TCAD as a tool for the interpretation of Terahertz Rectification in MOS-FET

Ivan Mazzetta, Stefano Perticaroli, Fabrizio Palma
Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome, 00184 Rome, Italy; fabrizio.palma@uniroma1.it
Outline

☼ THz applications and importance of MOS-FET as detector
☼ Harmonic balance analysis
☼ Analysis of MOS-FET response by the TCAD harmonic balance analysis
☼ Contribution to detector design
☼ Characteristic time response of detection
☼ Conclusions
Material Detection:
- Metal detection
- Explosive detection
- Chemical weapon
- Biological weapon

THz: Spectrum and Applications

![THz Spectrum and Applications](image)

**Material Detection:**
- Metal detection
- Explosive detection
- Chemical weapon
- Biological weapon

**Increasing difficulty**

**Explosives and narcotics identification**

Absorption (AU and offset)

- Semtex
- PE4
- RDX
- PETN
- HMX
- TNT

**Stand-off detection**

![Stand-off detection](image)

**1.56 THz**

**350 GHz**

**Visible**

*J.C. Dickson et al., Proc. SPIE 6212, 62120Q (2006)*

**THz: Spectrum and Applications**

TCAD as a tool for the interpretation of Terahertz Rectification in MOS-FET

MOS-AK Workshop 2021
THz: Spectrum and Applications

Security – threat detection

Bio-photonics

THz

NDT/ Quality Control

Spectroscopy

Pharmaceuticals

Hidden drug detection

In vivo skin cancer

THz image

Non-metallic weapon and explosive detection

Ancient pigment analysis

Real-time monitoring of water content

TCAD as a tool for the interpretation of Terahertz Rectification in MOS-FET
MOS-AK Workshop 2021
MOS-FET as THz detector
Terahertz Plasma Oscillations in semiconductor Nanostructures: Basic Physic and Applications

Figure 12  Measured output voltage as a function of gate bias voltage.

Liu, Z., Liu, L., Zhang, Z., Liu, J., & Wu, N., Science China Information Sciences, 60(8), 082401 (2017)
Plasma wave model

2D channel

Terahertz Plasma Oscillations in semiconductor Nanostructures: Basic Physic and Applications
Harmonic balance analysis
The hydrodynamic equations

\[ \frac{\partial \phi}{\partial x} = -E \]

Poisson equation

\[ \frac{\partial E}{\partial x} = \frac{q}{\varepsilon_S} (p - n + N_D) \]

Gauss equation

\[ \frac{dn}{dt} = -\frac{\partial n v_n}{\partial x} + D_n \frac{\partial^2 n}{\partial^2 x} \]

Electrons continuity equation

\[ \frac{\partial v_n}{\partial t} = -v_n \frac{\partial v_n}{\partial x} - \frac{q}{m_n} E - \frac{v_n}{\tau_n} \]

Electrons Velocity continuity equation

Nonlinear terms are present in two of the semiconductor equations
The time average of the carrier fluxes gives rise to DC “self-mixing” terms

\[ J_{DC} = -q \langle n v_n \rangle \]

This represents a non-homogeneous term in DC current balance equation.

The effect is the formation of a charge dipole parallel to the barrier.

The dipole structure gives rise to a potential across the barrier.
In the first report of the effect, showing the formation of a dipole structure, majority carriers were holes. The structure was rather simple, the barrier of a depletion layer in MOS capacitance structure.

The dipole structure gives rise to a potential drop between the substrate and the semiconductor surface.

Self-mixing potential - Photovoltage

Frequency dependence of self-mixing potential in the MOS structure as obtained from TCAD simulations, with three values of doping in the semiconductor body.

TCAD study of the THz response of MOS-FET
The structure has 200 nm n-channel length. The drain and the source diffusions have phosphorous doping concentration of $10^{+20}$ cm$^{-3}$. A VT implant is considered under the gate.
The THz potential distribution within the structure at 1THz
The photovoltage generated is evaluated at drain.
The photovoltage generated is evaluated at drain.
TCAD as a tool for the interpretation of Terahertz Rectification in MOS-FET

$V_G = 0.0 \, V$

$V_G = 0.5 \, V$

$V_G = 1.5 \, V$

$V_G = 2.5 \, V$
TCAD as a tool for the interpretation of Terahertz Rectification in MOS-FET

MOS-AK Workshop 2021
$V_G=0.0\ \text{V}$

$V_G=0.5\ \text{V}$

$V_G=1.5\ \text{V}$

$V_G=2.5\ \text{V}$
$V_G = 0.5 \, \text{V}$
Contribution to detector design
Harmonic balance analysis, at the first order, permits to determine real and imaginary part of the device impedance.
Impedance matching between antenna and detector

Antenna design

Equivalent Circuit

\[
\text{Re} \{Z_A\} = \text{Re} \{Z_D\} \\
\text{Im} \{Z_A\} = -\text{Im} \{Z_D\}
\]
Characteristic time response of detection
JLFET is a Silicon on Insulator (SOI) device, n-type channel, with doping $2 \times 10^{16}$ cm$^{-3}$, and a thickness of 170 nm. It has a 10 $\mu$m gate width, and 500 nm gap between the polySi gate and source and drain n$^+$ contact diffusions.
$V_{GS} = -2.0\, \text{V}$

From the steady state harmonic balance simulation, we extracted the geometrical distribution of the self-mixing dipole. In particular in depleted conditions, where there is no charge accumulated in the channel.
$V_{GS} = -2.0\, V$

Due to the vertical junction between the source diffusion and the channel, the main self-mixing dipole is a vertical, parallel plate structure of charges, with electron accumulated toward the channel.
Transient TCAD Simulations

Since the harmonic balance analysis furnish its results only in stationary conditions, the photo-charge transient was simulated by two electrodes embedded in the contact-doping/channel barrier. The contacts have the same length of the junction, and are separated by 10 nm. In the simulation they are feed by step of current in time of 1 μA, that mimics the $J_{DC}$ current.
The settling of the potential across the dipole induces:
- a current into the gate, due to displacement current across the gate oxide
- and a steady state current into the drain, across the channel.

In the simulations we considered both gate and drain short circuited to ground for the pulse.
The current along the channel, toward the drain is slower (blue line). Due to the accumulation of charge at the oxide interface a transient current is induced at the gate (red line). The GATE current is two orders of magnitude larger than the current at the drain. The GATE current pulse is shorter than 100 ps.
MOS-FET presents a strong capability to rectify THz radiation;

We adopted the harmonic balance analysis to study of the self-mixing effect in the semiconductor structures;

We developed a new interpretation of the generation of the photovoltage in the MOS-FET structure;

We showed that this analysis may furnish an essential contribution to the detector design;

Finally we used TCAD simulation to characterize the time response of the detection.
This research was partially funded by Italian PNRM E.F. 2018 n a2017.153M, Contract n. 2013a, 20.12.2018
THANK YOU FOR YOUR ATTENTION