Terahertz Plasma Oscillations in semiconductor Nanostructures: Basic Physic and Applications

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- Plasma waves sound Waves & Transistors
- Detection & Imaging
- Current research and unresolved problems
**Outline**

- Plasma waves & Transistors
  - Plasma waves and dimensionality
  - Field Effect Transistors
  - Plasma waves in the transistors

- Well established results and applications
  - Regimes of detection
  - Resonant detection
  - Non-resonant detection

- Current research and unresolved problems
  - Emission
  - Temperature
  - Resonant dreams with graphene
  - Circular polarisation
  - THz communication
Plasma waves and dimensionality

3D

\[ \omega_p = \sqrt{\frac{e^2 n_{3D}}{\varepsilon\varepsilon_0 m}} \]

2D

\[ \omega_p = \sqrt{\frac{e^2 n_{2D}}{2\varepsilon\varepsilon_0 m}} k \]

2D gated

\[ s = \sqrt{\frac{e^2 n_{2D} d}{\varepsilon\varepsilon_0 m}} \]
Standing Longitudinal Waves in the tube

Different modes
Musical wind instrument Analogy
(Air and Plasma Waves Comparison)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sound</th>
<th>2D plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>0.1-1 m</td>
<td>0.1-1 µm</td>
</tr>
<tr>
<td>Speed of waves (s)</td>
<td>300 m/s</td>
<td>$10^6$ m/s</td>
</tr>
<tr>
<td>Frequency (s/L)</td>
<td>0.3kHz-3kHz</td>
<td>1THz-10THz</td>
</tr>
</tbody>
</table>

BETTER THEN ACOUSTIC INSTRUMENTS ....... Voltage tunable

Plasma waves velocity in 2DEG gated gas

« Voltage tuneability »

\[ \omega_p = s k \]

\[ s = \sqrt{\frac{e^2 n_{2D} d}{\varepsilon \varepsilon_0 m}} \]

\[ n_{2D} = C U \]

\[ C = \frac{\varepsilon \varepsilon_0}{d} \]

\[ s = \sqrt{\frac{e U}{m}} \]
Frequency of the plasma oscillations

« Voltage tuneability»

\[ \omega = sk \]

\[ s = \sqrt{\frac{eU}{m}} \]

\[ k = \frac{2\pi}{\lambda}, \lambda = 4L \]

\[ f_p = \frac{1}{4L} \sqrt{\frac{eU}{m}} \]

\[ L = 0.1 - 1 \mu m \]

\[ U = 1V \]

\[ m = 0.06 - 0.24 \]

\[ f_p \approx 0.6THz - 4.0THz \]

Basic mode \( n=1, ..3,5,7 \)
Dreams of plasma waves resonances
(high frequency and short transistors)

\[ \omega \tau \gg 1 \]

Plasma waves are weakly damped

Short gate: \( L \ll s \tau \)
Experimental observations of plasma waves in 2DEG

S. J. Allen, D. C. Tsui, and R. A. Logan, PRL, 38, 980 (1977)

P. J. Burke et al. APL, 76 , 745 (2000)

GaAs/AlGaAs, gated 2DEG

![Graphs showing impedance and plasma wave velocity](image)

Fig. 2. Impedance of gated sample with 2D electron gas versus frequency. For this sample, \( \omega_p \tau = 1 \) at 1.25 GHz (where \( \tau \) is the momentum relaxation time).

Fig. 3. Plasma wave velocity versus electron density.

\[ L = 360 \mu m \quad \mu \approx 330 m^2/Vs \quad T \approx 1K \]
Can Plasma Waves Exist in main Semiconductor FETs???

\[ \text{reaching } \omega\tau \geq 1 \text{ at } 300K \text{ for } 1\text{THz} \]

\[ \mu_{Si} \sim 500 \text{ cm}^2/\text{Vs} \quad \omega \tau_{Si} \sim 0.4 \]

\[ \mu_{GaN} \sim 1500 \text{ cm}^2/\text{Vs} \quad \omega \tau_{GaN} \sim 1.2 \]

\[ \mu_{GaAs} \sim 6000 \text{ cm}^2/\text{Vs} \quad \omega \tau_{GaAs} \sim 1.2 \]

\[ \text{reaching frequency } 1\text{THz} \quad f \sim \sqrt{n_s/m^*}/L \]

For GaAs (1 THz) \( n = 2 \times 10^{12} \text{ cm}^{-2} \) & \( L = 600\text{nm} \).

For GaN (1 THz) \( n = 2 \times 10^{13} \text{ cm}^{-2} \) & \( L = 1000\text{nm} \).

For Si (1 THz) \( n = 2 \times 10^{12} \text{ cm}^{-2} \) & \( L = 300\text{nm} \).

!!!!!!!!!!!!!!!!!!!!!!!!NANOTECHNOLOGY!!!!!!!!!!!!!!!
Conclusions on plasma

- Plasma oscillations in gated 2DEG have acoustic like behaviour
- They were observed in big devices in cryogenic temperatures
- Plasma resonances can reach THz range for sub-micron devices
Field Effect Transistors

Carrier density regulated by the electric field of the gate
Field Effect Transistors

MOSFET

source

gate

drain

metal

oxide

$p$ substrate

$n$

$V_g = 0 \rightarrow n=0$

2DEG CREATION

HEMT

$V_g = 0 \rightarrow n\neq0$

source

gate

drain

Cap

$\text{Si} \delta$-doping

Schottky Barrier

Spacer

Channel

2DEG

 Barrier

Channel

2DEG DEPLETION
Transfer Characteristics

Threshold Voltage, $V_{TH} \rightarrow n = 0$

Threshold Voltage,

Drain Current, $I_{ds}$ (mA)
Gate Voltage, $U_g$ (V)

MOSFET
$U_{ds} = 0.1 \text{ V}$

HEMT
$U_{ds} = 1 \text{ mV}$

$ne = C\left(V_g - V_{TH}\right)$
Cross section of a MOSFET
(a) Transmission electron micrograph
(b) Phase image obtained by electron holography

100 nm gate AlGaN/GaN on silicon HEMT with a 1 µm source-drain separation

ETH Zurich

APL 80, 246, (2002)
Plasma waves excitation by THz radiation

THz radiation couples to the transistor by antennas – it can be represented as AC source between two electrodes
Regimes of plasma waves (high frequency)

\[
\omega \tau \gg 1 \quad \text{Plasma waves are weakly damped}
\]

Characteristic damping length: \( l = s \tau \)

Short gate: \( L \ll s \tau \)

Long gate: \( L \gg s \tau \)
Overdamped oscillations
(low frequency/mobility, 300K)

$t = 0.$

$\omega \tau \ll 1$

"x" distance normalized by "damping length"

$$l_{\text{eff}} = s \sqrt{\tau / \omega} = \sqrt{\mu U_g / \omega}$$
Transistor basic ideas

- Two main families of transistors –of FETs
- Basic FET Characteristics – transfer
- Plasma excitations can have a form of travelling waves or overdamped/dacaying oscillations (300K)
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  - Field Effect Transistors
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  - Non-resonant detection

- Current research and unresolved problems
  - Emission
  - Temperature
  - Resonant dreams with graphene
  - Circular polarisation
  - THz communication
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Rectification of THz radiation in FETs

- **Vgs**: Source-Gate bias
- **UA**: Irradiation induced *ac* voltage
- **ΔU**: *dc* photoresponse

!!Nonlinearity – THz modulates simultaneously !!carrier density and drift velocity!!
Experimental Setup
R. Tauk, F. Teppe, S. Boubanga, D. Coquillat, W. Knap, Y.M. Meziani
C. Gallon, F. Boeuf, T. Skotnicki, C. Fenouillet-Beranger, D. Maude, S. Rumyantsev, M.S. Shur Plasma wave detection of terahertz radiation by silicon field effects transistors: responsivity and noise equivalent power, accepted to APL
1) Experimental proofs of plasma waves existence

2) Can we make a resonators and see resonant voltage tunable THz detection ??

3) Ovedamped Plasma and THz imaging @ 300K
Regimes of plasma waves (high frequency)

\[ \omega \tau \gg 1 \quad \text{Plasma waves are weakly damped} \]

Characteristic damping length: \[ l = s \tau \]

Long gate: \[ L \gg s \tau \]
2DEG in Magnetic Field

CYCLOTRON ORBIT

\[ \omega_c = \frac{eB}{m^*} \]

ENERGY QUANTIZATION

\[ E = E_0 + (n + 1/2)\hbar\omega_c \]

http://www.warwick.ac.uk/~phsbm/2deg.htm
Cyclotron Resonance

\[ \hbar \omega_c \]

\[ \omega_c = \frac{eB}{m^*} \]
Schubnikov – de Haas Oscillations

\[ \rho = \rho_0 \frac{A}{shA} \exp \left( -\frac{\pi e 1}{m^* \tau_q B} \right) \cos \left( \frac{\pi n h 1}{e B} + \phi \right) \]
Quantum Hall Effect and SdH Studies

\[ \omega = sk \]

\[ \omega = \sqrt{\omega_c^2 + (sk)^2} \]

\[ k = \frac{\omega}{s} \sqrt{1 - \frac{\omega_c^2}{\omega^2}} \]

When \( \omega_c > \omega \) \( k \) is imaginary and plasma waves cannot propagate.

**THz rectification by In GaAs FET in magnetic fields**
THz rectification by In GaAs FET in magnetic fields experiment and theory

(a) 

\[ V_g = 0.1 \text{ V} \]

\[ N = 5.25 \]

(b) 

\[ V_g = -0.125 \text{ V} \]

\[ N = 2.3 \]

**Exp S. Boubanga-Tombet et al.**
**APL 2009**

**Theory M.Lifshits and M.I. Dyakonov**
**PRB –Rapid Com 2009**
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Short gate: \[ L \ll s\tau \]
Rectification of THz radiation in FETs

- $V_{gs}$: Source-Gate bias
- $U_a$: irradiation induced $ac$ voltage
- $\Delta U$: $dc$ photoresponse

!!Nonlinearity – THz modulates simultaneously !!carrier density and drift velocity!!
The gate voltage – tunes carrier density – plasma frequency … to resonance
The calculated plasmon frequency as a function of the gate voltage for shown by the solid line \( \sqrt{ } \) dependence. The error bars correspond to the linewidth of the measured plasmon resonance peaks.

A. El Fatimy et al, APL 89, 131926, 2006
Resonant Detector & Quality factor InGaAs

InGaAs
$L_g = 50 \text{ nm}$

$T = 10K$

Plasma Frequency (THz)

Gate voltage $V_g, V$

Response $\Delta V$ and, units

$\omega \tau \sim 3$ ????

$\mu = 36000 \text{ cm}^2/\text{V.s}$ ?? $\omega \tau \sim 13$ ??

Resonances are wider than expected...???

Discussion on plasma modes Broadening

Additional broadening mechanism

Dyakonov-Shur theory geometry

Experimental geometry

- W/L ~ 100
- roughness on the gate boundaries

Top view

S

D

L

W

Only longitudinal modes

All modes are permitted


M.I. Dyakonov Semiconductors, 2008, Vol. 42, No. 8
Samples - Multi-Channel InGaAs HEMTs

$I-V$ Characteristics at 20 K

$L = 400$ nm
$W = 200$ nm
$W_{gr} = 300$ nm

S. Boubanga-Tombet et al. APL, 92, 212101, (2008)
A. Shepetov et al. APL, 92, 242105, (2008)
Detection governed by dc current in Multi-Channel FET

Dc current leads to a strong shrinking of the line: From 58 GHz at $V_{ds} = 0$ V to 26 GHz at $V_{ds} = 100$ mV

DC current strongly reduce plasma wave damping

S. Boubanga-Tombet et al. APL, 92, 212101, (2008)
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300K - Overdamped plasma oscillations

$$\omega \tau \ll 1$$

Characteristic length:

$$l = s \sqrt{\tau / \omega}$$
Rectification of THz radiation in FETs

- $V_{gs}$: Source-Gate bias
- $U_a$: irradiation induced $ac$ voltage
- $\Delta U$: $dc$ photoresponse

!!Nonlinearity – THz modulates simultaneously !!carrier density and drift velocity!!
0.6 THz imaging with InGaAs HEMT – 300K

0.6 THz imaging - collaboration with University of Frankfurt
 Imaging at 1.6 THz with a single FET

Results from Vilnius (collaboration with Montpellier) (2008).
Detection of terahertz radiation by Si field effects transistors 300K

Responsivity, V/W

Gate voltage $V_g$, V

Gate length $L_g$, nm

Responsivity, arb. units

$f=0.7$THz
AC voltage $U_1$ and DC signal $U_2$

Dependence of the ac voltage $\frac{U_1}{U_a}$ at $\omega t = 2\pi n$ and of the dc photoinduced voltage $\frac{U_2}{\Delta U}$ on the distance from the source $x$ for a long gate.
THz detection & Signal to noise ratio in Si-MOSFETs


F=700GHz

Noise= 4kTR

NEP=10pW/Hz^{0.5}

L_g=120nm, V_g=0.3V
300K CMOS THz detectors
- Fast, sensitive & INTEGRABLE in MATRIXES!!!
- For 300K price effective focal plane arrays
- Fast enough for THz communication

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Sampling Frequency (MAX)</th>
<th>NEP (pW/Hz^{0.5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golay Cell</td>
<td>~20Hz</td>
<td>100</td>
</tr>
<tr>
<td>Pyroelectric</td>
<td>&lt;10KHz</td>
<td>1000</td>
</tr>
<tr>
<td>Schottky Diodes</td>
<td>&lt;20GHz</td>
<td>10</td>
</tr>
<tr>
<td>Microbolometers</td>
<td>&lt;1MHz</td>
<td>10</td>
</tr>
<tr>
<td>Si transistors</td>
<td>30GHz or higher</td>
<td>10</td>
</tr>
</tbody>
</table>
THz Imaging with Si-MOSFET Detectors
0.13µm CMOS

Detector Characteristics

<table>
<thead>
<tr>
<th></th>
<th>L (nm)</th>
<th>W (nm)</th>
<th>r (µm)</th>
<th>θ (deg)</th>
<th>Antenna Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>C14</td>
<td>130</td>
<td>250</td>
<td>60</td>
<td>120</td>
<td>gate-source</td>
</tr>
<tr>
<td>C15</td>
<td>130</td>
<td>250</td>
<td>60</td>
<td>120</td>
<td>source-drain</td>
</tr>
<tr>
<td>C5</td>
<td>300</td>
<td>500</td>
<td>60</td>
<td>120</td>
<td>gate-source</td>
</tr>
</tbody>
</table>
"Broadband terahertz imaging with highly sensitive silicon CMOS detectors,"

F. Schuster et al


Imaging with MOSFET – 0.3THz
“!!!!Cutting Edge Technology!!!”
Imagerie THz avec un Transistor MOSFET

Radiation : 0.3 THz ($\lambda = 1$ mm), Puissance 2 mW, 10 ms/point  Scan-Time: qq min
Measurement Imaging at 300GHz, tree leaves

225x600 scanned points
PANASONIC GaN detector 2011

- Patch antenna
- HFET

Diagram showing the angular distribution of electric field (E) in different directions (x, y, z) with respect to the antenna axis (E_{Antenna}). The graph illustrates the electric field magnitude (E in a.u.) at various angles (\phi in degrees) from 0° to 180°.
Other groups – Competitors/Collaborators in Si CMOS Imaging

- Goethe University of Frankfurt group of Prof. Roskos
- Dallas University /Texas Inst. USA Ken. O
- Wuppertal University Prof. Pfeifer
  First 1000 pixel Si CMOS camera
  (February 2012)
  (German – French project)
End of The Second Part
1) Experimental proofs of plasma waves existence

2) Can we make a resonators and see resonant votage tunable THz detection ??

3) Ovedamped Plasma and THz imaging @ 300K
Outline

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  - Plasma waves and dimensionality
  - Field Effect Transistors
  - Plasma waves in the transistors

- Well established results and applications
  - Magnetic field and plasma
  - Resonant detection
  - Non-resonant detection

- Current research and unresolved problems
  - Emission
  - Temperature
  - Resonant dreams with graphene
  - Circular polarisation
  - THz communication
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1) Can we have THz detection with Graphene??

2) Can we enhance nonresonant THz detection while lowering temperature

3) THz polarization measurements with HEMTS

4) Can FETs be THz emitters???
Frequency of the plasma oscillations !!!300K!!!

\[ f_p = \frac{1}{4L} \sqrt{\frac{eU}{m}} \]

\[ L = 0.1 - 1\mu m \]
\[ U = 1V \]
\[ m = 0.06 - 0.24 \]

\[ f_p \approx 0.6THz - 4.0THz \]

!!Only When Plasma waves are weakly damped!

\[ \omega \tau \gg 1 \]
THz detection by Graphene transistors

L. Vicarelli,¹ M.S. Vitiello,¹ D. Coquillat,² A.C. Ferrari,³ W. Knap,² M. Polini,¹ V. Pellegrini,¹ and A. Tredicucci¹

Common project: Pise¹, Montpellier², Cambridge³
MOTIVATION!!!

??300K RESONANCES
FOR SELECTIVE GATE TUNABLE
DETECTION AND EMISSION ???

NATURE MATERIALS  DEC 2012
1) Can we have THz detection with Graphene??

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\[ \Delta U \propto \frac{1}{\eta kT} \]

(Klimenko et al, JAP 2012)
(Klimenko et al JAP 2012)
Physical limitations – $U^*$

subthreshold

\[ \sigma \propto \exp \left( \frac{U}{U^*} \right) \text{ and } \Delta U \propto \frac{1}{U^*} \]

where

\[ U^* = \frac{\eta kT}{e} \text{ diffusion above } 30K \]

\[ U^* = \text{const} \text{ impurity band} \]

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Radiation helicity sensitive photoresponse in the plasmons effect based detection of terahertz radiation.

C. Drexler¹, N. Dyakonova², M. Schafberger¹, K. Karpierz³, J. Karch¹, H. Videlier², Y. Meziani⁴, P. Olbrich¹, W. Knap² and S. D. Ganichev¹

¹THz Center, University of Regensburg, 93040 Regensburg, Germany
²GES, UMR5650 CNRS et Universite Montpellier 2, France
³Institute of Experimental Physics, University of Warsaw, Poland and
⁴Departamento de Fisica Aplicada, Universidad de Salamanca, Spain

We report on the observation of the photon helicity sensitive photoresponse in GaAs/AlGaAs high electron mobility transistors (HEMT) excited by terahertz laser radiation. We demonstrate, that for a certain structure design and large negative bias voltages the sign of the photoresponse changes upon switching from right to left circular polarization. The effect is discussed in terms of the nonresonant broadband detection due to plasma oscillations. Our results may provide a bases for a sensitive all-electric room-temperature detection of the radiation Stokes parameters. Time resolved experiments indicate that the time resolution of the device is at least better than 1 ns.

PACS numbers: 29.40.-n,07.57.Kp,85.25.Pb,42.25.Ja

Linear polarization detection
Source drain voltage from FET at 800GHz

Figure 4. Polarization dependence of the response, $f = 0.8$ THz. Ellipses on the top illustrate the polarization states (after [40]).
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Shallow water analogy for a ballistic field effect transistor: New mechanism of plasma wave generation by DC current
Instability and THz generation

This mechanism of plasma wave generation is similar to sound generation in a whistle and wind musical instruments:

**Ingredients:**

a) Resonator  
b) Asymmetric boundary conditions

Instability - Threshold
Plasma waves instability & Emission -

Threshold like – phenomena – laser analogy

\[ A \propto \exp(\kappa t) \]

\[ \kappa = \frac{s^2 - v_0^2}{2Ls} \ln \left| \frac{s + v_0}{s - v_0} \right| \]

Cryogenic THz Spectrometer
W. Knap et al.,
The shift of the threshold voltage - the magnetoresistance of the ungated

N. Dyakonova et al. J. Appl. Phys. 97, 114313 (2005),
Emission spectra

Transistors of different gate length

Lg = 50, 60, 80... 100 nm  W = 20 µm

- Vg dependence is not observed
- Spectra is broad and there is no strong dependence on L

T = 4.2 K
Deep/shallow water analogy -
Discussion on plasma modes Broadening

Additional broadening mechanism

Dyakonov-Shur theory geometry

Top view

Only longitudinal modes

Experimental geometry

- $W/L \sim 100$
- roughness on the gate boundaries

Top view

All modes are permitted


M.I. Dyakonov Semiconductors, 2008, Vol. 42, No. 8
Shallow, deep and white water instabilities
Field Plate GaN transistor for THz emission
Fourier Transform analysis
GaN/AlGaN 200nm transistor
T=300K Vd=8V

Normalized signal (au)
Frequency (THZ)

Vg=-4V
Vg=0
Vg=-4V
$V_{ds} = 4\, \text{V}$

$V_{gs} = 0\, \text{V}$

$V_{gs} = -3.5\, \text{V}$

$V_{ds} = 4\, \text{V}$

$0.75\, \text{THz}$

$2.1\, \text{THz}$

$b)$

$\text{FWHM, THz}$

$\text{Vgs, Volt}$

$V_{gs} = 0\, \text{V}$

$Emission, \, \text{u.a}$

$Frequency, \, \text{THz}$

(a)

(b)
THZ emission from GaN/AlGaN
2DEG at AlGaN/GaN

HIGH MOBILITY at 300K:
2500 cm$^2$/Vs
World record!
Important for device performance
THz Source Based on GaN THZ Emission (UNIPRESS – UM2)
Plasmonic nanodevices for terahertz sensing and spectroscopy

Taiichi Otsuji, Tsuneyoshi Komori, Takayuki Watanabe, and Tetsuya Suemitsu

Novel solid-state emitters and detectors exploit electronic transitions in semiconductors to improve the operating frequency of devices intended for terahertz (THz) applications. This opens up new opportunities in sensing, medical imaging, and remote sensing.

15 February 2010, SPIE Newsroom. DOI: 10.1117/2.1201002.00011

Tunable and coherent sources of THz frequencies currently represent a rapidly growing area of research, and have become one of the hottest topics in modern electronics. Terahertz spectroscopy was historically limited to gas-filled cavities used in spectroscopy, while THz radiation was the province of aerobiology and analytical science. Now, the technology is emerging into an increasingly wide variety of applications, in information and communication technologies, medical sciences, nondestructive testing, homeland security, quality control of food and agriculture, and many more.

**Figure 3.** Transmission spectra for maple-syrup liquid measured using single- and triple-chip PRE(s), and an HP-Hg lamp.
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2) Can we enhance nonresonant THz detection while lowering temperature

3) THz polarization measurements with HEMTS

4) Can FETs be THz emitters???
1) Plasma and dimensionality (THz in gated 2DEG)

2) FET transistors and THz plasma oscillations (nano)

3) Experimental proofs of existence \( f(B) \)

4) Can we make a resonators and see resonant voltage tunable THz detection \( \text{?? (Yes ... broad \&LT)} \)

5) Can we make a resonators and see resonant voltage tunable THz emission \( \text{?? (Yes .... broad)} \)

6) Ovedamped Plasma and THz 300K imaging with Si MOSFETS (Leading current application)

7) Current and Future Research
(300K Res plasma in Graphene for detectors Polarization, GaN THz emitters)