Mixed-dimensional van der Waals heterostructures

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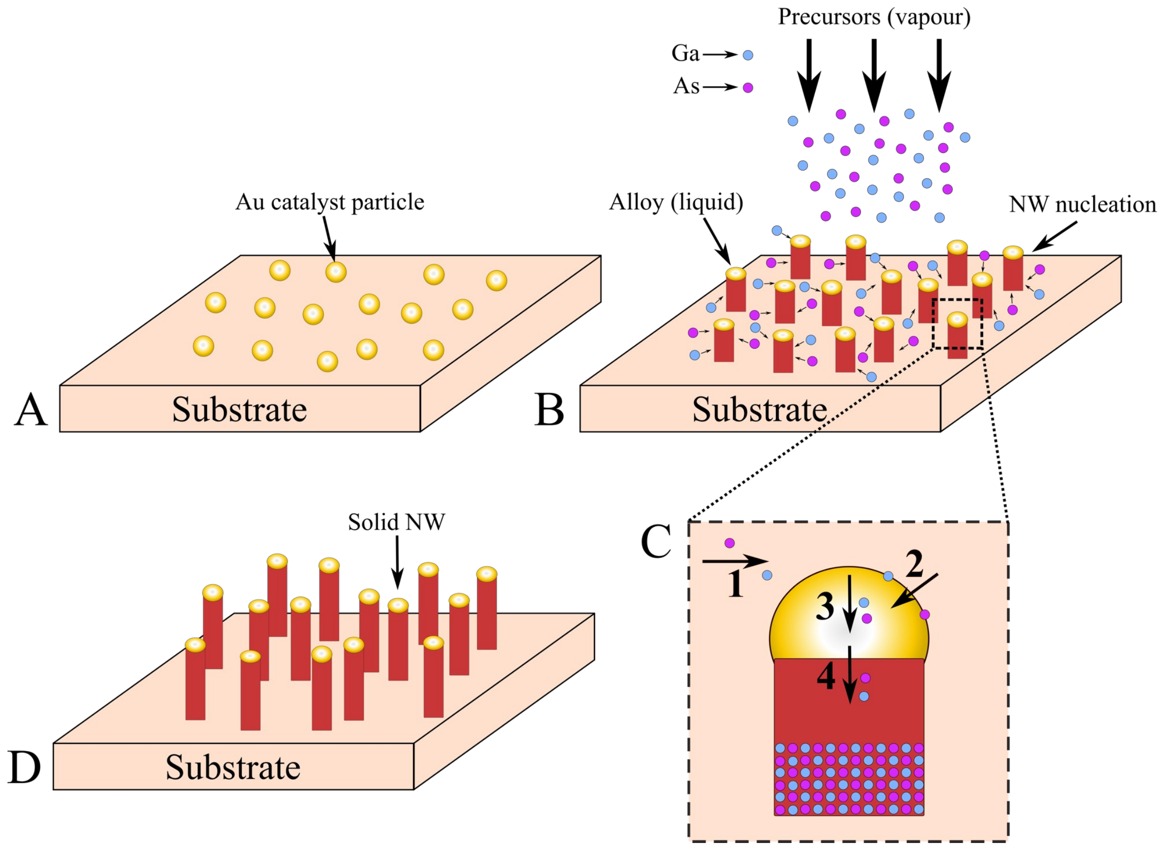
GreEnergy Workshop "Wideband optical antennae for use in energy harvesting applications"

OUTLINE

- Background
  - Nanowires
  - 2D materials
  - Hybrid mixed-dimensional materials
- InP nanowires grown on MoS_2
- MoS_2 transferred on nanowire
- MoS_2-on-nanowire photodetector
- Summary

NANOWIRES

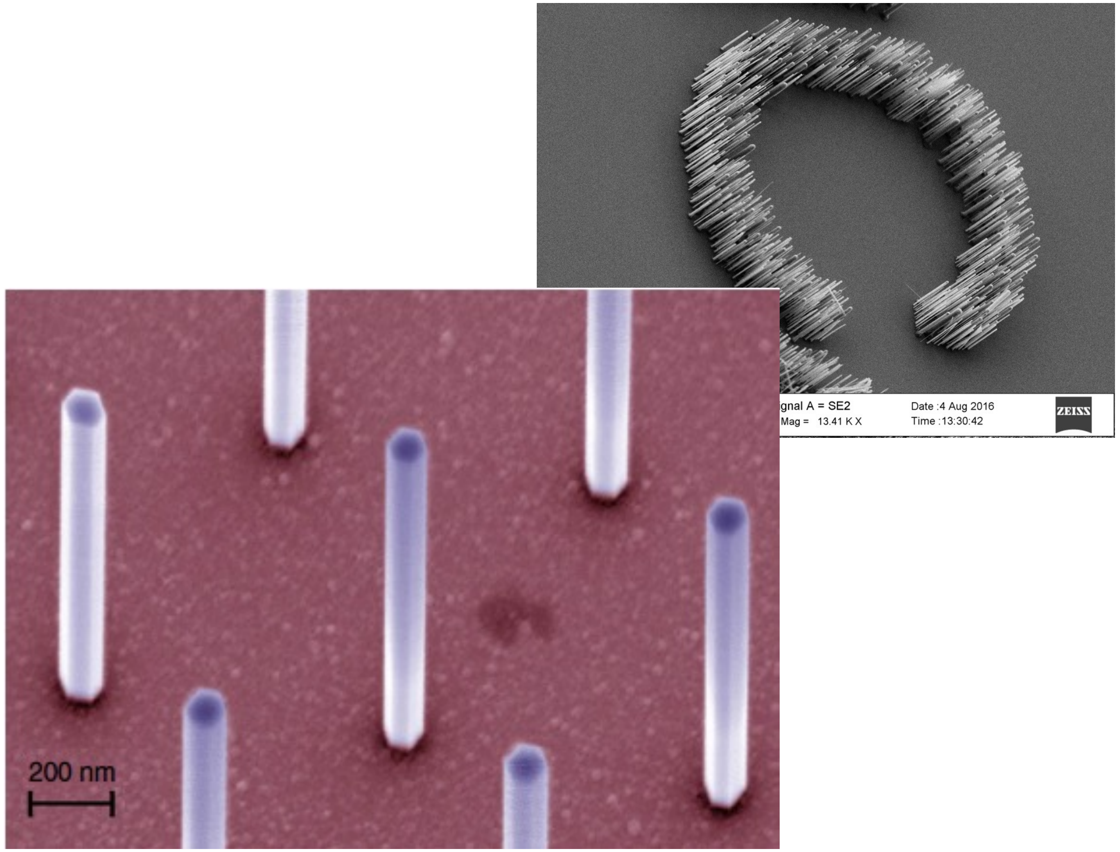
- VLS growth uses metal catalytic particles (mostly gold)
- Involves 3 phases: vapor-phase precursor, catalytic liquid alloy and solid crystal
- Includes (1) mass transport from the vapor phase (2) precursor molecule decomposition at vapor–liquid interface (3) atom diffusion in the liquid phase and (4) atom incorporation in a crystal



Schematic illustration of the vapor–liquid–solid (VLS) mechanism.

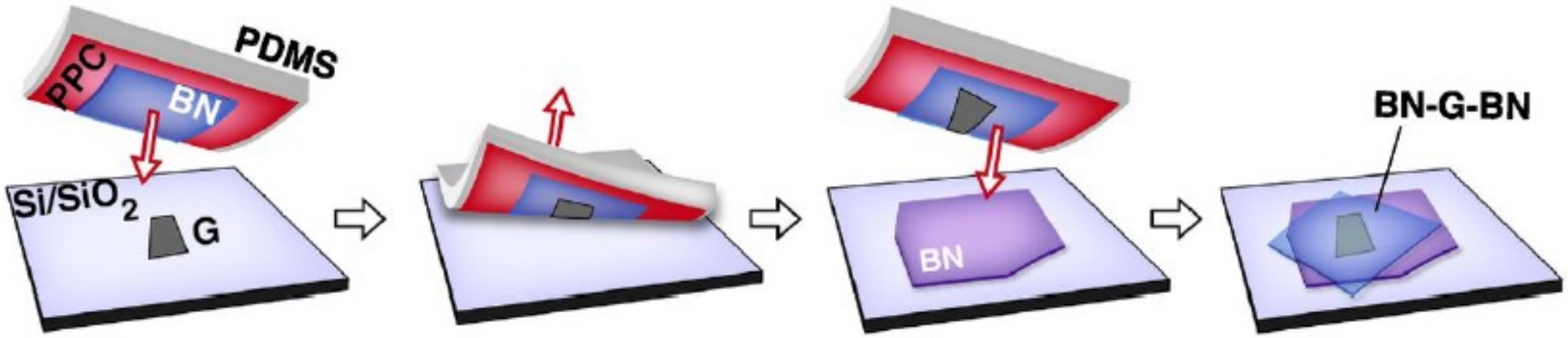
About nanowires

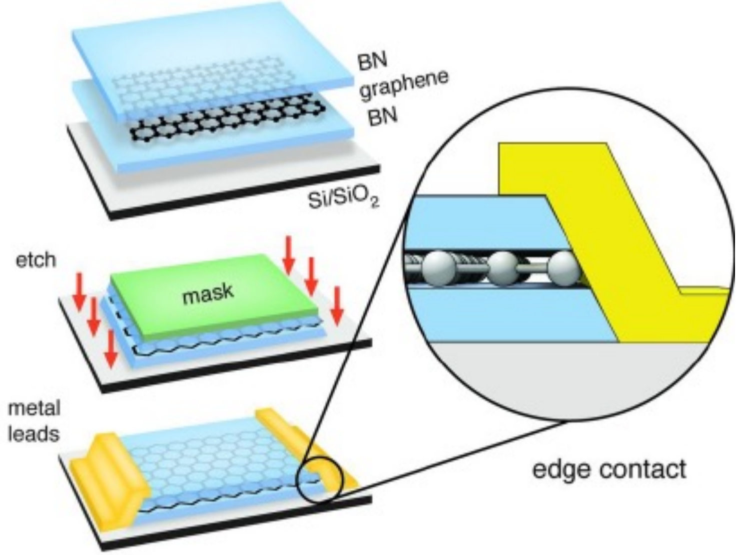
- One-dimensional nanostructures
- D < 100nm, L = 100nm - 20µm
- Extremely high surface-to-volume ratio
- Group III–V compound semiconductor materials, here InP and AlGaAs NWs
- Grown by MOCVD
- Unique properties

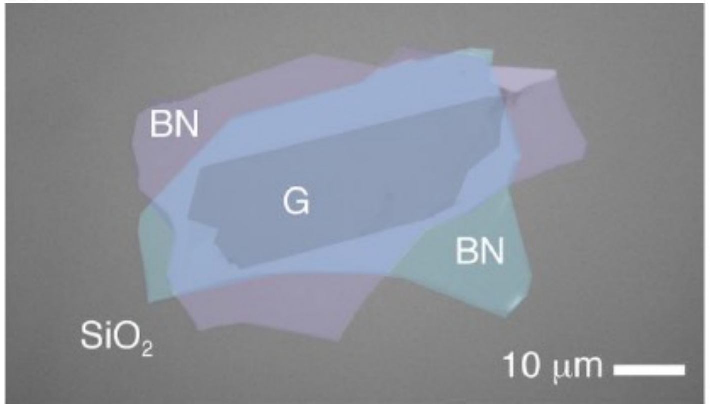


GaAs nanowires on GaAs substrate

2D materials: Pick-up technique for multilayer stacking







Encapsulated graphene in hBN
-> very high carrier mobility

L. Wang *et al.*, Science **342**, 614 (2013)

2D materials

- Transition metals dichalcogenides (TMDCs)

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg	3	4	5	6	7	8	9	10	11	12	Al	Si	P	**S**	Cl	Ar
K	Ca	Sc	**Ti**	**V**	Cr	Mn	Fe	**Co**	**Ni**	Cu	Zn	Ga	Ge	As	**Se**	Br	Kr
Rb	Sr	Y	**Zr**	**Nb**	**Mo**	**Tc**	Ru	**Rh**	**Pd**	Ag	Cd	In	Sn	Sb	**Te**	I	Xe
Cs	Ba	La - Lu	**Hf**	**Ta**	**W**	**Re**	Os	**Ir**	**Pt**	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac - Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo

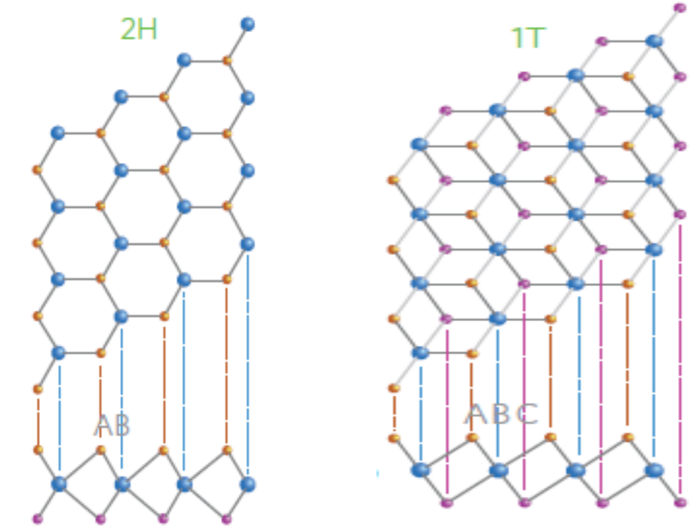
✓ Layered materials of atomically thickness (<1 nm)

✓ Clean and dangling bonds free surface

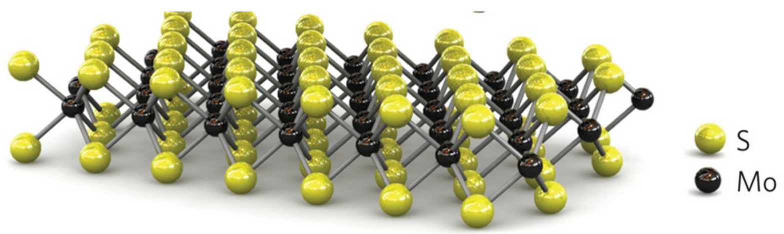
✓ Two phases (semiconducting and metallic)

✓ Grown by CVD or exfoliated from crystal

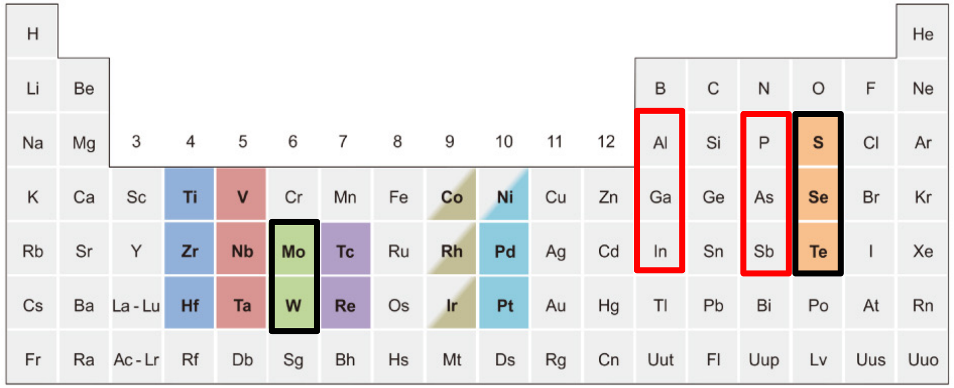
MoS_2, $MoSe_2$, $MoTe_2$



Semiconducting phase   Metallic phase



Hybrid 1D-2D materials



❑ Transition metals dichalcogenides (TMDCs)

MX_2
M = Metal (Mo, W, ….)
X = Chalcogen (S, Se & Te)
MoS_2, WSe_2, $MoTe_2$

- ✓ Layered materials of atomically thickness (<1 nm)
- ✓ Direct bandgap and strong spin–orbit coupling
- ✓ Two phases (Semiconducting and Metallic)

Nature, 550, 487–491(2017)

❑ III-V semiconductor nanowires (NW)

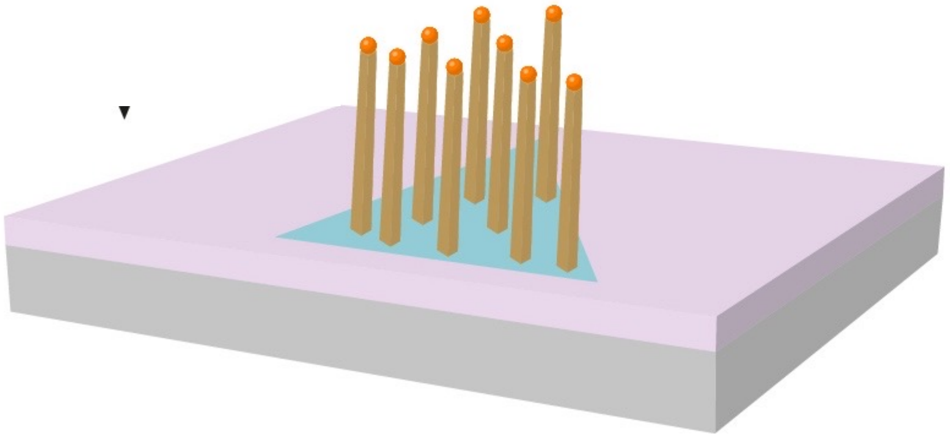
Group IIIA and VA
GaAs, InP, AlGaAs

- ✓ One dimensional nanostructures with simple and low-cost synthesis process
- ✓ Direct bandgap and strong light absorption
- ✓ High integration ability, and precise control in doping

ACS Appl. Mater. Interfaces, 14, 31140–31147 (2022)

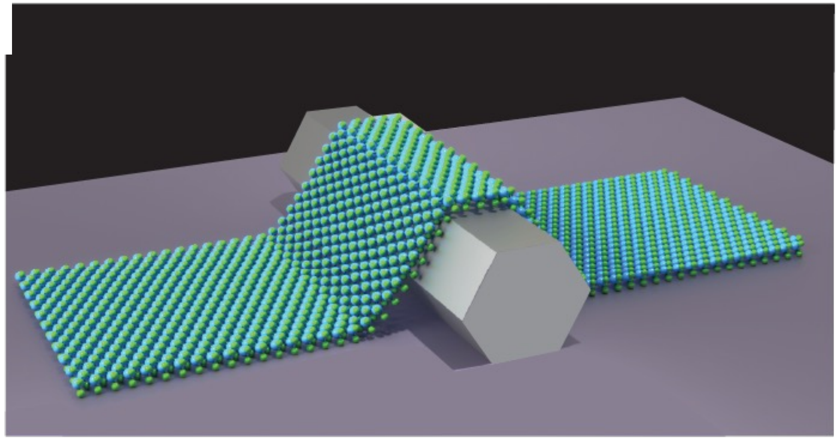
Studied MoS_2-NW heterostructures

- 2D-1D mixed dimensional heterostructures
- Proof-of-concept study



- Growing NWs on 2D materials for new photonic applications

Shafi et al., Chem. Mater. 34, 9055–9061 (2022)



- Transferring 2D materials on NWs for enhanced light matter interactions

Shafi et al., ACS Appl. Mater. Interfaces, 14, 31140–31147 (2022)

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- ❑ InP nanowires grown on MoS_2
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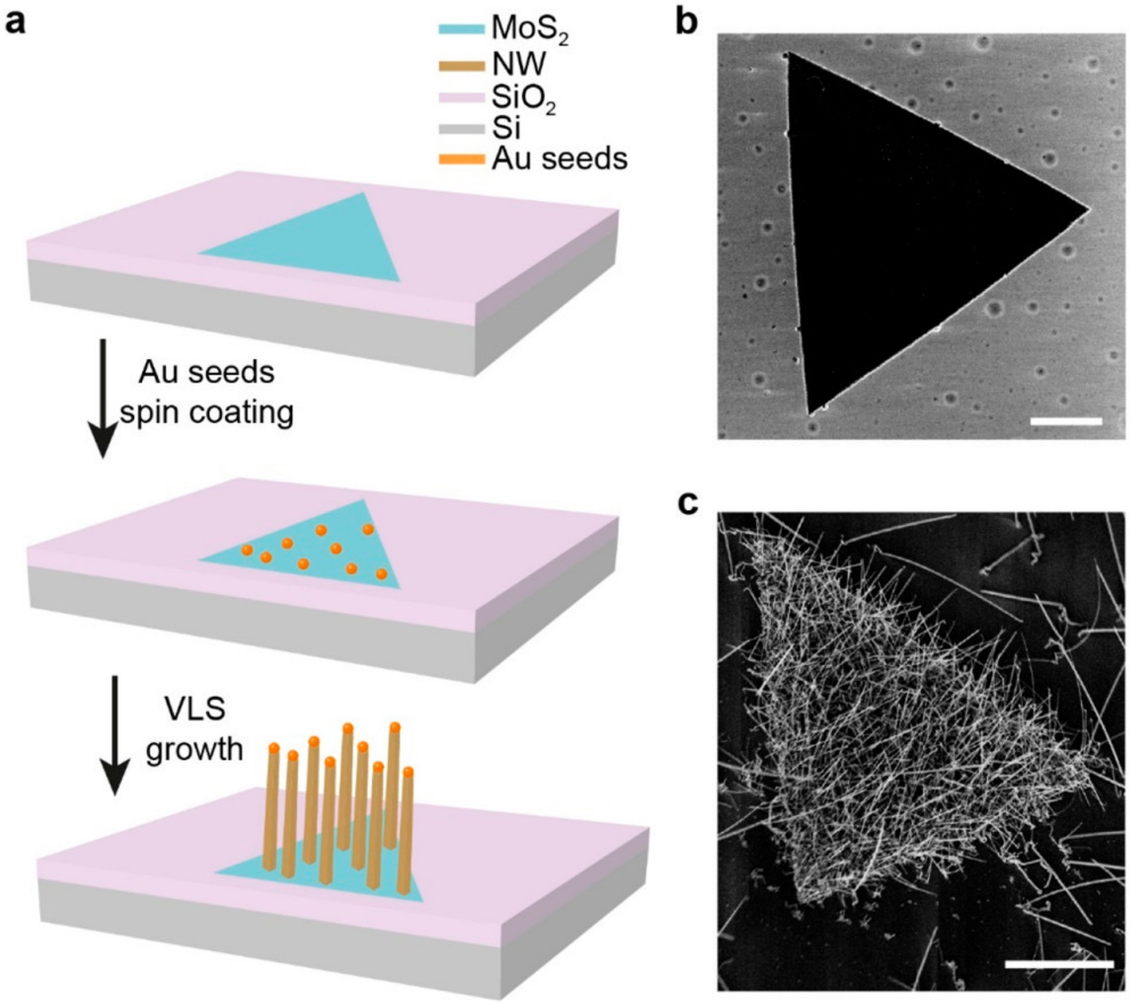
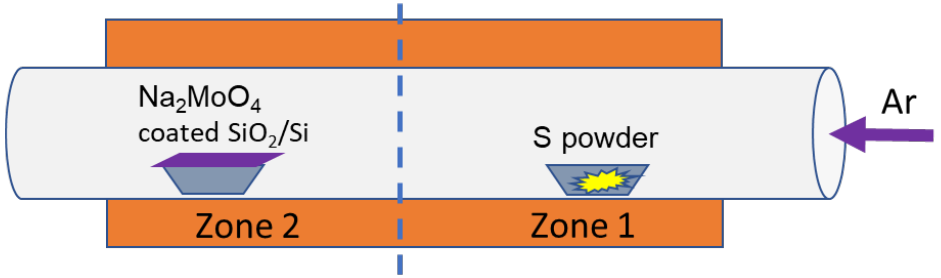
- ❑ MoS_2-on-nanowire photodetector
- ❑ Summary

InP nanowires grown on CVD MoS_2 flakes



MoS_2 flakes grown on SiO_2/Si wafer



Schematic of a dual zone salt-assisted CVD system for growing MoS_2 flakes. Na_2MoO_4 and S powder precursors are used for growing mono- and few-layers of MoS_2. Size 10 - 100 μm.

InP nanowires grown on CVD MoS_2 flakes

Choice of materials:

- InP is a direct bandgap material with very low surface recombination velocity and excellent optical quality.
- MoS_2 is a well-studied TMDC because of having a direct bandgap in monolayers, large excitonic binding energy, strong luminescence emission, and high carrier mobility.

=> Combination is fascinating for many photonic applications.

Challenges in maintaining the material quality during fabrication.

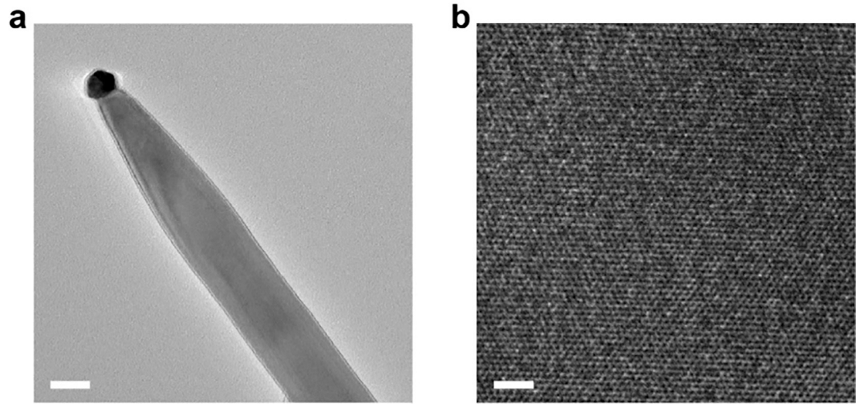
Chem. Mater. 34, 9055–9061 (2022)

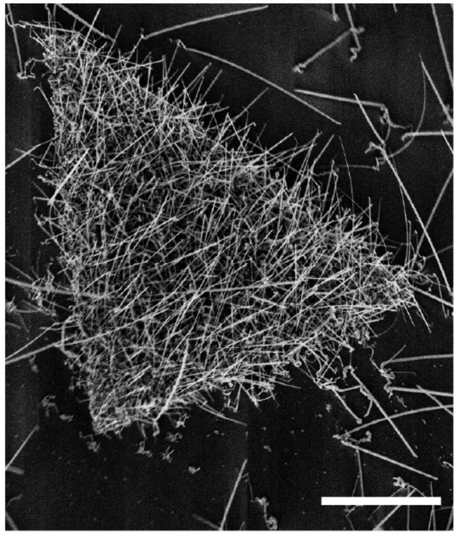
Growth of 1D-2D heterostructures

❑Growth of InP NWs on 2D MoS_2

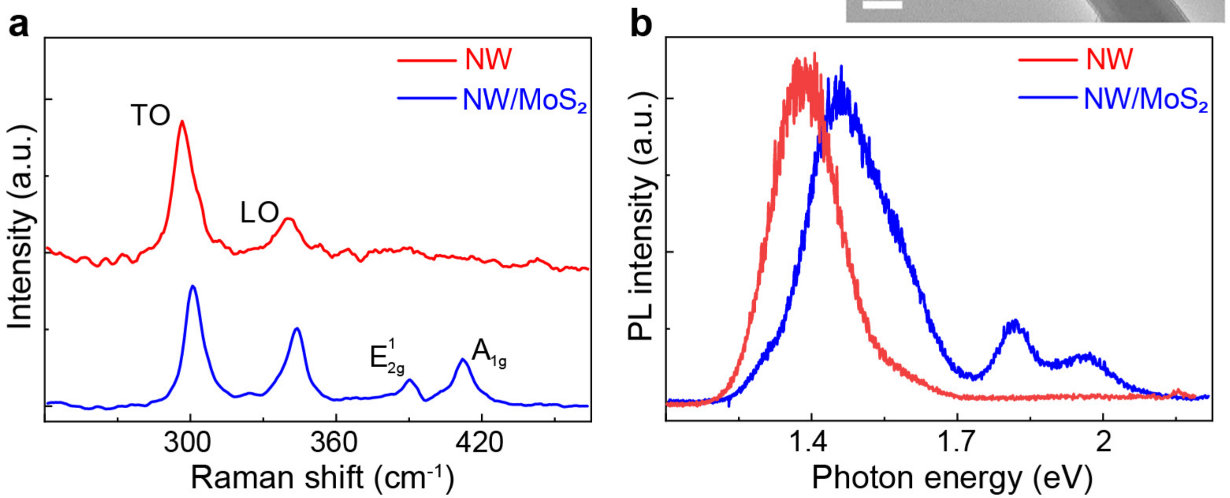
MOCVD growth of nanowires may cause defects to MoS_2

- ➢ Study of hybrid materials by Raman, XPS and PL





confocal micro-Raman system (WITec alpha300 RA+), backscattering geom.



ref. NW
diam. 63 nm

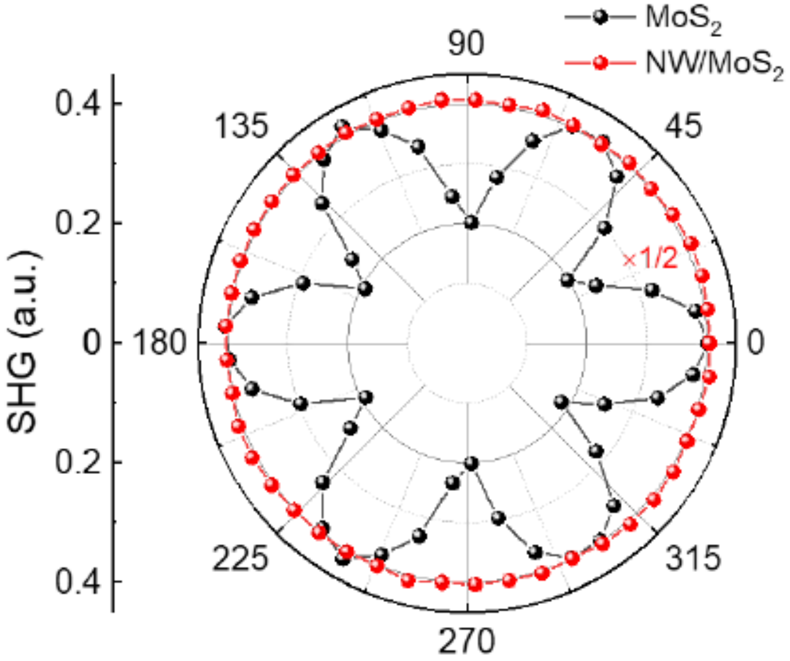
NW/MoS_2
diam. 20-30 nm

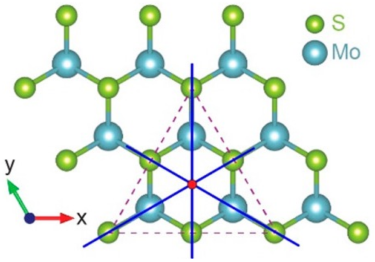
- ➢ Low temperature growth of InP nanowires at 430°C on MoS_2
- ➢ Good optical response from the heterostructure. Blueshift in PL due to NW size.

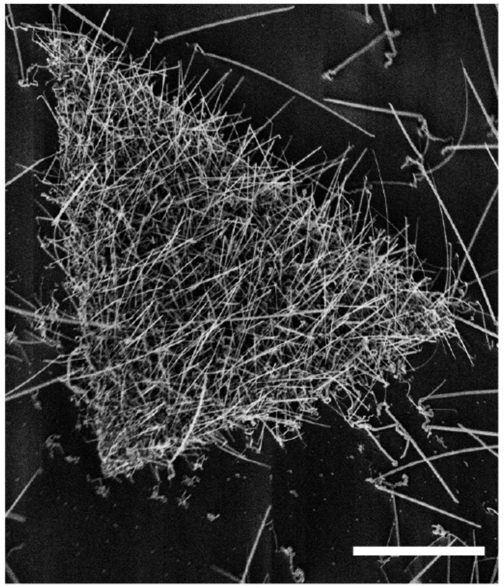
Chem. Mater. 34, 9055–9061 (2022)

Nonlinear response from InP/MoS_2 heterostructures

❑Polarization-dependent SHG





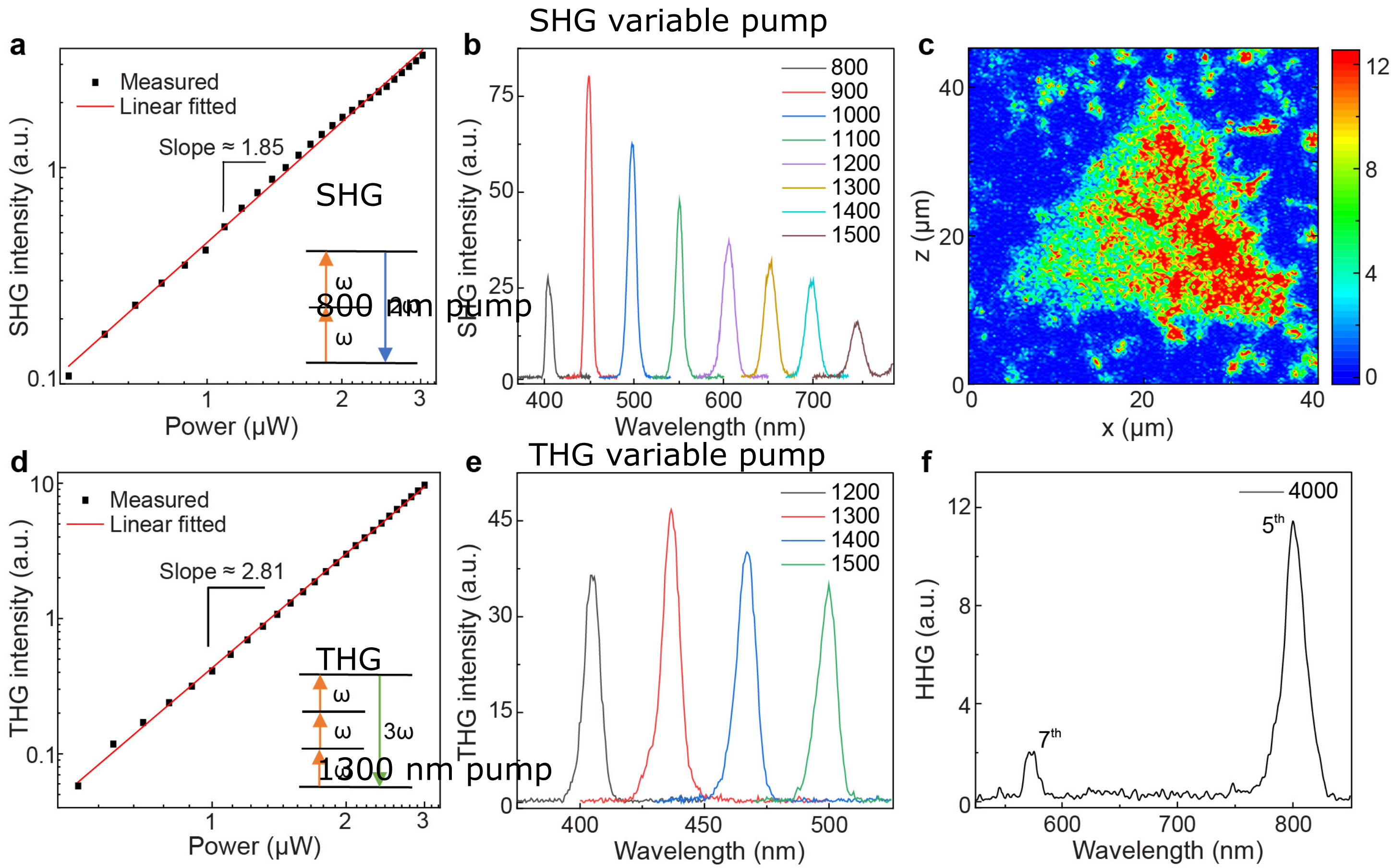


Polarization-dependent SHG from MoS_2 and NW/MoS_2 under parallel polarization configuration with an excitation of 800 nm.

- Bare MoS_2 shows a 6-fold SHG pattern, whereas the SHG from the heterostructure is independent of the pump polarization due to the random growth directions of the NW on MoS_2. The intensity of the heterostructure signals is 2x compared to bare MoS_2.

Nonlinear response from InP/MoS_2 heterostructures

Pump: ultrafast femtosecond laser Spectra-Physics TOPAS, pulse width ~230 fs, rate 2 kHz



SHG mapping

HHG
5th and 7th
4000 nm pump

even-order HHG from MoS_2 too weak to observe

- ➢ Strong 2nd and 3rd harmonic responses from the heterostructures
- Heterostructures also show odd-order (up to 7th) harmonic signals

Chem. Mater. 34, 9053–9061 (2022)

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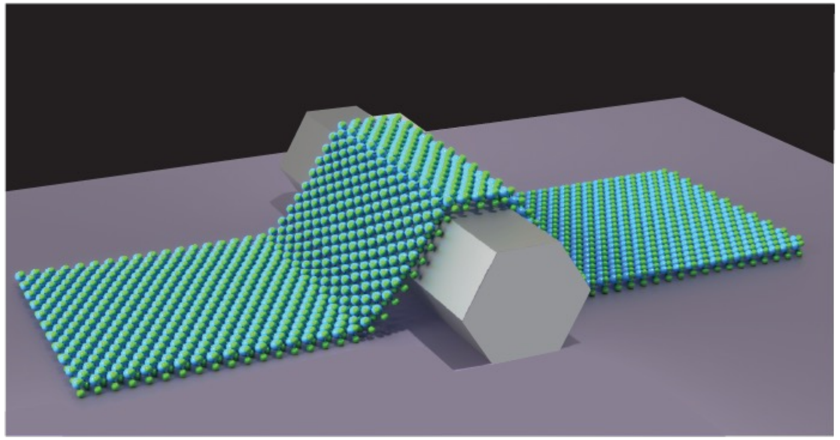
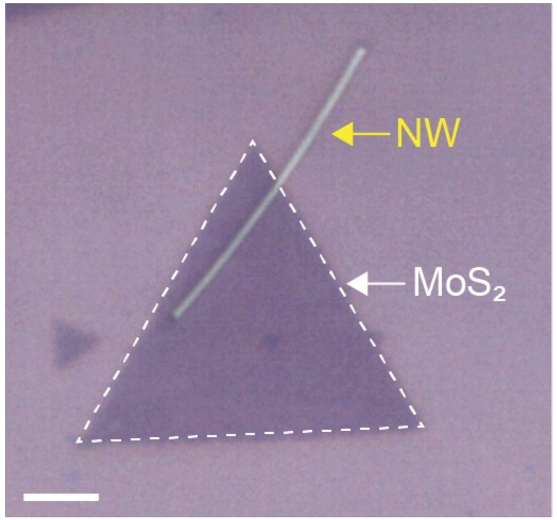
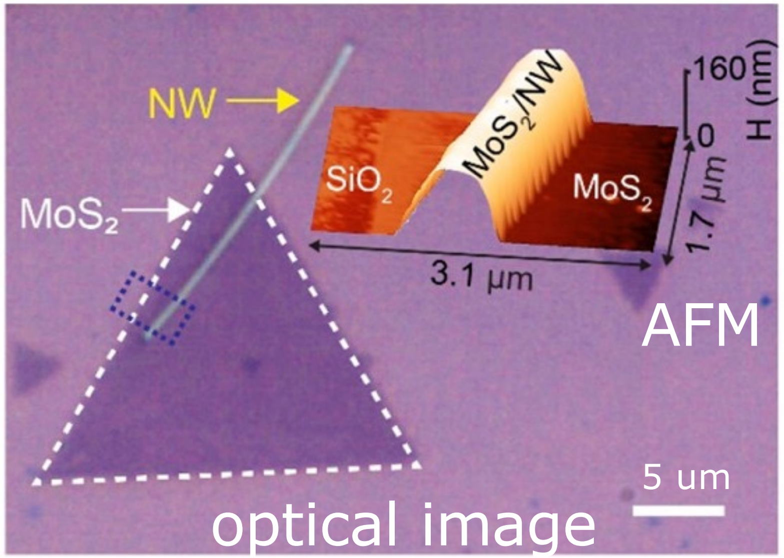
MoS_2 on AlGaAs nanowire



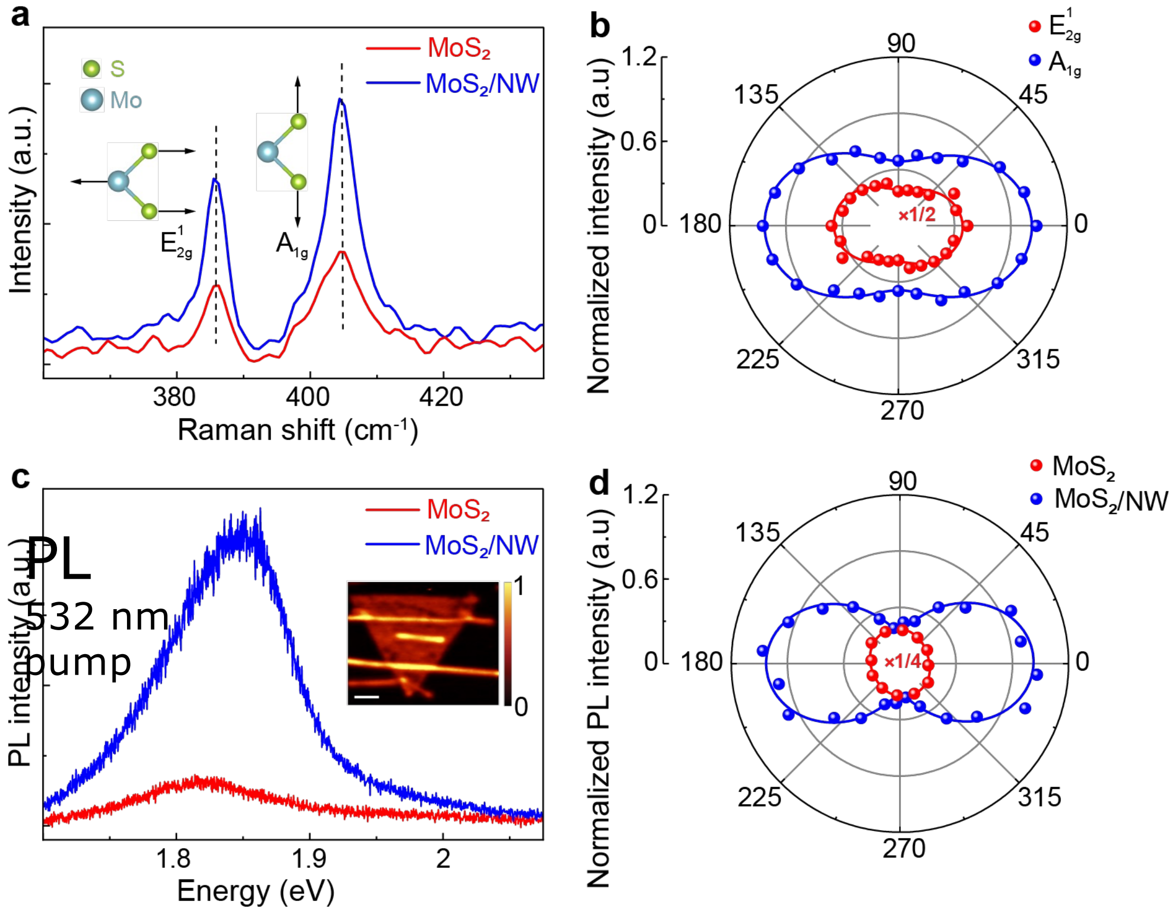


Monolayer and few layer MoS_2 crystals are grown on SiO_2/Si substrate using a salt-assisted CVD method. After a wet transfer process, the as-grown monolayer MoS_2 flakes are transferred onto the substrate where VLS grown AlGaAs nanowires are nanocombed.

Enhanced light matter coupling and anisotropy



AFM: NW diam. 80 – 140 nm



- Raman responses enhanced by 3 times with a ~35% anisotropy.
- PL enhances by 9 times with a 60% anisotropy.

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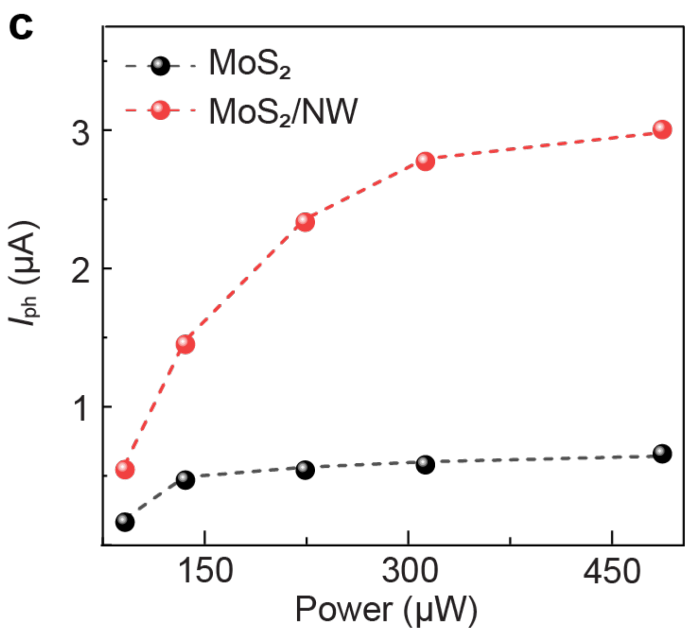
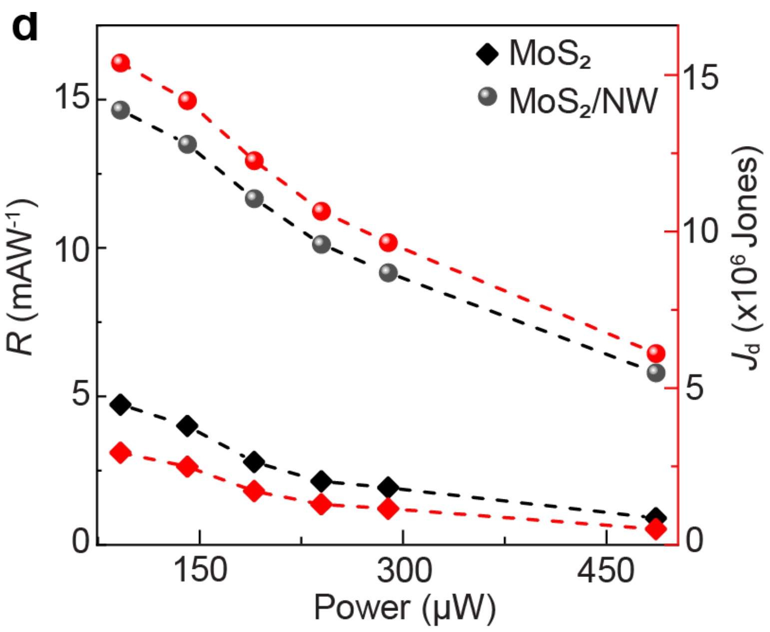
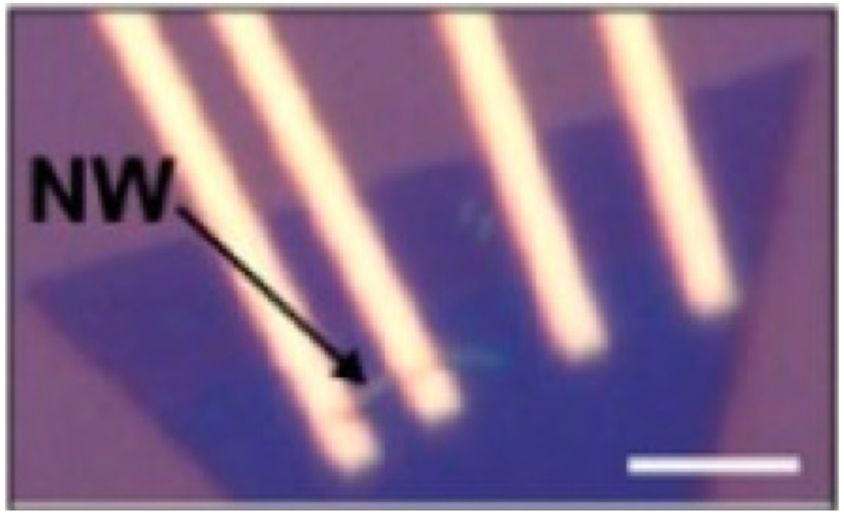
MoS_2/NW-heterostructure-based photodetector

Photoresponse from MoS_2/NW FET as compared to bare MoS_2





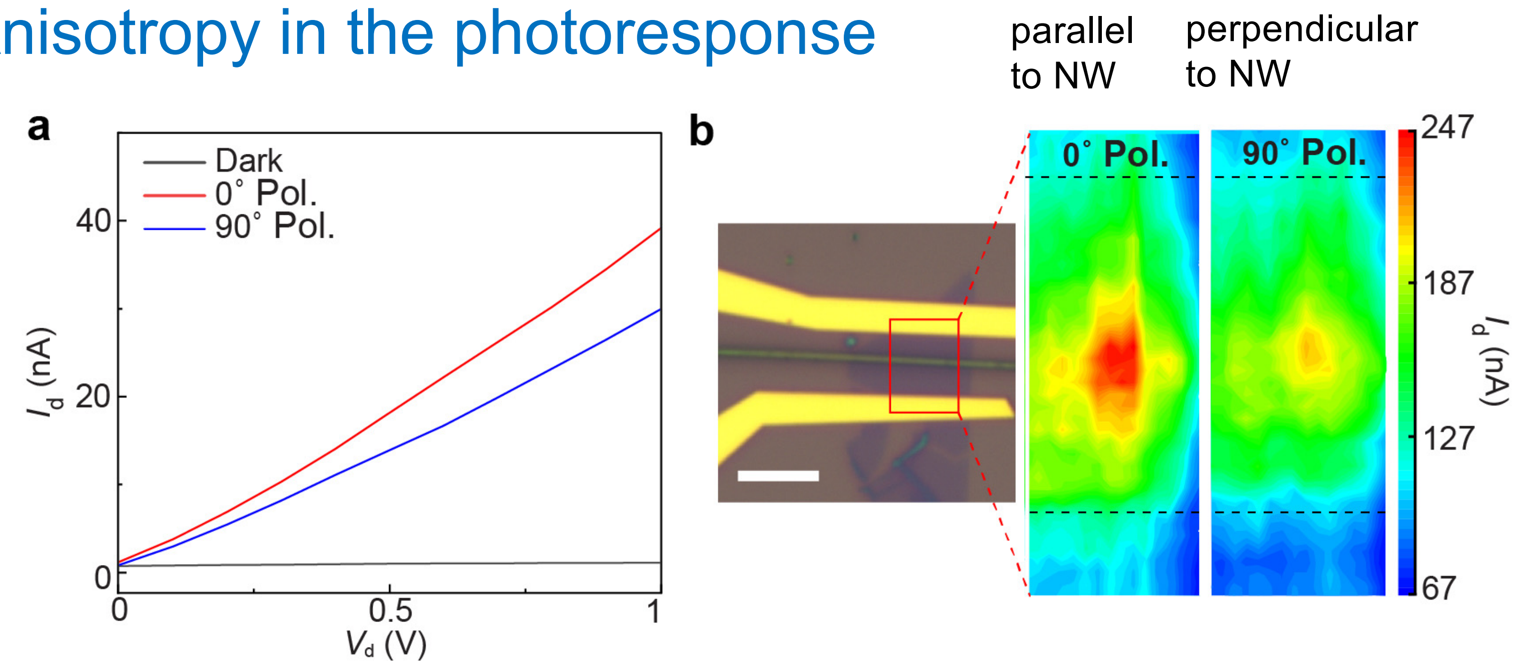


- Electron beam lithography and metallization were performed to realize Ti/Au (5/50 nm) electrodes

- MoS_2/NW shows 5 times enhanced photocurrent than bare MoS_2
- Responsivity and detectivity enhanced by 3 and 5 times, respectively

MoS_2/NW-heterostructure-based photodetector

❑ Anisotropy in the photoresponse



Anisotropy in the photoresponse of the mixed-dimensional MoS_2/NW heterostructure.

(a) Comparison of the *Id* of the MoS_2/NW device under dark conditions and under illumination of two different excitation polarizations. V_g = 10 V.

(b) Optical image of the device where the red rectangular box indicates the area of the photocurrent scan. Scale bar: 5 µm. The corresponding photocurrent maps with 0° and 90° excitation polarizations are shown on the right panel.

➢ Noticeable anisotropy in the photoresponse from MoS_2/NW

Summary

- Epitaxial growth of InP nanowires directly on MoS_2 demonstrated, forming high-quality hybrid 2D-1D material. Strong linear and nonlinear optical responses from the hybrid heterostructures are observed.

- Enhanced Raman and PL of MoS_2 are also observed from transferred MoS_2-on-NW heterostructures.

- The mixed-dimensional photodetectors offer improved device performance with polarization sensitivity.

- These proof-of-concept results may pave way to practical devices if more industrial-level fabrication is developed.

Thank you!

GreEnergy
Power from optical antennas

www.greenergy-project.eu
www.linkedin.com/company/greenergy-project

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