Integrated Circuits for RF Communication with Graphene based Devices

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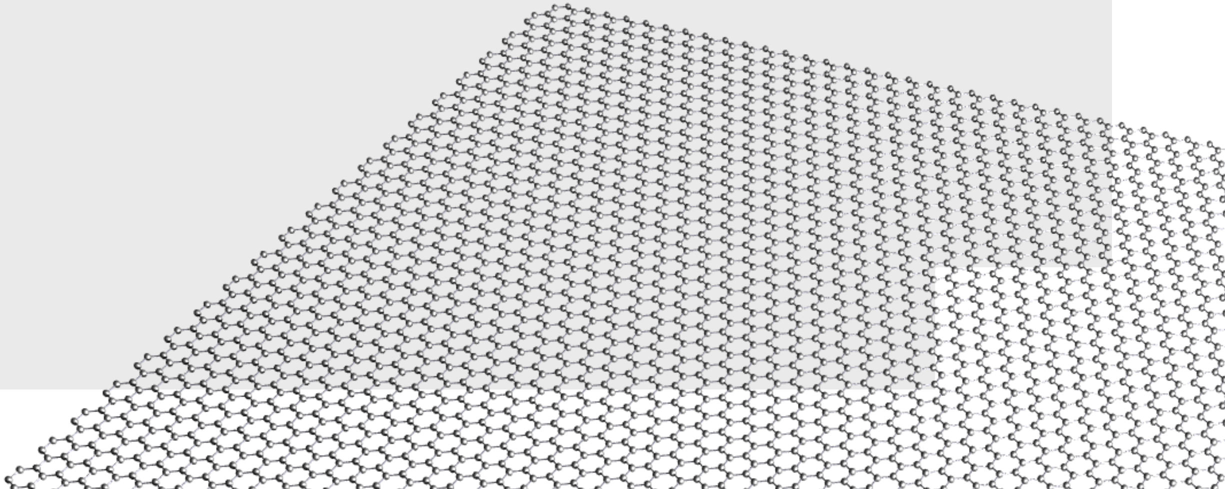
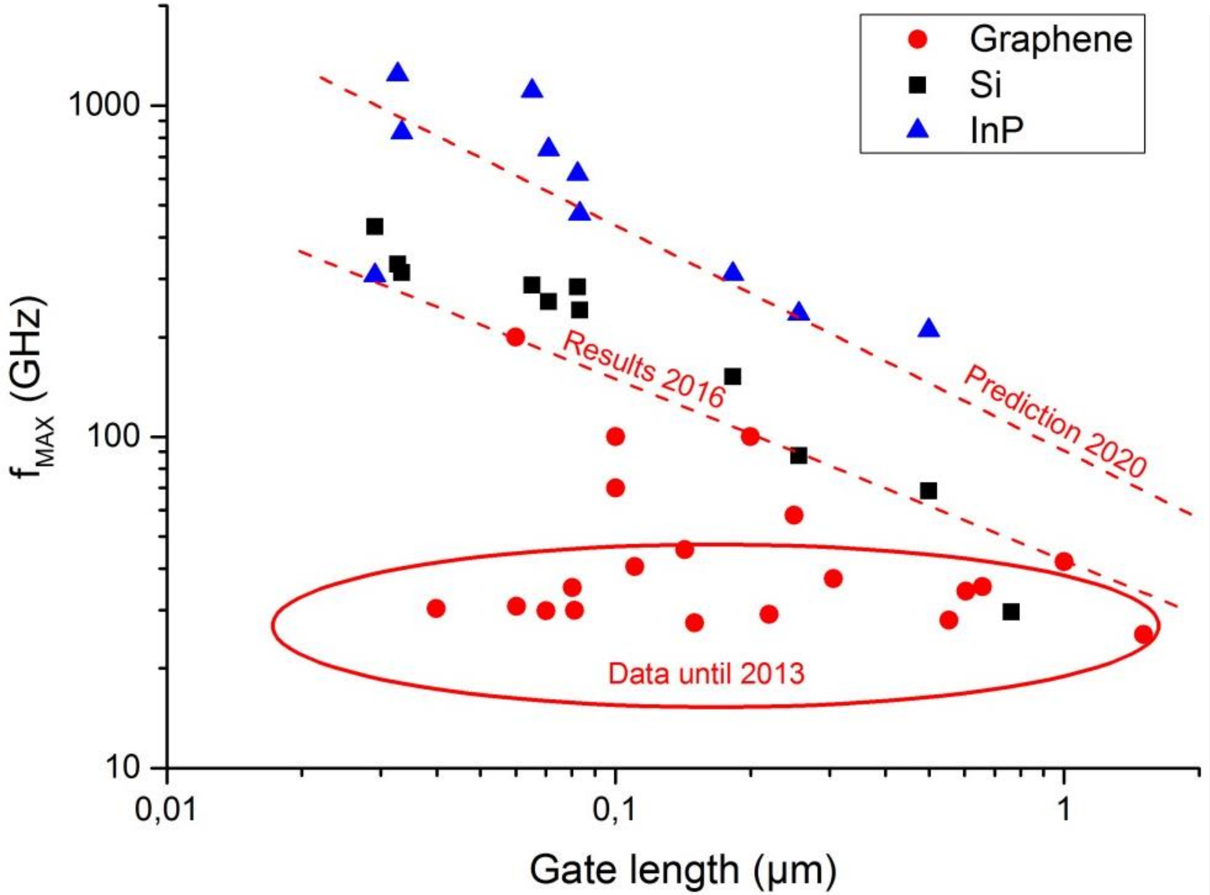


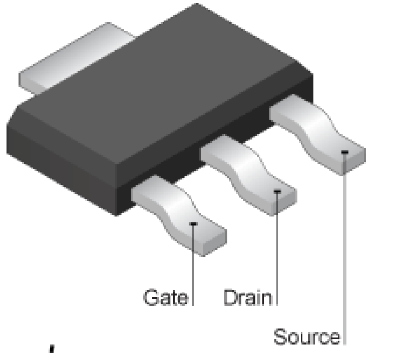
State-of-the-art: GFETs



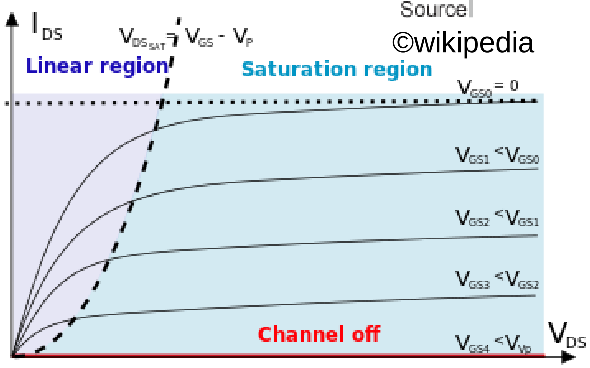
- ➢ f_{MAX} is still improving due to optimized GFET fabrication.
- ➢ Highest values are already competitive to Si CMOS.
- ➢ It is expected that InP can be matched until 2020.

High Frequency Electrical Components

Transistor



©wikipedia



- Amplification
- MOS integrated circuits
- CMOS circuits
- Analog switches
- Power detection

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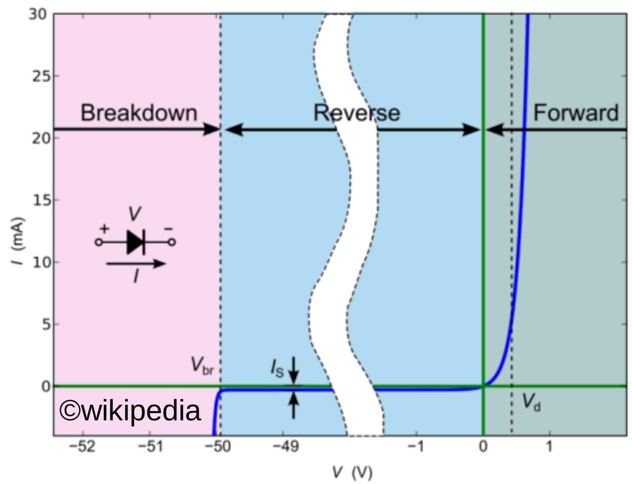
Diode



- Radio demodulation
- Power conversion
- Over-voltage protection
- Logic gates

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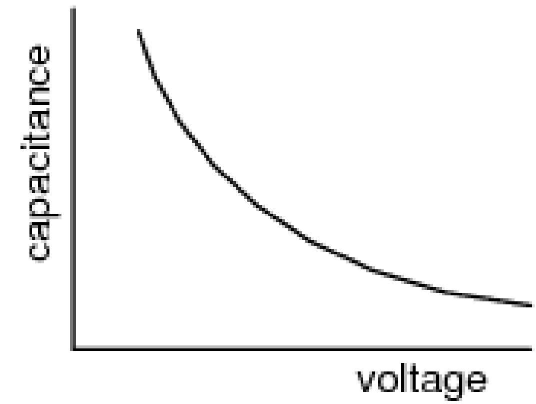
Varactor



- Voltage-controlled oscillators
- Parametric amplifiers
- Frequency multipliers

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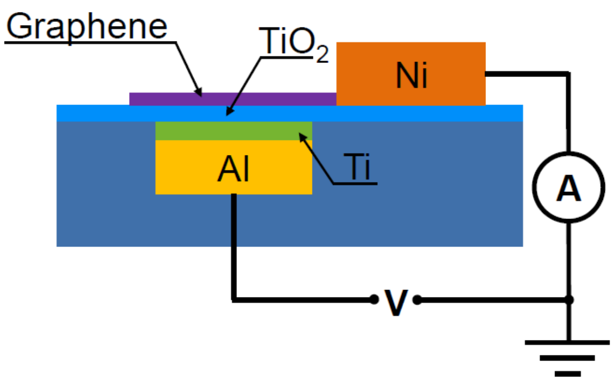
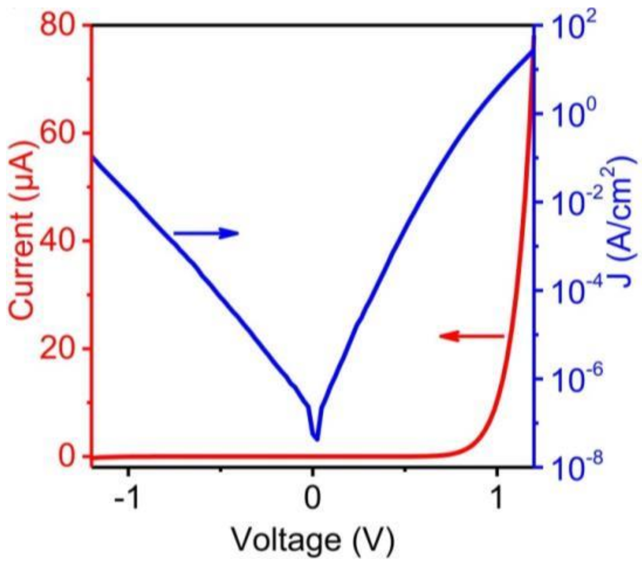
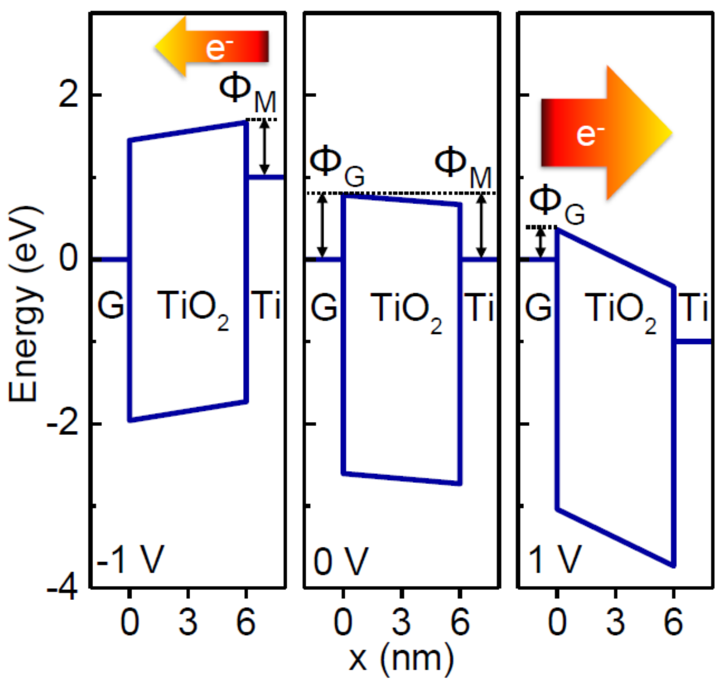
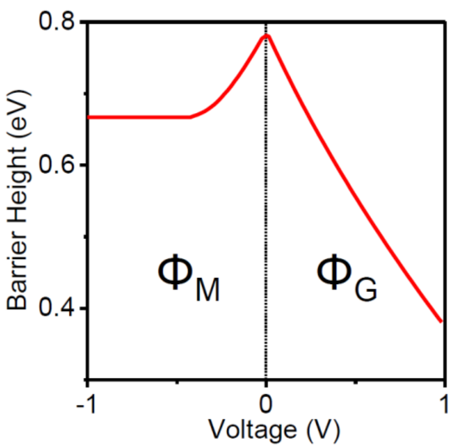
Metal Insulator Graphene (MIG) Diodes





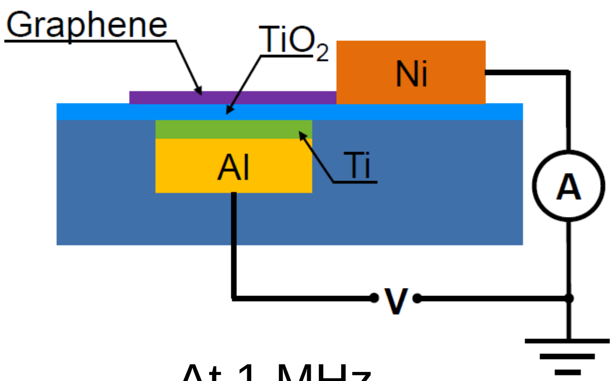
Bias induced barrier lowering





Shaygan *et al*. Nanoscale, 2017.

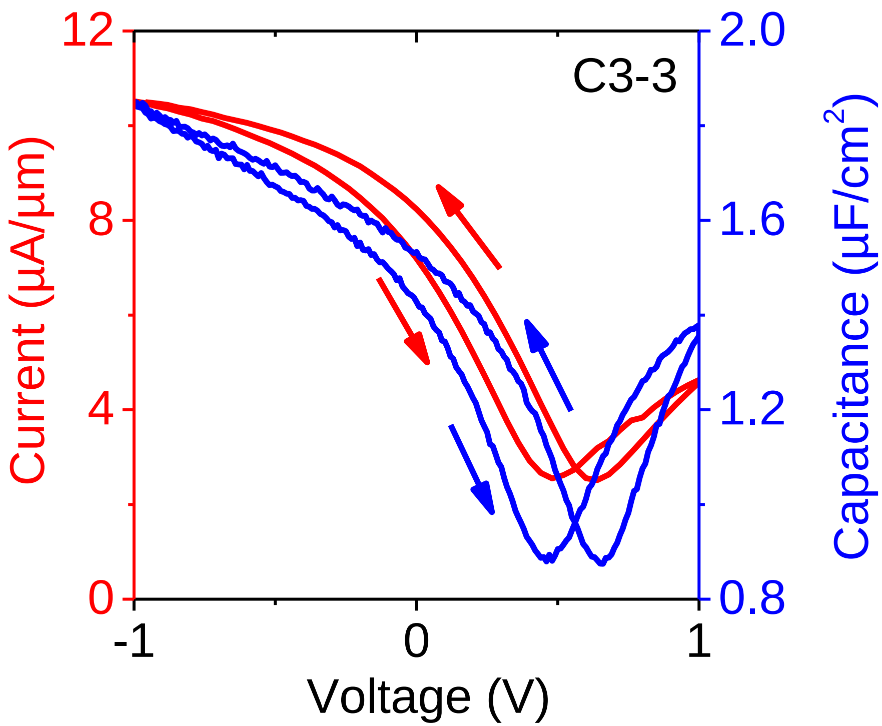
MIG varactors



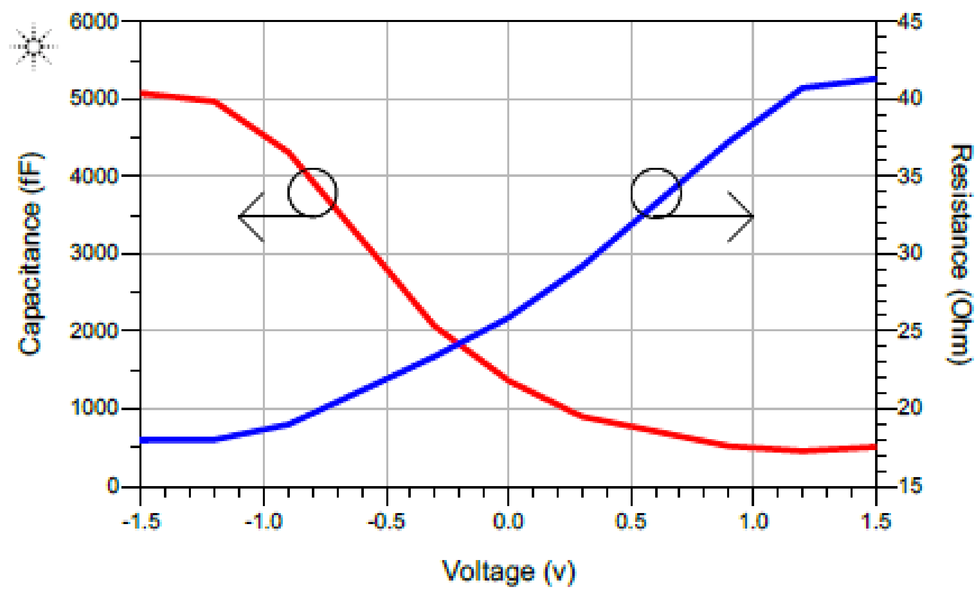
Varactor behaviour of MIG Diode:

- Quantum Capacitance of Graphene

At 1 MHz



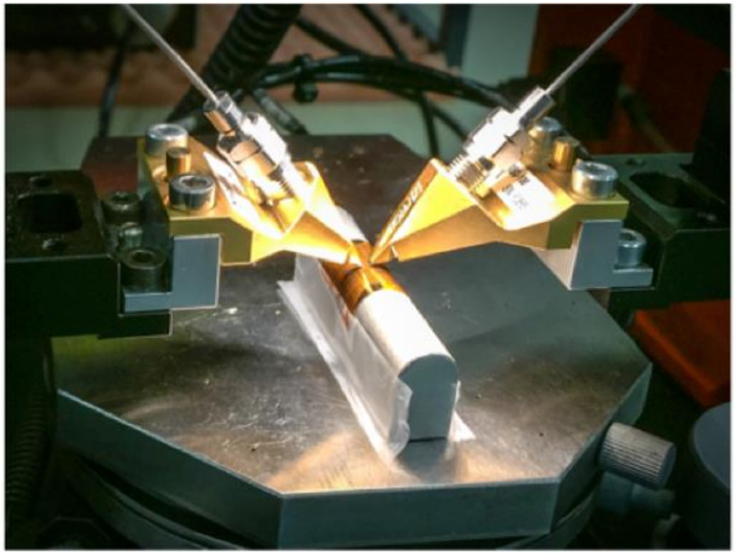
At 20 GHz from S parameters



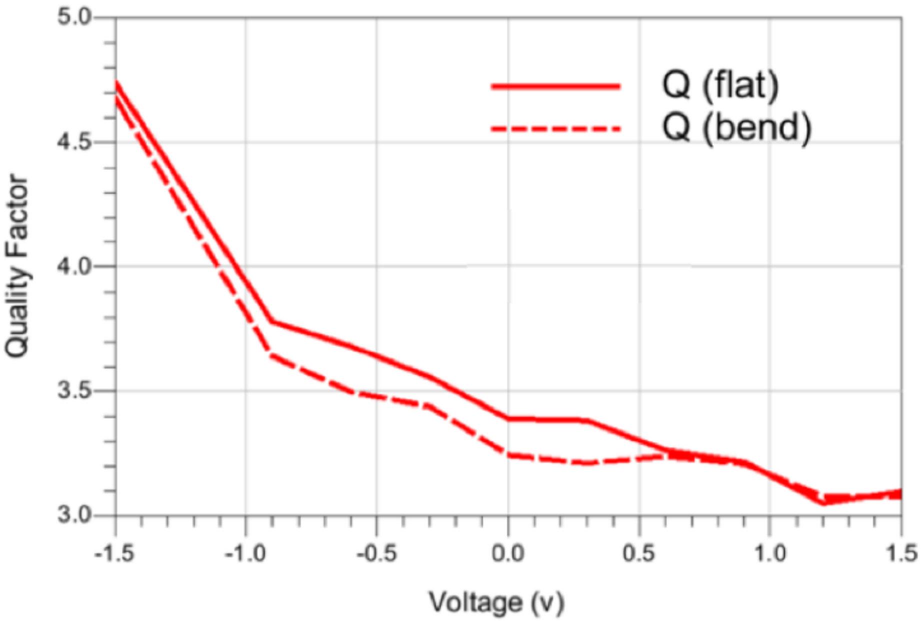
RWTH / AMO / Uni Pisa to be published (2018)

MIG diodes

RF measurments of diodes

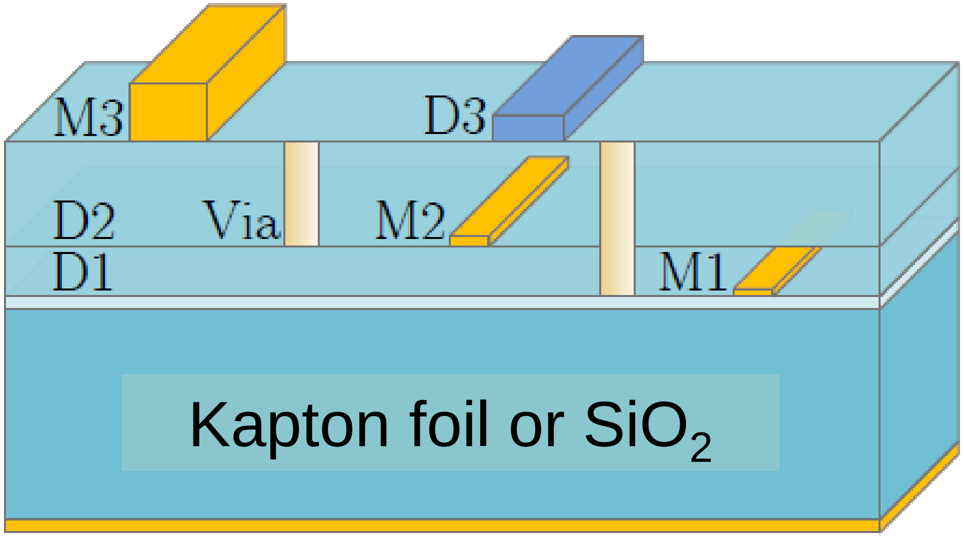


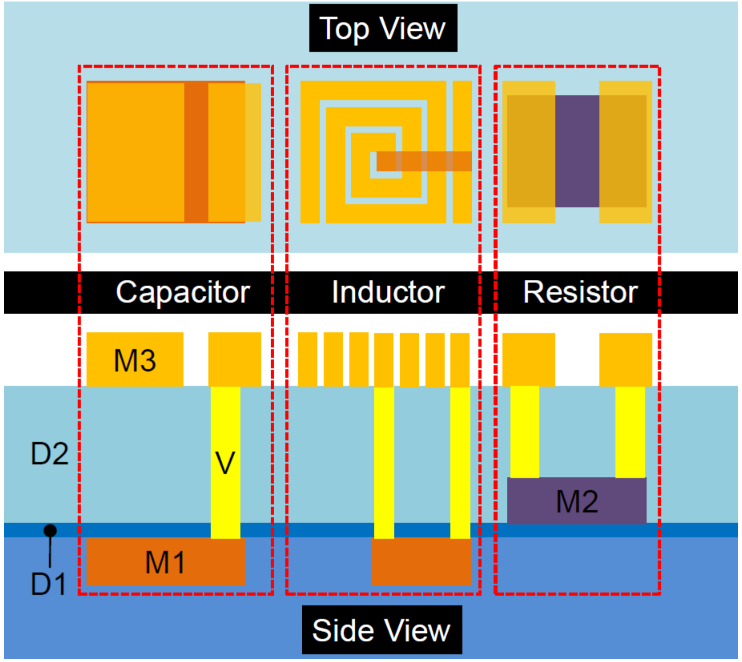
Measured Q-factor at 60 GHz



- ➢ Operation at 60 GHz demonstrated (Q=4). Cut-off frequency >100 GHz.
- ➢ Same performance in the bended state.
- ➢ With design optimization THz operation feasible.

MMIC Process on Any Substrate





3 Dielectric layers:

- D1: 5 nm TiO2 (diodes, varactors) or 5-10 nm Al2O3 (transistors)
- D2: 90nm Al203 (encapsulation, capacitors)
- D3 500 nm SU8 (inductors)

4 Metal layers:

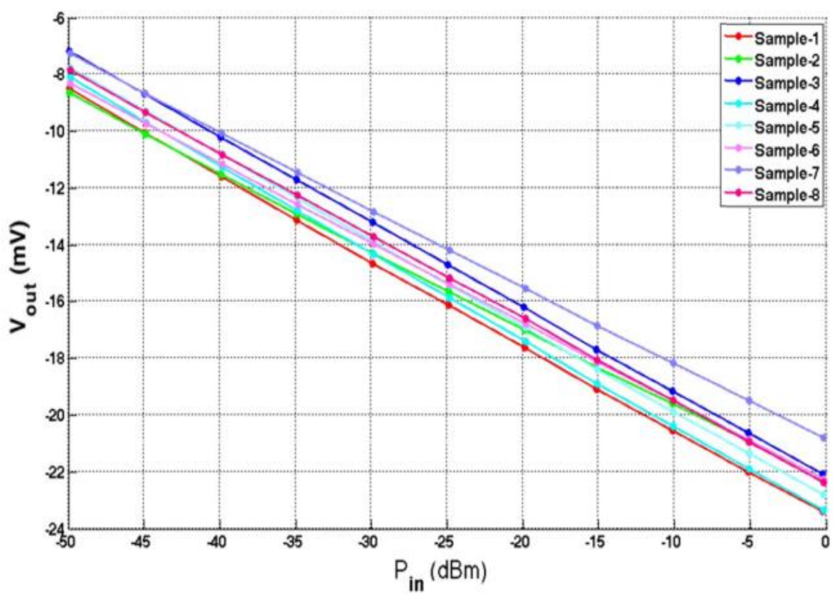
- M1: 100nm Al (gate electrode, passives)
- M2a: 20 nm Nickel (graphene contacts)
- M2b: 110 nm TiN (resistors)
- M3: 2µ Al (passives, interconnects)

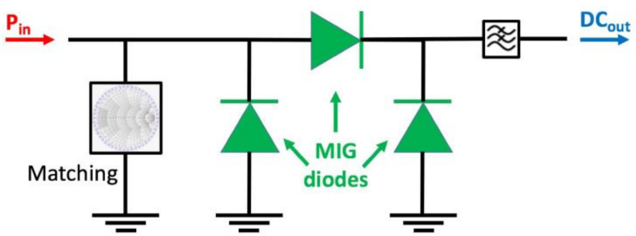
Graphene is between D1 and M2, and can be used in diodes, varactors or/and transistors.

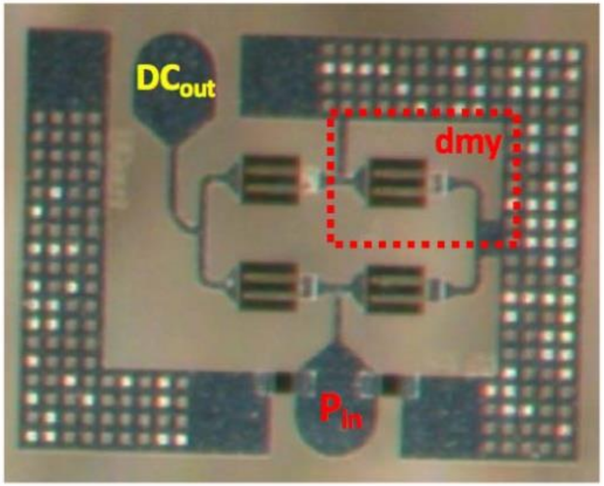
2015 German Microwave Conference (GeMiC) Nuremberg, pp. 299-302.

Linear in dB Power detector

- Implemented using:
  - GFET: up to 110 GHz
  - MIG-diode: up to 70 GHz





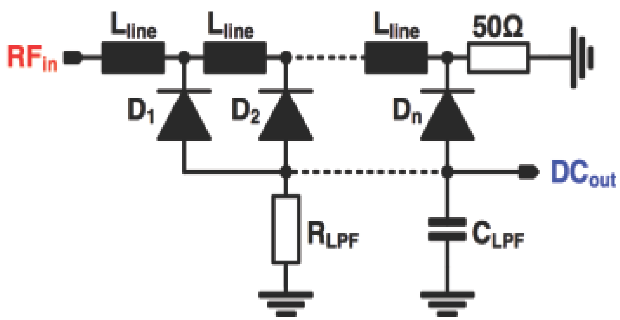


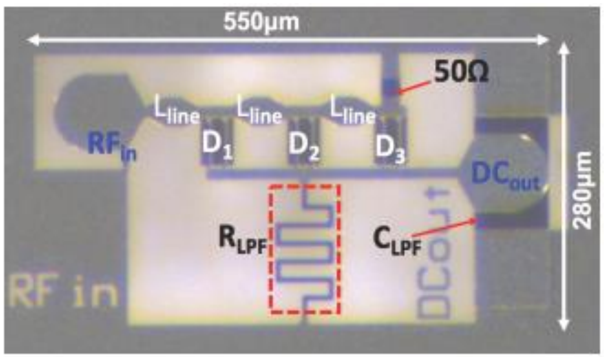
- Comparison with competing technologies

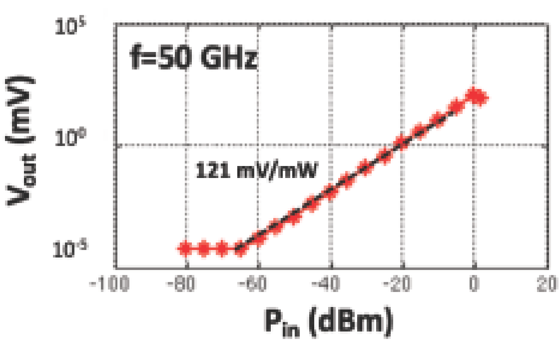
Ref.	Tech./Sub.	Scheme	DR (dB)	P_{min}/TSS (dBm)	Area (mm^2)	Responsivity (V/W)	Frequency (GHz)
[Saeed:2017cra]	500µm quartz	Linear-in-dB	50	-50	0.15	15	60
[Wei:2017do]	65nm CMOS	Distributed CG	20	-23	0.45	68	110
[Hrobak:2013bq]	GaAs Schottky	Single diode	25	-50	0.635	1000	110

M. Saeed, et. al , IEEE/MTT-S Inter. Micro. Symp. - IMS 2017, 2017.

Distributed feedback power detector







Ref.	Tech.	P_{DC} (mW)	DR (dB)	TSS (dBm)	Freq. (GHz)
[2]	GFET	0	40	-60	3
[8]	65nm-CMOS	0.029	21	-36	0.01-110
[9]	65nm-CMOS	0	20	-40	0.01-110
[10]	GaAs Schottky	0	25	-57	60-110
[13]	0.25μm SiGe	7.2	52	-45	7-20
This work	Custom MMIC	0	>60	-65	DC-70

Diode based power detector:

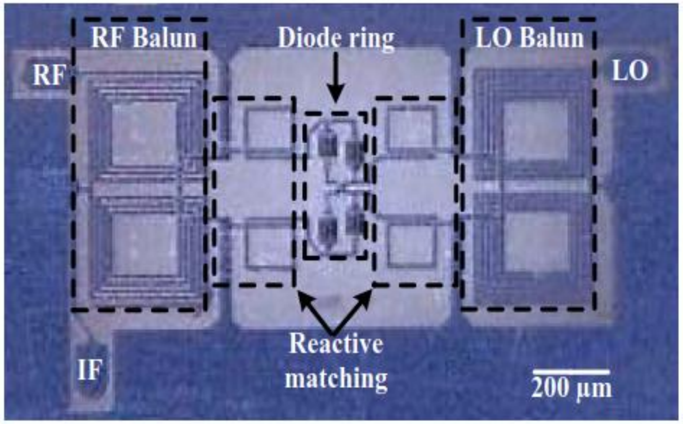
- Excellent linearity.
- High sensitivity.

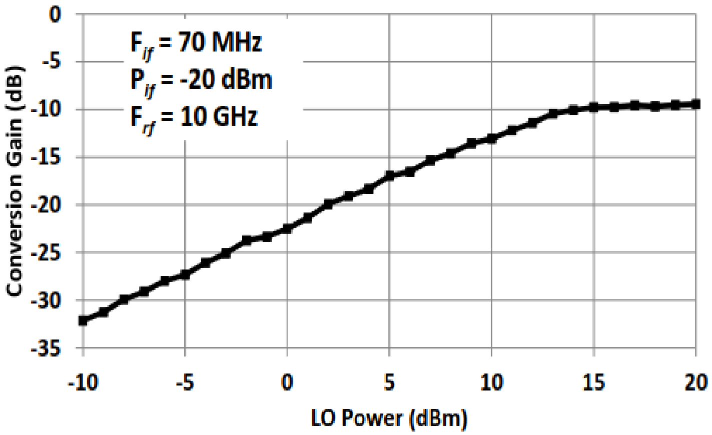
➢ Outperforms SOTA!

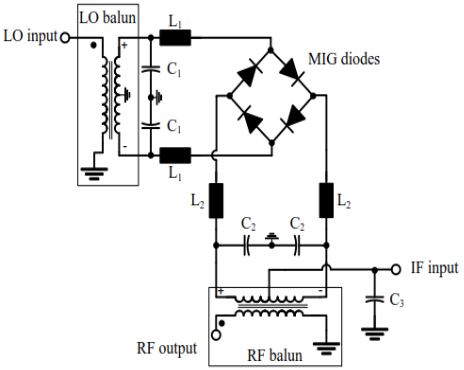
M. Saeed, et. al , IEEE/MTT-S Inter. Micro. Symp. - IMS 2018, 2018.

RF Mixer

6-12 GHz Double balanced upconversion mixer (MIG-diode on glass MMIC)





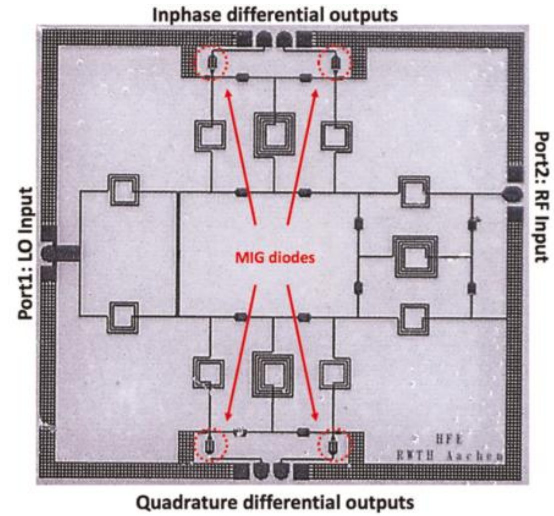


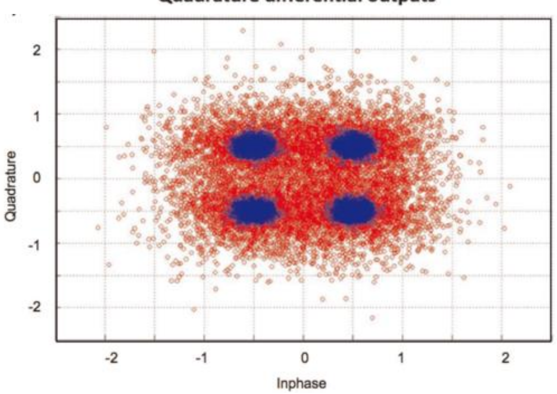
Ref.	Substrate	Device	Scheme	RF frequency	Conversion gain
[2]	Silicon-CMOS	GFET	Double-balanced, partially integrated, resistive mixer	3.5 GHz	-33 dB
[3]	Silicon	GFET	Single-device, hybrid, resistive mixer	4 GHz	-45 dB
[4]	SiC	GFET	Single-device, integrated, resistive mixer	88-100 GHz	-18 dB
[8]	GaAs	Schottky diode	Double-balanced, fully integrated, diode mixer	5-12 GHz	-9 dB
This work	**Glass**	**Graphene-diode**	**Double-balanced, fully integrated, diode mixer**	**6-12 GHz**	**-10 dB**

A. Hamed, et. al , IEEE/MTT-S Inter. Micro. Symp. - IMS 2018, 2018.

Graphene integrated circuits:
Receivers

- State-of-the-art graphene receiver:
  - Six-port receiver frontend
  - MIG-diodes based power detectors
  - Characterized at:
    - P_{in} = -15 dBm
    - f_{in} = 2.45 GHz
    - 20 Mbps, QPSK



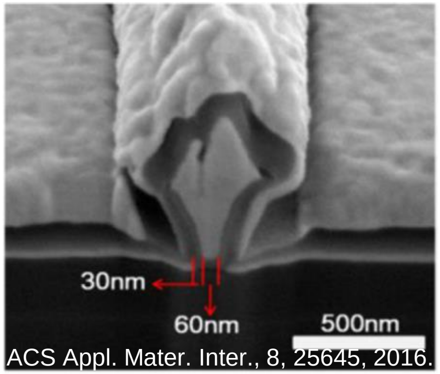


- Graphene receivers

Ref.	Tech./Sub.	Scheme	Modulation	f_{RF} (GHz)	P_{LO} (dBm)	P_{DC} (mW)	Conversion gain (dB)
[Yogeesh:2015fo]	125µm kapton	1-GFET	AM	2.45	NA	NA	-35
[Han:2014hn]	Si/SiO_2	3-stage /GFET	FM	4.3	-2	20	-10
[Saeed:2018cs]	500µm quartz	Sixport/4-MIG diodes	QPSK	2.45	0	0	-7

M. Saeed, et. al, "Nanoscale, 2018.

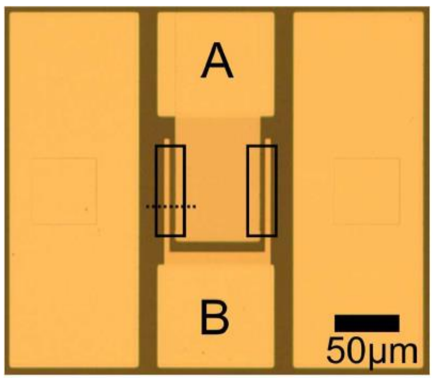
Summary



ACS Appl. Mater. Inter., 8, 25645, 2016.

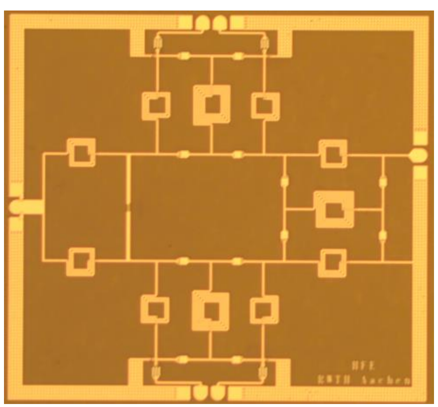
Transistors:

- f_{max} not yet superior to bulk Si and III/V.
- Limitations are parasitic effects: Gate resistance, contact resist, dielectric, and so on.
- But values are already outstanding for thin film transistors.



Diodes / Varactors:

- Interesting device concepts enabled by special graphene properties.
- Promising performance, especially suitable for high frequency.



MMIC Process:

- Competitive RF circuits are fabricated based on the in house process and functional circuits based on graphene are demonstrated.

AMO

Acknowledgement

<u>AMO Graphene Team</u>:

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Martin Otto, Zhenxing Wang,
Barbara Canto, Burkay Uzlu
Galip Hepgüler, Amir Nekounam,
Daniel Schneider, Santiago Cartamil

Aachen Graphene & 2D-Materials Center

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Aixtron, Alcatel-Lucent, Graphenea,
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Gianluca Fiori, Uni Pisa
Inessa Bolshakova, Lviv PNU
Frank Koppens, ICFO
Thomas Müller, TU Wien

SEVENTH FRAMEWORK PROGRAMME

Deutsche Forschungsgemeinschaft
DFG

GRAPHENE FLAGSHIP