Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Room temperature THz sources and detectors with semiconductor nanodevices, the ROOTHz project

Date Submitted: 11 March 2011

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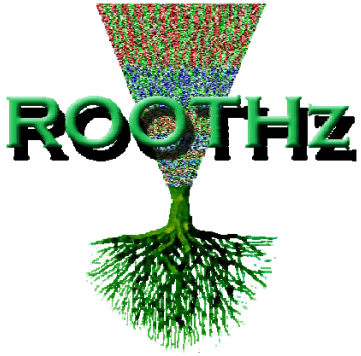
Abstract: ROOTHz is a 3 year project funded within the European 7th Framework Program that addresses the fabrication of room temperature, continuous wave, compact, tunable and powerful T-ray sources (at low cost, if possible). For this sake we propose to exploit THz Gunn oscillations in novel (narrow and wide bandgap) semiconductor nanodevices, which have been predicted by simulations but not experimentally confirmed yet. The fabrication of THz detectors with the same technology will complement this objective and make possible the demonstration of a simple THz detection/emission subsystem.

Purpose: Dissemination of the ROOTHz project objectives and achievements



Room temperature THz sources and detectors with semiconductor nanodevices, the ROOTHz project

Javier Mateos
University of Salamanca, Spain

OUTLINE

- Introduction: Importance of THz
- ROOTHz Project
- Self Switching Diodes (SSDs)
- Slot Diodes
- Conclusions

Importance of THz: T-rays

THz radiation can penetrate poor weather, dust and smoke far better than infrared or visible systems.

Satellite Telemetry

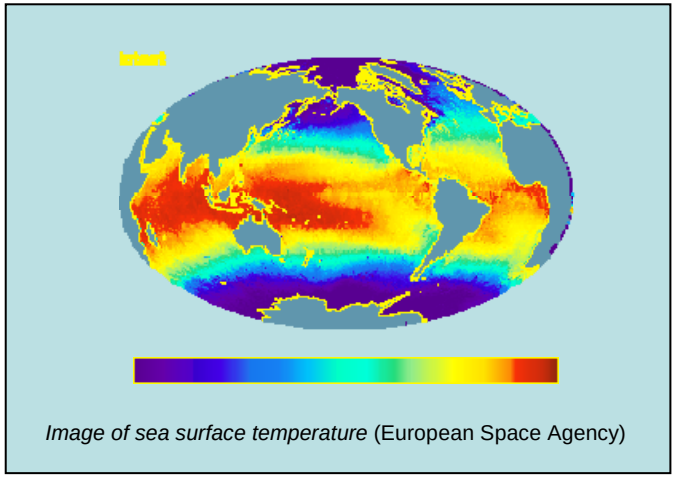


Image of sea surface temperature (European Space Agency)

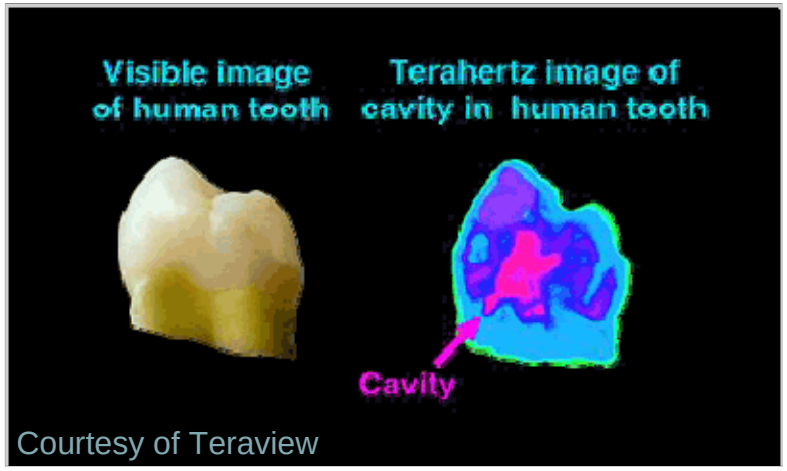
Aeronautics: guidance and landing

Importance of THz: T-rays

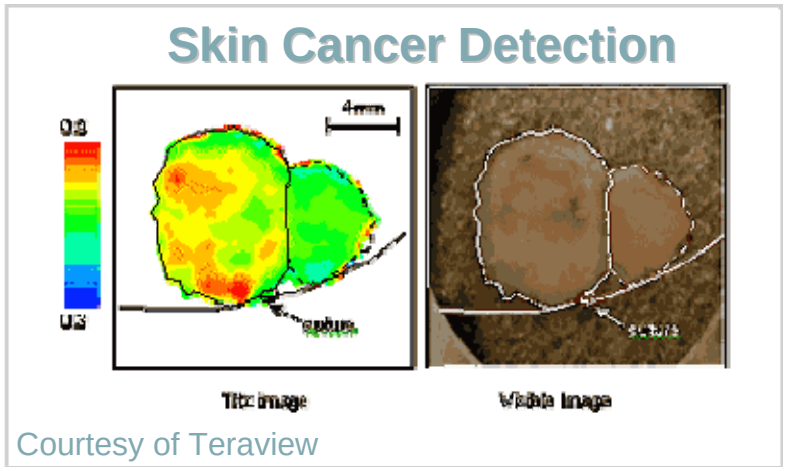
THz radiation can penetrate organic materials **without ionizing**.

Readily absorbed by water: distinguish between materials with varying water content

Medical imaging



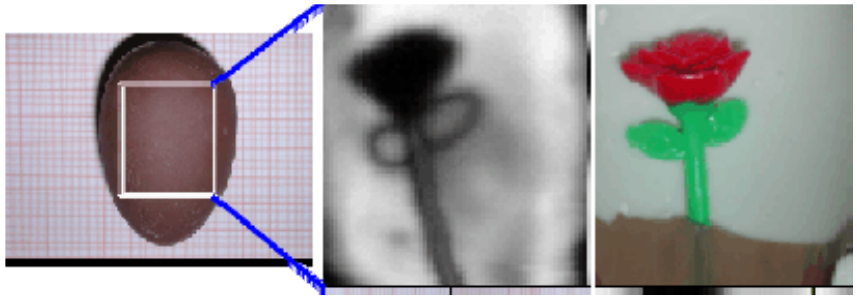
Courtesy of Teraview

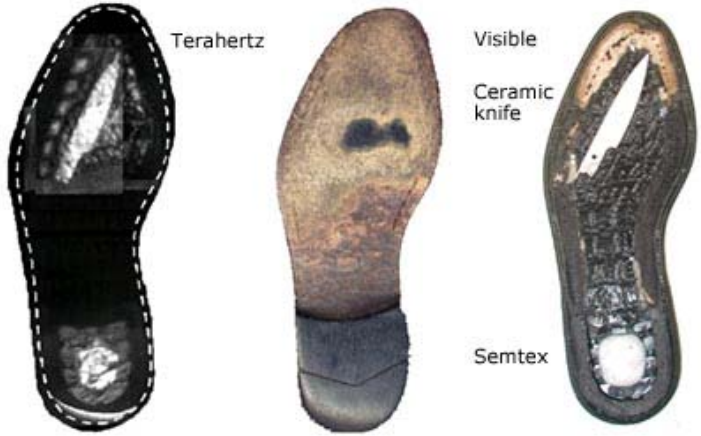


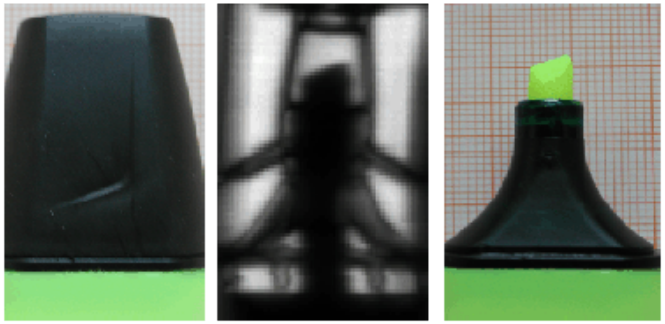
Courtesy of Teraview

Importance of THz: T-rays

THz radiation can penetrate dielectrics such as windows, paper, clothing and in certain instances even walls







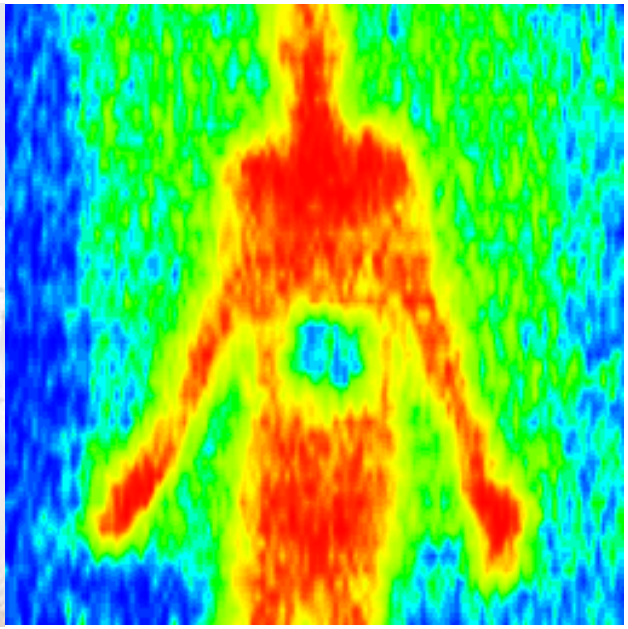
Importance of THz: T-rays

THz radiation can penetrate dielectrics such as windows, paper, clothing and in certain instances even walls

Weapon or Explosive Detection (metallic or non metallic)

Courtesy of Qinetiq

Courtesy of Qinetiq



Courtesy of Thruvision

Importance of THz: T-rays

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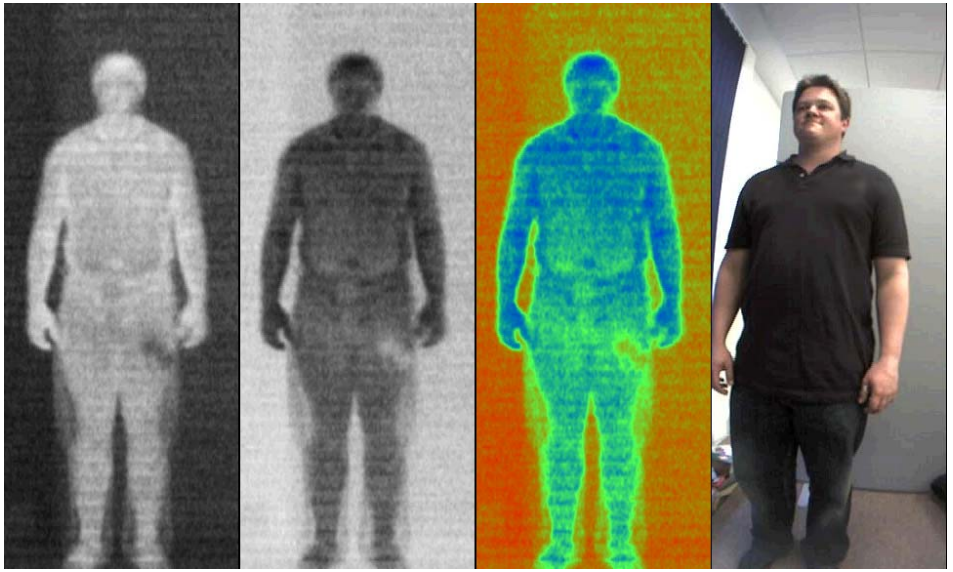
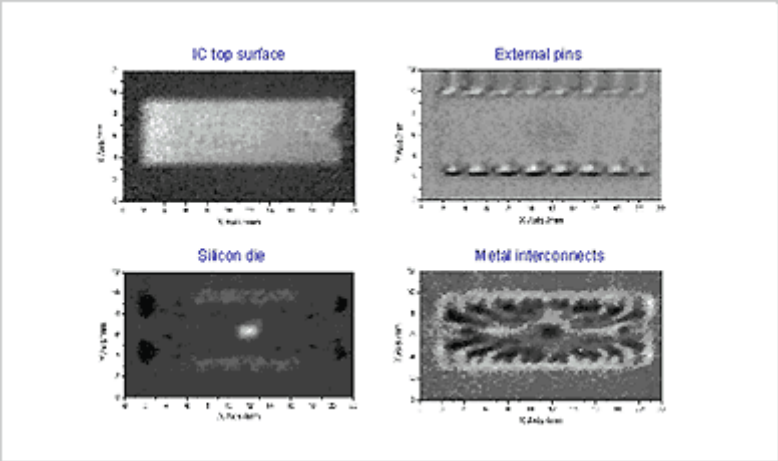
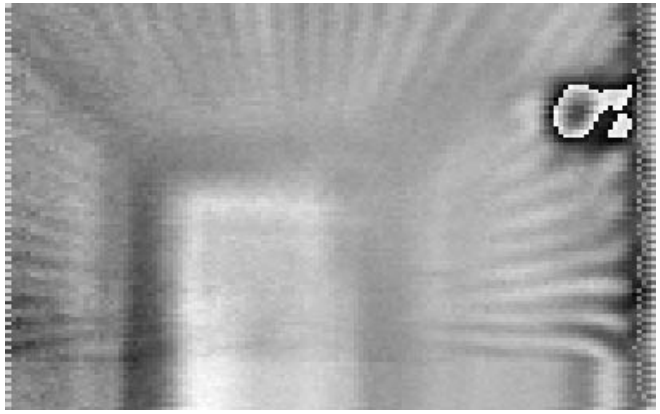


Importance of THz: T-rays

THz radiation can penetrate dielectrics such as windows, paper, clothing and in certain instances even walls

Non-destructive testing:
Integrated Circuit Package Inspection

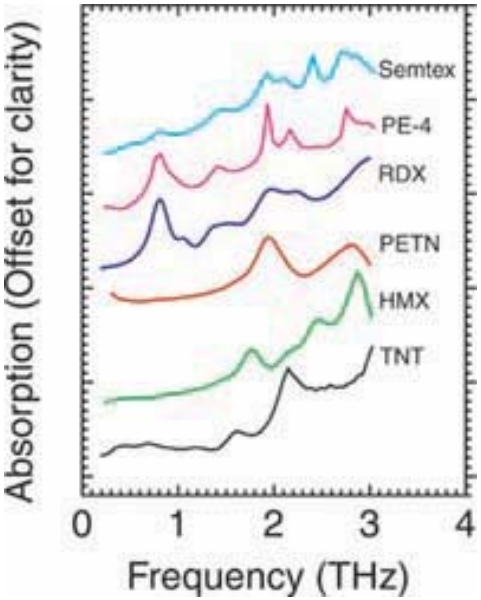


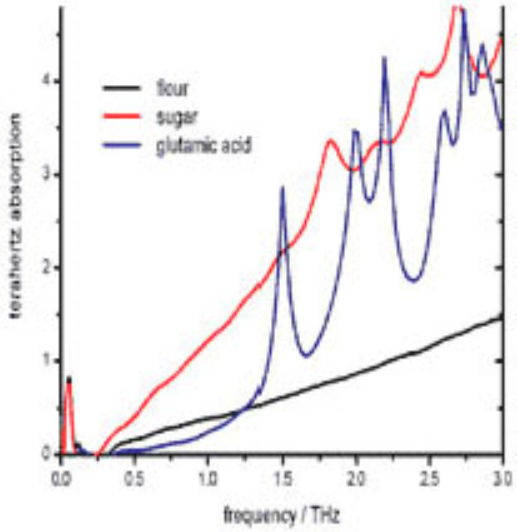


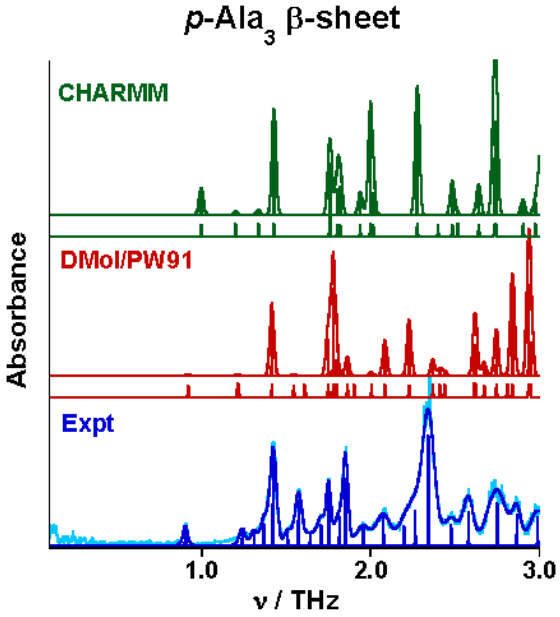
Courtesy of Teraview

Importance of THz: T-rays

THz radiation can be used to identify spectral fingerprints of explosives, narcotics, or active pharmaceutical ingredients

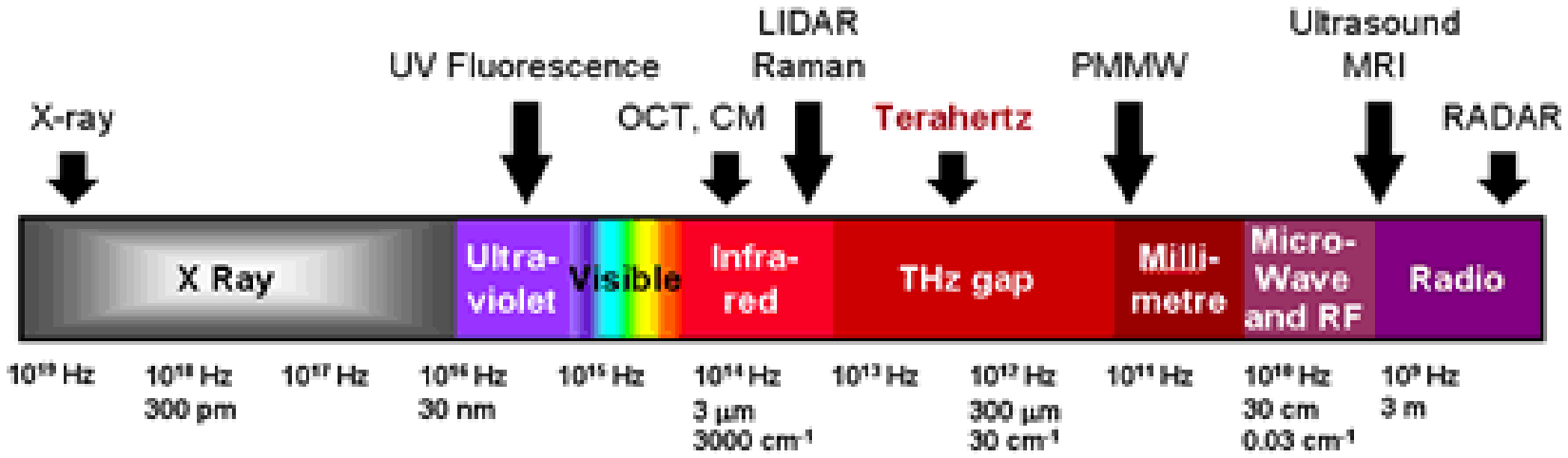






The THz Gap

PHOTONICS — THz Gap — ELECTRONICS



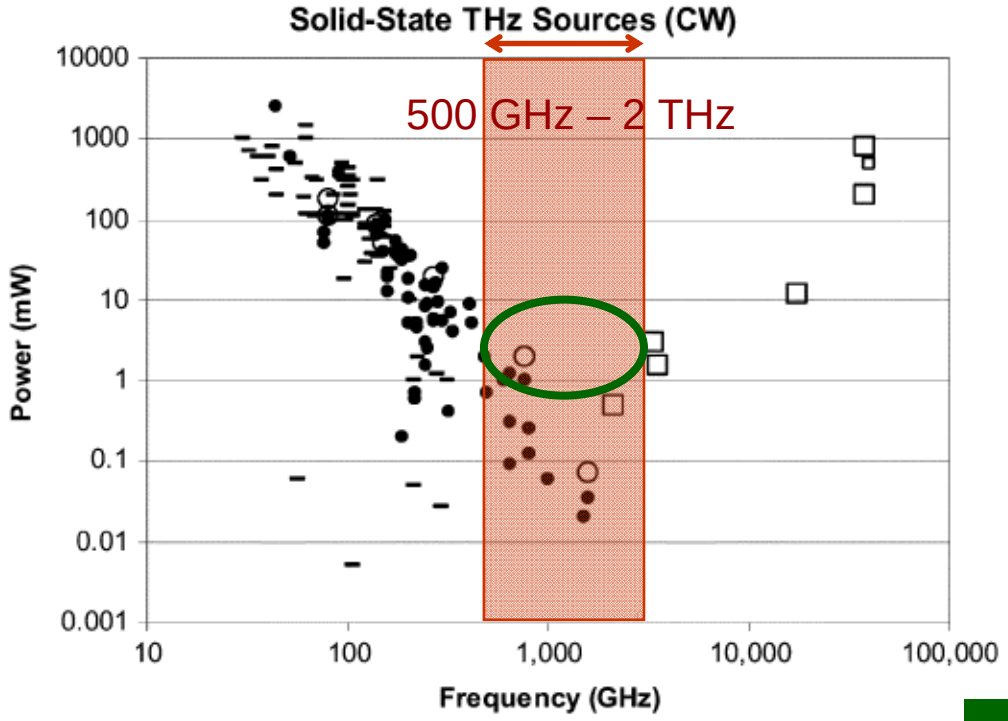
All-optical sources

- Mixing lasers with close frequencies
- Excitation of semiconductors or superconductors with femtosecond laser pulses
- Quantum cascade lasers

Bulky and expensive equipment

Semiconductor Nanodevices for Room Temperature THz Emission and Detection (ROOTHz Project)

The THz Gap



- □ Quantum cascade lasers (QCL)
- ○ QCL at cyogenic T
- ● Frequency multipliers
- — Other electronic devices: amplifiers, RTDs, IMPATT and Gunn diodes

Semiconductor Nanodevices for Room Temperature THz Emission and Detection (ROOTHz Project)

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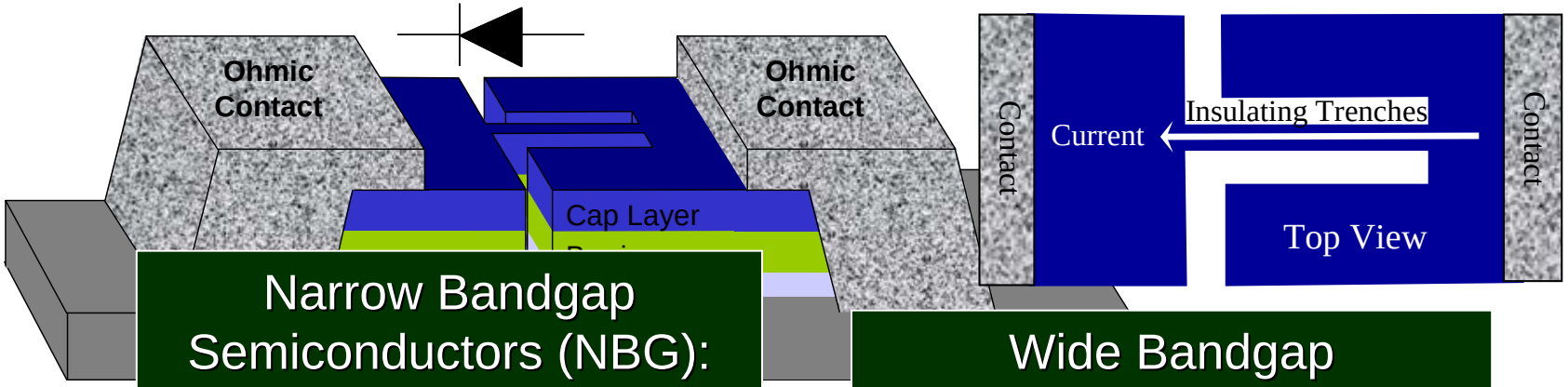
Semiconductor Nanodevices for Room Temperature THz Emission and Detection (ROOTHz Project)

- Funded under: 7th FWP (Seventh Framework Programme)
- Area: FET Open (ICT-2007.8.0)
- Project Reference: 243845
- Total cost: 2.1 M€
- EU contribution: 1.57 M€
- Execution: from 1st January 2010 to 31st December 2012
- Duration: 36 months
- Web: www.roothz.eu

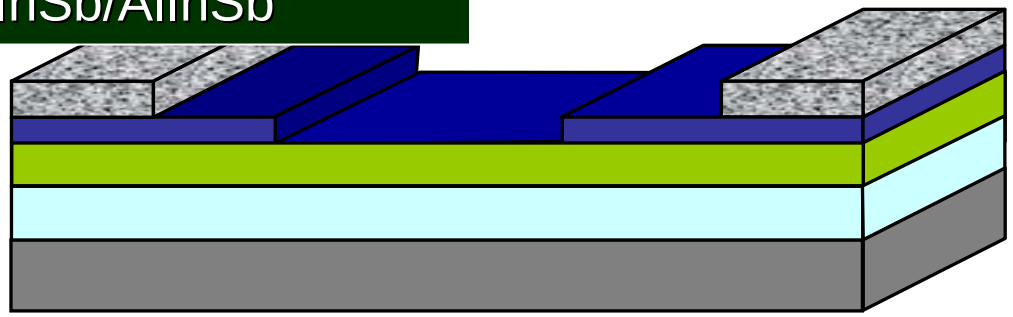
Semiconductor Nanodevices

Self Switching Diodes (SSDs)



Narrow Bandgap Semiconductors (NBG):
InGaAs/AlInAs
InAs/AlSb
InSb/AlInSb

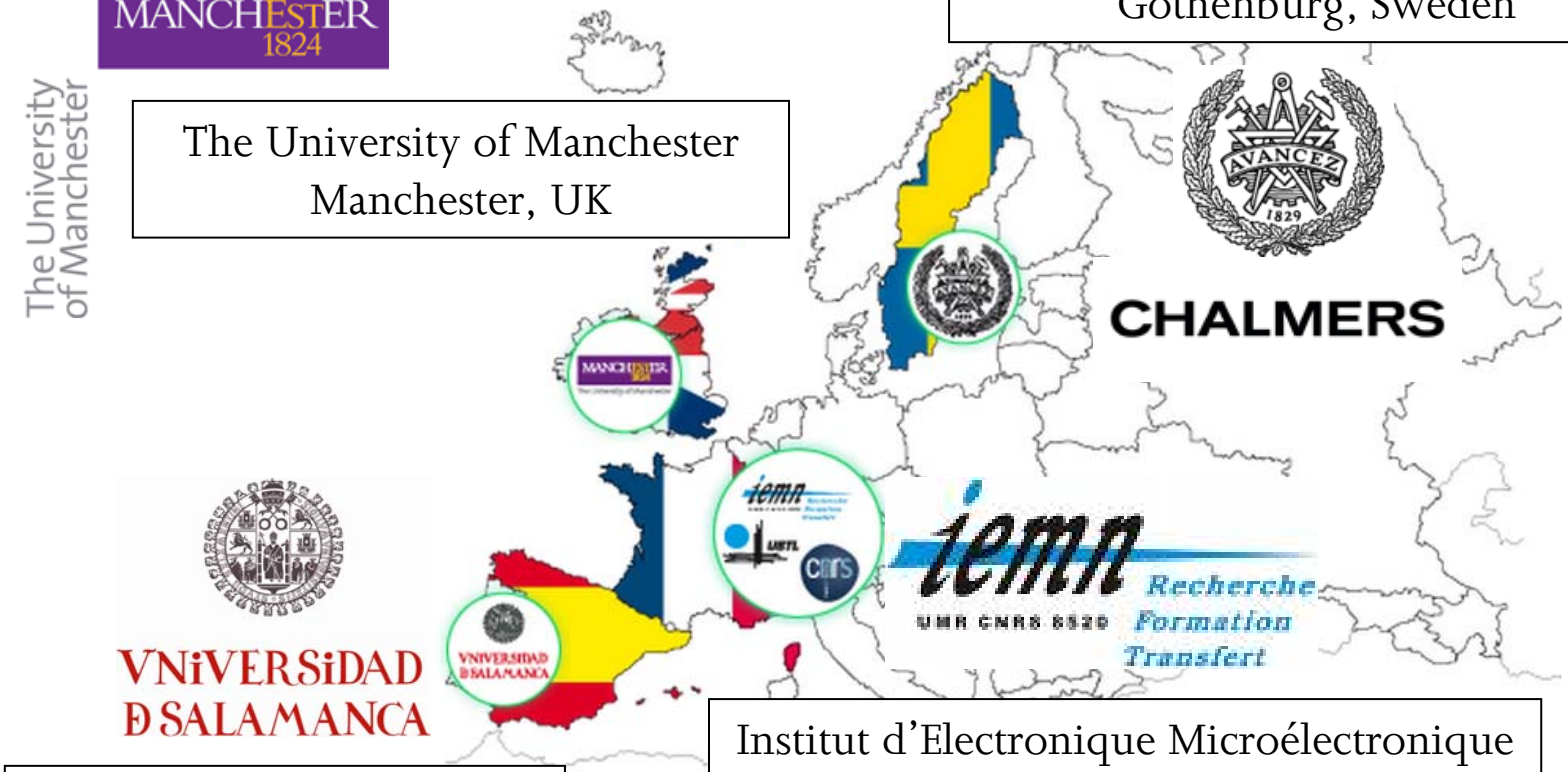
Wide Bandgap Semiconductors (WBG):
GaN/AlGaN



Partners

Chalmers University of Technology
Gothenburg, Sweden

The University of Manchester
Manchester, UK



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et de Nanotechnologie
Lille, France

Coordinator:
University of Salamanca
Salamanca, Spain

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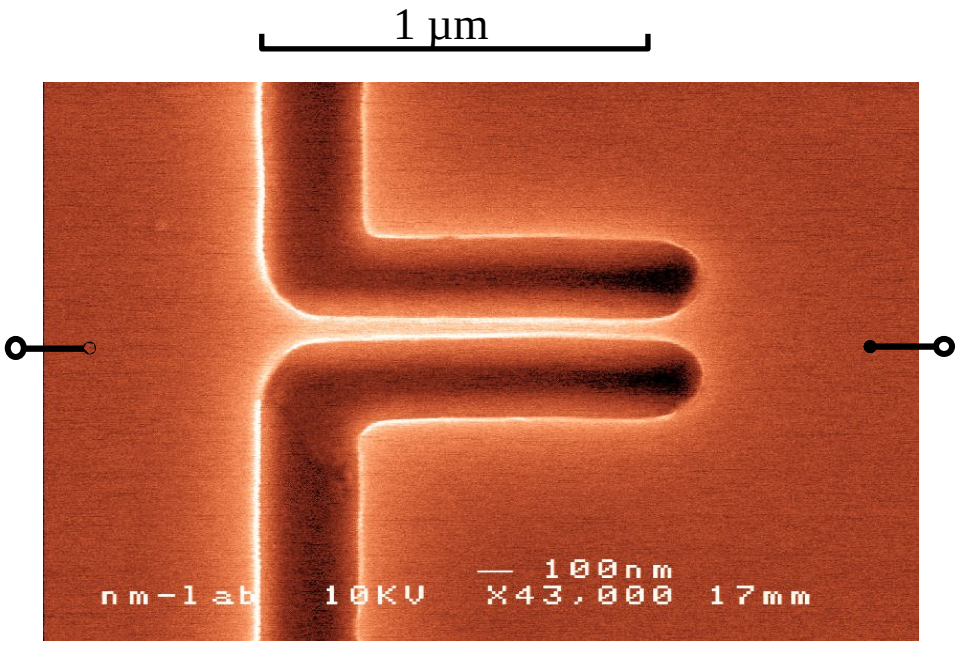
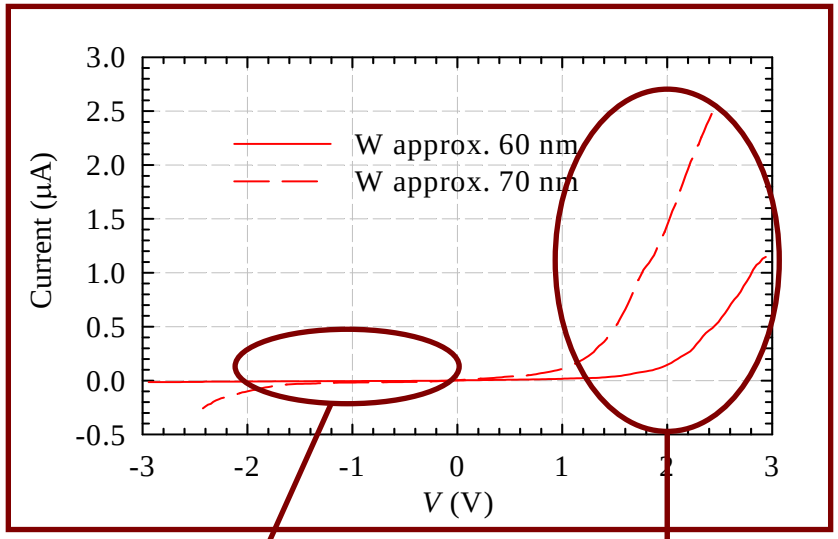
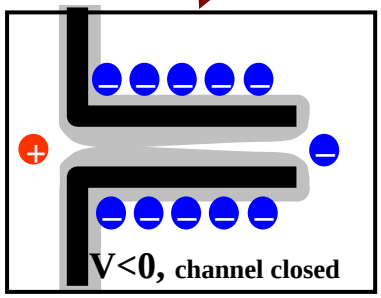
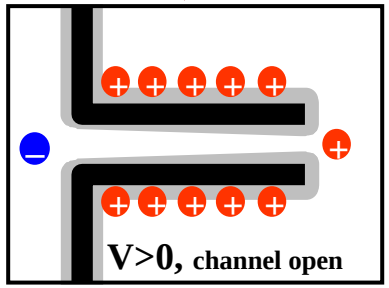
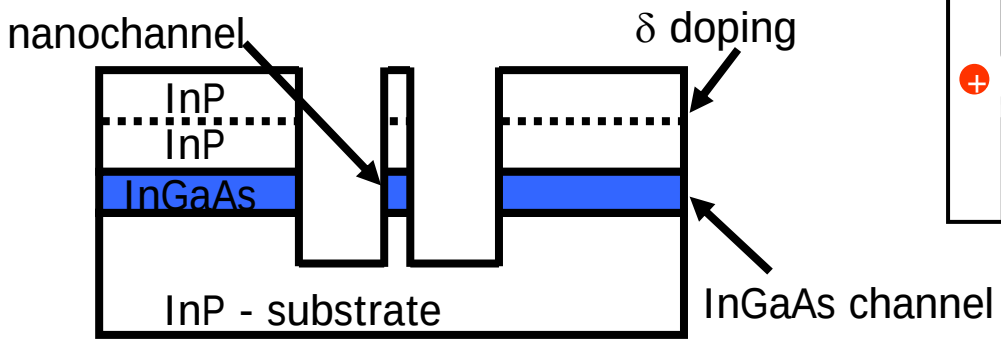
Self Switching Diodes (SSDs)



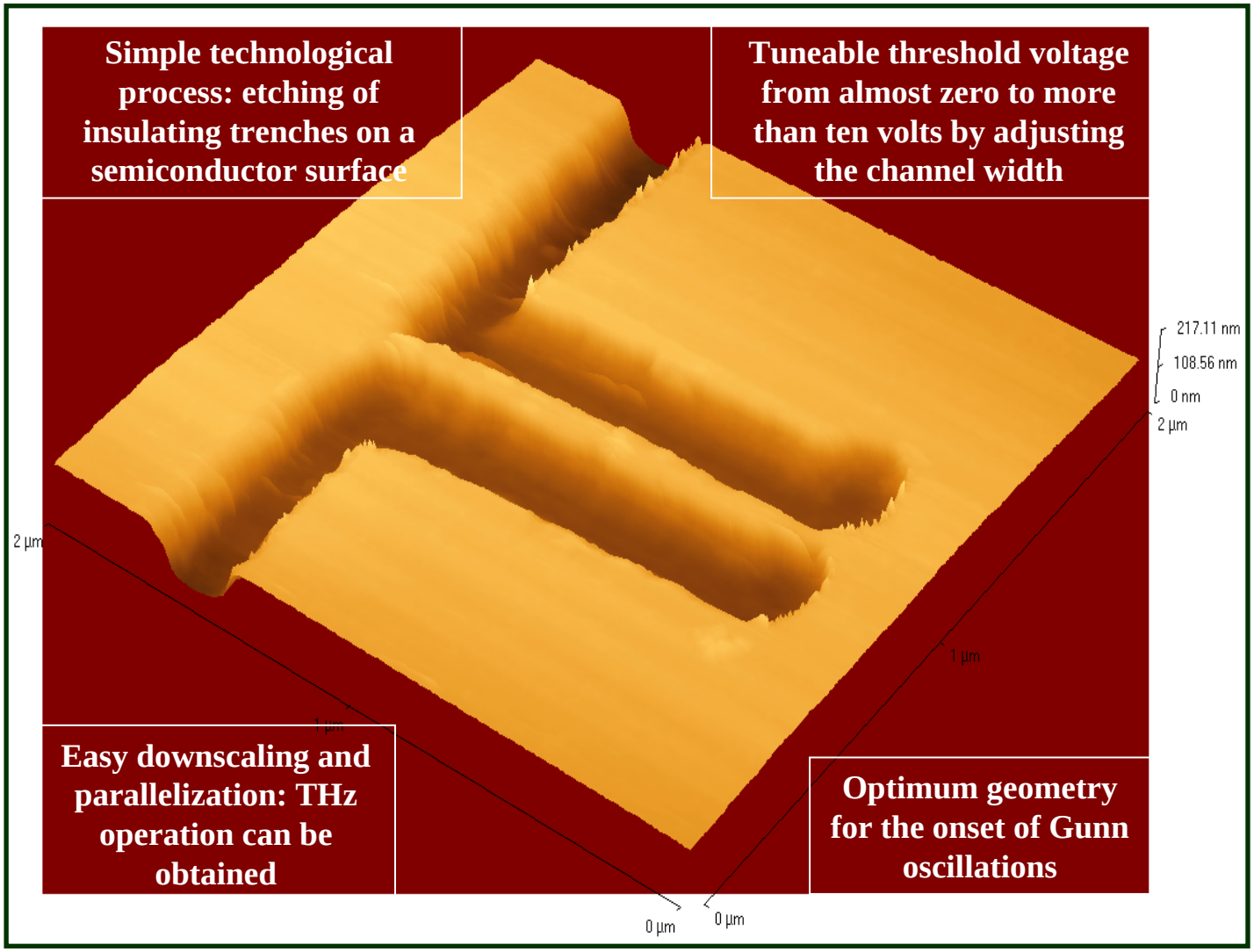








Self Switching Diodes (SSDs)



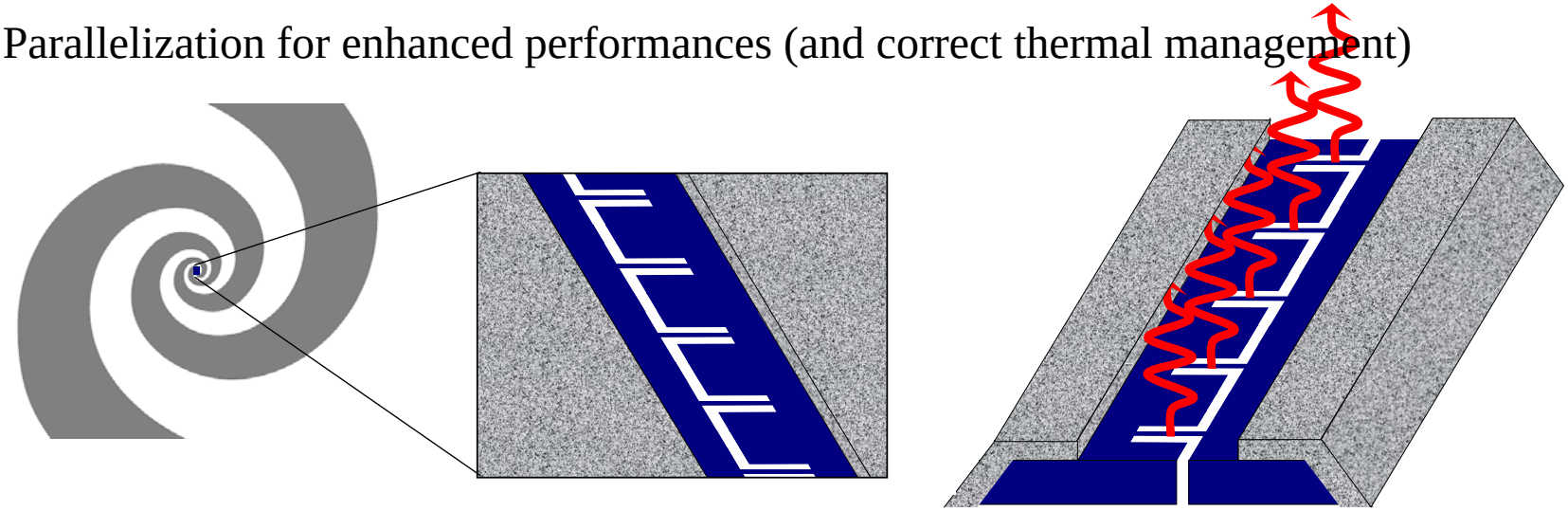
Self Switching Diodes (SSDs)

- **THz Detection**: non-linear I-V characteristics
  - ➢ Use of NBG materials (Room Temperature ballistic transport) for increased sensitivity and broadband

- **THz Emission**: Gunn Effect in InGaAs, **and GaN!**
  - ➢ Use of WBG materials for increased power

- Planar geometry (and antennas) allow for a better coupling

- Parallelization for enhanced performances (and correct thermal management)



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  - SSDs as THz emitters
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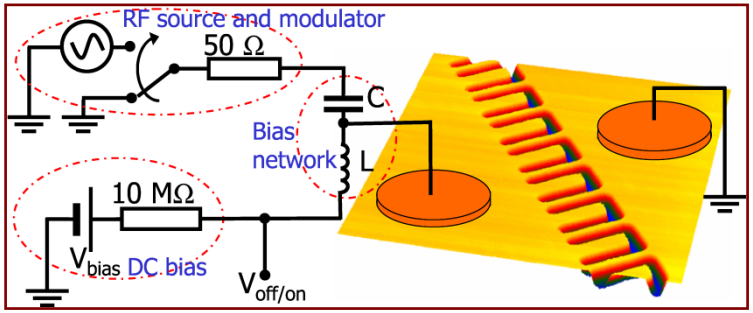
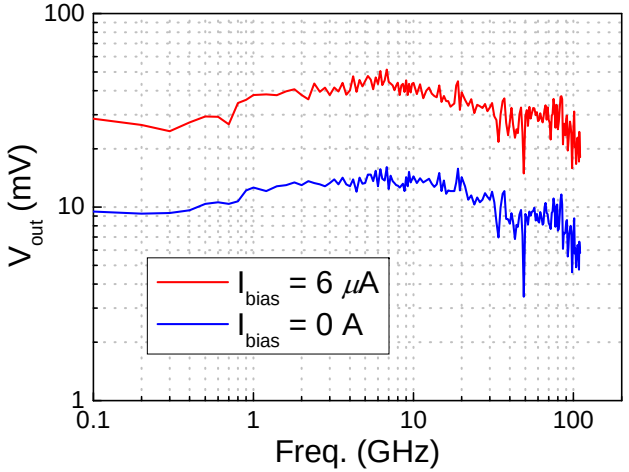
SSDs as THz detectors: Experiments

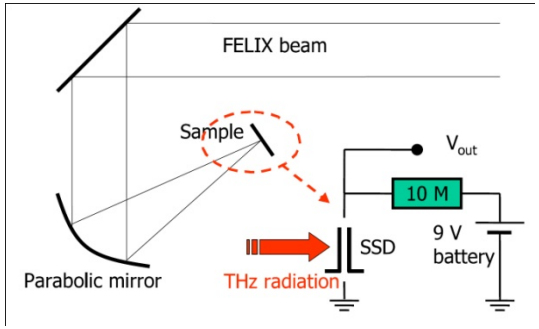


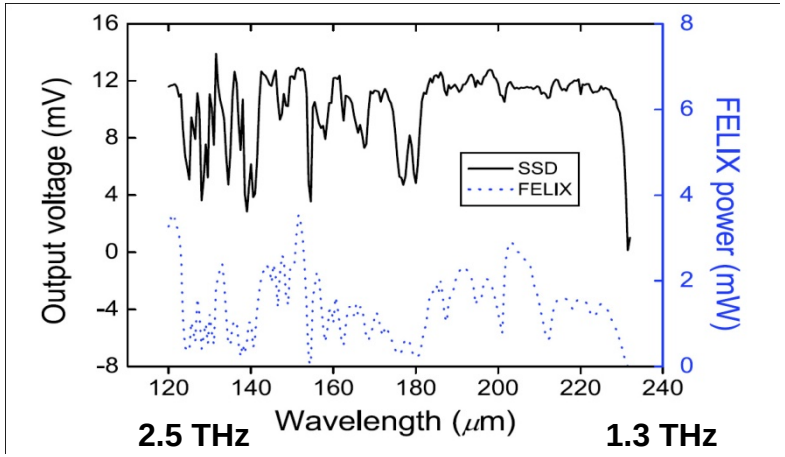


18 diodes in parallel

300 K, 75 mV/mW @110 GHz

C. Balocco, A. M. Song, M. Aberg, A. Forchel, T. González, J. Mateos *et al.*, *Nano Lett.* **5**, 1423 (2005)





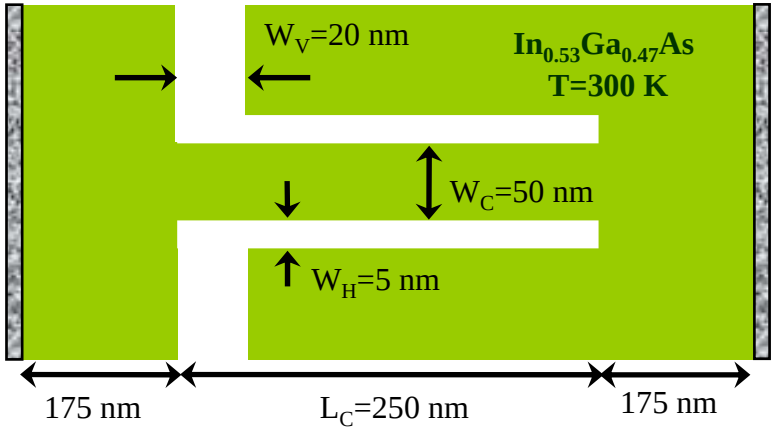
10 K, operative in the THz range
(drop in the response above 70 K)

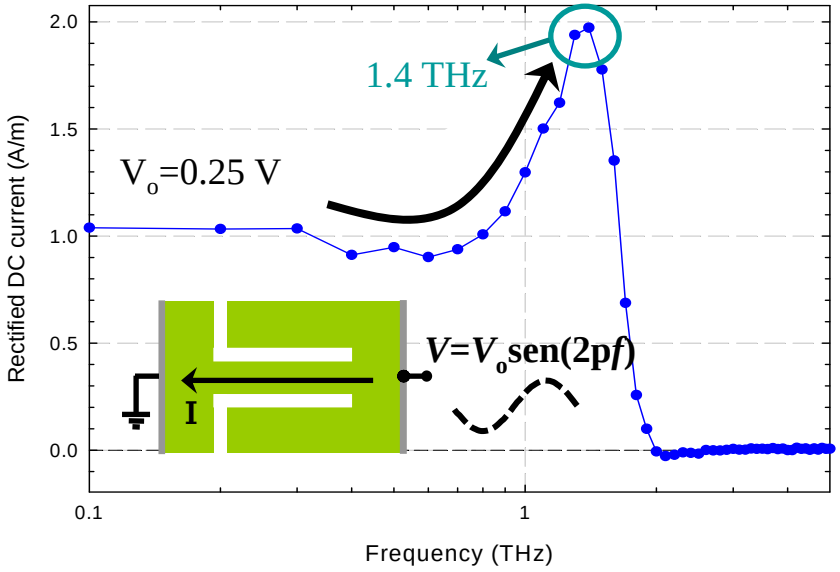
6 diodes in parallel

C. Balocco, M. Marshall, N. Q. Vinh and A. M. Song, *J. Phys.: Condens. Matter* **20**, 385203 (2008)

SSDs as THz detectors: Monte Carlo Simulations

- **THz Detection**: non-linear I-V characteristics
  - ➢ Use of NBG materials (Room Temperature ballistic transport) for increased sensitivity and broadband

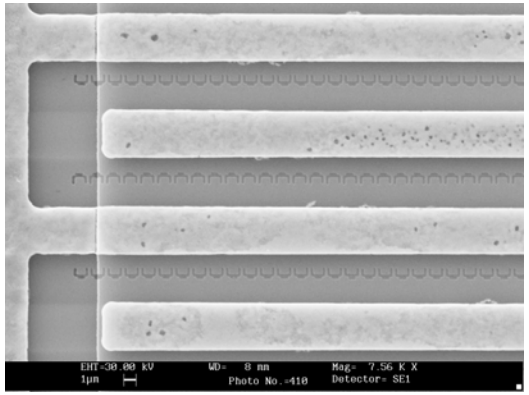


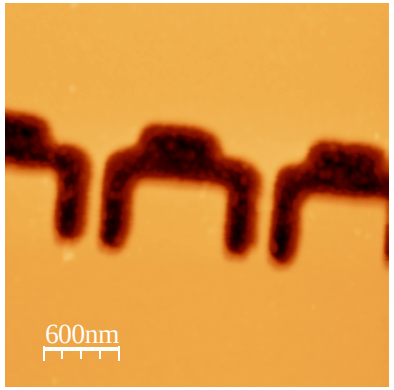


Enhanced rectification in the THz range (tunable by geometry)

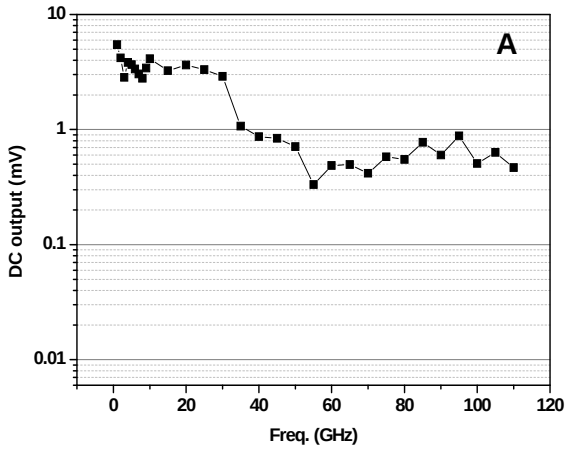
First Experimental Results

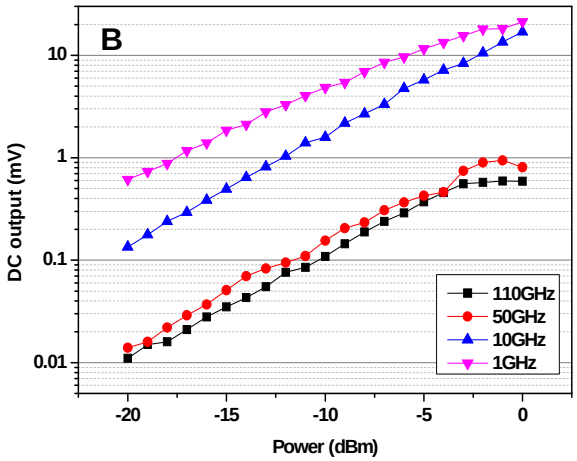
Interdigital InGaAs mesa with 2000 etched SSDs





RF power detector up to 110 GHz





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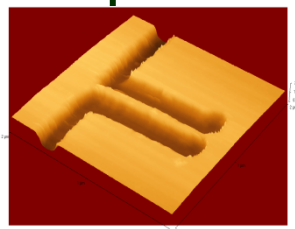
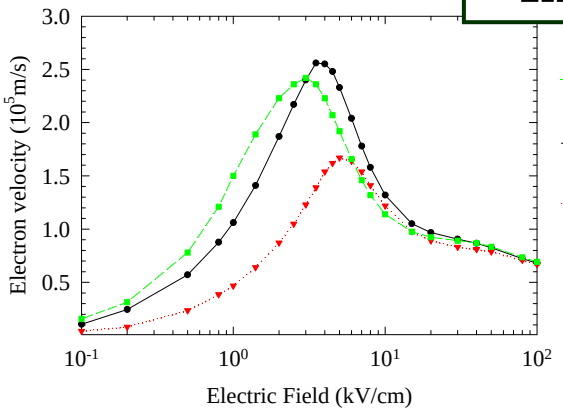
SSDs as THz emitters: Gunn Oscillations



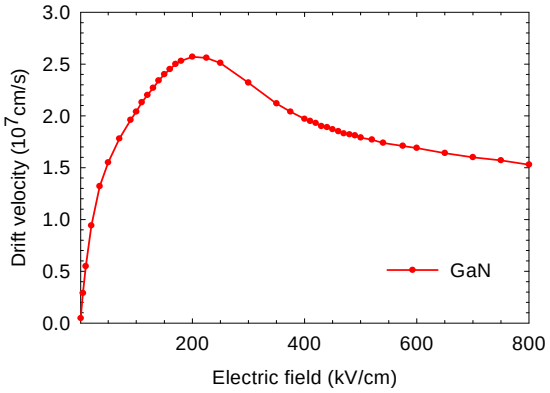
Suitable geometry → Focused electric field
→ Electron concentration increased by the side field effect

- InGaAs channels (narrow band gap)



- Pronounced NDM
- Low saturation velocity (low frequency)
- Low threshold field → low power

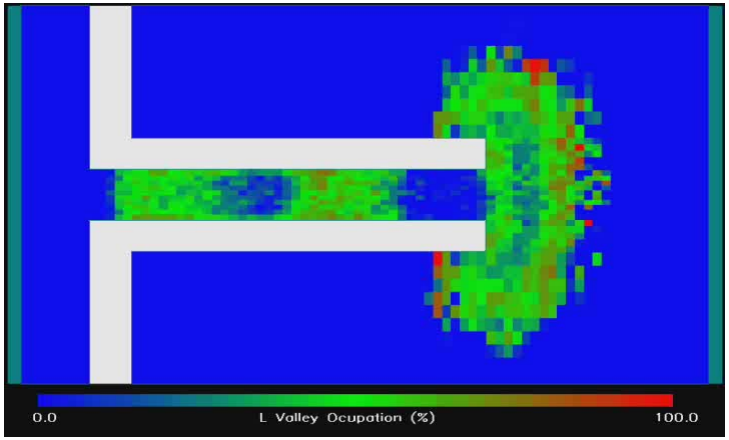
GaN channels (wide band gap)

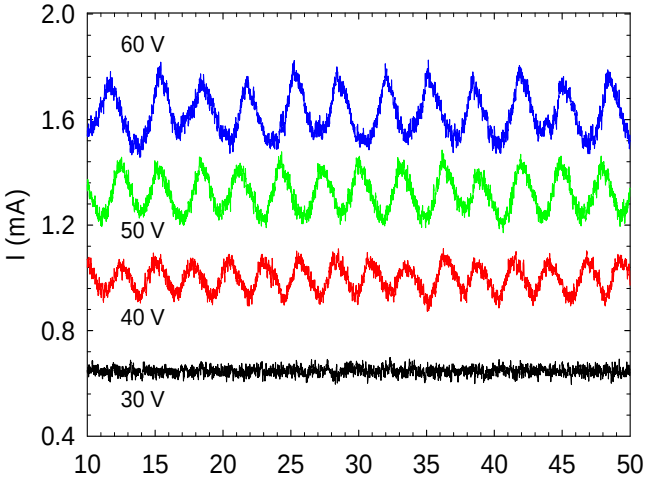


- Less pronounced NDM
- High saturation velocity + Low energy relaxation time } → **high frequency**
- High threshold field → **high power**

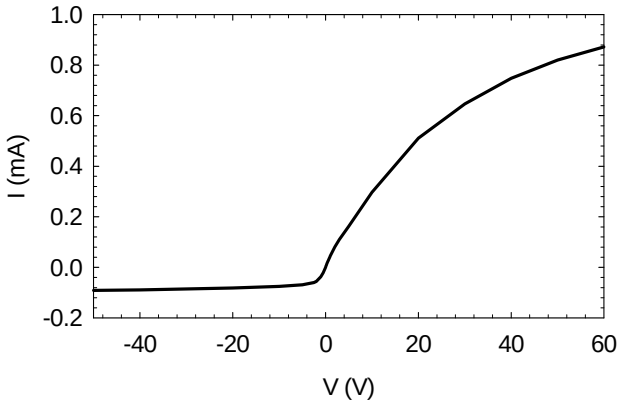
SSDs as THz emitters: Gunn Oscillations

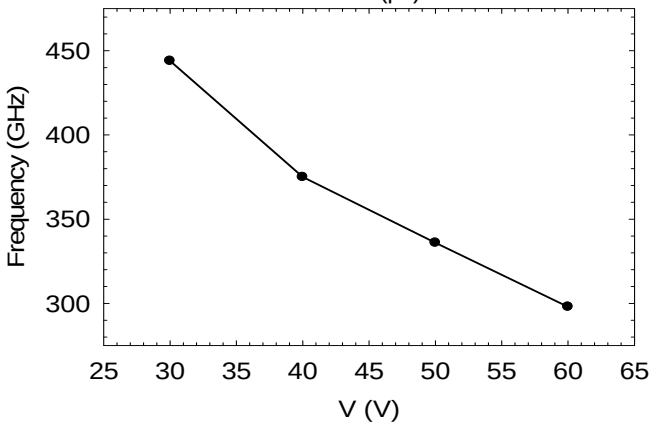
Monte Carlo Simulations





Gunn Oscillations in GaN SSDs

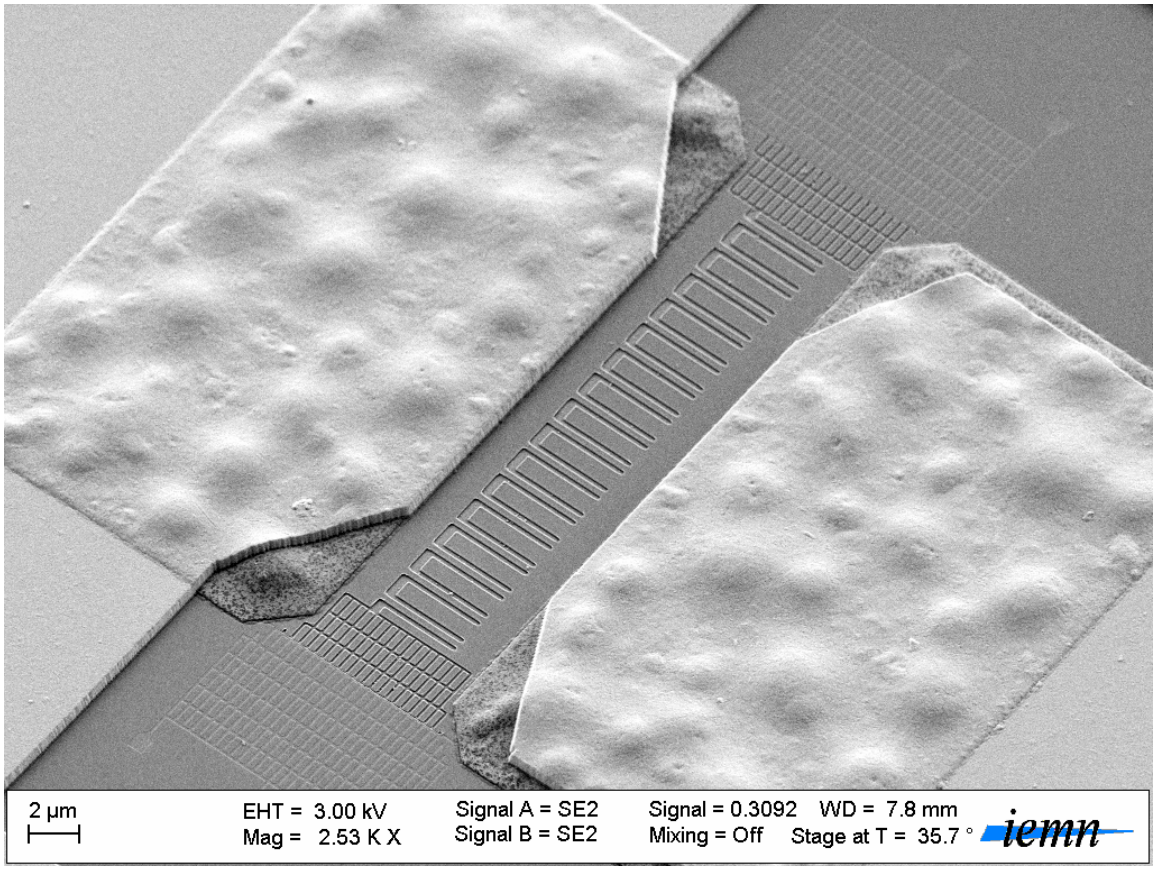




Oscillation frequencies above 400 GHz (voltage controlled and tunable by geometry)

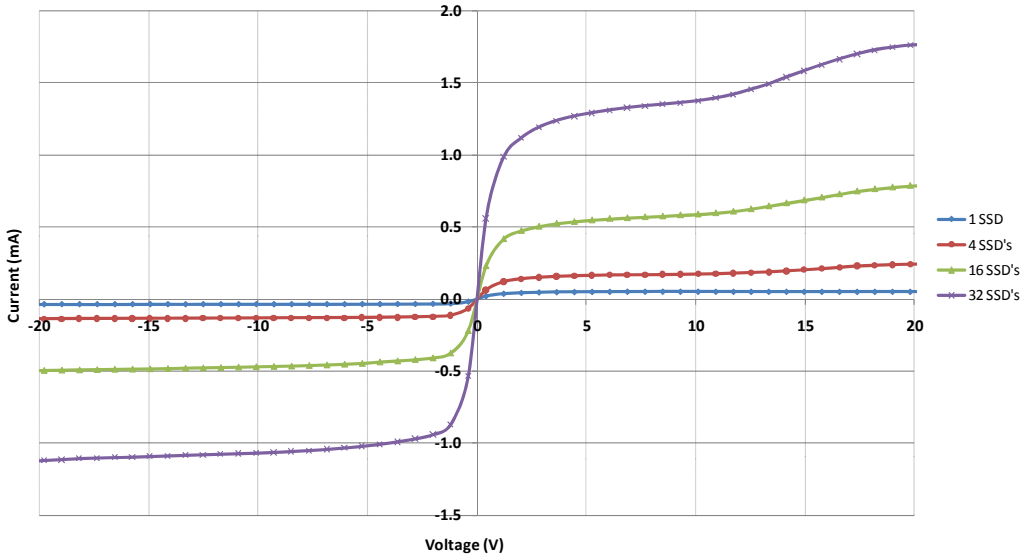
First Experimental Results

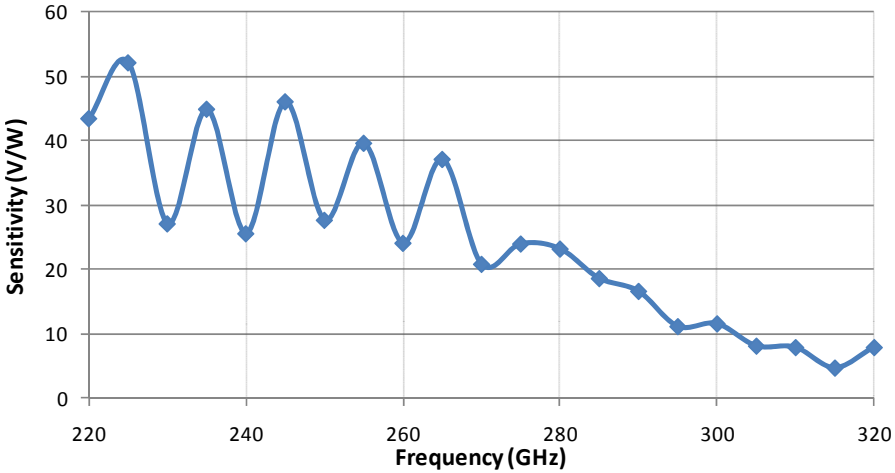
16 parallel GaN SSDs



First Experimental Results

DC curves: Fabrication of 32 SSDs in parallel validated





RF detection demonstrated even if with small sensitivity (maximum of 50 V/W)

Gunn oscillations not observed yet

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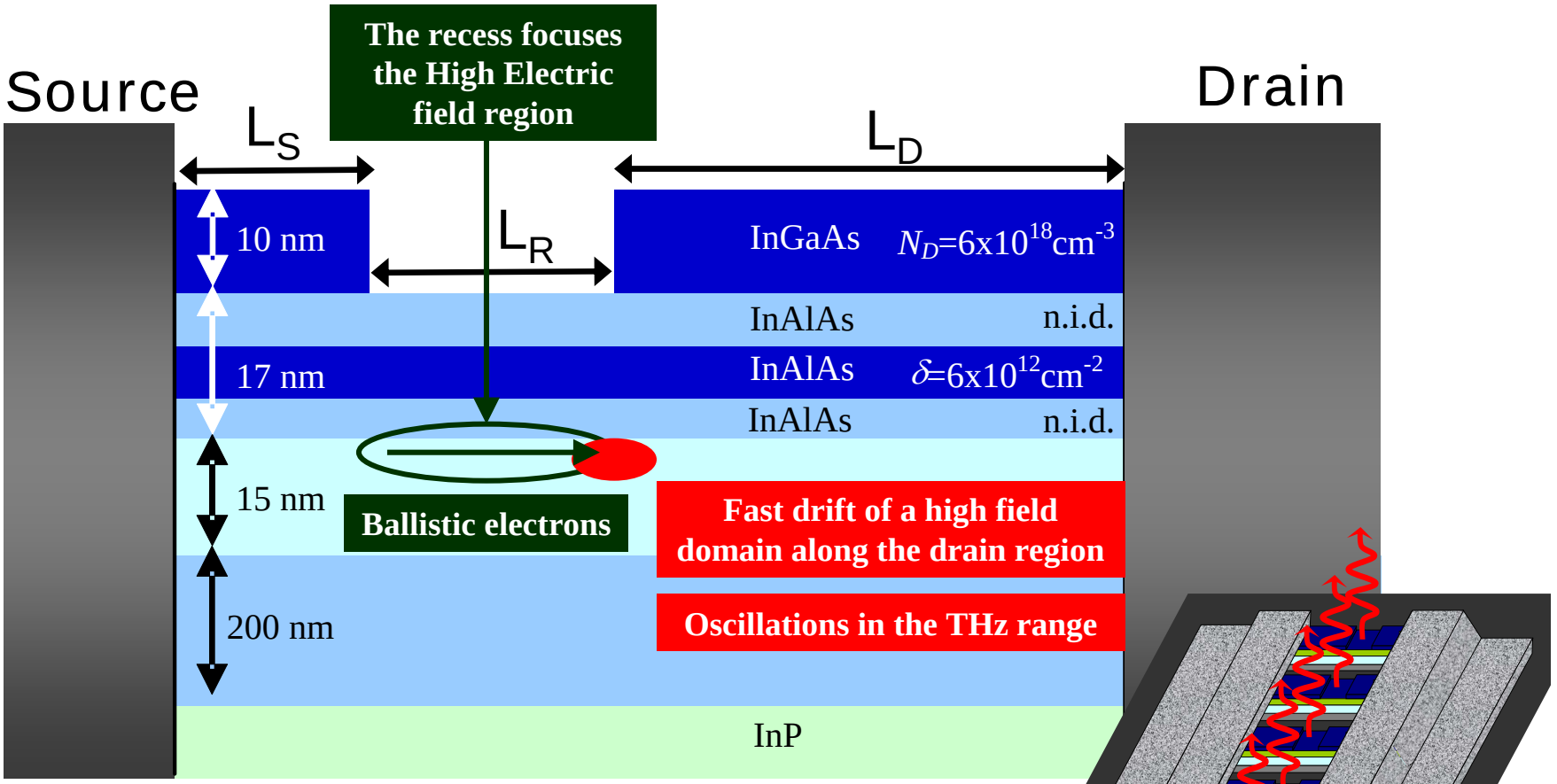
Slot Diodes: Ultra fast Gunn effect for THz generation



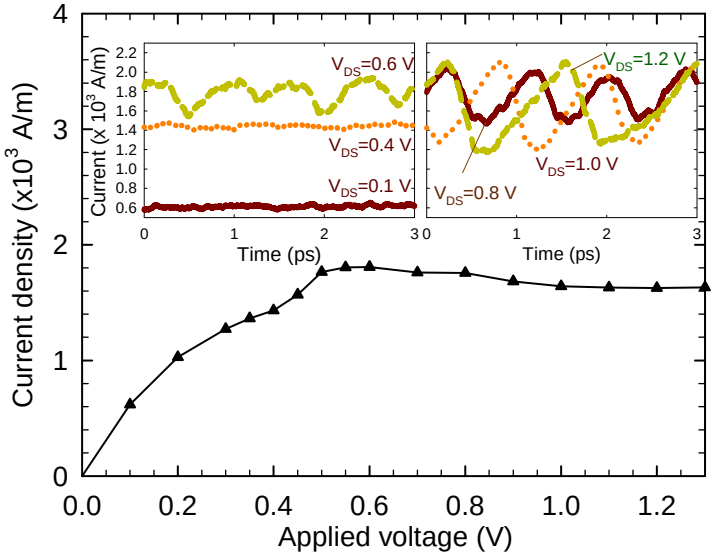
• **Planar geometry** and **Parallelization**

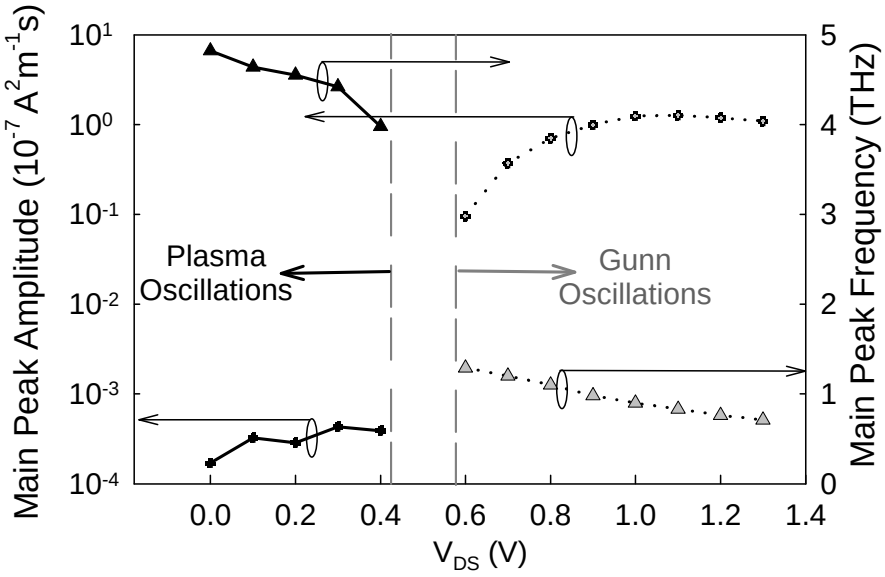
Slot Diodes: Ultra fast Gunn effect for THz generation

Monte Carlo Simulations

$V_{DS} < V_{th} \approx 0.6\,\mathbf{V}$ → Low-amplitude plasma oscillations

$V_{DS} > V_{th} \approx 0.6\,\mathbf{V}$ → High-amplitude Gunn-like oscillations

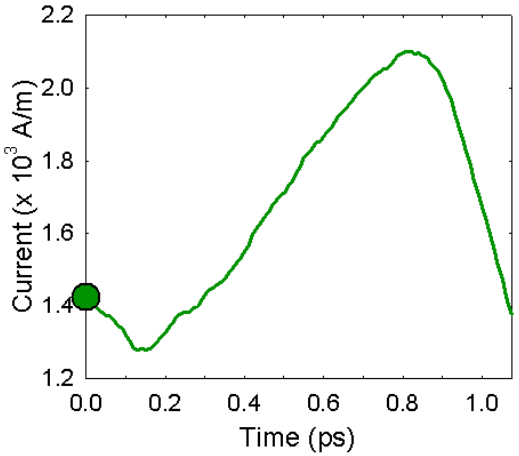


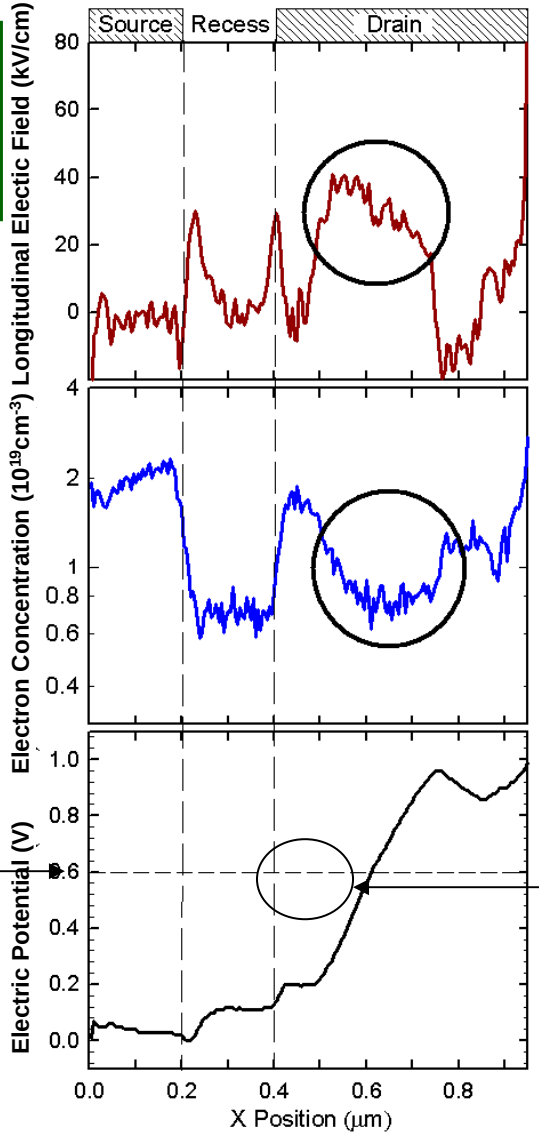


Ultra fast Gunn-like oscillations in the THz range (voltage controlled and tunable by geometry)

Slot Diodes: Ultra fast Gunn effect for THz generation

Domain moves at the very fast velocity of Γ-electrons that refill the depleted region





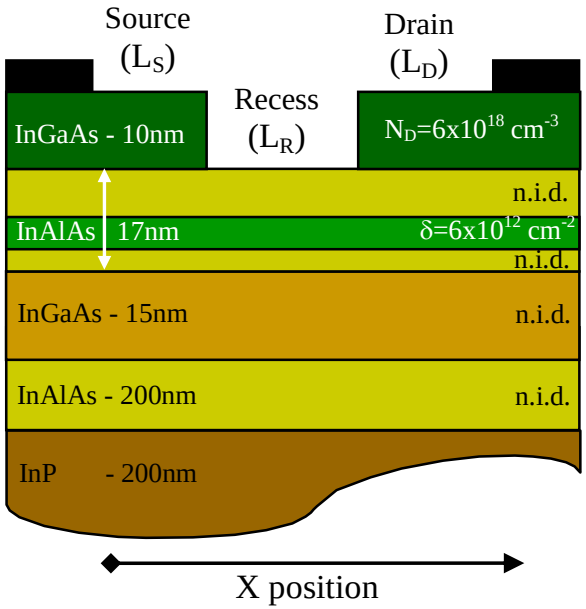
Intervalley energy level (0.6 eV)

High electric field domain created, increase of the potential drop within the drain region (and injection of Γ-electrons)

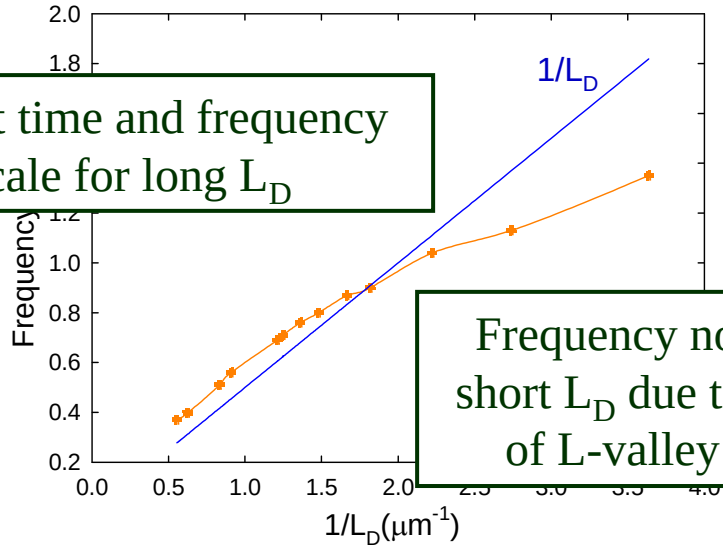
Concentration decrease due to the small velocity of electrons injected into the drain region (and fast Γ-electrons run away)

Injection into the upper valleys when there is enough potential drop in the recess region (and current decreases)

Slot Diodes: Ultra fast Gunn effect for THz generation



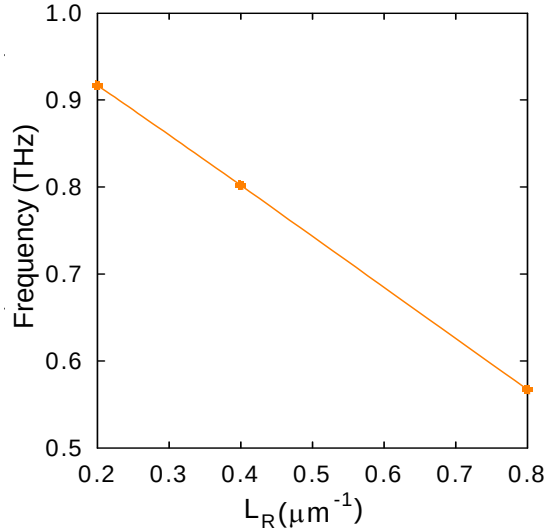
Transit time and frequency scale for long L_D



Influence of L_D

Frequency not scaling for short L_D due to the increase of L-valley population

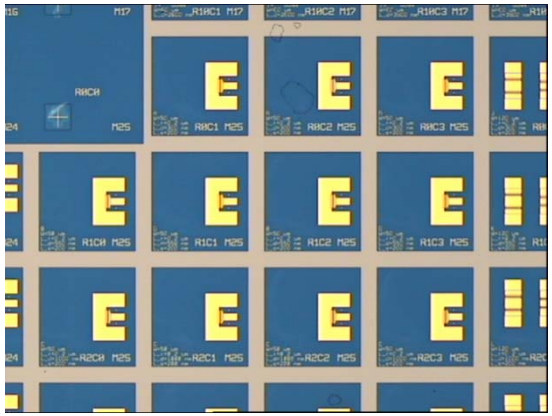
Longer recess lengths decrease the oscillation frequency due to the attenuation of the "electron-launching effect"

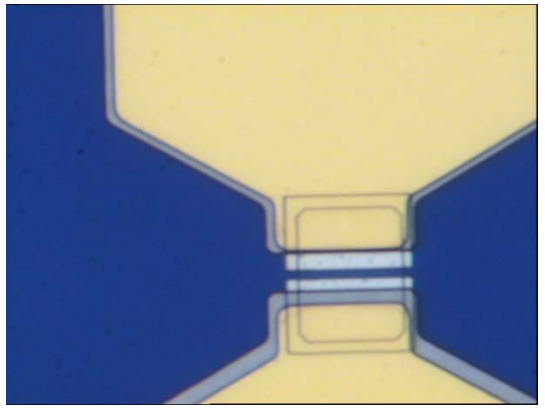


Influence of L_R

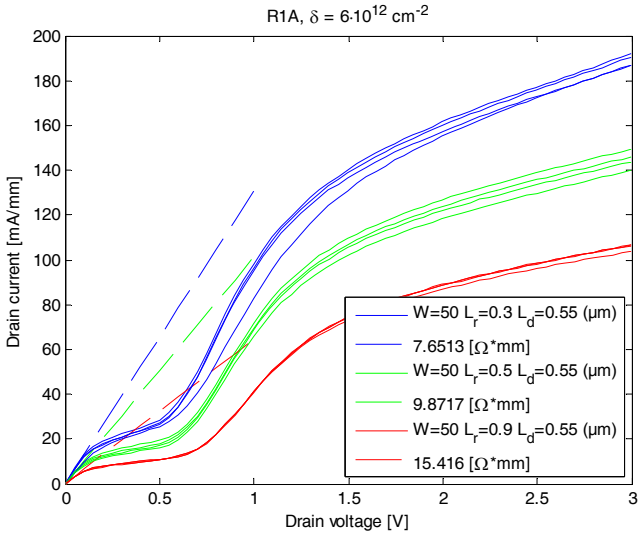
First Experimental Results

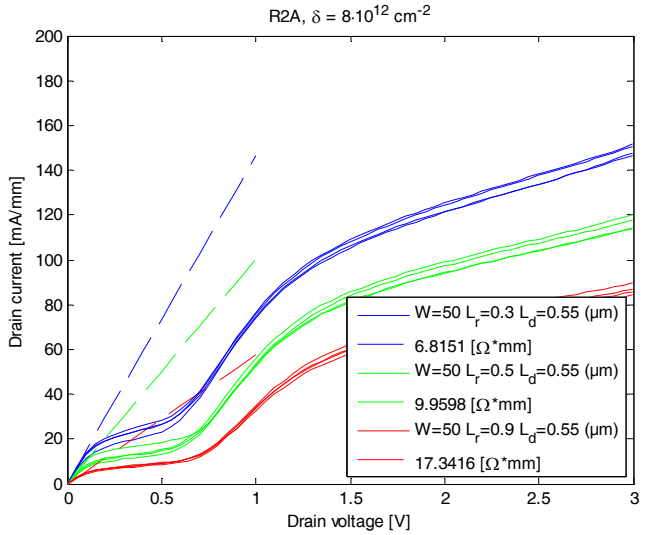
CHALMERS





Strong kink in the I-V curve of all the slot diodes fabricated





OUTLINE

- Introduction: Importance of THz
- ROOTHz Project
- Self Switching Diodes (SSDs)
- Slot Diodes
- Conclusions

Conclusions: ROOTHz objectives

Exploiting the special geometry and versatility of **SSDs and Slot Diodes** based on NBG and WBG semiconductors we aim to confirm the results of MC simulations for fabricating and demonstrating:

- **THz Detectors**: sensitivity above 500 mV/mW in the 0.5-2.0 THz band
- **THz Emitters**: **power exceeding 1mW**
  - Narrowband emitters at discrete frequencies of: 1.0, 1.5 and 2.0 THz
  - Broadband emitter in the 0.5-2.0 THz
- **Integrated THz detector/emitter prototype**: broadband emitter-detector in the range of 0.5-2.0 THz able to obtain the transmission or reflection spectrum of certain benchmark substances
- **Room Temperature operation**
- Demonstration of **Gunn oscillations in GaN SSDs**

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ROOTHz
Semiconductor Nanodevices for Room Temperature THz Emission and Detection
www.roothz.eu

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