GreEnergy Summer School 2022
Cutting-edge electronics for eco-friendly energy

Zhenxing Wang (AMO GmbH, Aachen, Germany)

Graphene for Energy Harvesting Applications

GreEnergy

AMO – Partner of Innovators

Factsheet of AMO

Gesellschaft für Angewandte Mikro- und Optoelektronik GmbH (AMO GmbH)

Managing Directors:

- Prof. Dr.-Ing. Max C. Lemme
- Dr. rer. nat. Michael Hornung

Location:
Aachen, Germany

- Nanotechnology SME (non-profit)
- founded in 1993
- 400 m^2 clean room

- > 75 staff members
- > 40 funded R&D projects
- > 150 R&D partners

Key Technologies

- Silicon Technology Base
- Nanofabrication (NIL, E-Beam, IL)
- New Materials Integration
  - high-k/metal gate
  - Graphene & 2D
  - Perovskites
  - Plasmonics

- Applications
  - Nanoelectronics
  - Nanophotonics
  - Integrated Sensors

GreEnergy

AMO Infrastructure

Lithography

Electron beam lithography

- High resolution (~5 nm), highly flexible

Optical lithography (6’’ I-line stepper, mask aligner)

- Easy and fast fabrication of complex design
- Interference lithography

Interference lithography

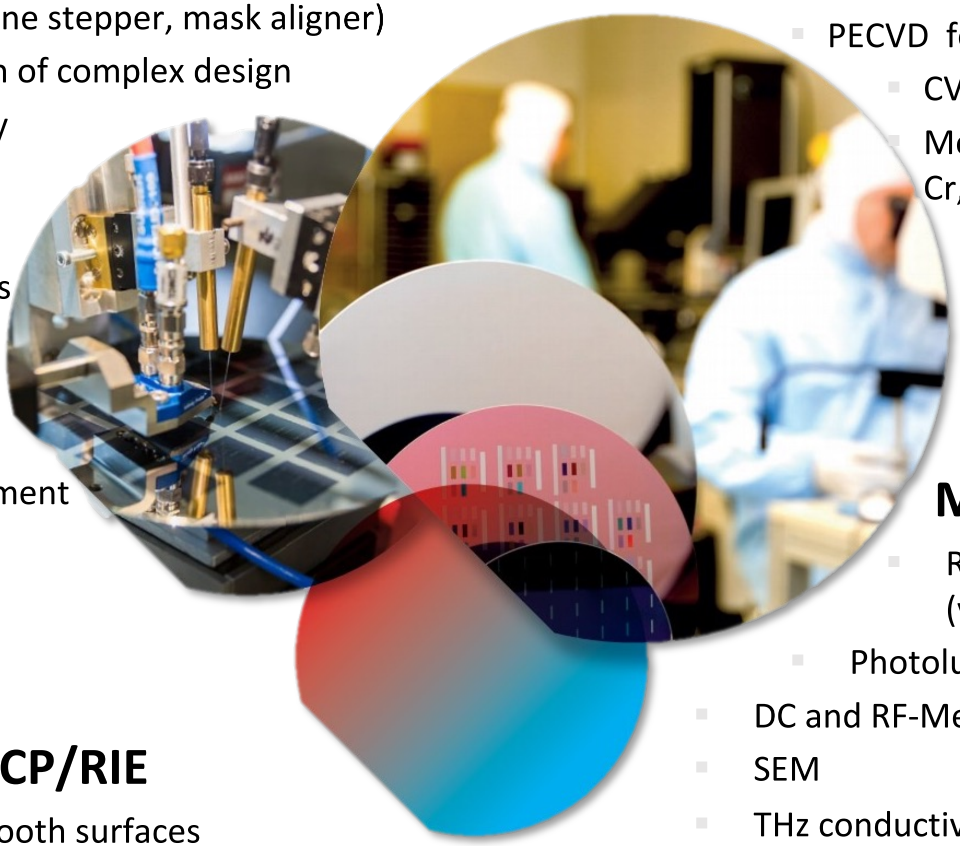
- Large area nano gratings

Nanoimprint lithography

- Flexible template and resist material development
- non planar surfaces

Pattern transfer by ICP/RIE

- Anisotropic profiles, smooth surfaces
- Flexible chemistry (F, Cl, Br…)



Deposition

- LPCVD Si3N4, SiO2,
- PE-ALD Al2O3, TiO2, AlN, TaN, TiN
- PECVD for 2D-materials (S, Se, Te)
- CVD for Graphene
- Metal evaporation (Al, Ti, Ni, Cr, Co)
- Metal sputtering (…)

Wet processing

Metrology

- Raman spectrometer (vacuum)
- Photoluminescence
- DC and RF-Measurements
- SEM
- THz conductivity (→ Protemics)
- Transient recording (→ AMOtronics)

GreEnergy

Overview: Graphene (TMDC) Electronics

AMO

HF Electronics
- Diode and Transistor
- Energy Harvesting
- Integrated Circuits

Flexible Electronics
- Flexible Circuits
- Flexible Sensor
- Device Under Strain

Sensor
- Hall Sensor
- Photodetector
- Pressure Sensor

Wafer-Scale Processing
- Growth
- Transfer
- Fabrication

WiPLASH

GreEnergy

2D exciting

MISEL

GRAPHENE FLAGSHIP

2D PILOT LINE

Graphene Introduction

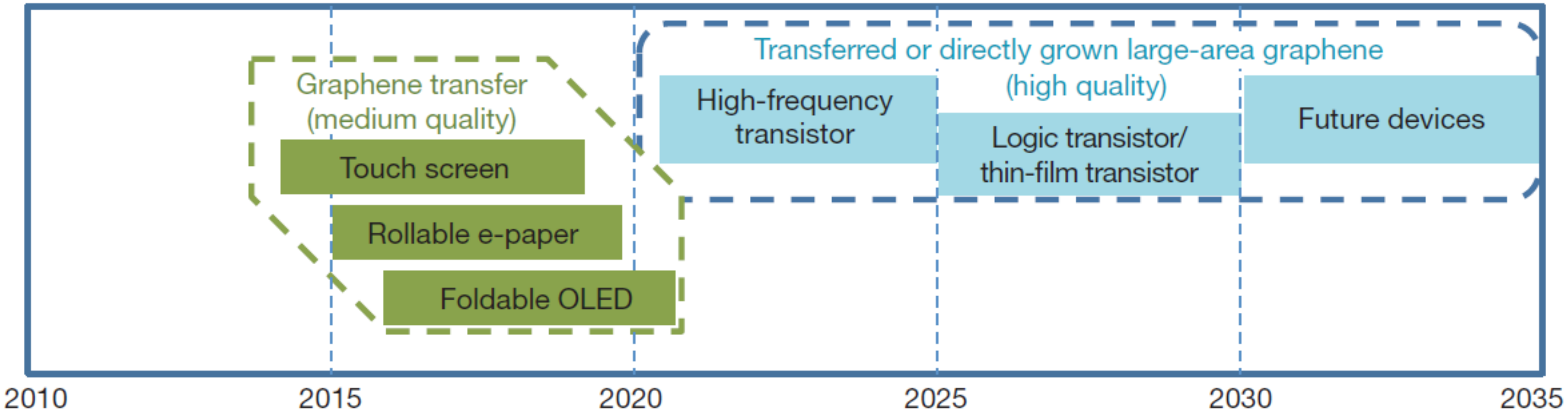
GreEnergy

Why is graphene good for electronics?

- High carrier mobility
- Ultimately thin
- Flexible and strong
- Chemically inert
- Large scale synthesis
- Solution processable
- Optical transparent
- Bio compatible
- ……


Flexible graphene-based smartphone produced by Chongqing Graphene Tech. Co., Ltd.

Nature Materials 15, 697–698 (2016)



K S Novoselov et al. Nature 490, 192-200 (2012)

GreEnergy

Graphene Synthesis Method

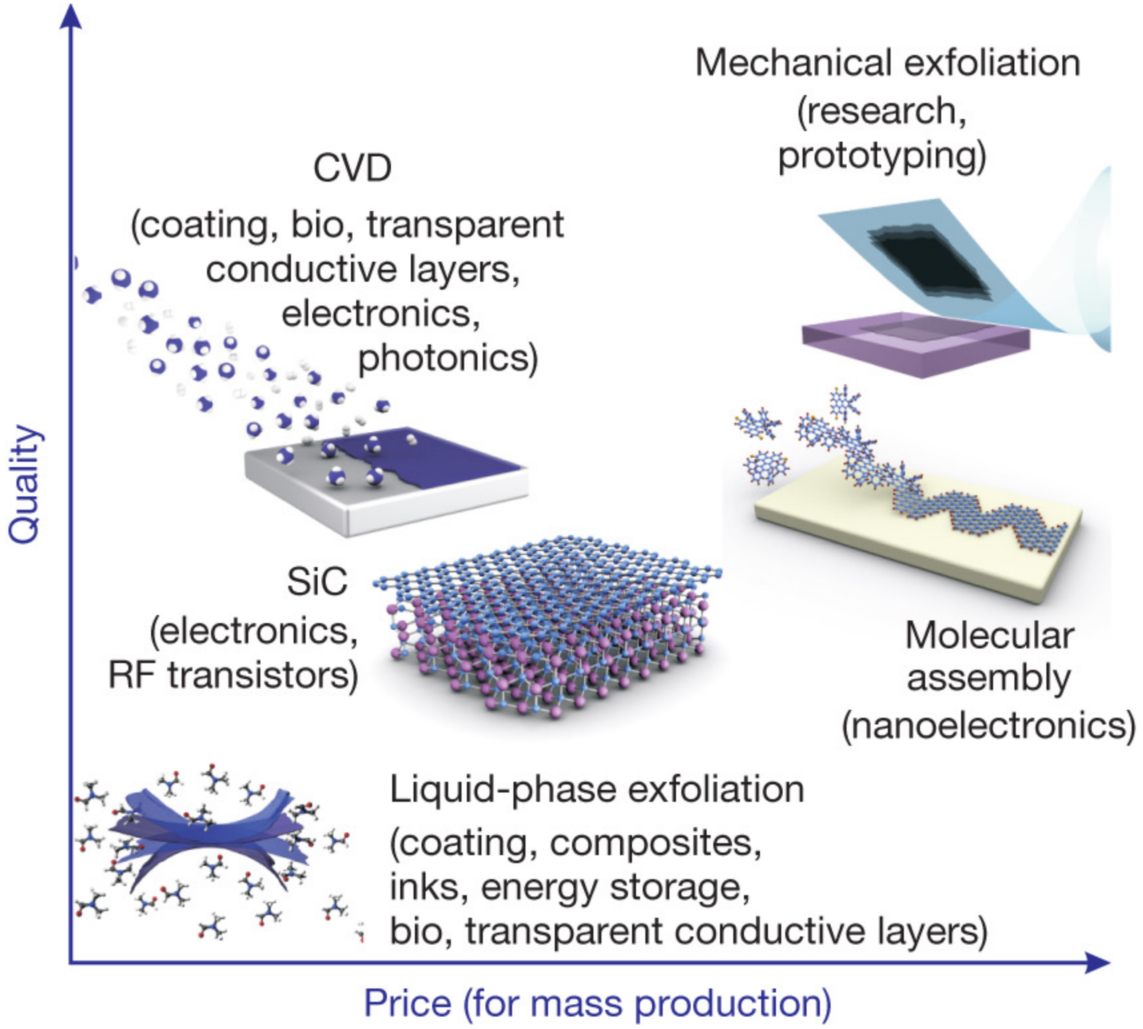
Method	Crystallite size (μm)	Sample size (mm)	Charge carrier mobility (at ambient temperature) ($cm^2 V^{-1} s^{-1}$)
Mechanical exfoliation	$>1,000$	>1	$>2 \times 10^5$ and $>10^6$ (at low temperature)
Chemical exfoliation	≤ 0.1	Infinite as a layer of overlapping flakes	100 (for a layer of overlapping flakes)
Chemical exfoliation via graphene oxide	~100	Infinite as a layer of overlapping flakes	1 (for a layer of overlapping flakes)
CVD	1,000	~1,000	10,000
SiC	50	100	10,000

GreEnergy

K S Novoselov et al. Nature 490, 192-200 (2012)

Quality vs. Price

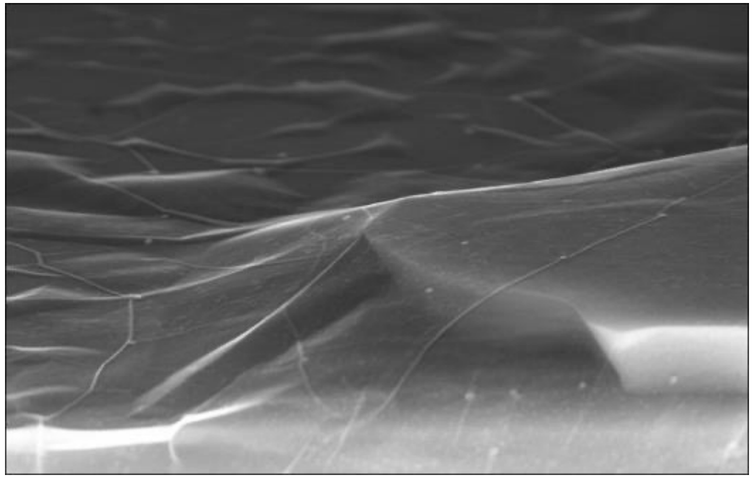
- CVD is a good choice!
- Transfer is needed, which means challenge in technology, but also means more degree of freedom on choice of substrates.



K S Novoselov et al. Nature 490, 192-200 (2012)

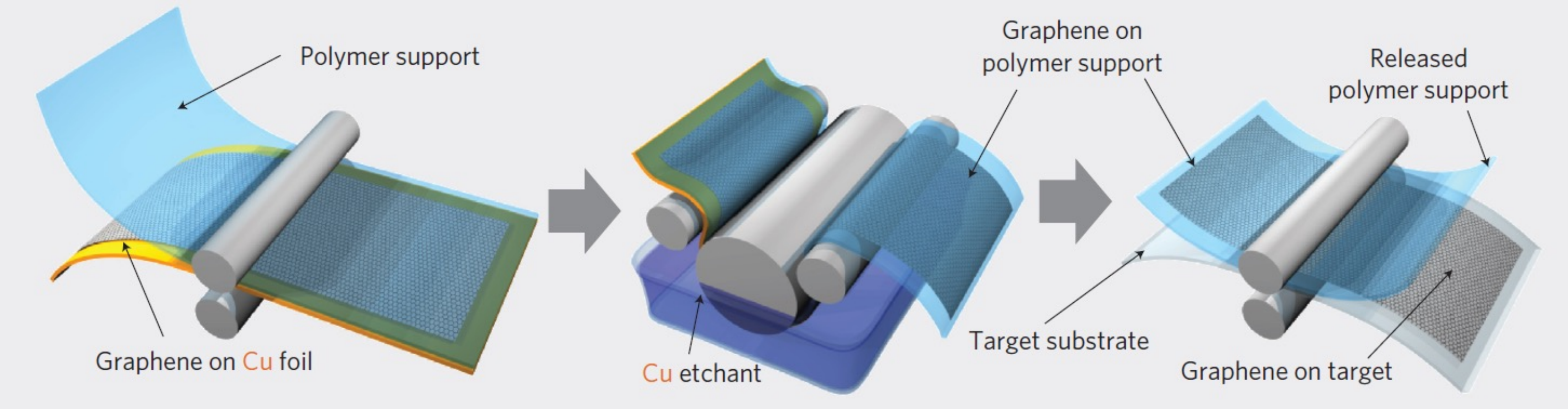
CVD Monolayer Graphene on Copper

On Wafers



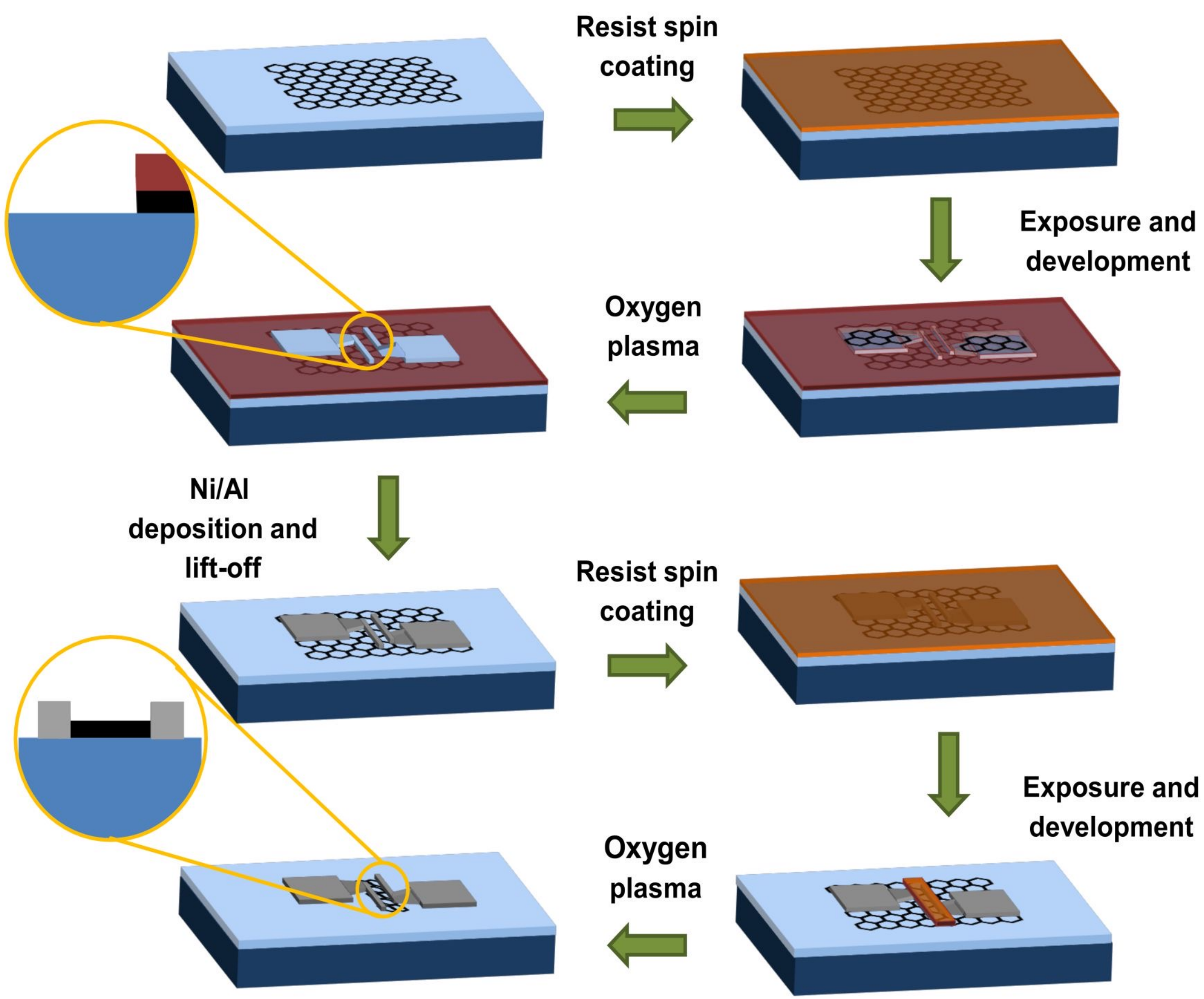
Courtesy of Aixtron

On Foil using Roll-To-Roll Process



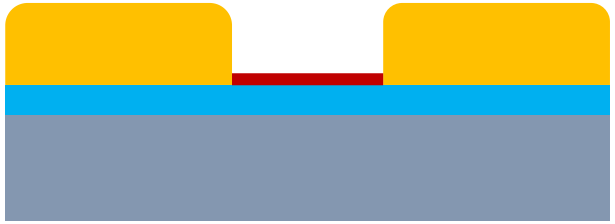
S. Bae et al. Nature Nano. 5, 571 (2010)

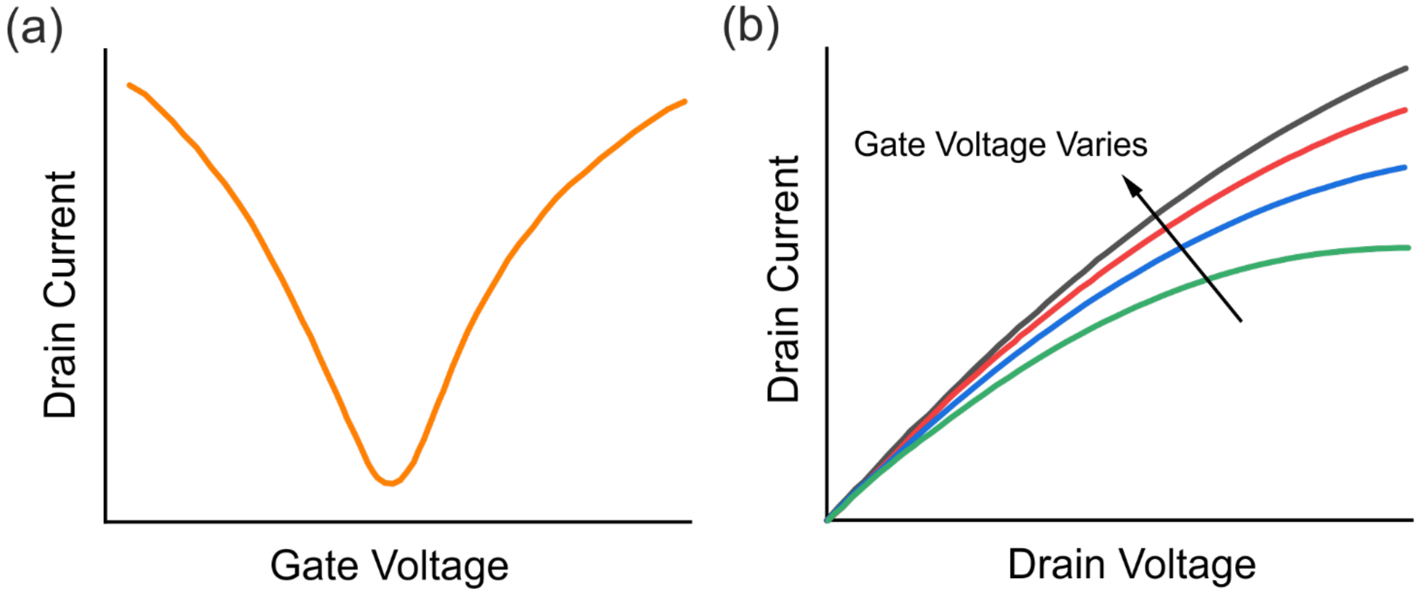
Edge Contact with Resist Mask



Shaygan et al. Annalen der Physik 2017, 529, 1600410.

Graphene Based Field Effect Devices





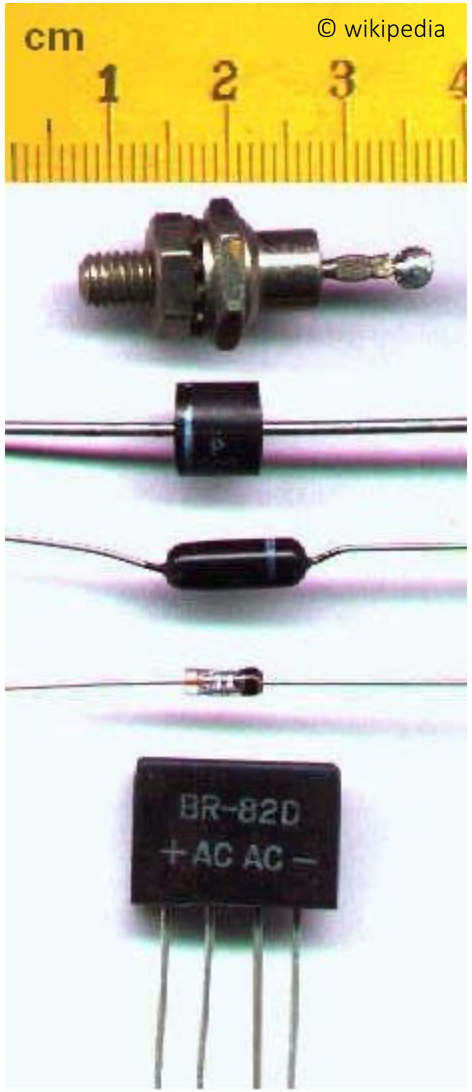
Z. Wang, D. Neumaier, M. C. Lemme. Book chapter: Carbon-Based Field-Effect Transistors, Springer, in press.

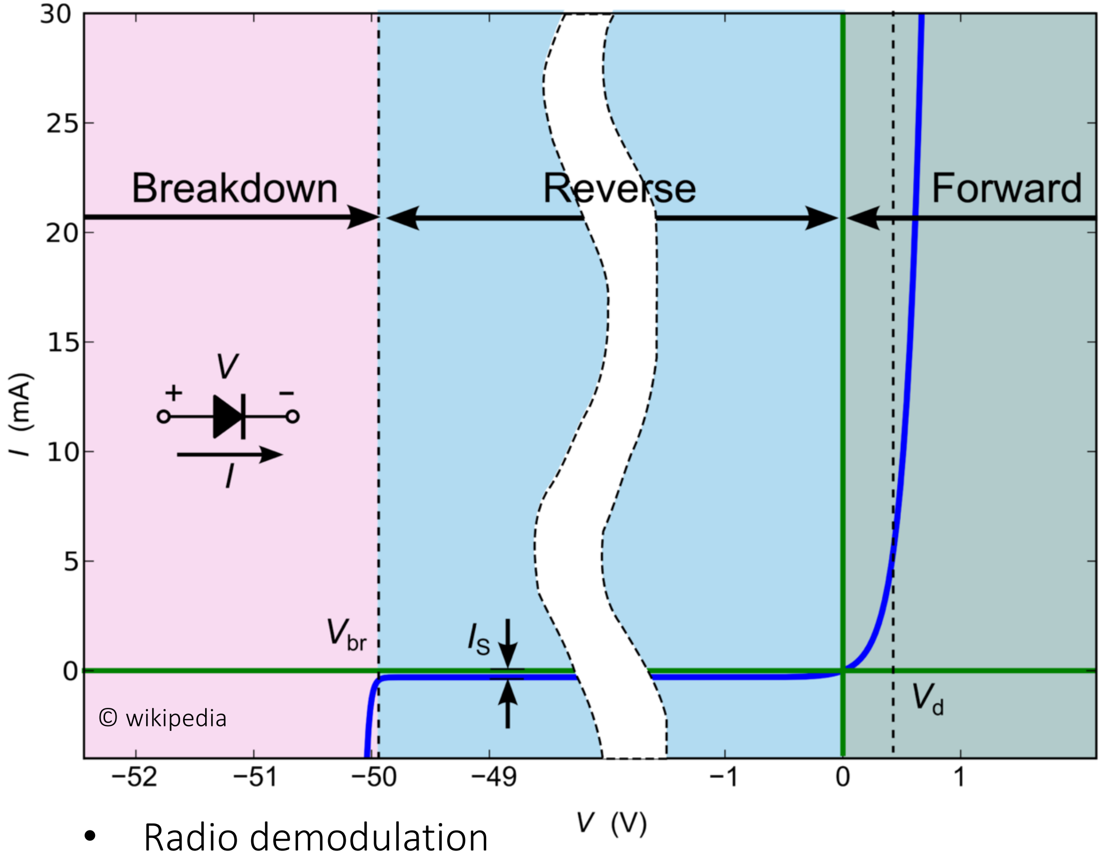
Metal-Insulator-Graphene Diode

Basic Device

GreEnergy

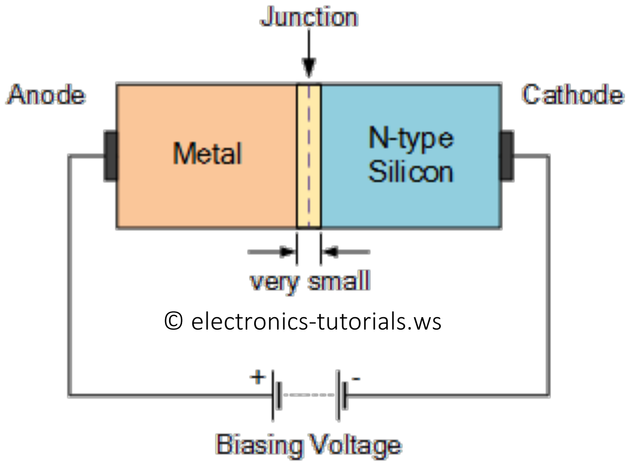
Diodes

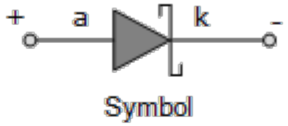


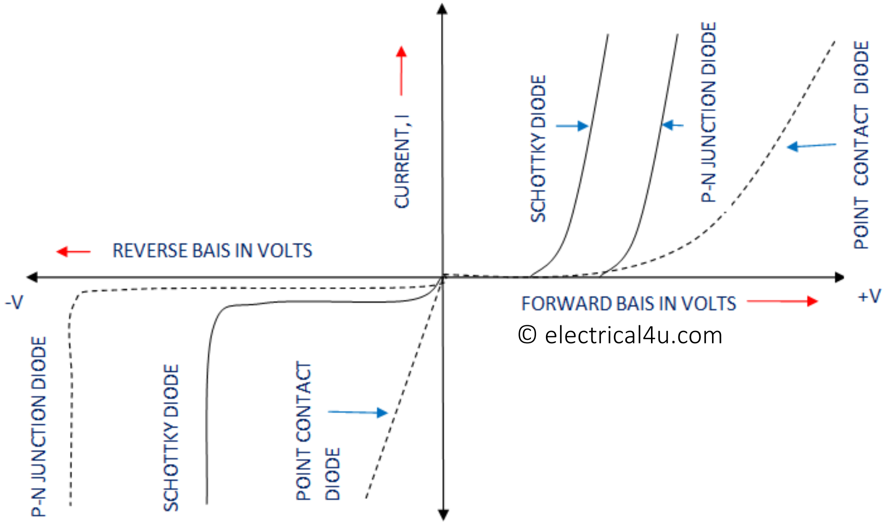


- Radio demodulation
- Power conversion
- Over-voltage protection
- Logic gates
- Ionizing radiation detectors
- Temperature measurements ……

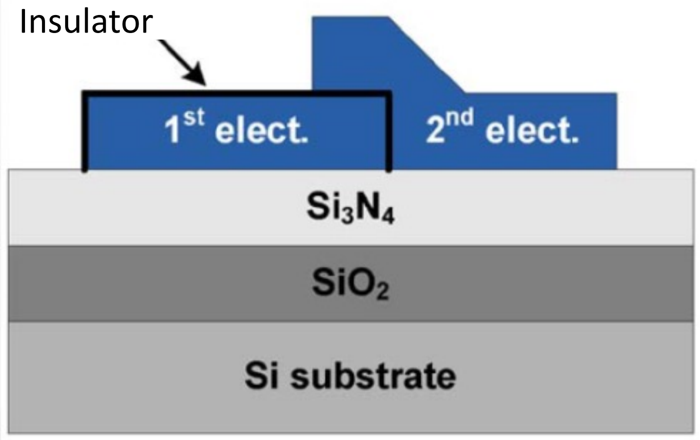
Conventional RF Diodes

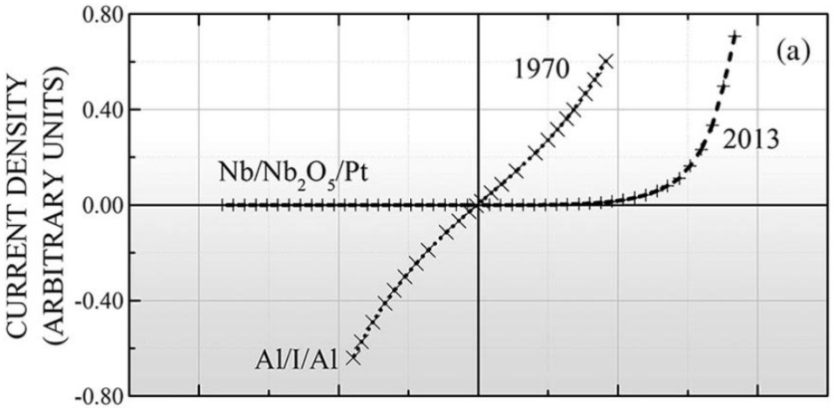






Schottky Diodes:
Not thin film technology.

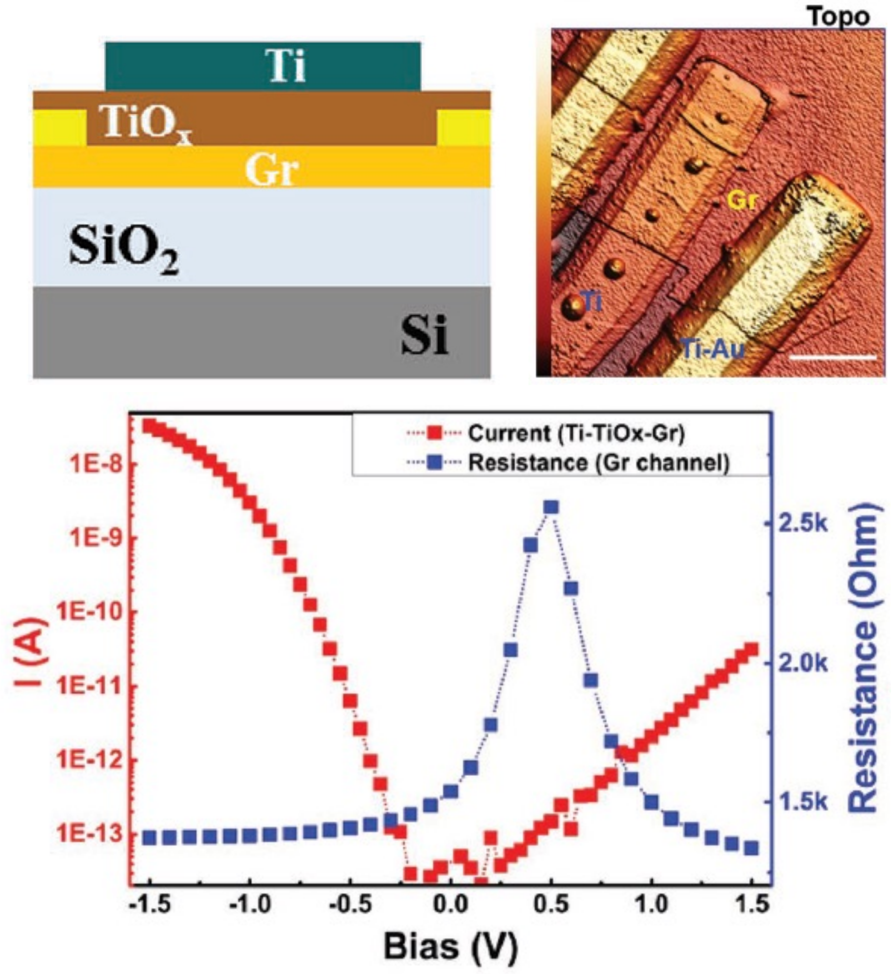


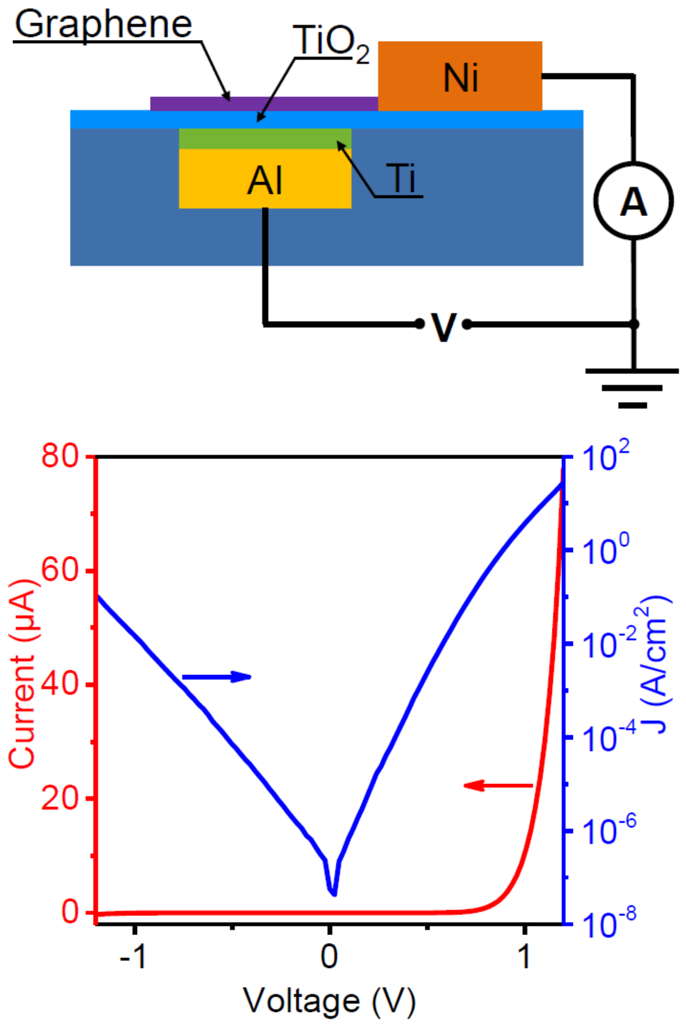


Metal-Insulator-Metal (MIM) Diodes:
Thin-film tech, but the frequency performance is not optimal.

IEEE Trans. Electron Dev., 58, 3519, 2011. Adv. Mater., 25, 1301, 2013. Proc. IEEE, 102, 1667, 2014.

Metal-Insulator-Graphene (MIG) Diodes





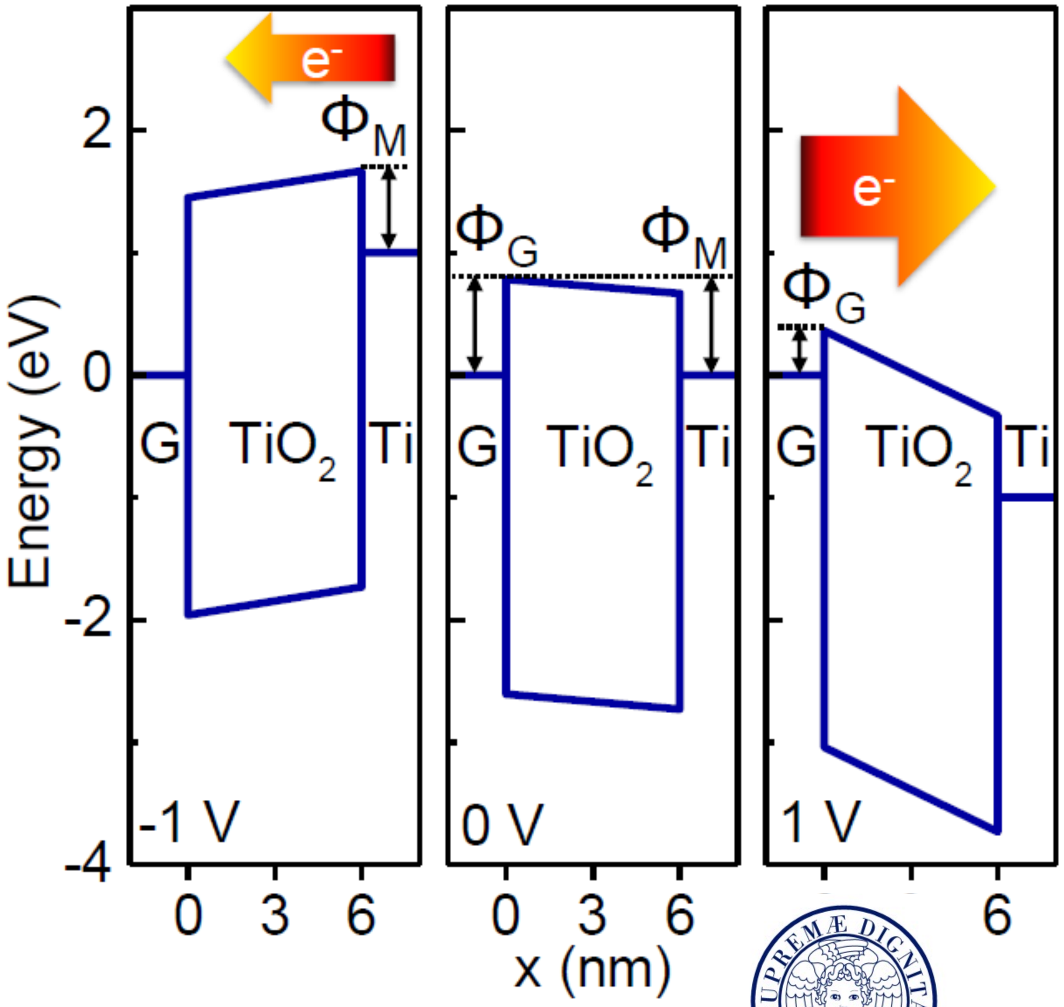
- High parasitic capacitance
- Oxide on graphene
- Exfoliated graphene

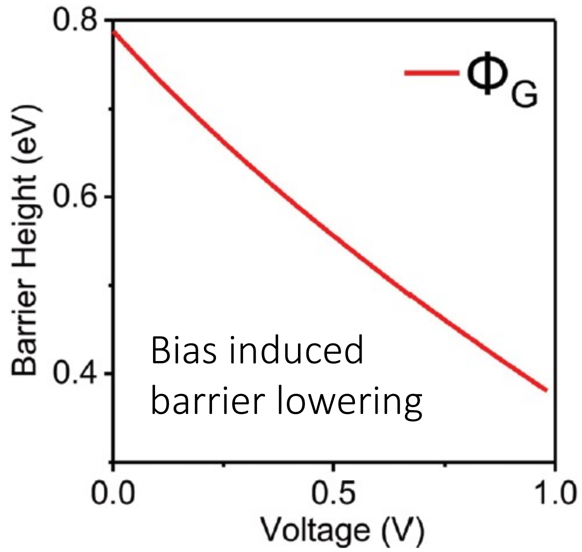
- Scalable process
- ALD for oxide
- CVD graphene

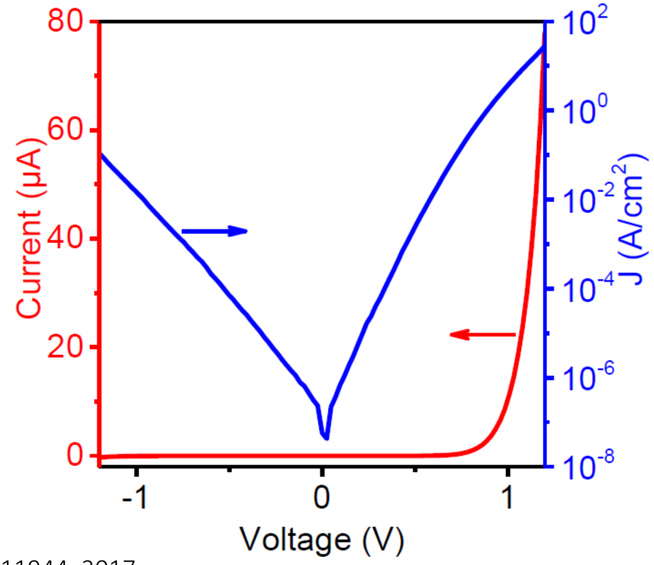
Adv. Electron. Mater., 2, 1600223, 2016.

Nanoscale, 9, 11944, 2017.

Transport Mechanism





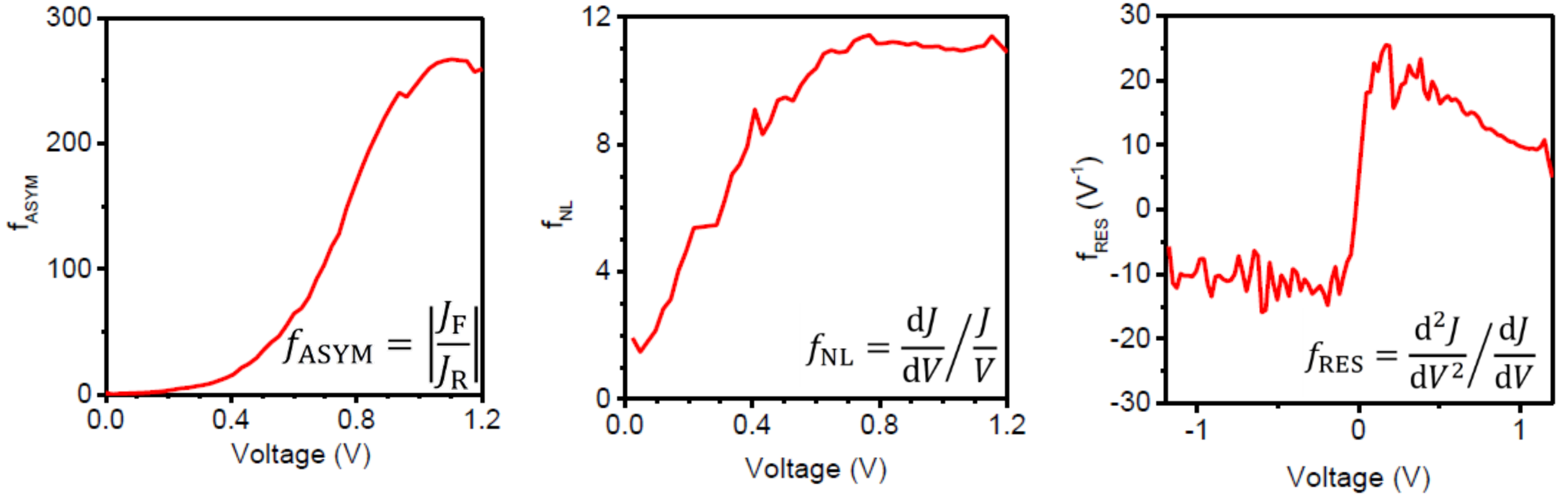


UNIVERSITÀ DI PISA

Nanoscale, 9, 11944, 2017.

GreEnergy

Benchmarking of MIG Diodes



Stack Material	J_{ON}(A/cm^2)	f_{ASYM}	f_{NL}	f_{RES}(V^{-1})
Nb/Nb_2O_5(5nm)/Pt [1]	2.0	9.8	8.2	16.9
Nb/Nb_2O_5(15nm)/Pt [2]	N/A	1500	4	20
Ti/TiO_2/Bilayer Graphene [3]	0.1	9000	8	10
Ti/TiO_2/Graphene [Average this work]	3.8	320	12	24
Ti/TiO_2/Graphene [Max. value this work]	7.5	520	15	26

[1] Chin et al., J. Vac. Sci. Technol. B, 31, 051204-1 (2013). [2] Periasamy et al., Adv. Mater. 23, 3080 (2011). [3] Urcuyo et al., Adv. Electron. Mater. 2, 1600223 (2016).

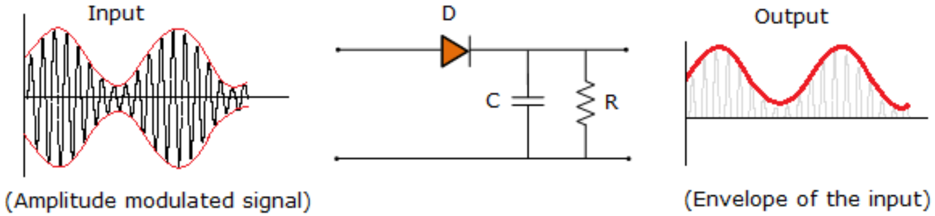
Nanoscale, 9, 11944, 2017.

Metal-Insulator-Graphene Diode

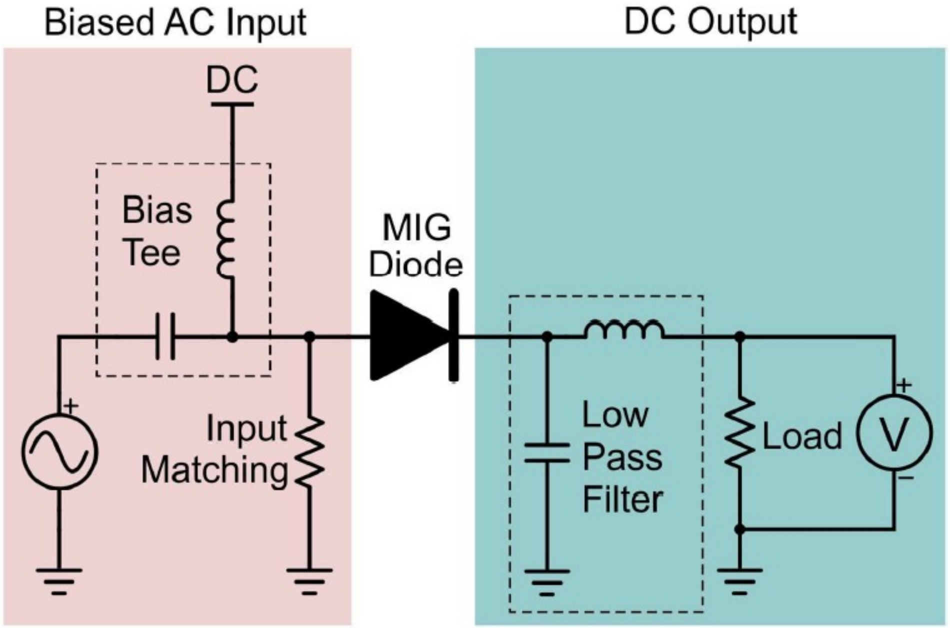
Application in RF Communications

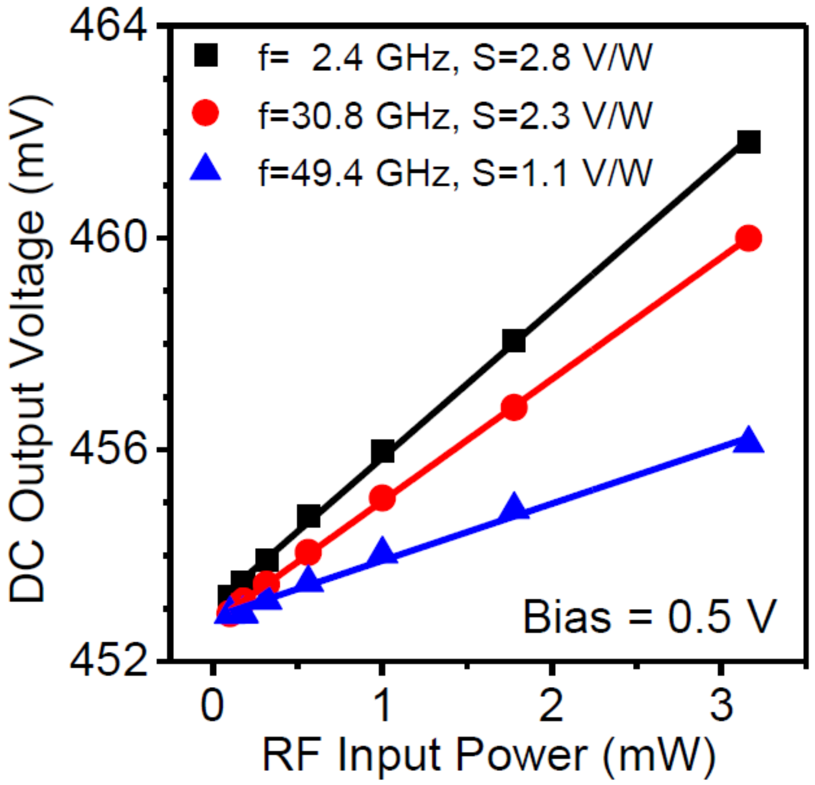
GreEnergy

RF Application of MIG Diodes



Diode for Demodulation

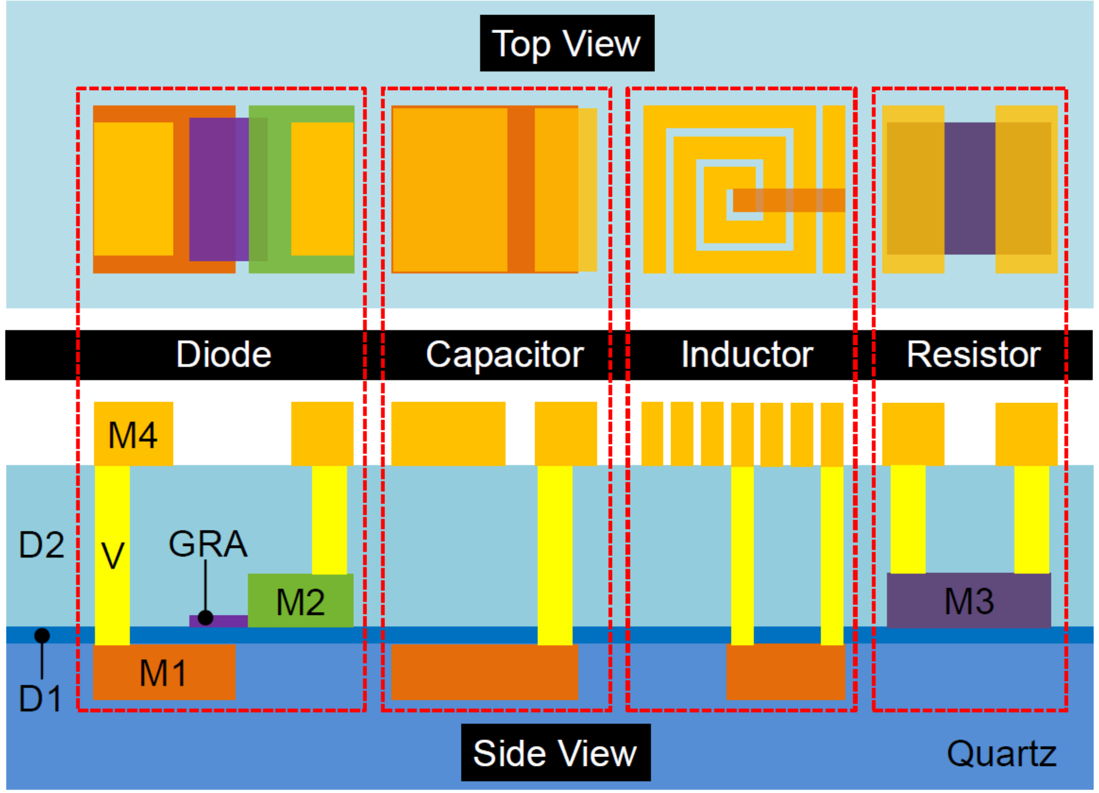




Nanoscale, 9, 11944, 2017.

MMIC Process for Rigid/Flexible Substrate

Monolithic Microwave Integrated Circuit @AMO



Graphene is between D1 and M2, and can be used in diodes, varactors or/and transistors.

2 Dielectric layers:

- D1: 5 nm TiO_2 (diodes) or 5-10 nm Al_2O_3 (FET)
- D2: 90nm Al_2O_3 (encapsulation, capacitors)

4 Metal layers:

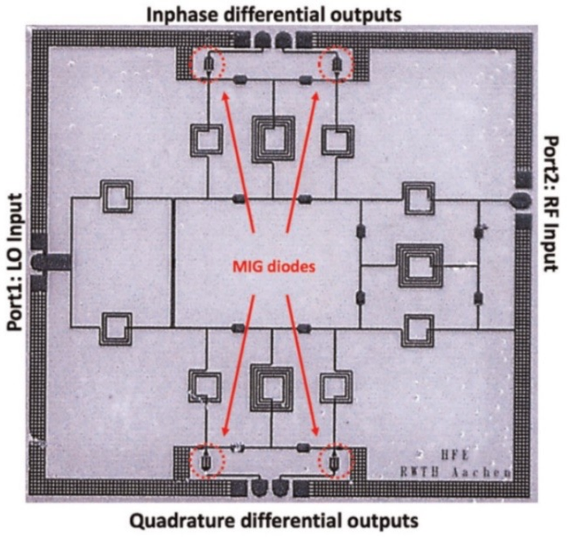
- M1: 100nm Al (gate electrode, passives)
- M2: 20 nm Nickel (graphene contacts)
- M3: 110 nm TiN (resistors)
- M4: 2µ Al (passives, interconnects)

GreEnergy

Nanoscale, 10, 93, 2018.

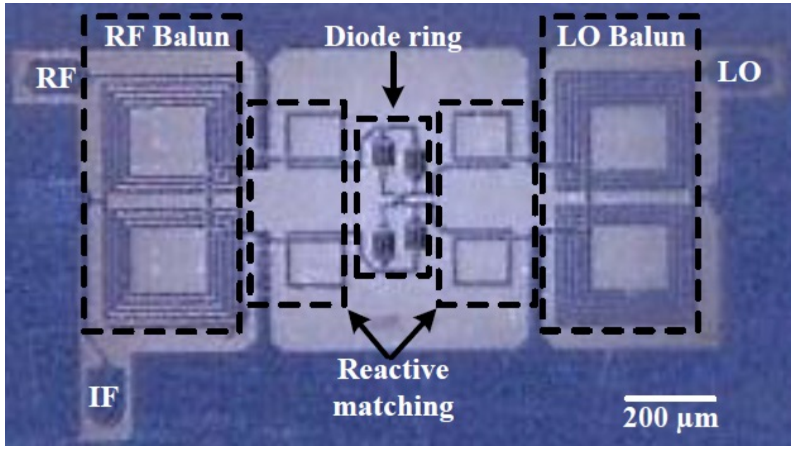
Circuits Examples

Six-port receiver: QPSK at 2.4GHz



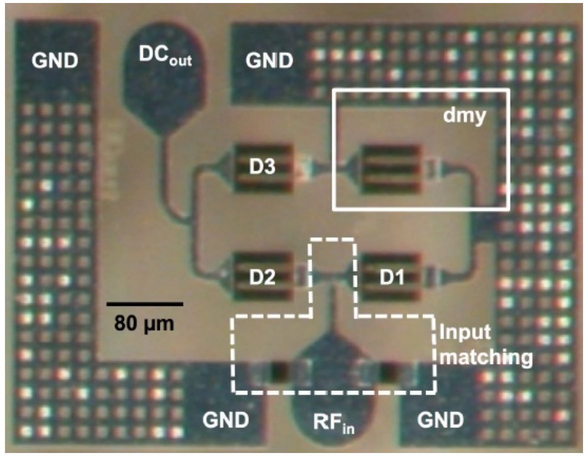
Saeed et al. Nanoscale, 2018, 10, 93

Double-Balanced Upconversion Mixer



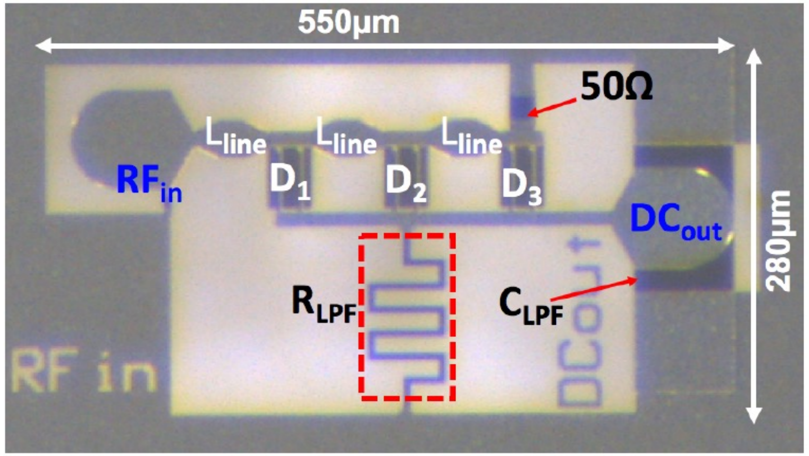
IEEE MTT-S International Microwave Symposium (IMS), 2018.

V-Band power detector



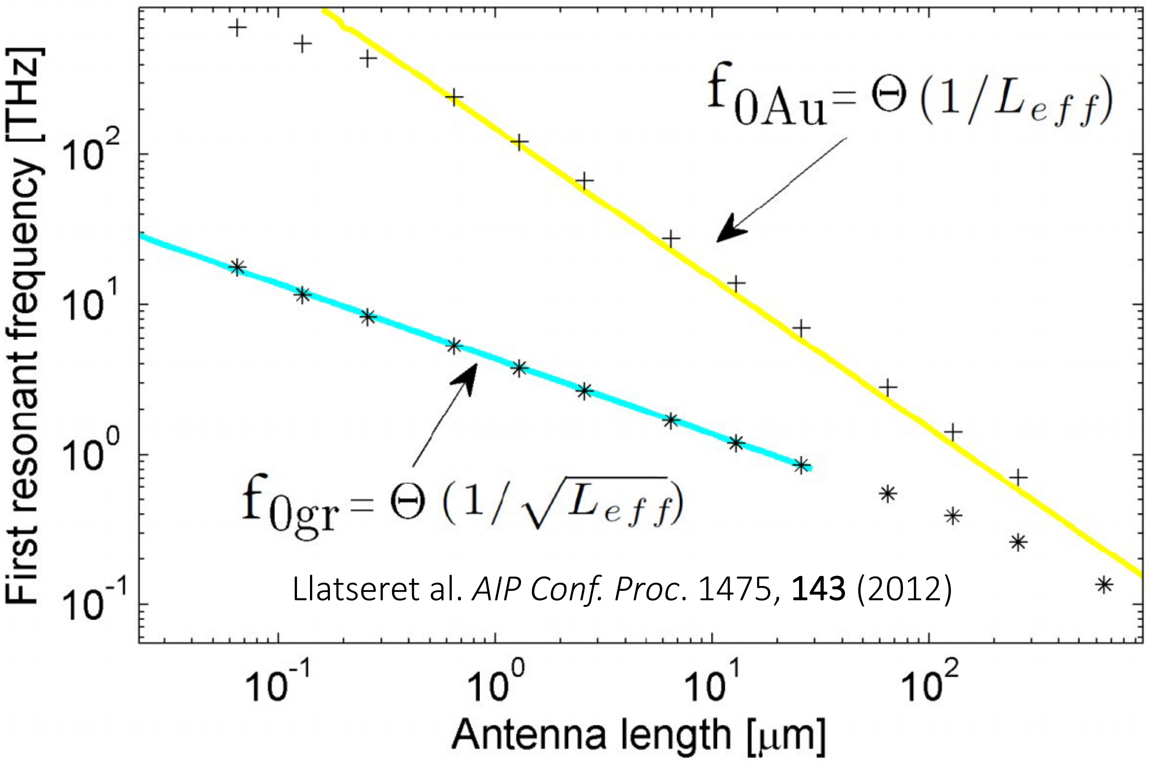
IEEE Trans. Microw. Theory Tech., 66, 2018, 2018.

3-Stage Distributed Power Detector

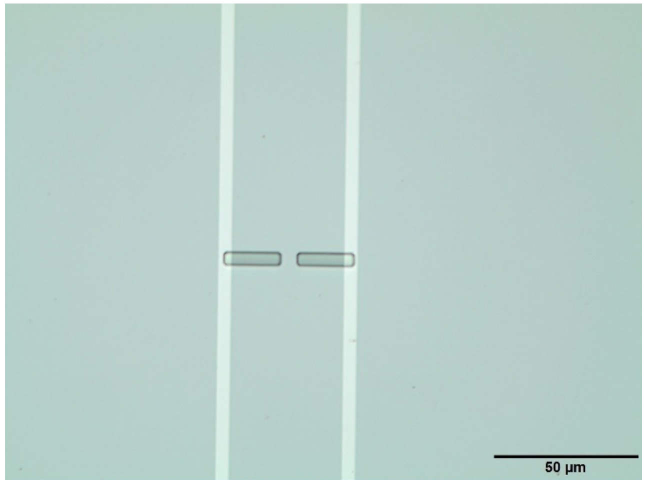


IEEE MTT-S International Microwave Symposium (IMS), 2018.

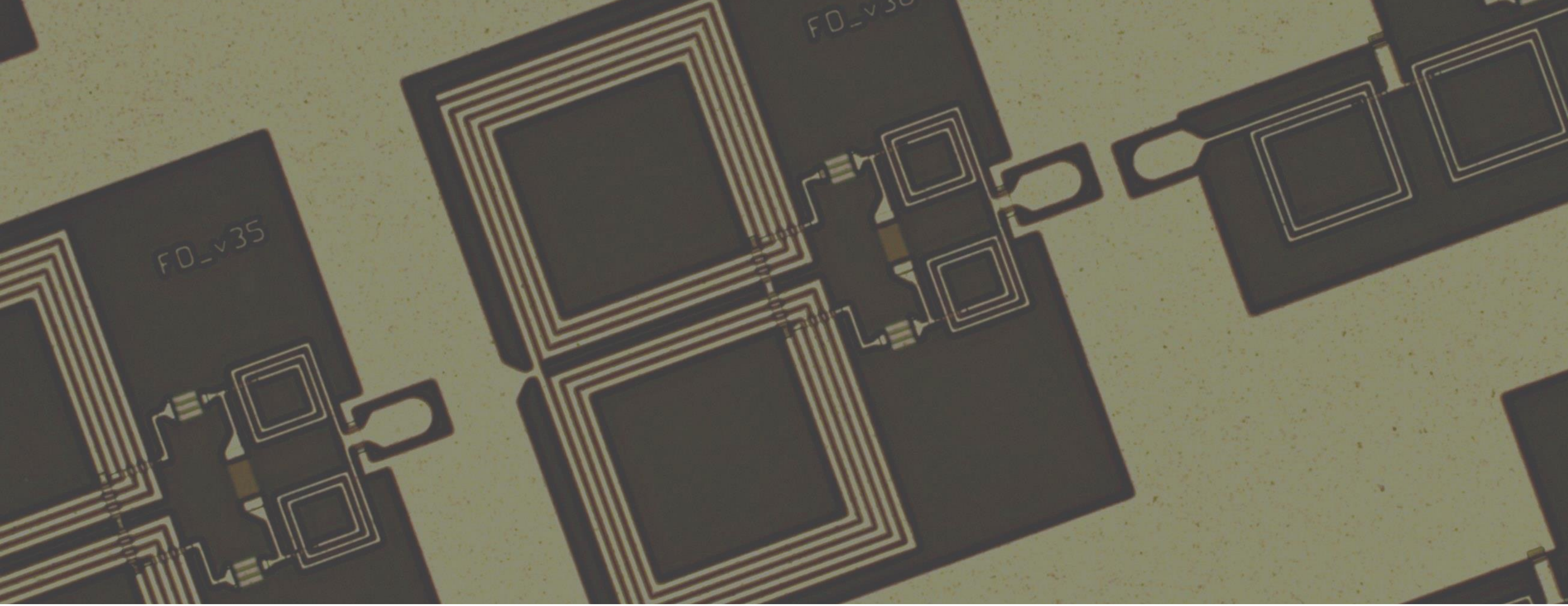
Graphene Antenna



Llatseret al. *AIP Conf. Proc*. 1475, **143** (2012)



- Graphene Antennas can be up to two orders of magnitude smaller
- Frequency tunable by Fermi level tuning



WiPLASH

www.wiplash.eu

Architecting More Than Moore - Wireless Plasticity for Massive Heterogeneous Computer Architectures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 863337 (WiPLASH).

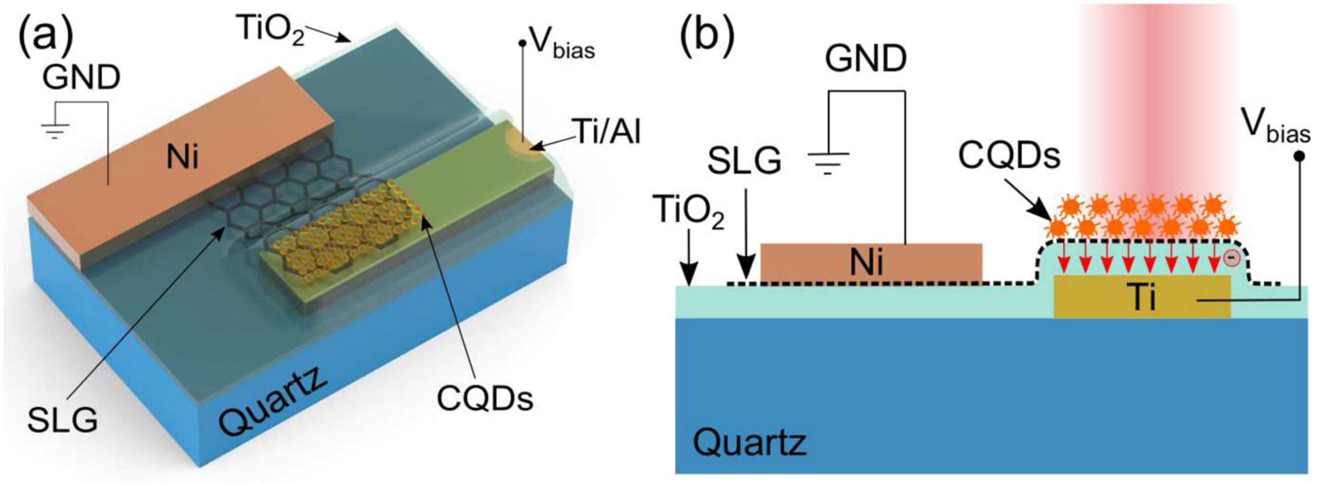
Poster from Kun-Ta Wang, Elana Pereira de Santana

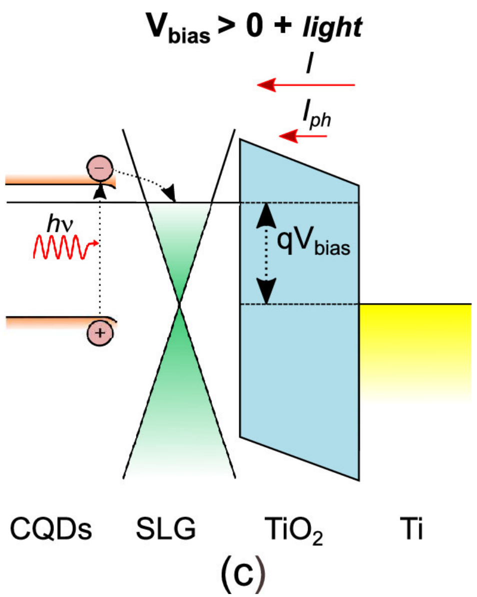
Metal-Insulator-Graphene Diode

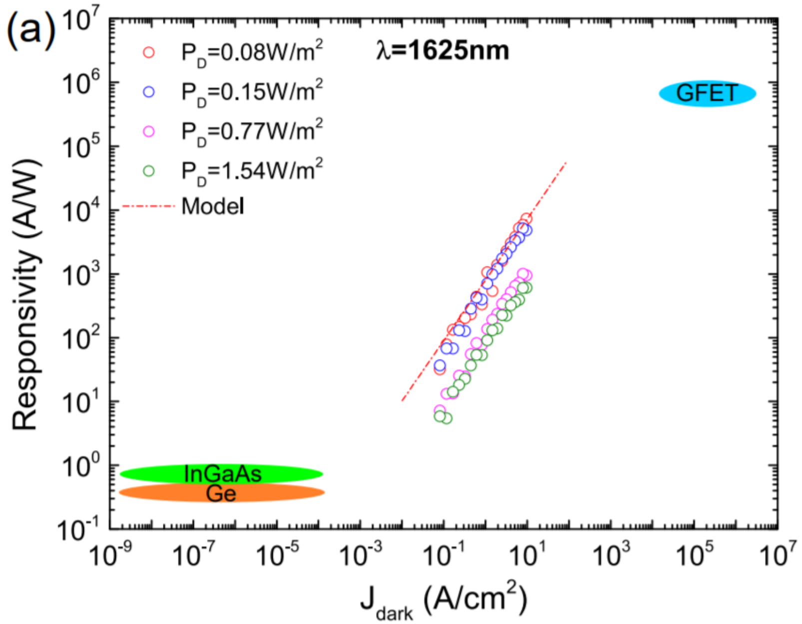
Application as Photosensors

GreEnergy

Photodiodes



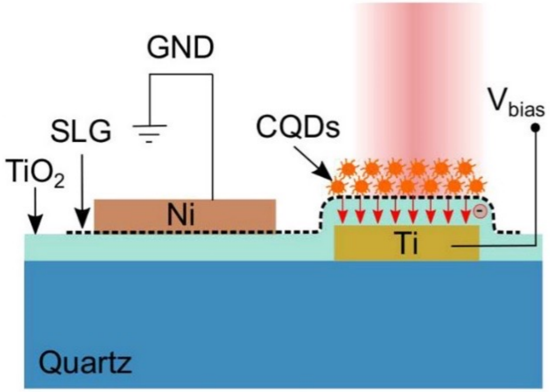


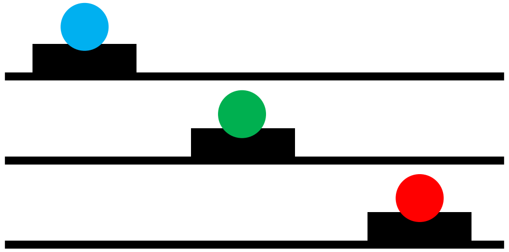


De Fazio *et al*.
ACS Nano 2020, 14, 9, 11897–11905

MISEL

Multispectral Intelligent vision System with Embedded Low-power neural computing





Adaptive multispectral (VIS-to-NIR) pixels for the camera

https://www.misel-project.eu/

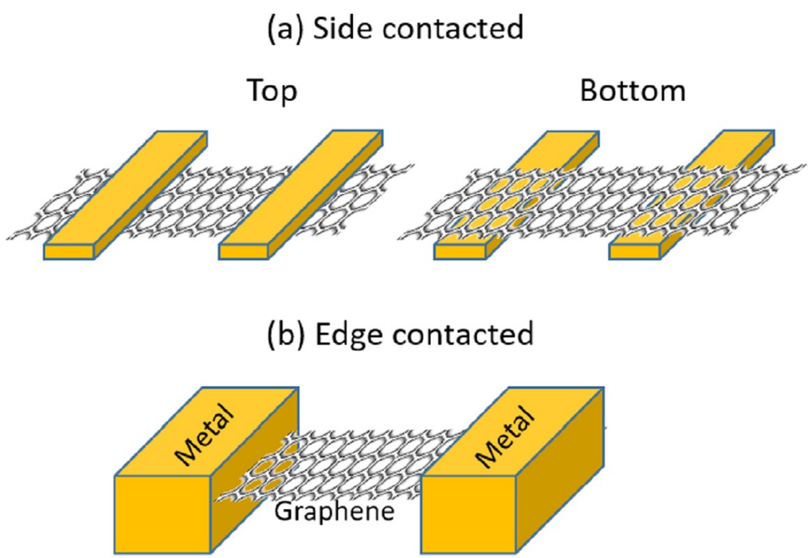
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101016734 (MISEL).

1D Metal-Insulator-Graphene Diode

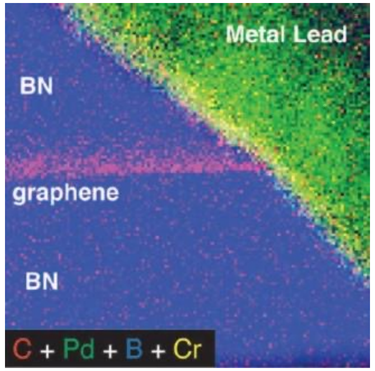
Basic Device and Application in Energy Harvesting

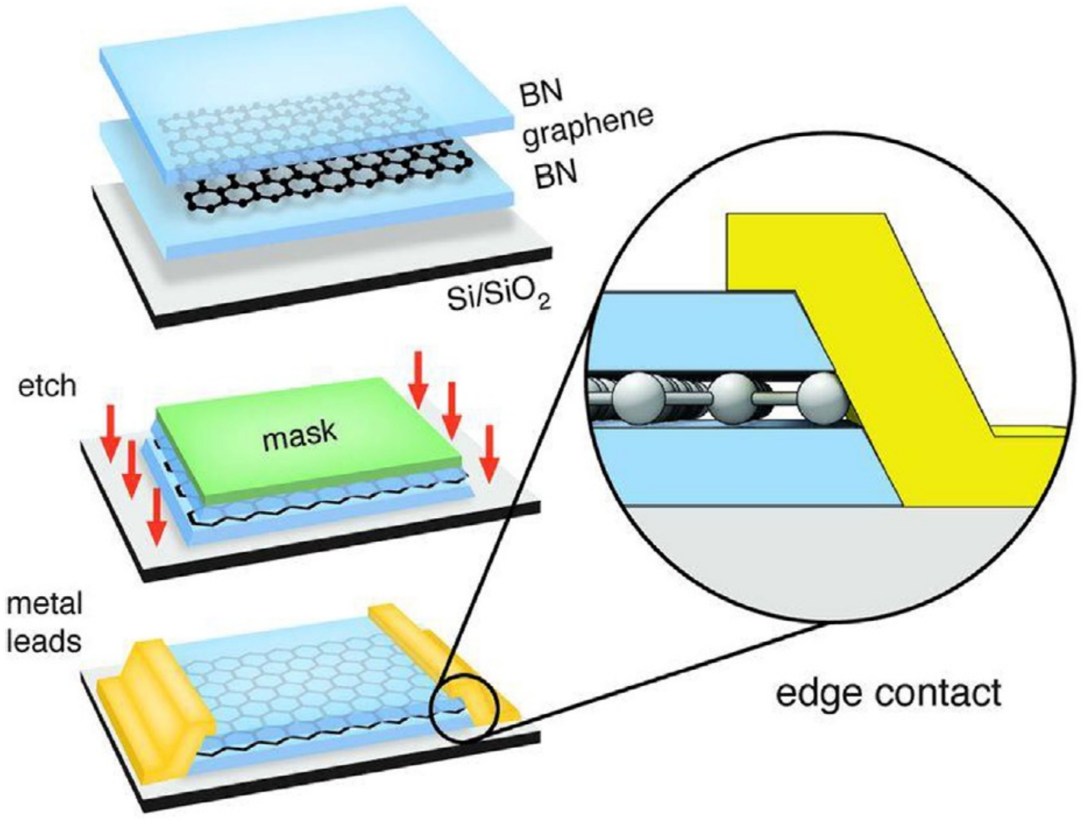
GreEnergy

Edge Contact to Graphene



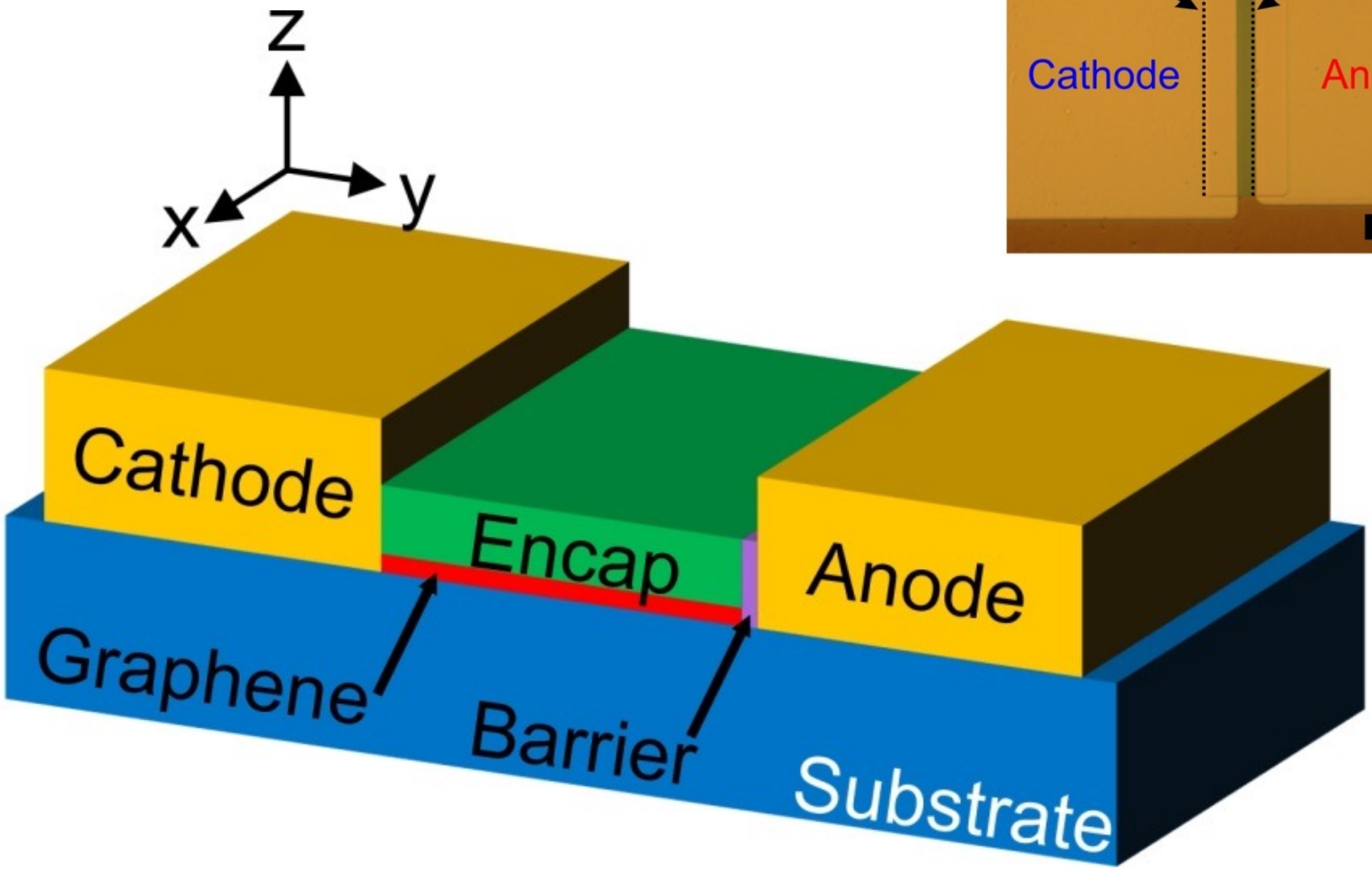
Progress in Surface Science 92 (2017) 143–175

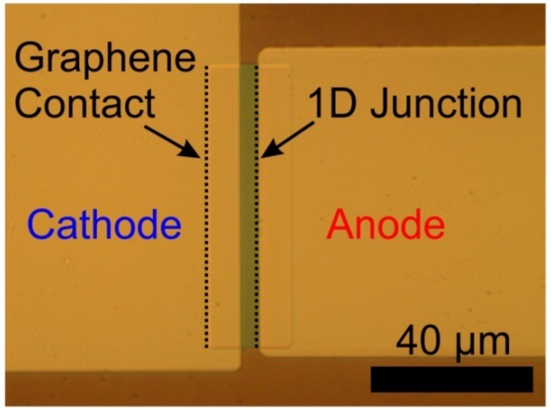




Science, 342, 614, 2013.

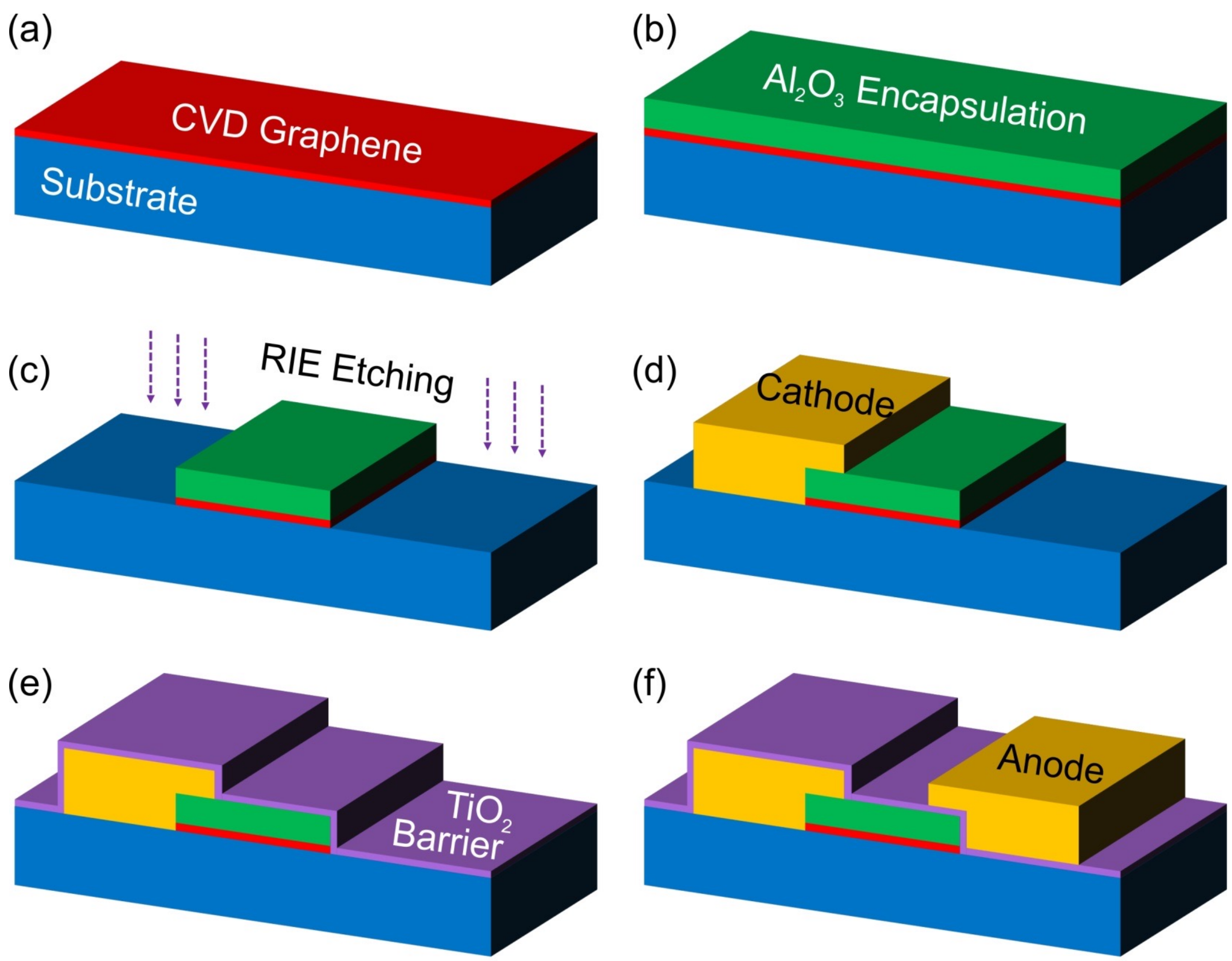
1D MIG Diode





ACS Appl. Electron. Mater. 2019, 1, 6, 945–950

1D MIG Diode - Fabrication

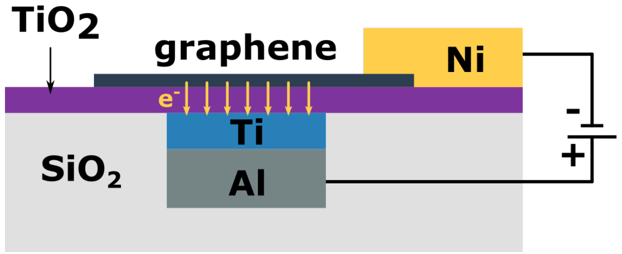


ACS Appl. Electron. Mater. 2019, 1, 6, 945–950

GreEnergy

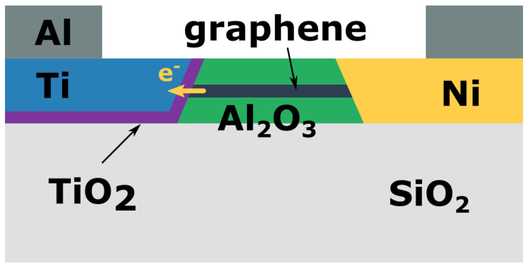
2D or not 2D?

2D



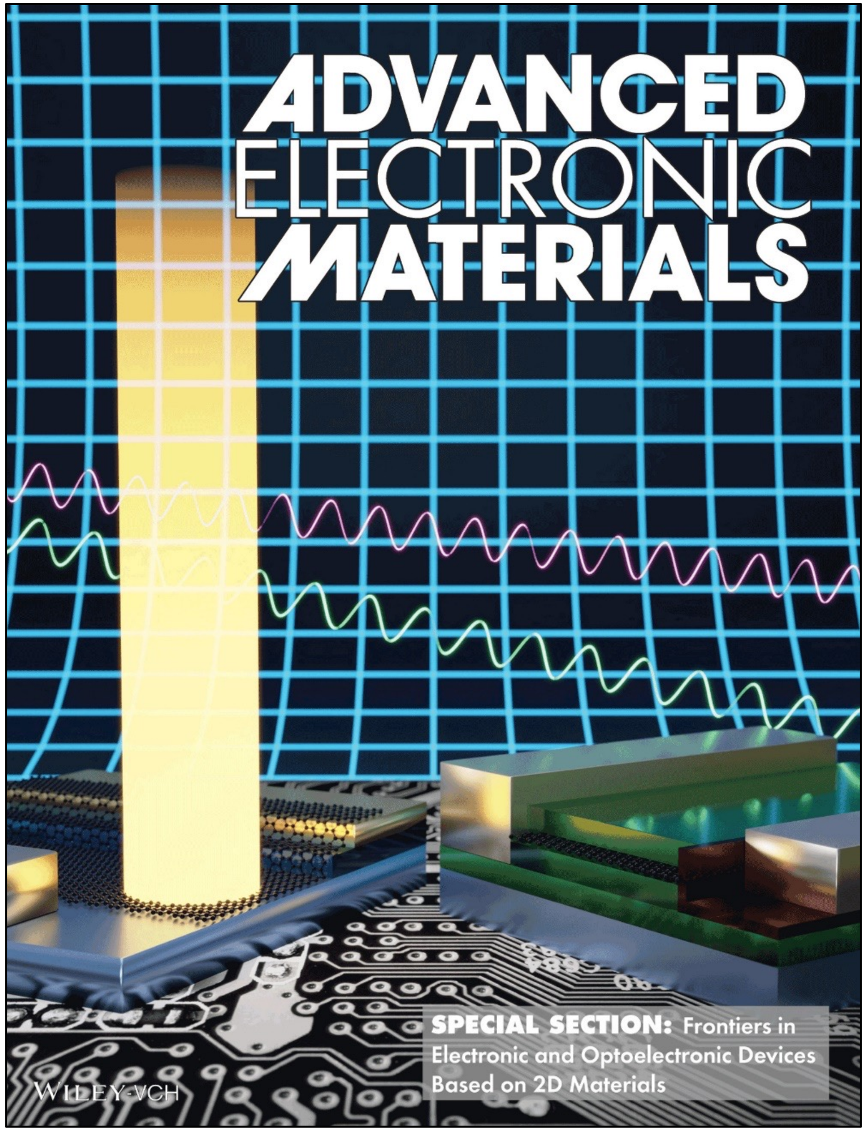
- easier fabrication
- weak interaction between graphene and oxide => high *R*
- parallel-plate structure => high *C*
- Large surface for functionalization

1D



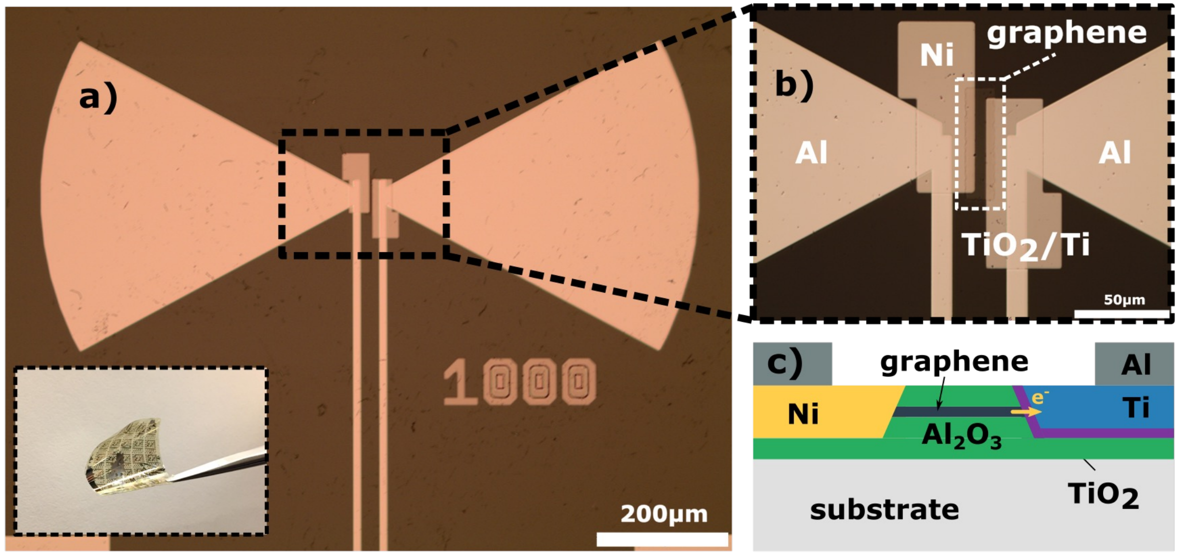
- *R*: lower contact resistance
- *C*: tiny junction cross-section (0.3nm)
- => higher cutoff frequency possible!

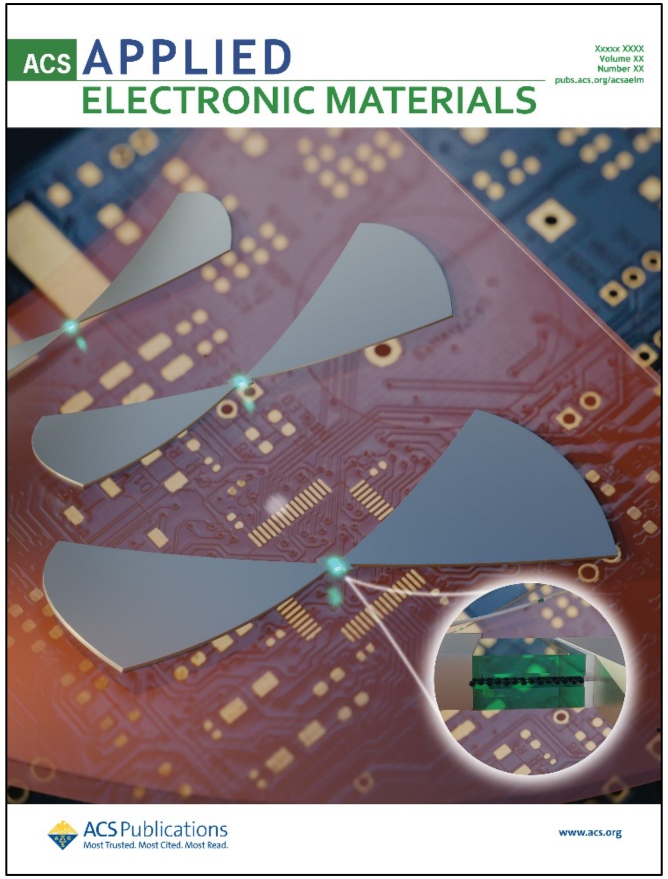
$$f_c = \frac{1}{2\pi \cdot R_a \cdot C_j} = \frac{1}{2\pi \cdot 6\ \Omega \cdot 11\ fF} = 2.4\ \mathrm{THz}$$



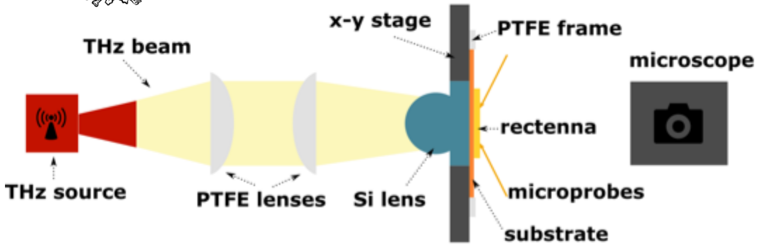
Z. Wang, et al. Adv. Electron. Mater. 7, 2001210, 2021.

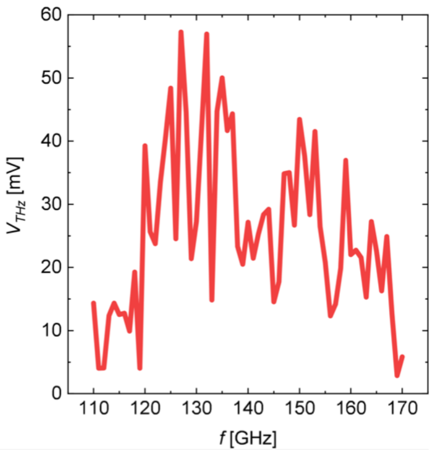
Flexible graphene THz rectennas





Cover Art: ACS Applied Electronic Materials





Poster from Andreas Hemmetter

ACS Applied Electronic Materials (2021) 3, 3747.

Summary

- Graphene can be produced by large scale with CVD
- Graphene based transistor is not ideal
- Metal-insulator-graphene diode is useful to realize rectification
- With the 1D configuration, we can go even higher frequency for the rectification
- In the end a rectifier based on graphene is demonstrated up to 170 GHz

Funding Acknowledgement

DFG

HiPeDi (WA 4139/1), GLECS2 (NE1633/3).

EU

Graphene Flagship (881603), 2D-EPL (952792),
G-Imager (820591), WiPLASH (863337),
GreEnergy (101006963), MISEL (101016734), PlasmoniAC (871391).

Teams and Collaborators (related to the work presented):

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) …

Thank you for your attention

More information is available at **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).