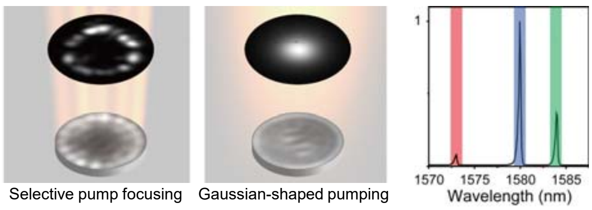
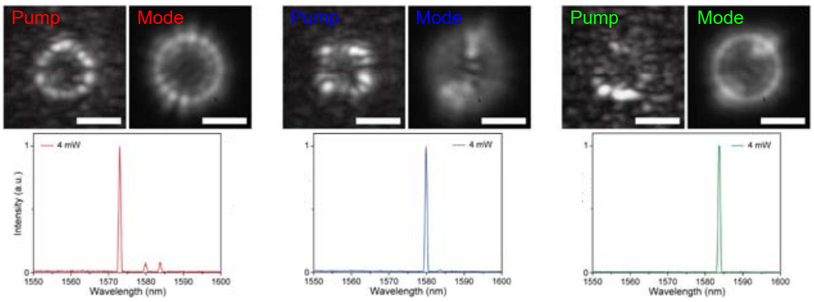
Nanolasers

Selective pump focusing on individual laser modes
ACS Photonics (2018)





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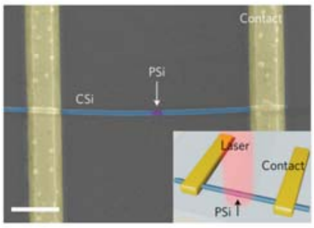
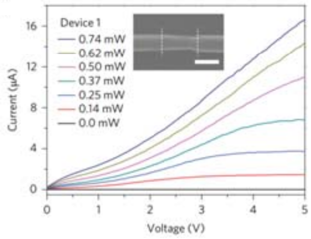
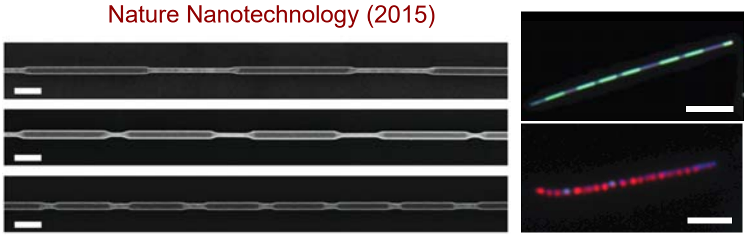
Nanowires

Photon-triggered nanowire transistor
Nature Nanotechnology (2017)





Periodic-shell nanowires
Nature Nanotechnology (2015)



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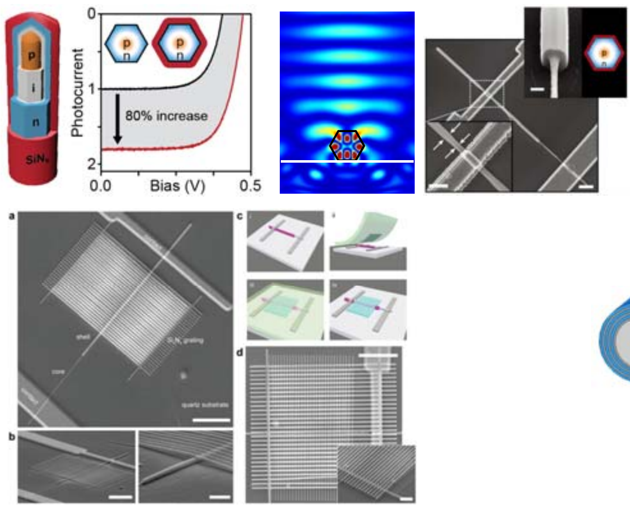
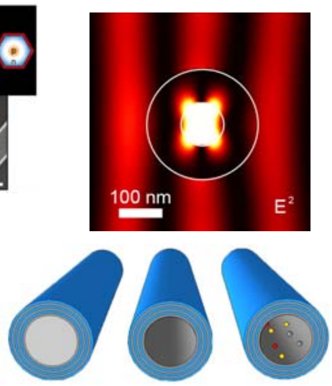
Nanowires

Nanowire solar cells
Nano Letters (2015) & Nano Letters (2017)

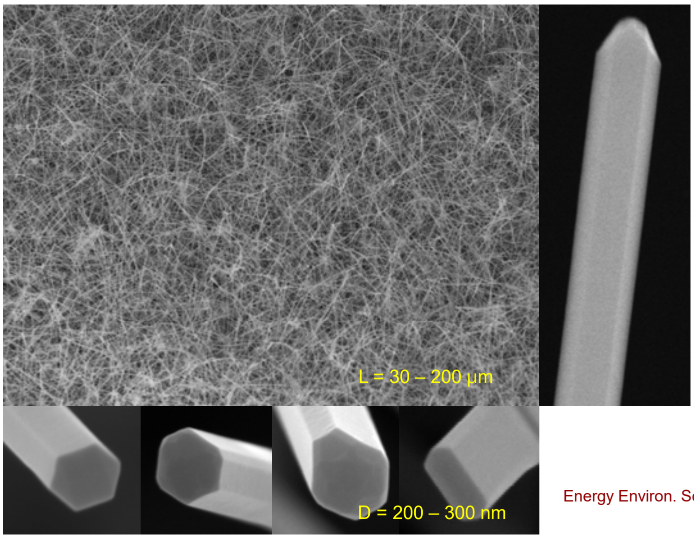


Nanowire metamaterials
Sci Rep (2015)



Semiconductor nanowires (NWs)

- **Synthesis of NWs yields greater control over and larger diversity of motifs.**



- Carrier mobility: ~560 cm^2/V (p-Si NW)
- Thermal conductivity: ~50 W/(m·K)
- Tunable electronic bandgap: CdS, CdSe (II-VI), GaAs, GaN (III-V))
- High index: n_{Si}: 4.0 @ 600 nm
- Light absorption in visible frequency
- Tunable light emission

Energy Environ. Sci. **6**, 719 (2013)

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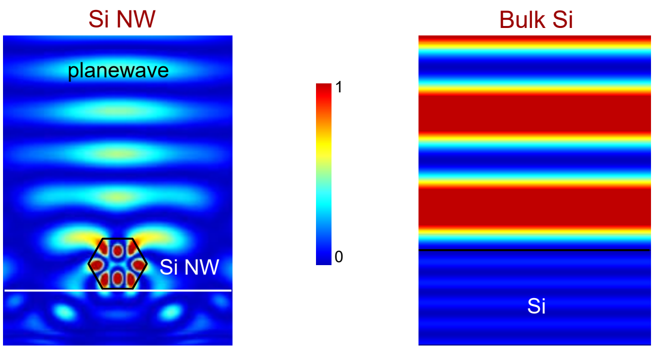
NW cavity as efficient photon absorber

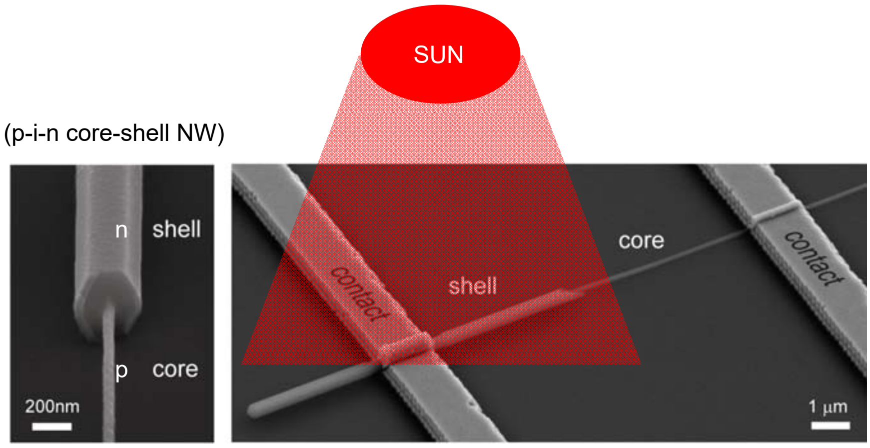
Snap shots of electric field intensity (FDTD simulation)



Unique optical properties of NW structures:

1) **Highly confined resonant modes**
2) **Optical antenna effects**

Single crystalline Si NW photovoltaics



T. J. Kempa, J. F. Cahoon, S.-K. Kim, R. W. Day, D. C. Bell, **H.-G. Park***, C. M. Lieber*, *Proc. Natl. Acad. Sci. USA* **109**, 1407 (2012).

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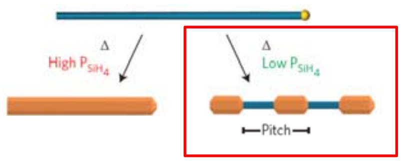
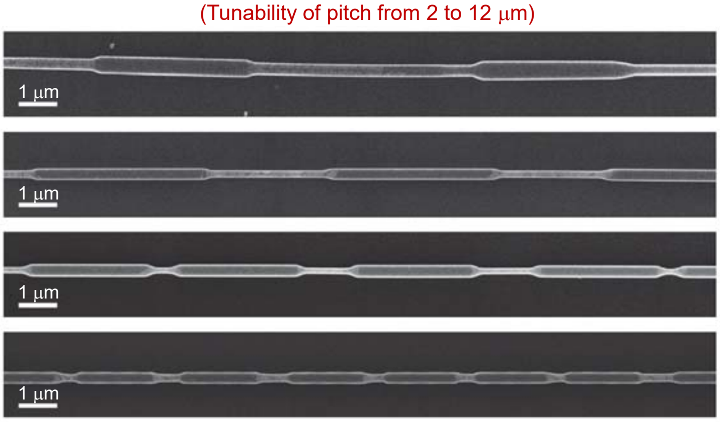
Plateau-Rayleigh crystal growth

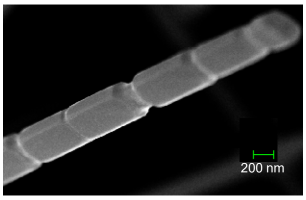


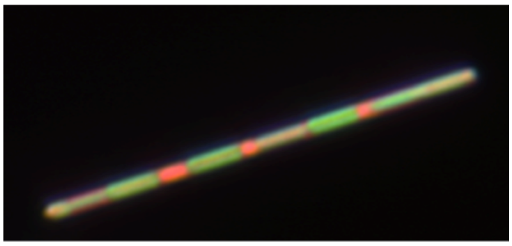
Periodic shell growth using P-R crystal growth, in the same temperature range (650-850°C) but with SiH_4 and H_2 partial pressures ~10-100 times lower than for conventional conformal shell growth.

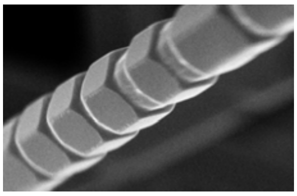
(Tunability of pitch from 2 to 12 μm)



New NW morphologies: Periodic axial modulations



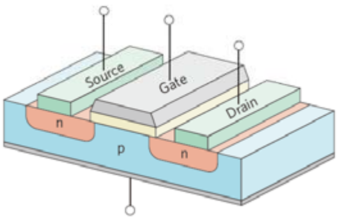


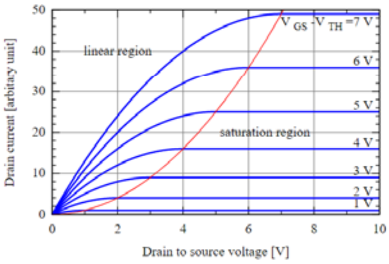


R. W. Day, M. N. Mankin, R. Gao, Y.-S. No, S.-K. Kim, D. C. Bell, **H.-G. Park***, C. M. Lieber*, "Plateau-Rayleigh crystal growth of periodic shells on one-dimensional substrates," *Nature Nanotechnol.* **10**, 345 (2015).

Field-effect transistors (MOSFET)

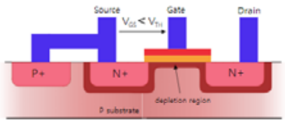
Nat. Nanotechnol. **12**, 938-939 (2017)



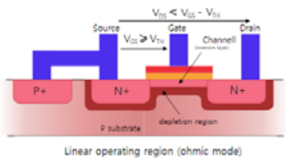


[Wikipedia images]

OFF state

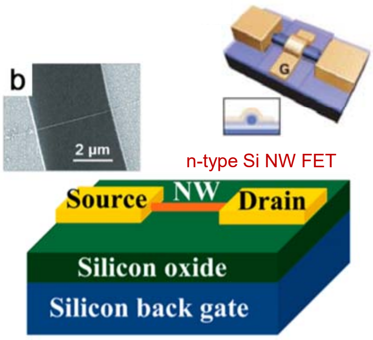


ON state

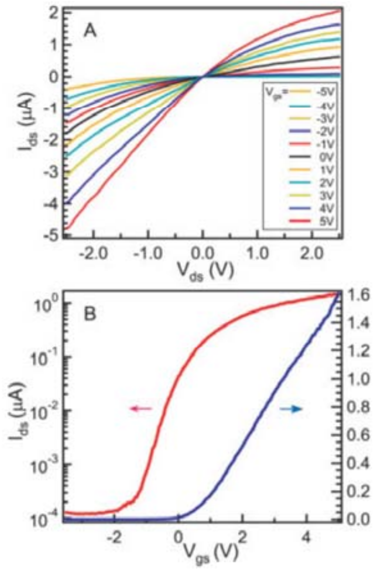


- A transistor operates by changing the current flowing between two electrodes (the source and drain) by orders of magnitude.
- The change in current is controlled by a third electrode, the gate, to which a voltage is applied.

Nanowire field-effect transistors



Adv. Mater. **16**, 1890-1893 (2004)



- NW FETs: the electrostatic potential of the NWs is tuned by the gate voltage (V_g), which modulates the carrier concentration and conductance of the NW.

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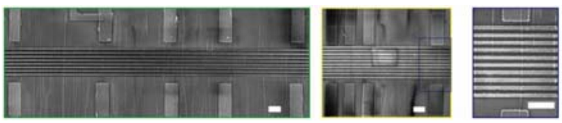
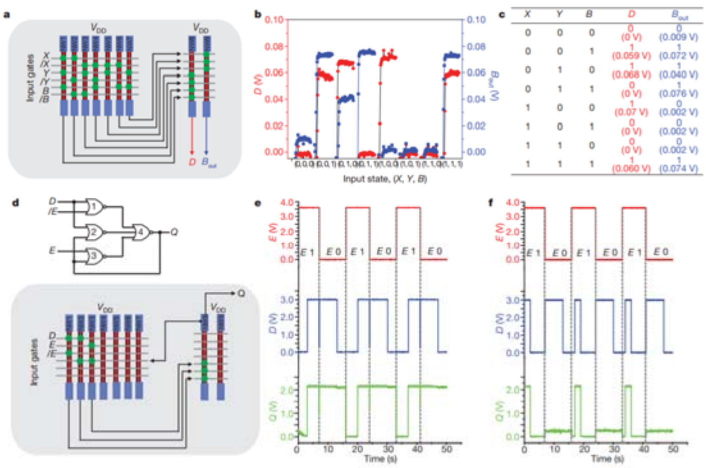
Nanowire processors

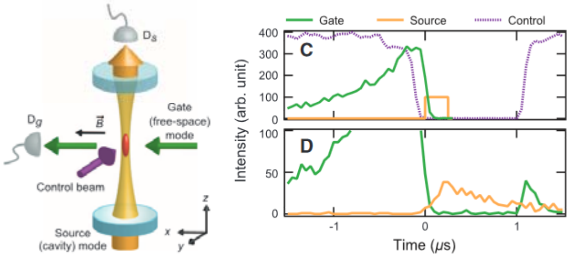


- Integration of programmable NW FETs.

Nature **470**, 240 (2011)

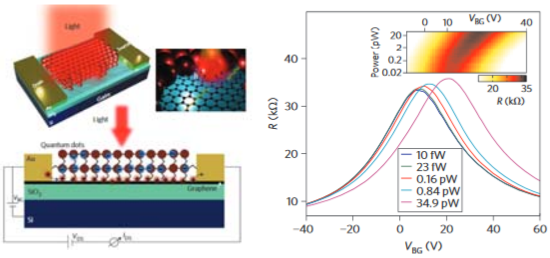


All-optical transistors & phototransistors



Science **341**, 768 (2013)

• All-optical transistor: all-optical switch and transistor gated by one stored photon.



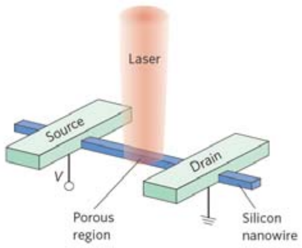
Nat. Nanotechnol. **7**, 363 (2012)

• Phototransistor: hybrid graphene-quantum dot phototransistors with ultrahigh gain.

A new transistor: photon-triggered transistor

• Electronic currents are optically switched and amplified **without an electrical gate**. Such photon-triggered electronic circuits have been a long-standing goal of photonics.

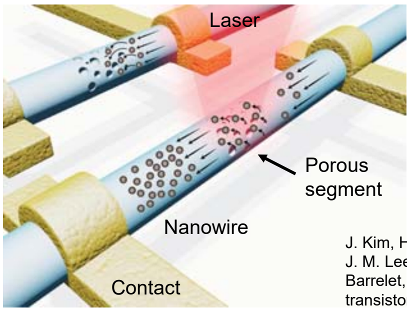
• In fact, it has been challenging to (1) implement conformal high-κ gate dielectrics to NWs for strong gate response and (2) assemble NW FET arrays through the precise alignment of NWs.



• Usage of optically-gated NW devices can be an ideal approach to surmount these hurdles in a simple manner!

Nat. Nanotechnol. **12**, 938-939 (2017)

Photon-triggered nanowire transistors (PTNTs)



J. Kim, H.-C. Lee, K.-H. Kim, M.-S. Hwang, J.-S. Park, J. M. Lee, J.-P. So, J.-H. Choi, S.-H. Kwon, C. J. Barrelet, and **H.-G. Park***, "Photon-triggered nanowire transistors," *Nature Nanotechnology* **12**, 963 (2017).

- The photon-triggered nanowire transistor consists of **a reservoir that supplies carriers** connected to **a channel that collects carriers** emitted from the reservoir.
- **Porous Si (PSi)** segment acts as a reservoir of high-density localized states.
- **Crystalline Si (CSi)** segment constitutes a channel with a higher carrier mobility.

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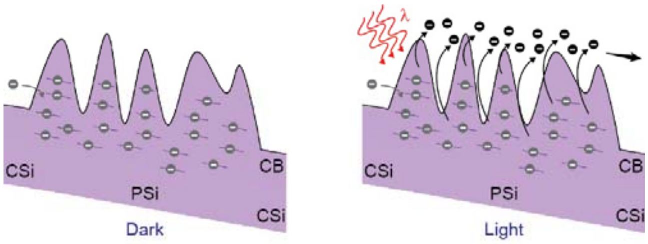
Mechanism of operation

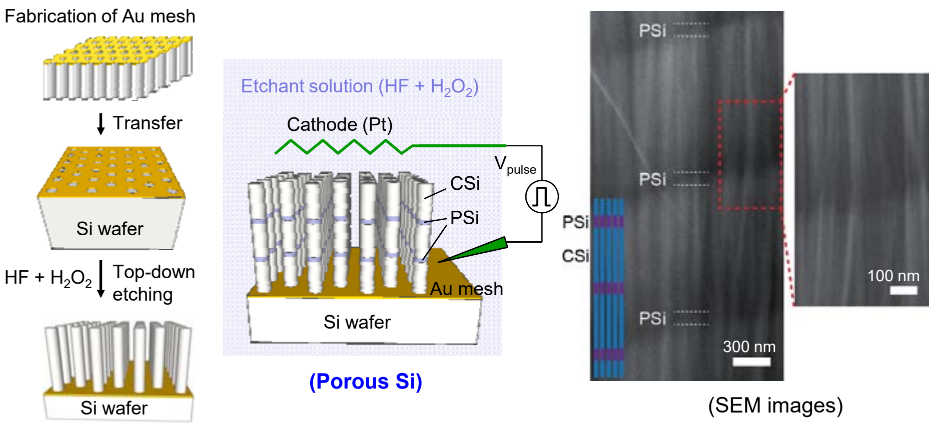


- Schematics of band diagrams of a Si NW with a single PSi segment in dark (left) and light (right) conditions:

- In the dark, injected carriers are **trapped in the localized states** of the PSi segment and the current is blocked.

- When light is incident to the PSi segment, the trapped electrons are excited into higher electronic states, **triggering a current across the electrodes**.

Fabrication of NWs



(Porous Si)

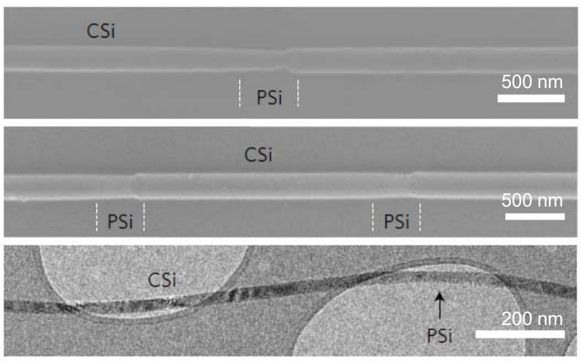
(SEM images)

• Metal-assisted chemical etching (MaCE) was used to fabricate Si NWs with PSi segments. We used (100) n-type Si substrate (resistance of 1-5 Ω·cm).

• **The length and location of the PSi segments can be controlled by the pulse width and pitch.**

Si NWs with PSi segments

(SEM/TEM images of synthesized NWs)



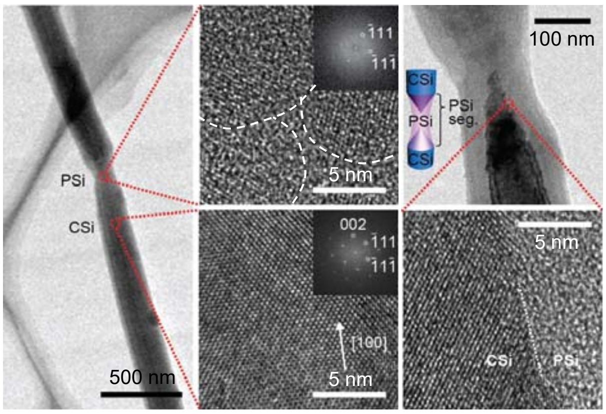
• The diameters of Si NWs are 25 nm or 180-200 nm.

• The lengths of PSi segment are 100 nm (thin NW) or 400-450 nm (thick NW).

• More than one PSi segment can be synthesized in a single Si NW.

Nat. Nanotechnol. **12**, 963-968 (2017)

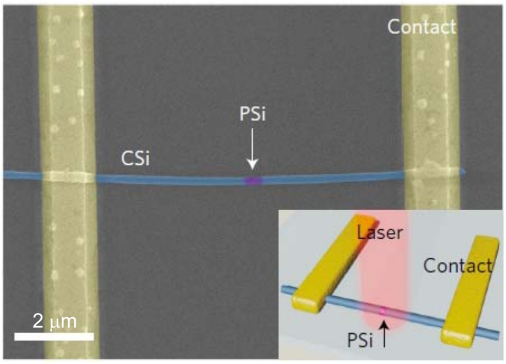
TEM analysis



- In the CSi, a single crystal lattice is observed, whereas in the PSi segment a porous crystal lattice is observed.
- Weak but observable patterns appear in the fast Fourier transform of the PSi segment because of the presence of the lattice.

KOREA UNIVERSITY Department of Physics, Nano Laser Lab

PTNT devices



- We fabricated source and drain metal (Ti/Pd/Au) contacts at both ends of the NW and applied bias voltages, to examine and control the current along the NW with a single PSi segment.
- A continuous-wave (CW) pump laser with a wavelength of 658 nm was focused onto the PSi segment.

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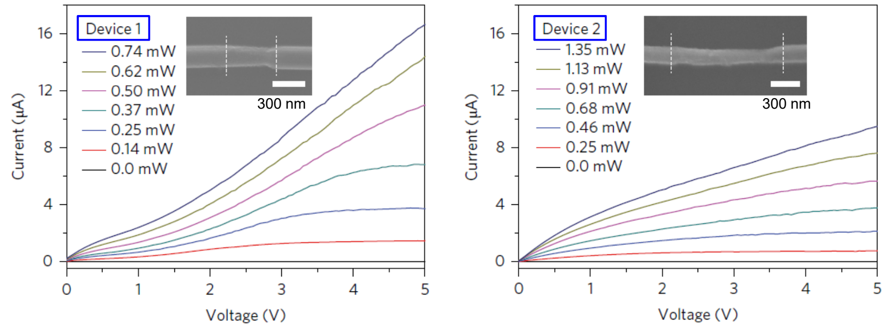
I-V characteristics of PTNTs

(Measured I-V curves using different laser pumping powers)



- We examined two devices each with a different PSi segment length: ~450 nm (device 1) and ~1180 nm (device 2).
- In the dark, the current increased from 0 to ~2 pA for the 0 to 5 V voltage sweeps.
- In the light, a significant current was observed: ~16 μA (device 1; 0.74 mW) and ~9 μA (device 2; 1.35 mW) at 5 V.
- **Maximum current enhancement (on/off current ratio) was ~8 × 10^6 (device 1).**

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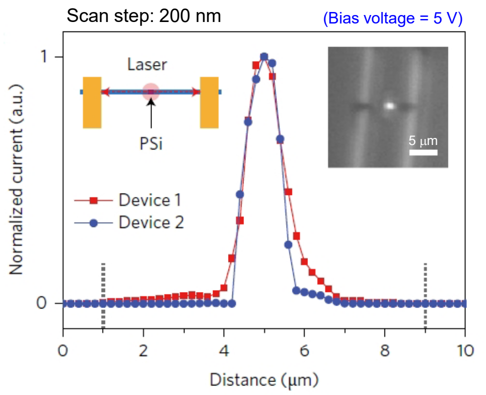
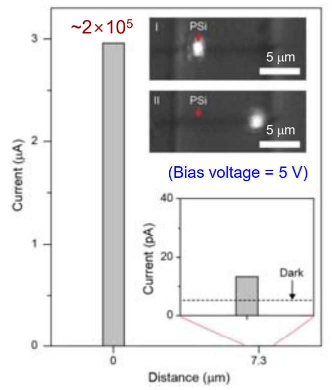
Spatial dependence of PTNTs



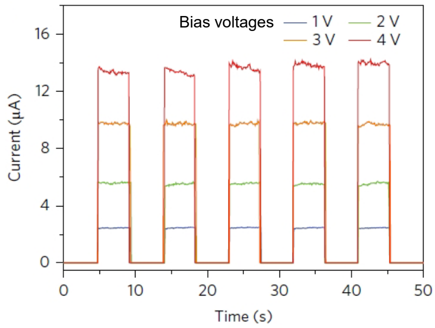
- We measured the current for devices 1 and 2 via a line scan along their NW axes.
- The current increased rapidly and reached a maximum value at the center of the PSi segment.

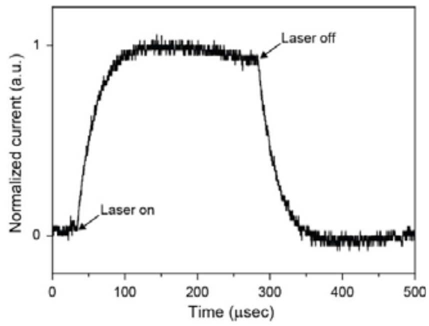


- Currents were measured in a long Si NW with a PSi segment.
- **The current was generated from the PSi segment of the device.**

Temporal response of PTNTs

(Time-dependent current response to pump laser)





- (Left graph) In response to the laser cycle, the measured current level reproducibly cycles between the off and the on states.
- (Right graph) We measured the transient current when a short laser pulse (with a width of 250 μs) was injected into the PSi segment. → The rise/fall time of **~28 μs** is comparable to the photoresponse time previously reported in Si NW devices.[1]

[1] *Sci. Rep.* 4, 3914 (2014) & *Appl. Phys. Lett.* 103, 083114 (2013)

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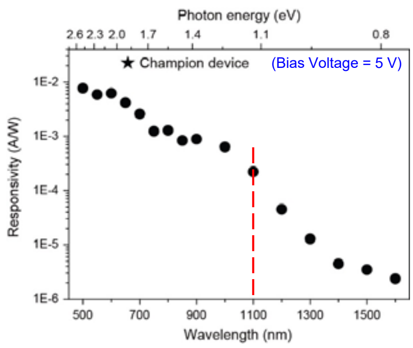
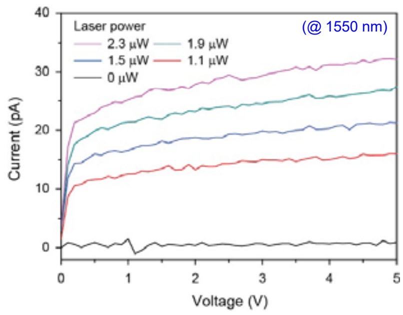
Wavelength-dependent responsivity of PTNTs



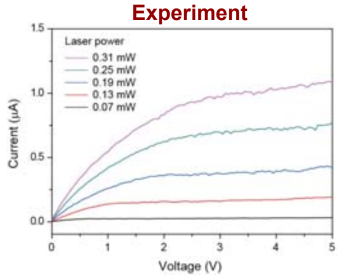


- In the measurement of a current responsivity as a function of the incident wavelength, a smaller responsivity is observed for a longer wavelength (left graph). A current is also measured when the photon energy is less than the band gap of Si (right graph).
- This wavelength-dependent current generation can be understood by a broad range of energy levels for the trap states. **The current is generated by photon triggering of the trapped electrons in the PSi segment.**

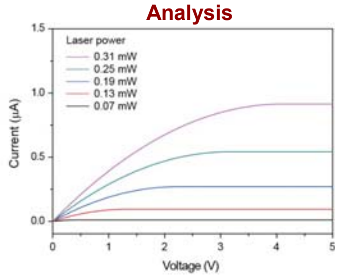
FET model for PTNTs

- We analyze the electrical characteristics of PTNTs using a conventional FET model by making an analogy between PTNTs and FETs.
- PTNT device properties mirror several of the same electrical characteristics of conventional FETs.

Experiment



Analysis



$$Q = -\frac{e}{l}\left(N_{ph} - N_{TH}\right)\tau$$

The electric charge per unit length of the PTNT.

$$C_{eff} = e\tau N_{ph}/V_g l = e\tau N_{TH}/V_{TH} l$$

C_{eff} is assumed to be a constant for a given NW.

$$Q = -C_{eff}\left(V_g - V_{TH}\right)$$

V_g and V_{TH} are the effective gate V and the threshold V.

$$I = \frac{\mu C_{eff}}{l}\left(V_g - V_{TH} - \frac{V}{2}\right)V$$

The current I with the analogy of the conventional FET model.

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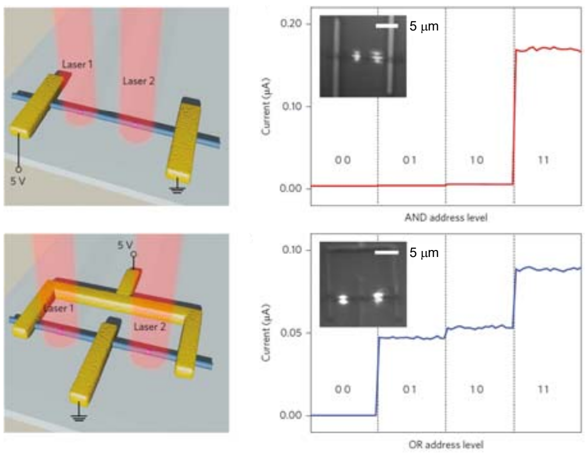
Logic gates (AND, OR)

AND

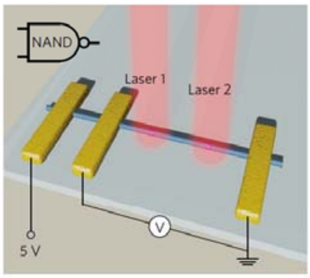
OR

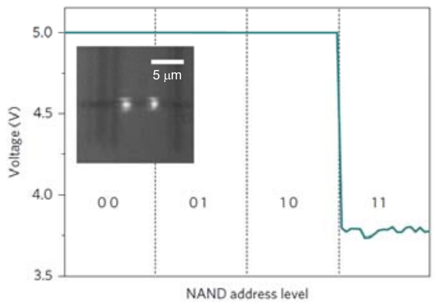


- The device functionality of PTNTs can be extended by adding more PSi segments to the NW and adjusting the design of the metal contacts.
- The AND and OR gates with two CW pump **laser inputs** and the **current output**.

Logic gates (NAND)

NAND





- The NAND gate with two CW pump **laser inputs** and the **voltage output**.
- The voltage value for the '11' state is determined by the electrical resistances in the CSi region and the region including the PSi segments.
- **The localized optical gating of PTNTs enabled the successful demonstration of various logic gates.**

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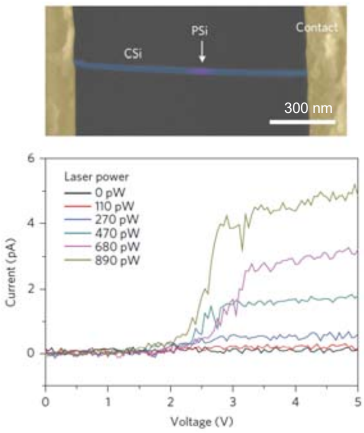
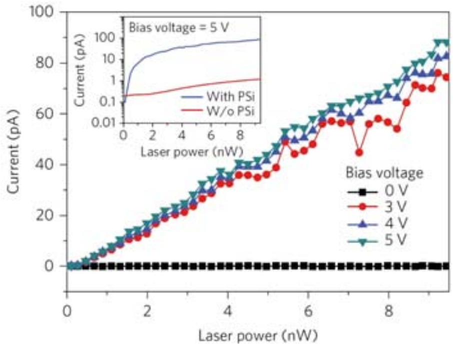
DEPARTMENT OF PHYSICS, NANO LASER LAB

Small-diameter PTNT

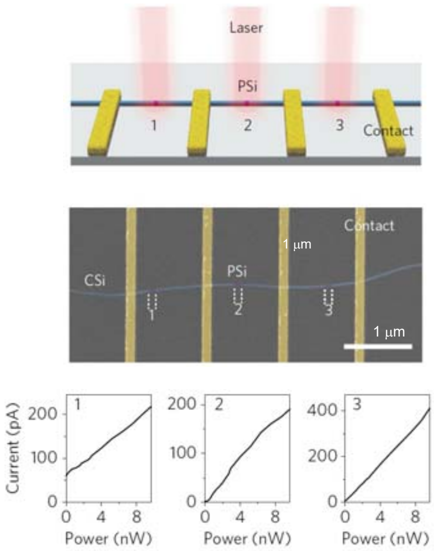


- Si NW with a diameter of 25 nm and a PSi length of 100 nm.
- A measurable current for laser powers larger than ~270 pW.



- Currents are measured in the small-diameter PTNT: the current increases linearly as the laser power increases.
- The device without a PSi segment shows an extremely small current (inset). This indicates again that **the photon-triggered current is generated only in the PSi segment**.

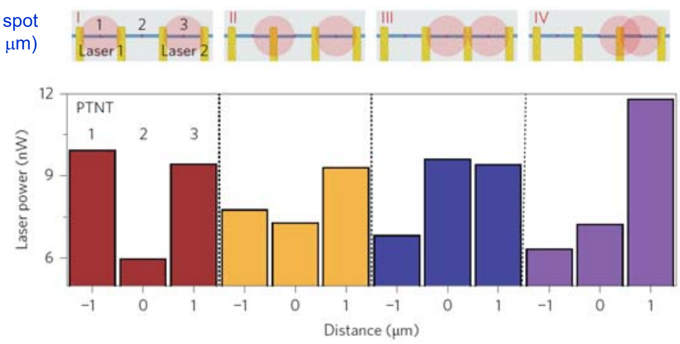
Photodetection system (1)



- We demonstrated a high-resolution photodetection system that consisted of **three PSi segments acting as three pixels**.
- The pump laser was focused on one PSi segment where the PTNT acts as a single pixel.
- We measured the current-laser power curves for the PTNTs with PSi segments 1, 2 and 3 to examine the photoresponse features of the individual PTNTs.
- The measured currents from the PTNTs were linearly proportional to the power of the pump laser.
- We will need to calibrate each device as a function of laser power.

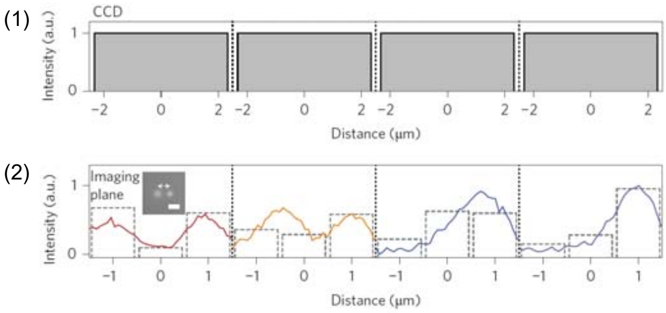
Photodetection system (2)

(Laser spot size: 1 μm)



- We performed an experiment to distinguish two closely located laser spots (Case I to IV): Laser 1 is initially positioned on Pixel 1, and scanned to the right across Pixel 2 with a scan step of 500 nm. Laser 2 remains positioned on Pixel 3.
- **Laser powers were calibrated from the measured currents** at PSi segments 1, 2 and 3 for each pumping case.
- Our NW photodetection system successfully recorded and precisely distinguished the **positions and powers** of the pump lasers with a spatial resolution of <1 μm.

Photodetection system: control experiments



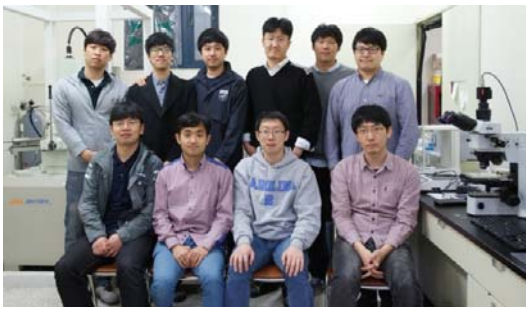
• (1) We conducted the identical experiments using a conventional Si CCD with a pixel size of 4.65 μm: the two pump lasers were indistinguishable because of the poor spatial resolution of the CCD.

• (2) We measured intensity profiles of the two pump lasers using an imaging system: the image of the laser spots is magnified 50 times by an objective lens.

→ The measurement results complement the results using the PTNT photodetection system: Our NW photodetection system works well **without the usage of additional optical components.**

Acknowledgements

The group members



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