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Modeling of THz detection using FETs

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Outline

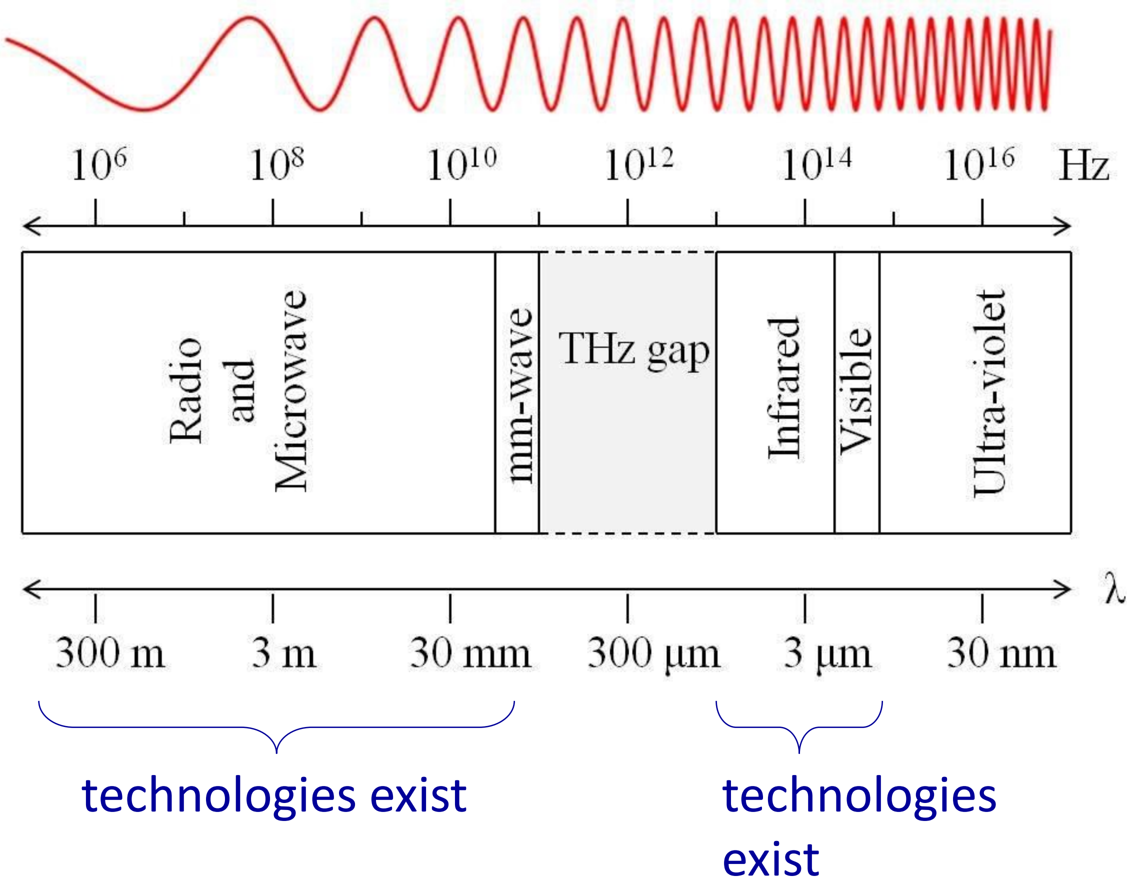
- THz radiation
- Field-effect transistors (FETs) as THz radiation detectors
- Measurements of FET-based THz radiation detectors
- Mechanisms and models of FET response to THz radiation
  - Plasmon-based, Resistive mixing (RM), Distributed resistive mixing
  - Compact modeling of THz FETs
- Development of FET-based THz radiation detectors in Ł-IMiF
  - Technology, measurements and characterization
  - Modeling
- Summary

THz radiation; Features

Exceptional wave features:

- **Resolution:** smaller wavelengths compared to the microwaves ➔ better spatial imaging resolution;
- **Safety:** photon energies much lower compared to X-rays ➔ THz radiation is non-ionizing;
- **Spectral fingerprint:** Inter- and intra-vibrational modes of many molecules lie in THz range;
- **Penetration of THz waves:**
  - attenuated by H_2O particles (atmosphere, all living organisms), and by particles of some other chemical compounds (e.g. explosives);
  - lower scattering and larger penetration (range ~ cm) compared to infrared (range ~ µm) ➔ dry, non-metallic materials are transparent in THz (opaque in visible)

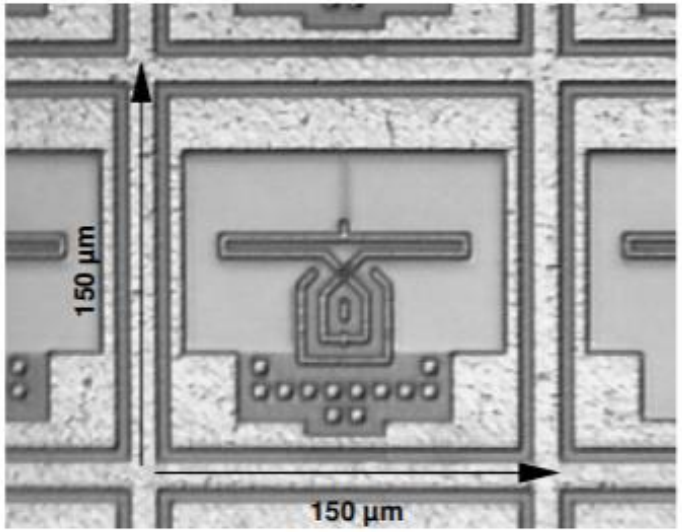
https://www.allaboutcircuits.com/technical-articles/introduction-to-terahertz/



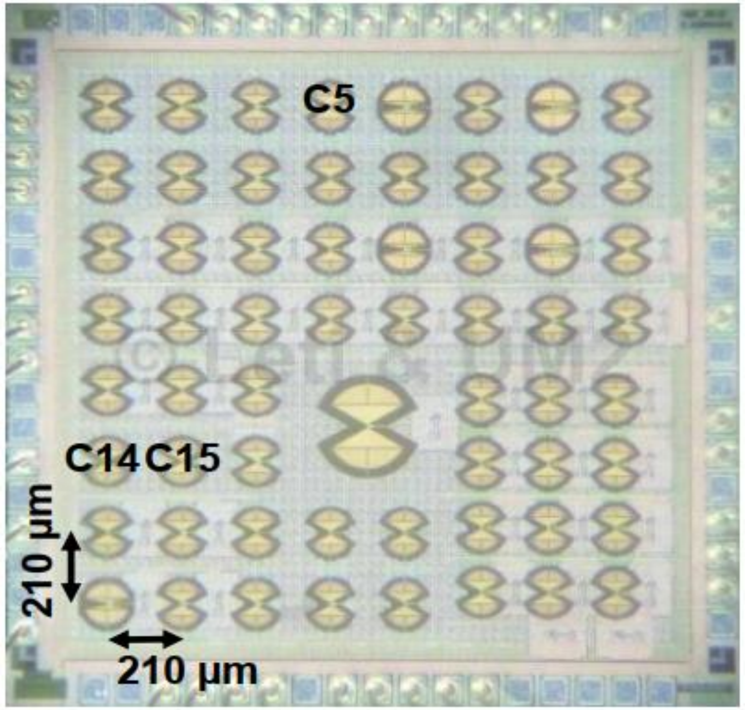
FETs as THz radiation detectors

- FETs (HEMTs, MOSFETs, …) are a highly cost-efficient platform for development of THz radiation detectors;
- Typically n-channel devices are used (p-channel ?);
- Detection of the THz radiation using silicon FETs takes place at frequencies hundreds times higher than the frequency range at which such devices can be used as a signal amplifiers ➔ classic electron transport models are not appropriate do describe the detection mechanism;
- Typical FET configuration: antennas connected to gate, source electrodes; drain open or biased with a DC current source; drain DC voltage is a photoresponse:
  - depends on:
    - THz signal power,
    - gate bias (conduction conditions in the channel),
    - frequency;
  - is order of μV..mV;
  - are other FET configurations possible ?

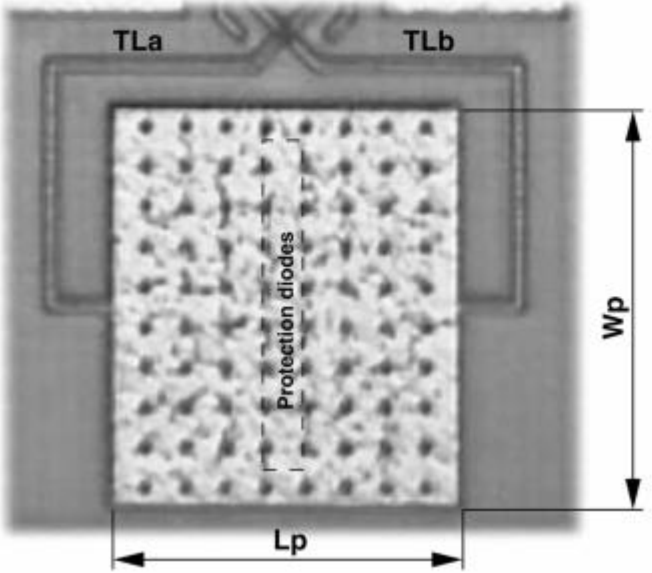
FETs as THz radiation detectors: Monolithic antennas



A pixel with the folded dipole antenna 0.6 THz; IHP's 0.25-µm logic CMOS, NMOS f_T = 35 GHz
U. Pfeiffer, E. Ojefors, "A 600-GHz CMOS Focal-Plane Array for Terahertz Imaging Applications", Proc. ESSCIRC, pp. 110-113, Sep. 2008

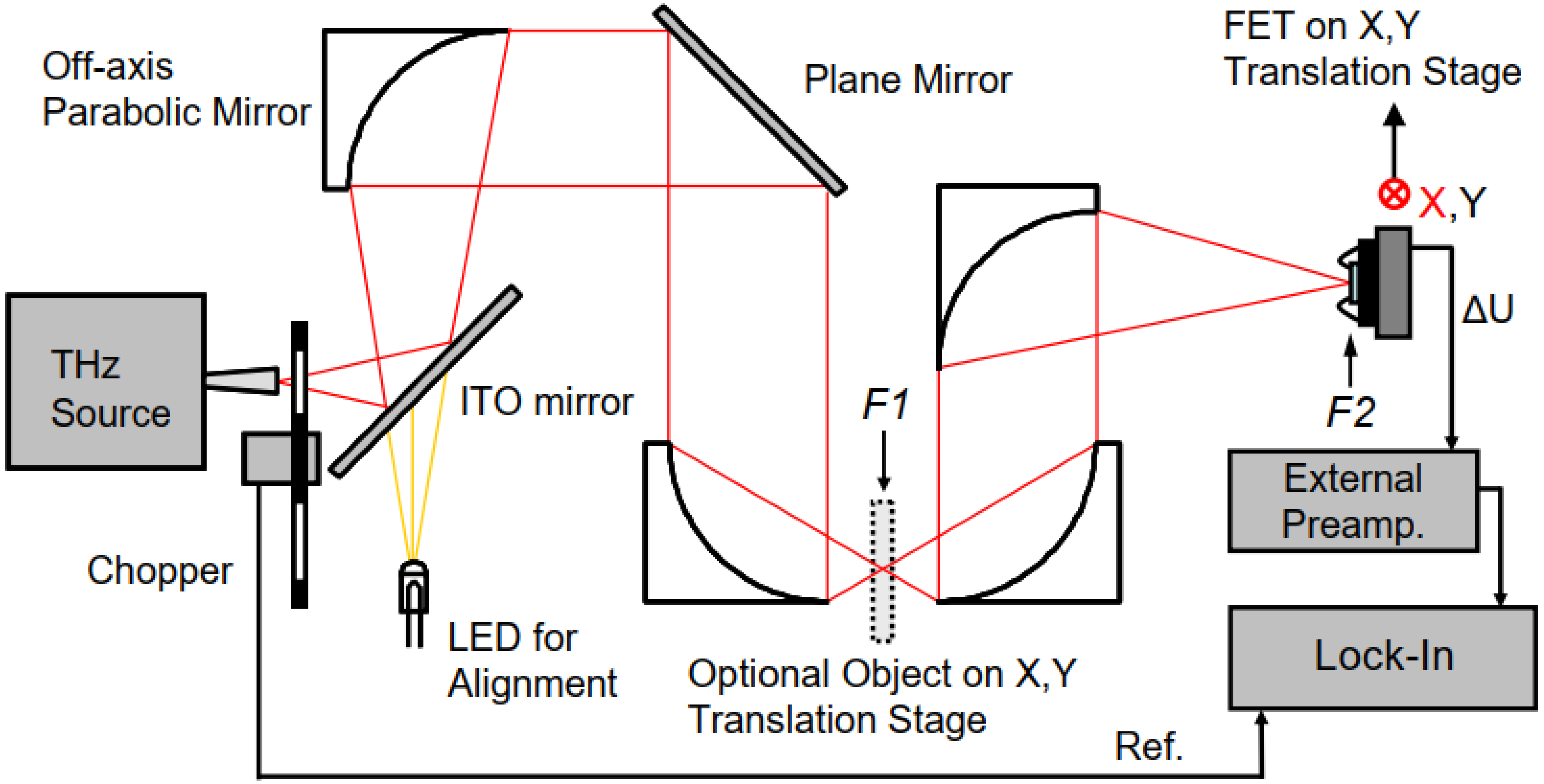


Pixels with broad-band bowtie antennas; f≈0.3 THz; 130 nm CMOS technology on bulk Si substr.
F. Schuster, et al. "Broadband terahertz imaging with highly sensitive silicon CMOS detectors", Optics Express, 19(8), 2011, pp. 7827-32

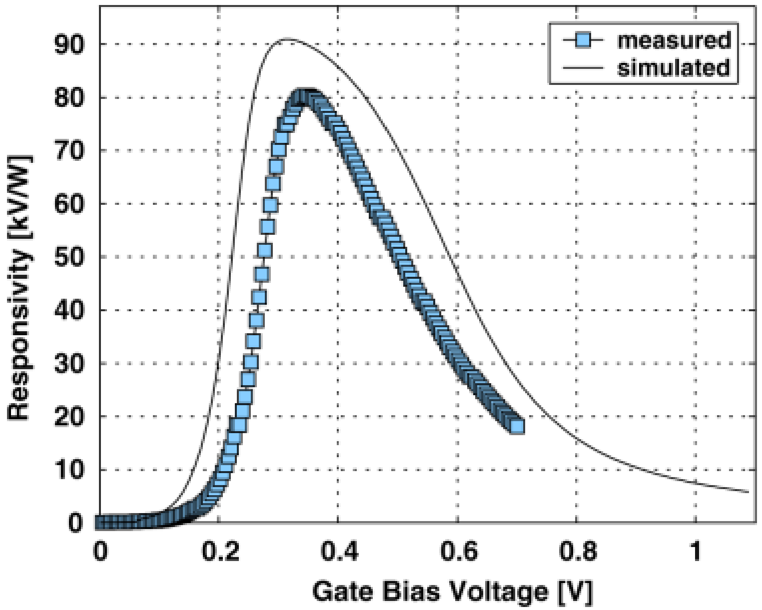


Pixels with differential patch antenna. (Lp=88µm, Wp=100µm) 0.6 THz; IHP's 0.25-µm BiCMOS
E. Öjefors, U. Pfeiffer, et al., "A 0.65 THz Focal-Plane Array in a Quarter-Micron CMOS ProcessTechnology", IEEE JSSC, Vol. 44, No. 7, 2009

Measurements of FET-based THz radiation detectors



E. Öjefors, U. Pfeiffer, et al., "A 0.65 THz Focal-Plane Array in a Quarter-Micron CMOS ProcessTechnology", IEEE JSSC, Vol. 44, No. 7, 2009



For responsivity measurements and imaging of the source beam, the detector is moved through the focal point F2 ; for transmission imaging of objects the detector stays immobile in F2, while the object is moved through the focal point F1 *F. Schuster, et al. "Broadband terahertz imaging with highly sensitive silicon CMOS detectors", Optics Express, 19(8), 2011, pp. 7827-32*

Mechanisms and models of FET response to THz radiation

- A mechanism of the FET photoresponse is still not clear;
- There are two models commonly accepted by electronic R&D community, used for interpretation of the THz detection using FETs:
  - **plasmonic:** a plasmon is induced in the FET channel by the THz field,
  - **resistive-mixing**: mixing of the THz signals coming simultaneously to the gate and drain terminals;
  - **distributed resistive mixing**: a distributed equivalent network representing the MOSFET channel model ➔ a more reliable NQS model of the MOSFETs;
  - **self-mixing;**
- There is a hypothesis that **thermal effects** play a main role in responsivity of **graphene FETs** to THz radiation *L. Viti, et al., "Thermoelectric graphene photodetectors with sub-nanosecond response times at terahertz frequencies," Nanophotonics, vol. 10, no. 1, pp. 89-98, 2021*

Mechanisms and models: **Plasmon-based model**

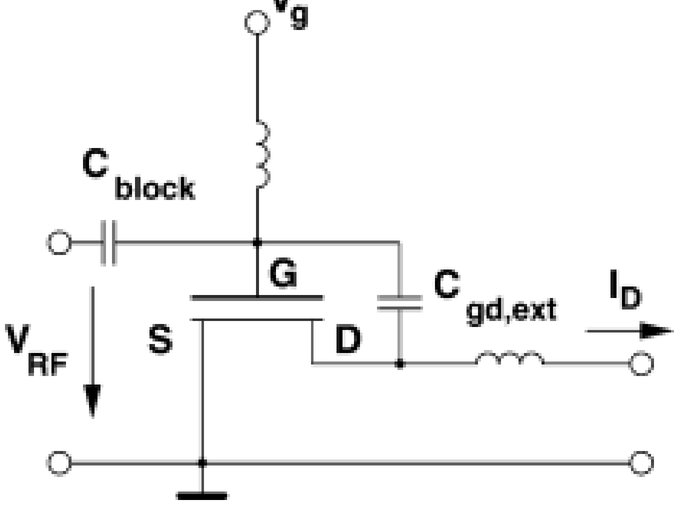
- Inspired by a similarity between a behaviour of electrons in the channel of HEMTs or MOSFETs and waves in a shallow water;
- Derived using one-dimensional Euler equations expressing **conservation of the charge density** and **conservation of the charge carrier momentum** (analogous to conservation of the mass transfer and mass momentum in fluidics) and quasi-static (?) graduał-channel approximation for charge-voltage relation;
  M. Dyakonov, M. Shur, "Detection, Mixing, and Frequency Multiplication of Terahertz Radiation by Two-Dimensional Electronic Fluid", IEEE Trans. El. Dev., Vol. 43, No. 3, pp. 380-387 (1996);
  M. Dyakonov and M. Shur, "Plasma wave electronics: novel terahertz devices using two dimensional electron fluid," IEEE Trans. on Electron Devices, vol. 43, no. 10, pp. 1640-1645 (1996);
- The THz DC photoresponse V_{photo} between D and S:
  - THz excitation coupled to the FET between G and S terminals induces the **electron wave** in the channel;
  - Two asymptotic modes of the plasmon behavior:
    - **resonant mode** (plasmons form standing waves in the whole channel, e.g. HEMTs at cryo. temp.);
    - **non-resonant mode** (the waves are dumped at larger distance from the source);
  - V_{photo} proportional to the received power;

$$\frac{V_{photo}}{V_{GS}-V_T} = \frac{1}{4}\left(\frac{V_a}{V_{GS}-V_T}\right)^2 f(\omega)$$

Mechanisms and models: **Resistive mixing**

- The circuit-based approach developed starting from a basic QS compact model of the MOSFET I-V characteristics;

  E. Öjefors, et al., "A 0.65 THz Focal-Plane Array in a Quarter-Micron CMOS Process Technology", IEEE J. Solid-State Circuits, Vol. 44, No. 7, pp. 1968-1976 (2009)



- In a nonlinear device (FET) the electrical signals of the same frequency and phase appearing at the gate and drain terminals are multiplied ➔ output DC photoresponse; a simple quasi
- The THz signal at the drain results from a coupling capacitance C_{gd} (may be an external $C_{gd,ext}$);
- The THz detection model based on the resistive-mixing approach and the plasmons in the non-resonant mode is equivalent to;

  A. Lisauskas, et al., “Rational design of high-responsivity detectors of terahertz radiation based on distributed self-mixing in silicon field-effect transistors,” J. Applied Physics 105, 114511 (2009)

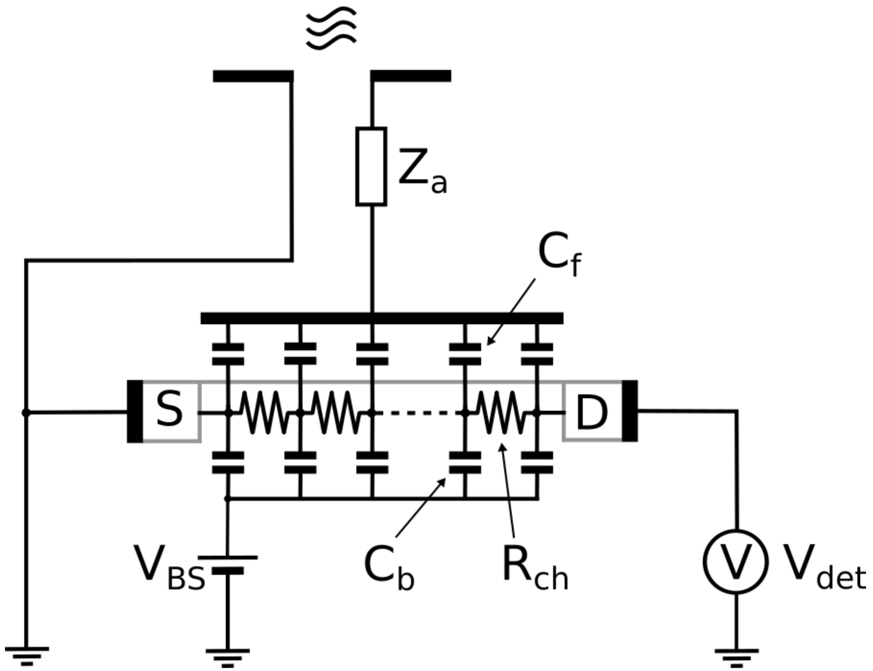
$$V_{photo} = \frac{{V_a}^2}{4(V_{GS} - V_T)}$$

Mechanisms and models: **Distributed resistive mixing**

Generalization of *resistive mixing* model.

E. Öjefors, et al., "A 0.65 THz Focal-Plane Array in a Quarter-Micron CMOS Process Technology", IEEE J. Solid-State Circuits, Vol. 44, No. 7, pp. 1968-1976 (2009)

M. Sakowicz, M. B. Lifshits, O. A. Klimenko, et al., "Terahertz responsivity of field effect transistors versus their static channel conductivity and loading effects," J of Applied Physics 110, 054512 (2011)



- The 2nd order non-stationary nonlinear differential equation derived by combining the charge conservation and drift current equations.
- Approximate solution in the small-signal domain

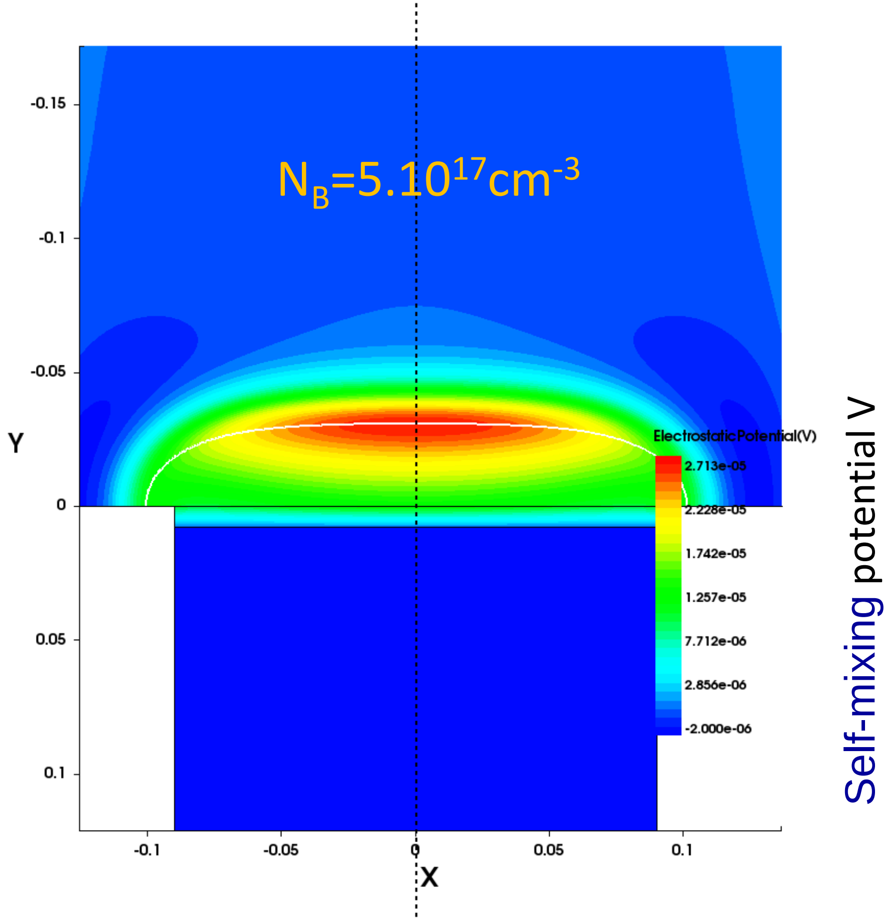
$$V_{photo} = \frac{{V_a}^2}{4}\left(\frac{1}{\sigma}\frac{d\sigma}{dV_{GS}}\right)$$

For $V_{GS}>V_T$ models: D&S, RM, DRM give the same results.

Mechanisms and models: **Self-mixing**

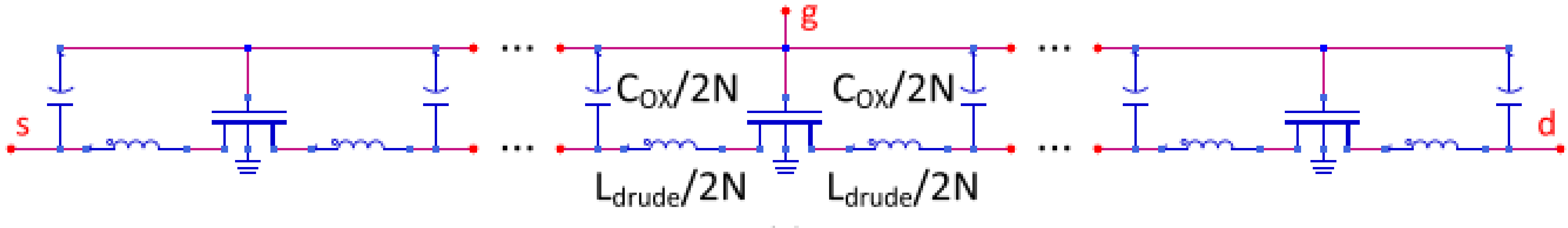
Self-mixing:

- The THz photoresponse of the MOS devices is a direct effect of a so-called self-mixing of the high frequency field (potential, carriers) in the depletion regions at the energy barriers;
- Hydrodynamic transport model and harmonic balance (HB) method implemented TCAD.
  F. Palma, R. Rao, "Terahertz Detection in MOS-FET: a new model by the self-mixing", IRMMW-THz 2018



Mechanisms and models: **Compact modeling**

X. Liu, T. Ytterdal, V. Y. Kachorovskii and M. S. Shur, "Compact Terahertz SPICE/ADS Model," TED-66, no. 6, pp. 2496-2501, 2019



- EKV model of MOSFETs;
- Channel segmentation;
- Inertia of carrier transport (important for plasmonic resonant detection) accounted for by the kinetic electron inductance L_{drude} given by $L_{drude} = \tau/g_{ch}$, where $\tau = m\mu/q$ is the electron momentum relaxation time, m is the electron effective mass, q is the electric charge, $g_{ch} = \partial I_d/\partial V_d$;
- The compact SPICE model implemented with Verilog-A in ADS and suitable for both large and small signal simulations.

Mechanisms and models: **Discussion**

D&S model

- Considered attractive for the interpretation of the FET response to THz radiation;
- Pretty consistent from the point of view of the physical mechanism in the FETs with an infinitesimally thin electron layer (2DEG) built in the device and gate-controllable (HEMTs) or induced by the gate voltage (inversion-mode MOSFETs);
- Allows theoretically for the prediction of the FET photoresponse;
- Valid only if the channel is fully open;
    - MOSFET measurement results demonstrate not only that the photoresponse is observed also in the moderate inversion but V_{photo} maximum is obtained for $V_{GS}<V_T$;
- Controversial assumption of the D&S approach: despite the high frequencies exceeding the maximum frequency of operation as an electronic device a quasi-static formula used $q_{ch}=C_i(V_{GS}-V_T)$;
    - it is indirectly assumed that the HF current flows uniformly along the channel; intuitively not true (proven by 2D EM simulations of the HF signal propagation);

Mechanisms and models: **Discussion**

RM, DRM models

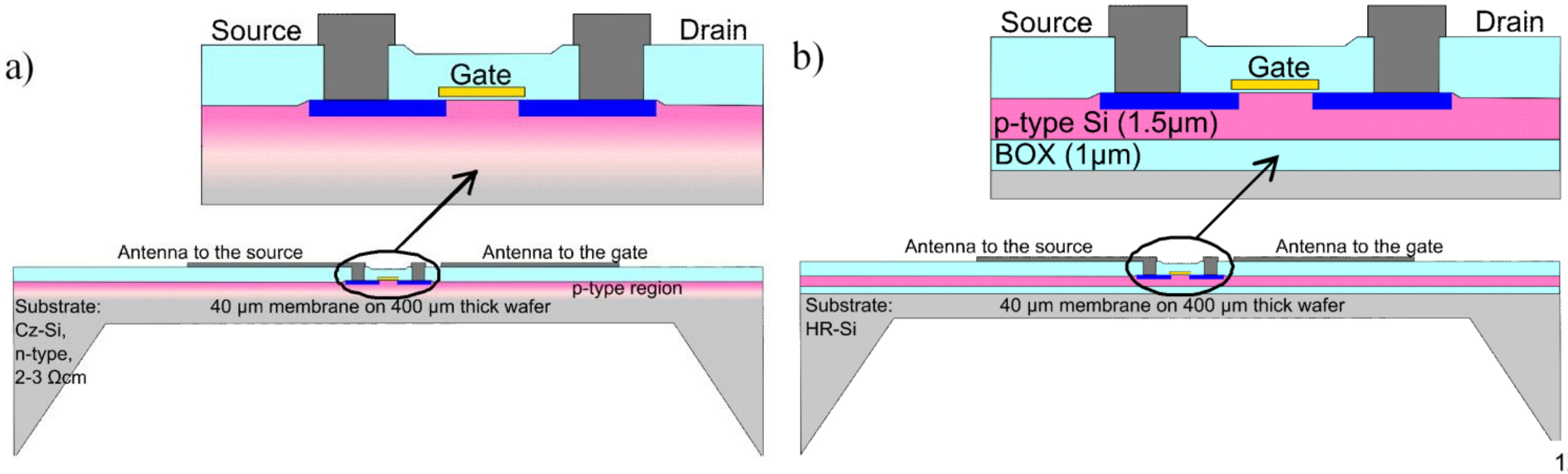
- R*esistive mixing* is commonly used in microwave mixers;
- Frequencies of the RF signals used in such circuits are below the FET maximum frequencies. However, RM model of THz detection, concerns frequency range far beyond the device maximum, despite it was developed based on a quasi-static model of FET I-V characteristics;
- *Distributed resistive mixing* model also uses a standard description of the electronic devices in the equivalent network. This makes it *non-quasi-static*, however still not suitable for THz signal propagation analysis in the FETs. Such analysis can be made by electromagnetic numerical simulation.

The TCAD simulation discussion is a broad issue and is beyond the scope of this paper.

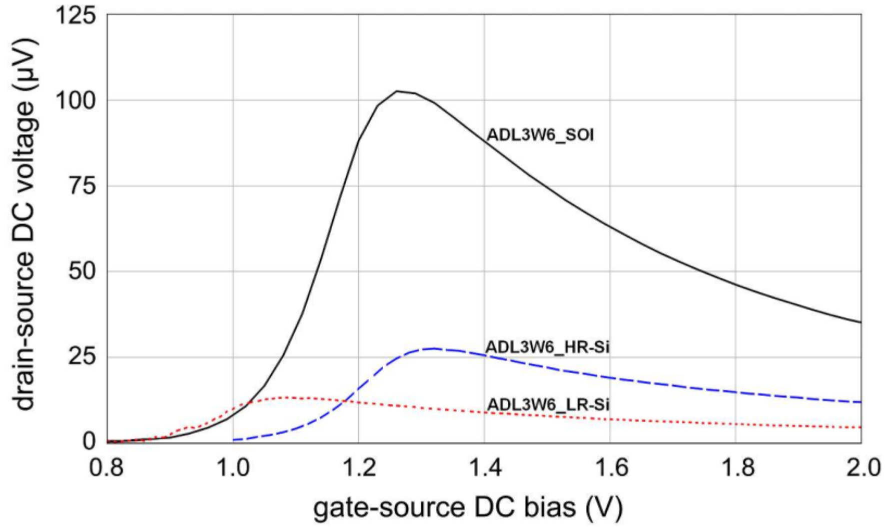
There are a few questions concerning the validity of two basic models of the THz detection using the FETs, even though they are equivalent from the point of view of the photoresponse estimate. To approach these problems, we made experiments and using MOSFETs on Si and SOI wafers, and *junctionless* FETs (JLFETs) as THz detectors.

Development in Ł-IMiF; **Bulk Si, SOI n-MOSFETs**

K. Kucharski, et al., "An Influence of Silicon Substrate Parameters on a Responsivity of MOSFET-Based Terahertz Detectors", Acta Physica Polonica A, No. 5, Vol. 130 (2016)

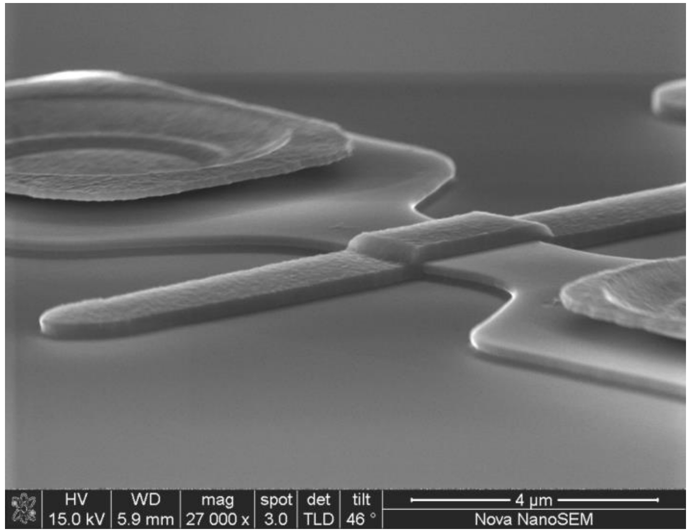


n-channel MOSFETs on 40 μm thick substrates:
(a) Cz-Si wafer (membrane),
(b) SOI wafer with HR substrate (membrane),
(c) HR Si wafer thinned via grinding.

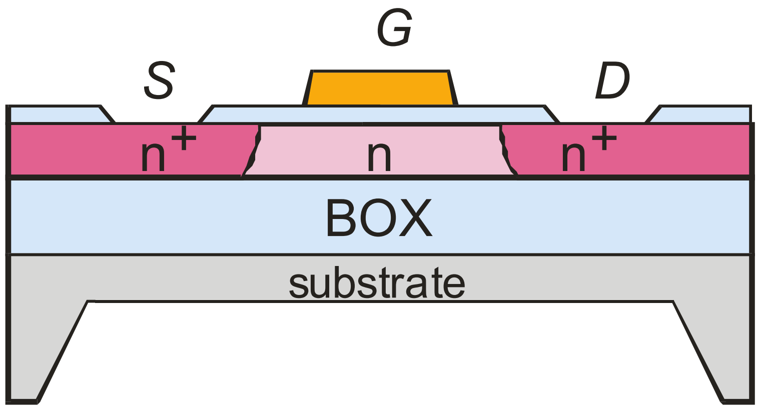


Lock-in technique

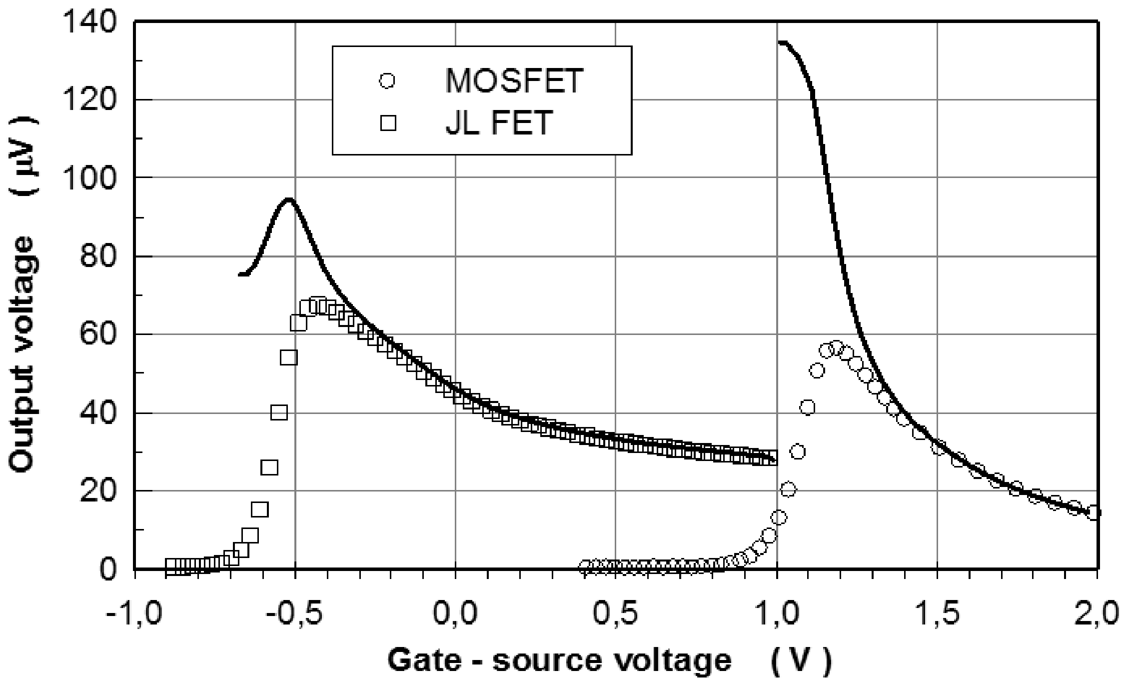
Development in Ł-IMiF; **JLFETs**



photolithographically defined reference device

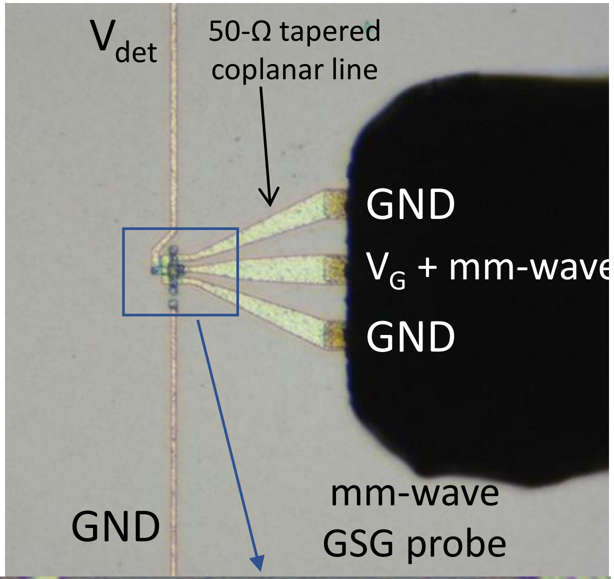


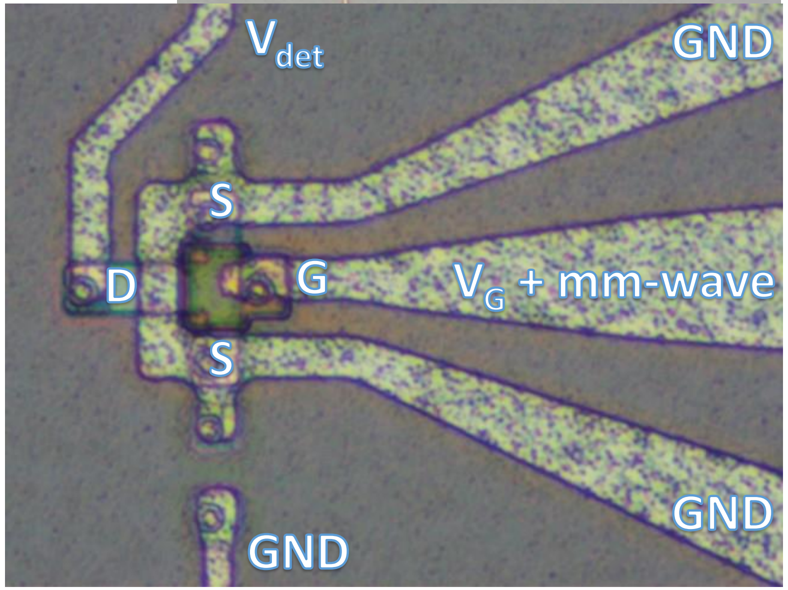
40 µm thick membranes were formed by local chemical etching (KOH) of the silicon at the substrate backside

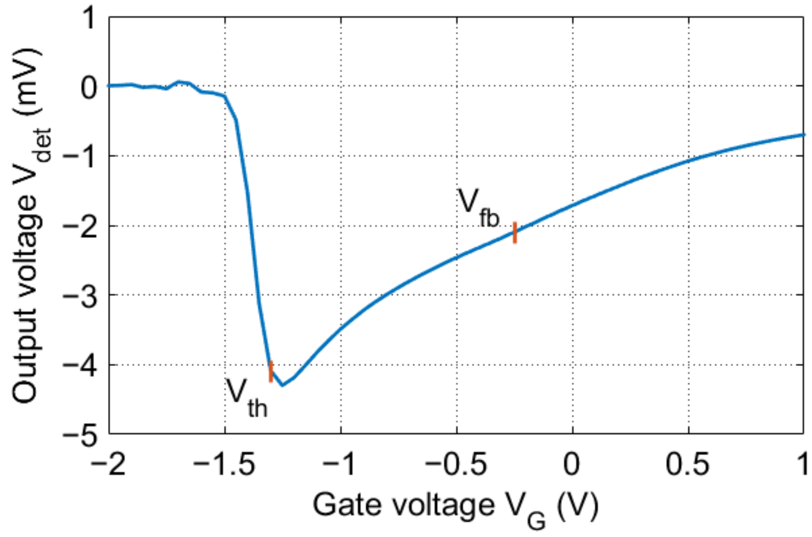


Marczewski J., Knap W., Tomaszewski D., Zaborowski M., Zagrajek P.: "Silicon Junctionless Field Effect Transistors as Room Temperature THz Detectors", Journal of Applied Physics, vol. 118, p. 104502-8 (2015)

THz det. in Ł-IMiF: **Probe measurements of sub-THz detector**







- The mm-wave power is delivered together with DC voltage V_G by **mm-wave GSG probe** to the gate electrode
- **T-shaped transistor channel**
  - Two symmetrical source electrodes are grounded
  - Drain electrode serves as detector output (V_{det})
- Impedance measurements allow **estimation of reflected power**, consequently responsivity can be precisely determined.
- High efficiency of energy transfer in contact measurements allows avoiding lock-in technique and measurement of **signed V_{det} voltage**

THz det. in Ł-IMiF: Modeling based on RM approach

$$V_{photo} = \frac{V_a{}^2}{4} \cdot \frac{1}{G_{ch}} \cdot \frac{\partial G_{ch}}{\partial V_{GS}} = \frac{V_a{}^2}{4} \cdot \frac{\partial ln(G_{ch})}{\partial V_{GS}}$$

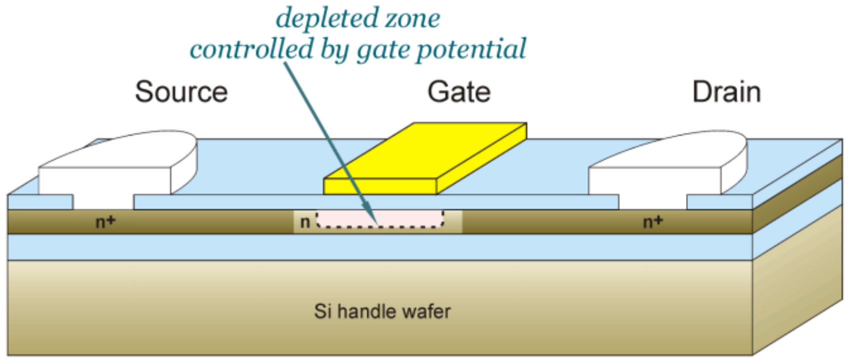
M. Sakowicz, et al.,"Terahertz responsivity of field effect transistors versus their static channel conductivity and loading effects", J. Applied Physics 110, 054512 (2011)

Predicted a direct relation between the photoresponse and the electrical characteristics of the field-effect devices;

- Partial depletion of the channel ($V_{th} < V_{GS} \leq V_{fb}$)

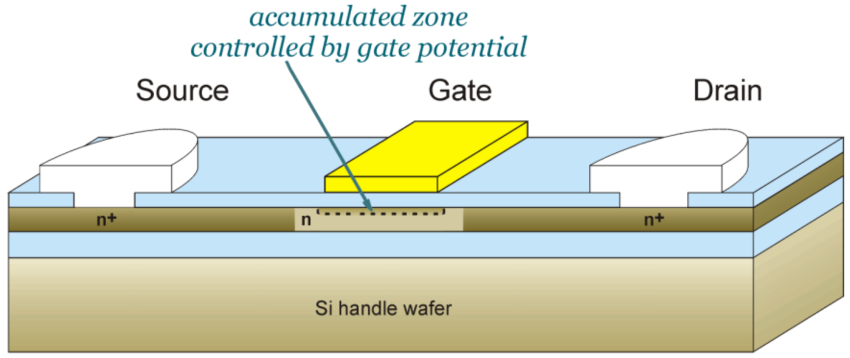
$$G_{ch,depl} = \frac{W}{L} \cdot \mu \cdot [q \cdot N_{ch} \cdot (t_{Si} - t_{depl})]$$

$$t_{depl} = \frac{\varepsilon_{Si}}{C_{ox}} \cdot \left(\sqrt{1 - \frac{4}{\gamma^2} \cdot (V_{GS} - V_{fb})} - 1 \right)$$

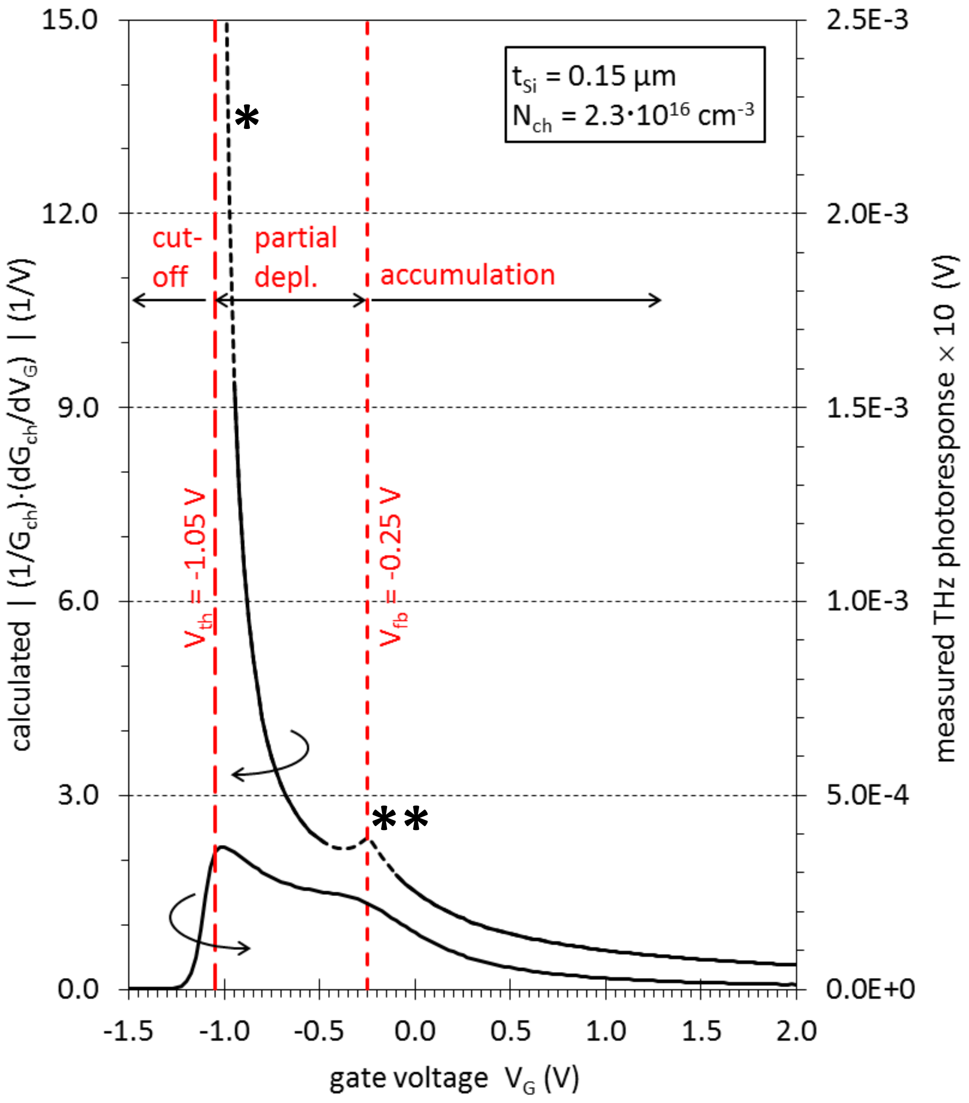


- Accumulation of the channel ($V_{fb} < V_{GS}$)

$$G_{ch,acc} = \frac{W}{L} \cdot \mu \cdot [q \cdot N_{ch} \cdot t_{Si} + C_{ox} \cdot (V_{GS} - V_{fb})]$$



THz det. in Ł-IMiF: Modeling based on RM approach



Channel layer thickness	t_{Si}	m	$1.5 \cdot 10^{-7}$
Channel type			n
Channel doping	N_d	cm^{-3}	$2.3 \cdot 10^{16}$
Gate oxide thickness	t_{ox}	m	$2.6 \cdot 10^{-8}$
Fixed charge density	N_{fix}	cm^{-2}	$6.0 \cdot 10^{10}$
Channel width	W	μm	6.0
Channel length	L	μm	3.6
Electron mobility	μ	cm^2/Vs	500.0

- Comparison of the G_{ch} model with the THz photoresponse of the JLFET with $2.3 \cdot 10^{16}$ cm^{-3} channel doping;
- The modelled characteristics $1/G_{ch} \cdot \partial G_{ch}/\partial V_{GS}$ vs V_{GS} reflects features of the photoresponse;

* The model does not reflect a measured phototresponse roll-off induced by the experimental setup;

** The model partially reflects a transition between partial depletion and accumulation of the channel

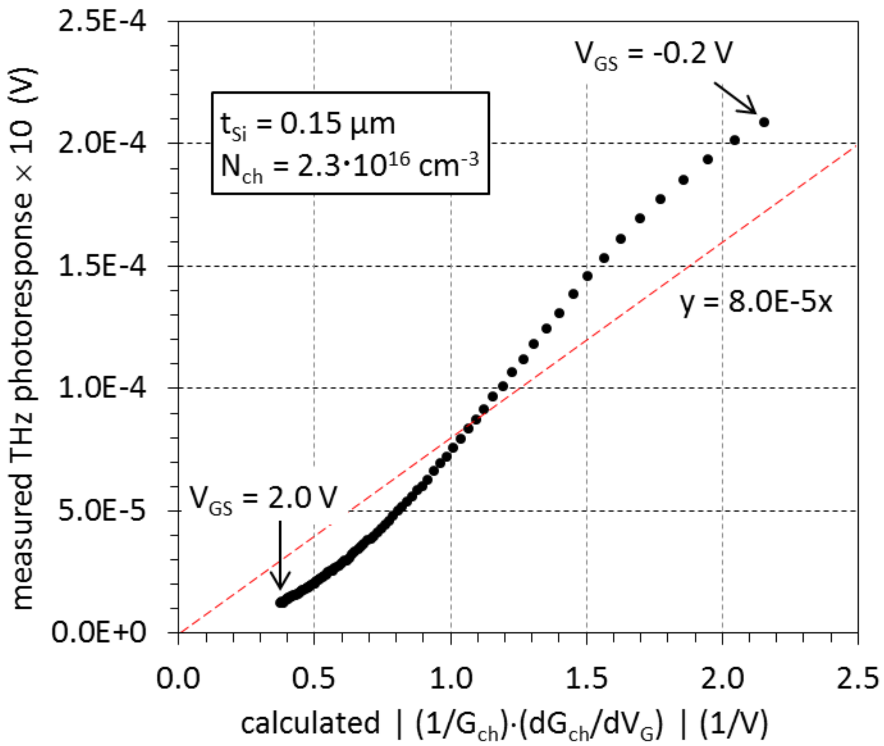
THz det. in Ł-IMiF: Modeling based on RM approach

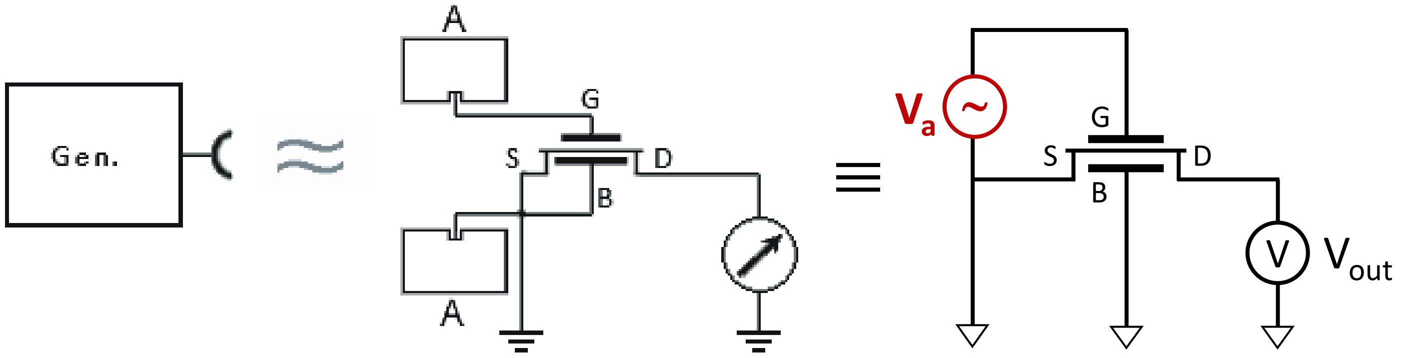
$$V_{photo} = \frac{V_a{}^2}{4} \cdot \frac{1}{G_{ch}} \cdot \frac{\partial G_{ch}}{\partial V_{GS}} = \frac{V_a{}^2}{4} \cdot \frac{\partial ln(G_{ch})}{\partial V_{GS}}$$

An existing correlation between
- the calculated $1/G_{ch} \cdot \partial G_{ch}/\partial V_{GS}$
- the measured photoresponse V_{photo}

⇩

estimation of V_a – an amplitude of a small-signal AC voltage induced by the antenna at the FET input.





based on accumulation range

$V_a \approx 5.7$ mV

Summary

- Different aspects of modeling of THz detection using FETs were presented:
- Shortcomings of the existing models were identified;
- The lack of a model is a serious obstacle to the optimization of the detectors.
- Status of research in Ł-IMiF was presented.

Acknowledgments

- ITE/Ł-IMiF statutory projects - funding
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- Ms. J. Malesińska – electrical measurements, qualification
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- Prof. J. Łusakowski (FP UW) – valuable consultations

Thank You