Flexible Electronics with 2D Materials

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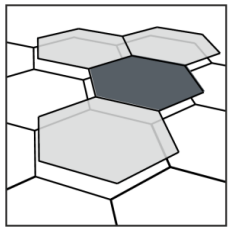
April 27, 2023

AMO GmbH

Introduction to AMO GmbH



Aachen Graphene & 2D-Materials Center

www.graphene.ac

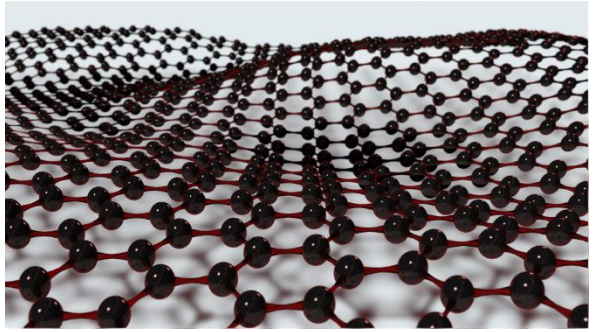
- Key facts:
  - Non-profit SME
  - Founded in 1993
  - 400m^2 cleanroom
  - > 60 staff members
  - > 40 funded R&D projects
  - > 150 R&D partners
- Key technologies:
  - Nanofabrication
  - Silicon Technology base
  - New materials integration
    - High-k/metal gate
    - Plasmonics
    - Graphene & 2D materials
    - Perovskites
  - Applications
    - Nanoelectronics
    - Integrated sensors
    - Nanophotonics
    - Neuromorphic computing
      → **Talk by Stephan Suckow, Friday, Session 9 @ 15:35**

AMO Infrastructure

- Lithography
  - Electron beam lithography
  - Optical lithography (6'' i-line stepper, mask aligner)
  - Interference lithography
  - Nanoimprint lithography
- Pattern transfer by ICP/RIE
  - Anisotropic profiles, smooth surfaces
  - Flexible chemistry (F, Cl, Br…)
- Deposition
  - LPCVD Si_3N_4, SiO_2
  - PE-ALD Al_2O_3, TiO_2, AlN, TaN, TiN
  - PECVD for 2D-materials (S, Se, Te)
  - CVD for Graphene
  - Metal evaporation (Al, Ti, Pd, Pt, Ni, Cr, Co)
  - Metal sputtering (…)
- Wet processing
- Metrology
  - Raman spectrometer (vacuum)
  - Photoluminescence
  - DC and RF-Measurements (vacuum, cryogenic)
  - SEM
  - AFM
  - THz conductivity (→ *Protemics*)
  - Transient recording (→ *AMOtronics*)

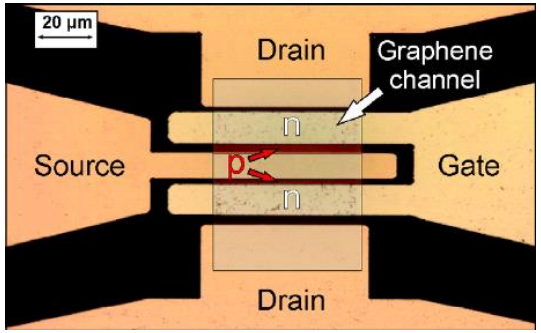
Current Interest

2D Materials



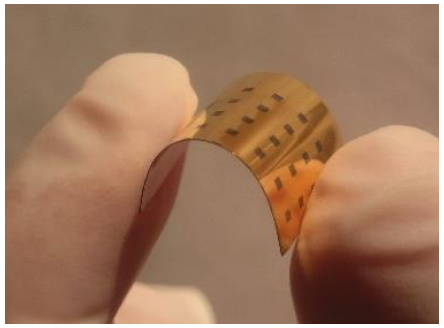
2D material growth & integration

Graphene Electronics



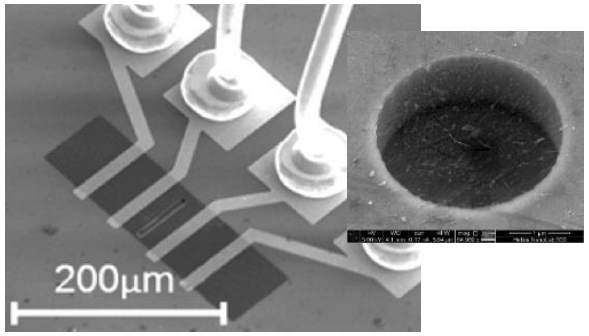
Graphene-based RF circuits/components

Flexible Electronics



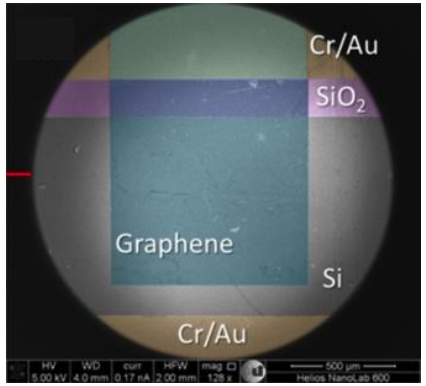
Flexible photodetectors

MEMS/NEMS



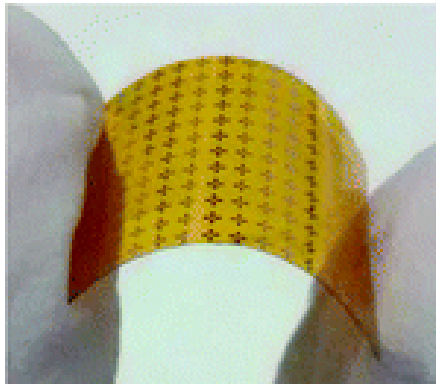
Pressure & strain sensors

Optoelectronics



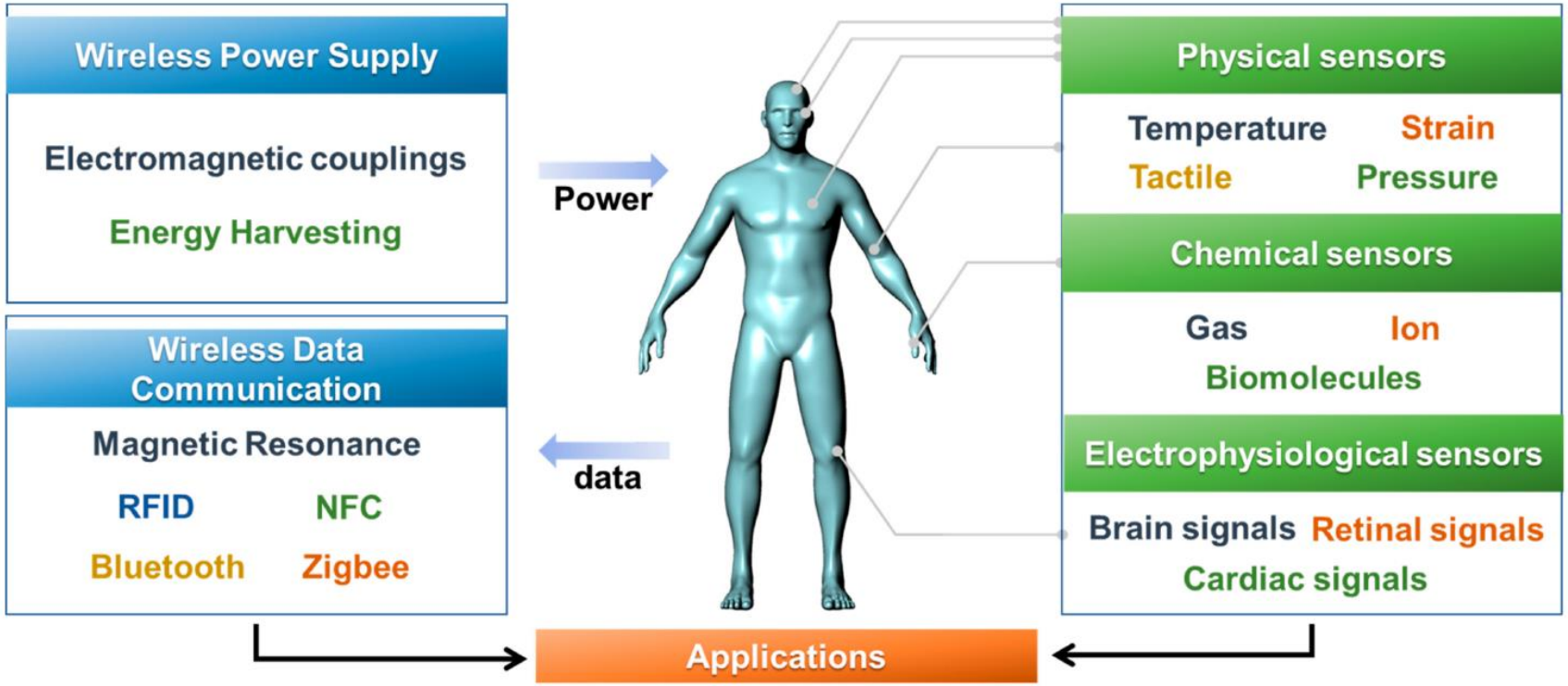
Graphene-based photodetectors

Sensors



Flexible Hall sensors

Wearable System Requirements



- Communication circuitry
- Self-powering
- Flexible
- Sensing functionality
- Scalable

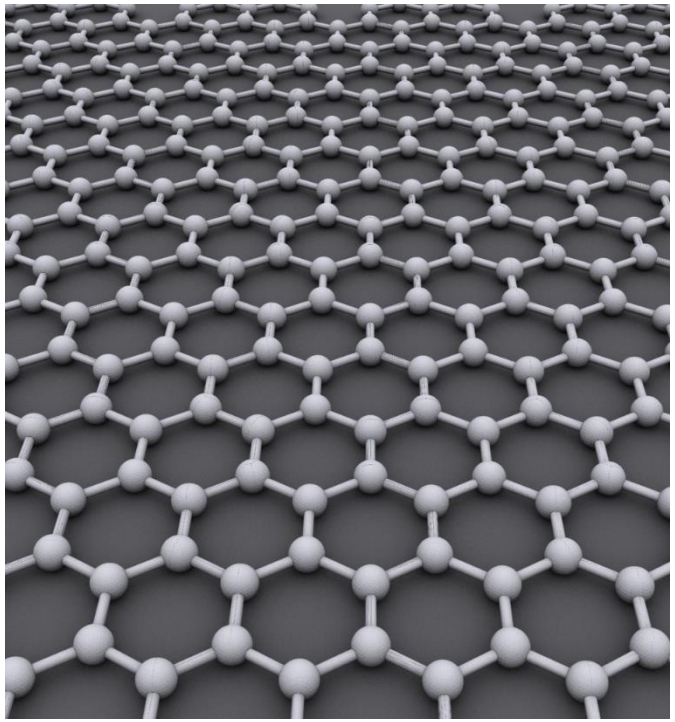
***Sensors*, 19, 4353 (2019)**

Materials for Flexible Electronics

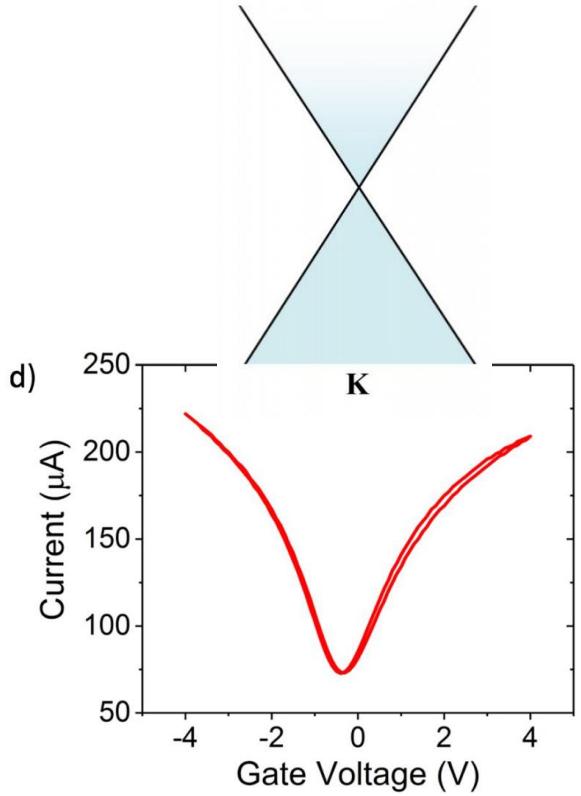
- Thinned Si
- Metal oxides
- Polymers
- …

→ **Graphene (& other 2D materials: hBN, MoS_2, WSe_2, $PtSe_2$, ...)**

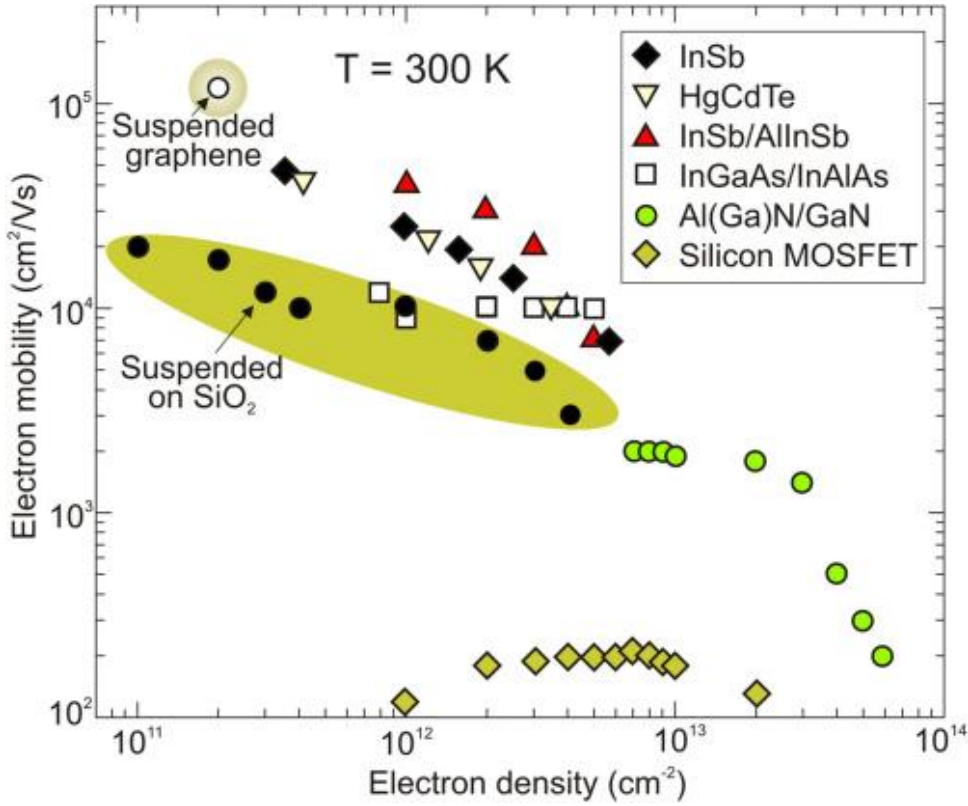
2-dimensional, flexible



semi-metal, no bandgap

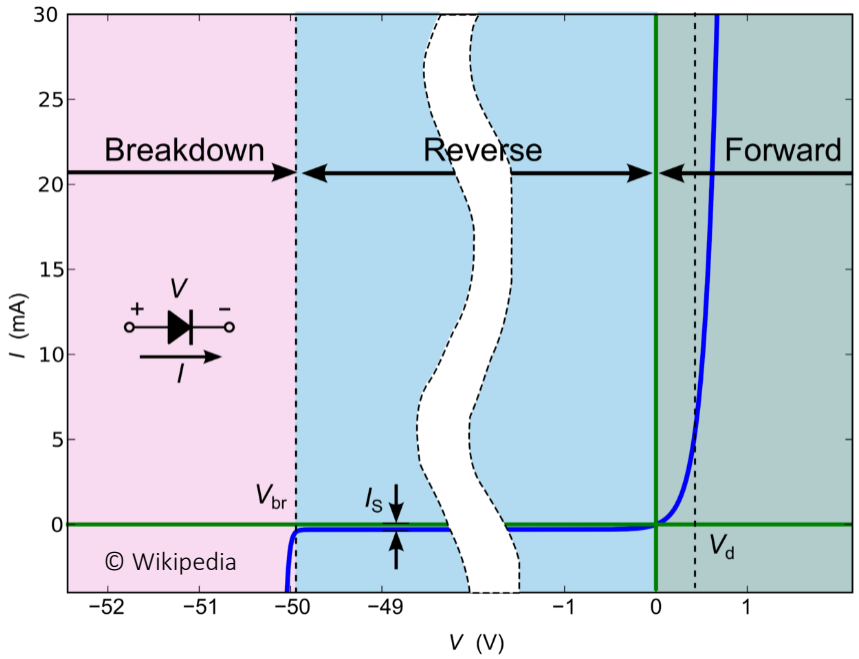


huge mobility



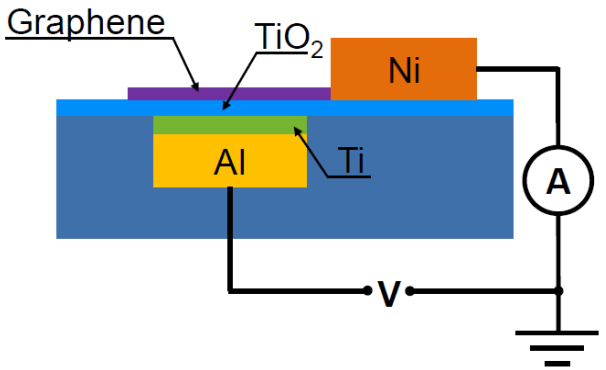
***Nanoscale*, 9, 11944 (2017)**
Adv. in Optics and Photonics, 11, 2, 314-379 (2019)

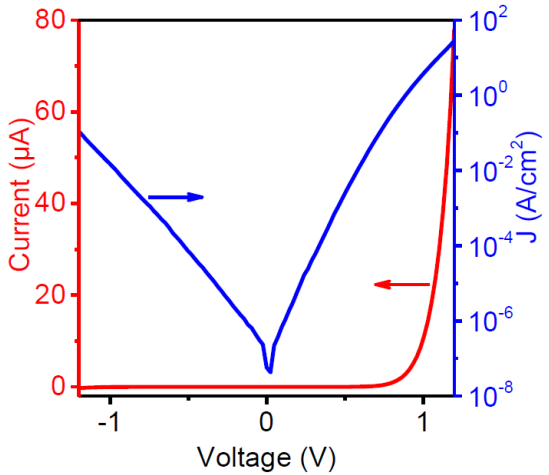
Diodes



- Radio demodulation
- Power conversion
- Over-voltage protection
- Logic gates
- Ionizing radiation detectors
- Temperature measurements
- …

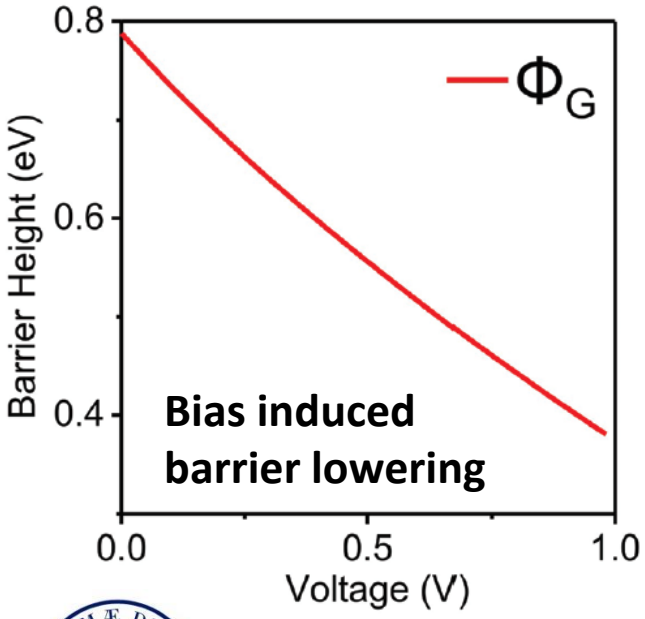
	Frequency response	DC performance	Thin-film processing
p-n junction	✗	✓	✗
Schottky	●	✓	✗
MIM	✓	✗	✓
MIG	✓	✓	✓

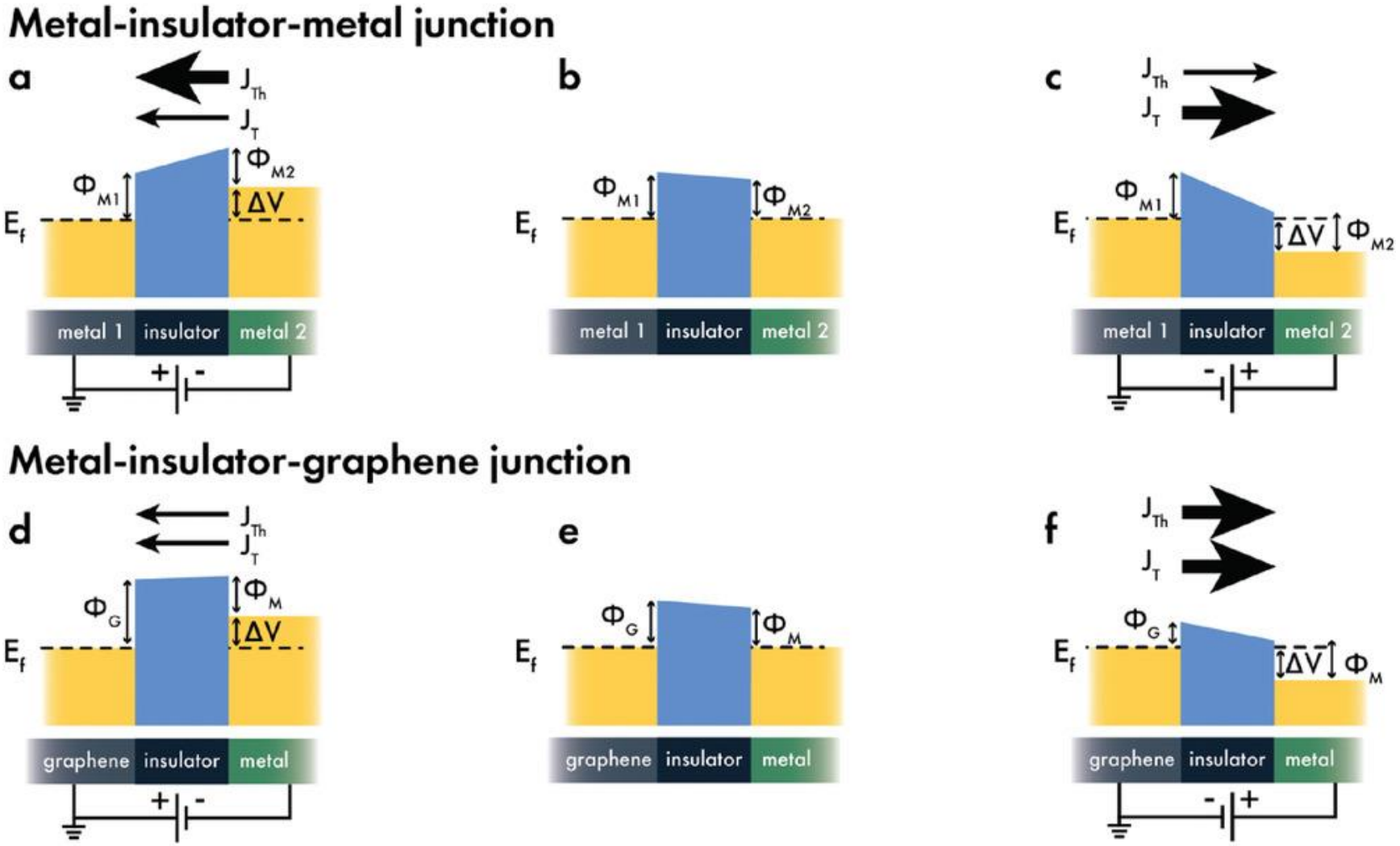




***Advanced Materials*, 25, 1301 (2013)**
***Proc. IEEE*, 102, 1667 (2014)**
***IEEE Trans. Electron Dev.*, 58, 3519 (2011)**

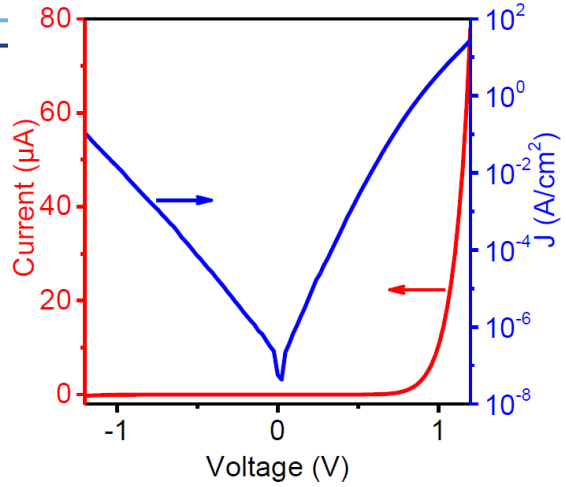
Metal-Insulator-Graphene Diodes

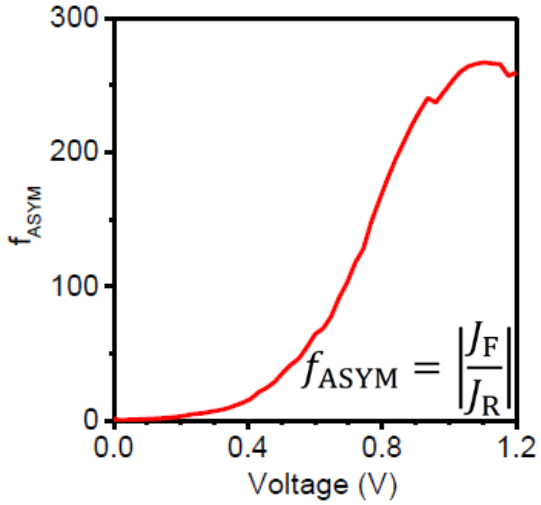


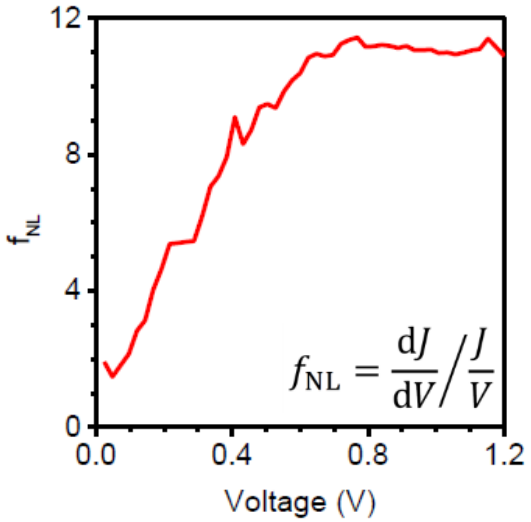


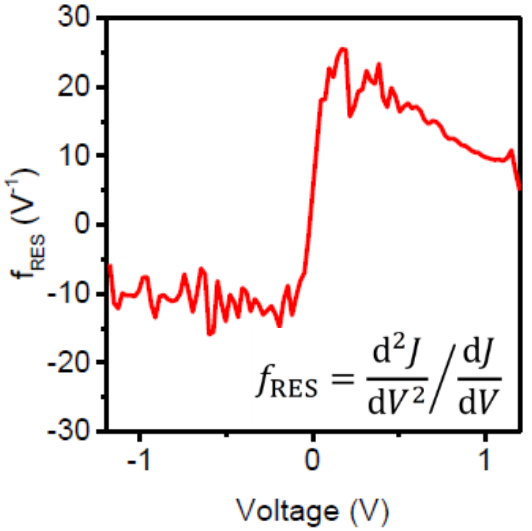
***Adv. Electronic Materials*, 2, 1600223 (2016)**
***Nanoscale*, 9, 11944 (2017)**

Metal-Insulator-Graphene Diodes





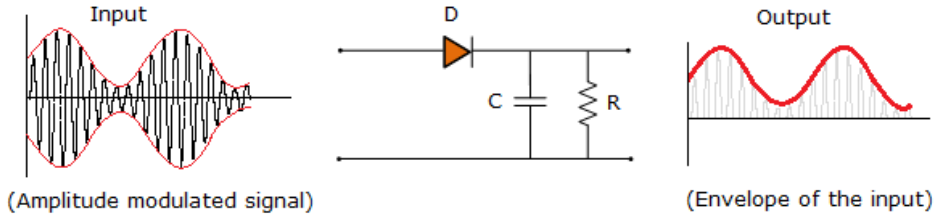




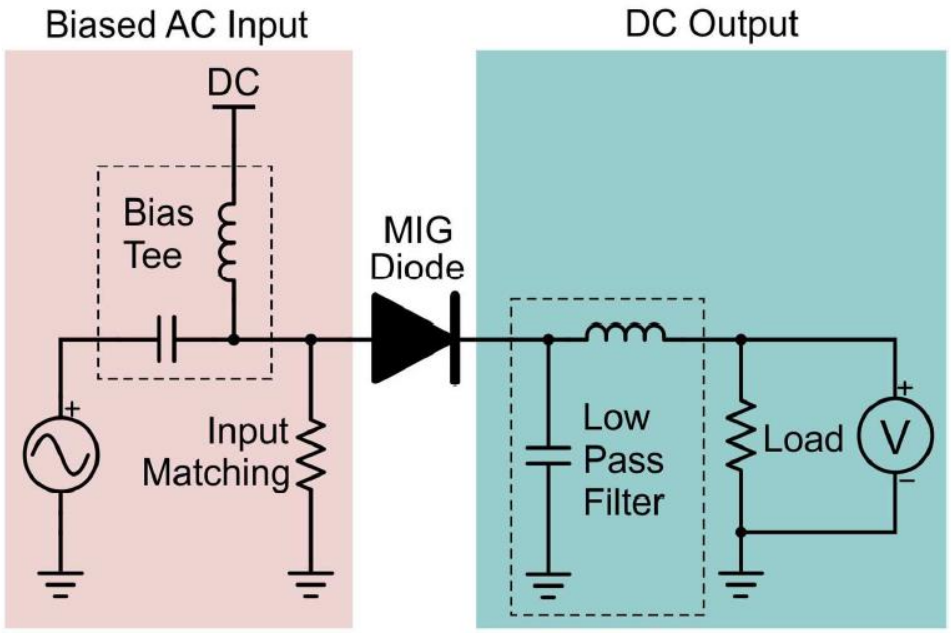
stack	J_{on} [A/cm^2]	f_{ASYM}	f_{NL}	f_{RES} [V^{-1}]
Nb/5nm Nb_2O_5/Pt	2.0	9.8	8.2	16.9
Nb/15nm Nb_2O_5/Pt	N/A	1500	4	20
Ti/TiO_2/bilayer graphene	0.1	9000	8	10
Ti/TiO_2/graphene (average/maximum)	**3.8 (7.5)**	**320 (520)**	**12 (15)**	**24 (26)**

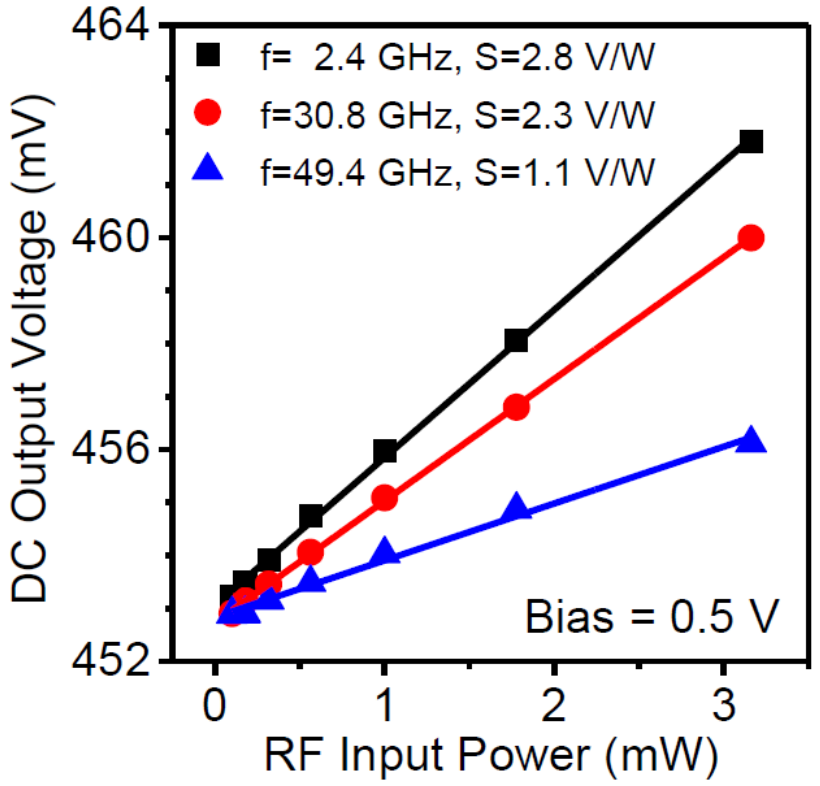
***J. Vac. Sci. Technol. B*, 31, 051204-1 (2013)**
***Advanced Materials*, 23, 3080 (2011)**
***Adv. Electronic Materials*, 2, 1600223 (2016)**
***Nanoscale*, 9, 11944 (2017)**

MIG Diodes in RF Applications



Diode for Demodulation





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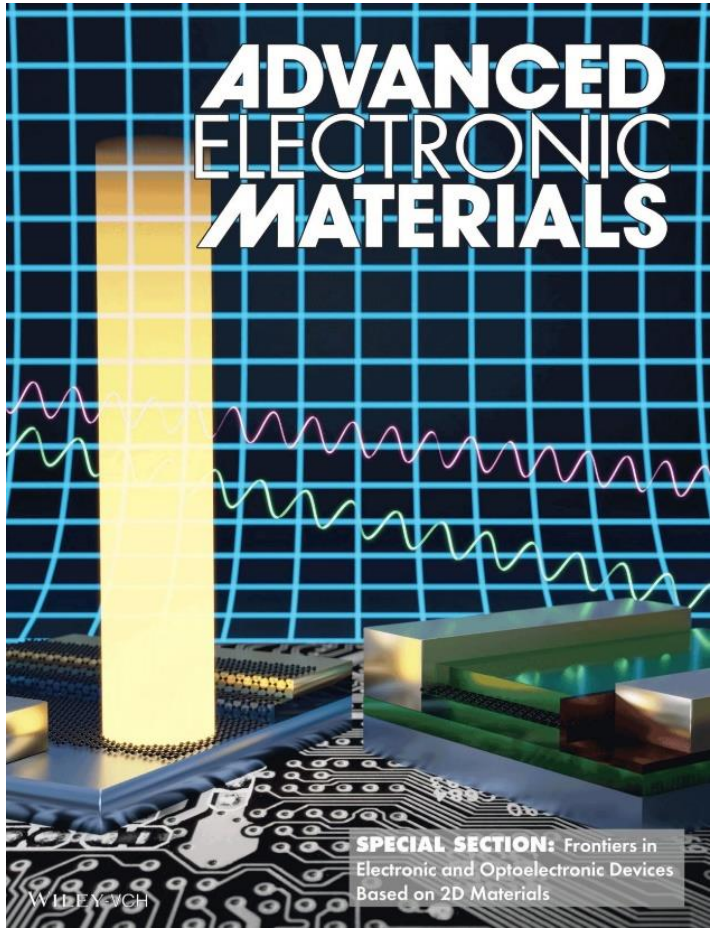
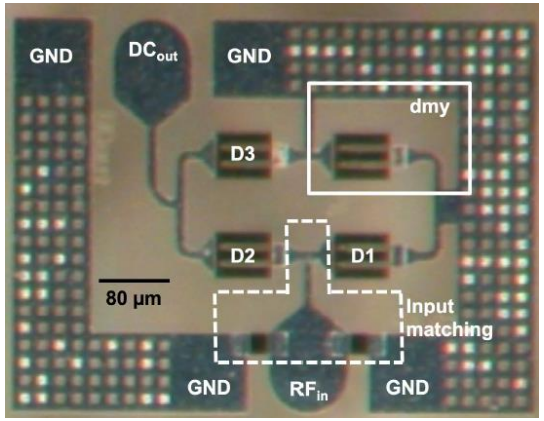
***IEEE Electron Device Letters*, 40, 1005 (2019)**
***Nanoscale*, 9, 11944 (2017)**

Circuit Examples

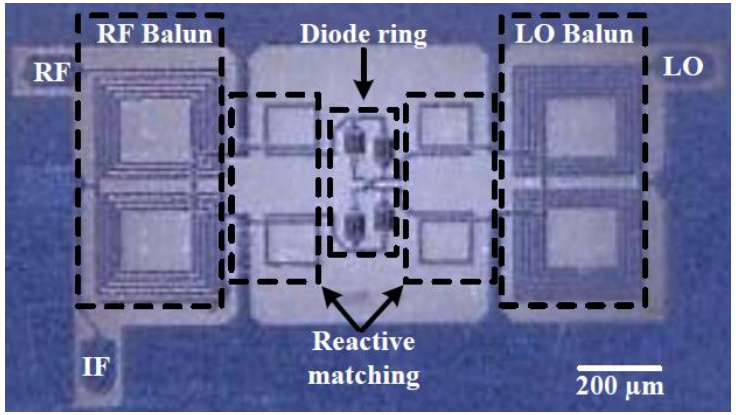


***Adv. Electronic Materials*, 7, 2001210 (2021)**

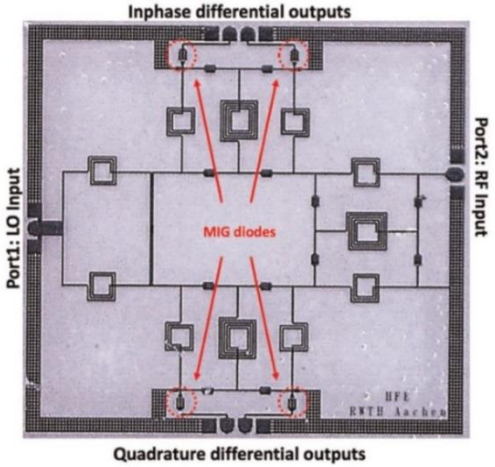
V-Band power detector



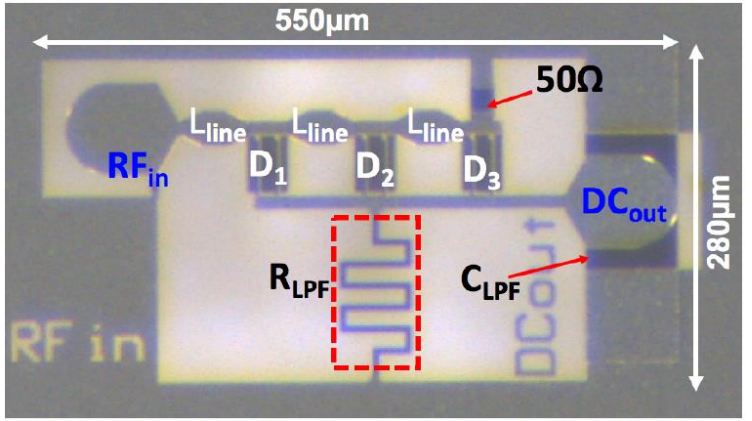
Double-Balanced Upconversion Mixer



Six-port receiver: QPSK at 2.4GHz

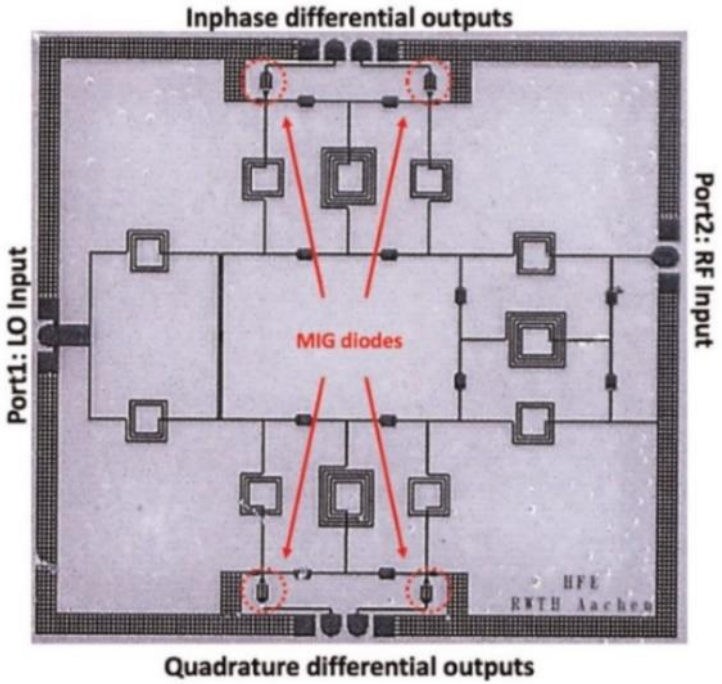


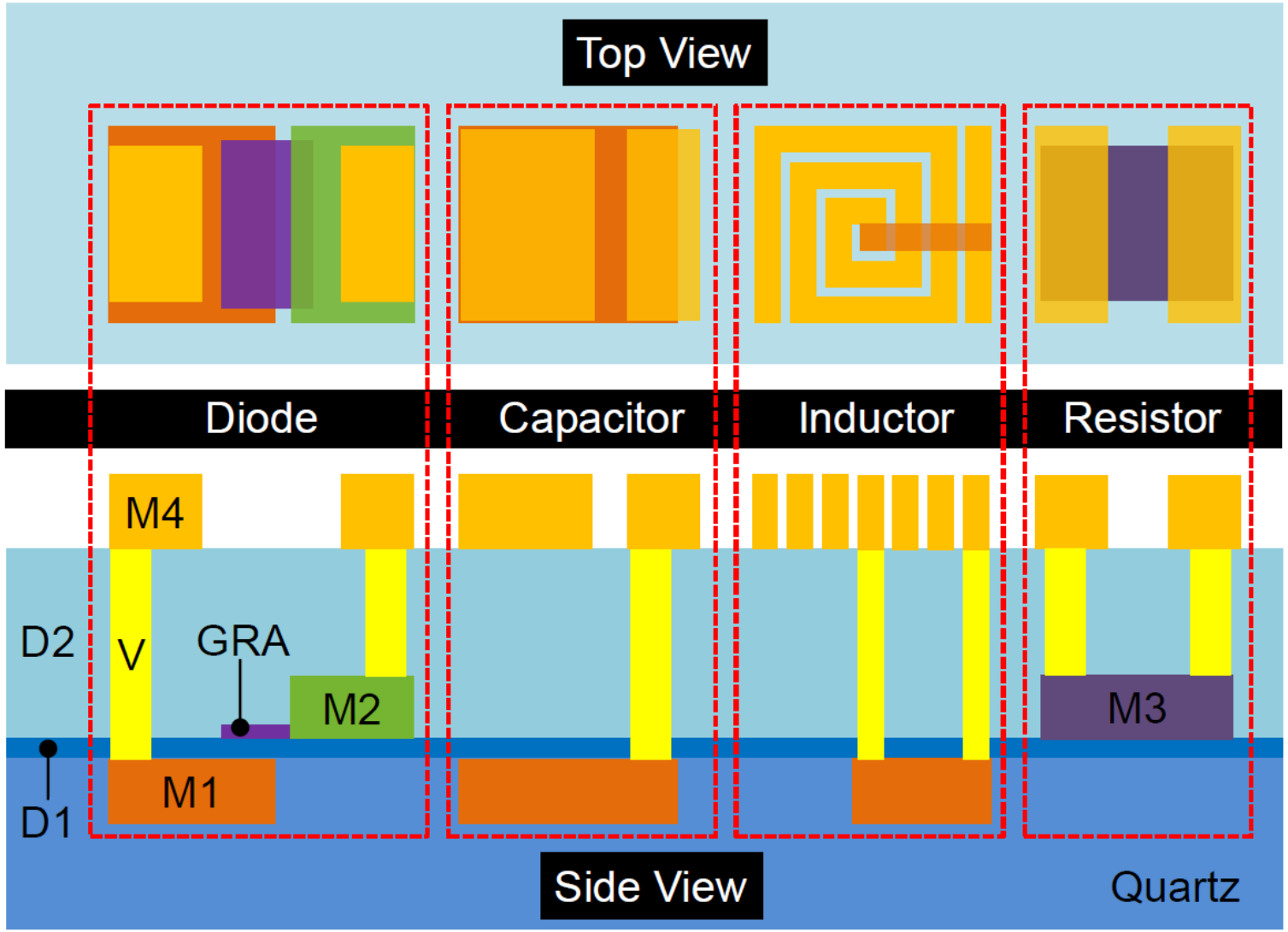
3-Stage Distributed Power Detector



***IEEE Trans. Microw. Theory Tech.*, 66 (2018)**
***IEEE MTT-S International Microwave Symposium* (2018)**
***Nanoscale*, 10, 93 (2018)**

MMIC Process on Rigid/Flexible Substrate

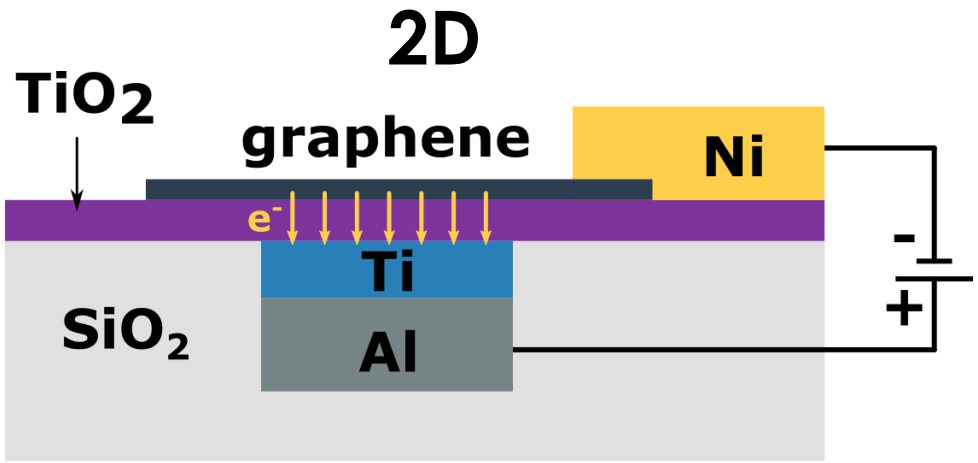




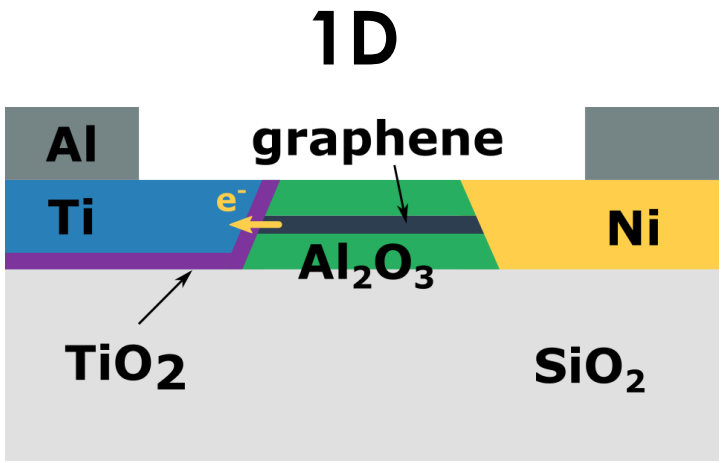
***Nanoscale*, 10, 93 (2018)**

2D or not 2D?

$$f_c = \frac{1}{2\pi R_s C_b}$$



- easier fabrication
- weak interaction between graphene and oxide => high *R*
- parallel-plate structure => high *C*

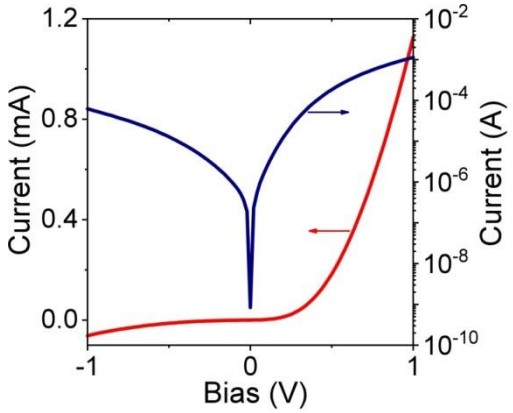


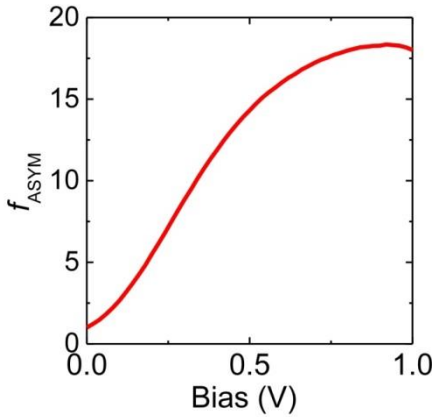
- *R*: lower contact resistance
- *C*: tiny junction cross-section (0.3nm)
- => higher cutoff frequency possible!

***Science*, 342, 614 (2013)**
***ACS Appl. Electronic Materials*, 1, 6, 945–950 (2019)**
***Adv. Electronic Materials*, 7, 2001210 (2021)**

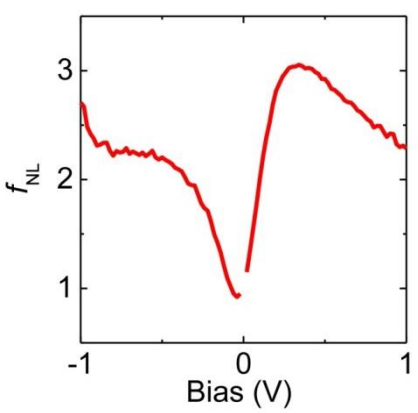
1D MIG Diodes

High current
High performance

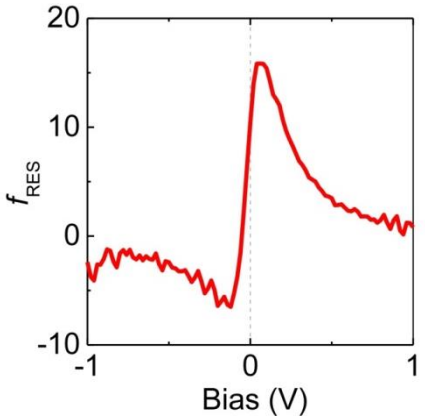




$$f_{\mathrm{ASYM}} = \left| \frac{J_{\mathrm{F}}}{J_{\mathrm{R}}} \right|$$

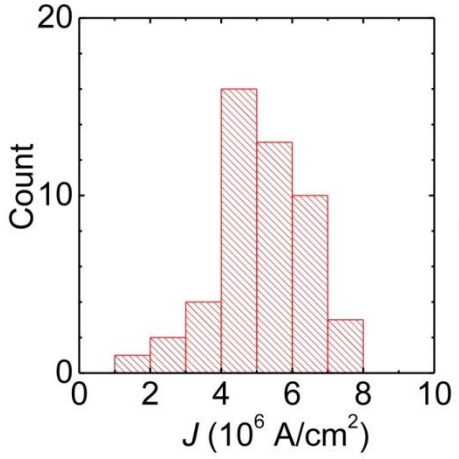


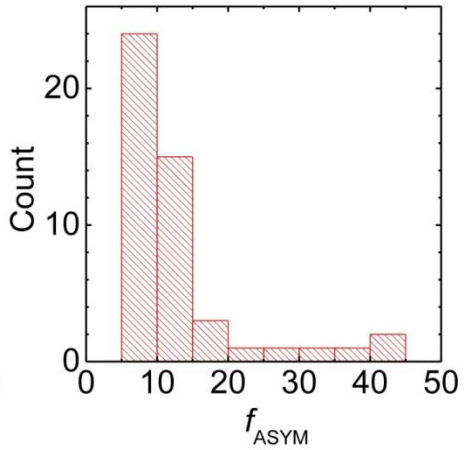
$$f_{\mathrm{NL}} = \frac{\mathrm{d}J}{\mathrm{d}V} \Big/ \frac{J}{V}$$

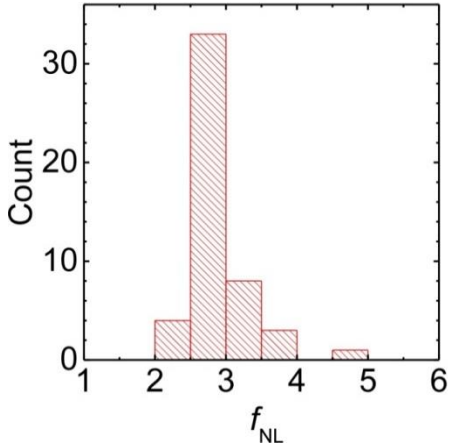


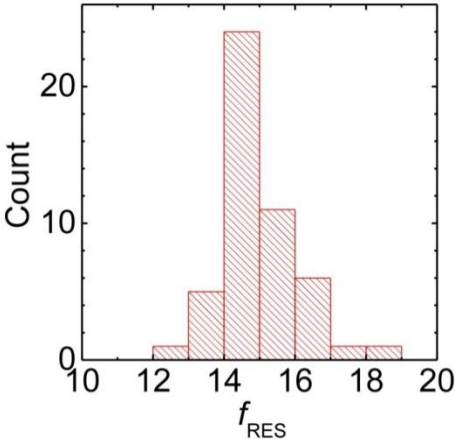
$$f_{\mathrm{RES}} = \frac{\mathrm{d}^2 J}{\mathrm{d}V^2} \Big/ \frac{\mathrm{d}J}{\mathrm{d}V}$$

Reproducible
Scalable



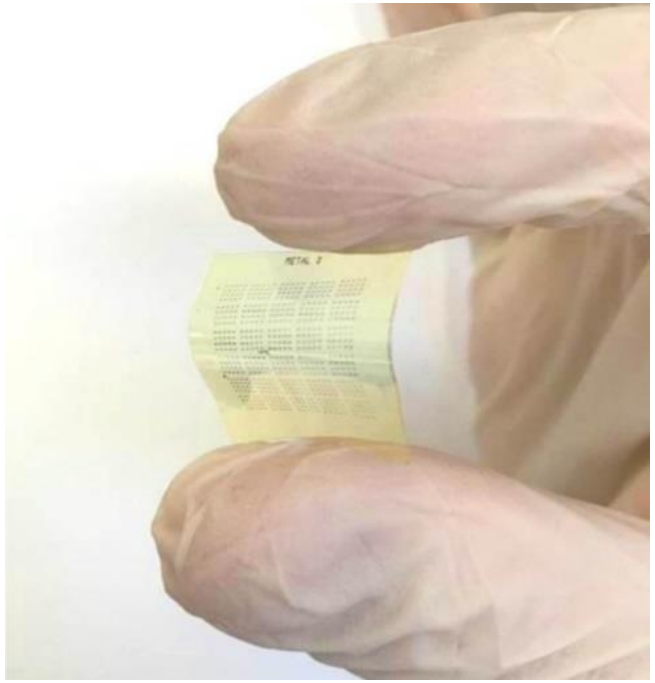


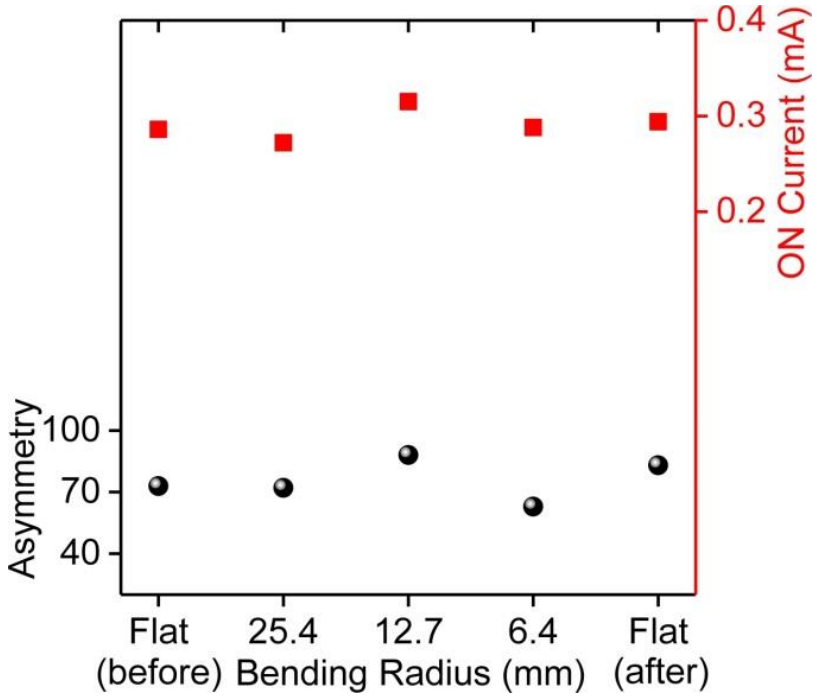


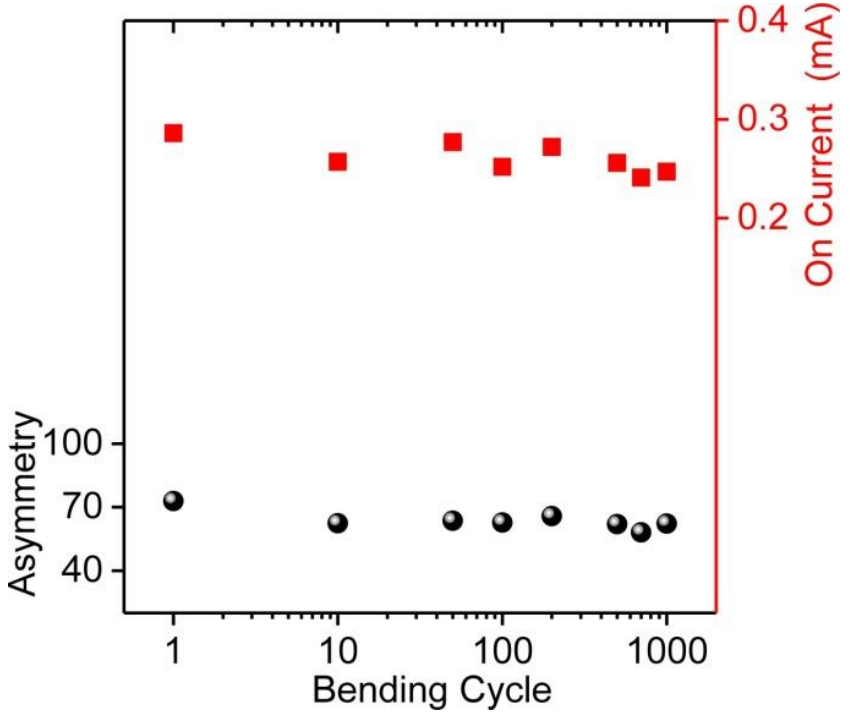


***ACS Appl. Electronic Materials*, 1, 6, 945–950 (2019)**

Flexibility of the 1D-MIG Diode

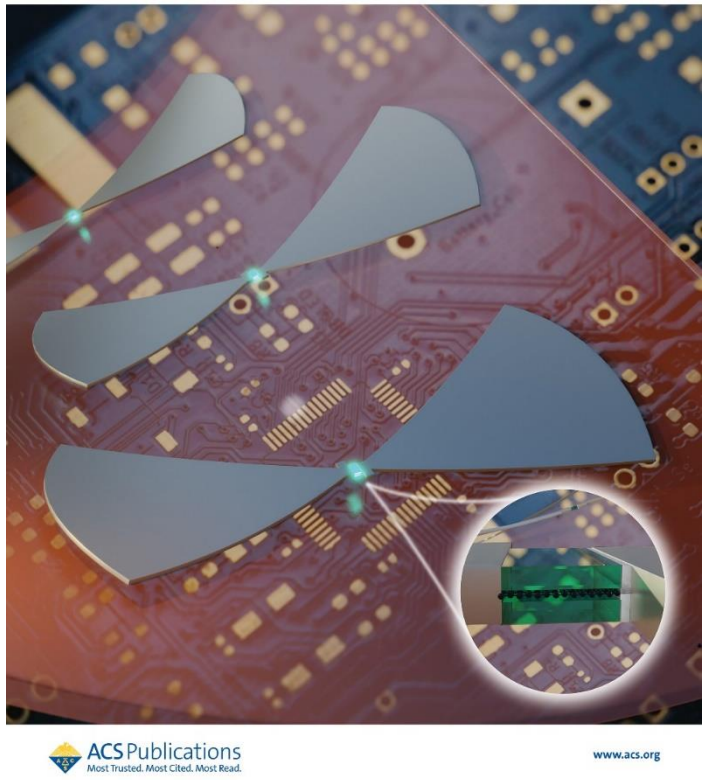


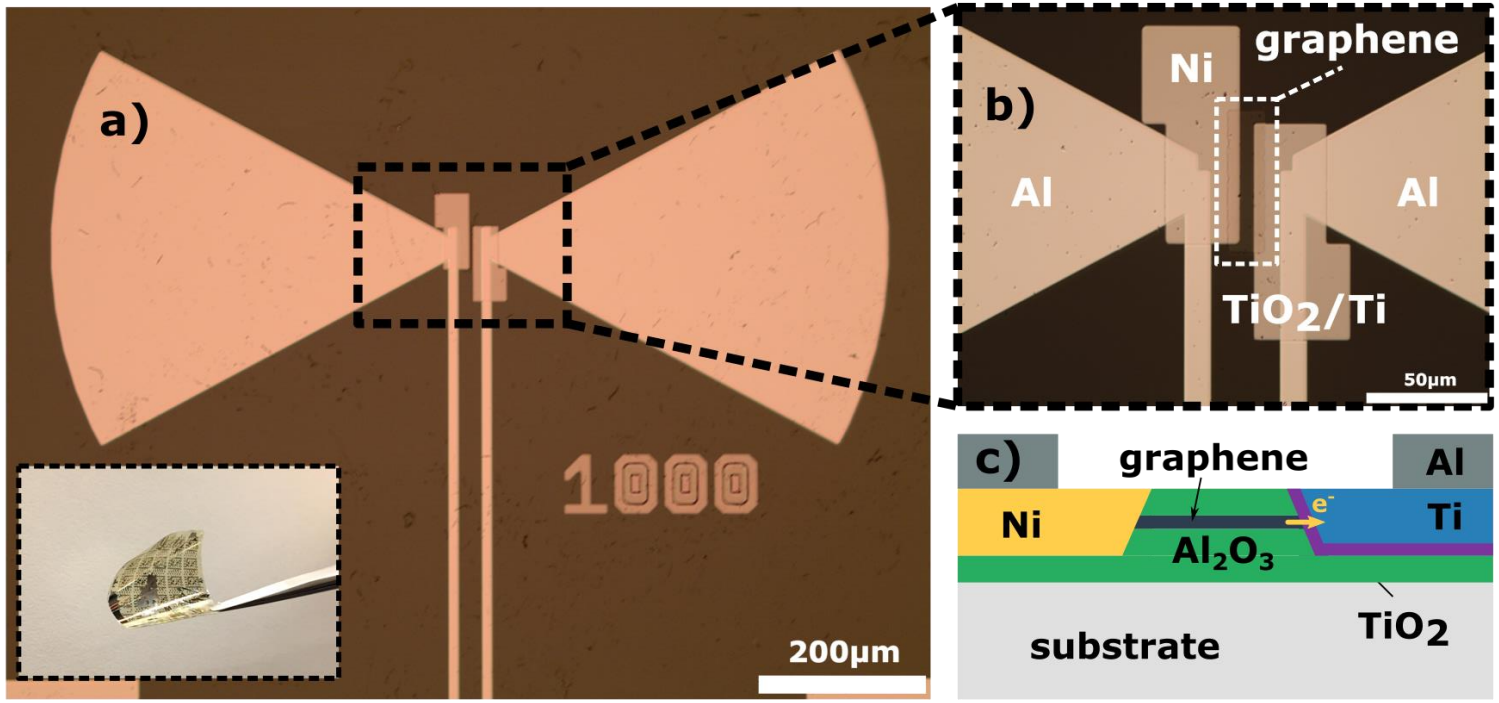




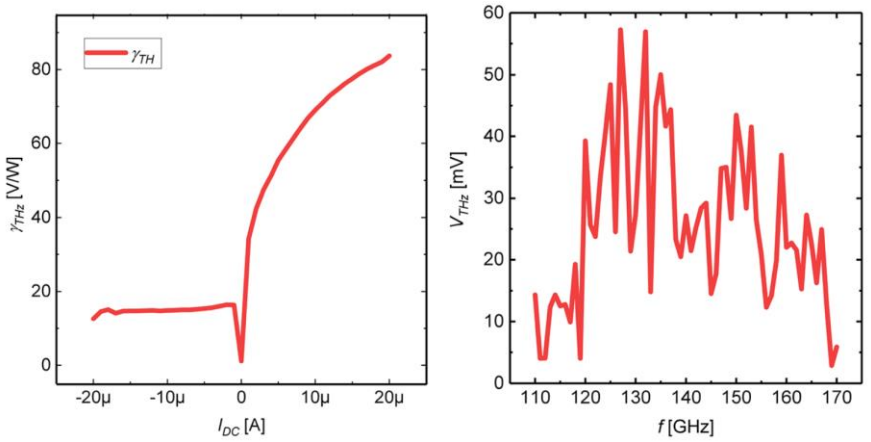
***ACS Appl. Electronic Materials*, 1, 6, 945–950 (2019)**

Flexible THz Rectennas





- High responsivity (>80 V/W @ 167 GHz)
- Low noise (80 pW/√Hz)
- Flexible



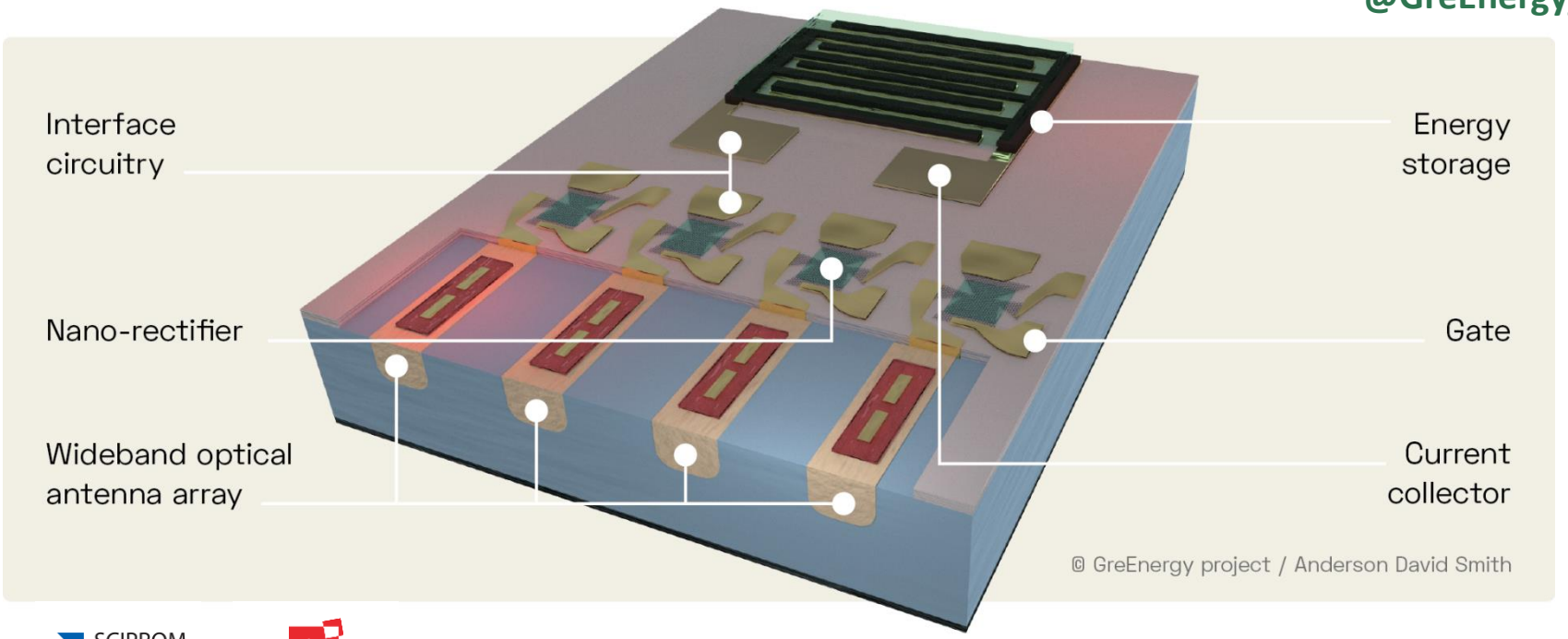
ACS Appl. Electronic Materials, 3, 9, 3747-3753 (2021)

GreEnergy

ICOS
International Cooperation On Semiconductors

GreEnergy
Power from optical antennas

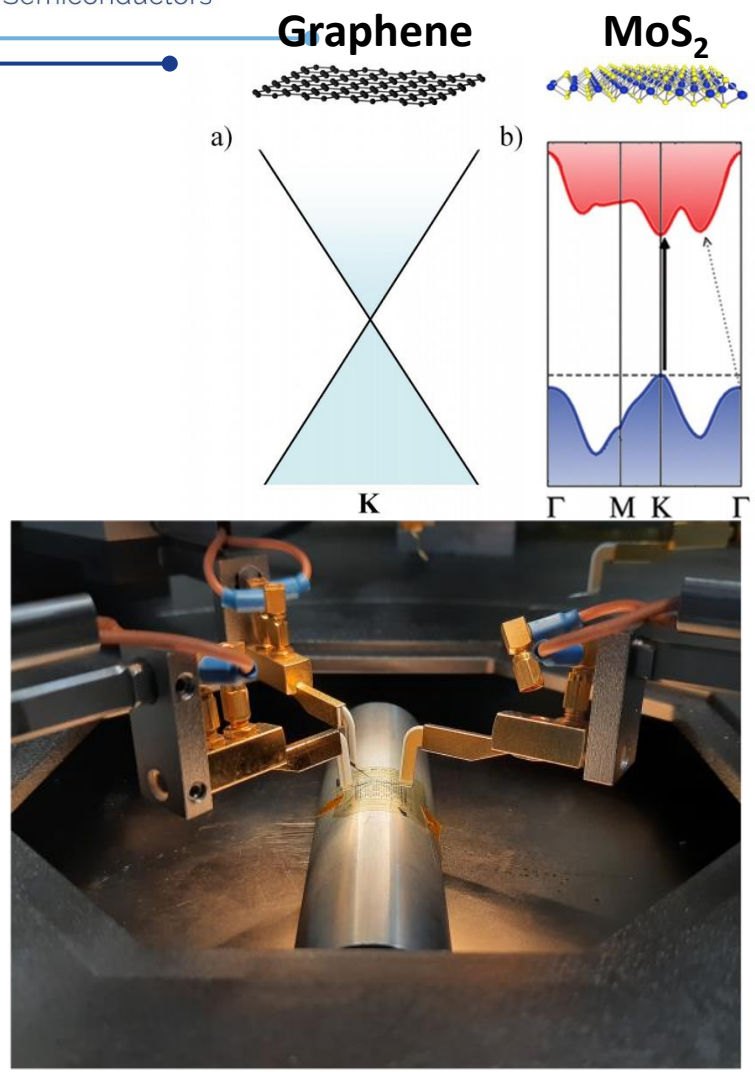
www.greenergy-project.eu
info@greenergy-project.eu
@GreEnergy_EU

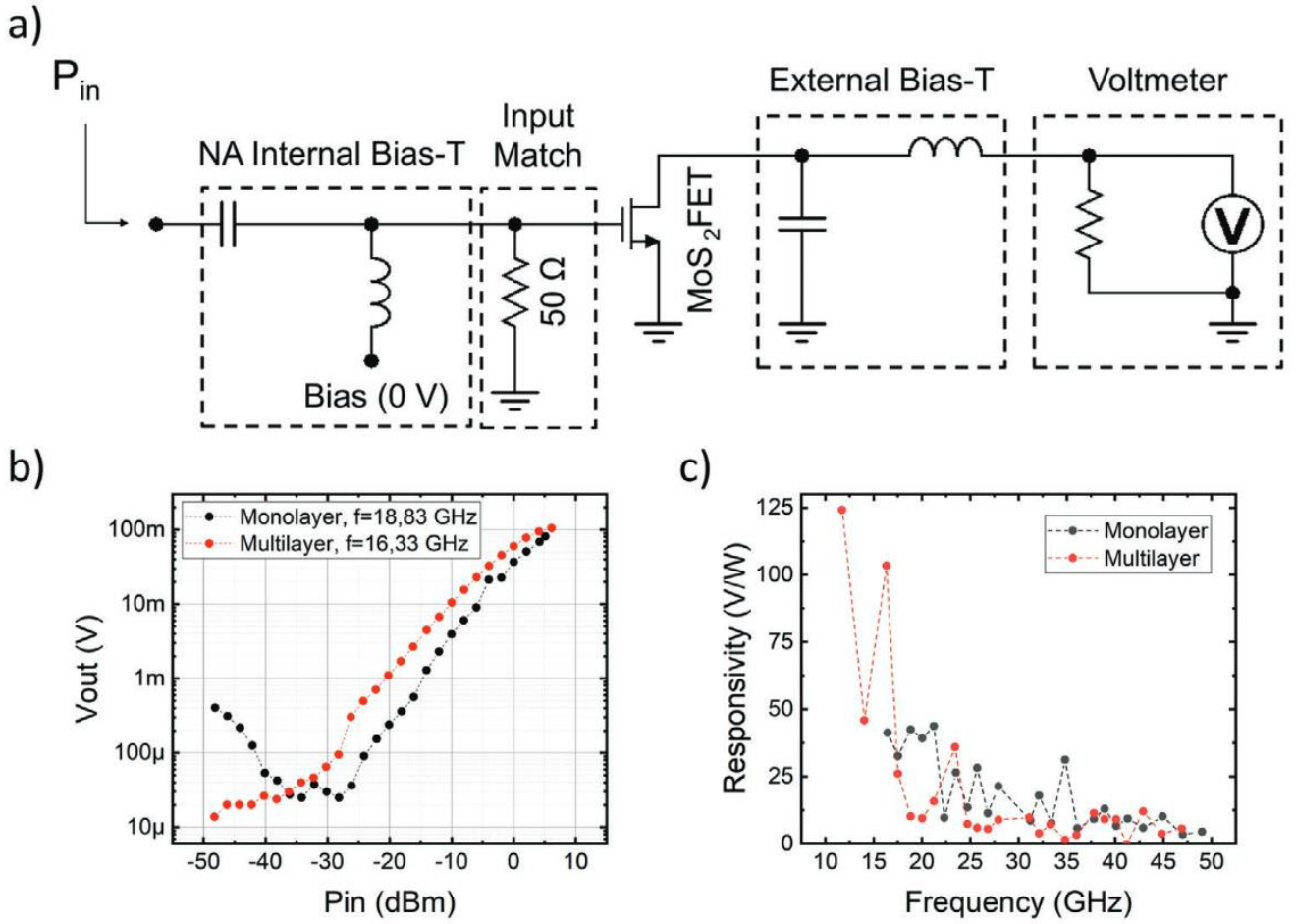


www.greenergy-project.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006963 (GreEnergy).

MoS_2 Power Detectors

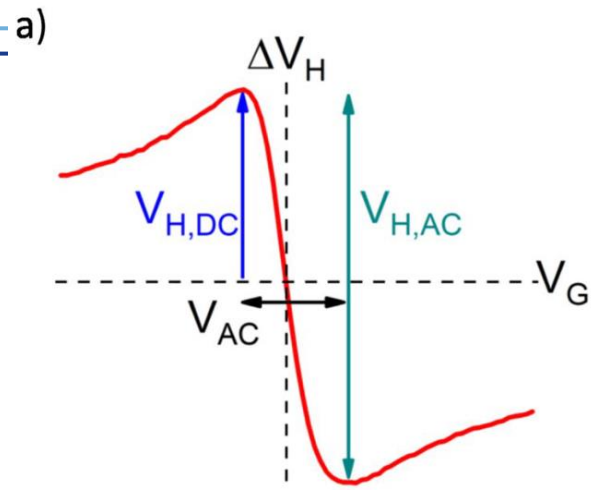


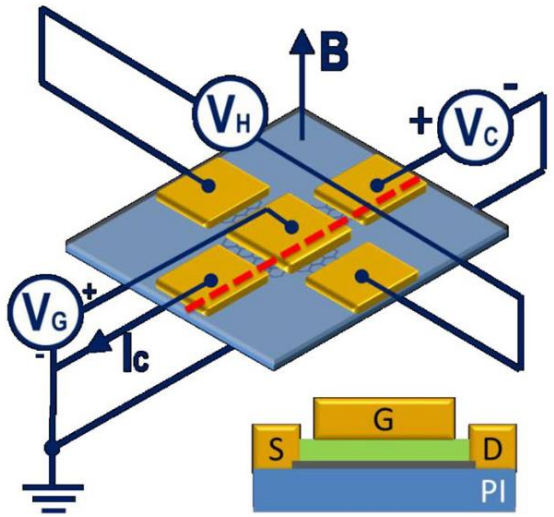


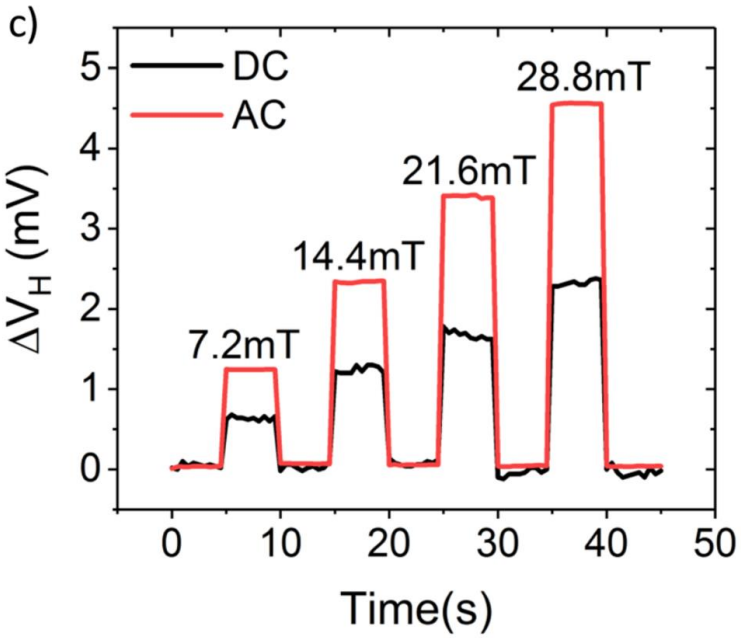
- Best-performing zero-bias power detector on flexible substrate
- > 30 dB dynamic range

***Advanced Materials*, 34, 48, 2108469 (2022)**
***Optical Material Express*, 4, 1, 63-78 (2014)**

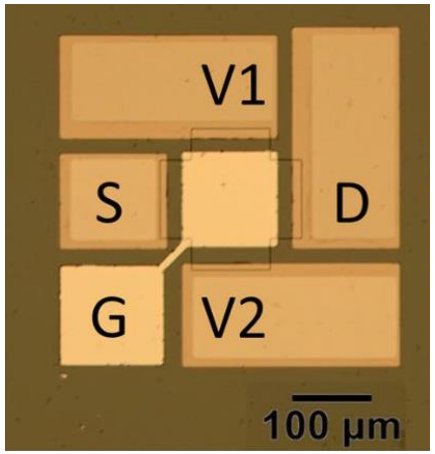
Flexible Hall Sensor







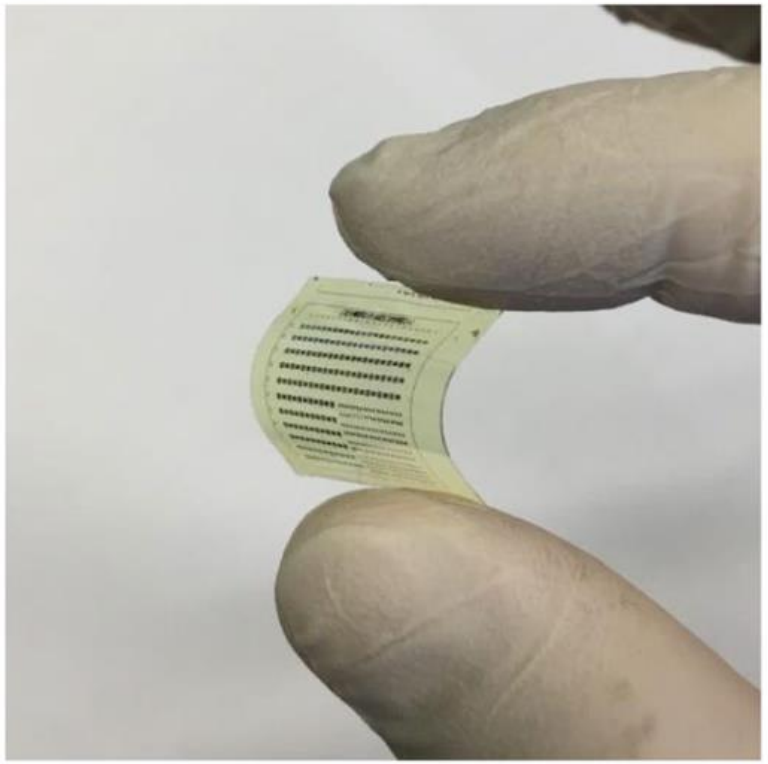
- Ambipolar (AC) operation → double sensitivity (0.55V/VT)
- High SNR readout (min. B-field: 290nT/√Hz)
- Flexible



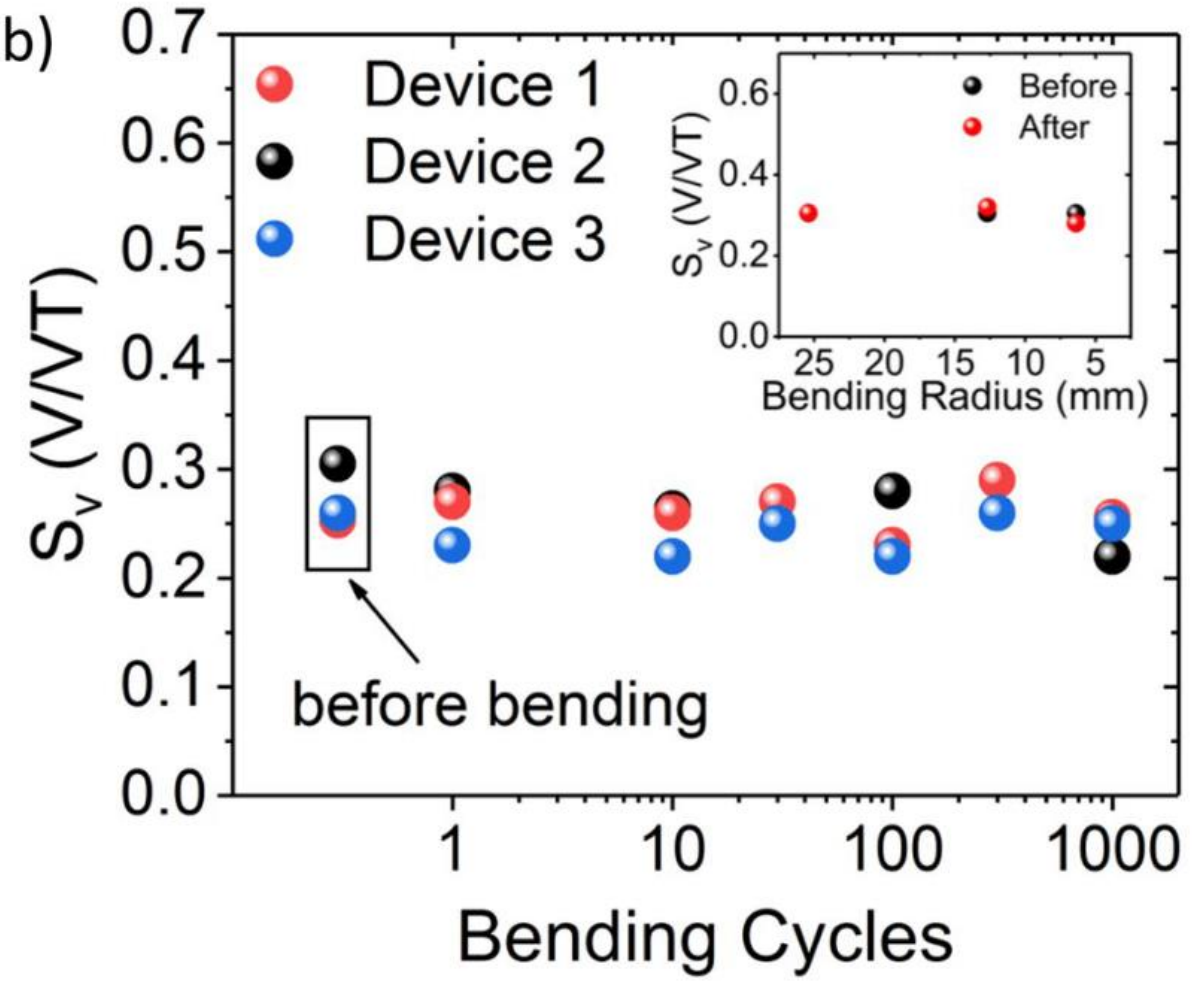
***Scientific Reports*, 9, 18059 (2019)**

Flexible Hall Sensor

a)



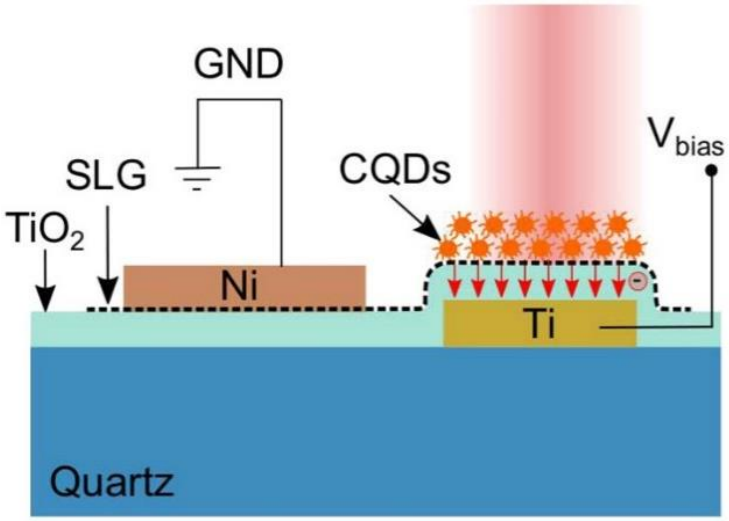
b)



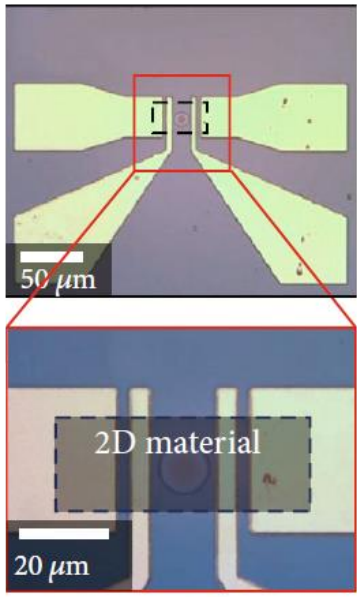
***Scientific Reports*, 9, 18059 (2019)**

Other 2D Material Sensors

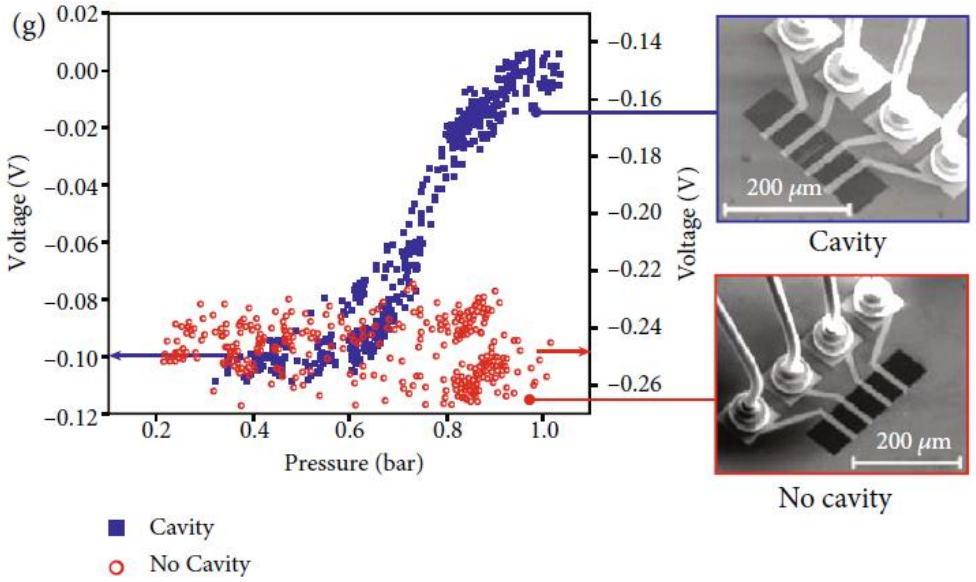
MIG/quantum dot photodetector



misel-project.eu



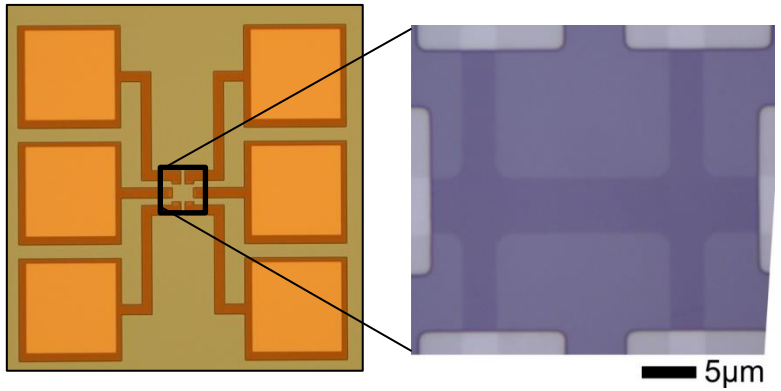
Piezoresistive pressure sensor

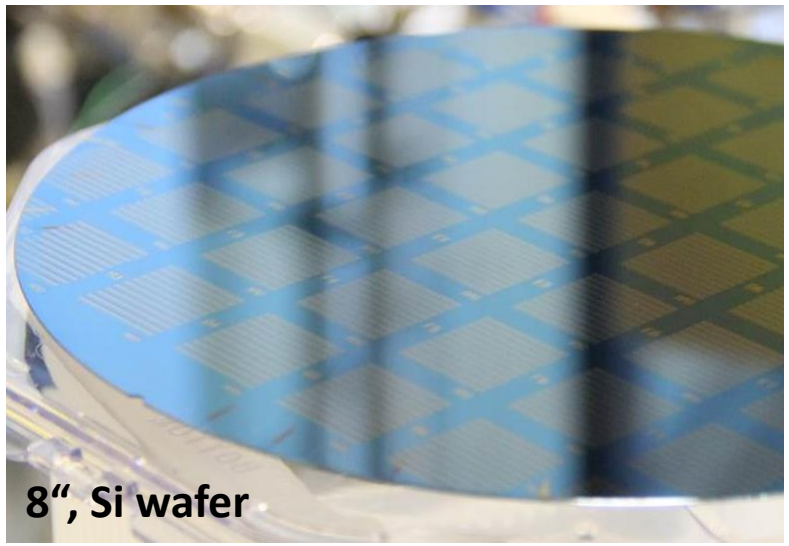


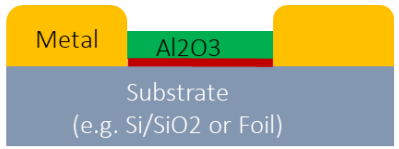
Temperature, chemical, biosensor, ...

***ACS Nano*, 14, 11897 (2020)**
***Research*, 2020, 8748602 (2020)**

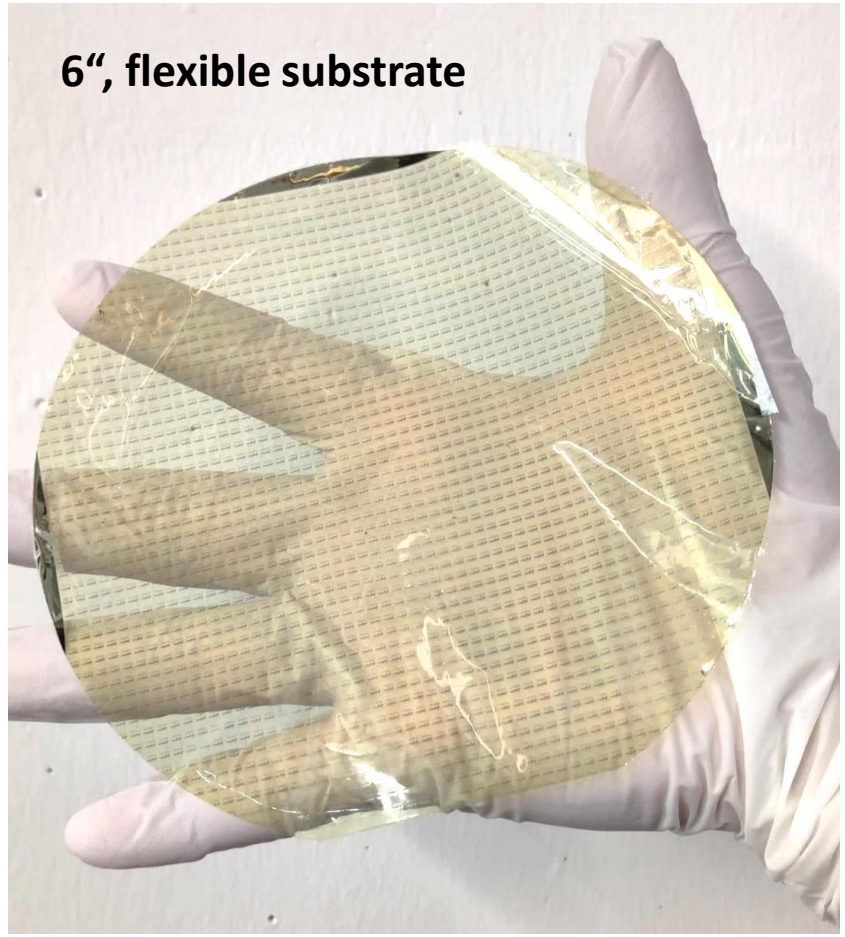
Scalability





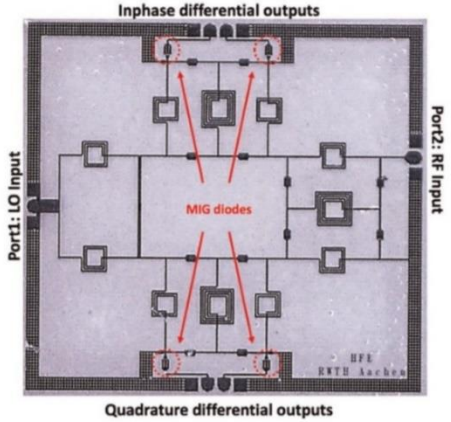


Encapsulated GFETs with global BG

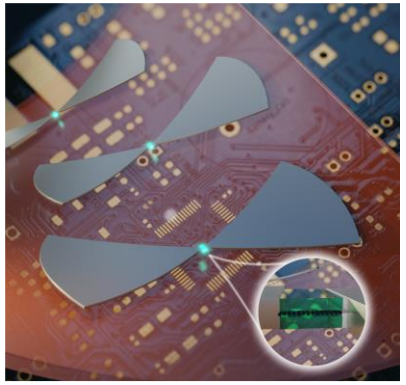


graphene-flagship.eu/innovation/pilot-line

Summary

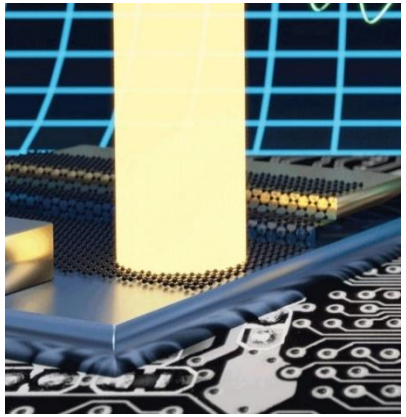


✓ **Communication circuitry**

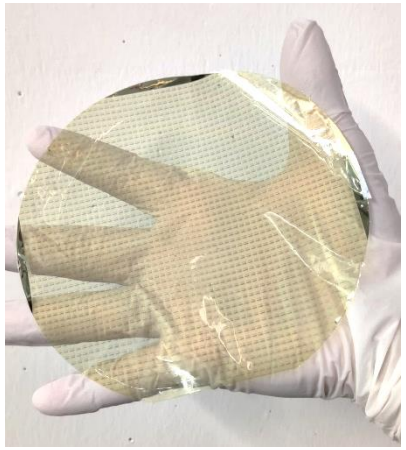


✓ **Self-powering**

✓ **Flexible**



✓ **Sensing functionality**



✓ **Scalable**

- **Open:**
  - **System**
  - **Reproducibility**
  - **Cost**

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AMO Team

ELD Team (https://www.eld.rwth-aachen.de)

Aixtron, Oxford, Graphenea, Nokia, Infineon, IHP, VTT, IMEC, R. Negra (RWTH), C. Stampfer (RWTH), J. Stake (Chalmers), F. Koppens (ICFO), G. Fiori (Pisa), D. Jimenez (UAB), P. Haring-Bolivar (Siegen) …

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