Terahertz Plasma Oscillations in semiconductor Nanostructures: Basic Physic and Applications

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SNS – Pise Italy

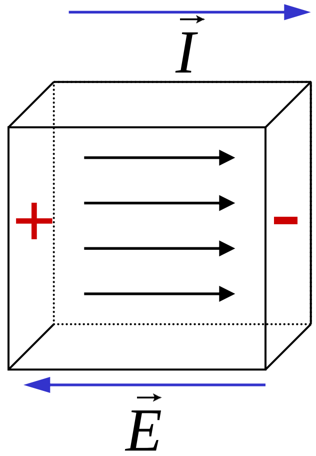
- Plasma waves sound Waves &Transistors
- Detection & Imaging
- Current research and unresolved problems

Outline

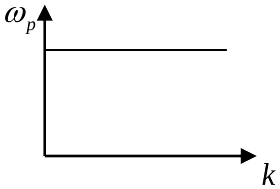
- Plasma waves &Transistors
  - Plasma waves and dimensionality
  - Fiel Effect Transistors
  - Plasma waves in the transistors
- Well establised results and apllications
  - Regimes of detection
  - Resonant detection
  - Non-resonant detection
- Current research and unresolved problems
  - Emission
  - Temperature
  - Resonat dreams with graphene
  - Circular polarisation
  - THz communication

Plasma waves and dimensionality

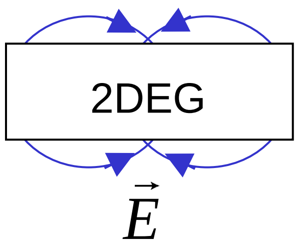
3D



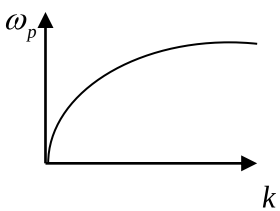
$$\omega_p = \sqrt{\frac{e^2 n_{3D}}{\varepsilon\varepsilon_0 m}}$$



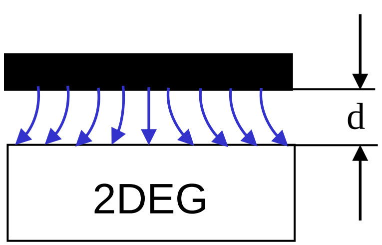
2D



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

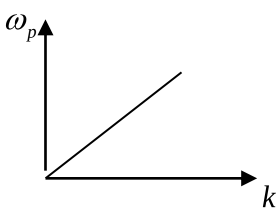


2D
gated

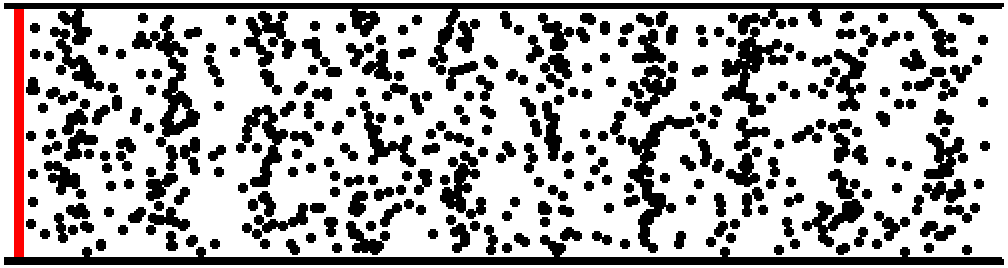


$$\omega_p = sk$$

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



Standing Longitudinal Waves in the tube



Different modes

Musical wind instrument Analogy

(Air and Plasma Waves Comparison)

Parameter	**Sound**	**2D plasma**
Dimension	0.1-1 m	0.1-1 µm
Speed of waves (s)	300 m/s	10^6 m/s
Frequency (s/L)	0.3kHz-3kHz	1THz-10THz

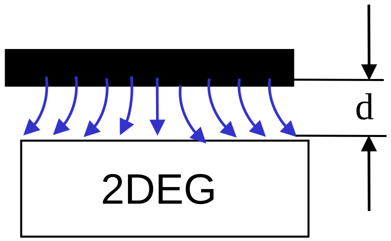
BETTER THEN ACOUSTIC INSTRUMENTS …….Voltage tunable

Appl. Phys. Lett. 67, 1137 (1995) M. Dyakonov et al.

Plasma waves velocity in 2DEG gated gas

« Voltage tuneability»

2D
gated



$$\omega_p = sk$$

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

$$n_{2D} = CU$$

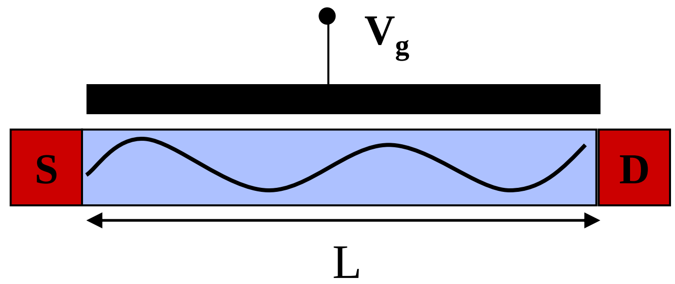
$$C = \frac{\varepsilon\varepsilon_0}{d}$$

$$s = \sqrt{\frac{eU}{m}}$$

k

Frequency of the plasma oscillations

« Voltage tuneability»



$$\omega = sk$$

$$s = \sqrt{\frac{eU}{m}}$$

$$k = \frac{2\pi}{\lambda}, \quad \lambda = 4L$$

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

$$L = 0.1 - 1\mu m$$

$$U = 1V$$

$$m = 0.06 - 0.24$$

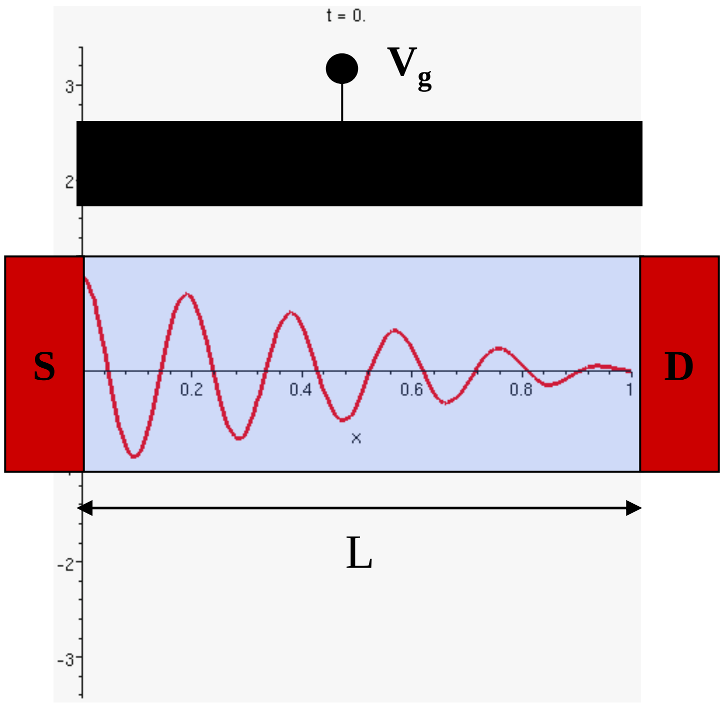
$$f_p \approx 0.6THz - 4.0THz$$

Basic mode n=1, ..3,5,7

Dreams of plasma waves resonances (high frequency and short transistors)

$$\omega\tau >> 1$$

Plasma waves are weakly damped



Short gate: $L << s\tau$

Experimental observations of plasma waves in 2DEG

S. J. Allen, D. C. Tsui, and R. A. Logan, PRL, **38**, 980 (1977)
D. C. Tsui, E. Gornik, and R. A. Logan, Sol. St. Comm, **35**, 875 (1980)

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

GaAs/AlGaAs, gated 2DEG

192

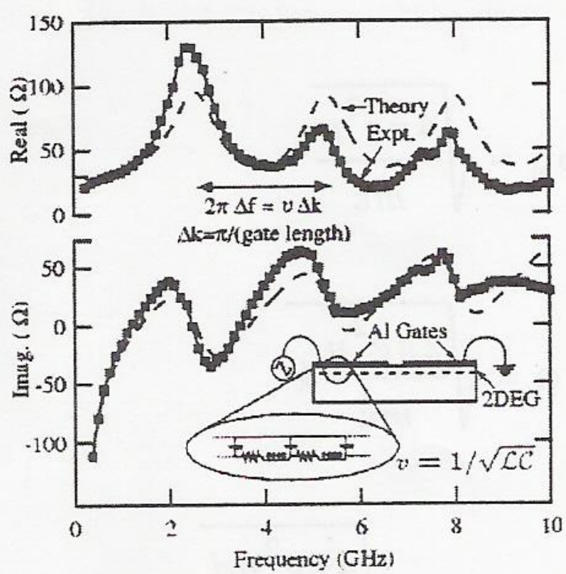


Fig. 2. Impedance of gated sample with 2D electron gas versus frequency. For this sample, $\omega_p\tau = 1$ at 1.25 GHz (where τ is the momentum relaxation time).[7]

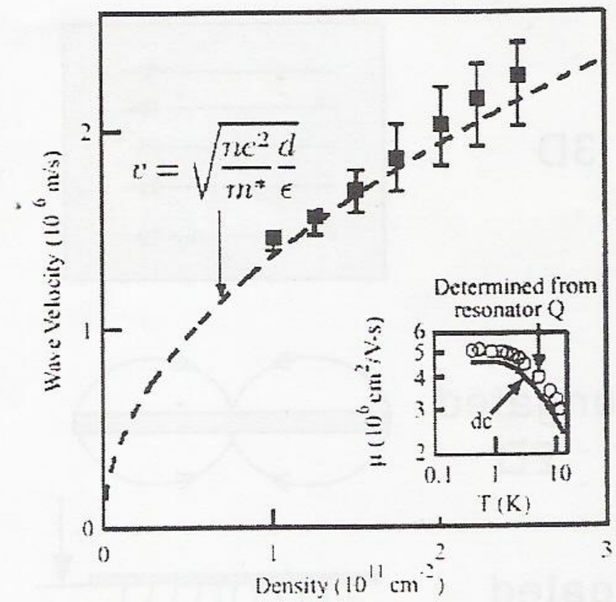


Fig. 3. Plasma wave velocity versus electron density.[7]

L=360μm $\mu \approx 330\, m^2/Vs\_T \sim 1K$

Can Plasma Waves Exist in main Semiconductor FETs???

$$reaching\_\_\omega\tau \geq 1\_at\_300K\_for\_1THz???$$

$$\mu_{Si} \sim 500\ \ cm^2/Vs \qquad \omega\tau_{Si} \sim 0.4$$

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

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

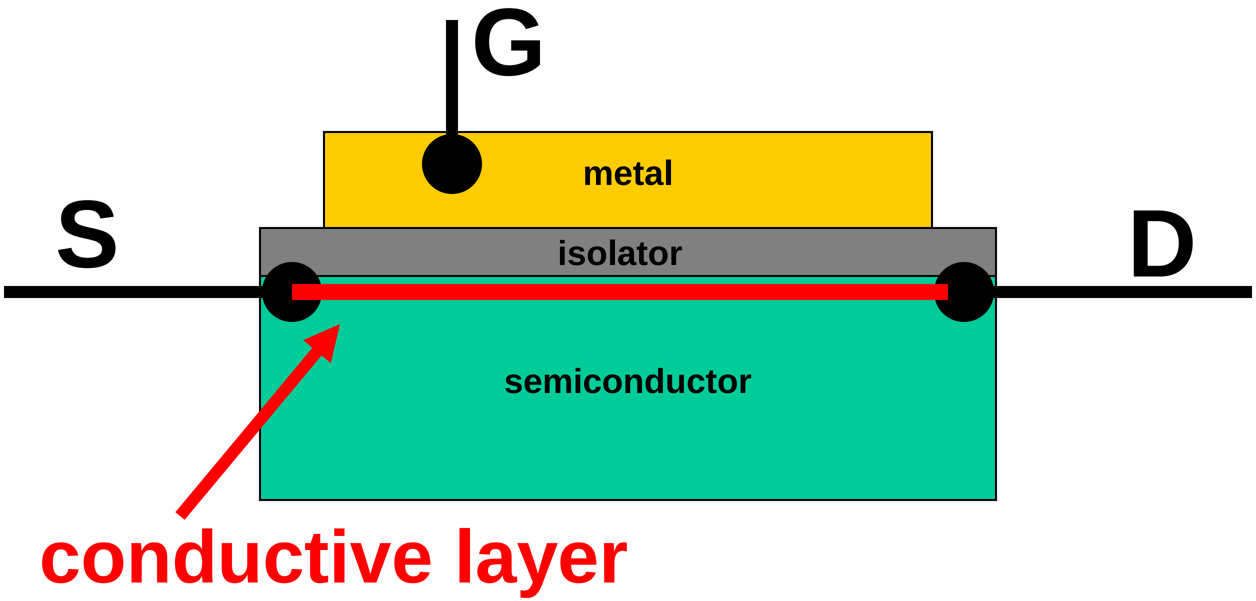
$$reaching\_frequency\_1THz??\_f \sim \sqrt{n_s/m^*}\Big/L\_$$

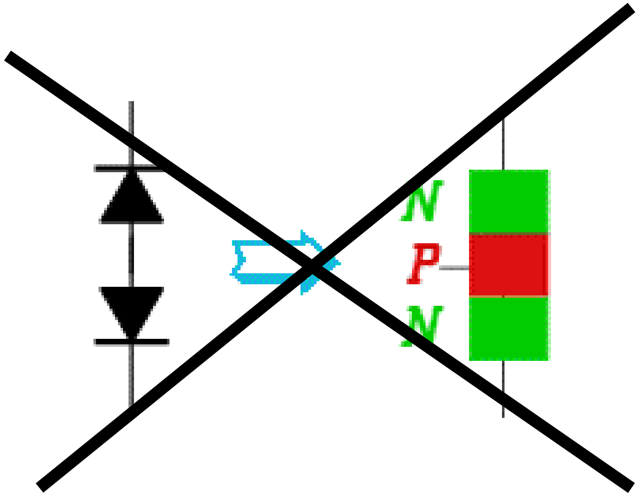
<u>For GaAs</u> (1 THz) n = 2×10^{12} cm^{-2} & L = 600nm.
<u>For GaN</u> (1 THz) n = 2 ×10^{13} cm^{-2} & *L* =1000nm
<u>For Si</u> (1 THz) n = 2 ×10^{12} cm^{-2} & *L* =300nm
!!!!!!!!!!!!!!NANOTECHNOLOGY!!!!!!!!!!!!!!

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

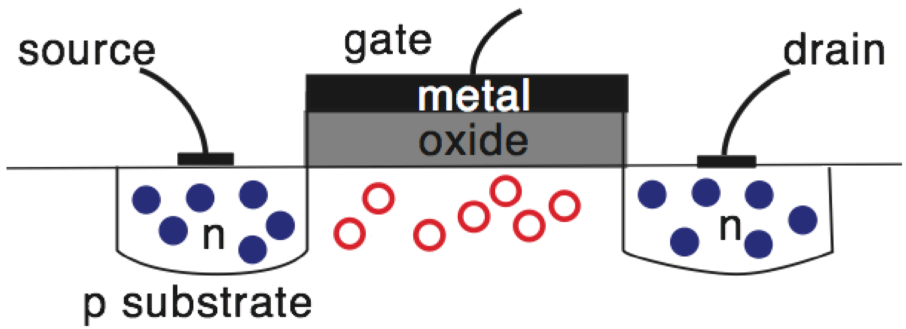




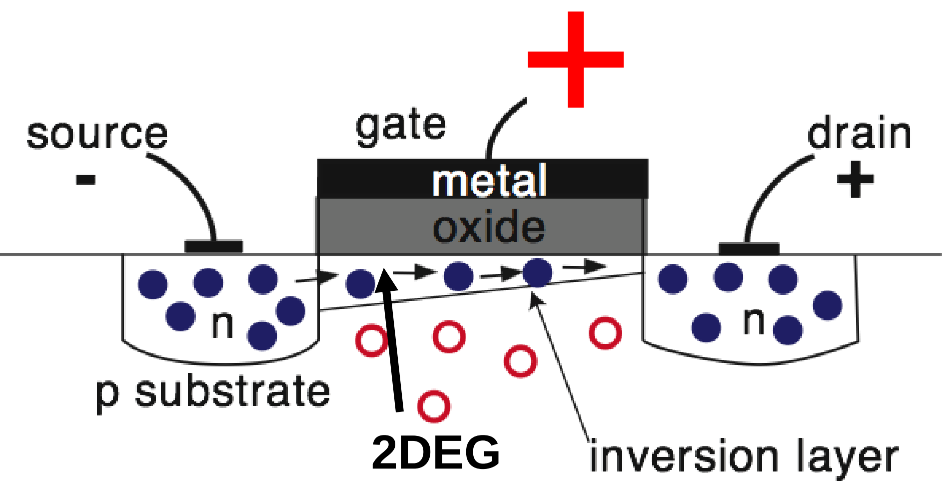
Carrier density regulated by the electric field of the gate

Field Effect Transistors

MOSFET

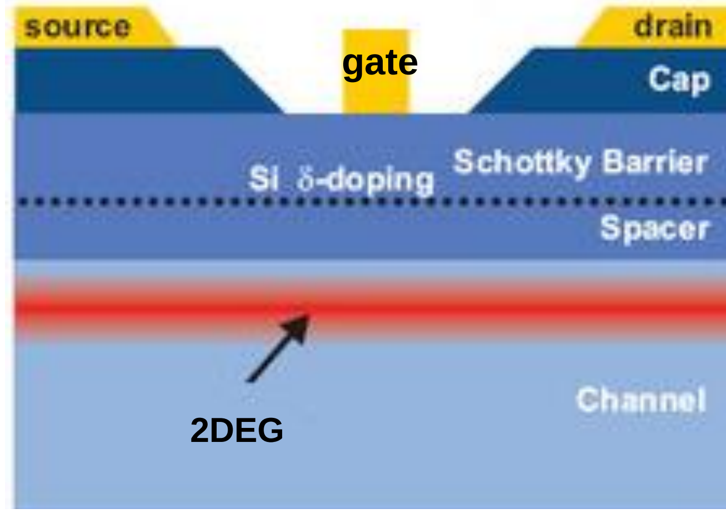


$V_g = 0$ -> n=0

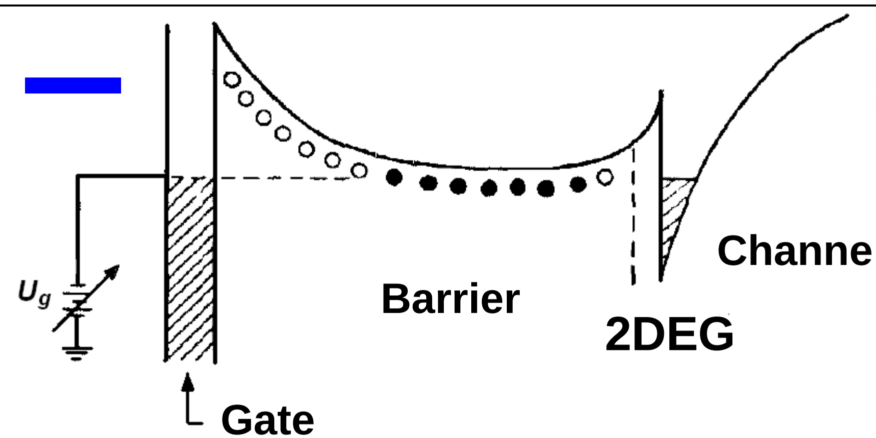


2DEG CREATION

HEMT

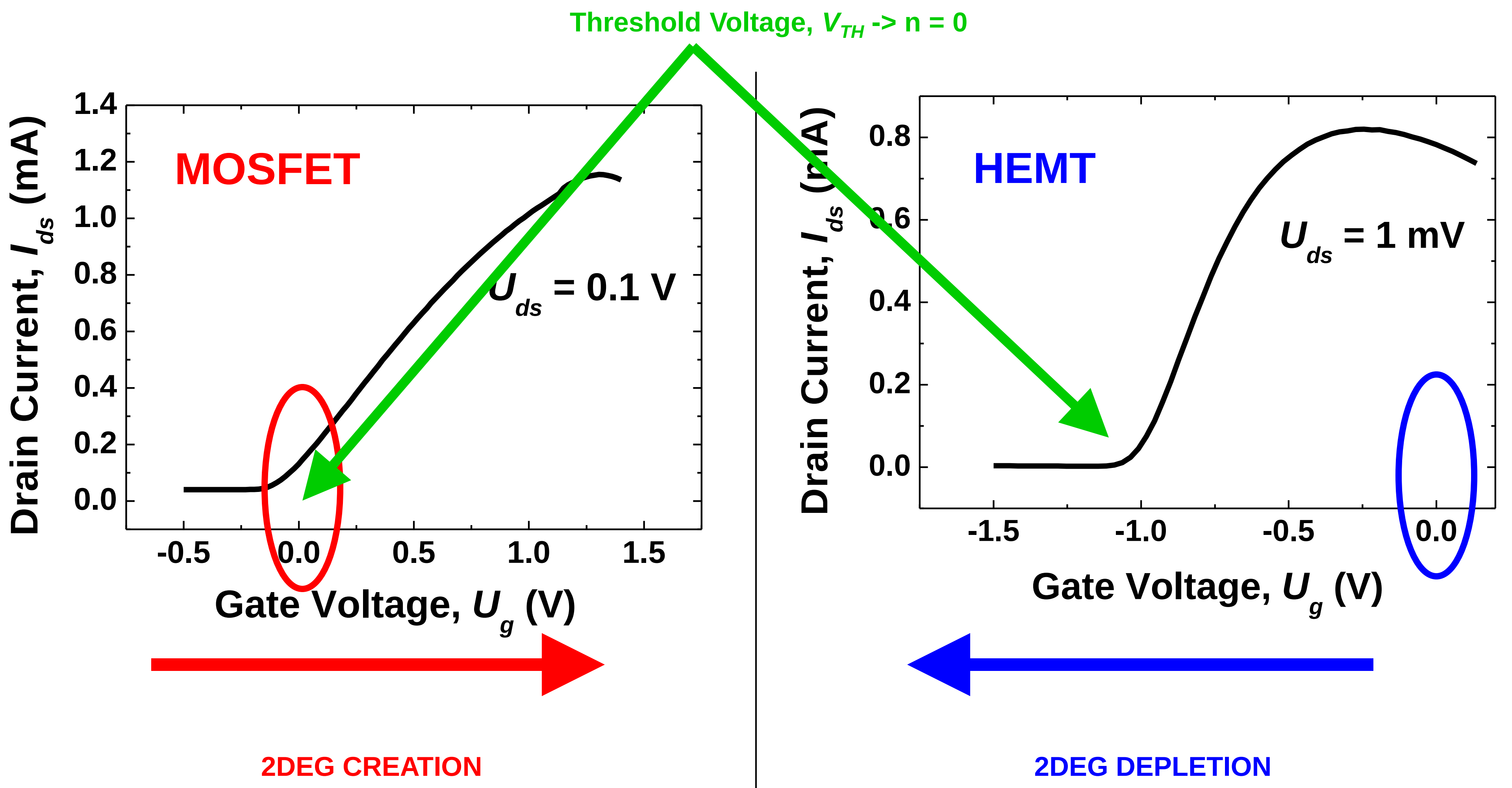


$V_g = 0$ -> $n \neq 0$



2DEG DEPLETION

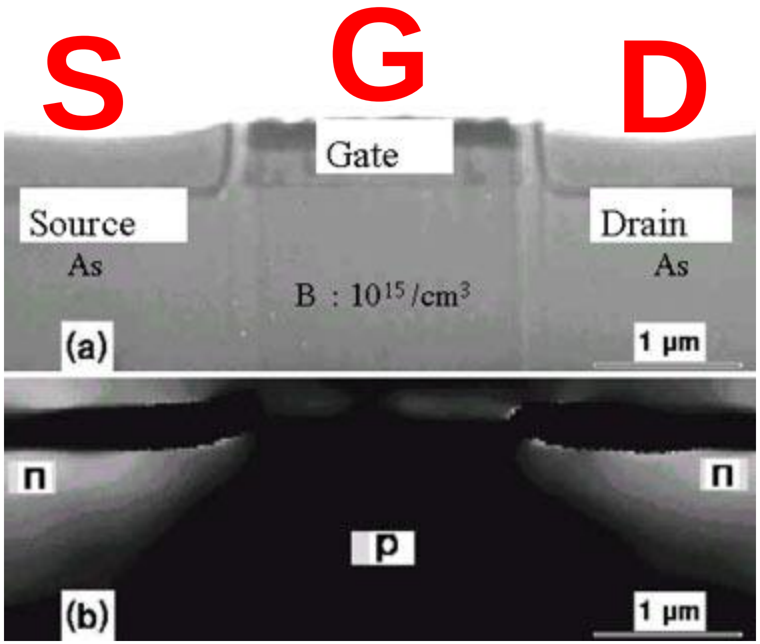
Transfer Characteristics



$$ne = C\left(V_g - V_{TH}\right)$$

Field Effect Transistors

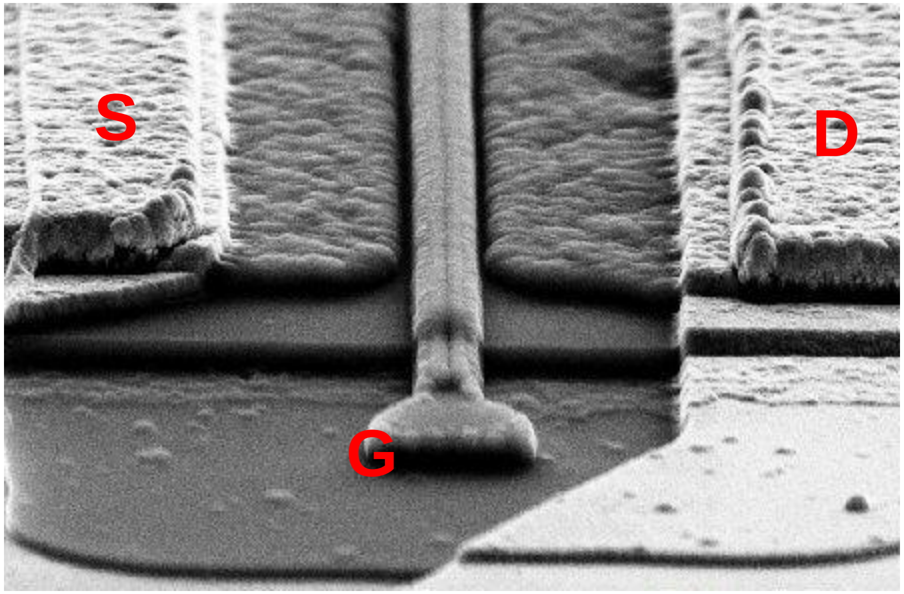
MOSFET



Cross section of a MOSFET
(a) Transmission electron micrograph
(b) Phase image obtained by
electron holography

APL 80, 246, (2002)

HEMT

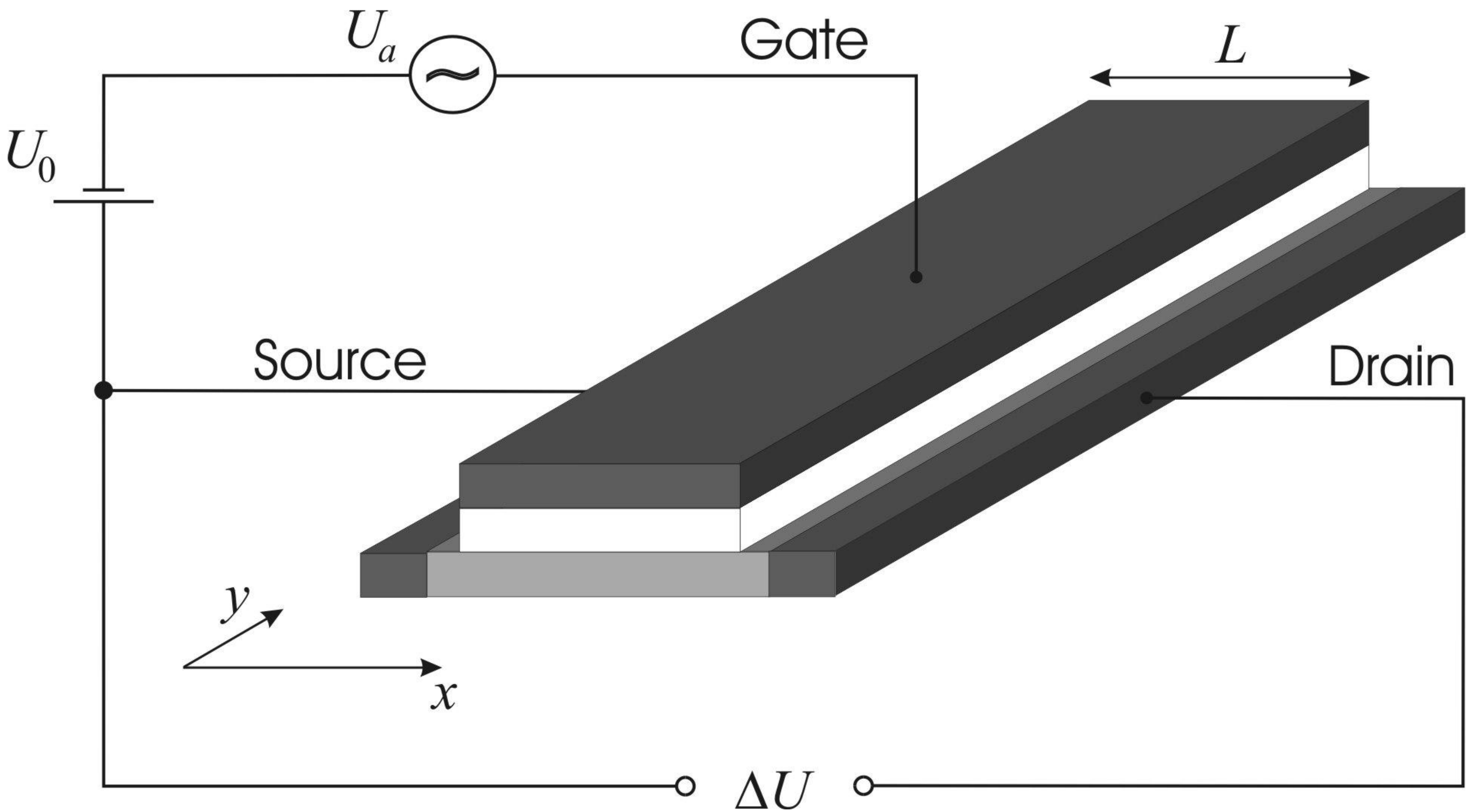


100 nm gate AlGaN/GaN on silicon HEMT with a 1 μm source-drain separation

ETH Zurich

Plasma waves excitation by THz radiation

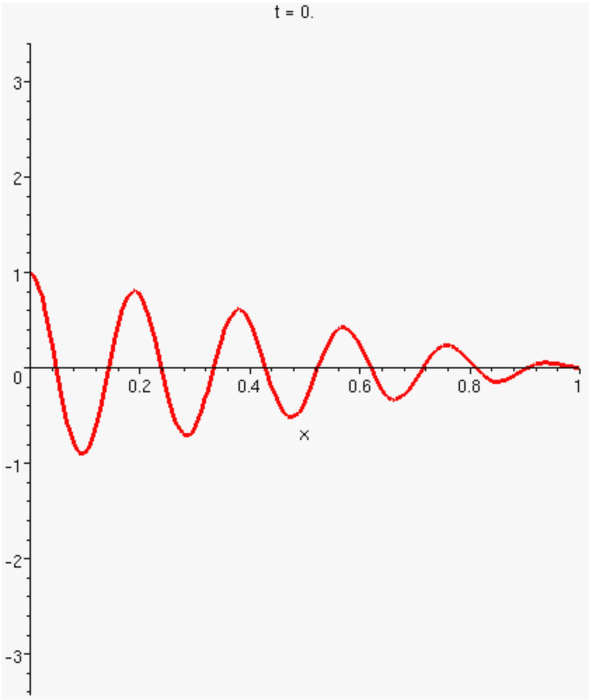
THz radiation couples to the transistor by antennas – it can be represented as AC source between two electrodes

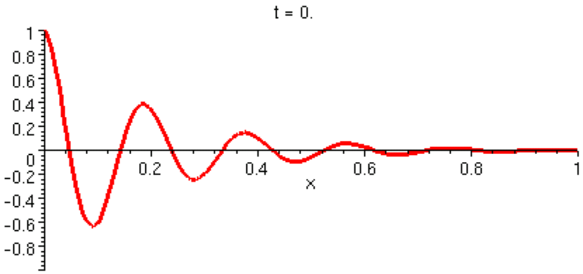


Regimes of plasma waves (high frequency)

$$\omega\tau >> 1$$ Plasma waves are weakly damped

Characteristic damping length: $l = s\tau$

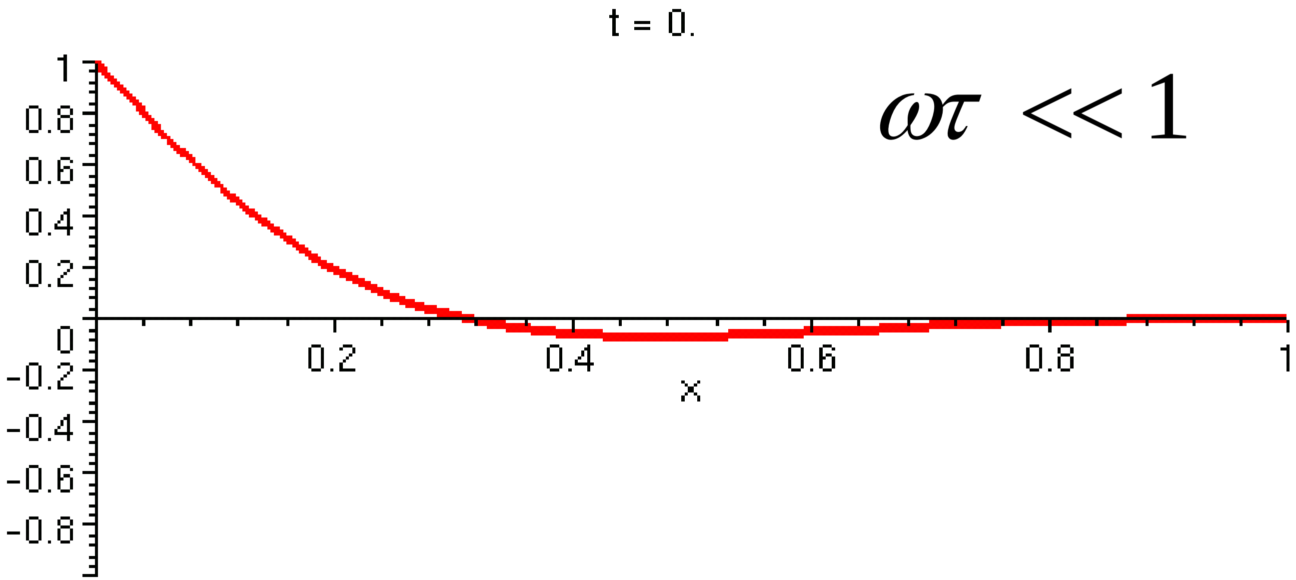




Short gate: $L << s\tau$

Long gate: $L >> s\tau$

Overdamped oscillations
(low frequency/mobility ,300K)



$$\omega\tau \ll 1$$

"*x*" distance normalized by " damping length"

$$l_{eff} = s\sqrt{\tau / \omega} = \sqrt{\mu U_g / \omega}$$

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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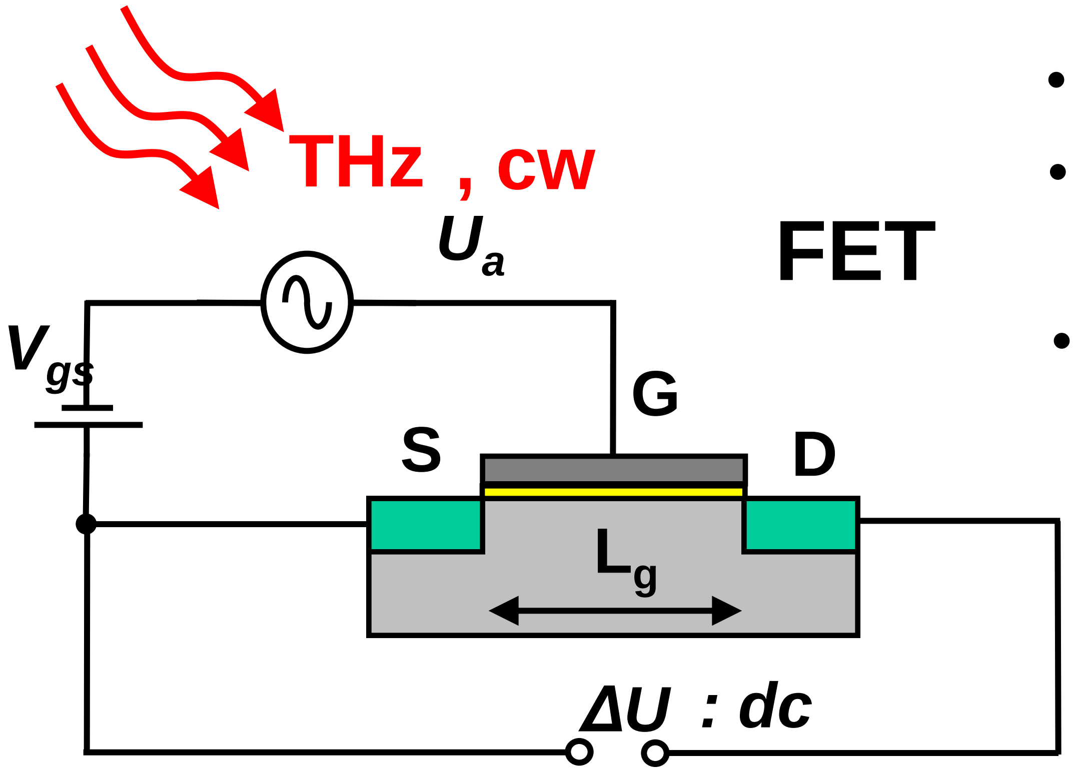
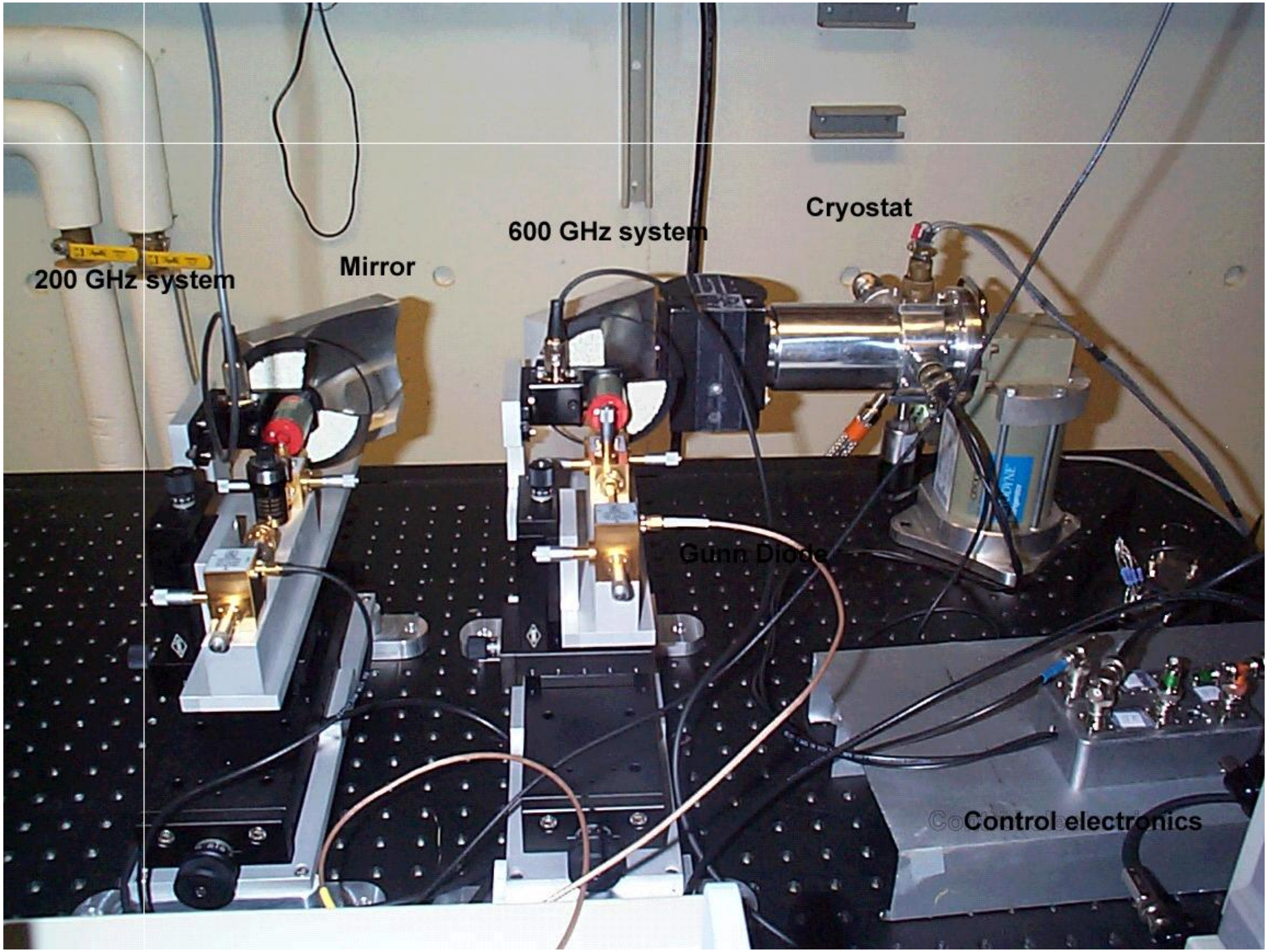
Rectification of THz radiation in FETs



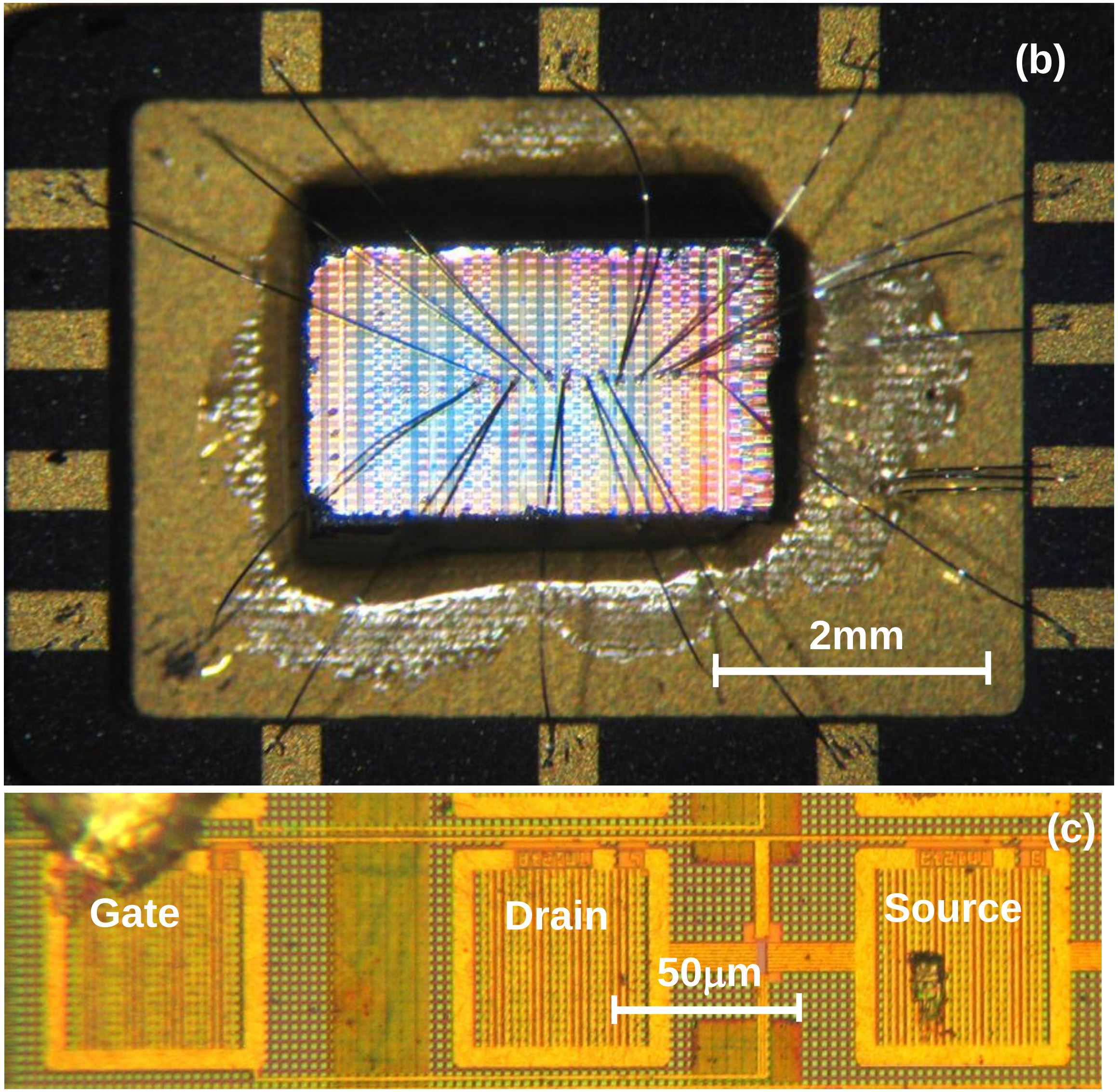
- *Vgs*: Source-Gate bias
- *Ua*: irradiation induced *ac* voltage
- *ΔU*: *dc* photoresponse

!!Nonlinearity – THz modulates simultaneously !!carrier density and drift velocity!!

Experimental Setup



Devices

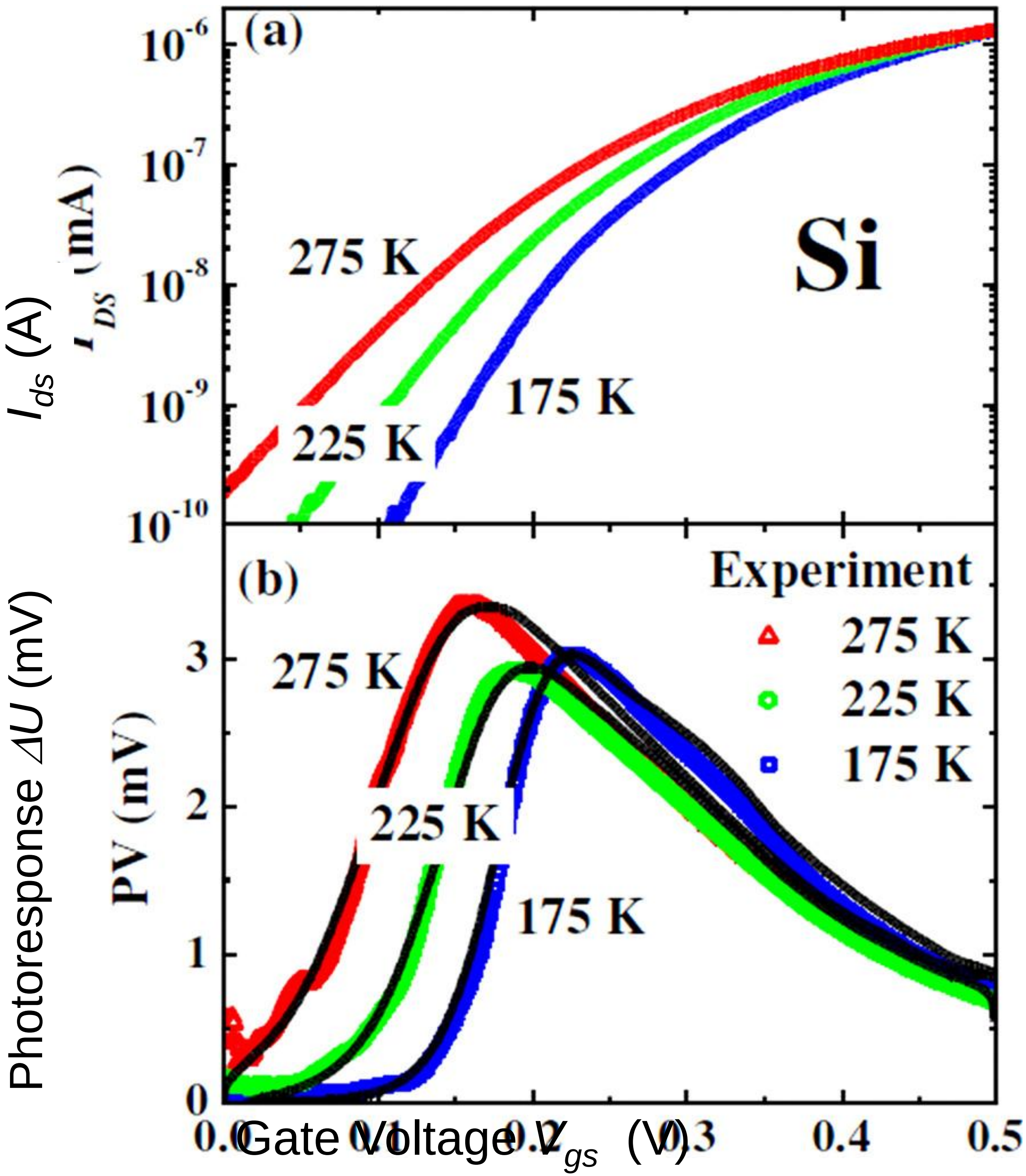


0.7THz → $\lambda/2=214\mu m$

Diffraction limited spot:

214X214μm

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



Sakowicz *et al.*
JAP, 2011

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

3) Ovedamped Plasma and THz imaging @ 300K

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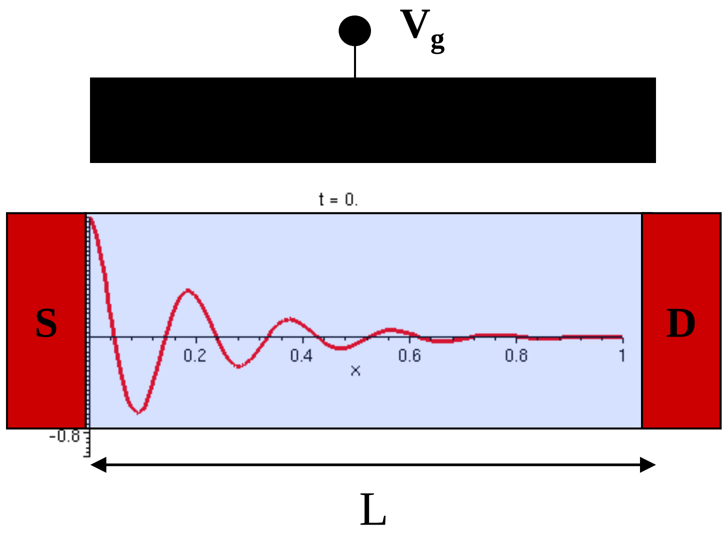
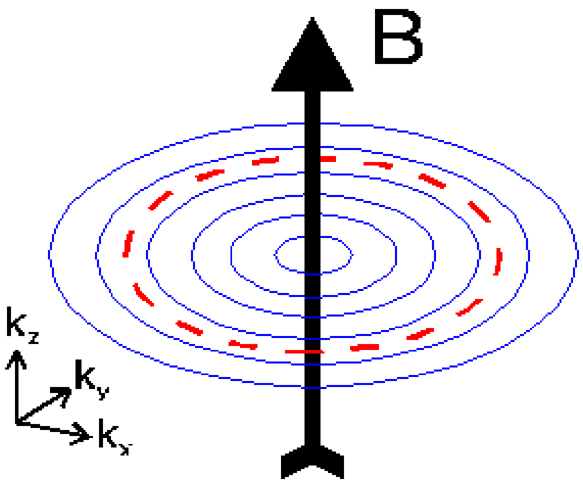
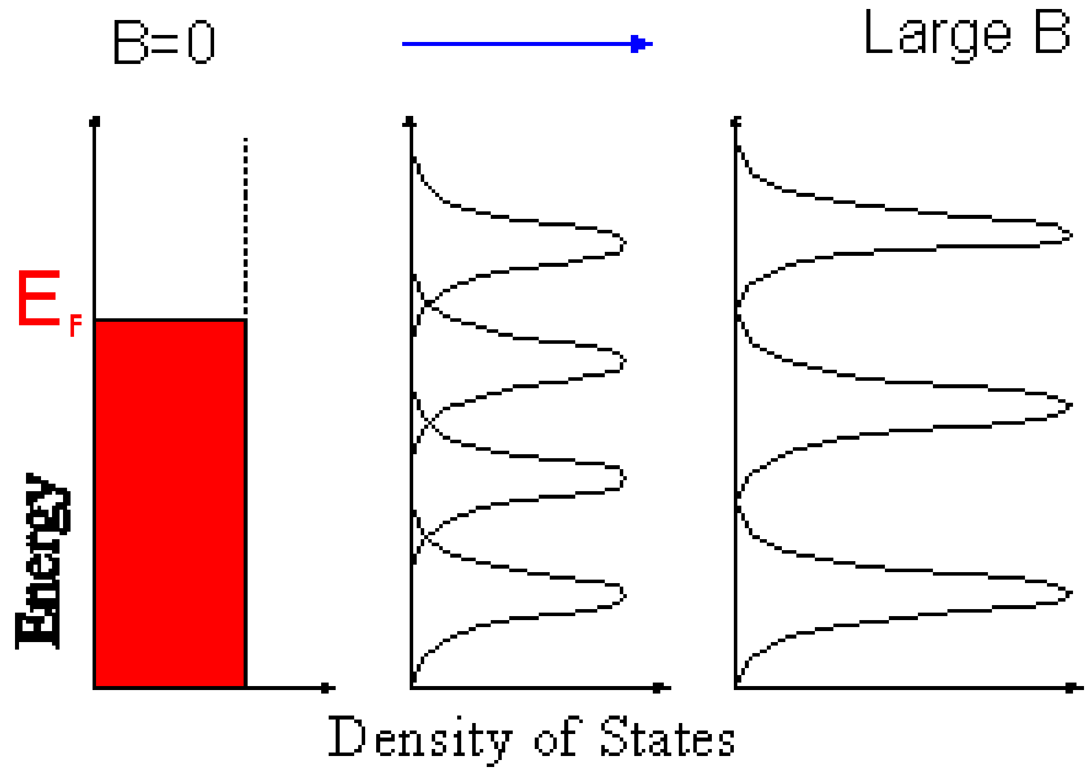


Long gate: $L >> s\tau$

2DEG in Magnetic Field





CYCLOTRON ORBIT

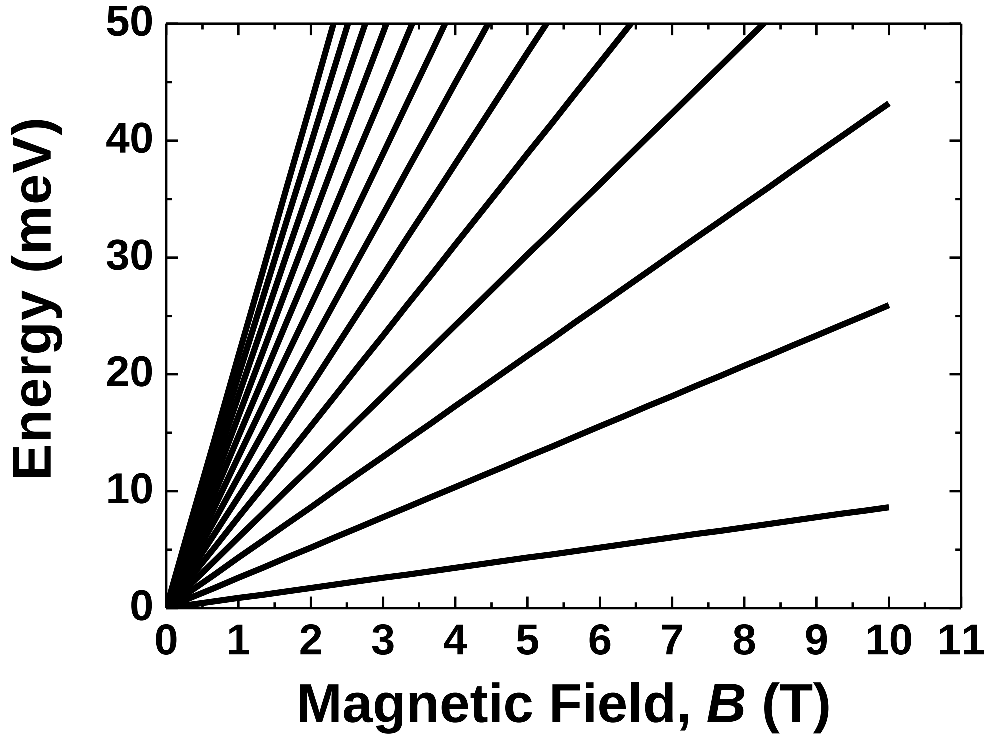
$$\omega_c = \frac{eB}{m^*}$$

ENERGY QUANTIZATION

$$E = E_0 + \left(n + 1/2\right)\hbar\omega_c$$

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

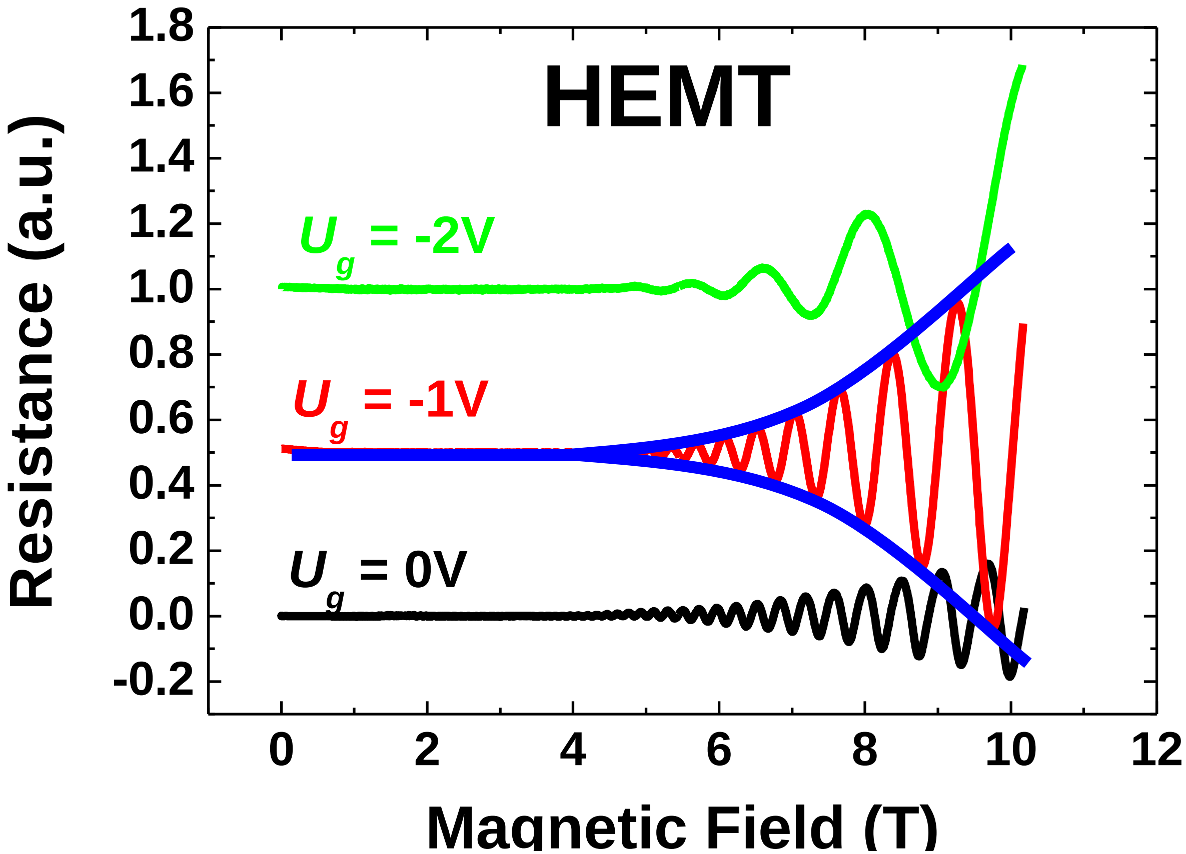
Cyclotron Resonance



$$\hbar\omega_c \qquad \omega_c = \frac{eB}{m^*}$$

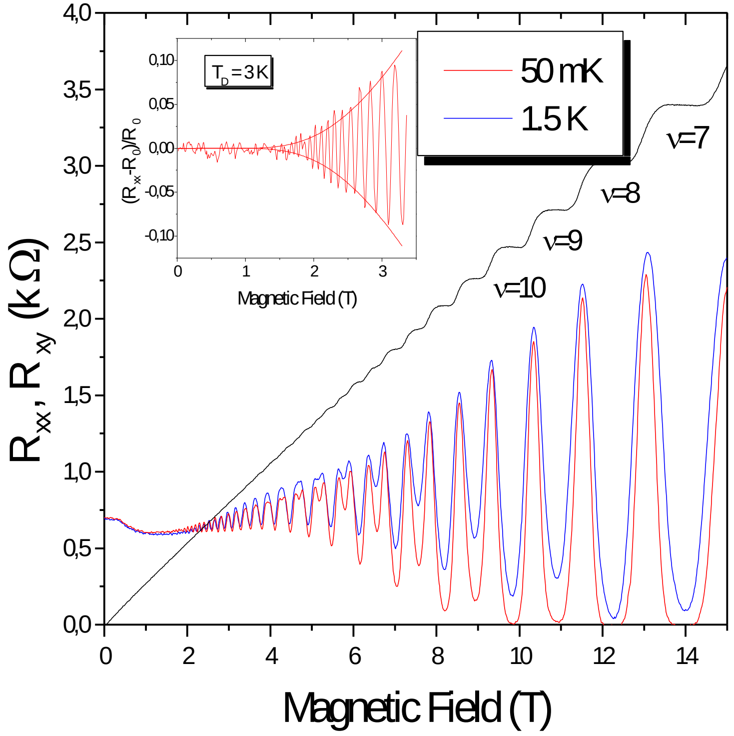
Schubnikov – de Haas Oscillations

$$\rho = \rho_0 \frac{A}{shA} \exp\left(-\frac{\pi e}{m^* \tau_q} \frac{1}{B} \right) \cos\left(\frac{\pi n h}{e} \frac{1}{B} + \phi \right)$$



n
increases

Quantum Hall Effect and SdH Studies



- Fig. 2-

Frassinet et al. Appl. Phys. Lett. 77,2551(2000)

Plasma waves and Cyclotron resonace

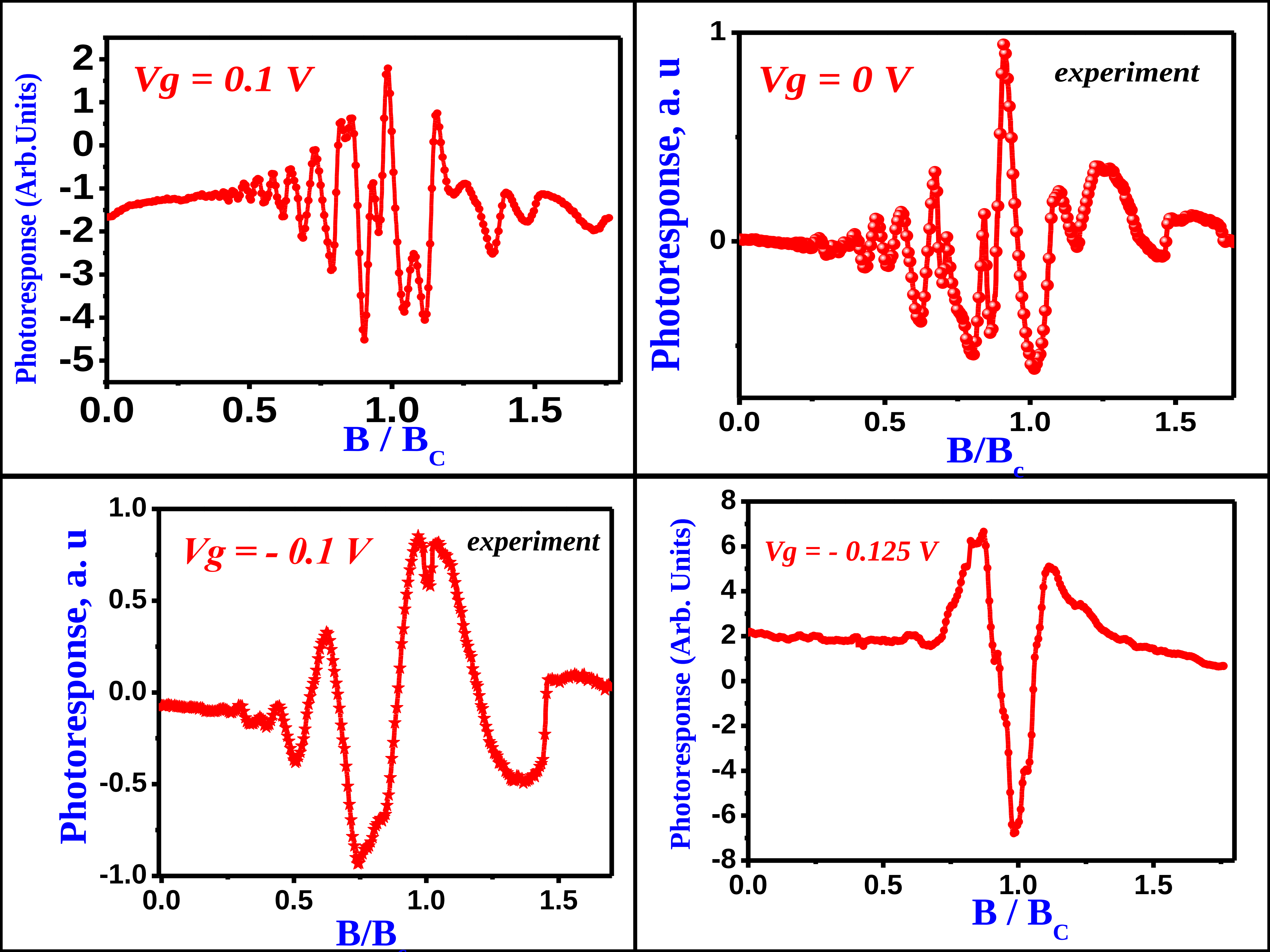
$$\omega = sk$$

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

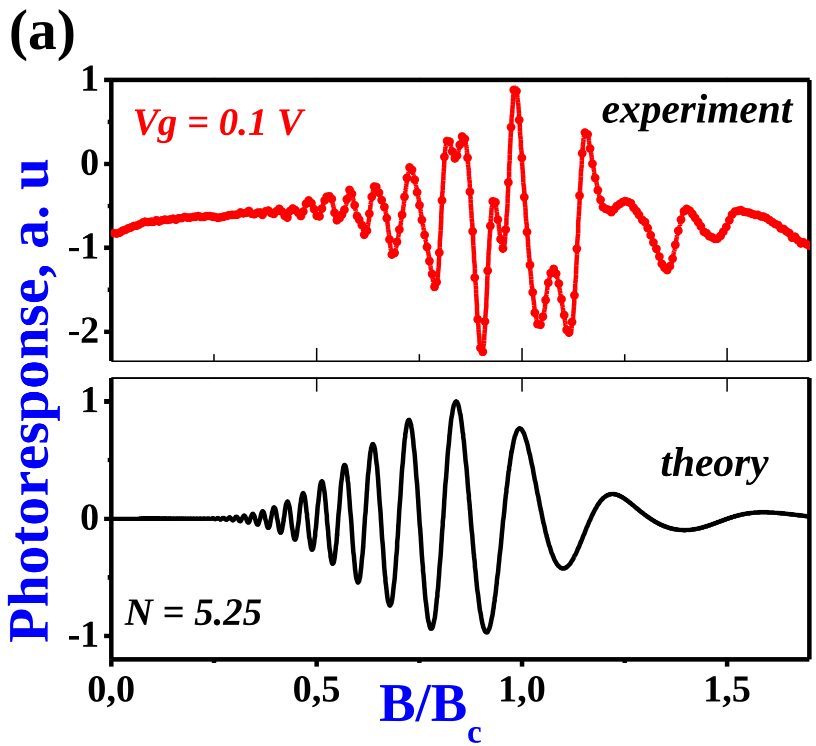
$$k = \frac{\omega}{s}\sqrt{1 - \frac{\omega_c^2}{\omega^2}}$$

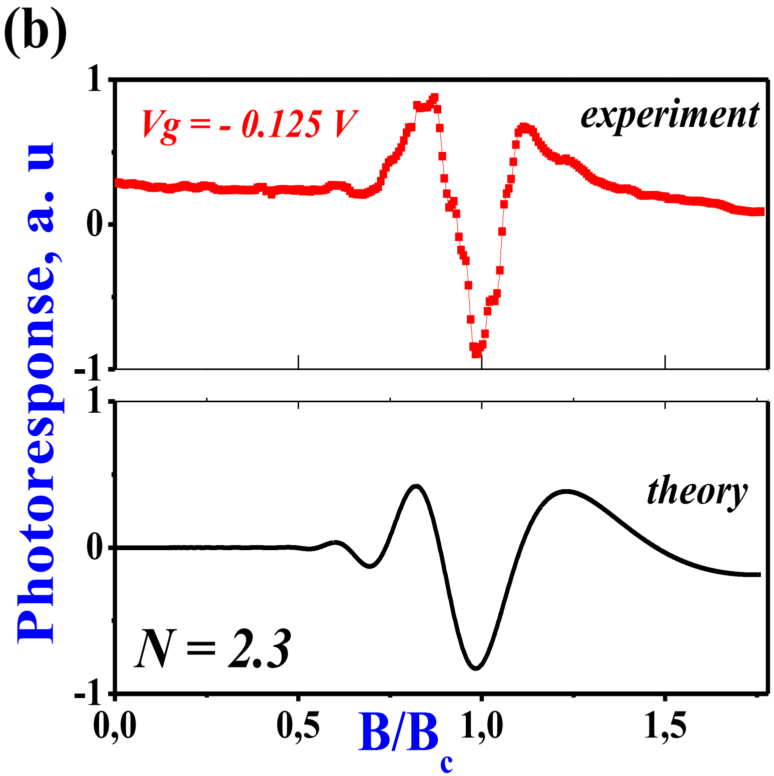
When $\omega_c > \omega$ k is imaginary and plasma waves can not propagete

THz rectification by In GaAs FET in magnetic fields


Vg = 0.1 V
Photoresponse (Arb.Units)
B / B_C
Vg = 0 V
experiment
Photoresponse, a. u
B/B_c
Vg = - 0.1 V
experiment
Photoresponse, a. u
B/B
Vg = - 0.125 V
Photoresponse (Arb. Units)
B / B_C

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





Exp S. Boubanga-Tombet et al. APL 2009

Theory M.Lifshits and M.I. Dyakonov PRB –Rapid Com 2009

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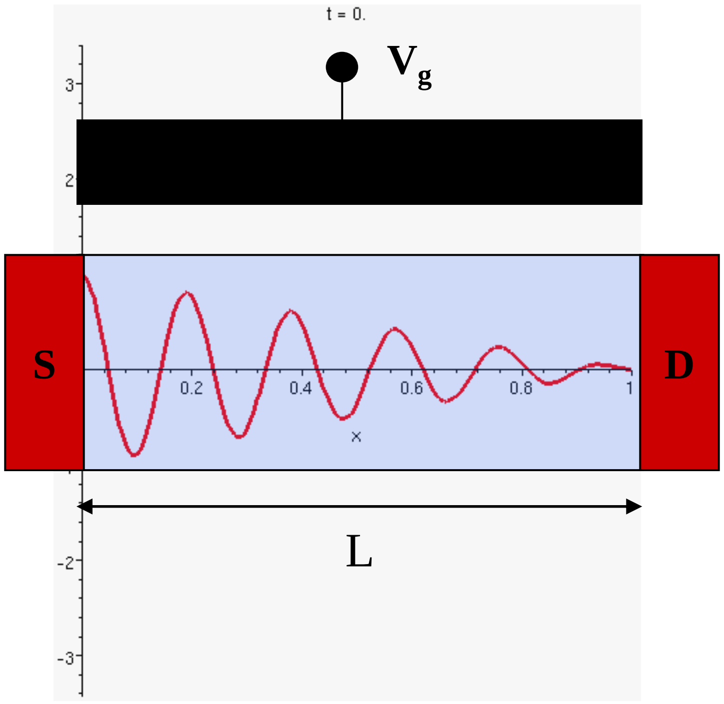
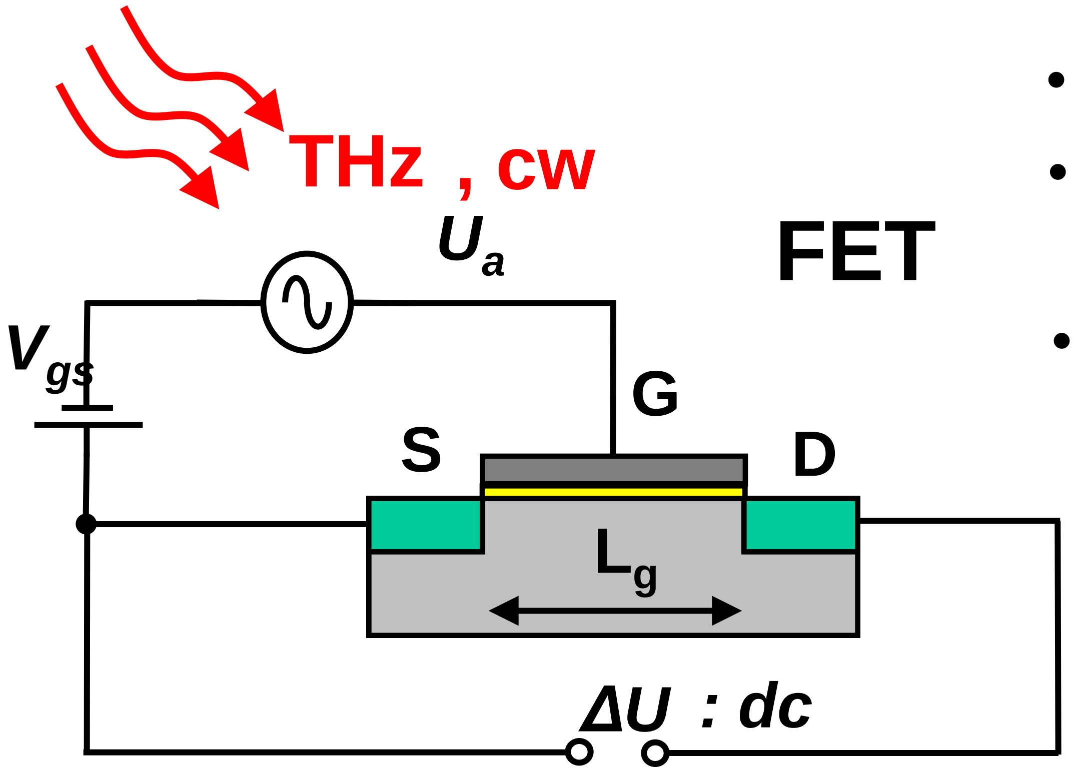


Short gate: $L << s\tau$

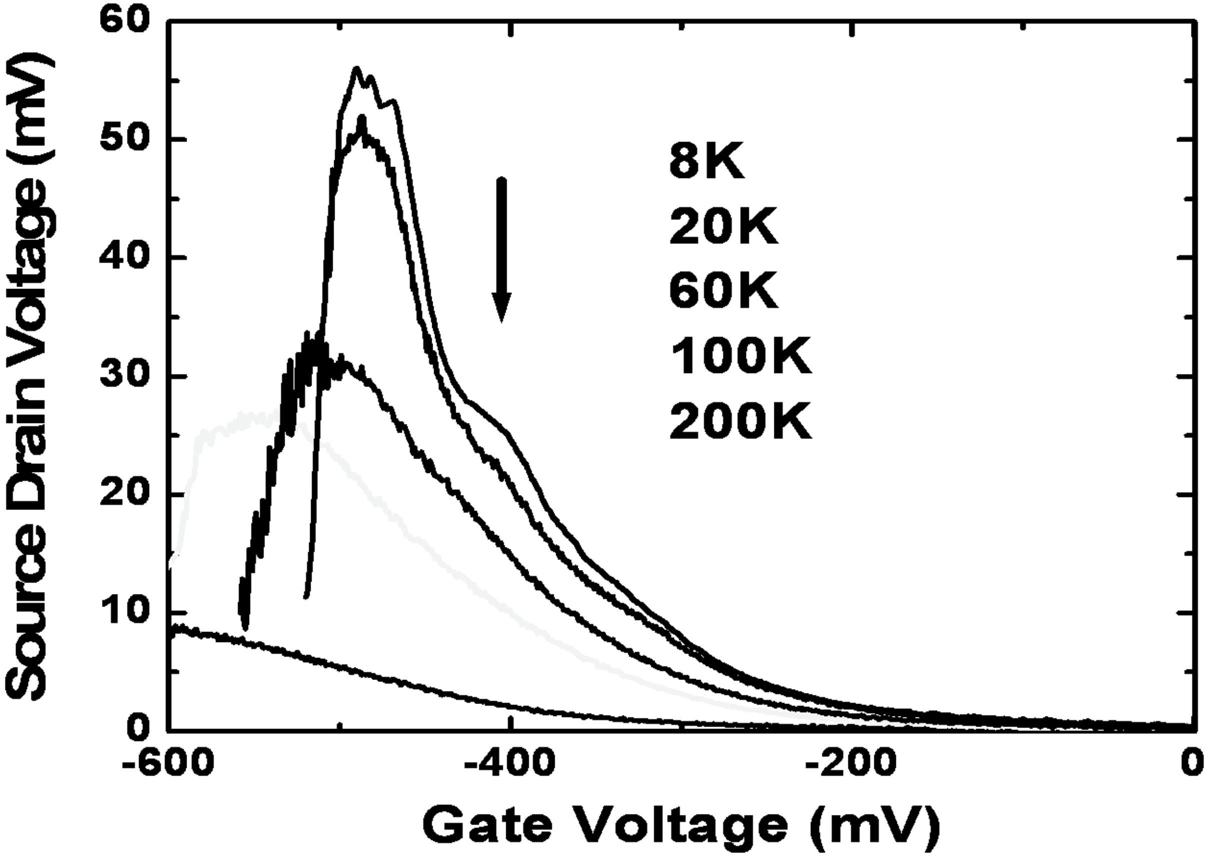
Rectification of THz radiation in FETs



- *Vgs*: Source-Gate bias
- *Ua*: irradiation induced *ac* voltage
- *ΔU*: *dc* photoresponse

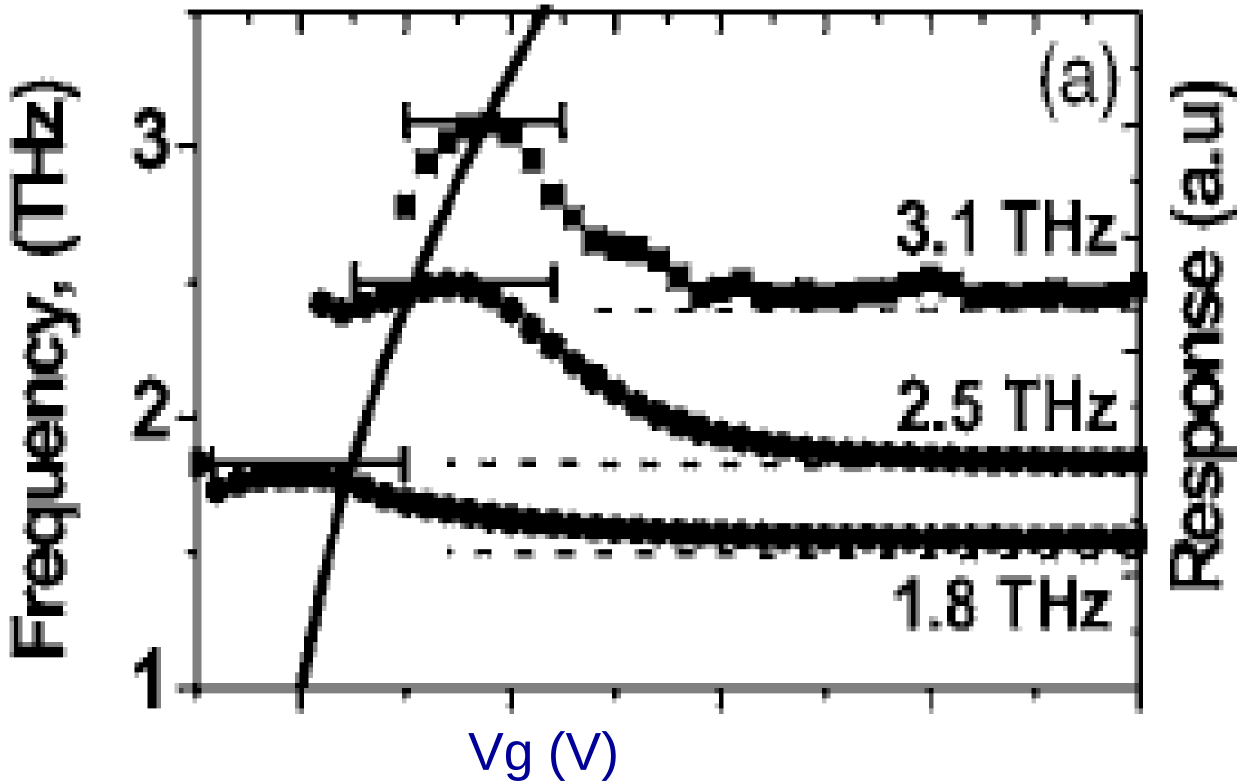
!!Nonlinearity – THz modulates simultaneously !!carrier density and drift velocity!!

First -Resonant Detection
0.6THz $\omega\tau$~1 Experiment ,250nm GaAs FET (Appl Phys Lett 2001)



The gate voltage – tunes carrier density – plasma frequency …to resonance

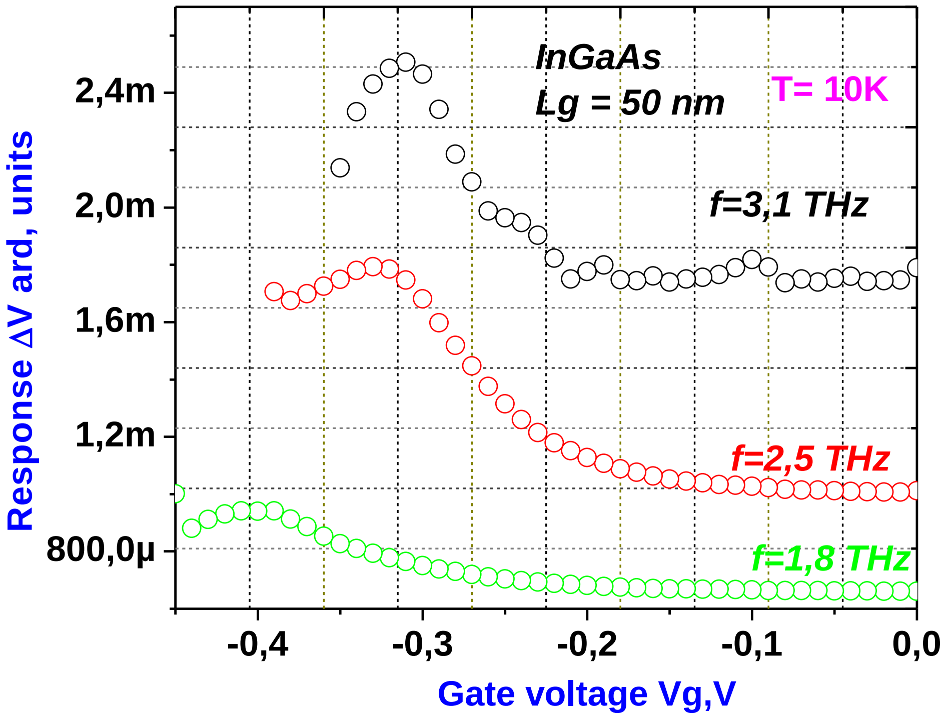
Resonant and “voltage-tunable” terahertz detection in InGaAs/InP nanometer transistors

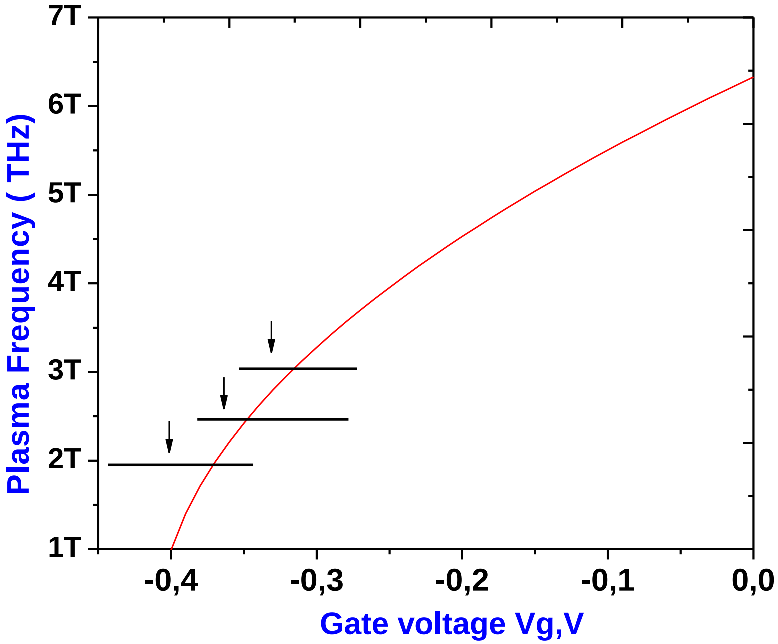


The calculated plasmon frequency as a function of the gate voltage for Shown by the solid line SQRT dependece .
The error bars correspond to the linewidth of the measured plasmon resonance peaks.

A. El Fatimy et al, APL 89, 131926, 2006

Resonant Detector & Quality factor InGaAs





Line width : $\omega\tau$ ~ ***3 ????***

μ = 36 000 cm^2/V.s ?? $\omega\tau$ ~ ***13??***

Resonances are wider than expected…???

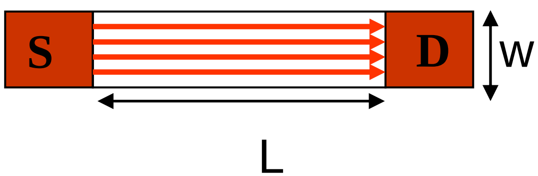
A. El Fatimy et al. APL, 89, 131926 ,(2006)

Discussion on plasma modes Broadening

Additional broadening mechanism

Dyakonov-Shur theory geometry

Top view



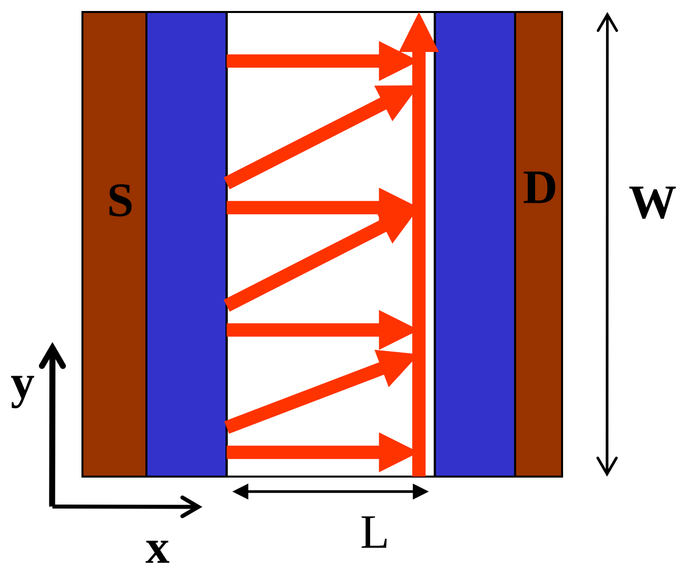
Only longitudinal modes

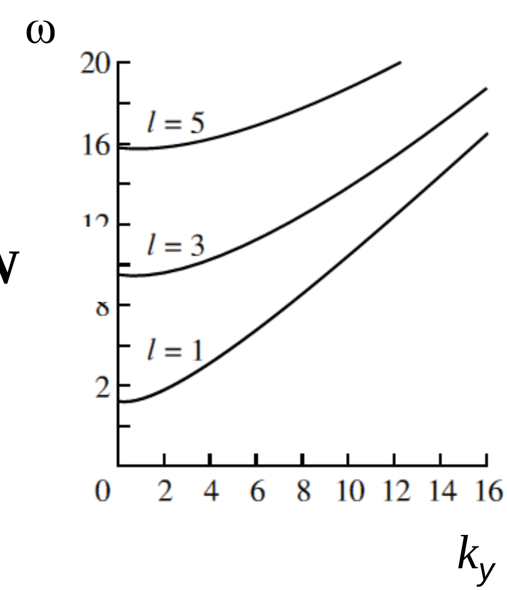
M. Dyakonov and M. Shur, IEEE Vol. 43, No. 3, (1996)

Experimental geometry

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

Top view

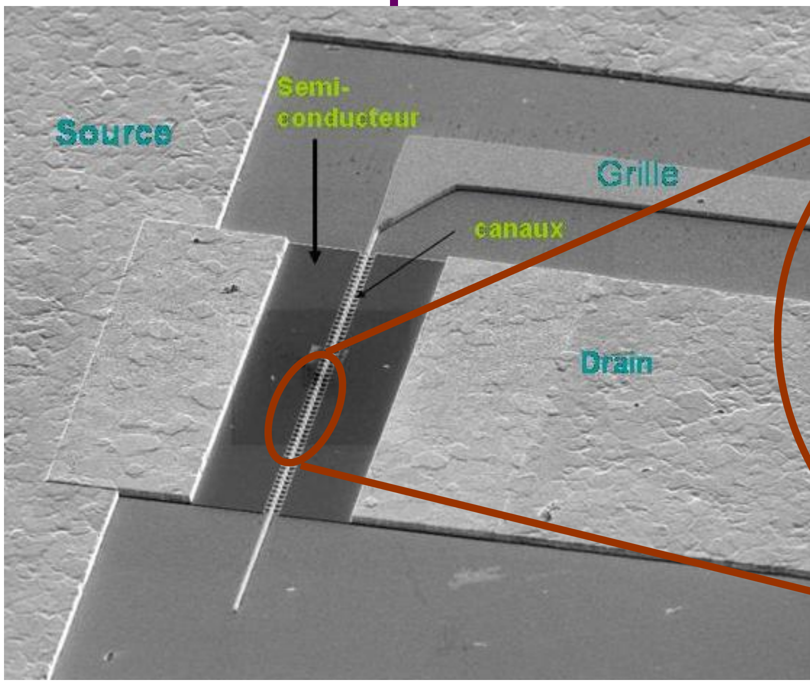


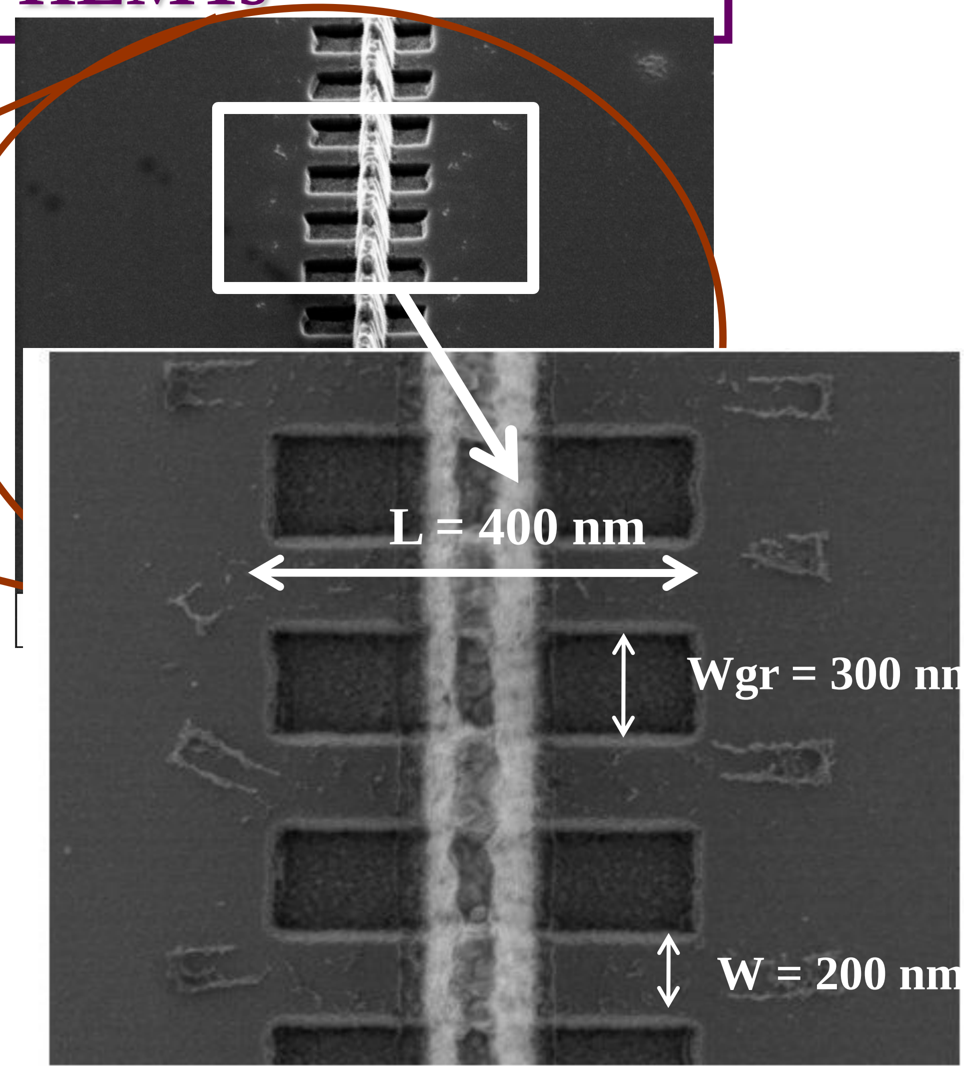


All modes are permitted

M.I. Dyakonov ***Semiconductors, 2008, Vol. 42, No. 8***

Samples - Multi-Channel InGaAs HEMTs



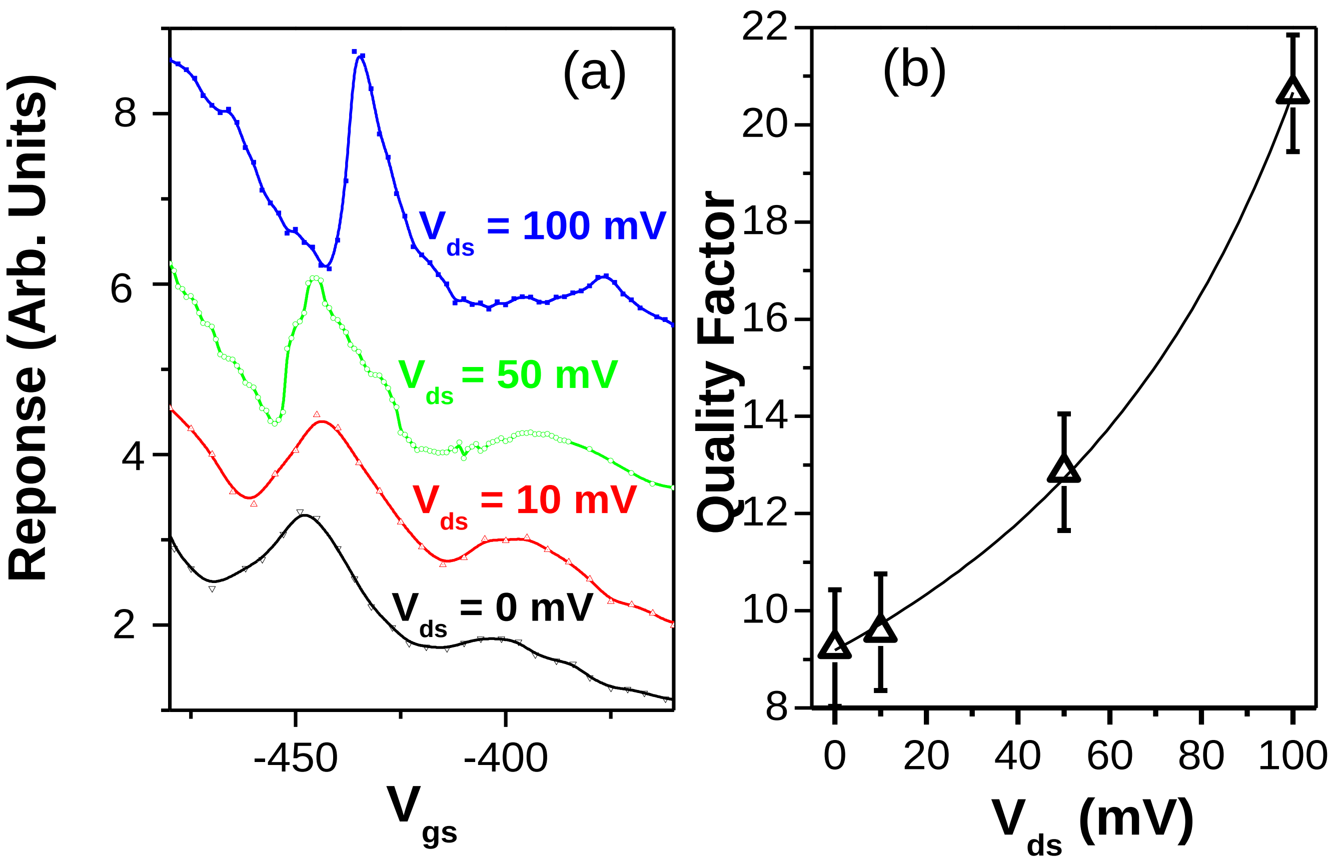


I-V Characteristics at 20 K

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



Incoming frequency = 0.54 TH

T = 10 K

$$v_d = \frac{\mu V_{ds}}{L}$$

μ = 11 m^2/V.s

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)

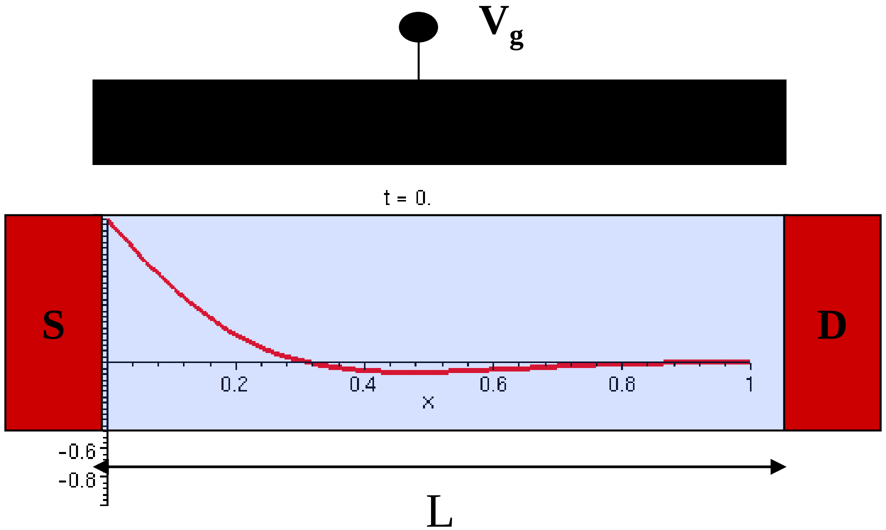
1)Experimental proofs of plasma waves existence

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

3) Ovedamped Plasma and THz imaging @ 300K

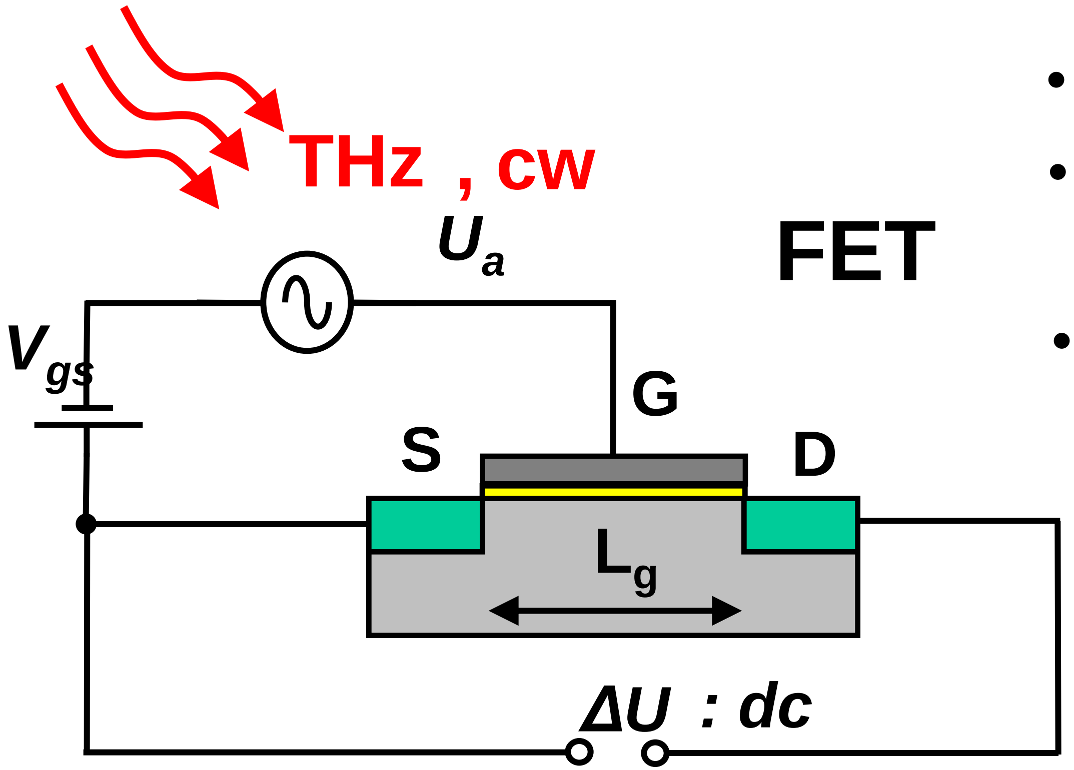
300K - Overdamped plasma oscillations

$$\omega\tau \ll 1$$



Characteristic length: $l = s\sqrt{\tau / \omega}$

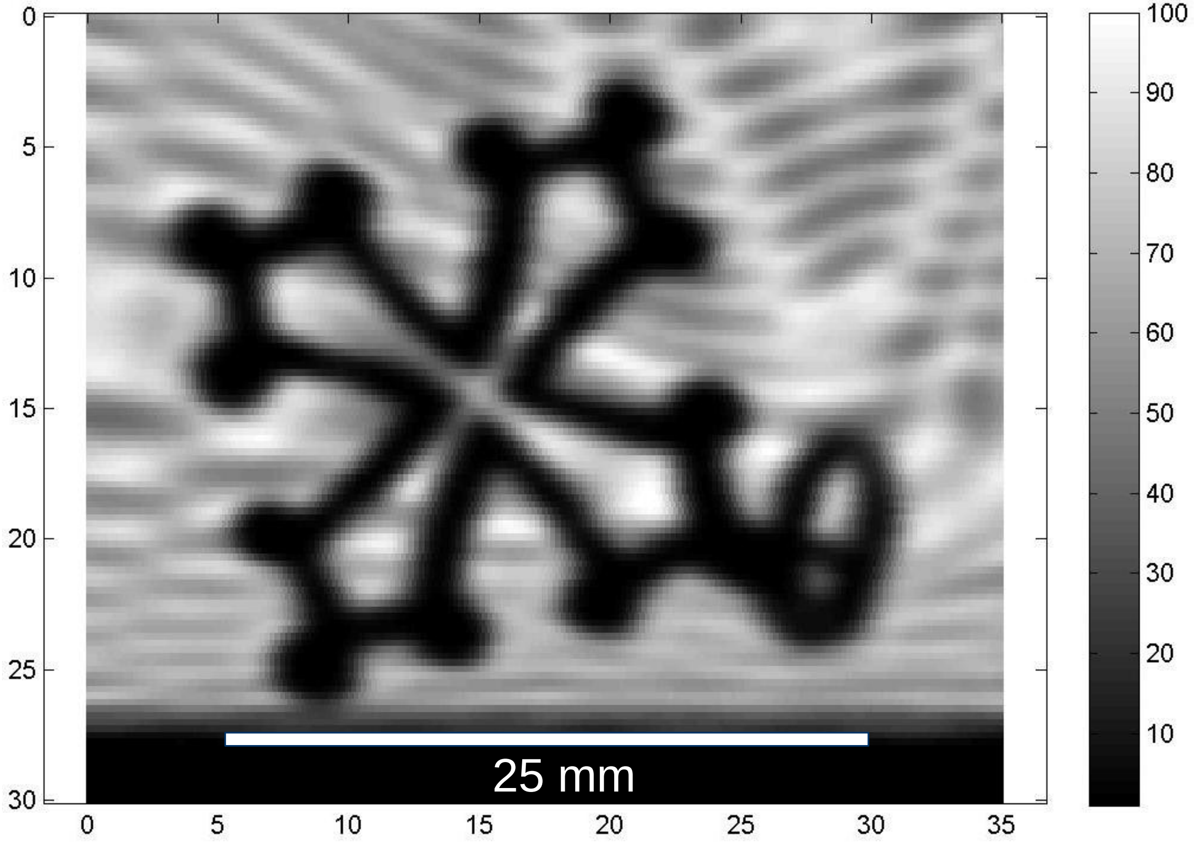
Rectification of THz radiation in FETs



- *Vgs*: Source-Gate bias
- *Ua*: irradiation induced *ac* voltage
- *ΔU*: *dc* photoresponse

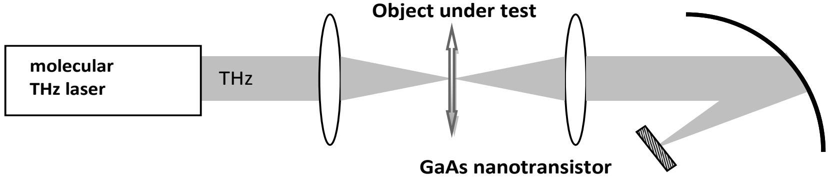
!!Nonlinearity – THz modulates simultaneously !!carrier density and drift velocity!!

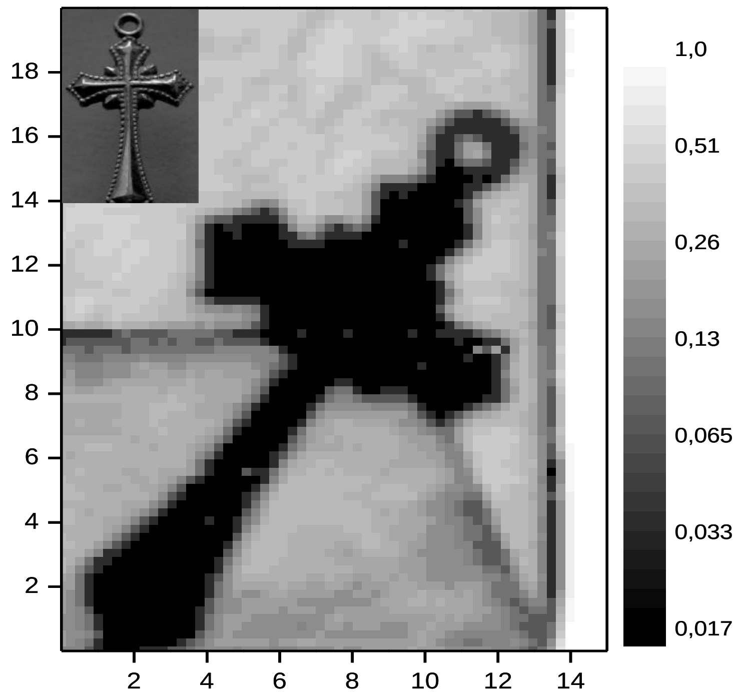
0.6 THz imaging with InGaAs HEMT – 300K



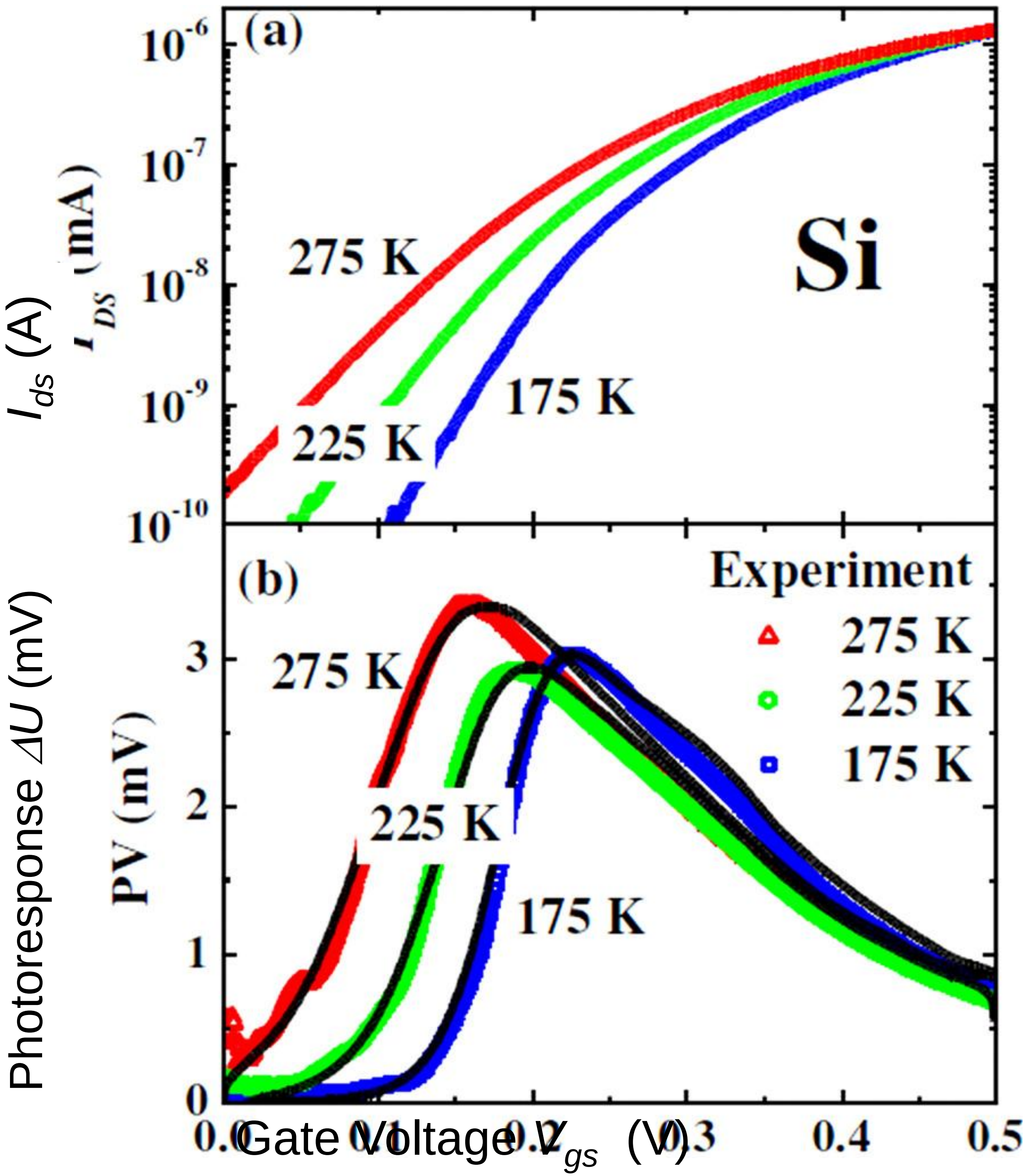
0.6 THz imaging - collaboration with University of Frankfurt
A. Lisauskas, W. von Spiegel, S. Boubanga, A. El Fatimy, D. Coquillat, F. Teppe, N. Dyakonova, W. Knap, and H. G. Roskos, Electr. Lett. **44**, 408 (2008).

Imaging at **1.6 THz** with a single FET

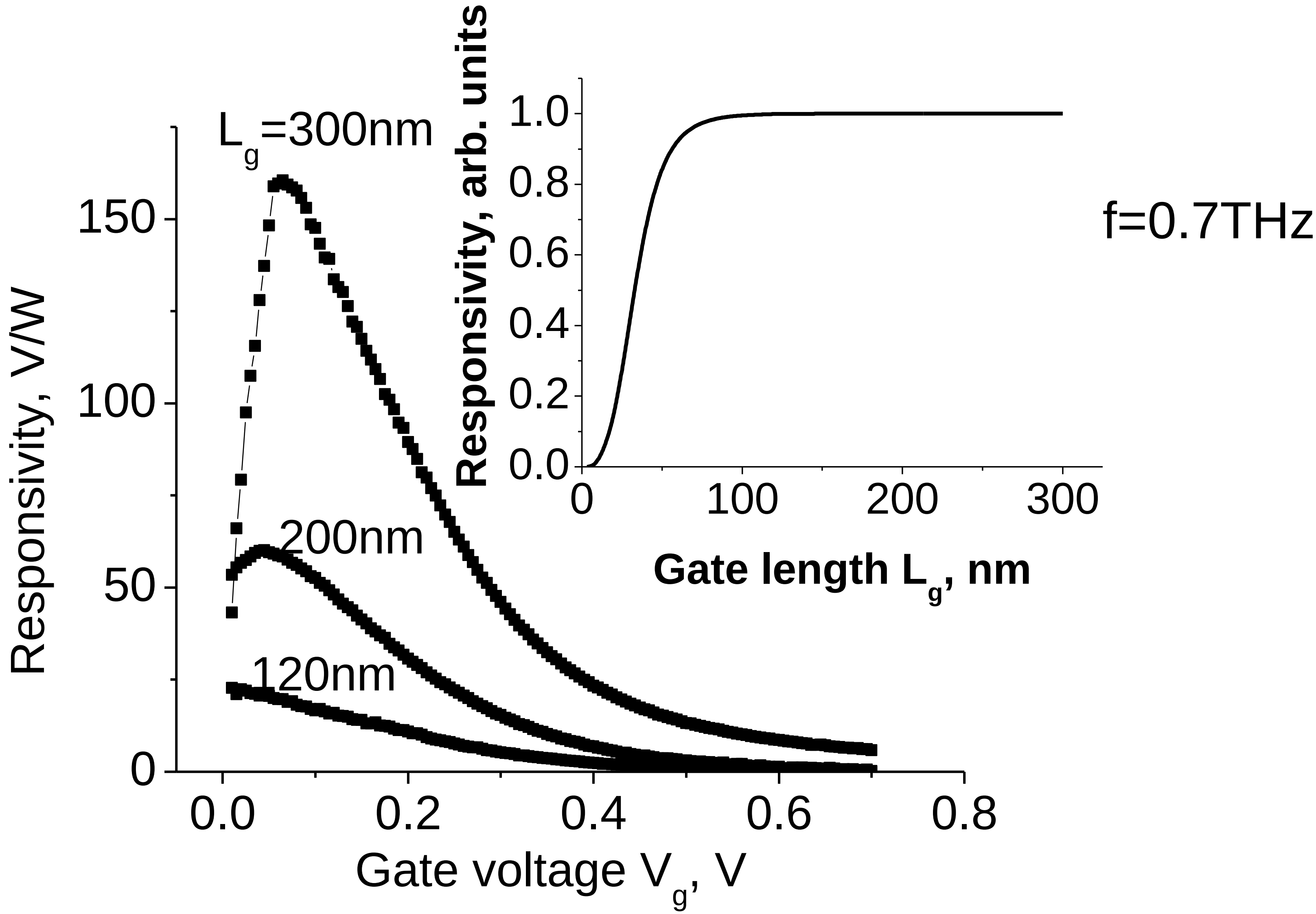




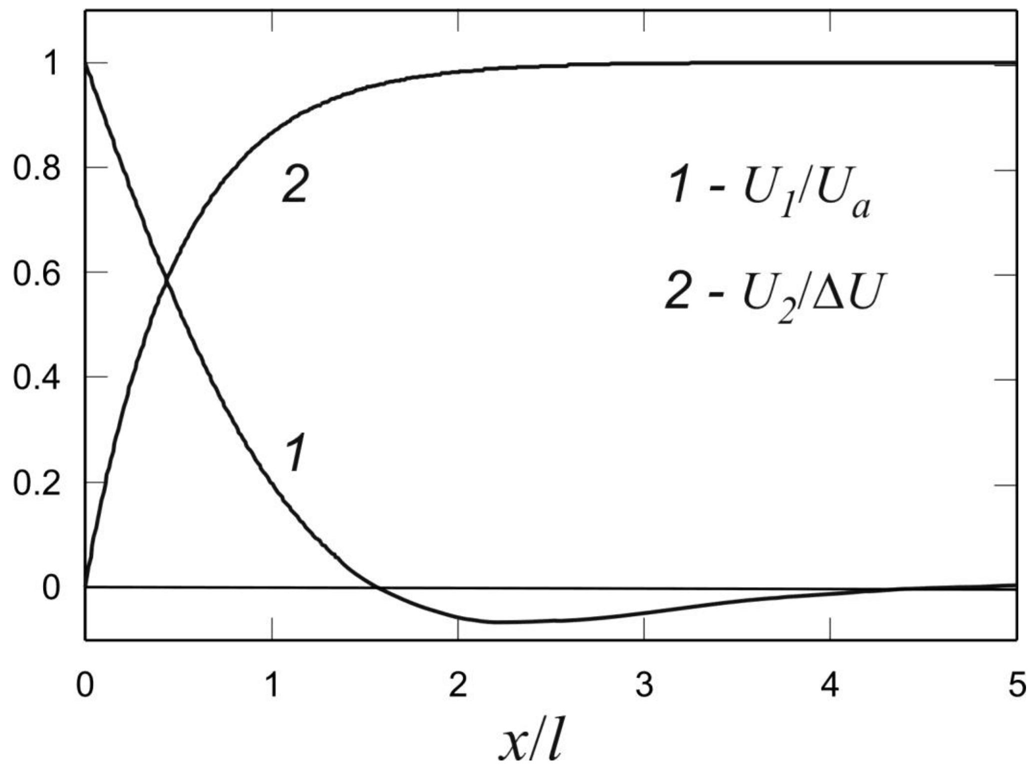
Results from Vilnius (collaboration with Montpellier) (2008).


(a)
Si
275 K
225 K
175 K
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
I_{DS} (mA)
I_{ds} (A)
(b)
Experiment
275 K
225 K
175 K
275 K
225 K
175 K
PV (mV)
Photoresponse ΔU (mV)
0
1
2
3
0.0
0.1
0.2
0.3
0.4
0.5
Gate Voltage V_{gs} (V)

Detection of terahertz radiation by Si field effects transistors 300K



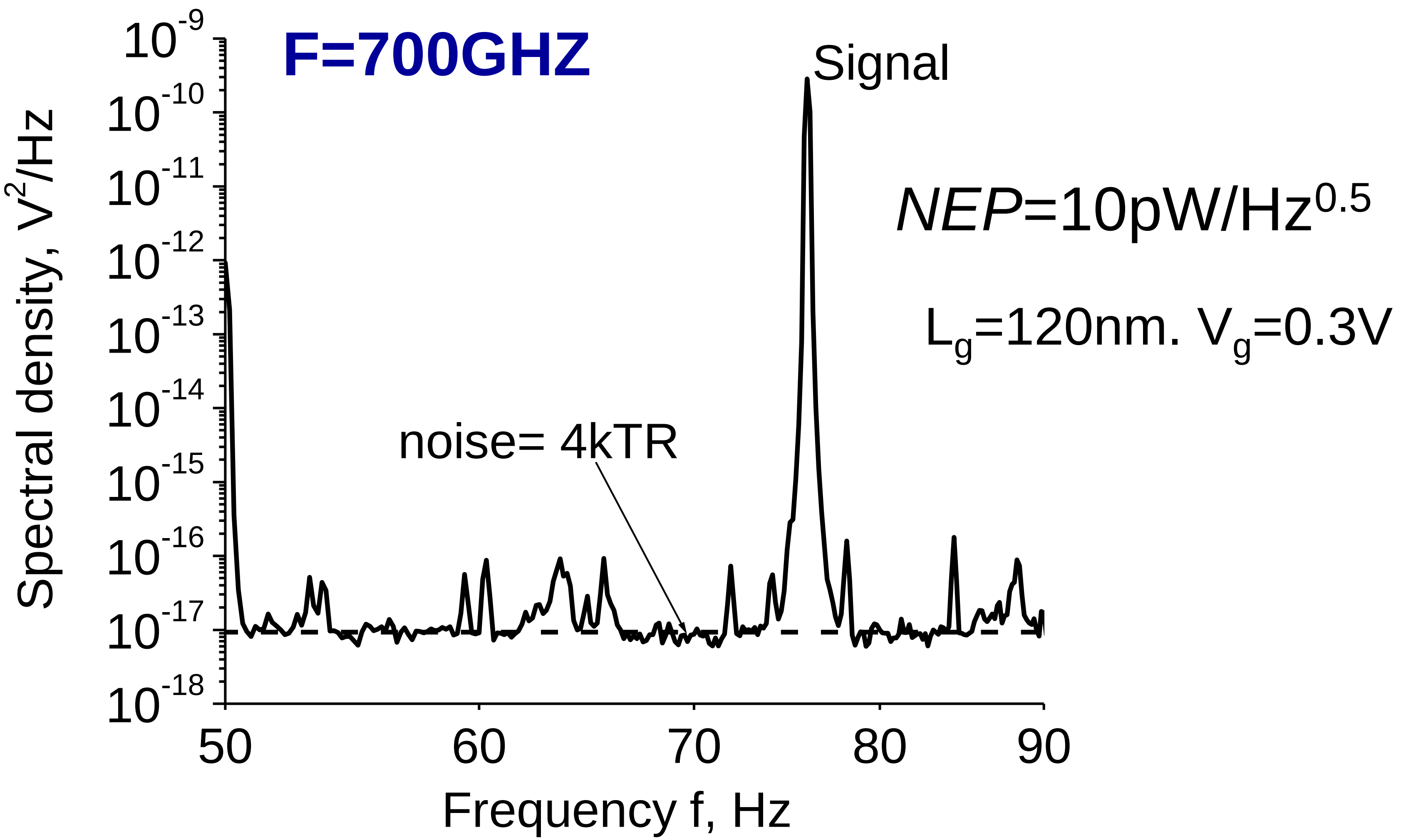
AC voltage U1 and DC signal U2



Dependence of the ac voltage $U1/Ua$ at $\omega t = 2\pi n$
and of the dc photoinduced voltage $U2/\Delta U$
on the distance from the source x for a long gate

THz detection & Signal to noise ratio in Si-MOSFETs

Appl Phys. Letters 2004 & 2006



300K CMOS THz detectors
-Fast, sensitive & INTEGRABLE in MATRIXES!!!
-For 300K price effective focal plane arrays
-Fast enough for THz communication

		Sampling frequency (MAX)		NEP (**pW/Hz$^{0.5}$**)
Golay Cell		~20Hz		**100**
Pyroelectric		<10KHz		**1000**
Schottky Diodes		**<20GHz**		**10**
Microbolometers		<1MHz		**10**
Si transistors		**30GHz or higher**		**10**

micro and nanoelectronics
microsystems
ambient intelligence
image chain
biology and health

UNIVERSITÉ MONTPELLIER 2
SCIENCES ET TECHNIQUES

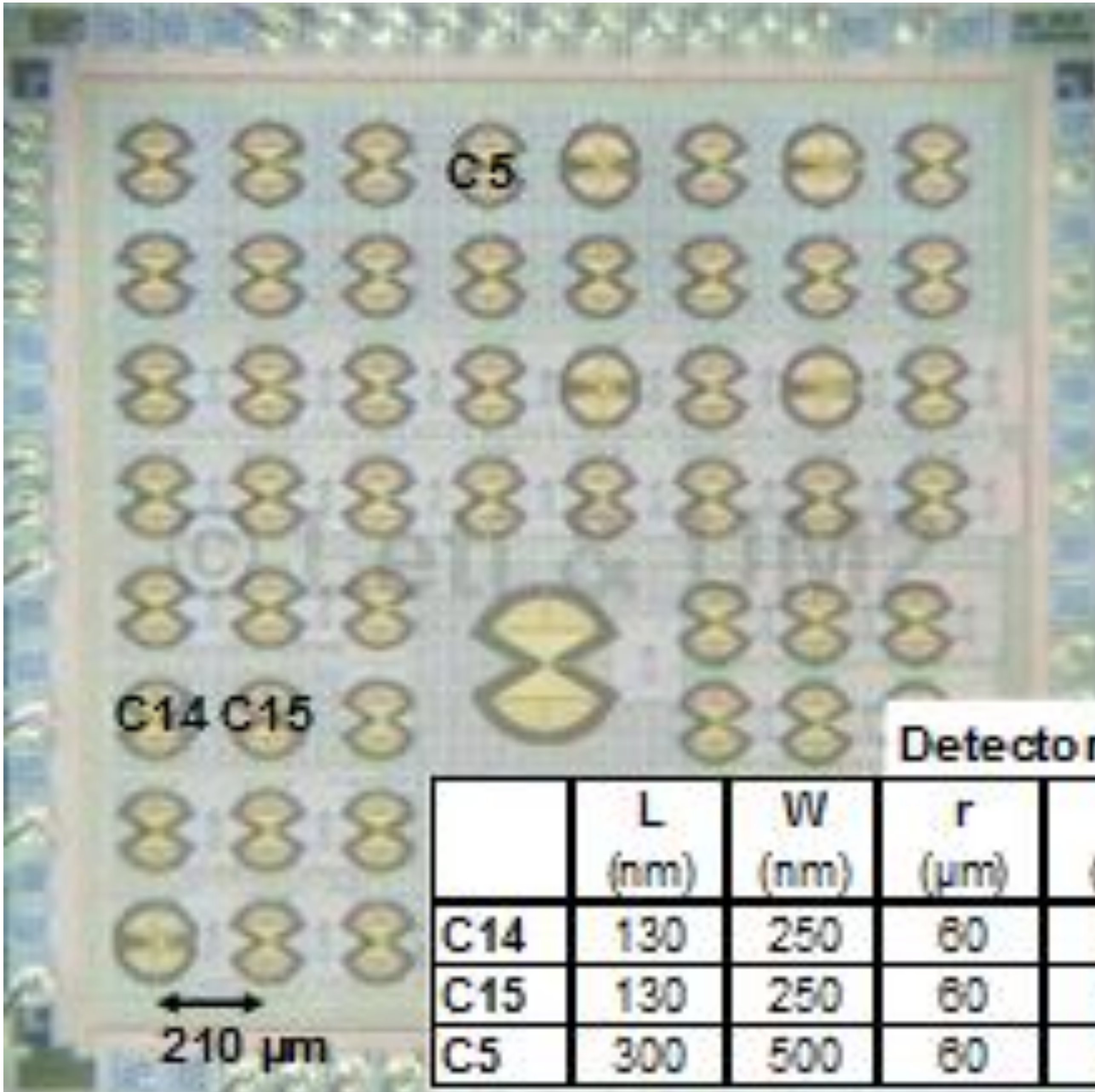
THz Imaging with Si-MOSFET Detectors

MINATEC®

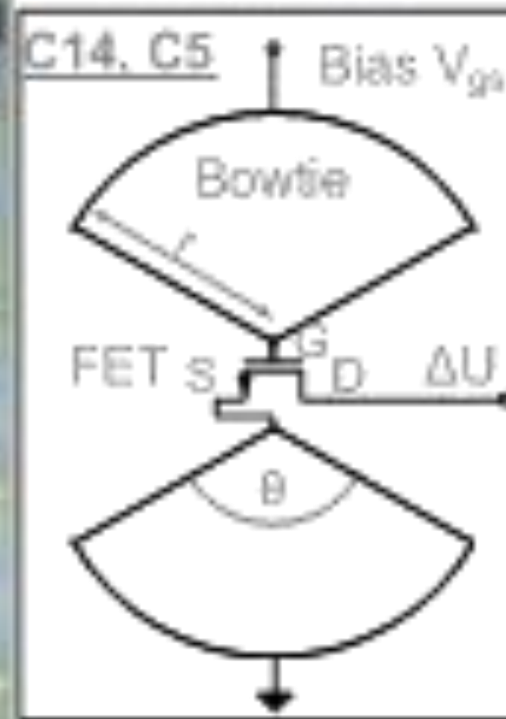
leti

cea

0.13µm CMOS

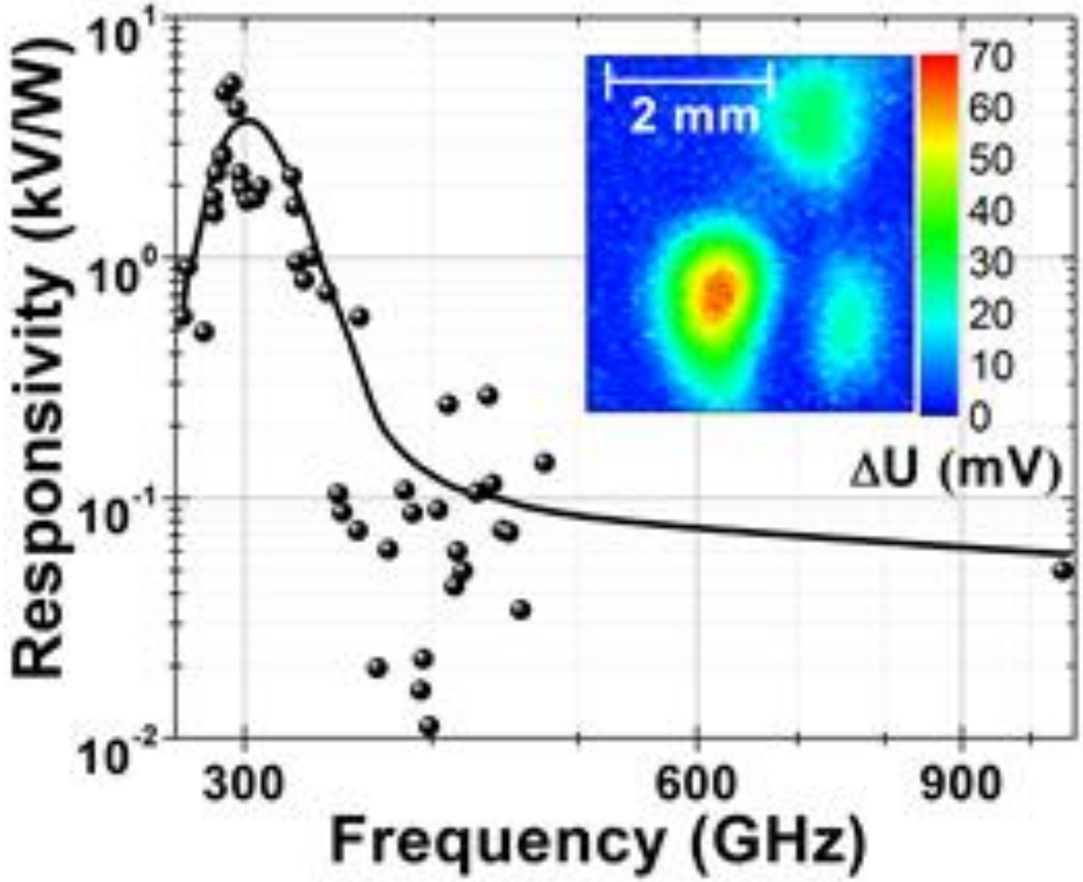


Schematic



Detector Characteristics

	L (nm)	W (nm)	r (µm)	θ (deg)	Antenna Connection
C14	130	250	60	120	gate-source
C15	130	250	60	120	source-drain
C5	300	500	60	120	gate-source



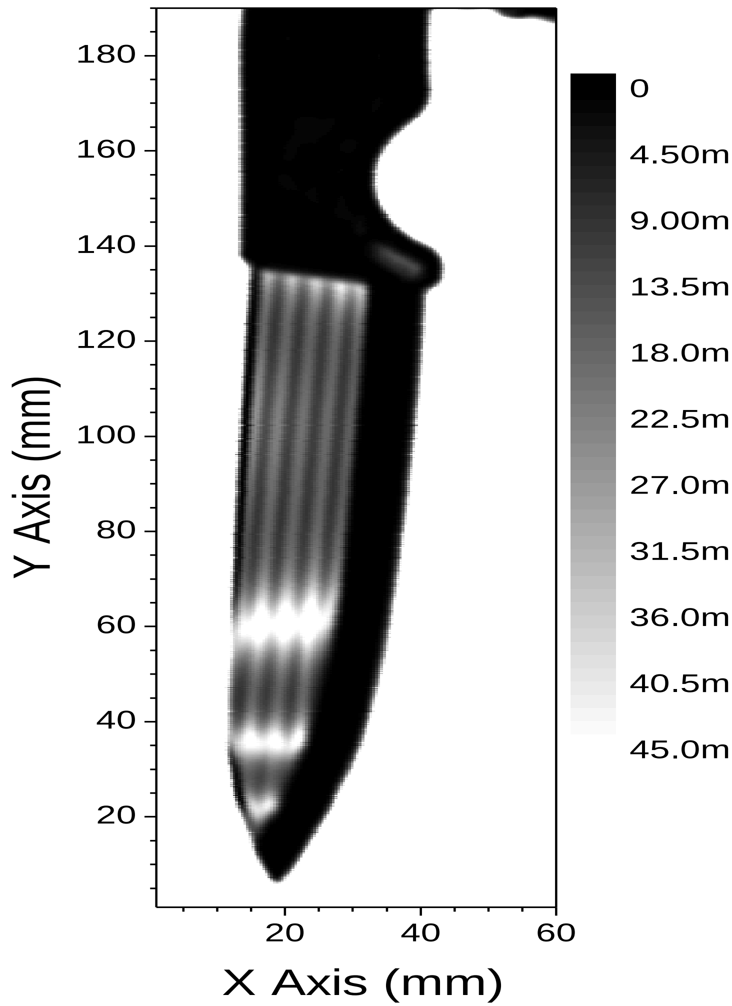
"Broadband terahertz imaging with highly sensitive silicon CMOS detectors,"

F.Schuster et al

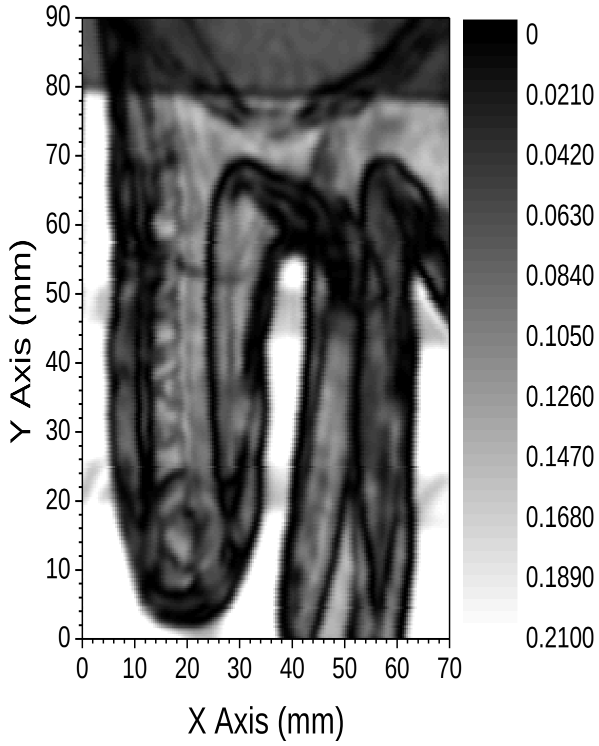
Optics Express, vol. 19, pp. 7827-7832, (2011)

Laser Focus World, vol. 47(7), pp. 37–41, (2011)

Imaging with MOSFET –0.3THz "!!!!Cutting Edge Technology!!!"

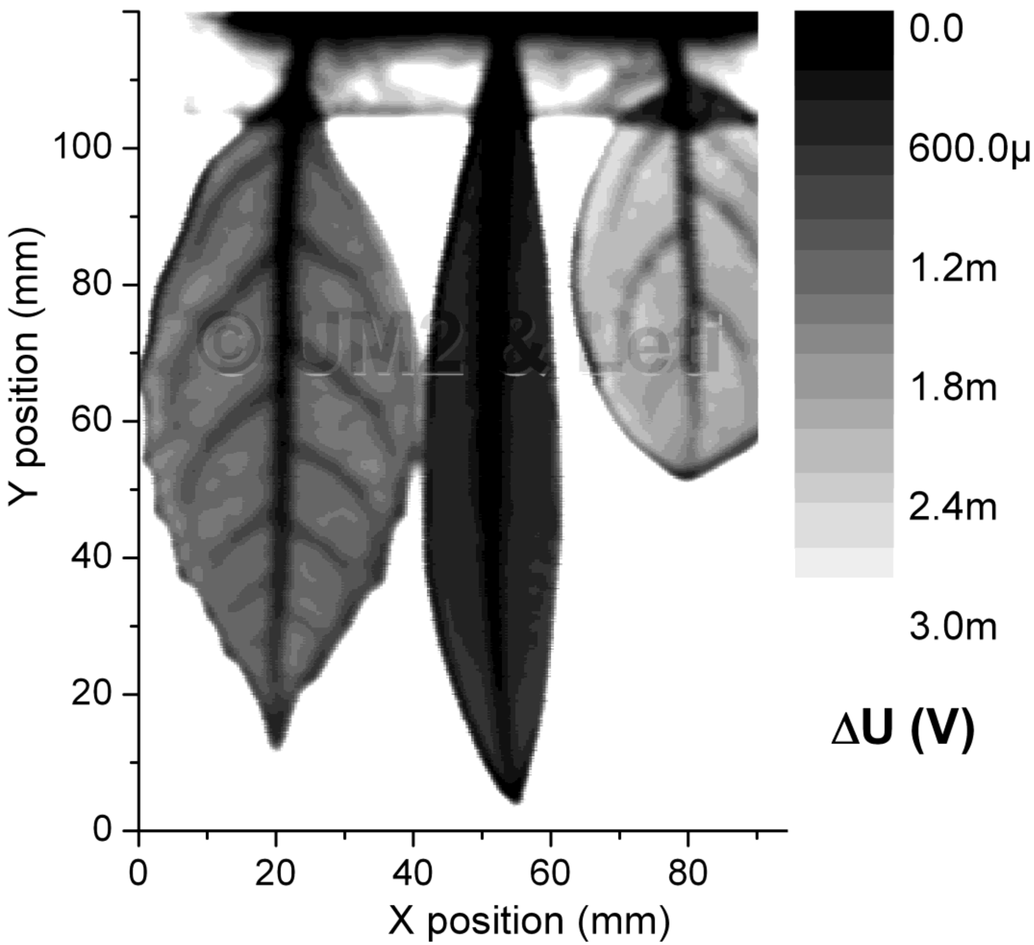


Imagerie THz avec un Transistor MOSFET



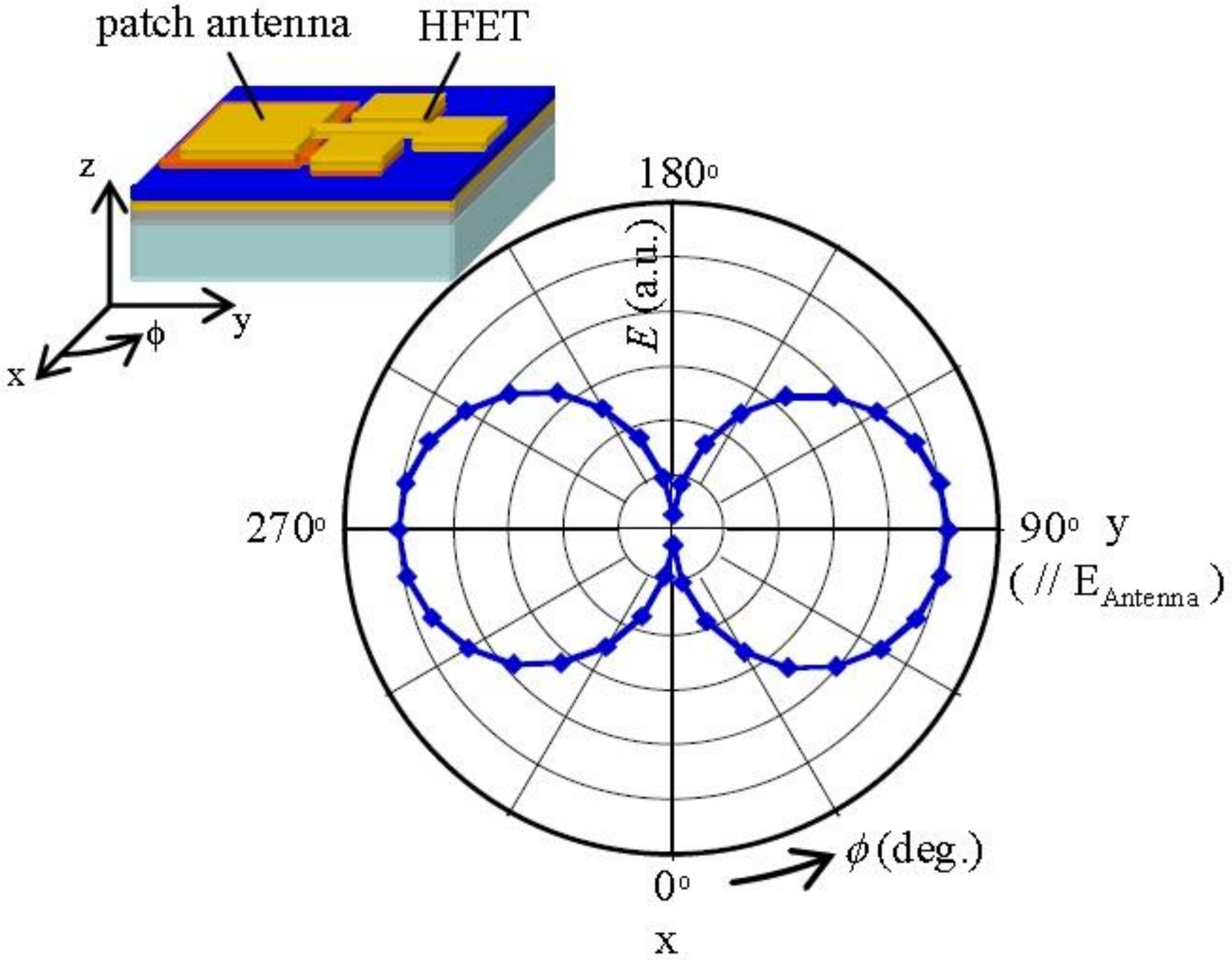
Radiation : 0.3 THz (λ= 1 mm),
Puissance 2 mW
10 ms/point Scan-Time: qq min

Measurement Imaging at 300GHz, tree leaves

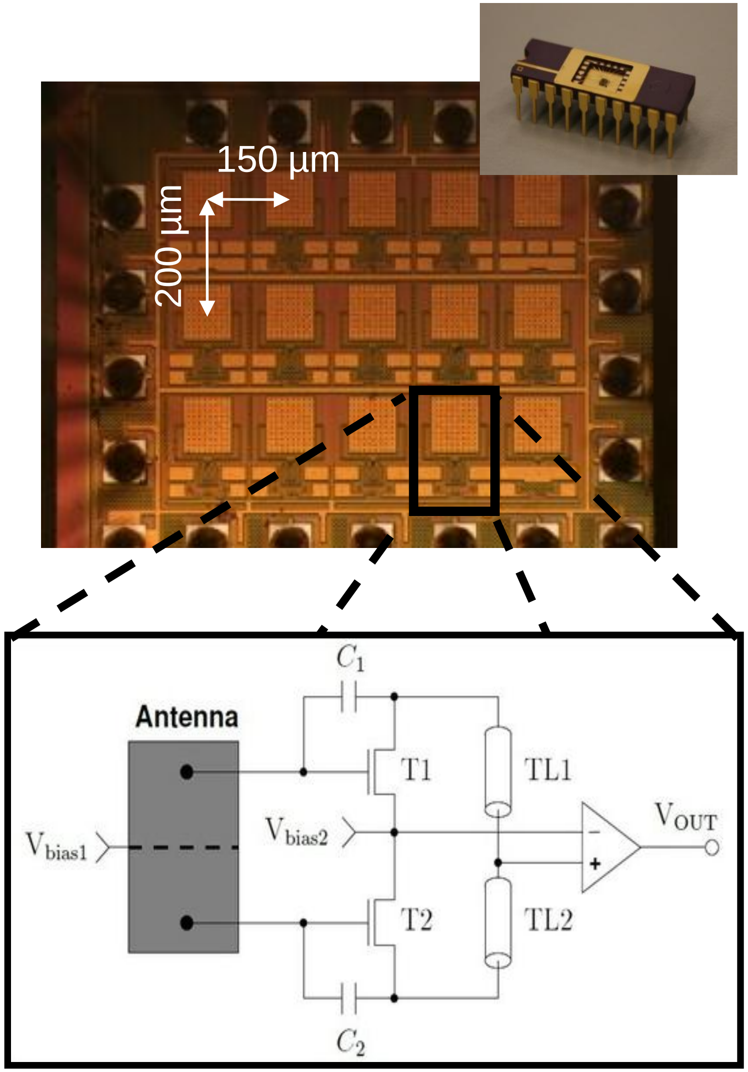


225x600 scanned points

PANASONIC GaN detector 2011



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

- Plasma waves &Transistors
    - Plasma waves and dimensionality
    - Fiel Effect Transistors
    - Plasma waves in the transistors
- Well establised results and apllications
    - Magnetic field and plasma
    - Resonant detection
    - Non-resonant detection
- Current research and unresolved problems
    - Emission
    - Temperature
    - Resonat dreams with graphene
    - Circular polarisation
    - THz communication

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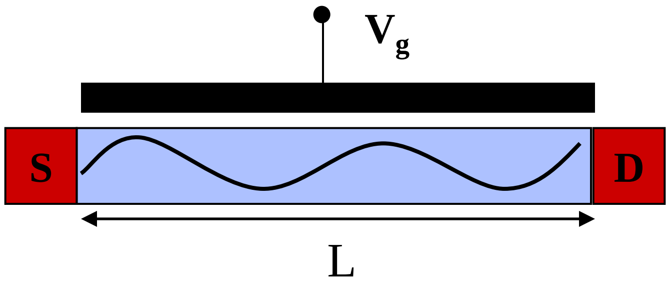
1) Can we have THz detection with Graphene??

2) Can we enhance nonresonat THz detection while lowering temperature

3) THz polarization measurements with HEMTS

4) Can FETs be THz emitters???

Frequency of the plasma oscillations !!!300K!!!



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

$$L = 0.1 - 1\mu m$$

$$U = 1V$$

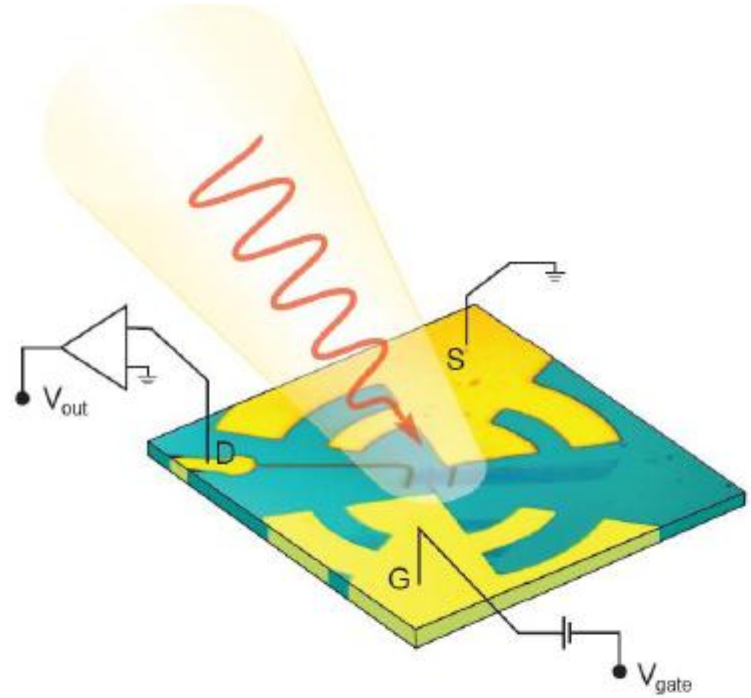
$$m = 0.06 - 0.24$$

$$f_p \approx 0.6THz - 4.0THz$$

!!Only When Plasma waves are weakly damped!

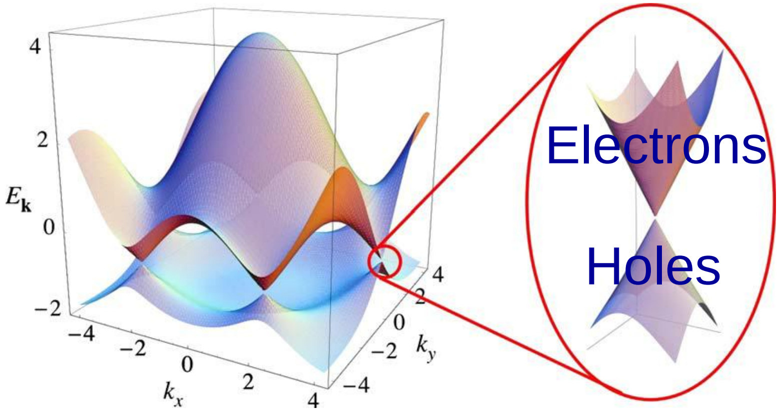
$$\omega\tau >> 1$$

THz detection by Graphene transistors

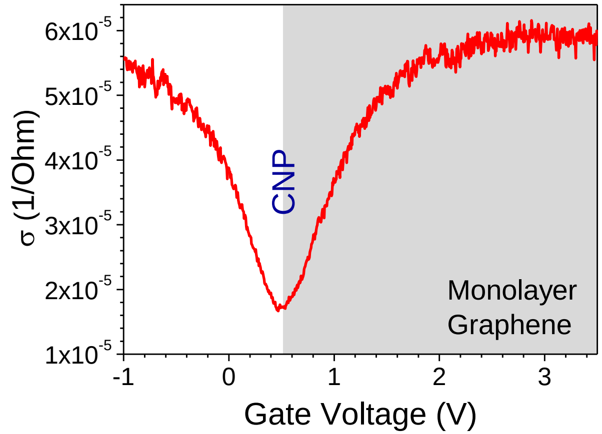


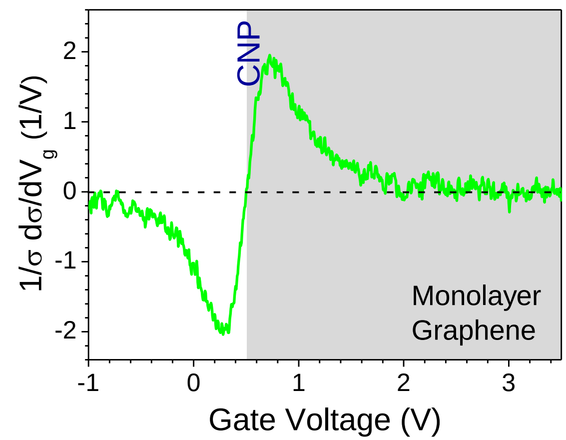
L. Vicarelli,[1] M.S. Vitiello,[1] D. Coquillat,[2] A.C. Ferrari,[3] W. Knap,[2]
M. Polini,[1] V. Pellegrini,[1] and A. Tredicucci[1]

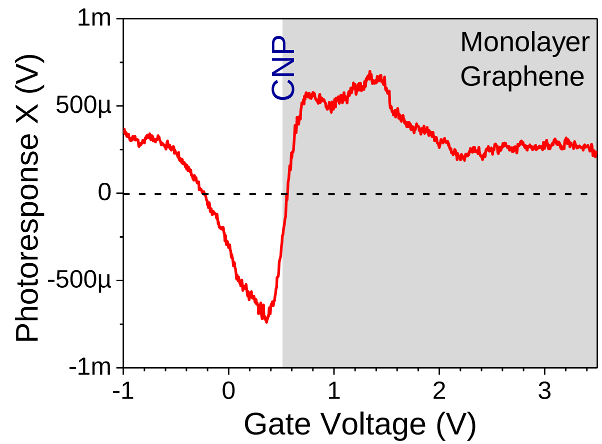
Common project : Pise[1], Montpellier[2], Cambridge[3]



$$\Delta U = \frac{U_a^2}{4}\left[\frac{1}{\sigma}\frac{d\sigma}{dU}\right]_{U=V_g}$$







MOTIVATION!!!

??300K RESONANCES

FOR SELECTIVE GATE TUNABLE

DETECTION AND EMISSION ???

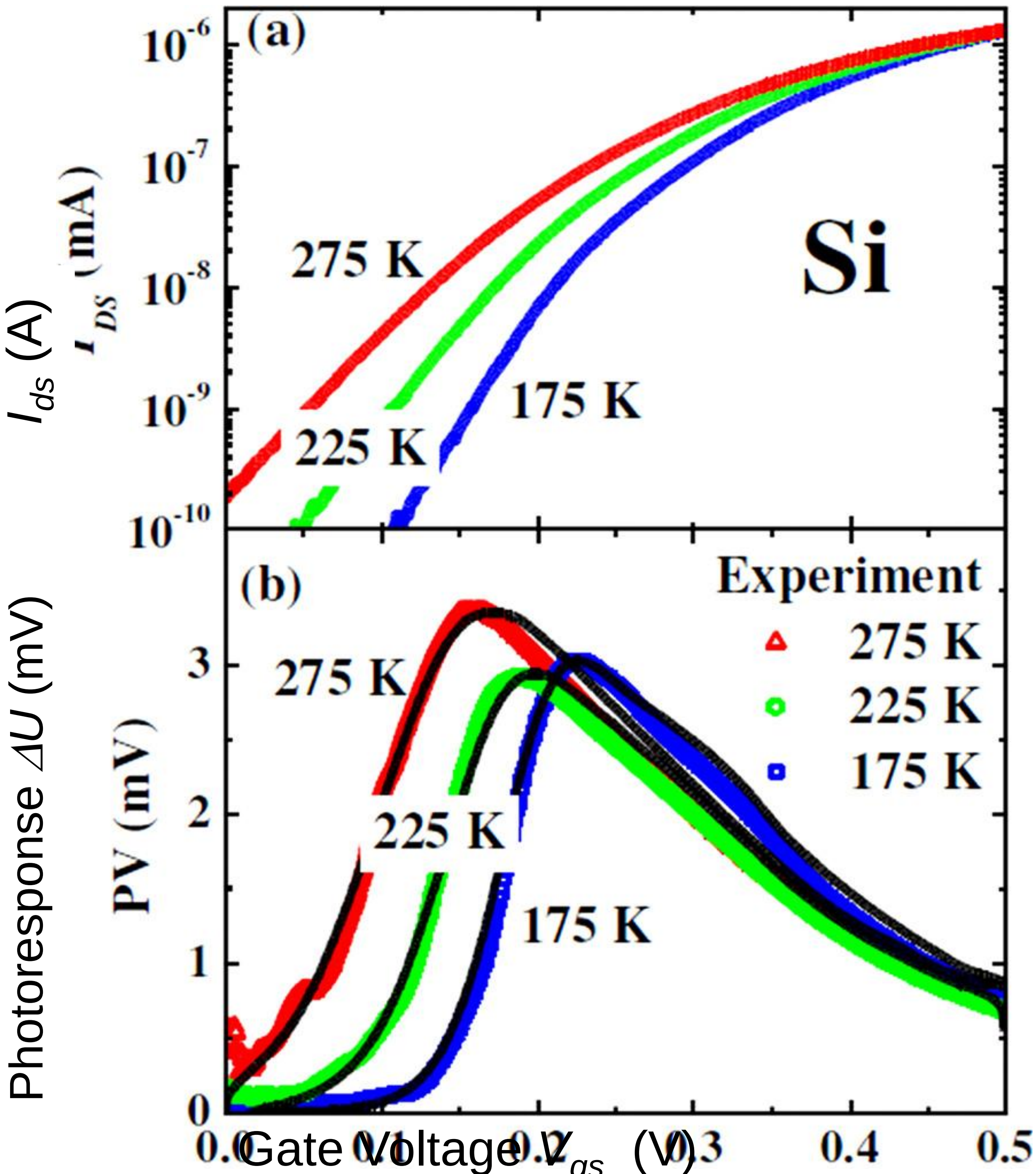
NATURE MATERIALS DEC 2012

1) **Can we have THz detection with Graphene??**

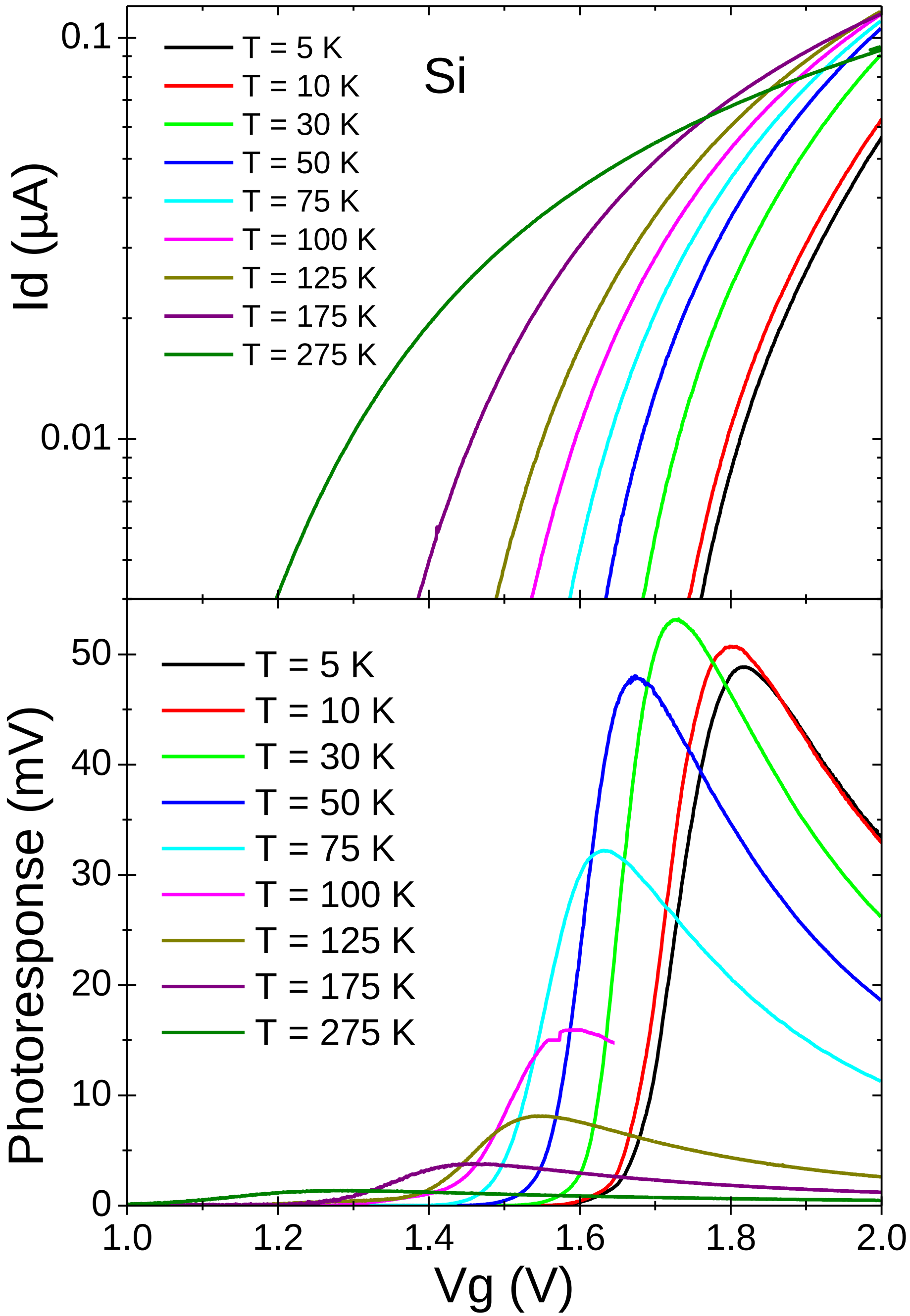
2) **Can we enhance nonresonat THz detection while lowering temperature**

3) **THz polarization measurements with HEMTS**

4) **Can FETs be THz emitters???**



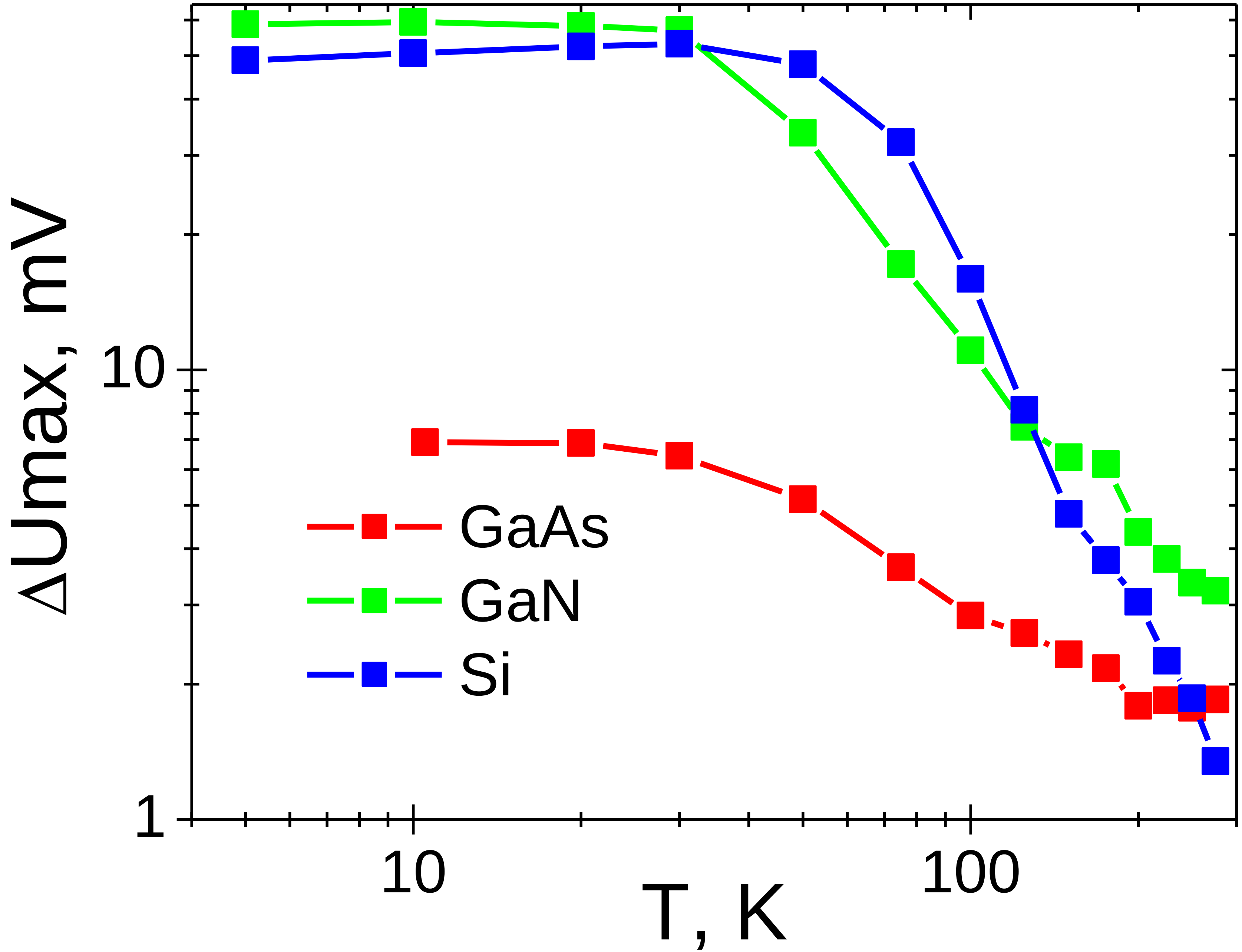
Sakowicz *et*
JAP, 2011



(Klimenko et al
JAP 2012)

$$??THz\_signal$$

$$\Delta U \propto 1/\eta kT$$



(Klimenko et al JAP 2012)

Physical limitations – U*

subthreshold

$$\sigma \propto \exp\_U/U*\_\_and\_\_\Delta U \propto 1/U*$$

$$where$$

$$U* = \eta kT/e\_\_\_diffusion\_above\_30K$$

$$U* = const\_\_\_???\_impurity\_band$$

Klimenko et al Journal of Applied Phys 2012

1) Can we have THz detection with Graphene??

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J. Appl. Phys. **111** 124504 (2012)

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

C. Drexler[1], N. Dyakonova[2], M. Schafberger[1], K. Karpierz[3], J. Karch[1], H. Videlier[2], Y. Meziani[4], P. Olbrich[1], W. Knap[2] and S. D. Ganichev[1]

[1] *THz Center, University of Regensburg, 93040 Regensburg, Germany*

[2] *GES, UMR5650 CNRS et Universite Montpellier 2, France*

[3] *Institute of Experimental Physics, University of Warsaw, Poland and*

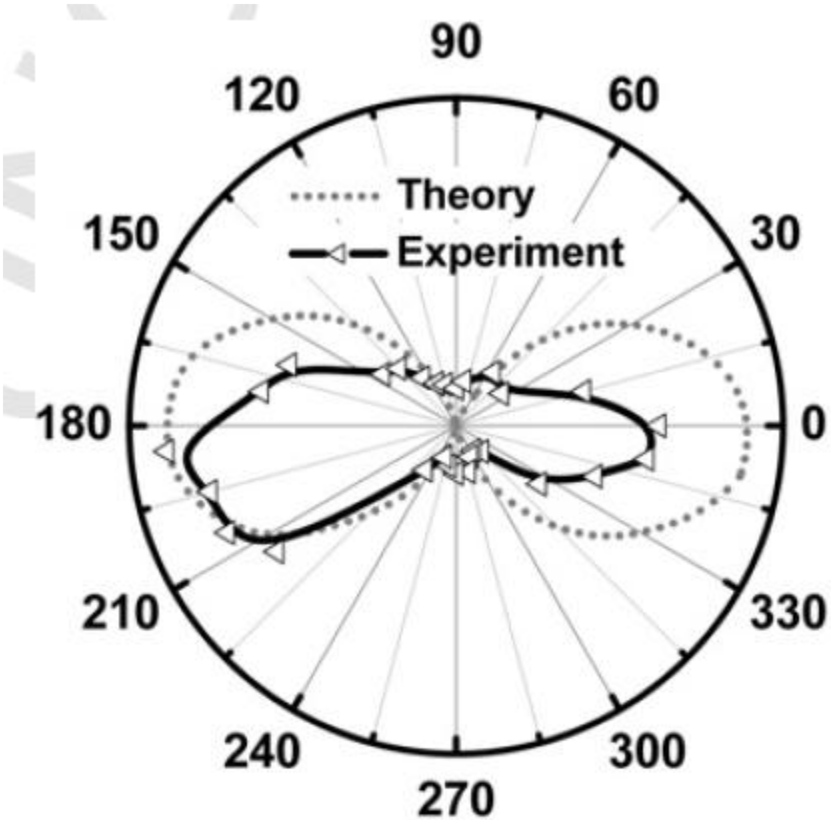
[4] *Departamento de Fisica Aplicada, Universidad de Salamanca, Spain*

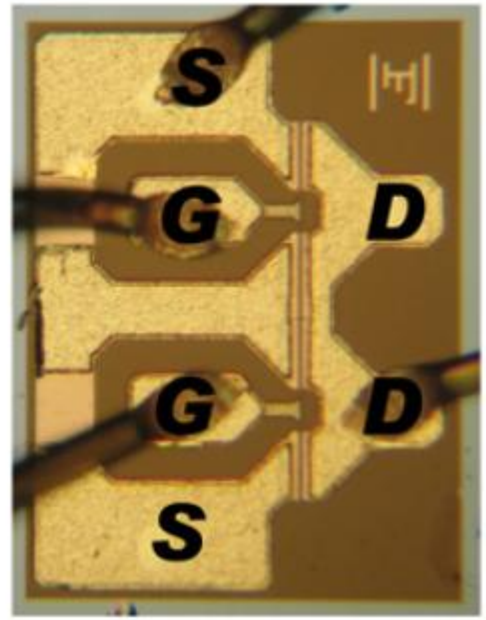
We report on the observation of the photon helicity sensitive photoresponce in GaAs/AlGaAs high electron mobility transistors (HEMT) excited by terahertz laser radiation. We demonstrate, that for a certain structure design and large negative bias voltages the sign of the photoresponse changes upon switching 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

theory M.Dyakonov *J. Appl. Phys.* (2013)

Linear polarization detection





Source drain voltage from FET at 800GHz

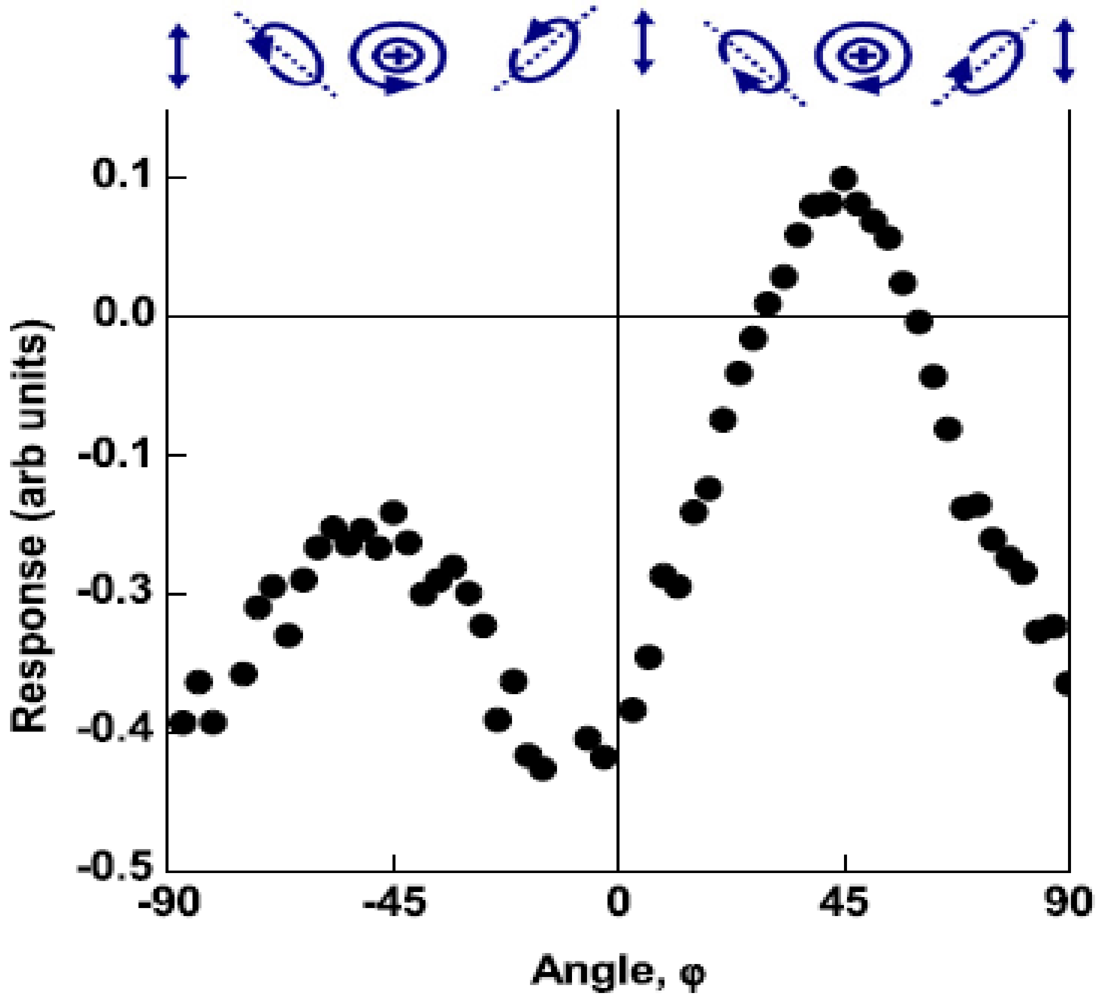


Figure 4. Polarization dependence of the response, $f = 0.8$ THz. Ellipses on the top illustrate the polarization states (after [40]).

1) Can we have THz detection with Graphene??

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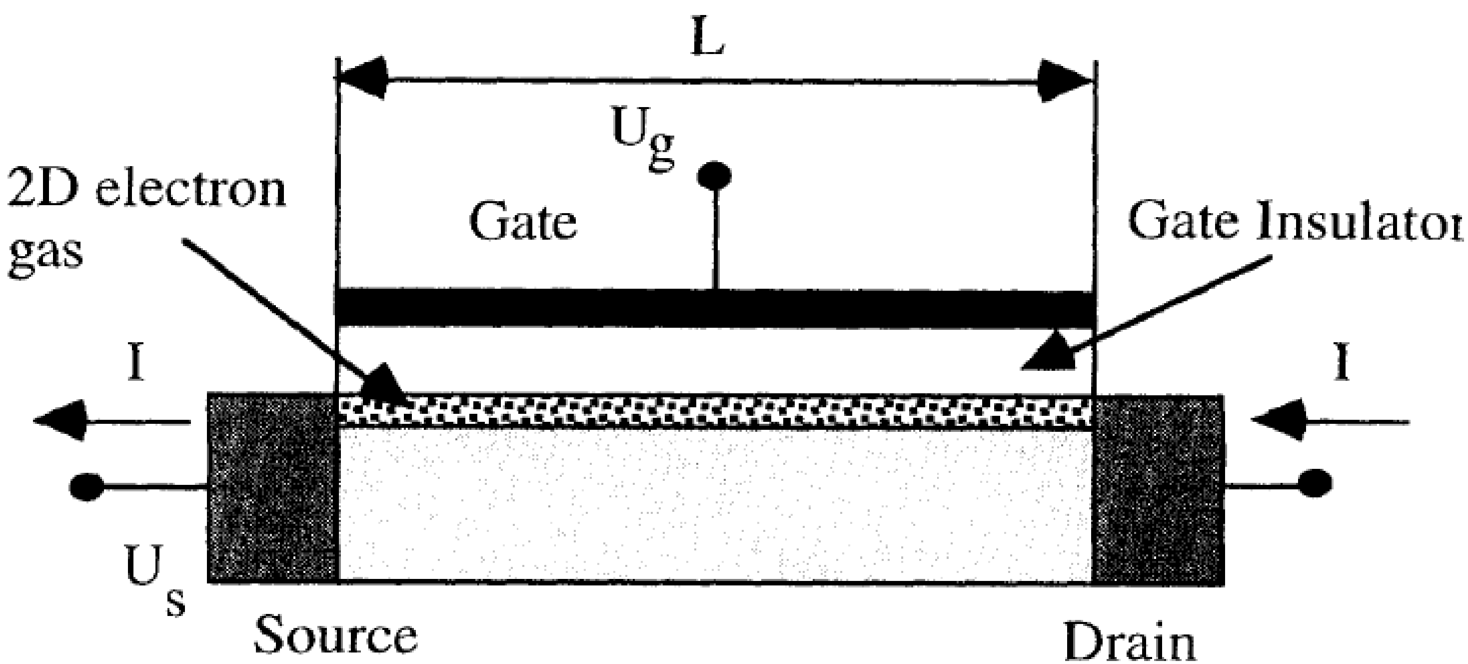
Plasma Waves FET as THz Emitter

Shallow water analogy for a ballistic field effect transistor: New mechanism of plasma wave generation by DC current
M. Dyakonov and M. S. Shur, *Phys. Rev. Lett.* **71**, 2465 (1993)



Instability and THz generation

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

<u>Ingredients:</u>

a) Resonator

b) Asymmetric boundary conditions

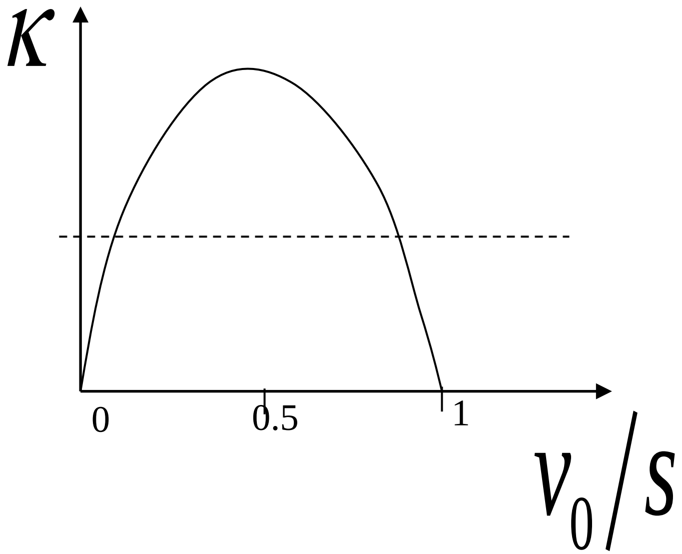
Instability - Threshold

Plasma waves instability &Emission-

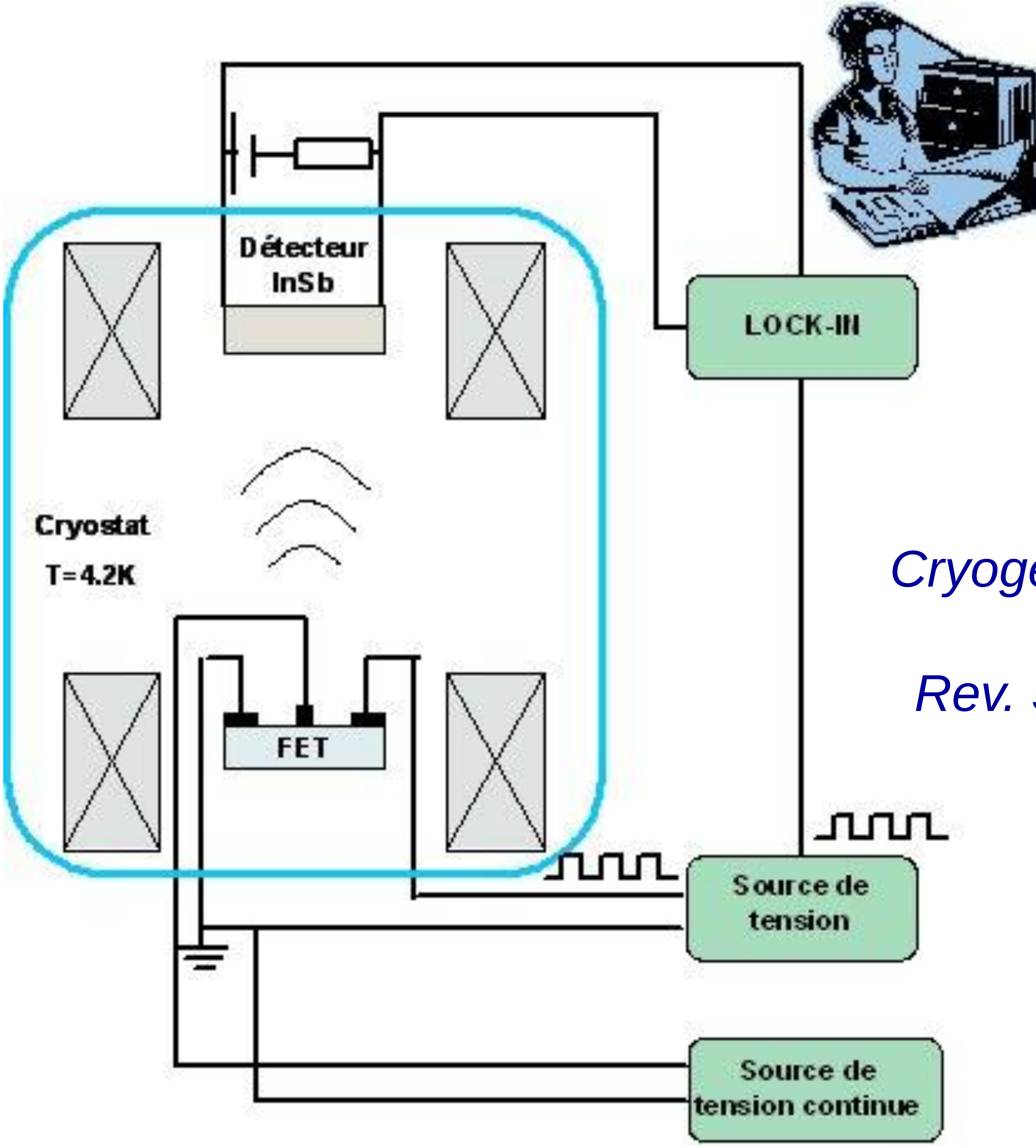
Threshold like - phenomena – laser analogy

$$A \propto \exp(\kappa t)$$

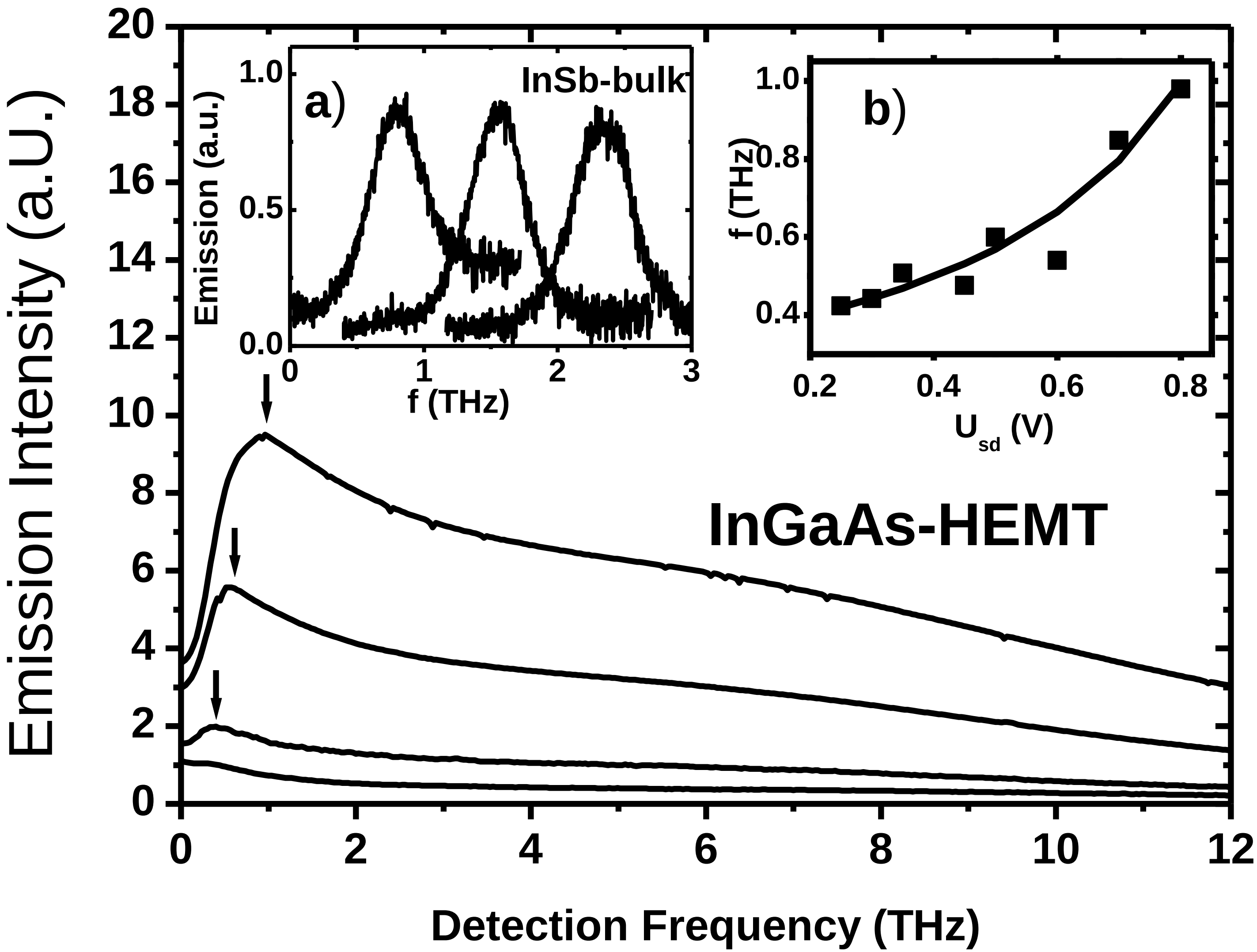
$$\kappa = \frac{s^2 - v_0^2}{2Ls} \ln\left|\frac{s + v_0}{s - v_0}\right|$$



M. Dyakonov, M. Shur, *Phys. Rev. Lett.* 71, 2465, (1993)

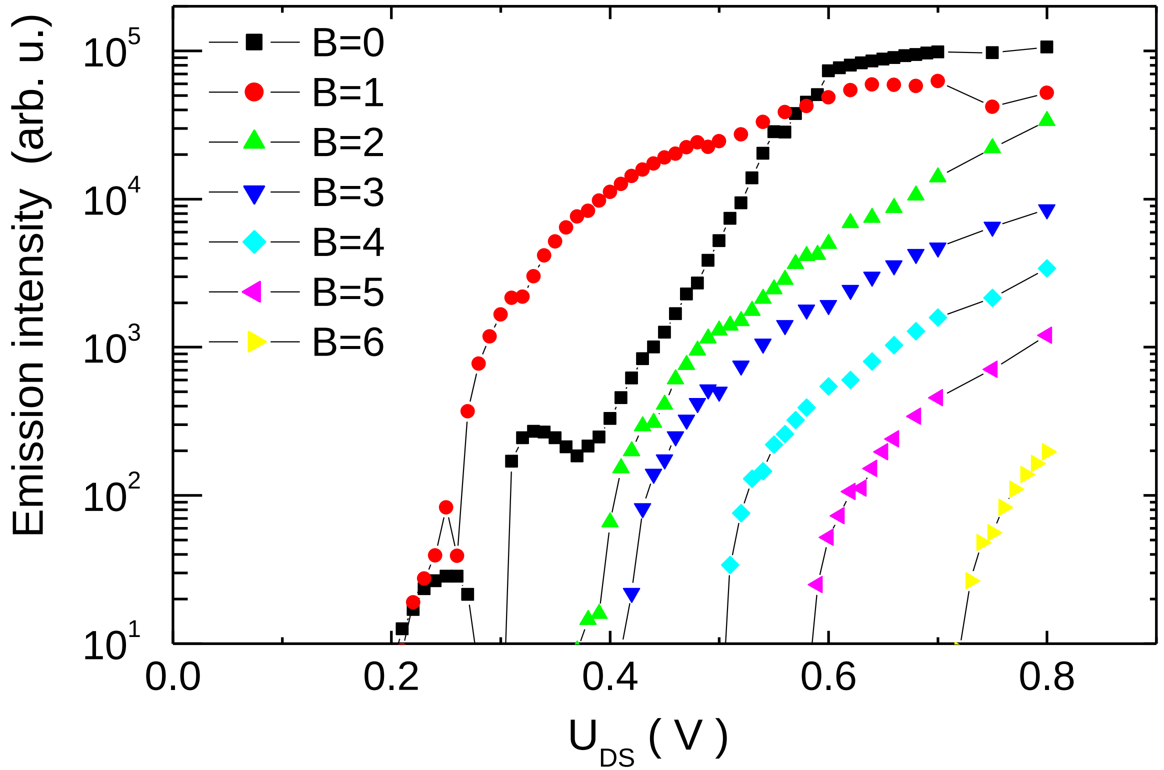


Cryogenic THz Spectromet
W. Knap et al.,
Rev. Scient. Instr. ***63****, 329*
(1992)


Emission Intensity (a.U.)
Detection Frequency (THz)
InGaAs-HEMT
a)
InSb-bulk
Emission (a.u.)
f (THz)
b)
f (THz)
U_{sd} (V)
0
2
4
6
8
10
12
14
16
18
20
0.0
0.5
1.0
1
2
3
0.4
0.6
0.8
0.2

APL-2004

Threshold behaviour in the magnetic field

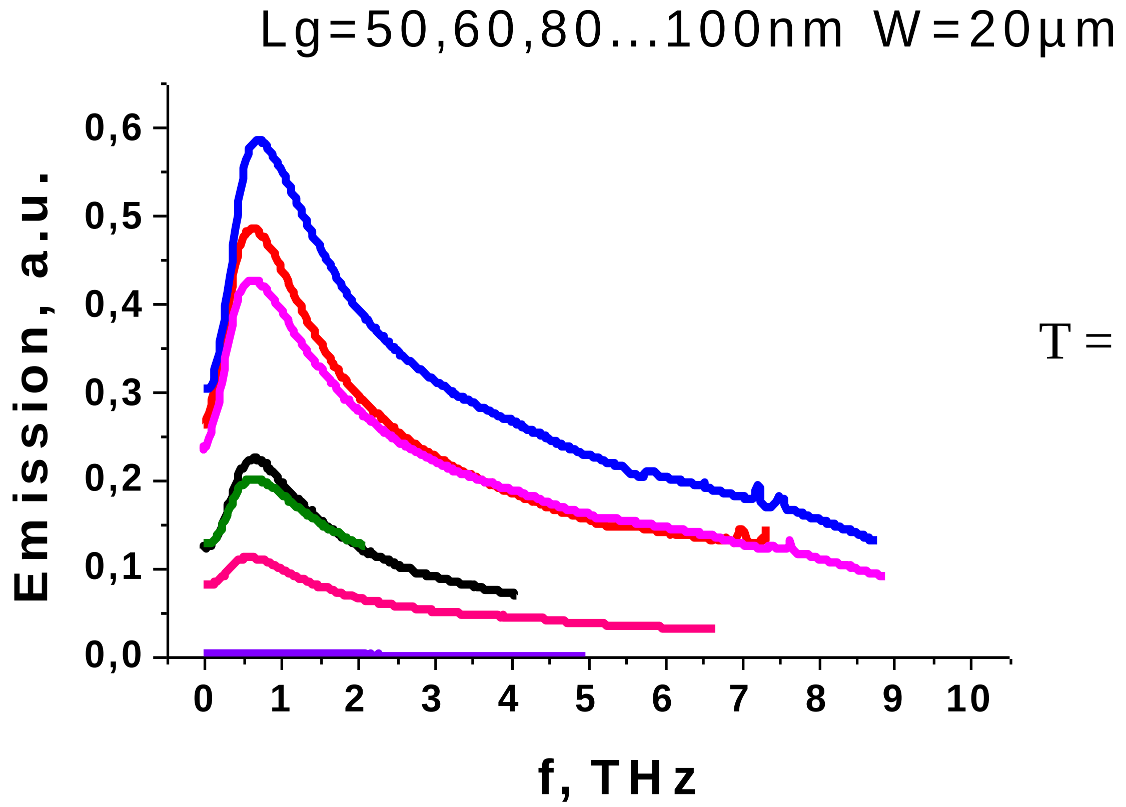


The shift of the threshold voltage - the magnetoresistance of the ungated

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

Emission spectra

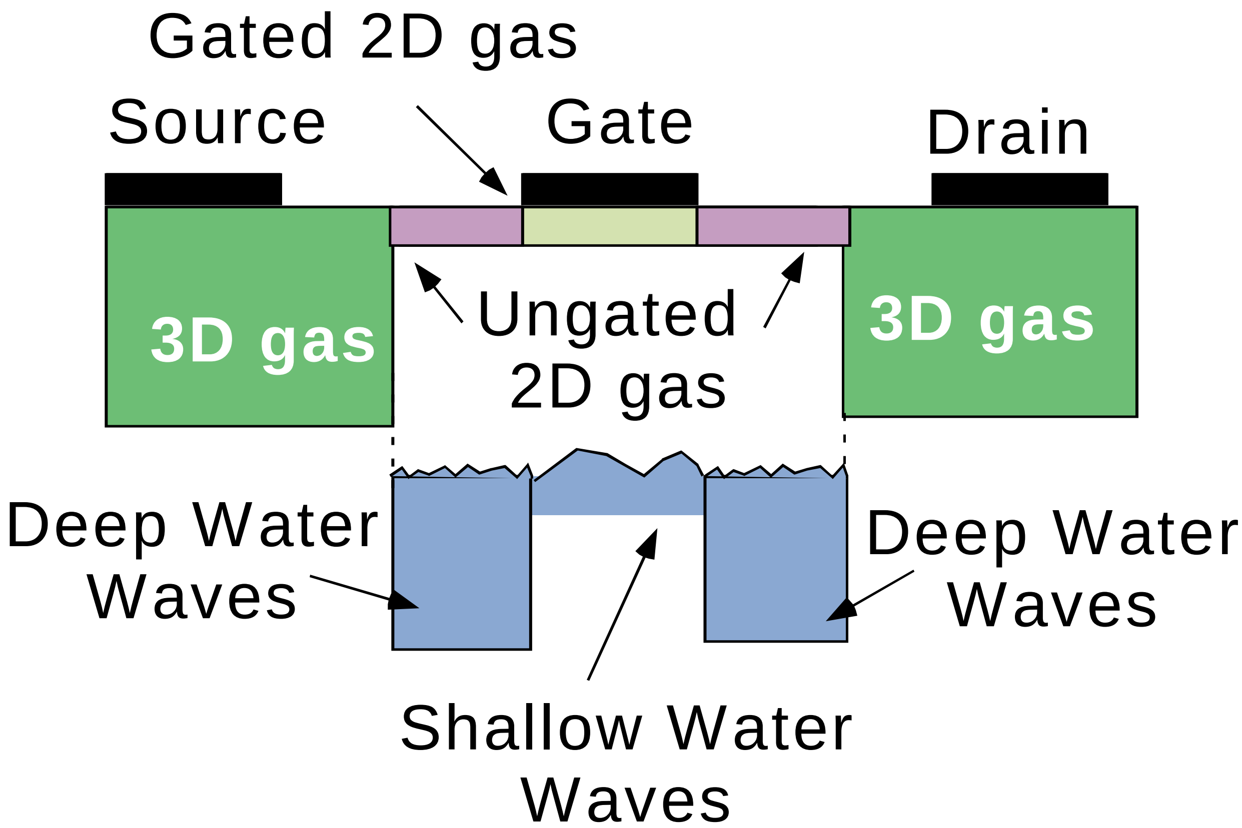
Transistors of different gate length



T = 4.2K

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

Deep/shallow water analogy -

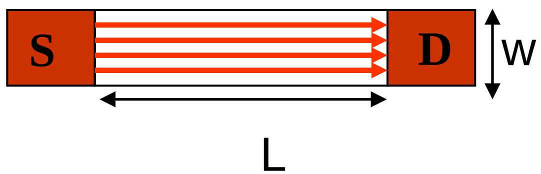


Discussion on plasma modes Broadening

Additional broadening mechanism

Dyakonov-Shur theory geometry

Top view



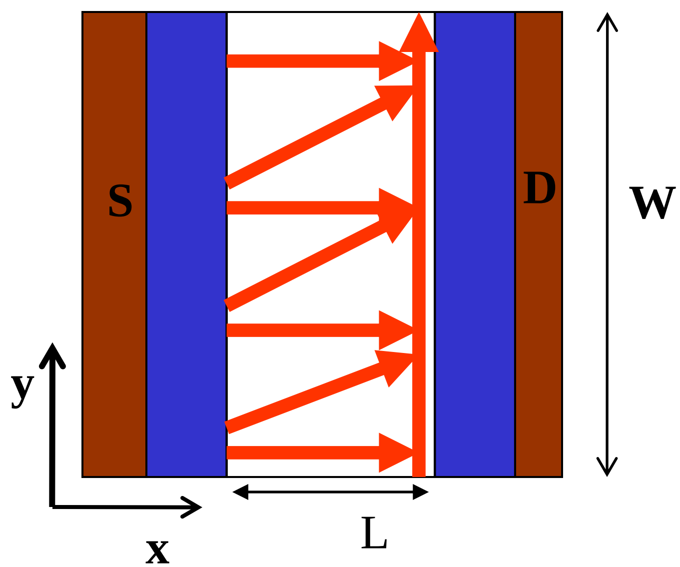
Only longitudinal modes

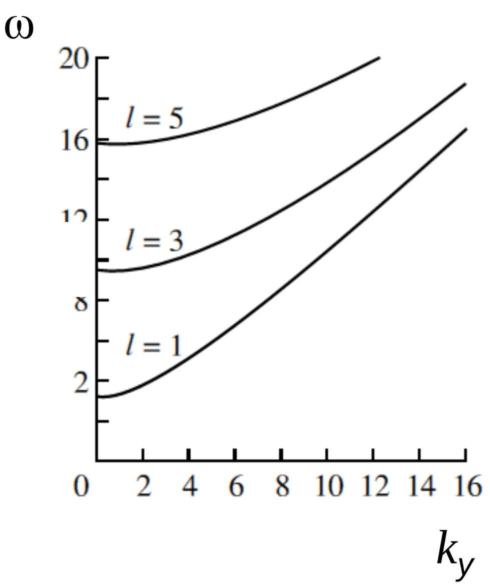
M. Dyakonov and M. Shur, IEEE Vol. 43, No. 3, (1996)

Experimental geometry

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

Top view

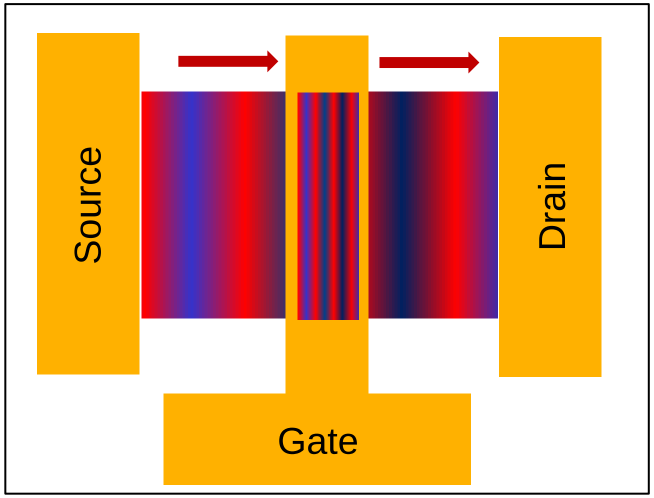


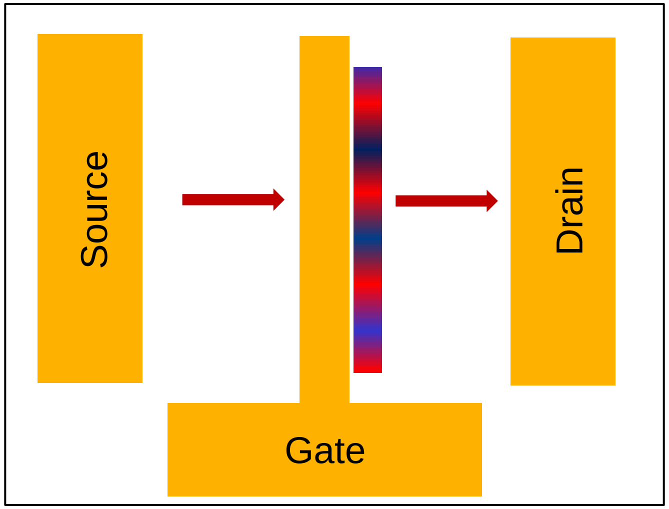


All modes are permitted

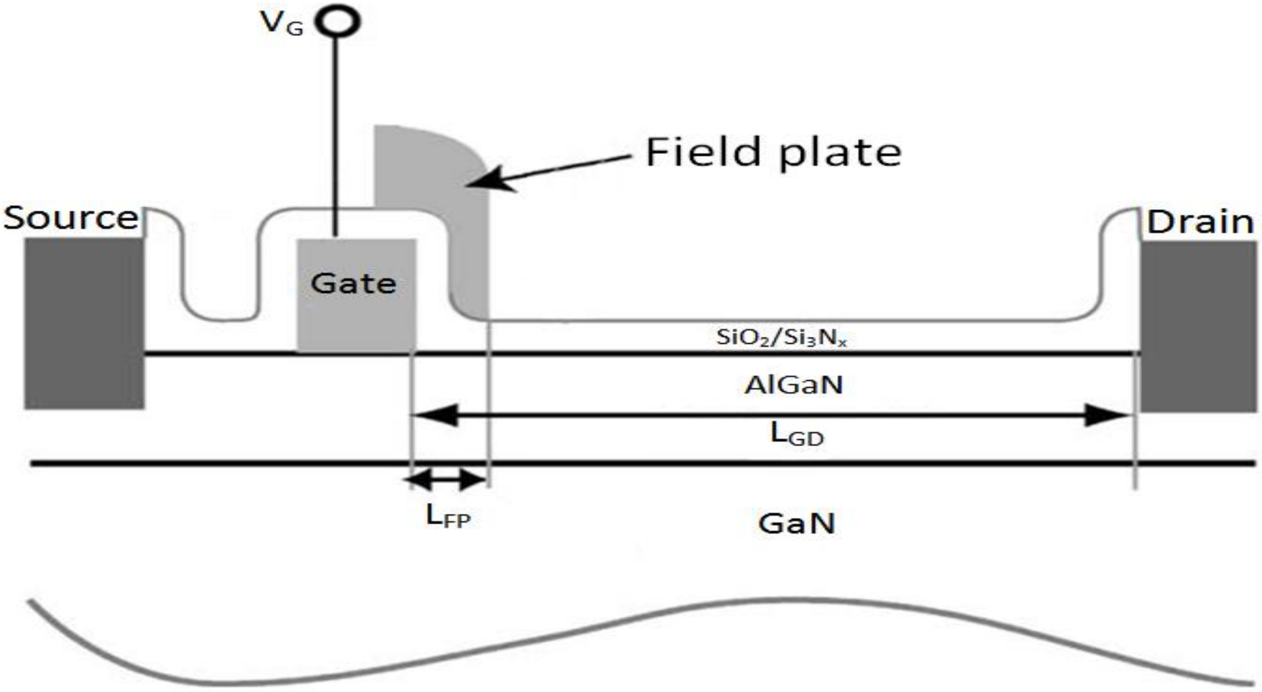
M.I. Dyakonov Semiconductors, 2008, Vol. 42, No. 8

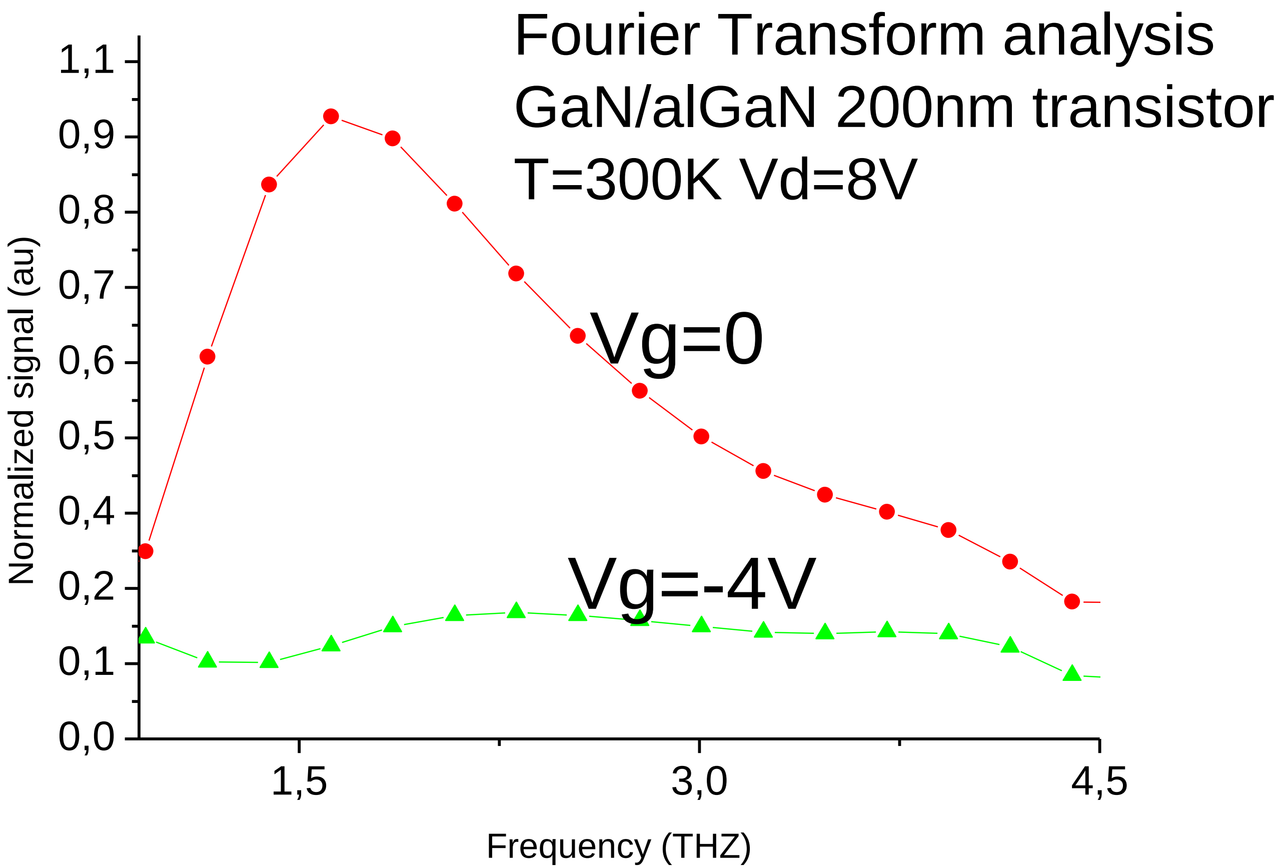
Shallow , deep and white water instabilities

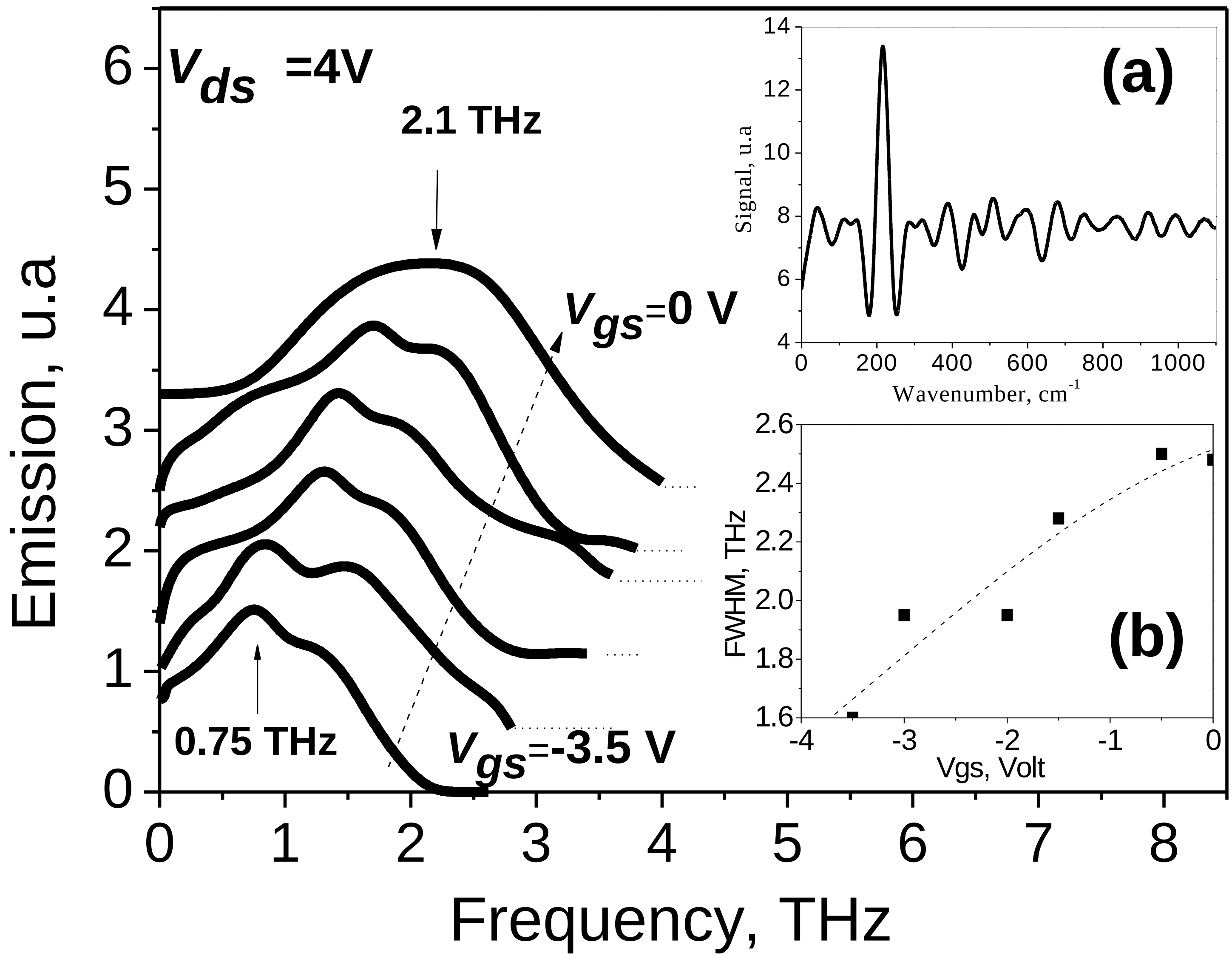




Field Plate GaN transistor for THz emission

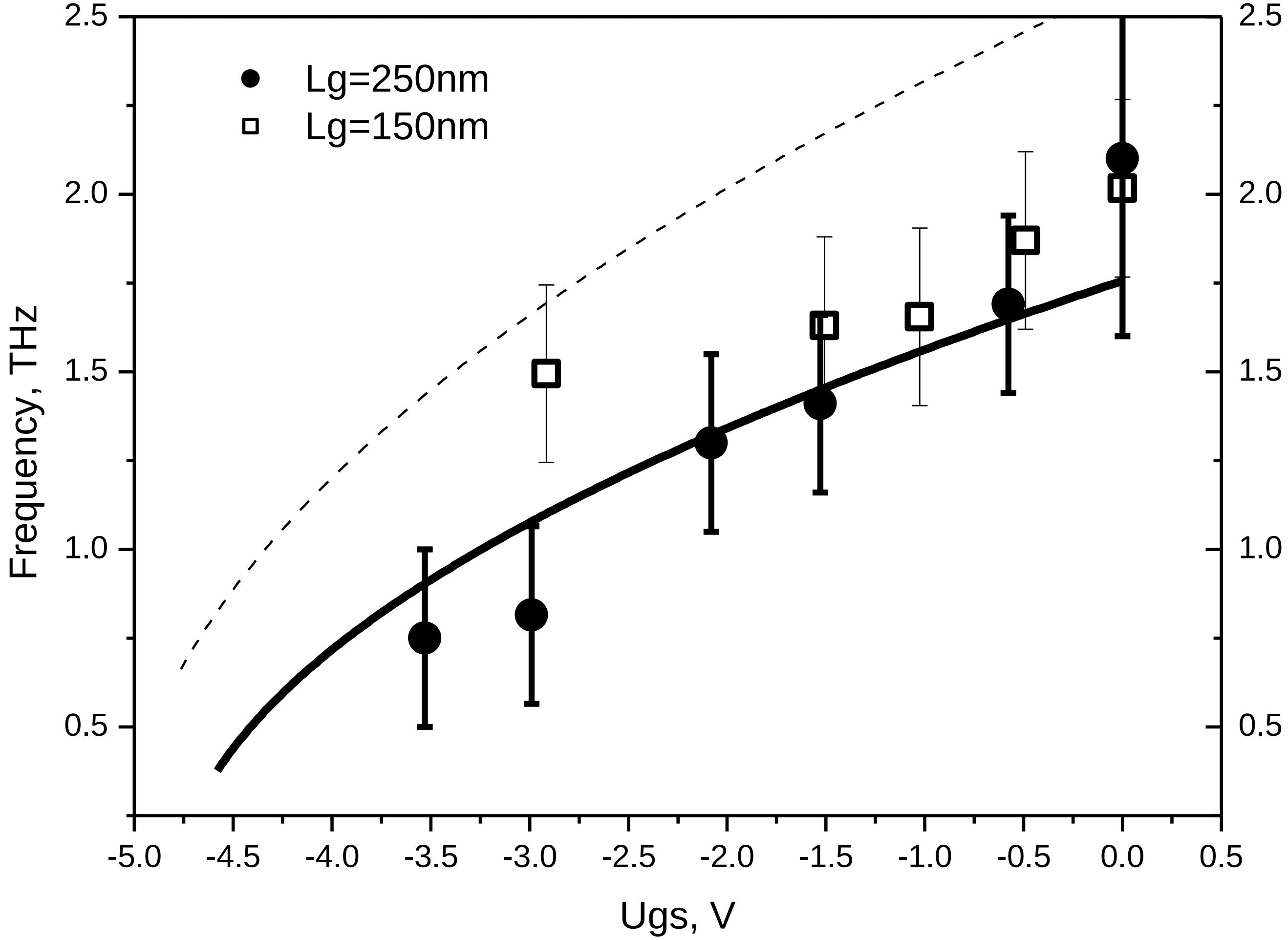



Fourier Transform analysis
GaN/alGaN 200nm transistor
T=300K Vd=8V
Vg=0
Vg=-4V
Normalized signal (au)
Frequency (THZ)
0,0
0,1
0,2
0,4
0,5
0,6
0,7
0,8
0,9
1,1
1,5
3,0
4,5

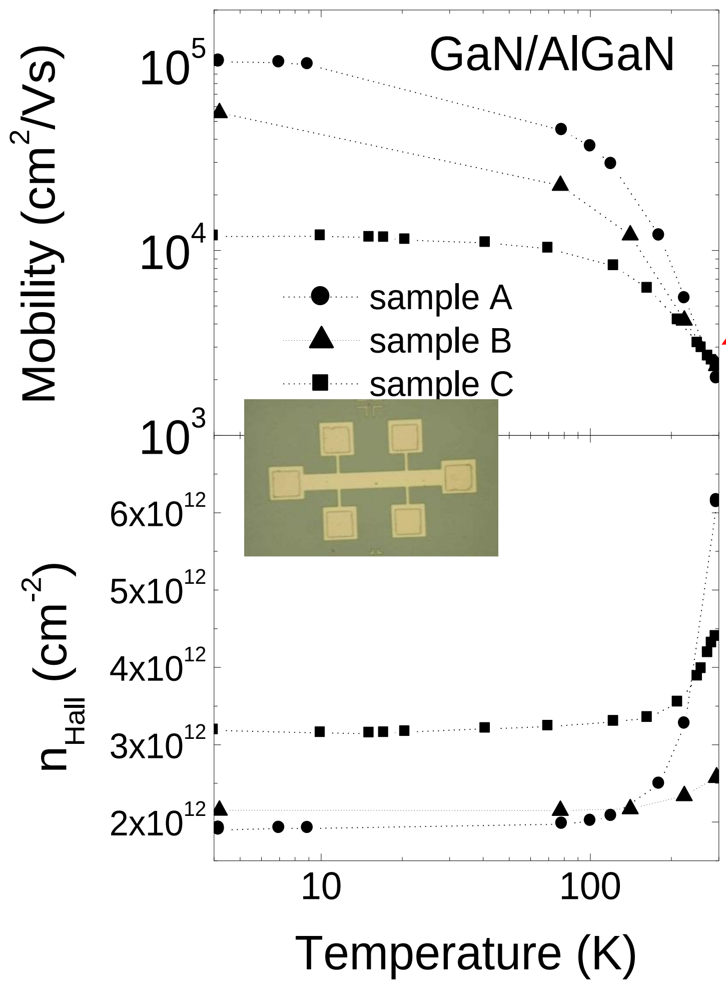


V_{ds} =4V
2.1 THz
V_{gs}=0 V
0.75 THz
V_{gs}=-3.5 V
Emission, u.a
Frequency, THz
(a)
Signal, u.a
Wavenumber, cm^{-1}
(b)
FWHM, THz
Vgs, Volt

THZ emission from GaN/AlGaN



2DEG at AlGaN/GaN



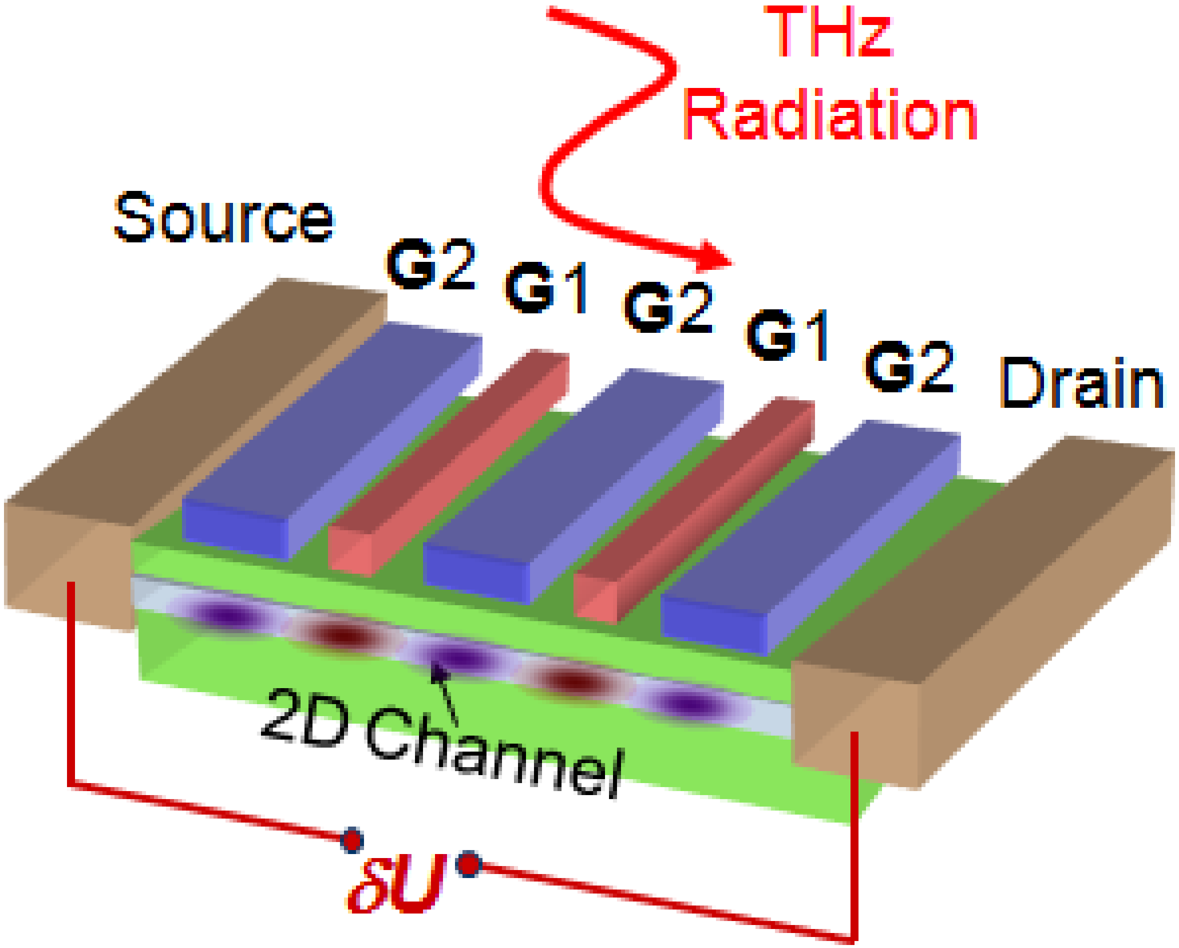
HIGH MOBILITY at 300K :

2500 cm²/Vs

World record!

Important for device performance

THz Source Based on GaN
THZ Emission (UNIPRESS – UM2)



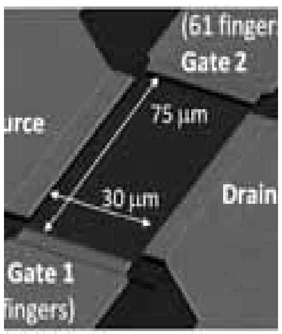
Multi GaInAs HEMT Emitters

Plasmonic nanodevices for terahertz sensing and spectroscopy

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

Novel solid-state emitters and detectors exploit electror improve the operating frequency of devices intended fo applications.

15 February 2010, SPIE Newsroom. DOI: 10.1117/2.1201



Tunable and coherent sources c (THz) frequencies currently repr hottest topics in modern electro radiation was the province of as analytical science. Now, the tecl in an increasingly wide variety c in information and communicati medical sciences, nondestructiv homeland security, quality control of food and agricultu

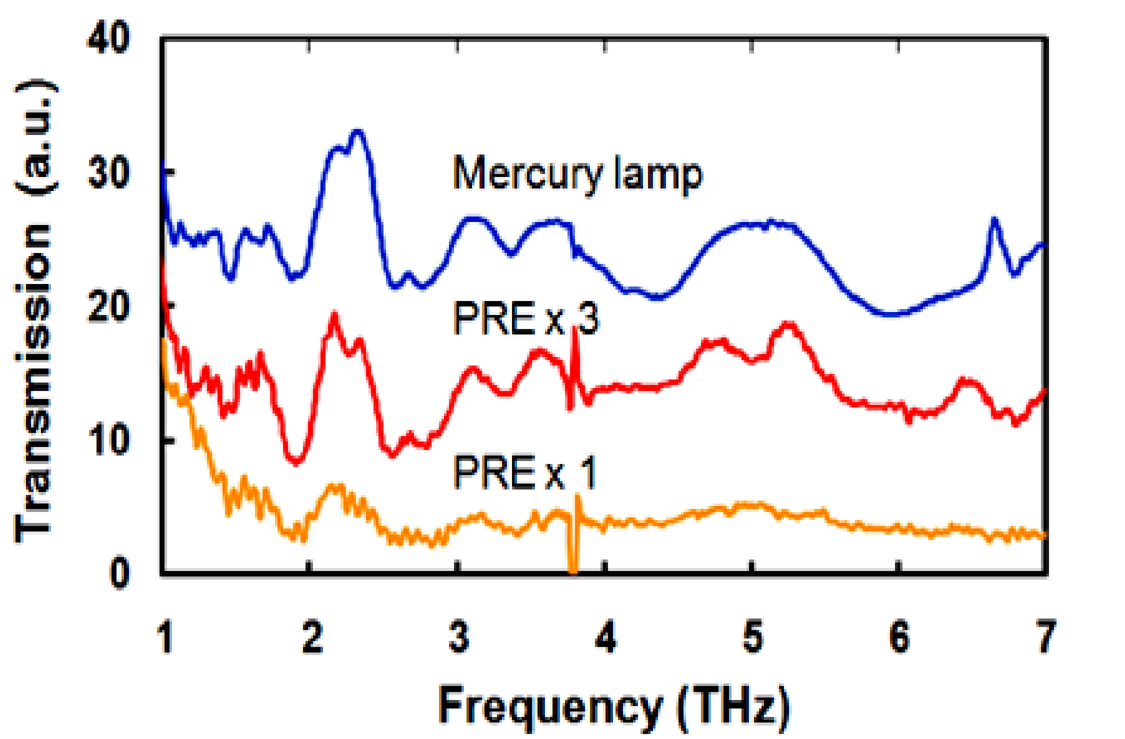


Figure 3. *Transmission spectra for maple-syrup liquid measured using single - and triple-chip PRE(s), and an HP-Hg lamp.*

1) Can we have THz detection with Graphene??

2) Can we enhance nonresonat 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 oscilations(nano)

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

4)Can we make a resonators and see resonant votage tunable THz detection ?? (Yes …broad &LT)

5)Can we make a resonators and see resonant votage tunable THz emission ?? (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)