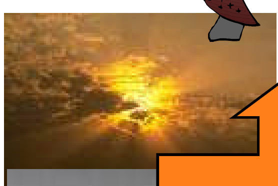
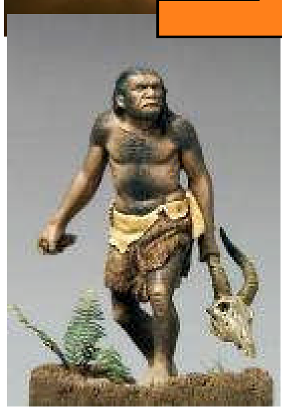
Terahertz Electronics

Michael Shur

Electrical, Computer, and Systems Engineering and
Center for Integrated Electronics
Rm 9015, CII, Rensselaer Polytechnic Institute
110 8-th Street, Troy, New York 12180-3590
http://www.ecse.rpi.edu/shur/

Human Civilization and Electromagnetic Spectrum
Visible Spectrum

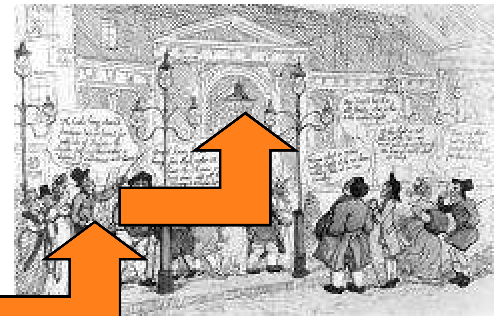




From using Sun

To the first torch 500,000 years ago

To the first candle 1,000 BC

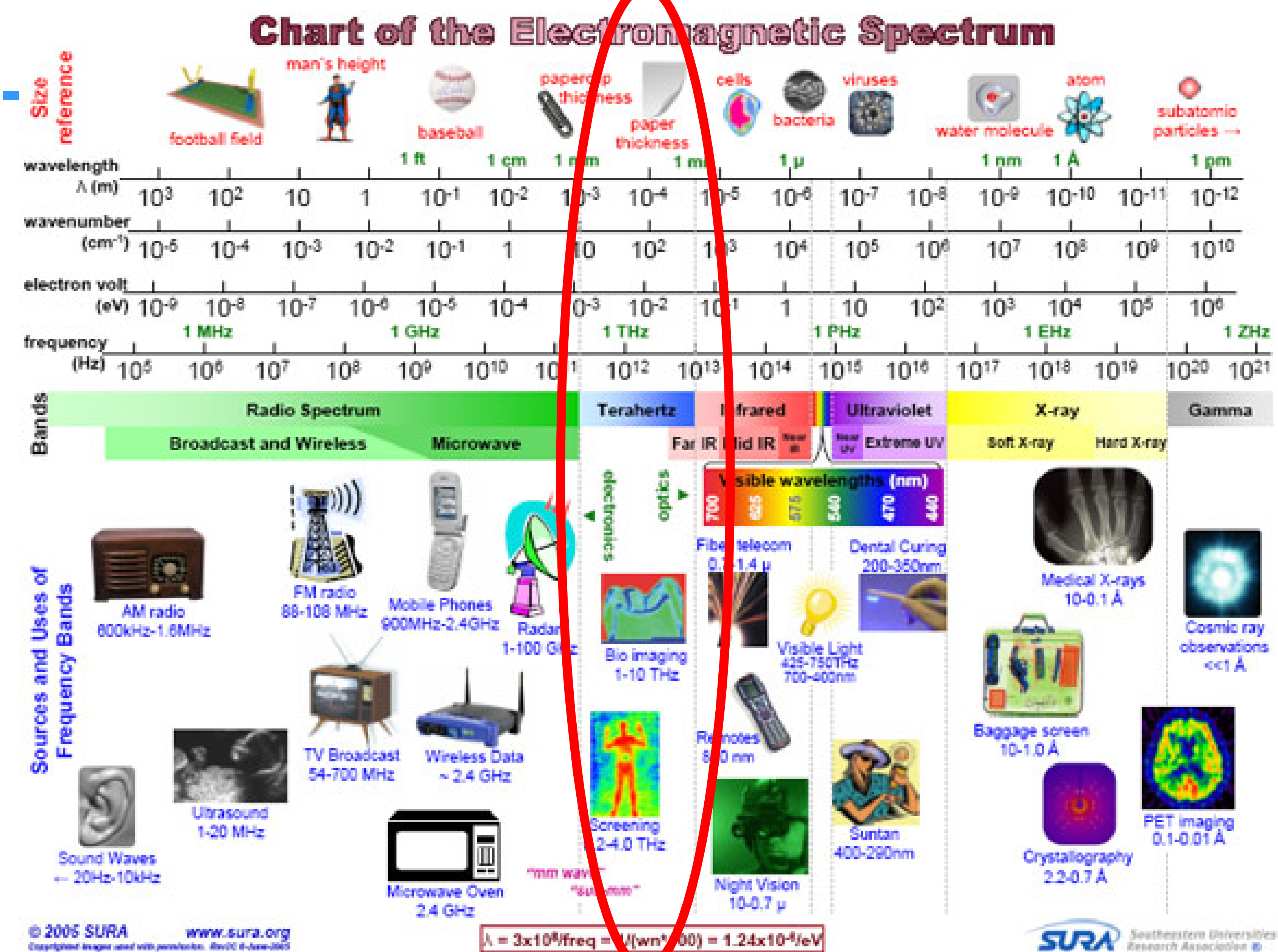


To gas lighting 1772

To Edison bulb 1879

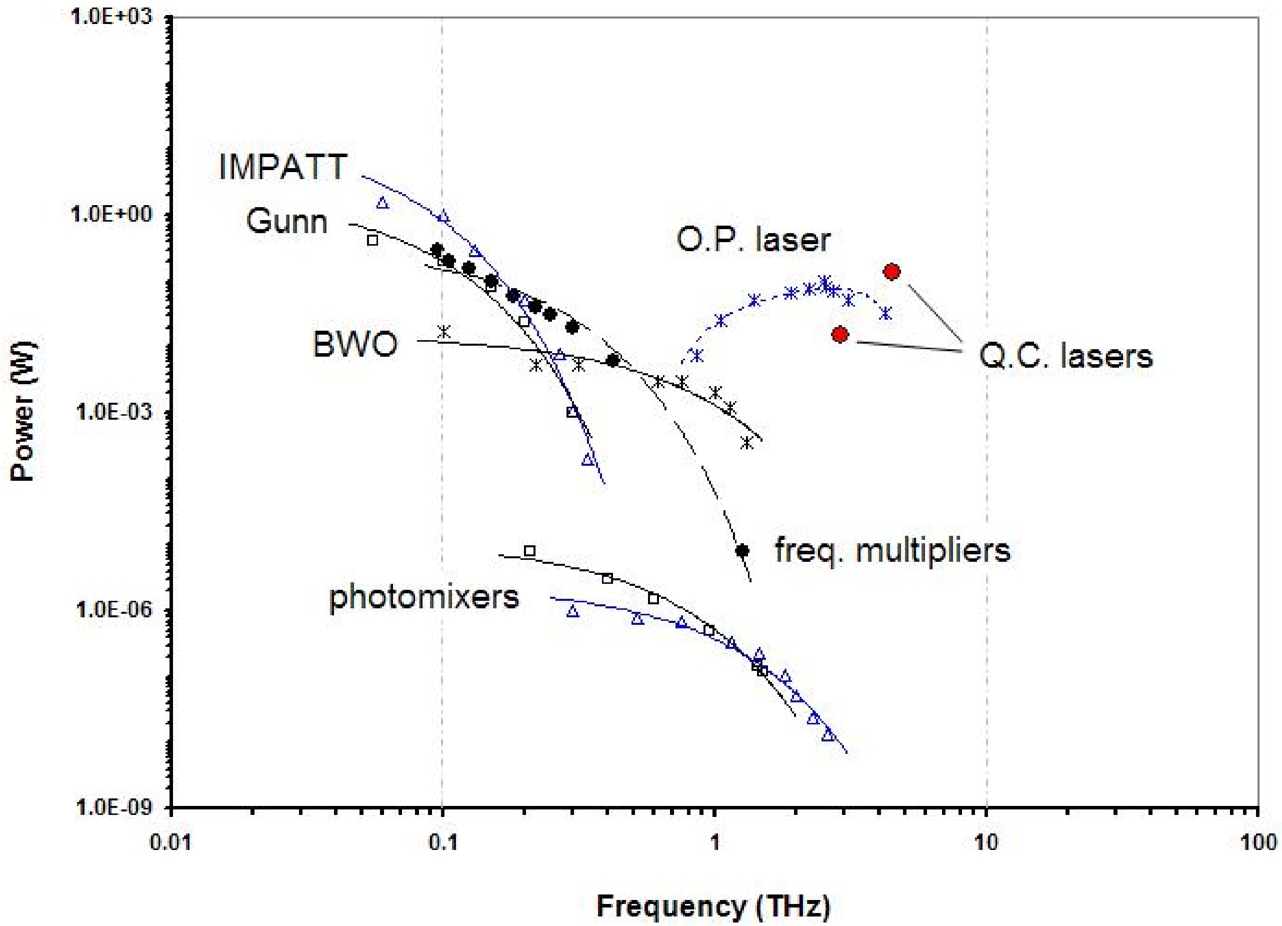
Being replaced by LEDs
Smart Solid State Lighting

From tryshotcode.com/terahertz1.aspx

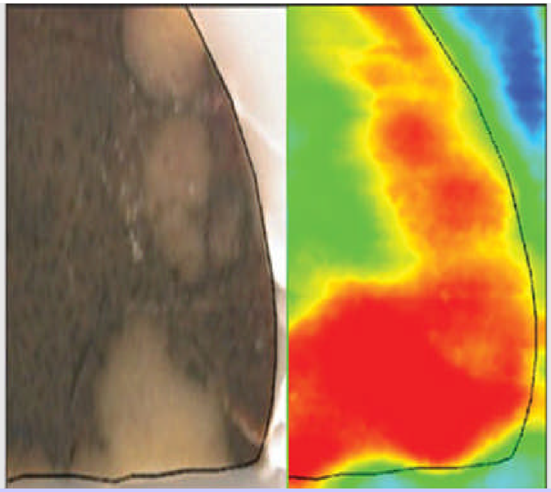


THz gap

From W.J. Stillman and M.S. Shur, Closing the Gap: Plasma Wave Electronic Terahertz Detectors, Journal of Nanoelectronics and Optoelectronics, Vol. 2, Number 3, pp. 209-221, December 2007

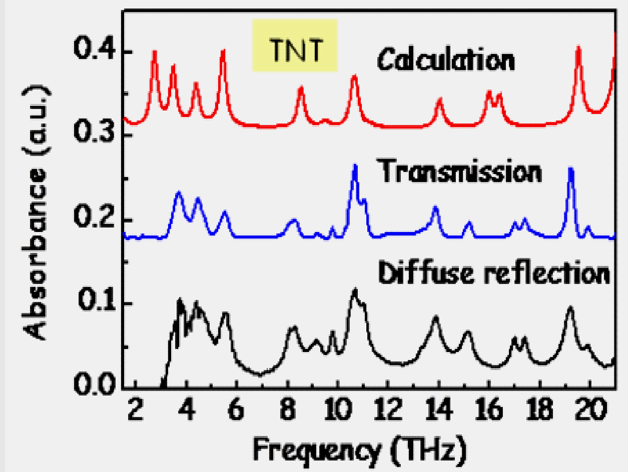


THz Applications



THz cancer detection.[1]

THz applications in dentistry.[2]



Explosive detection using THz radiation.[3]

---

[1] PTBnews: http://www.ptb.de/en/publikationen/news/html/news021/artikel/02104.htm.
[2] BBC News, Monday, June 14, 1999, news.bbc.co.uk/1/hi/sci/tech/368558.stm.
[3] Y. Chen, H. Liu, M.J. Fitch, R. Osiander, J.B. Spicer, M.S. Shur, X.-C. Zhang, "THz diffuse reflectance spectra of selected explosives and related compounds", Passive Millimeter-Wave Imaging Technology VIII. Edited by R.J. Hwa, D.L. Woolard, and M.J. Rosker, Proc. of SPIE, Vol. 5790, p. 19 (2005).

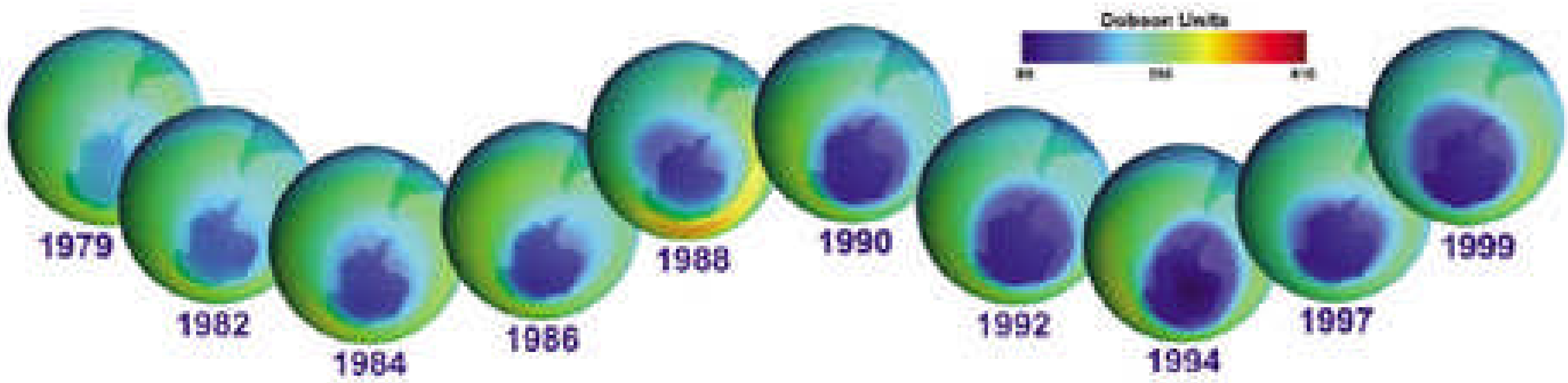
IRAM interferometer (Plateau de Bure, French Alps)

Institute de Radioastronomie Millimetrique

From *Pierre ENCRENAZ & Gérard BEAUDIN* Recent developments in millimeter and submillimeter waves. http://gemo.obspm.fr/ArticleLigne/RecentDvlp.html

- Started in 1985
- 6 antennas of 15 meters diameter
- Wavelength of 1.3 mm (230 GHz)
- Antennas of the IRAM interferometer can move on rail tracks up to a maximum separation of 408 m in the E-W direction and 232 m in the N-S direction
- Resolution of 0.5 arcsecs (resolving an apple at a distance of 30 km).

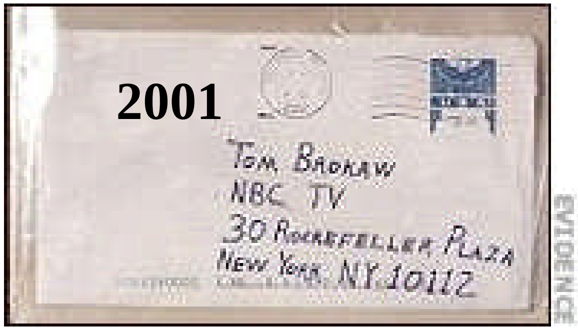
Development of Ozone Hole

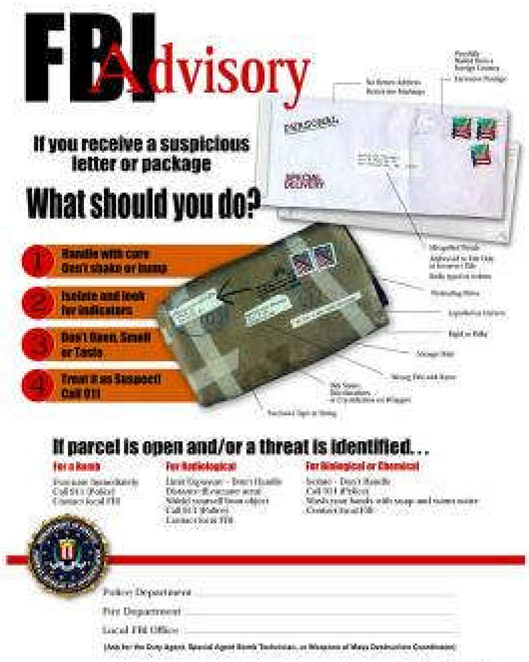


http://science.hq.nasa.gov/missions/satellite_22.htm

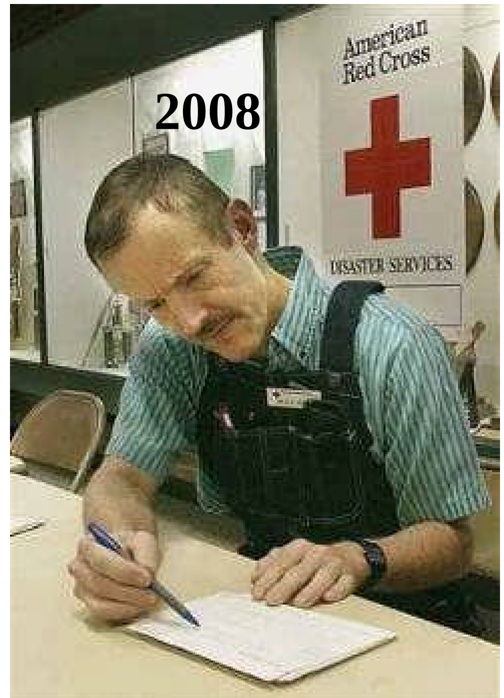
One out of five Americans will develop cancer over their lifetime

THz Applications Biohazard detection





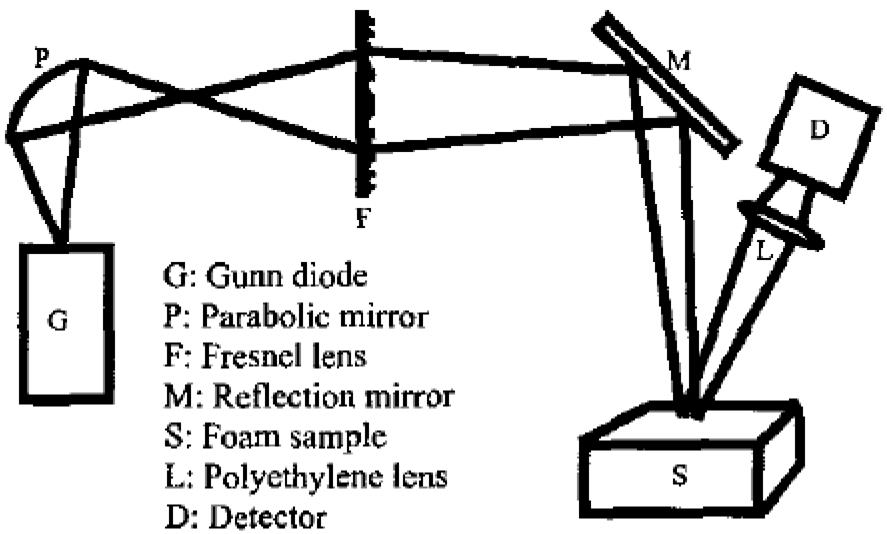
From www.crimelibrary.com/.../anthrax/3.html

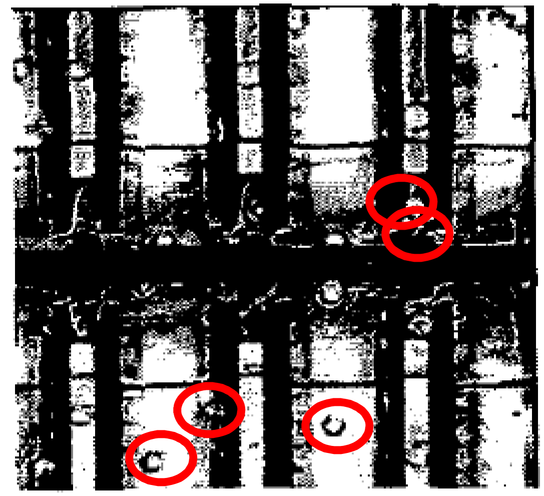


Army scientist Bruce E. Ivins

From http://www.wkrg.com/national/article/suicide_latest_twist_in_7_year_anthrax_saga/16504/

Inspection of Space Shuttle Tiles Using Gunn Diodes



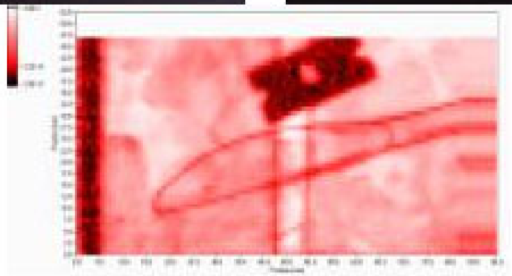


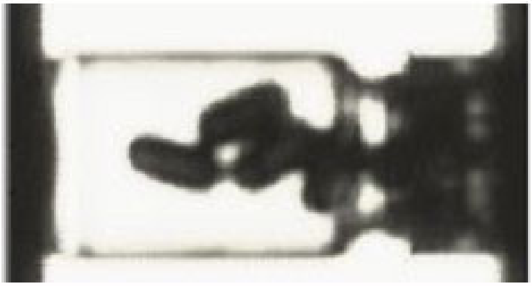
From http://lighthousepatriotjournal.files.wordpress.com/2007/02/phony-shuttle-pic.jpg

From Hua Zhong, N. Karpowicz, Jingzhou Xu, Yanqing Deng, W. Ussery, M. Shur, X.-C. Zhang, Inspection of space shuttle insulation foam defects using a 0.2 THz Gunn diode oscillator, Infrared and Millimeter Waves, 2004 and 12th International Conference on Terahertz Electronics, Conference Digest of the 2004 Joint 29th International Conference, pp.753 - 754

Seeing inside packages

PICOMETRIX
an API company



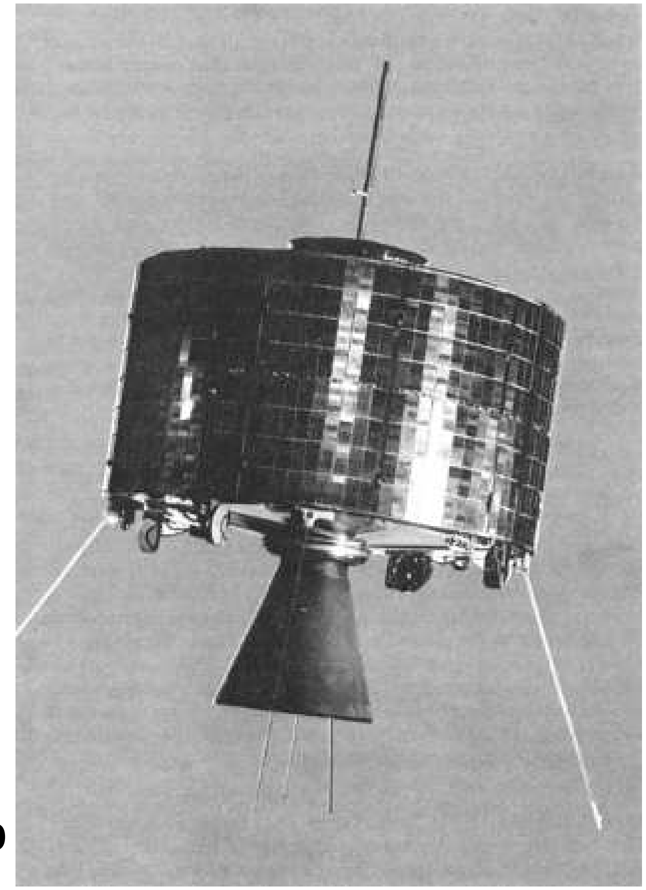


A THz image of a shipping box filled with packing material contained a plastic knife and a razor blade.

Image from:http://www.advancedphotonix.com/ap_products/thz_app_packageimage.asp

THz wireless covert communications

From: http://www.atl.lmco.com/business/ATL7.php



Difficult on Earth (water vapors) – 100's m max?
Possible in above clouds and in space

First generation SYNCOM satellite (NASA image)

High Resolution Imaging (200 micron resolution)

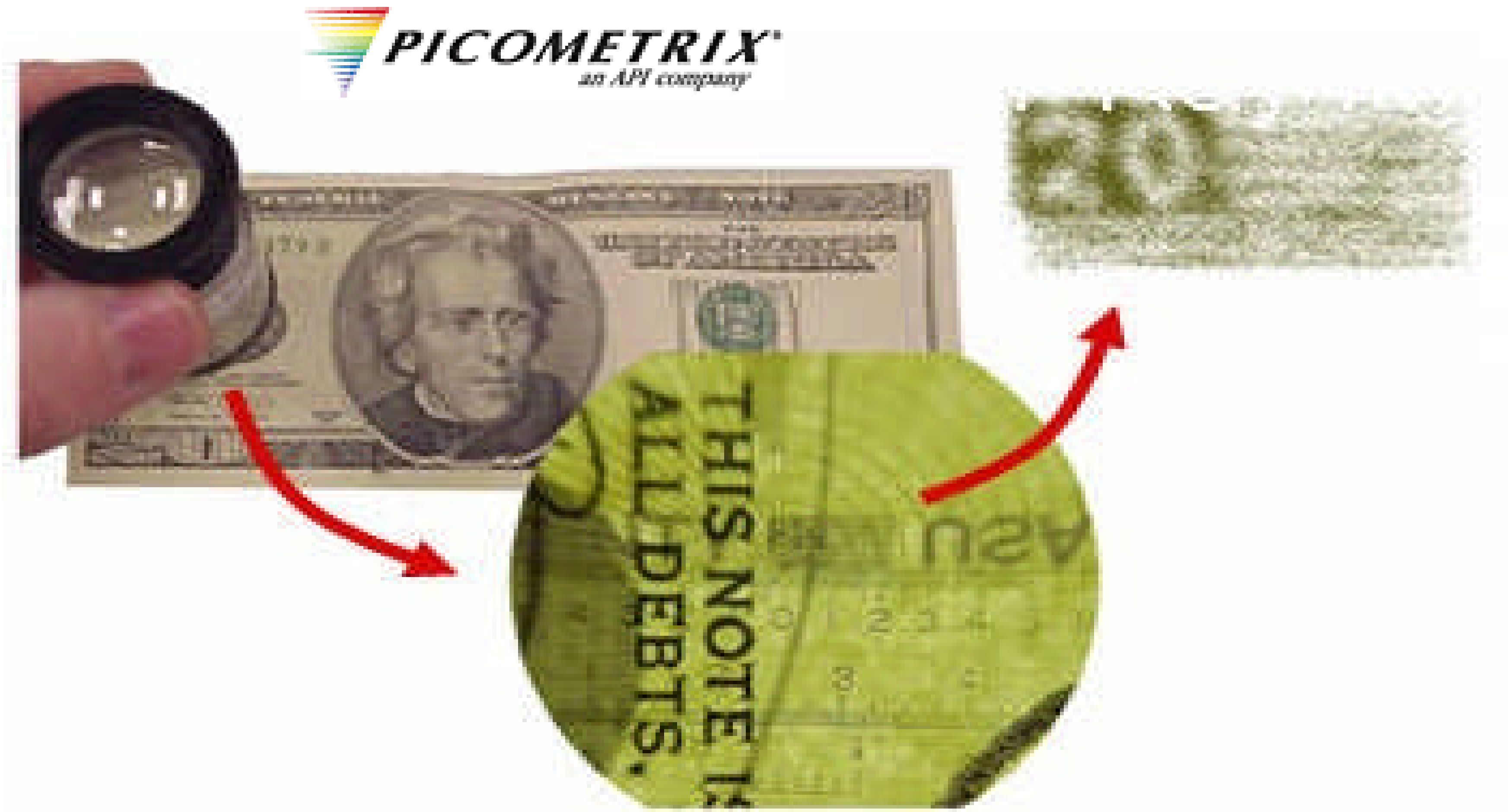
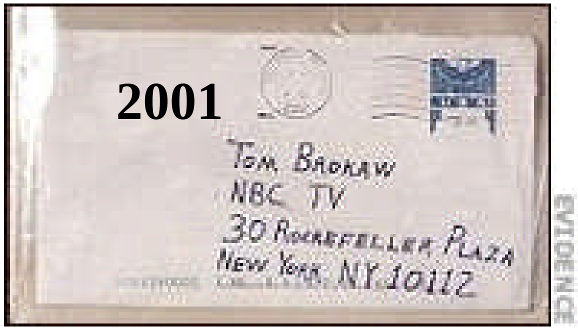
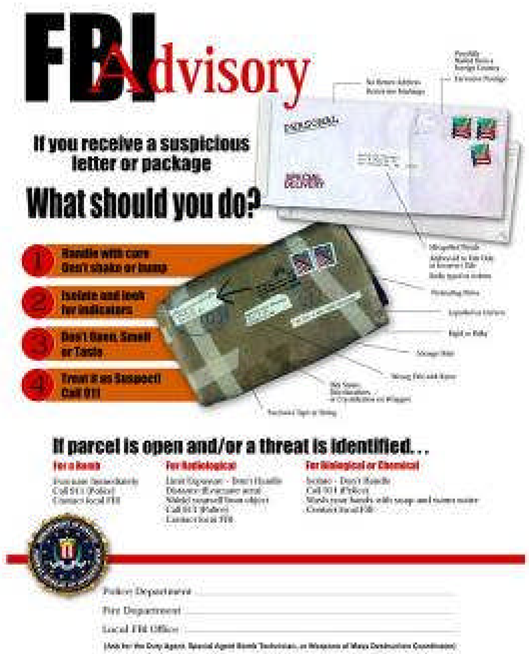


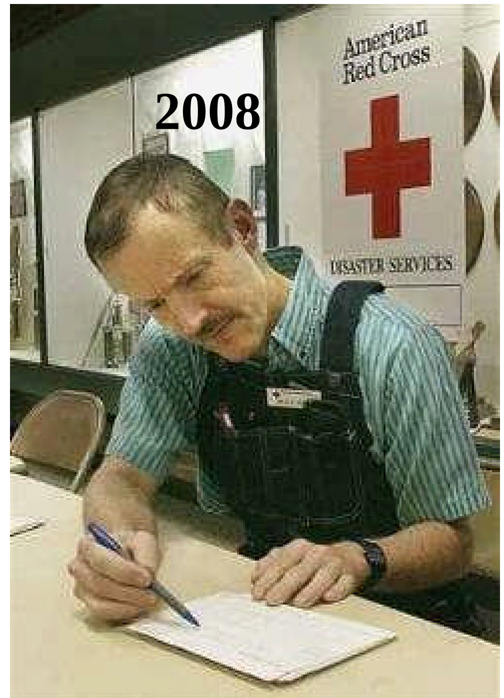
Image from: http://www.advancedphotonix.com/ap_products/thz_app_hiresimage.asp

THz applications





From www.crimelibrary.com/.../anthrax/3.html



Army scientist Bruce E. Ivins

From http://www.wkrg.com/national/article/suicide_latest_twist_in_7_year_anthrax_saga/16504/

THz systems (a) TeraView's TPI imaga 2000: 3D THz imaging system for tablet coatings and cores (b) Picometrix

(a)

(b)

From http://www.pharmaceutical-technology.com/contractor_images/teraview/1s-terraview.jpg

From http://www.advancedphotonix.com/ap_products/terahertz.asp

Compact THz Photonics System –Mini-Z

2007 $30,000 Lemelson-Rensselaer Student Prize.

Brian Schulkin (RPI, graduate student of Professor Zhang) has invented an ultralight, handheld terahertz spectrometer

Room Temperature THz laser

Mikhail Belkin and Federico Capasso

APL, May 19, 2008

A photograph of a bar with 10 terahertz laser sources developed by the Harvard University engineers. One of the lasers is connected to the contact pad (seen on the left) by two thin gold wires. A 2mm-diameter Silicon hyper-hemispherical lens is attached to the facet of the device to collimate the terahertz output. The emission frequency is 5 THz, corresponding to a wavelength of 60 microns. (Credit: Courtesy of the Capasso Lab, Harvard School of Engineering and Applied Sciences)

Harvard University (2008, May 20). First Room-temperature Semiconductor Source Of Coherent Terahertz Radiation Demonstrated. *ScienceDaily*. Retrieved August 29, 2008, from http://www.sciencedaily.com- /releases/2008/05/080519083023.htm

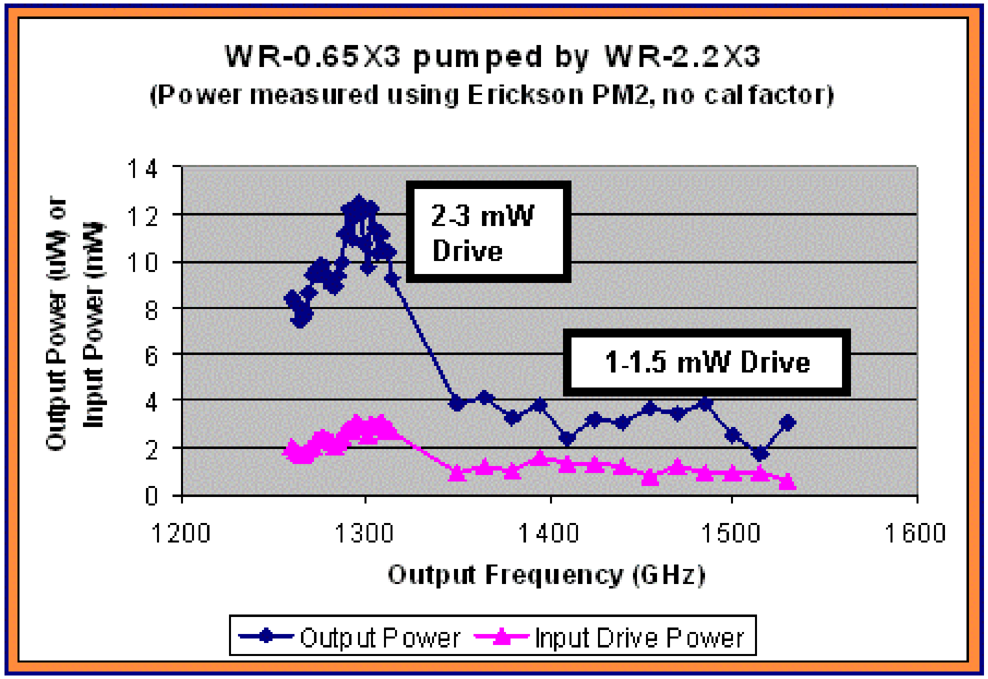
Schottky Diode Tripler $\cos^2(\omega t) = (1+\cos 2\omega t)/2$

VDI Virginia Diodes, Inc.

VDI Model: WR0.65x3

1100-1700 GHz Output, Full-band Frequency Tripler

- 0.3-0.5% Efficiency
- No Bias
- Planar construction
- Input flange: WR-2.0
- Output flange: Feedhorn
- Size: 1.2 x 0.8 x 0.25 inch



Contact VDI today for specifications and quotation details.

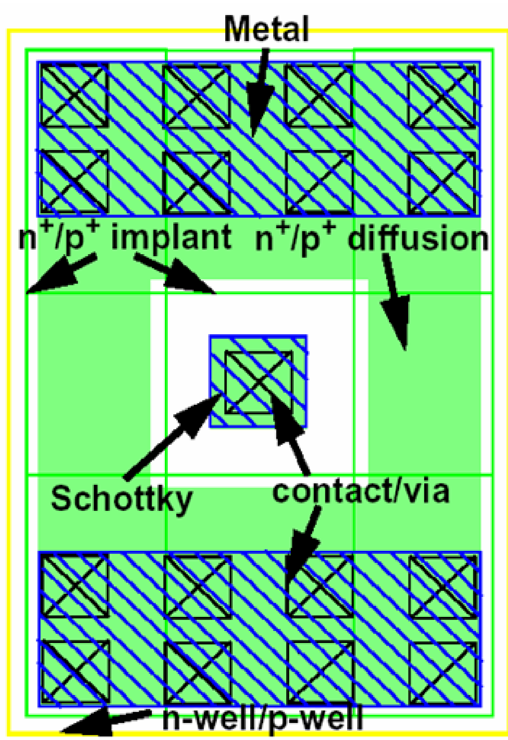
Virginia Diodes, Inc., Ph:434.297.3257, FAX:434.297.3258, www.virginiadiodes.com, VDIRFQ@virginiadiodes.com

Courtesy of Virginia Diodes, Inc. Reproduced with permission

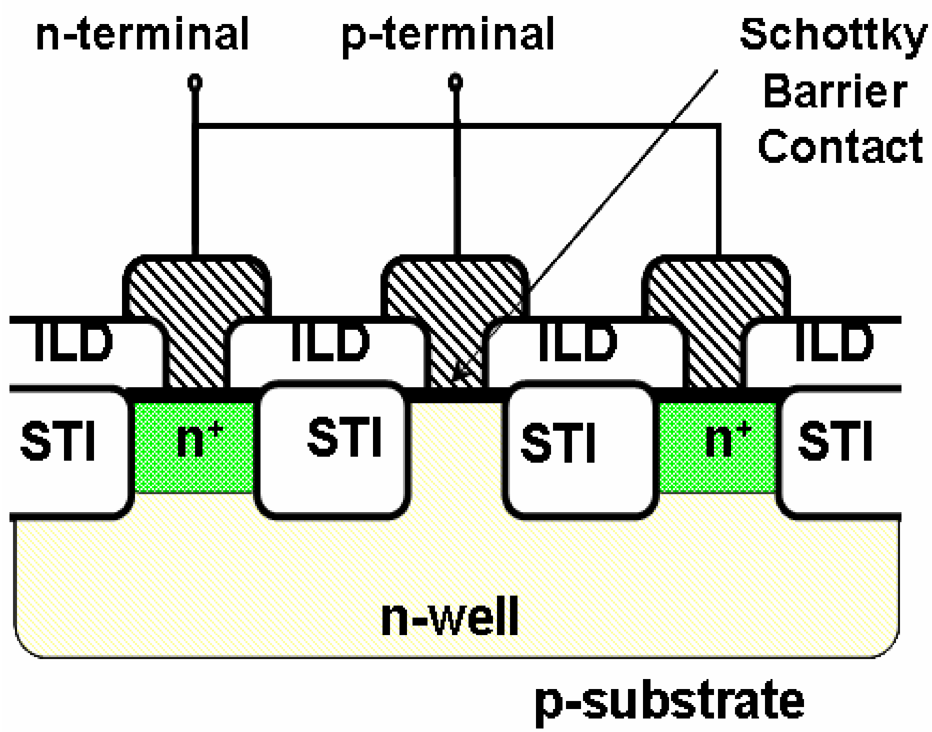
Comparison of high-speed mixer/rectifier diodes (from White Paper for Phiar Corporation, 2003)

	MIM Detector	MIIM Optenna	Whisker-GaAs Schottky	Planar GaAs Schottky
Junction area (cm^2)	1x10-10	1x10-10	5x10-10	N/A
Cutoff frequency	3 THz	9 THz	25 THz	13 THz
Junction capacitance	0.4 fF	0.18 fF	0.25 fF	2 fF
Differential resistance	130 Ω	100 Ω	25 Ω	6 Ω
Ideality factor	>7	~1.5	1.51	1.5
Noise current	20 $pA/Hz^{1/2}$	0.25 $pA/Hz^{1/2}$	30 $pA/Hz^{1/2}$	N/A
Peak Responsivity (A/W)	**~0.5**	**9**	**8**	**N/A**

Mm wave Schottky diode in 0.13 micron process



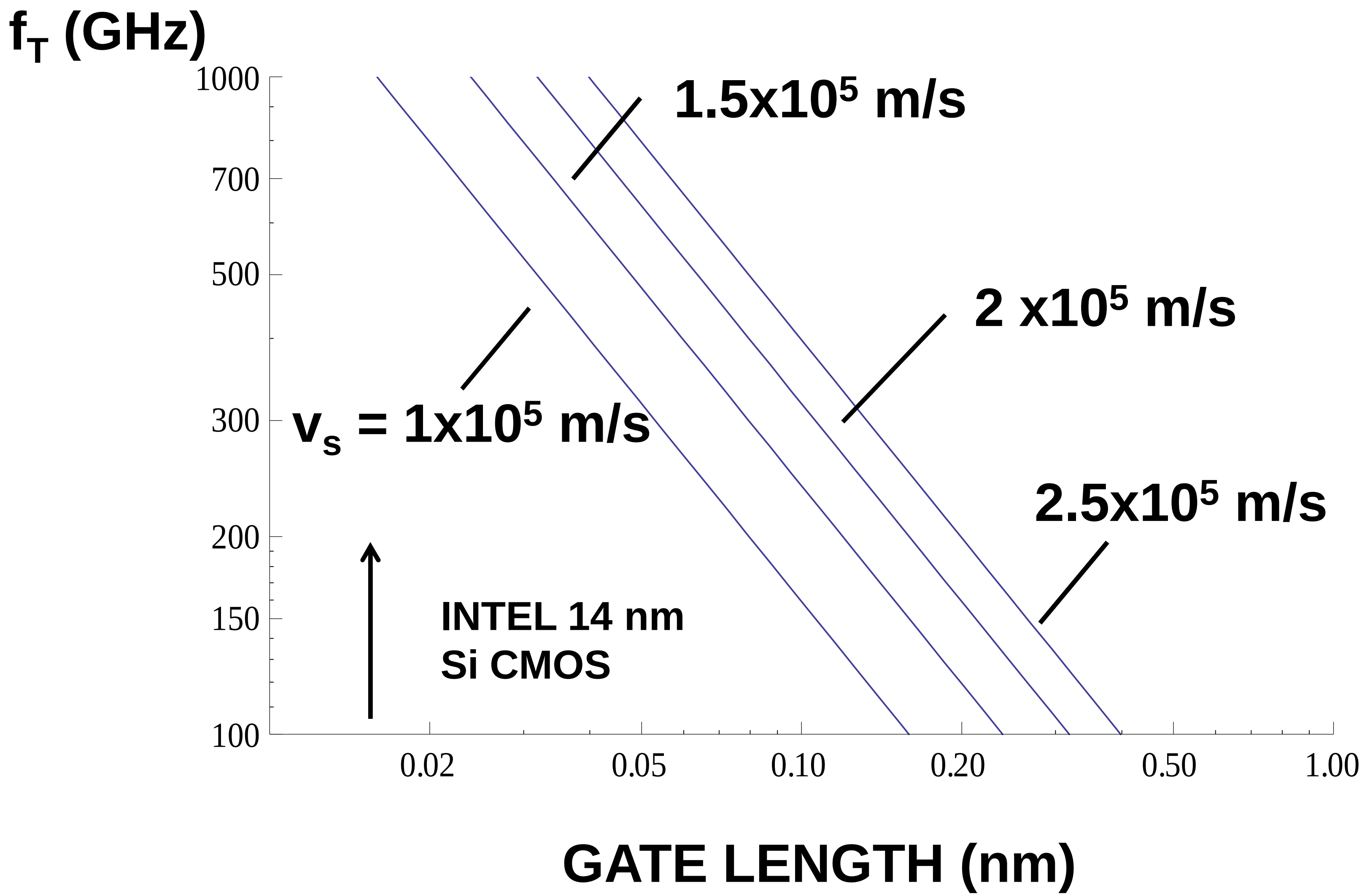
One cell layout



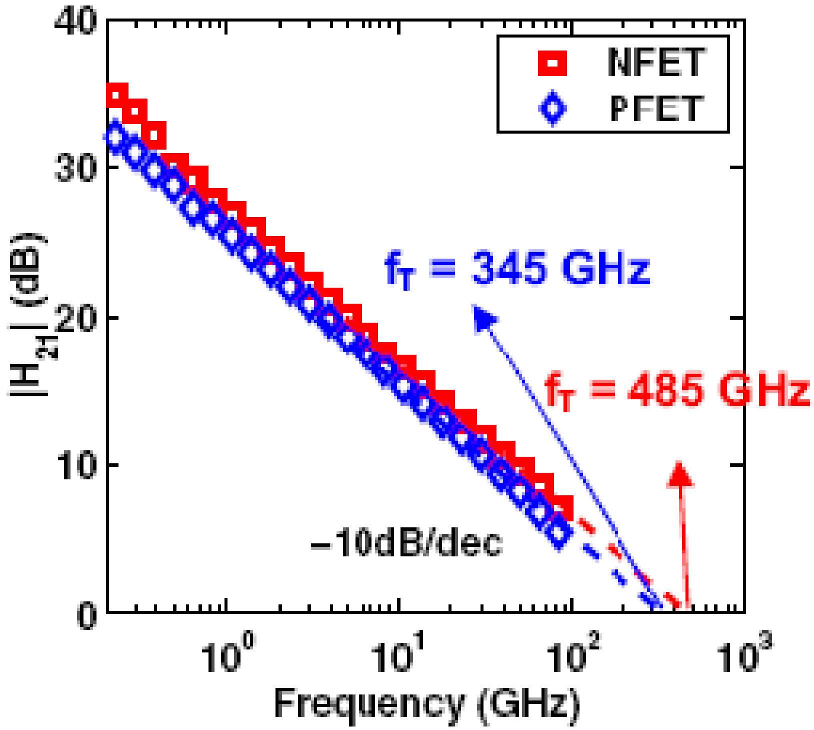
Diode cross section

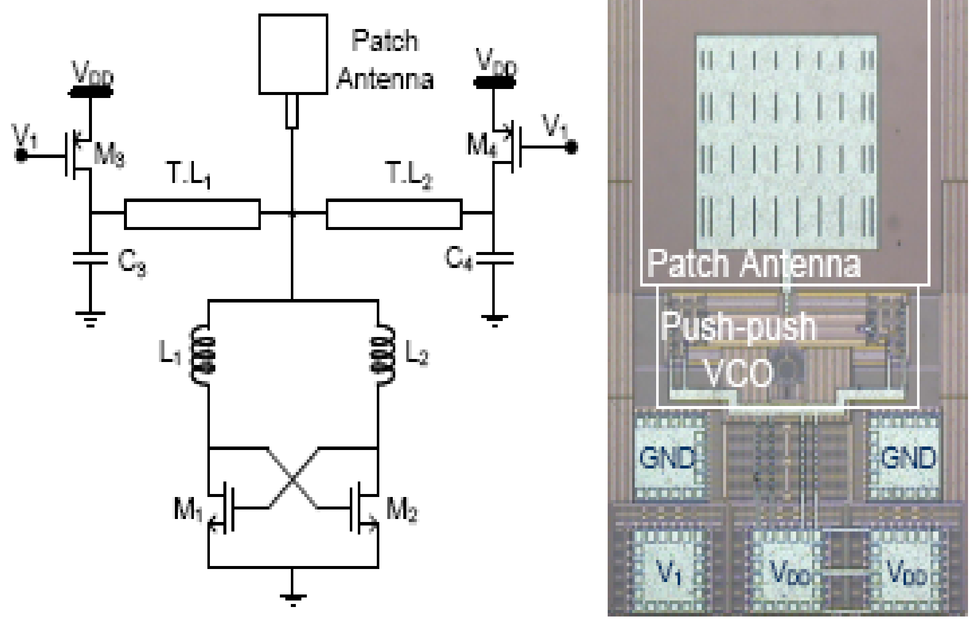
From S. Sankaran, and K. K. O, "Schottky Barrier Diodes for mm-Wave and Detection in a Foundry CMOS Process," *IEEE Elec. Dev. Letts*., vol. 26, no. 7, pp. 492-494, July 2005

FET Cutoff frequency $f_T = 1/(2\pi\tau)$



0.41 THz Si 45 nm CMOS VCO

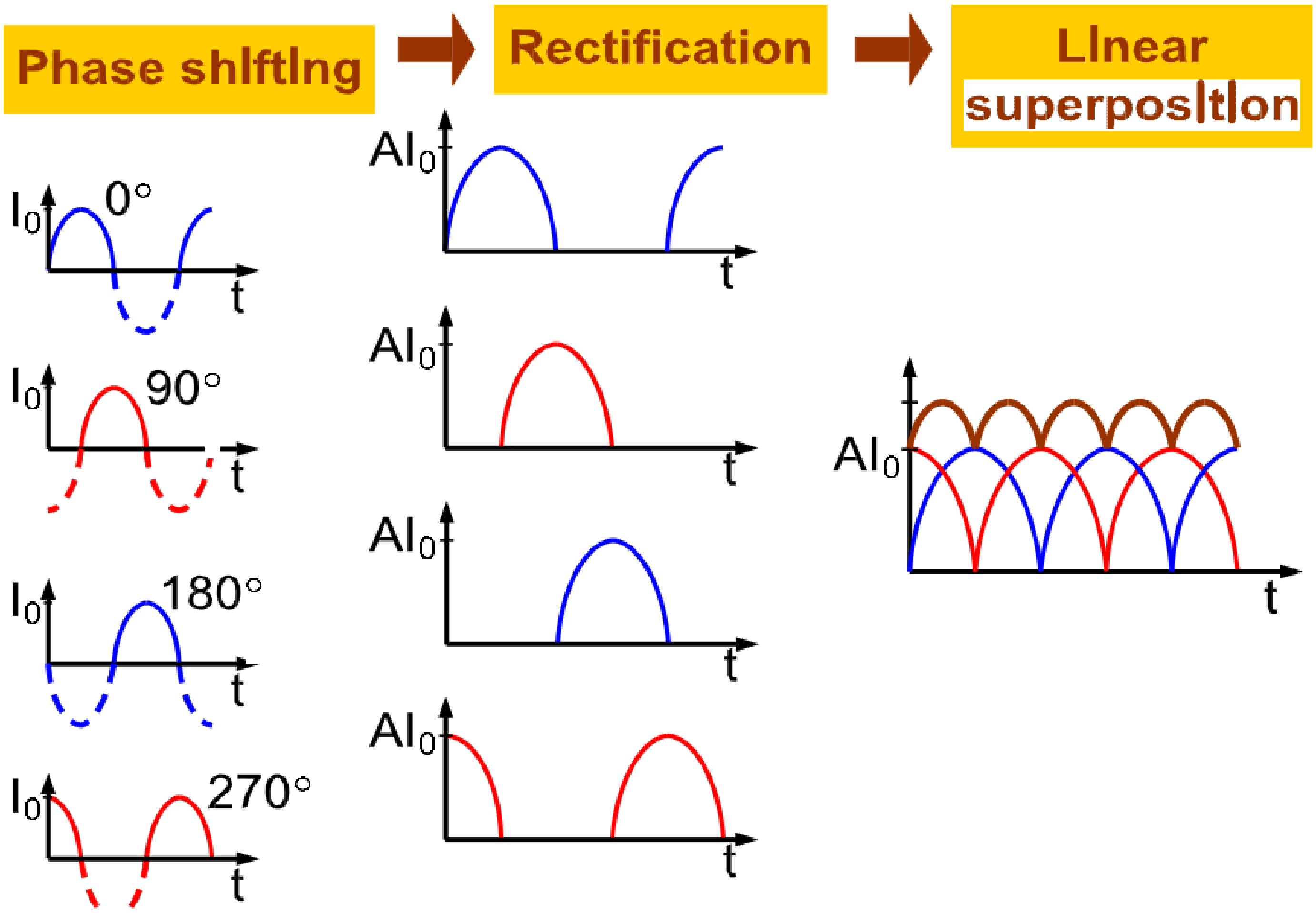




From S. Lee, B. Jagannathan, S. Narasimha, Anthony Chou, N. Zamdmer, J. Johnson, R. Williams, L. Wagner, J. Kim, J.-O. Plouchart, J. Pekarik, S. Springer and G. Freeman, IEDM Technical Digest, p. 225 (2007)

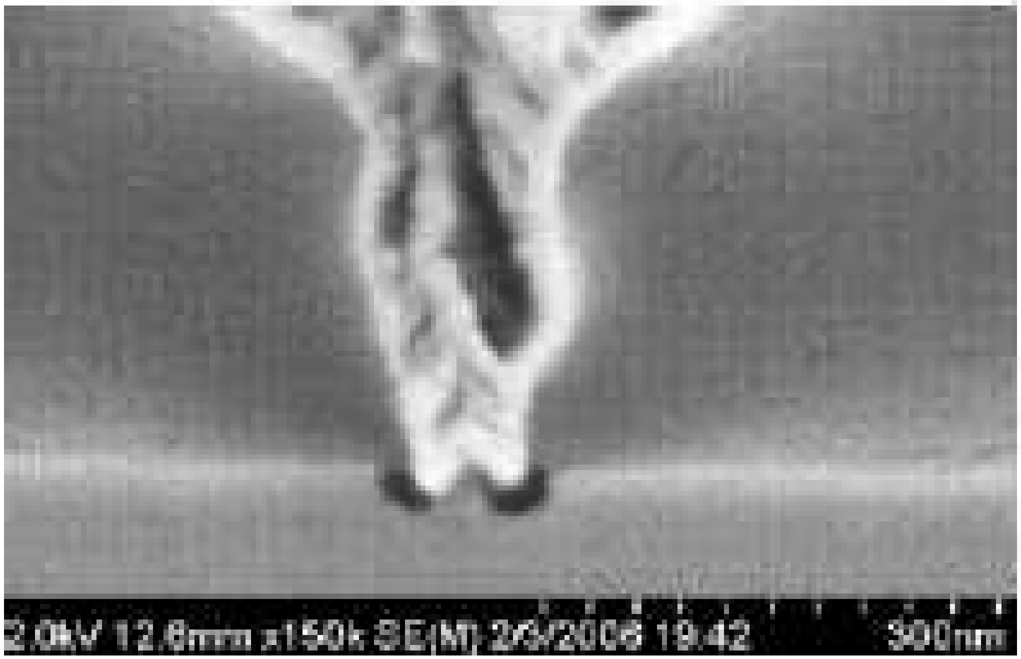
After E. Y. Seok et al., "410-GHz CMOS Push-push Oscillator with a Patch Antenna," *2008 International Solid-State Circuits Conference,* pp. 472-473, Feb. 2008, San Francisco, CA

Linear Superposition



After Daquan Huang; LaRocca, T.R.; Chang, M.-C.F.; Samoska, L.; Fung, A.; Campbell, R.L.; Andrews, M.; IEEE Journal of Solid-State Circuits, Vol. 43 Issue:12, pp. 2730 – 2738, Dec. 2008

Northrop Grumman f_{max} is higher than 1 THz



From R. Lai, X. B. Mei, W.R. Deal, W. Yoshida, Y. M. Kim, P.H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, A. Fung, Sub 50 nm InP HEMT Device with Fmax Greater than 1 THz, IEDM Technical Digest, p. 609 (2007)

InGaAs/InP Based HEMT

35 nm gate device cross section

Solid-State Amplifiers for Terahertz Electronics

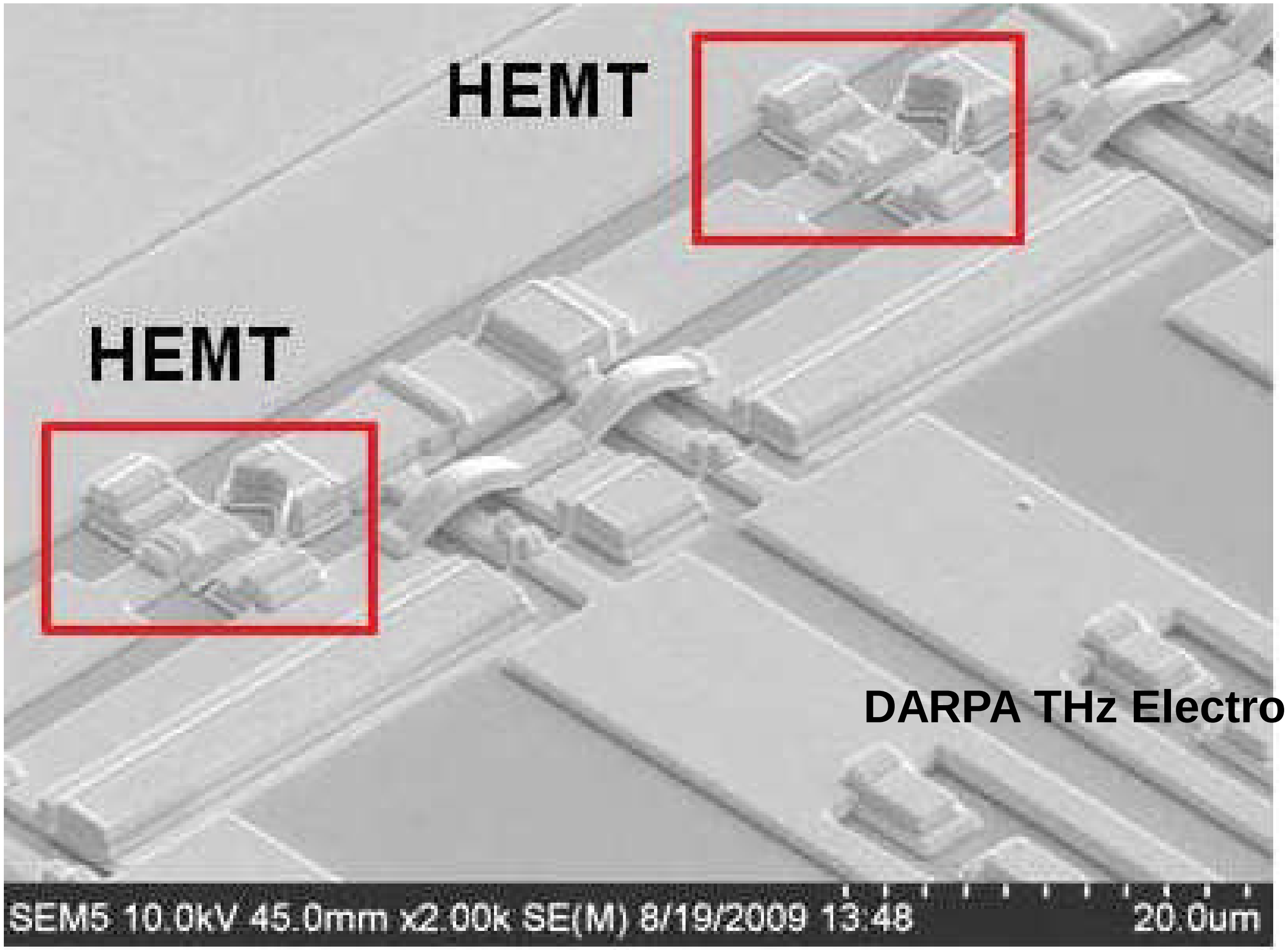
W.R. Deal, V. Radisic, D. Scott, X.B. Mei

Northrop Grumman Aerospace Systems, Redondo Beach, CA, 90278, USA

	InP HEMTs		InP HBTs	
	Current	Next Gen	Current	Next Gen
Feature Size	50 nm gate	30 nm gate	250 nm emitter	150 nm emitter
fT	**0.55 THz**	0.69 THz(projected)	**0.53 THz**	0.64 THz (projected)
fMAX	**>1 THz**	>1.2THz(projected)	**> 0.63 THz**	>1.2THz (projected)
Highest IC	**0.48 THz**		**0.32 THz**	

DARPA THz Electronics Program

SEM showing detail from a prototype 670 GHz integrated circuit utilizing 10 um transistors.

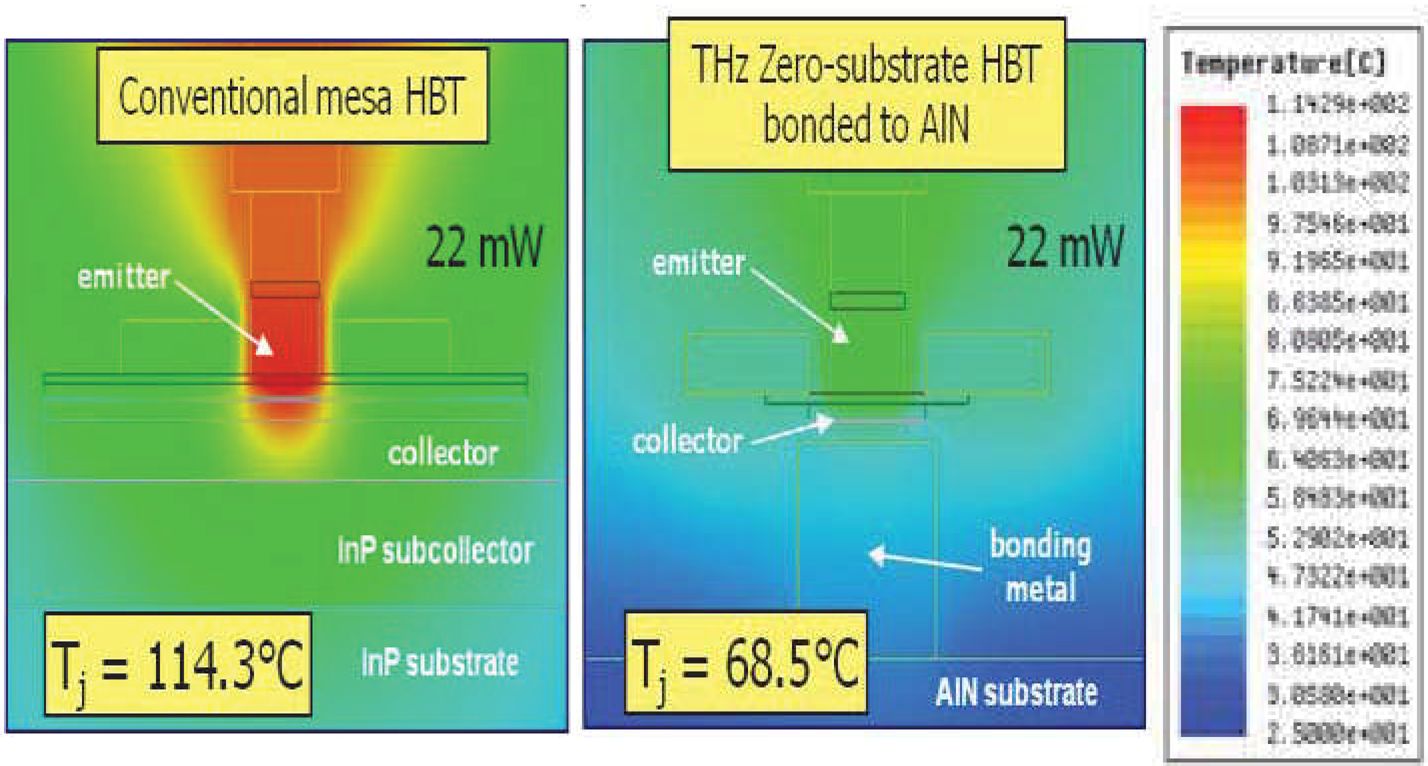


DARPA THz Electronics Program

From Solid-State Amplifiers for Terahertz Electronics

W.R. Deal, V. Radisic, D. Scott, X.B. Mei Northrop Grumman Aerospace Systems, Redondo Beach, CA, 90278, USA

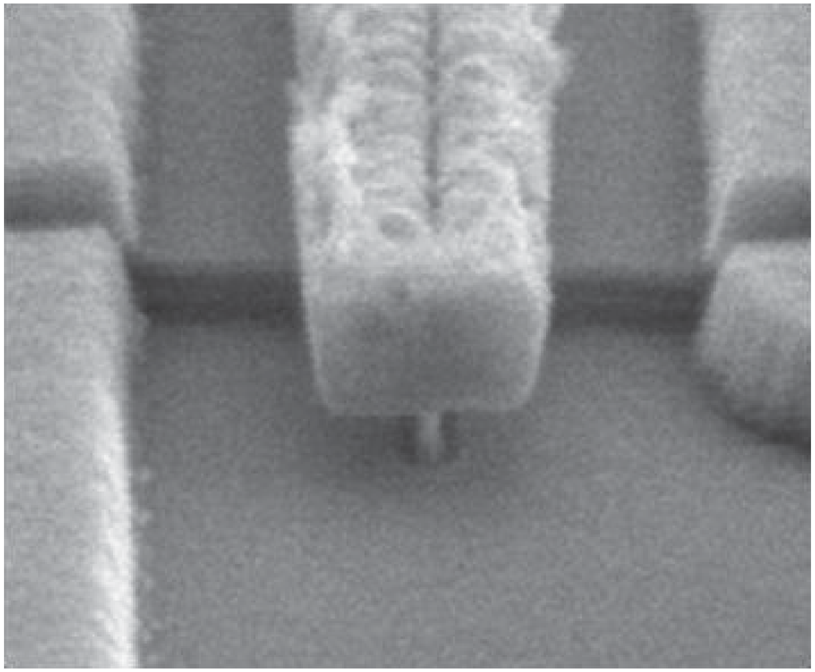
Temperature Reduction



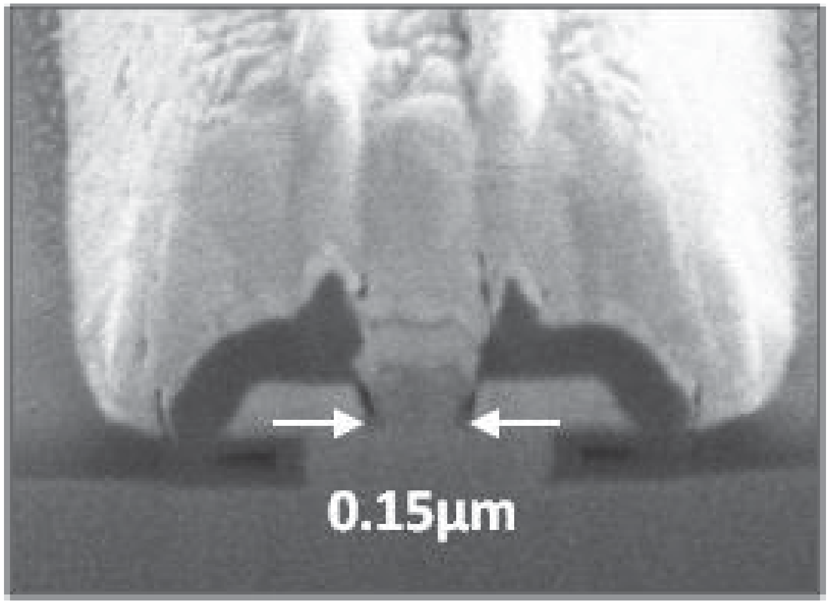
From Solid-State Amplifiers for Terahertz Electronics
W.R. Deal, V. Radisic, D. Scott, X.B. Mei Northrop Grumman Aerospace Systems, Redondo Beach, CA, 90278, USA

DARPA THz Electronics Program

SEM Images



30 nm InP HEMT

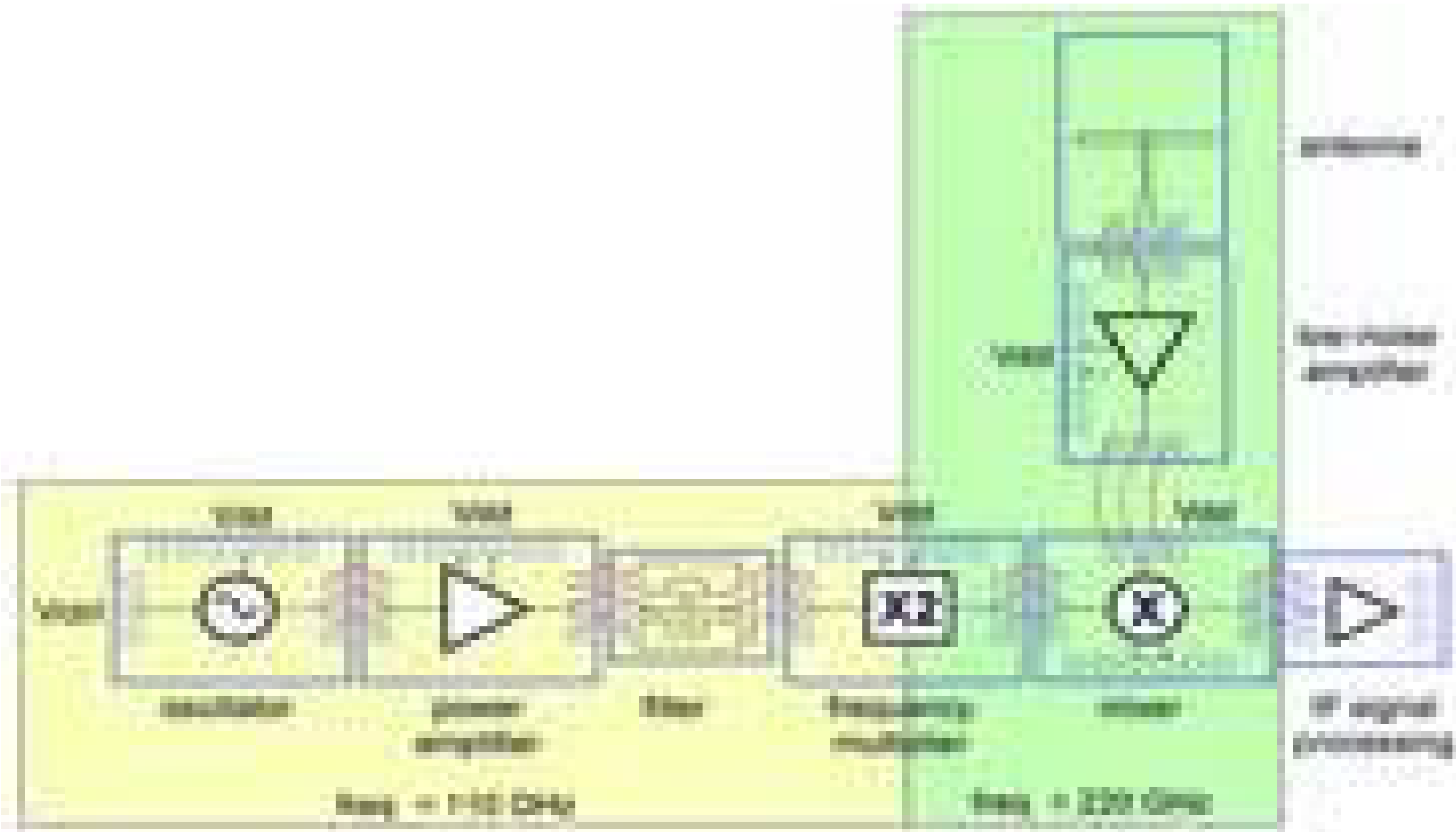


150 nm InP HBT

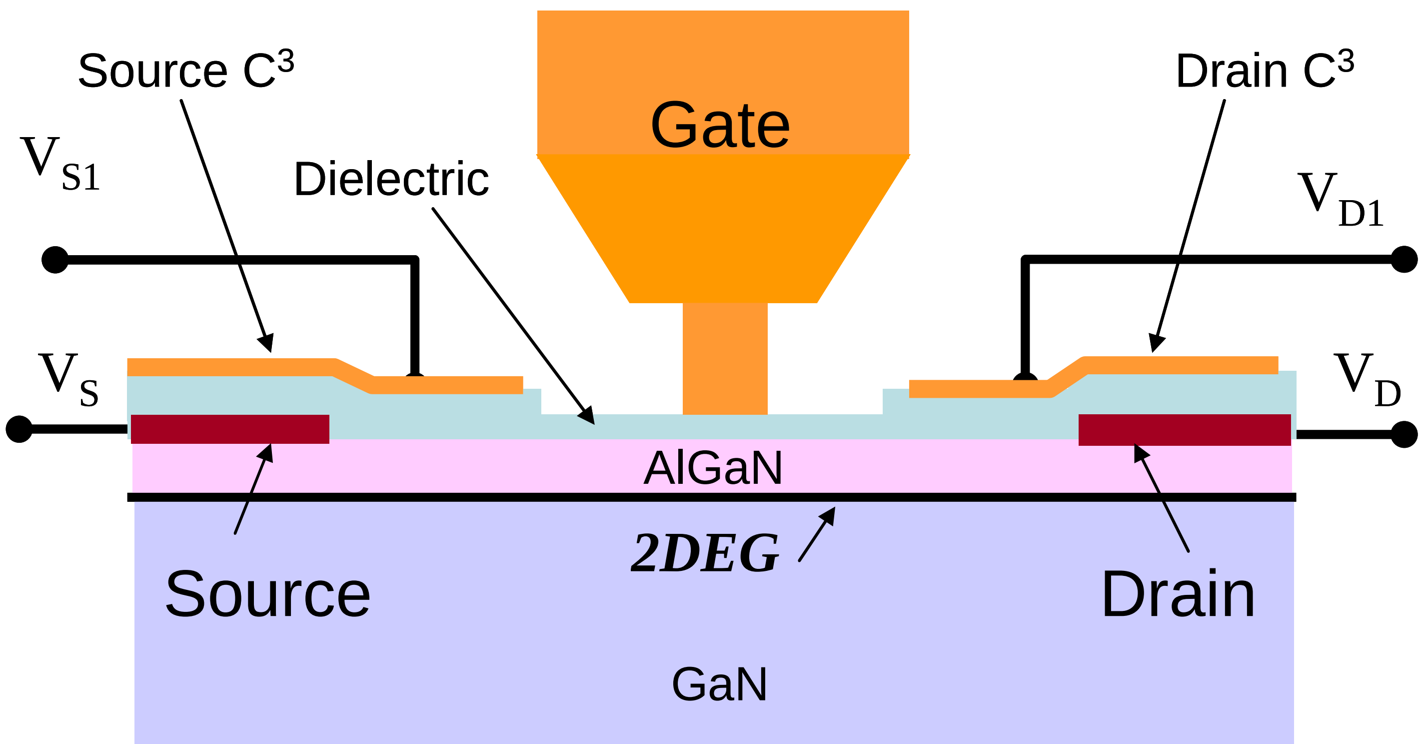
DARPA THz Electronics Program

From Solid-State Amplifiers for Terahertz Electronics
W.R. Deal, V. Radisic, D. Scott, X.B. Mei Northrop Grumman Aerospace Systems, Redondo Beach, CA, 90278, USA

500 GHz HBT Technology
(**from** Terahertz Electronics : Ferdinand-Braun Institut, Prof. Victor Krozer)



Five-terminal AlGaN/GaN MOSHFET with additional biased capacitively coupled contacts



From G. Simin, M. Shur and R. Gaska, IJHSES Vol. 19, No. 7–14, 1 (2009)

Ballistic Transport

M. S. Shur and L. F. Eastman (1979)

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-26, NO. 11, NOVEMBER 1979 124 1677

Ballistic Transport in Semiconductor at Low Temperatures for Low-Power High-Speed Logic

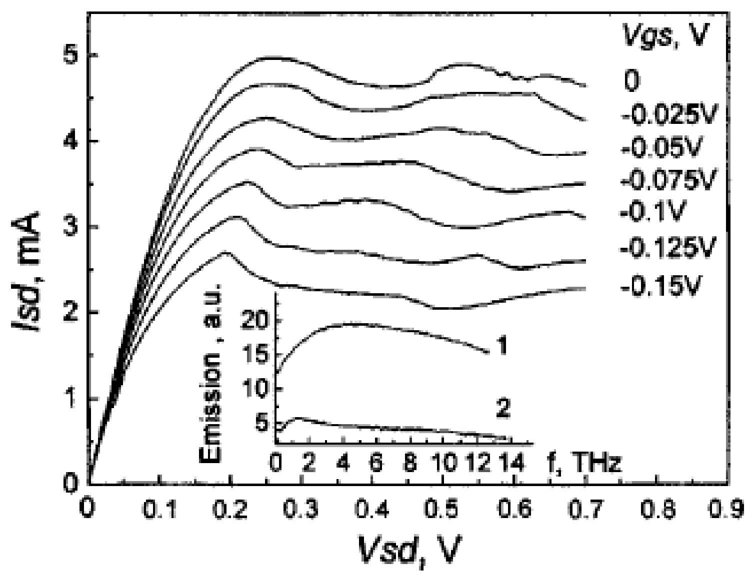
Ballistic Transistor Has Virtually Unimpeded Current Flow (Dec. 6, 1999)

From http://www.bell-labs.com/news/1999/december/6/1.html

Intel is buiding a 14-nm Si CMOS foundry

This will make all Si transistors to be ballistic

Ballistic I-Vs look "Normal"



InGaAs 60 nm gate (emitting THz radiation)

From N. Dyakonova, F. Teppe, J. Lusakowski, W. Knap, M. Levinshtein, V. Kachorovskii, A. Dmitriev, M. S. Shur, S. Bollaert, and A. Cappy, Magnetic field effect on the terahertz emission from nanometer InGaAs/AlInAs high electron mobility transistors, J. Appl. Phys. 97, 114313 (2005)

Plasma wave electronics

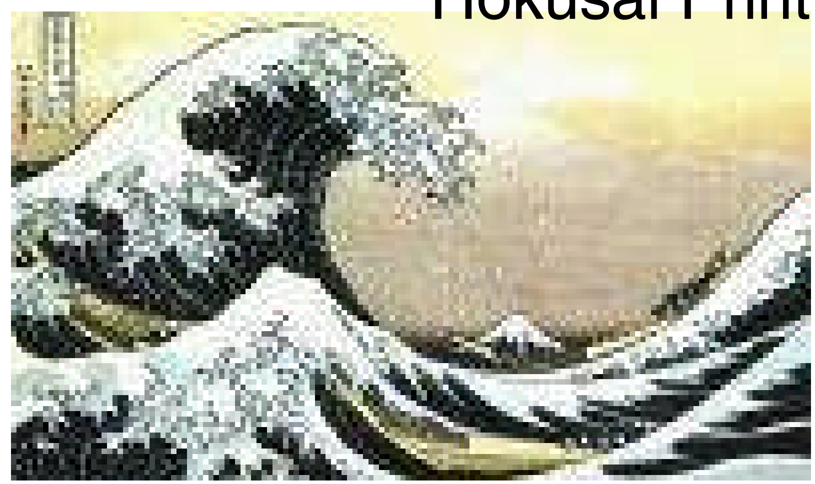
- Plasma wave instability (Dyakonov-Shur instability) can be used for generation of THz radiation**)

- Nonlinearity of plasma wave excitations can be used for THz detection*)

ω =s k   s ~ 10^6 m/s

Lg ~ 10^-8 – 10^-6 m but λ~ 3 10^-4 m

Hokusai Print



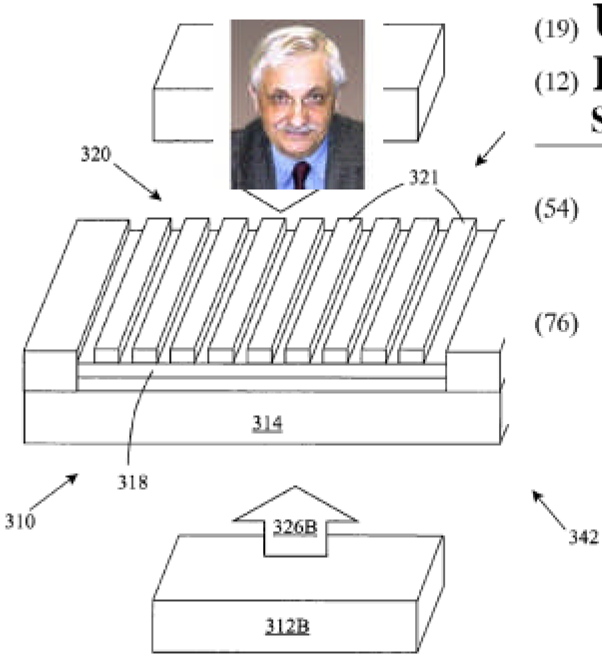
Water wave analogy

*)M. Dyakonov and M. S. Shur, IEEE Trans. Elec. Dev. 43, 380 (1996)

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

THz Oscillator Array (Photonic Excitation)

Proposal to use arrays for emission:
M. I. Dyakonov and M. S. Shur, Plasma Wave Electronics: Novel Terahertz Devices using Two Dimensional Electron Fluid, IEEE Transactions on Electron Devices, Vol. 43, No. 10, pp. 1640-1646, October (1996)



(19) **United States**
(12) **Patent Application Publication** (10) **Pub. No.: US 2004/0201076 A1**
Shur et al. (43) **Pub. Date: Oct. 14, 2004**

(54) **METHOD OF RADIATION GENERATION AND MANIPULATION**

(76) Inventors: **Michael Shur**, Latham, NY (US); **Victor Ryzhii**, Aizu-Wakamatsu City (JP); **Remigijus Gaska**, Columbia, SC (US)

Related U.S. Application Data

(60) Provisional application No. 60/461,100, filed on Apr. 8, 2003.

Publication Classification

(51) **Int. Cl.**^{7} **H01L 31/06**; H01L 21/331

Patent Filed April 8 2003
Patent allowed July 8 2009

THz Oscillator Array (electronic of photonic) 2004

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2006/0081889 A1**

Shur et al. (43) **Pub. Date: Apr. 20, 2006**

(54) **DEVICE AND METHOD FOR MANAGING RADIATION**

(76) Inventors: **Michael Shur**, Latham, NY (US); **Remigijus Gaska**, Columbia, SC (US)

Correspondence Address:
HOFFMAN WARNICK & D'ALESSANDRO, LLC
75 STATE STREET
14TH FL
ALBANY, NY 12207 (US)

(21) Appl. No.: **11/111,541**

(22) Filed: **Apr. 21, 2005**

Related U.S. Application Data

(60) Provisional application No. 60/565,351, filed on Apr. 26, 2004.

Publication Classification

(51) **Int. Cl.**
H01L 29/768 (2006.01)

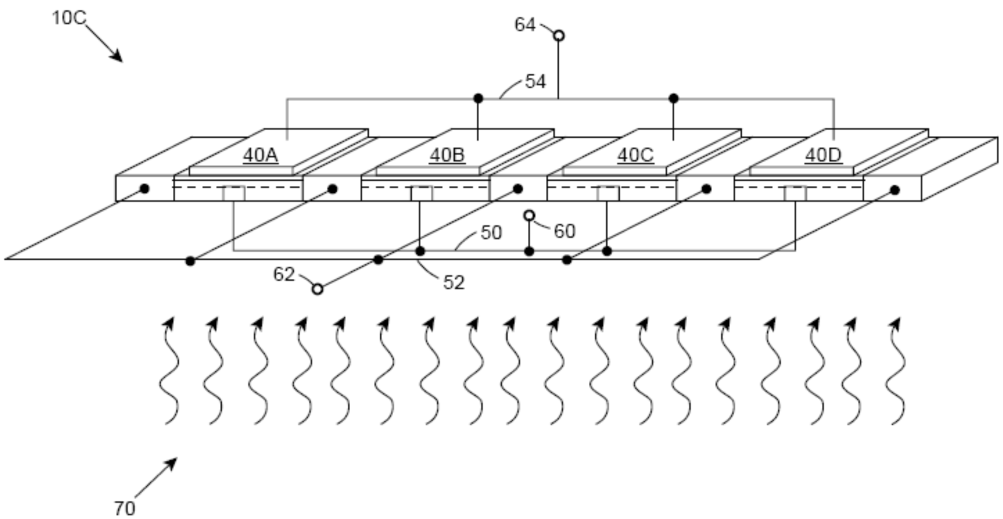
(52) **U.S. Cl.** **257/221**

(57) **ABSTRACT**

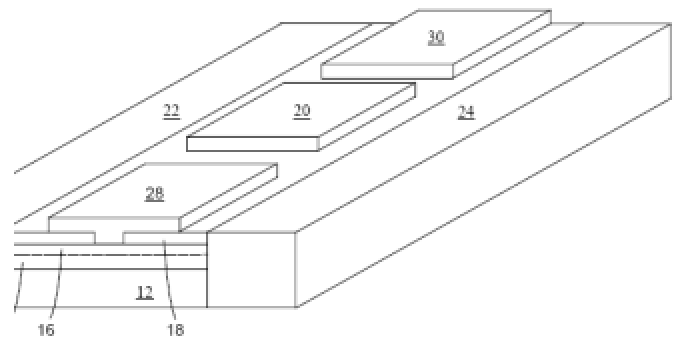
A device and method for managing terahertz and/or microwave radiation are provided. The device can comprise one or more field effect transistors (FETs) that each include at least one channel contact to a central region of the device channel of the FET. The frequency of the radiation managed by the device can be tuned/adjusted by applying a bias voltage to the FET. The radiation can be impinged on the device, and can be detected by measuring a voltage that is induced by the radiation. Further, the device can generate terahertz and/or microwave radiation by, for example, inducing a voltage between two edge contacts on either side of the device channel and applying the voltage to the channel contact.

1D and 2D arrays (Publication US 2006/0081889)

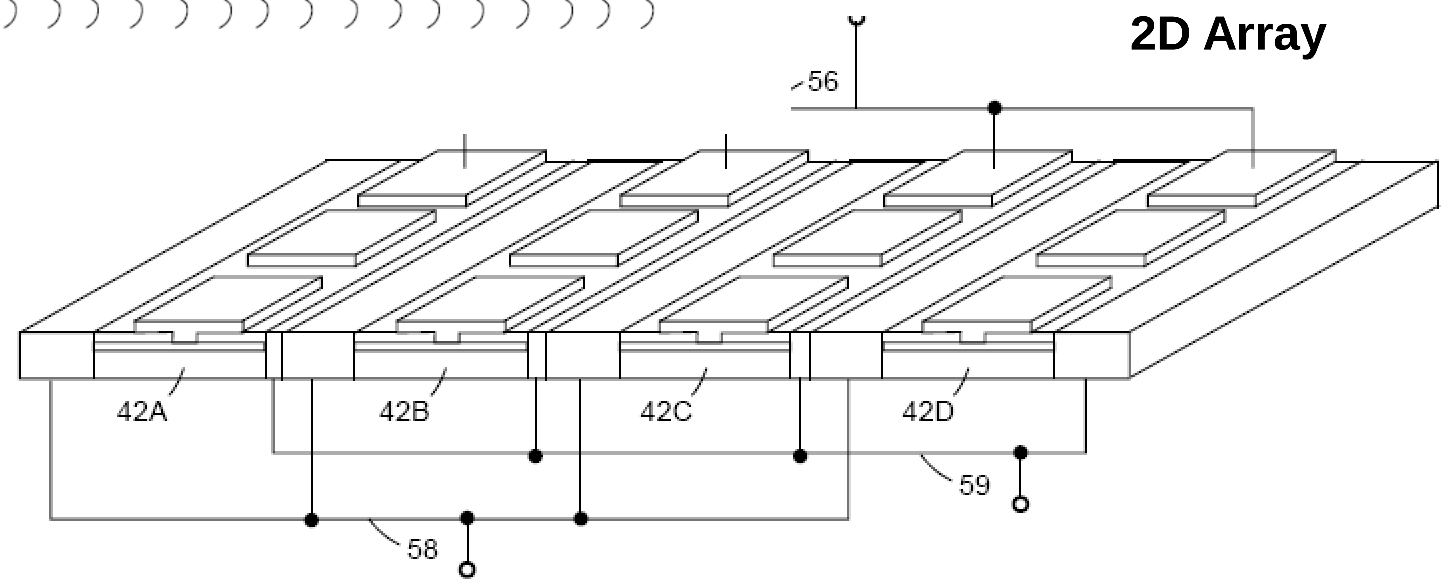
Regular Array



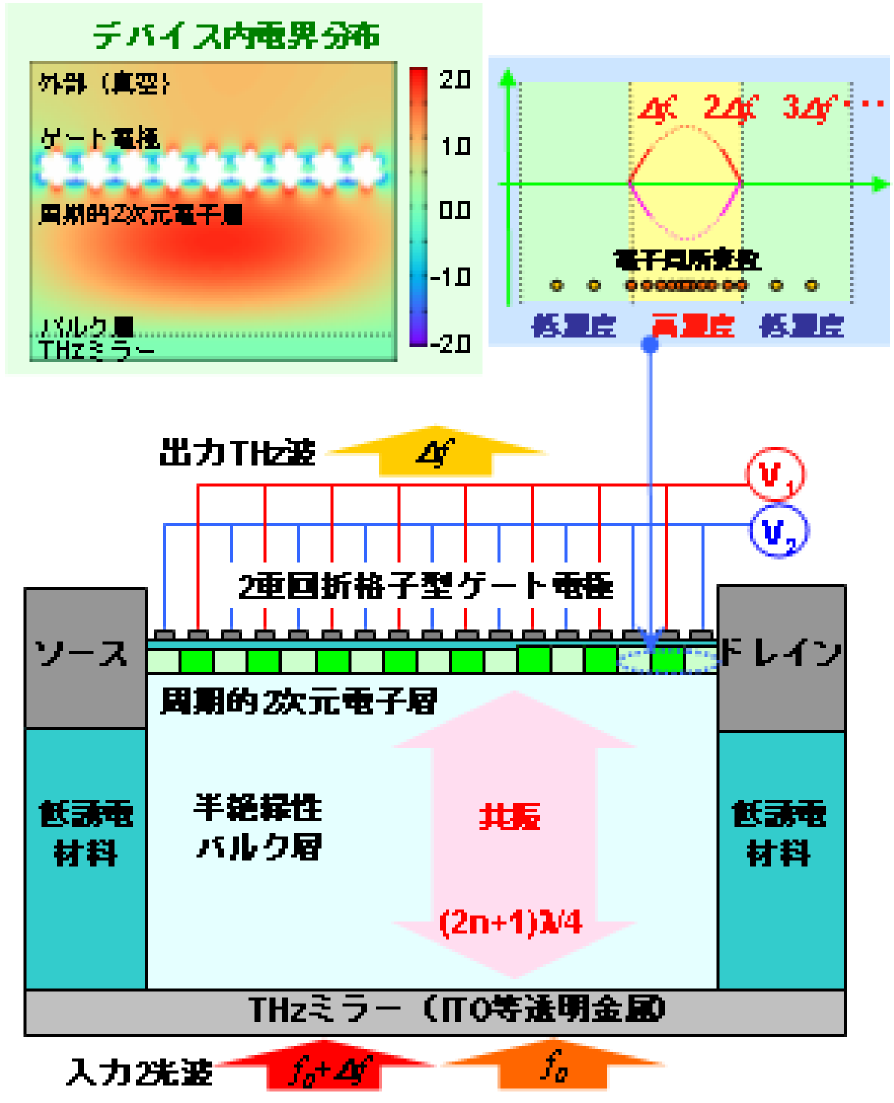
"Sectioned" Gate



2D Array



Prof. Otsuji Plasmonic Array Devices

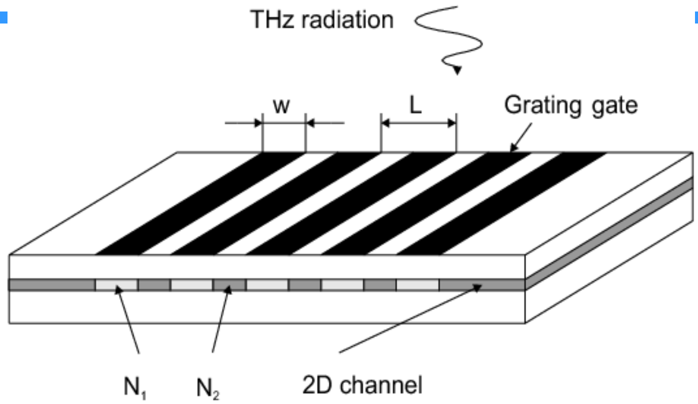


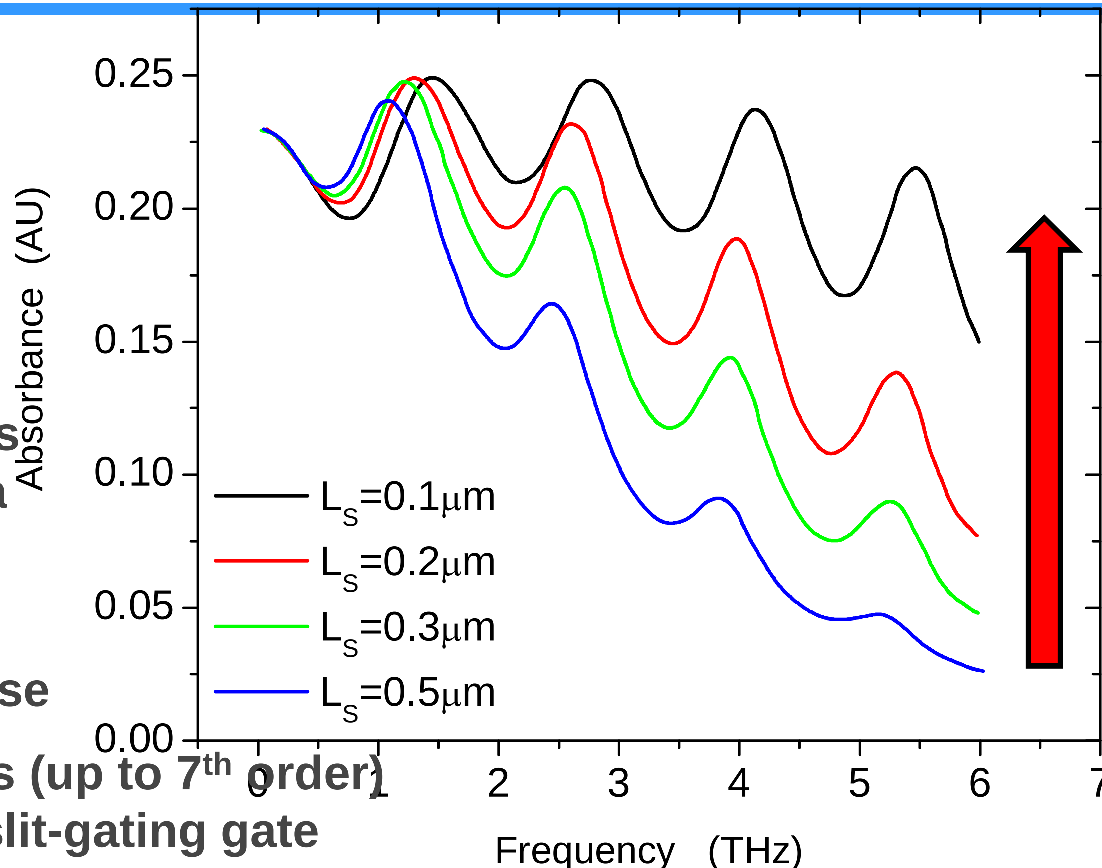
プラズマ共鳴フォトミキサー（PRX）

2004

2009 IEEE
Sensors Conference

Grating Gate Devices and FET Arrays



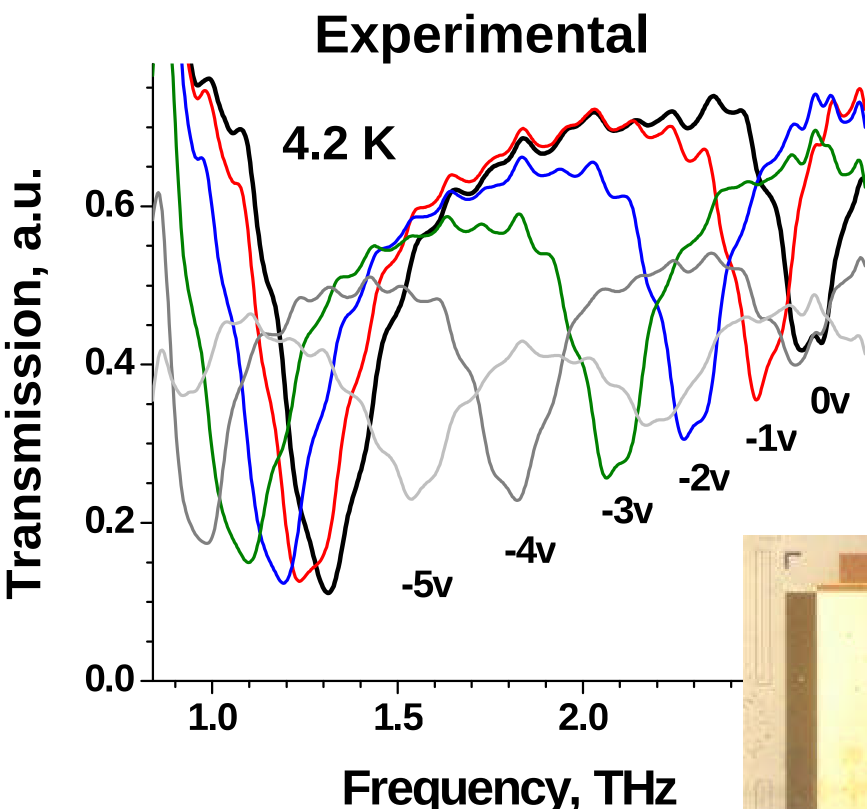


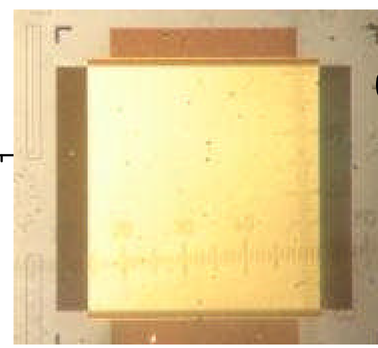
- grating-gate of a large area serves as an aerial matched THz antenna
- due to constructive interference between the gates the plasmons in all FET-units are excited in phase
- higher-order plasmon resonances (up to 7th order) can be effectively excited with a slit-gating gate due to strong electric-field harmonics generated in slits

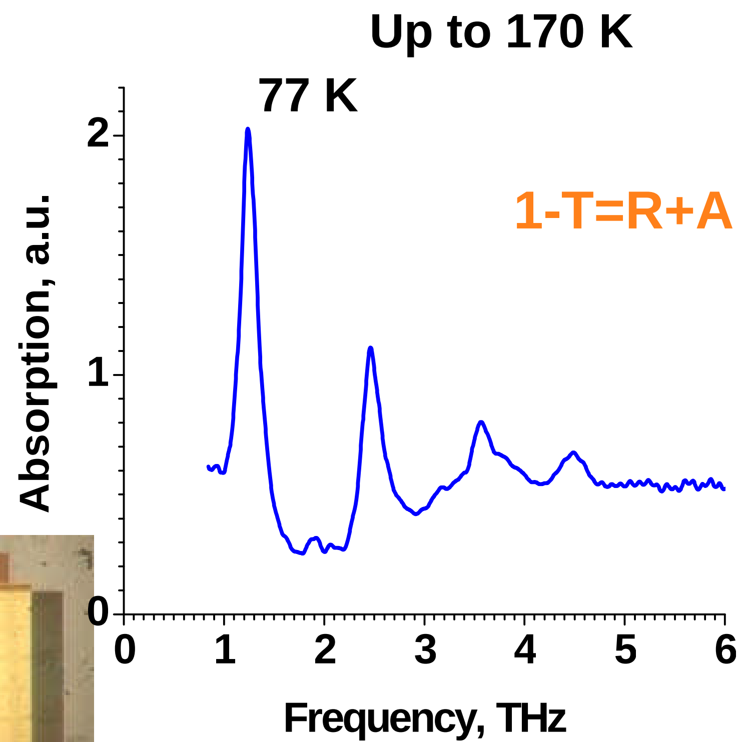
Plasmon absorption in a slit-grating gate device is 10^3 times stronger than in array of non-interacting FET units

V. Popov, M. Shur, G. Tsymbalov, D. Fateev, Inter. Jr. High Speed Electronics and Systems, September 2007

Transmission spectra of grating-gate GaN structure at at different gate biases

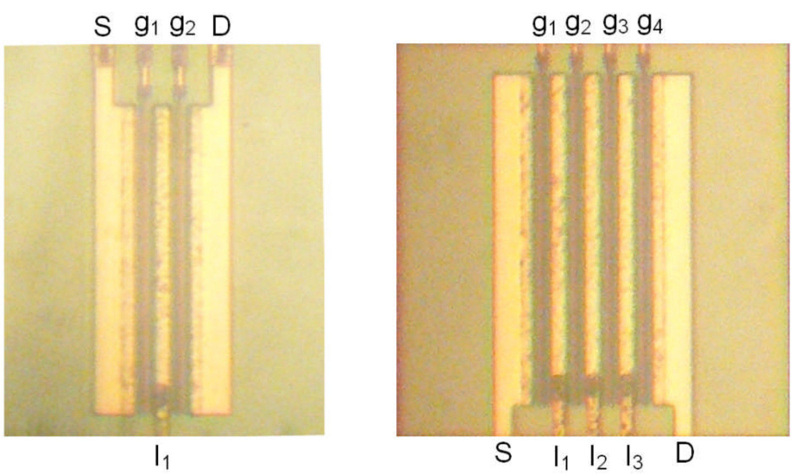




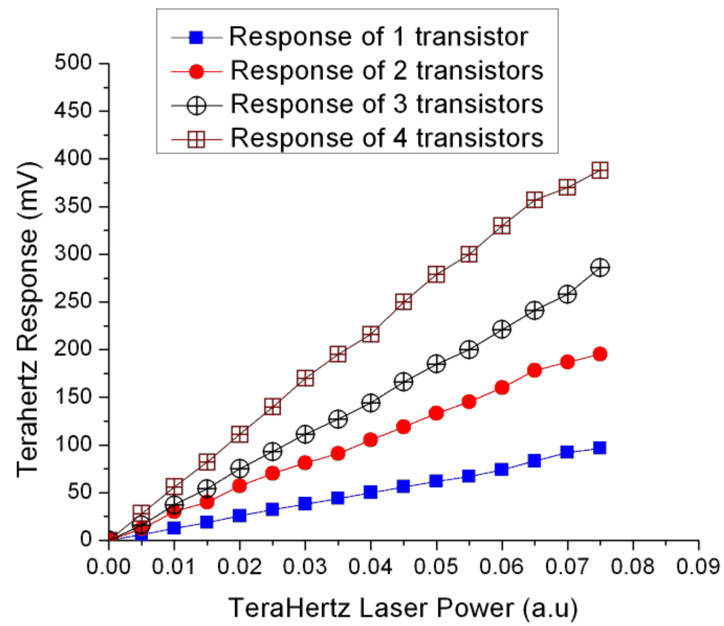


A.V. Muravjov, D.B. Veksler, V.V. Popov, O. Polischuk, X. Hu, R. Gaska, N. Pala, H. Saxena, R.E. Peale, M.S. Shur, Temperature dependence of plasmonic terahertz absorption in grating-gate GaN HEMT structures, to be submitted to APL, 2009

Multiple Plasmonic Detectors Connected in Series



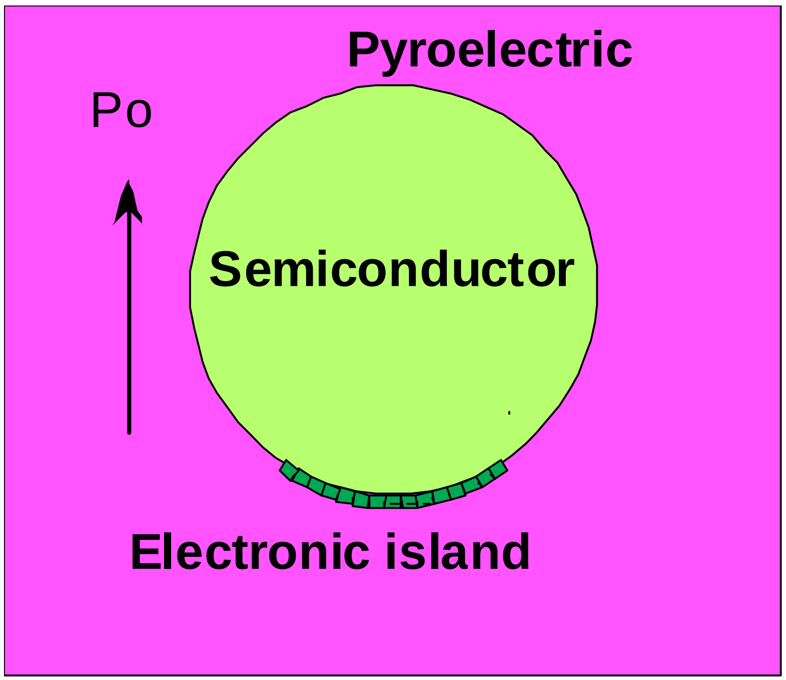
(a) (b)

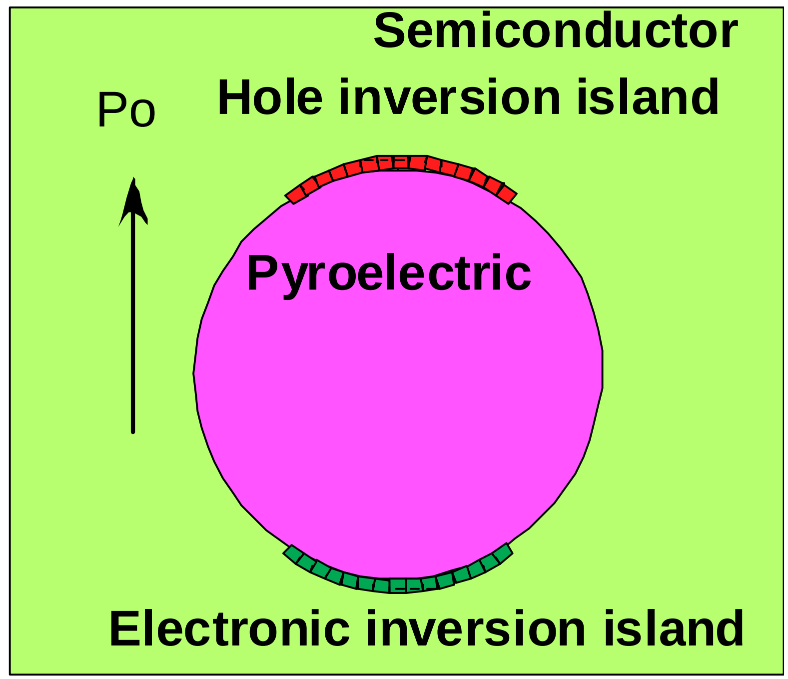


T. A. Elkhatib, D. B. Veksler, K.N. Salama, Xi-C. Zhang, and M. S. Shur. Enhanced Terahertz Detection using Multiple GaAs HEMTs Connected in Series, Microwave Symposium Digest, MTT'09, MTT-S International, pp. 937-940, (2009)

Electronic island at the surface of semiconductor grain in pyroelectric matrix

Inversion electron and hole islands at the surface of pyroelectric grain in semiconductor matrix



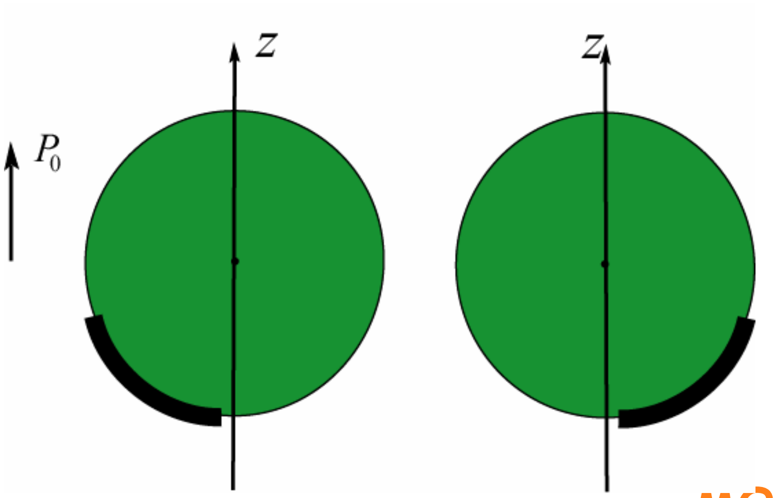


Control by external field – Zero dimensional Field Effect (ZFE)

After V. Kachorovskii and M. S. Shur, APL, March 29 (2004)

Terahertz oscillations

2D island might oscillate as a whole over grain surface.
The oscillations can be exited by AC field perpendicular to Po



Oscillation frequency

$$\omega_0 = \sqrt{\frac{4\pi e P_0}{(\varepsilon + 2\varepsilon_p) m R}}$$

MOVABLE QUANTUM DOTS (MQD)

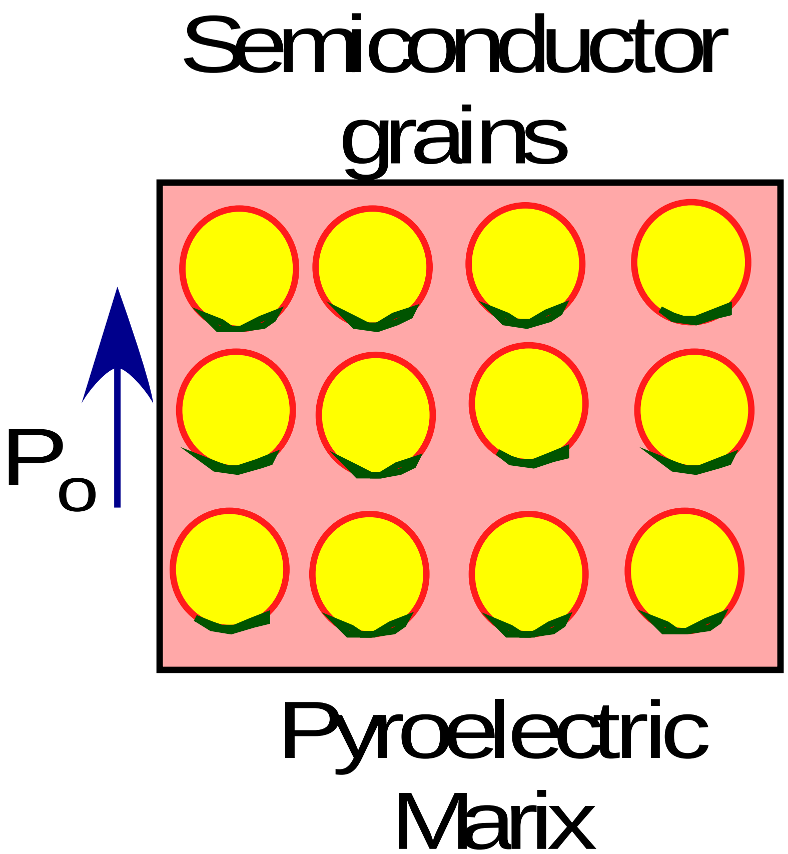
Oscillation frequency is of the order of a terahertz

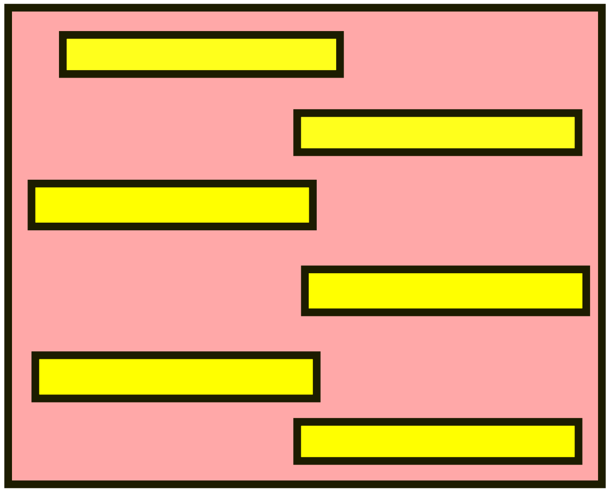
$$\omega_0 \pi / 2 \sim 1 \textit{ THz} \text{ to } 30 \textit{ THz}$$

CAN SWITCH OR SHIFT FREQUENCY
BY EXTERNAL FIELD OR BY LIGHT

After V. Kachorovskii and M. S. Shur, APL, March 29 (2004)

Semiconductor Grains Forming Plasmonic crystal

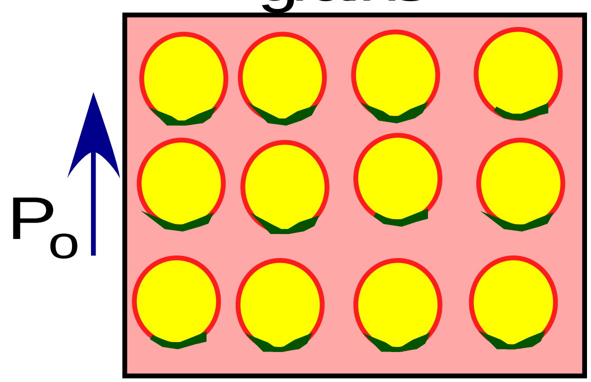




Dispersion in plasmonic crystal

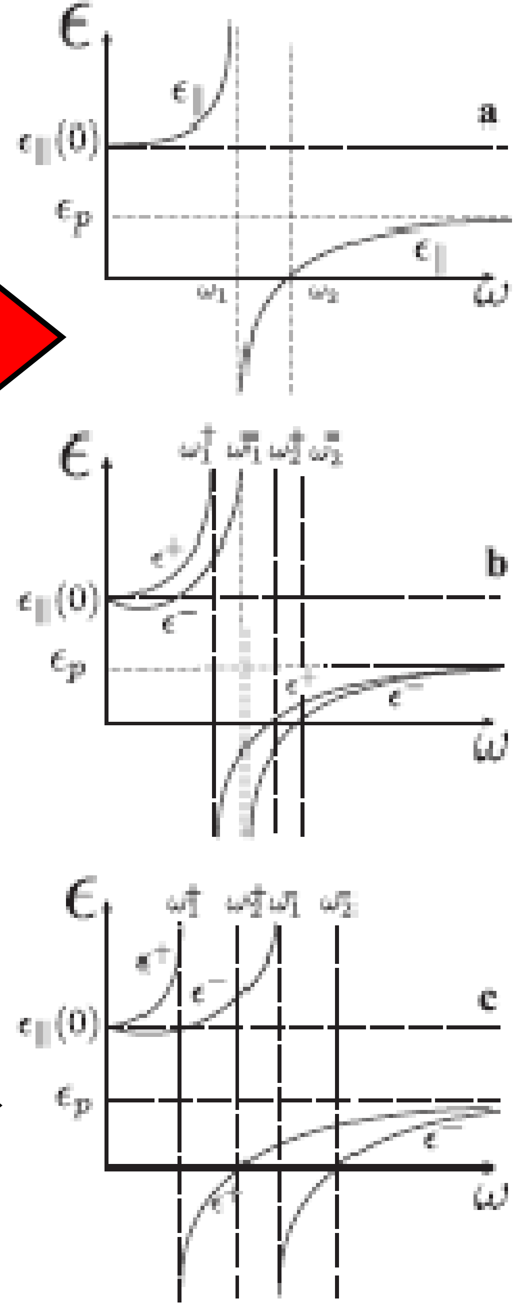
The gap can be tuned
by weak magnetic fields

Semiconductor
grains

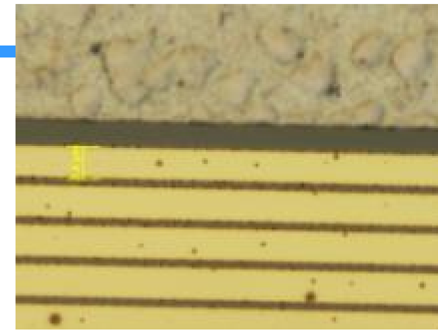


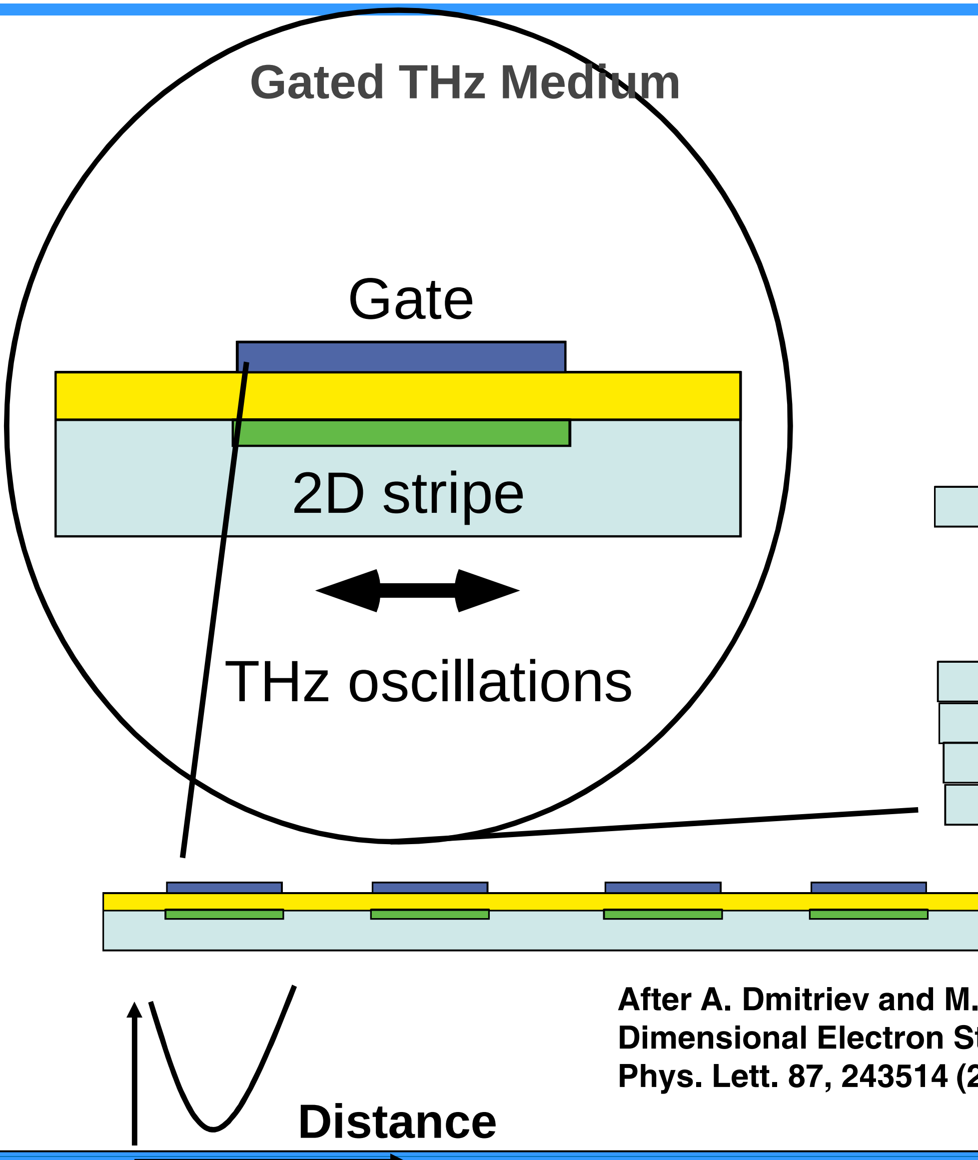
Pyroelectric
Marix

Spectrum in
a high magnetic field

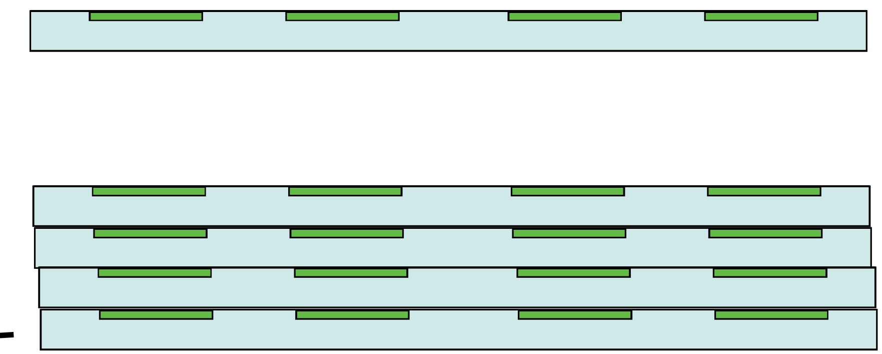


2D Stripes for Plasmonic Crystals





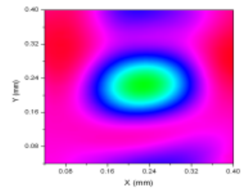
Ungated THz Medium



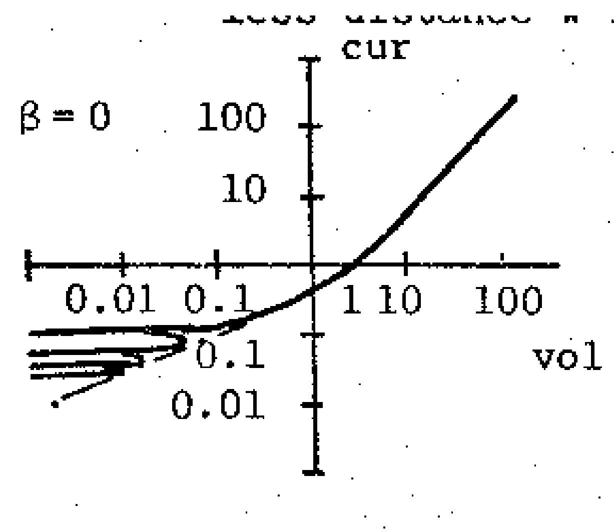
After A. Dmitriev and M. S. Shur, Plasma Oscillations of Two Dimensional Electron Stripe, Applied Physics Letters, Appl. Phys. Lett. 87, 243514 (2005)

Questions to answer and problems to resolve

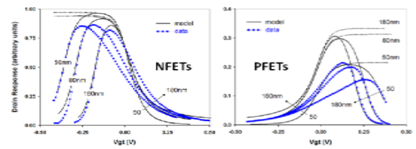
COUPLING



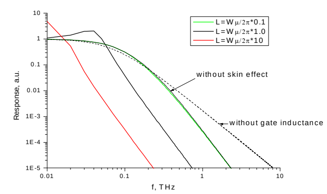
CONTACTS



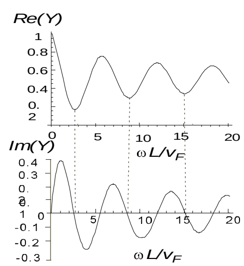
MATCHING



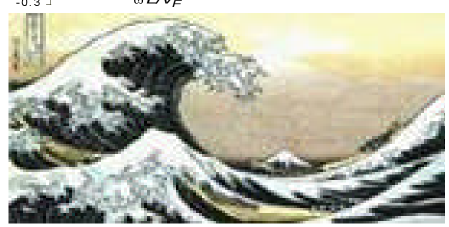
THz GATE CURRENT



BALLISTIC EFFECTS

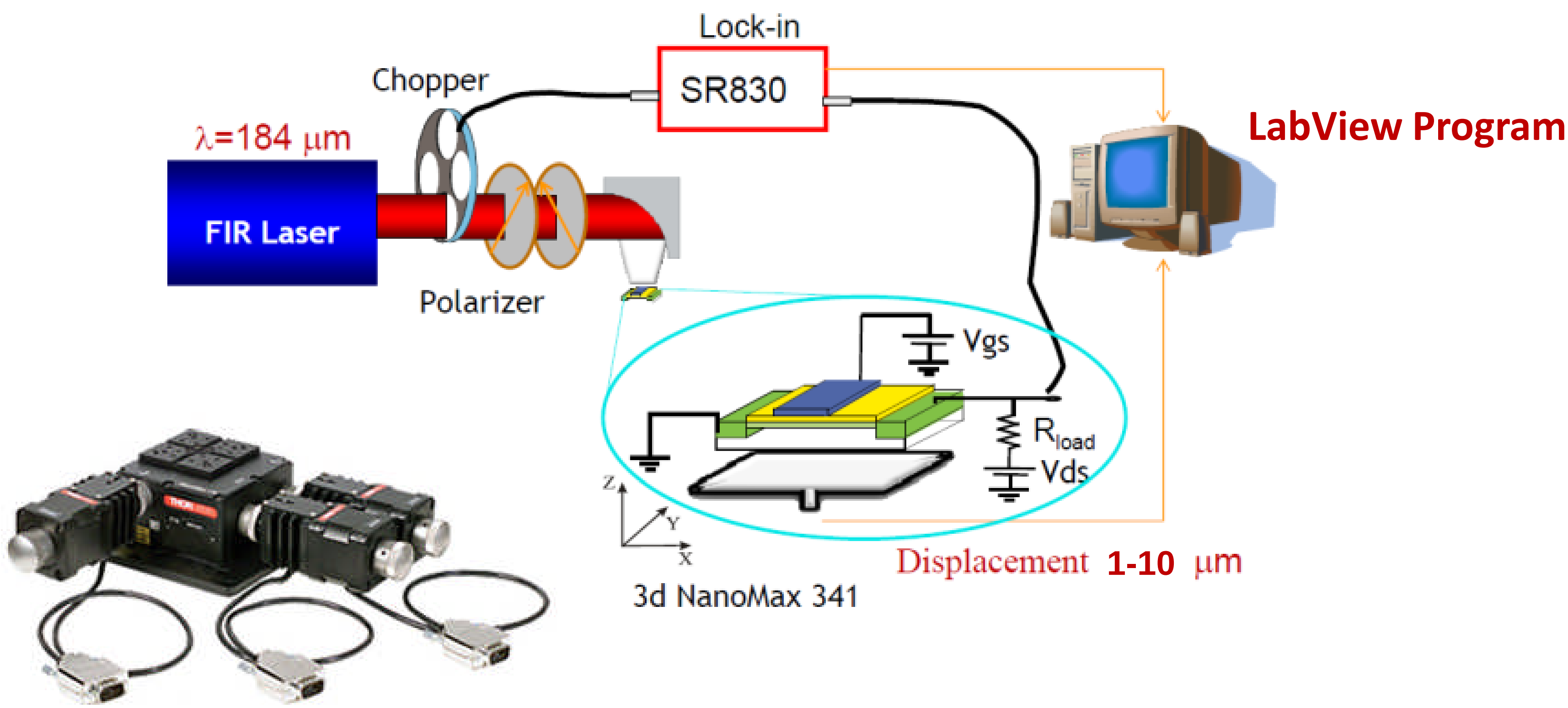


HIGH FIELD TRANSPORT



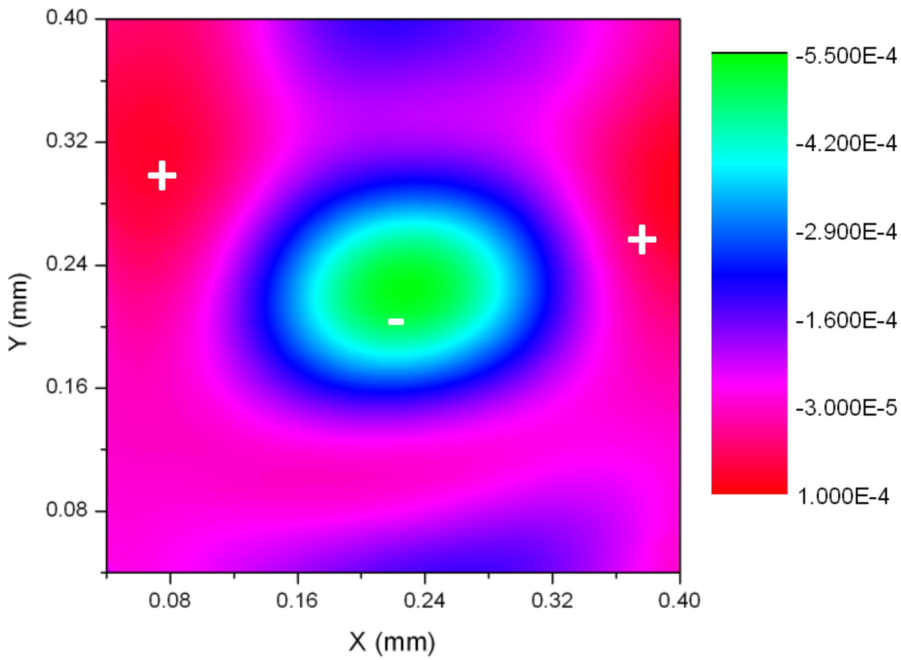
How does THz radiation couple to a FET?

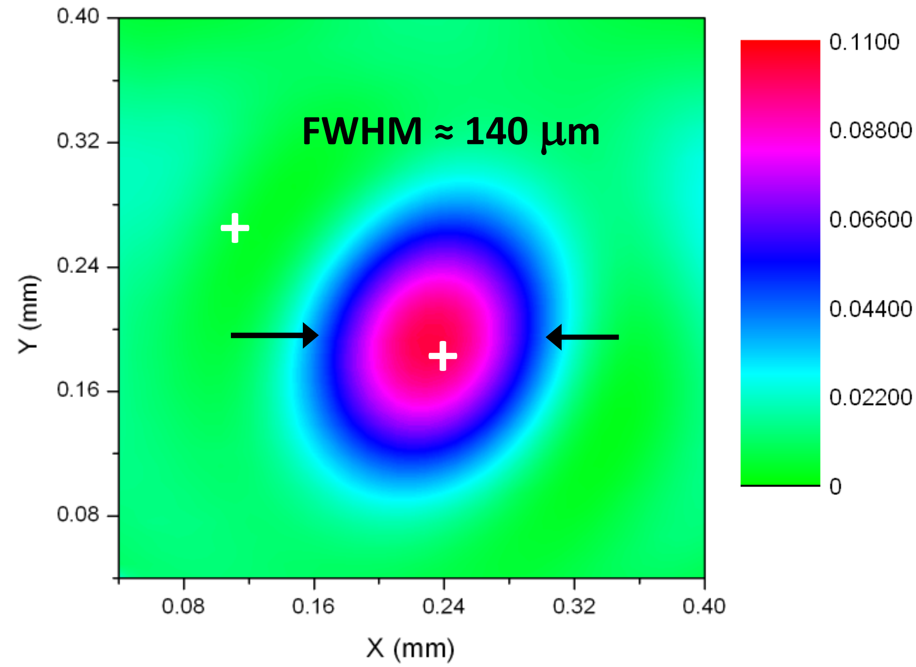
Experimental Setup



D. Veksler, A. V. Muraviev, T. A. Elkhatib, K. N. Salama, and M. Shur, "Plasma wave FET for sub-wavelength THz imaging," *Proceedings of IEEE ISDRS 2007, College Park, MD, USA, pp. 1–2, December 2007.*

THz responsivity pattern at different biases





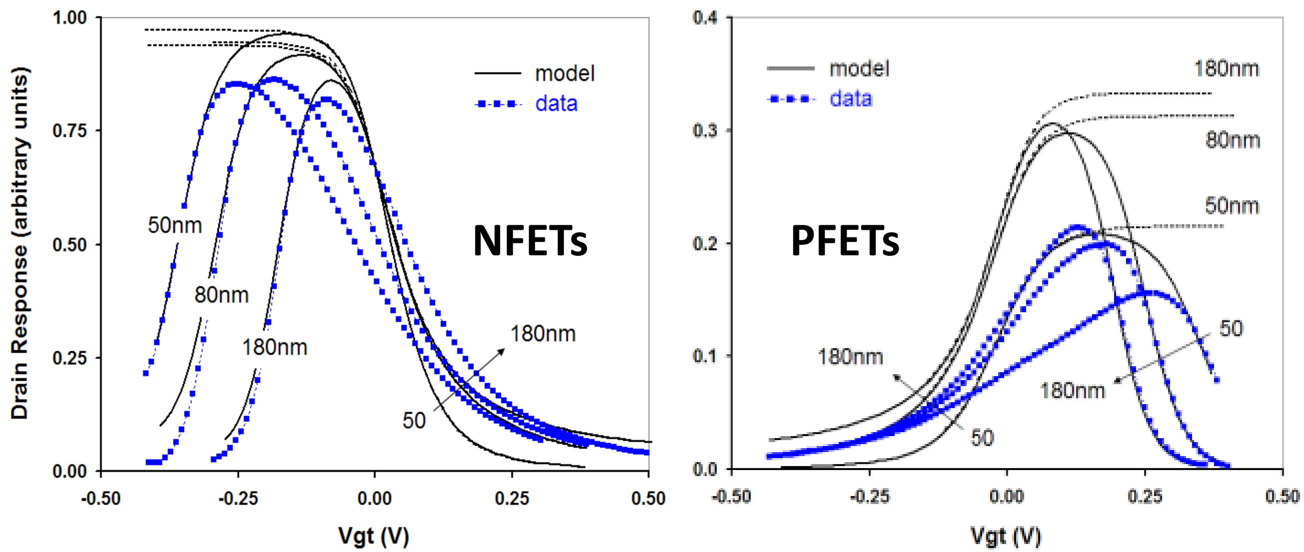
THz responsivity pattern in the linear regime with zero dc drain current.

THz responsivity pattern in the deep saturation regime representing THz Laser Beam Profile. (10µm step)

T. A. Elkhatib, V. Y. Kachorovskii, A. V. Muravjov, X.-C. Zhang, and M. S. Shur, "Terahertz coupling to Plasma Wave FET at different Bias conditions," *in abstract of the 36th international symposium of compound semiconductors*, Santa Barbara, pp. 263-264, September (2009).

THz response of CMOS (non-resonant)

Matching Problem

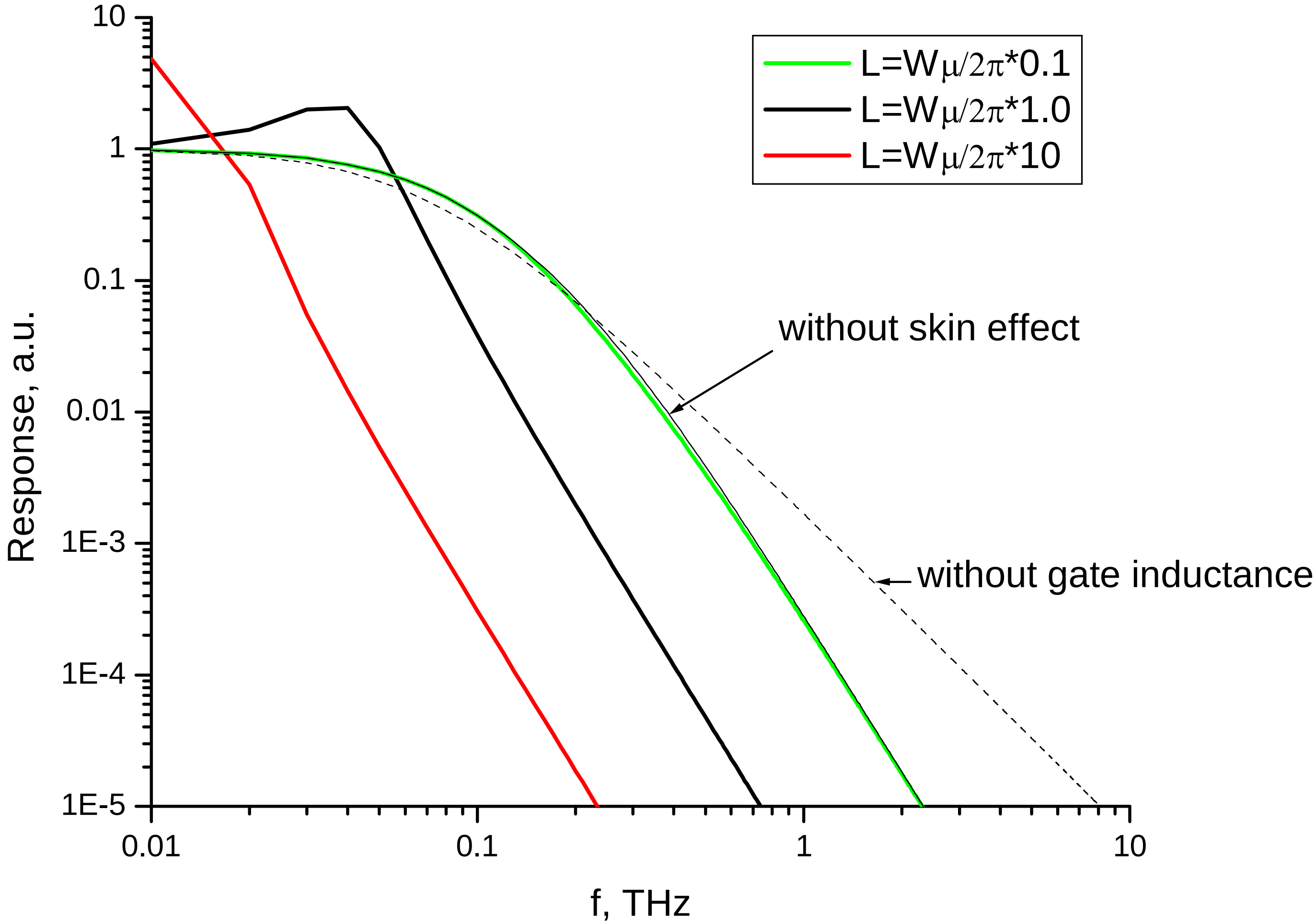


First demonstration of terahertz and sub-terahertz response in silicon CMOS

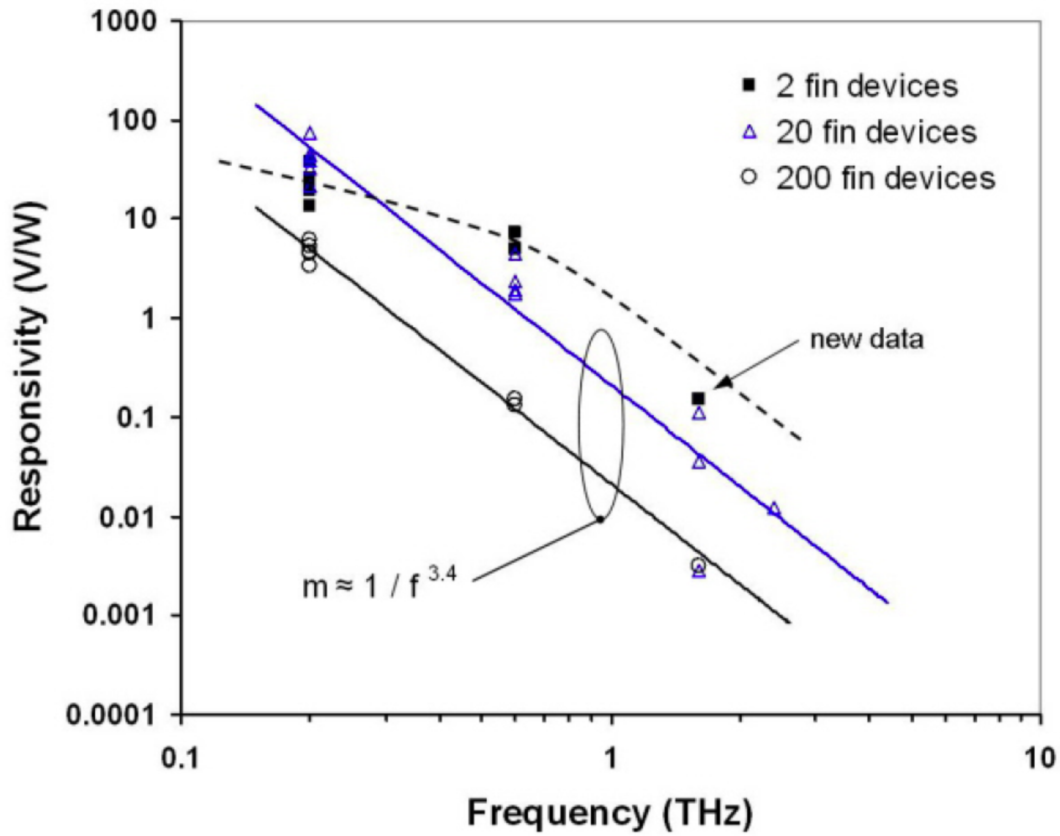
- ***Extension earlier work on n-channel Si FET response to p-channel devices.***
- ***Compare and contrast n and p-channel responsivity, detectivity and response speed in open drain and drain current enhanced response configurations.***

From W. Stillman, F. Guarin, V. Yu. Kachorovskii, N. Pala, S. Rumyantsev, M.S. Shur, and D. Veksler, Nanometer Scale Complementary Silicon MOSFETs as Detectors of Terahertz and Sub-terahertz Radiation, in Abstracts of IEEE sensors Conference, Atlanta, GA, October 2007, pp. 479-480

THz gate current

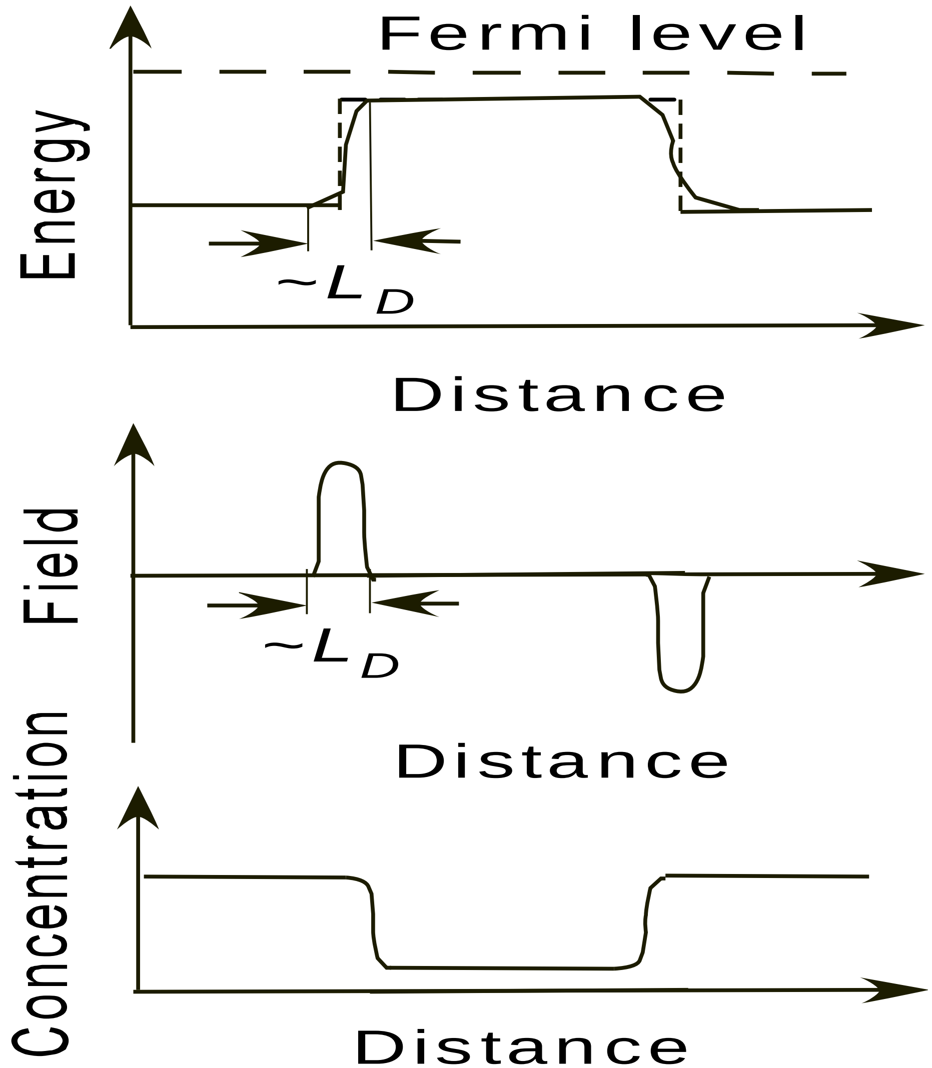


Responsivity versus frequency



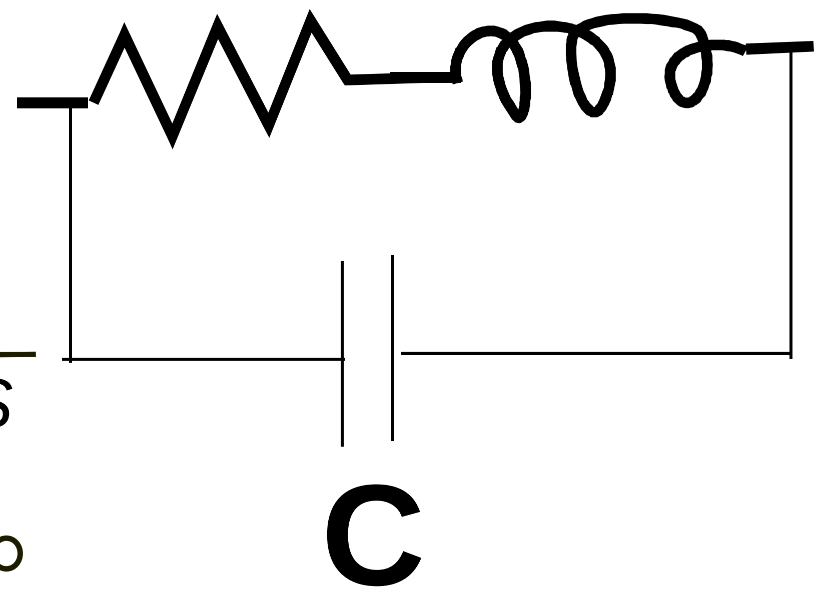
From W. Stillman, C. Donais, S. Rumyantsev, D. Veksler, and M. Shur, Si FINFET Terahertz Detectors, to be presented at WOFE-9, Rincon, PR (2009)

Ballistic Effects: Band, field, and concentration profiles of ballistic n^+-n-n^+ sample in equilibrium

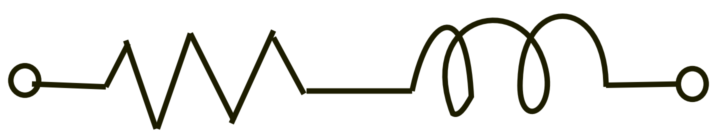


Conventional response at high frequencies: Drude Equation and Equivalent Circuit

$$\sigma = \frac{\sigma_0}{1 + i\omega\tau}$$

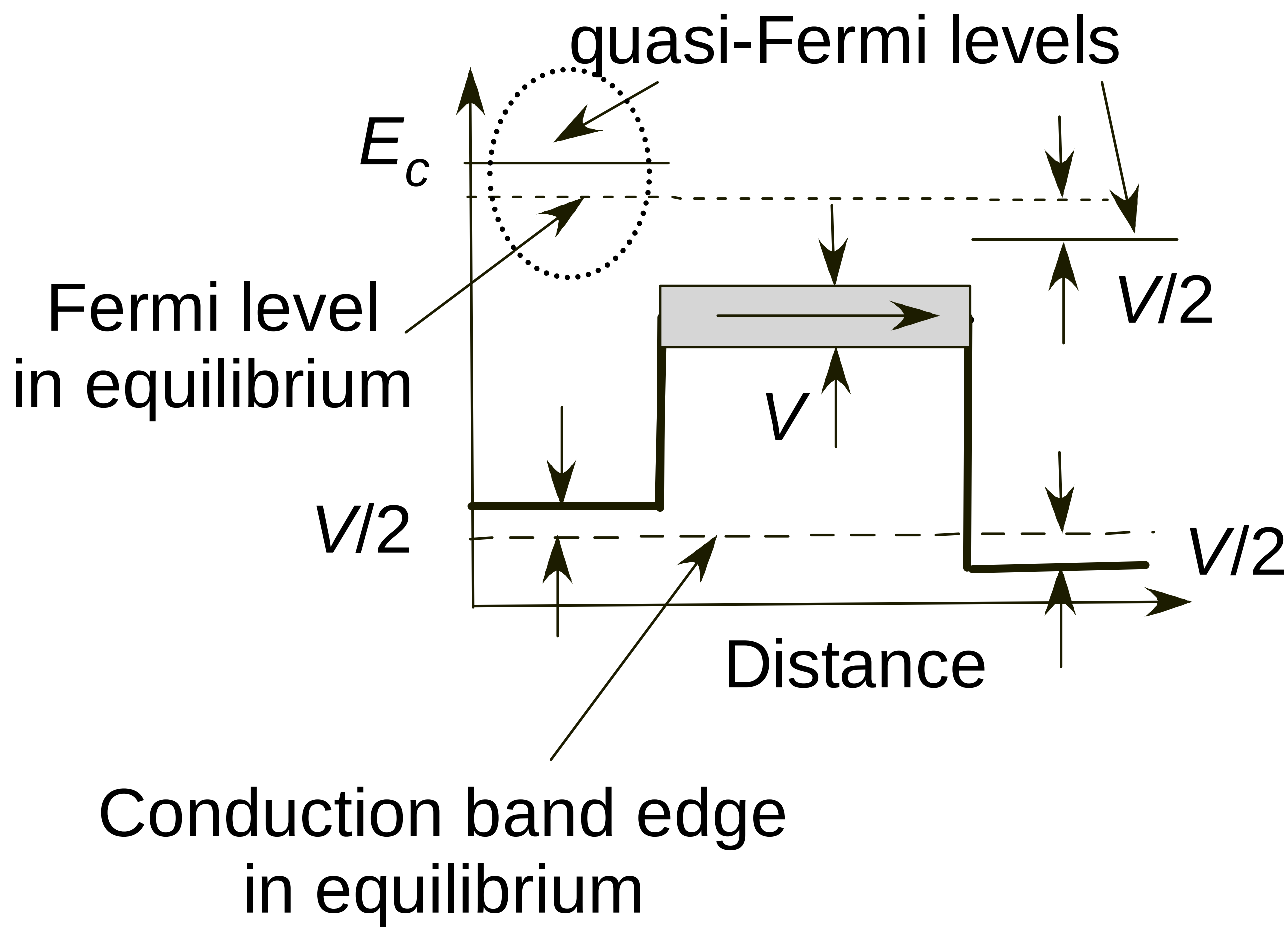


3D $\quad \sigma_o = \frac{e\,\mu\,n\,S}{L} \qquad \mathbf{L} = \frac{L\,m}{e^2\,n\,S}$



2D $\quad \sigma_o = e\,\mu\,n_s\,W \qquad \mathbf{L} = \frac{m}{e^2\,n_s\,W}$

Energy band diagram for a ballistic sample



In the dashed energy region electron are moving only from the left to the right

DC Ballistic mobility

Current is independent of sample length

$$\mu_{bal} = \alpha \frac{eL}{mv}$$

Values of constant α and thermal and Fermi velocities for 2D and 3D geometries (see Eq. (1)). k_B is the Boltzmann constant, T is temperature (K).

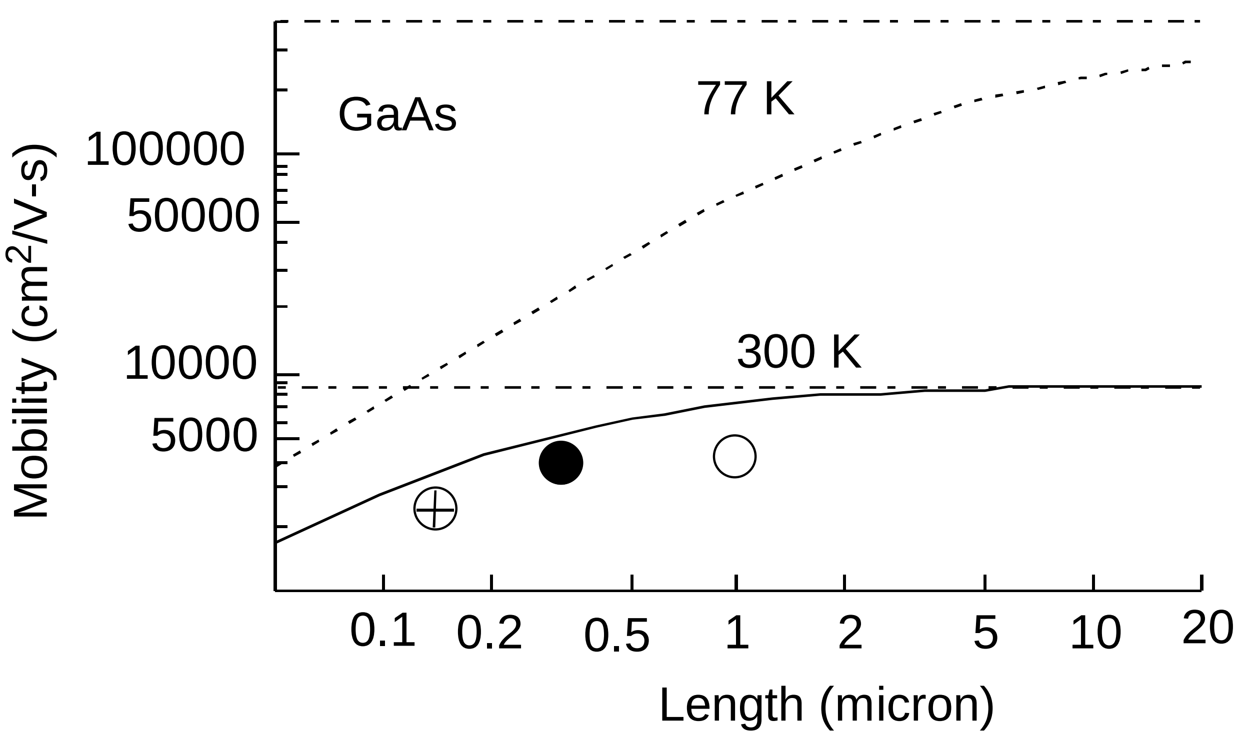
Geometry	Degenerate		Non-degenerate	
2D	$\alpha = \frac{2}{\pi}$	$v_F = \frac{\hbar}{m}\sqrt{2\pi n_s}$ [8]	$\alpha = \frac{1}{2}$	$v_{th} = \left(\frac{\pi k_B T}{2m}\right)^{1/2}$ [4]
3D	$\alpha = 3/4$	$v_F = \frac{\hbar}{m}\left(3\pi^2 n_s\right)^{3/4}$	$\alpha = \frac{2}{\pi}$	$v_{th} = \left(\frac{8k_B T}{\pi m}\right)^{1/2}$ [3]

[3]A. van der Ziel, M. S. Shur, K. Lee, T. H. Chen and K. Amberiadis, IEEE Transactions on Electron Devices, Vol. ED-30, No. 2, pp. 128-137, February (1983)

[4] M. Dyakonov and M. S. Shur, in, The Physics of Semiconductors ed. by M. Scheffler and R. Zimmermann (World Scientific, 1996), pp. 145-148, (1996)

[8] S. Rumyantsev, M. S. Shur, W. Knap, N. Dyakonova, F. Pascal, A. Hoffman, Y Ghuel, C. Gaquiere, and D. in Noise in Devices and Circuits II, Proceedings of SPIE Vol. 5470 , pp. 277-285 (2004)

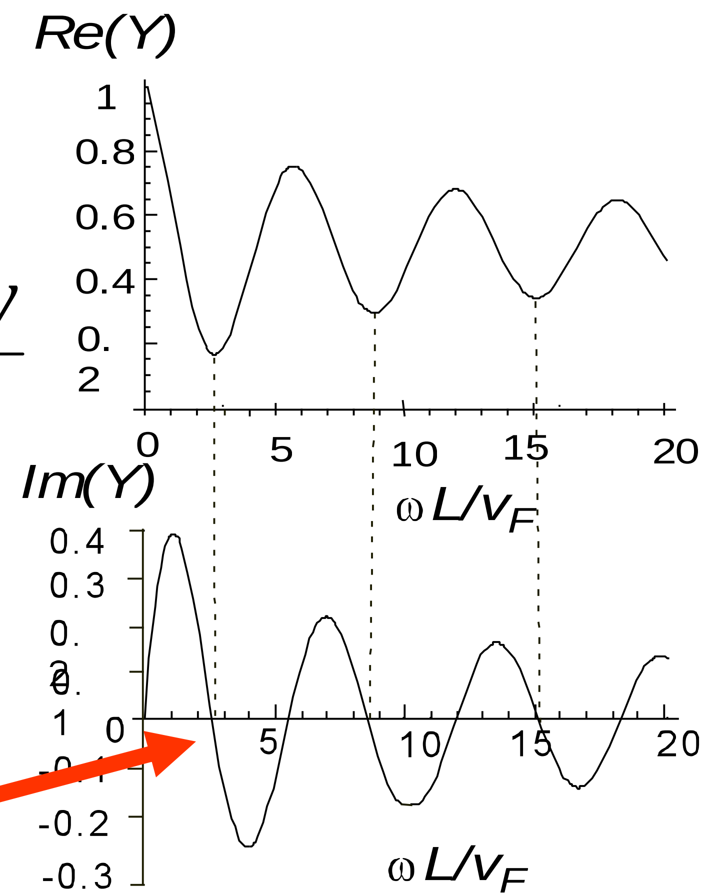
Experimental Evidence for Ballistic Mobility (after Shur (2002)



From M. S. Shur, IEEE EDL, Vol. 23, No 9, pp. 511 -513, September (2002)

Ballistic Admittance versus Frequency

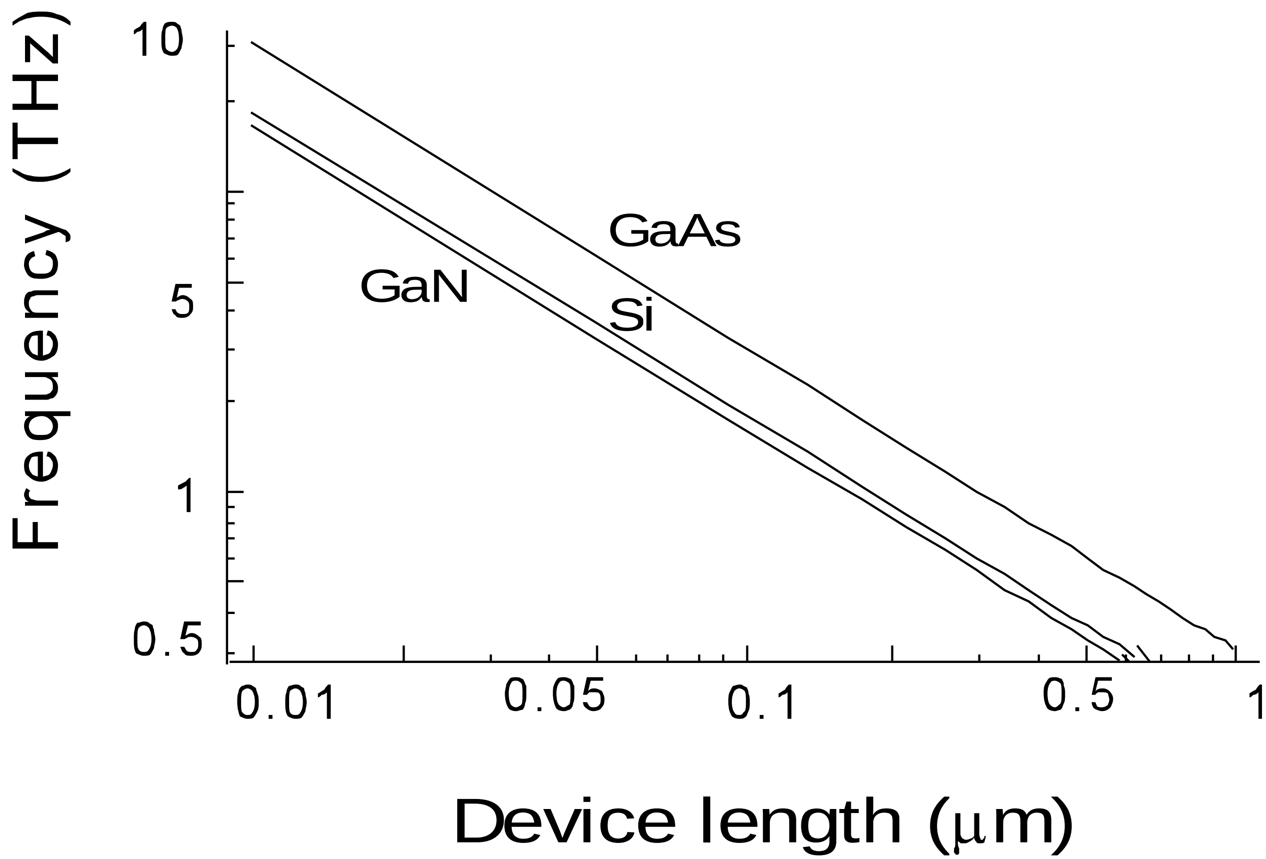
$$Q = \frac{\omega}{\mathrm{Re}Y}\frac{d\,\mathrm{Im}Y}{d\omega} = \frac{\theta}{\mathrm{Re}\,y}\frac{d\,\mathrm{Im}\,y}{d\theta}$$



Q ~ 7

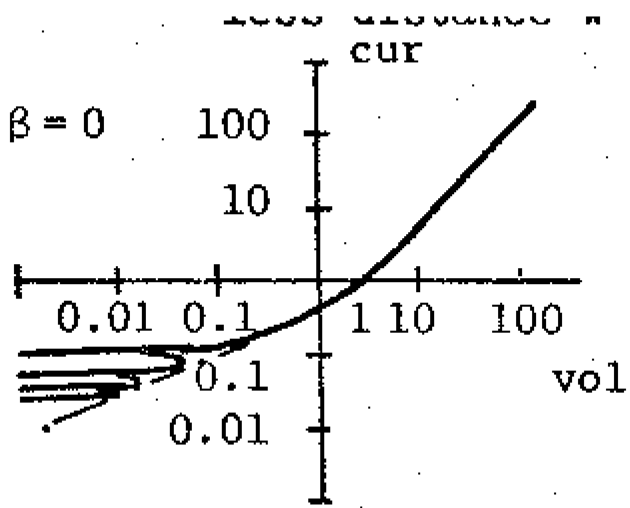
After A. P. Dmitriev and M. S. Shur, Appl. Phys. Lett., 89, 142102, (2006)

Oscillation (first zero Im (Z)) frequency

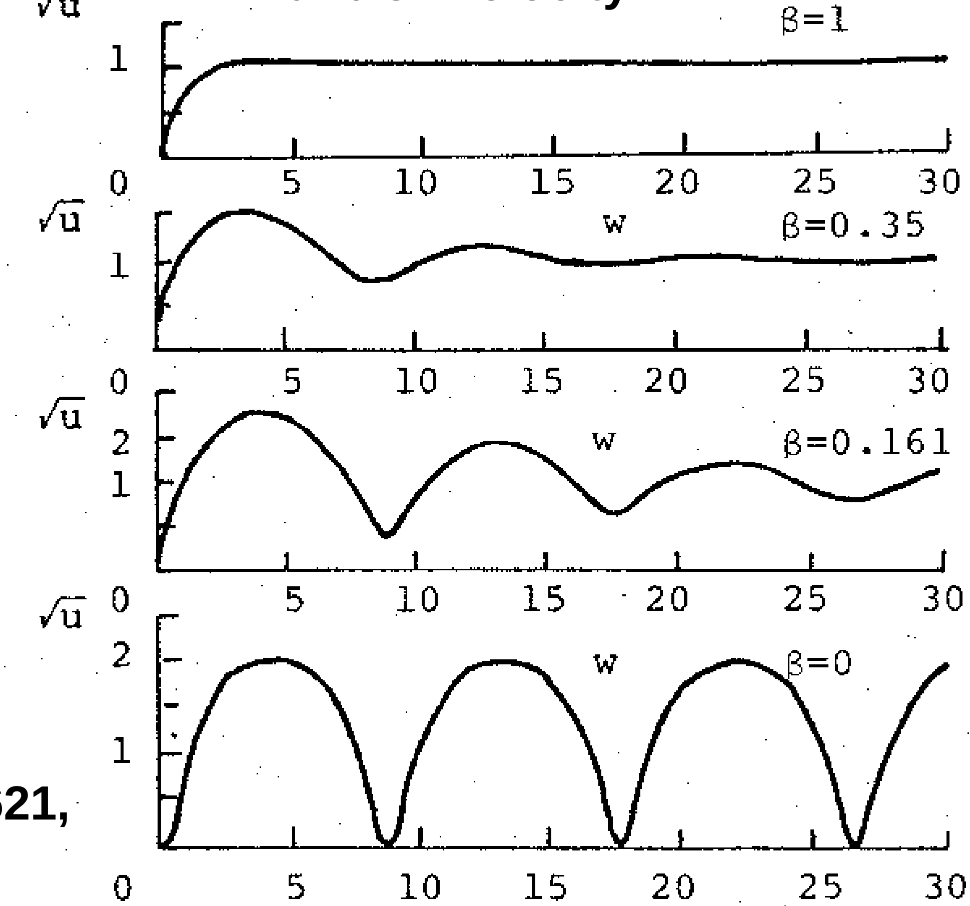


After A. P. Dmitriev and M. S. Shur, Appl. Phys. Lett., 89, 142102, (2006)

Space charge injection into a ballistic sample



Beta ~ 1/tau
u^0.5 - velocity

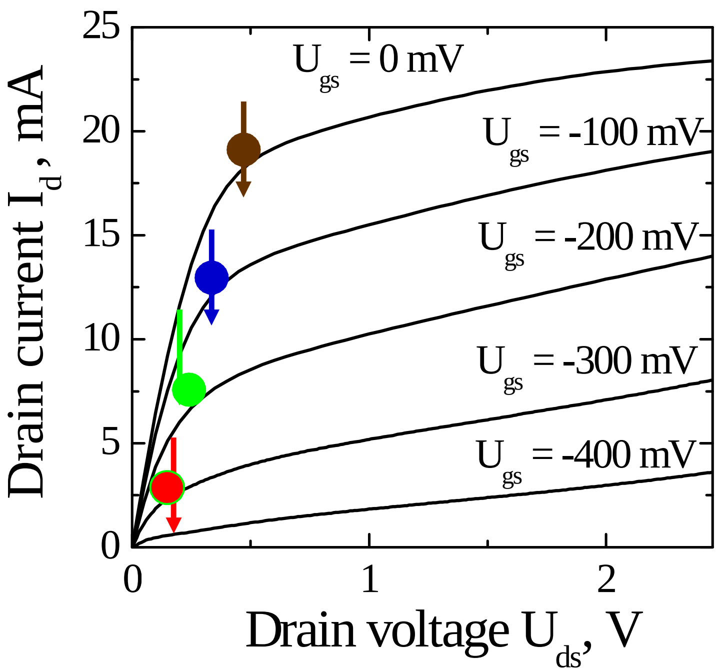


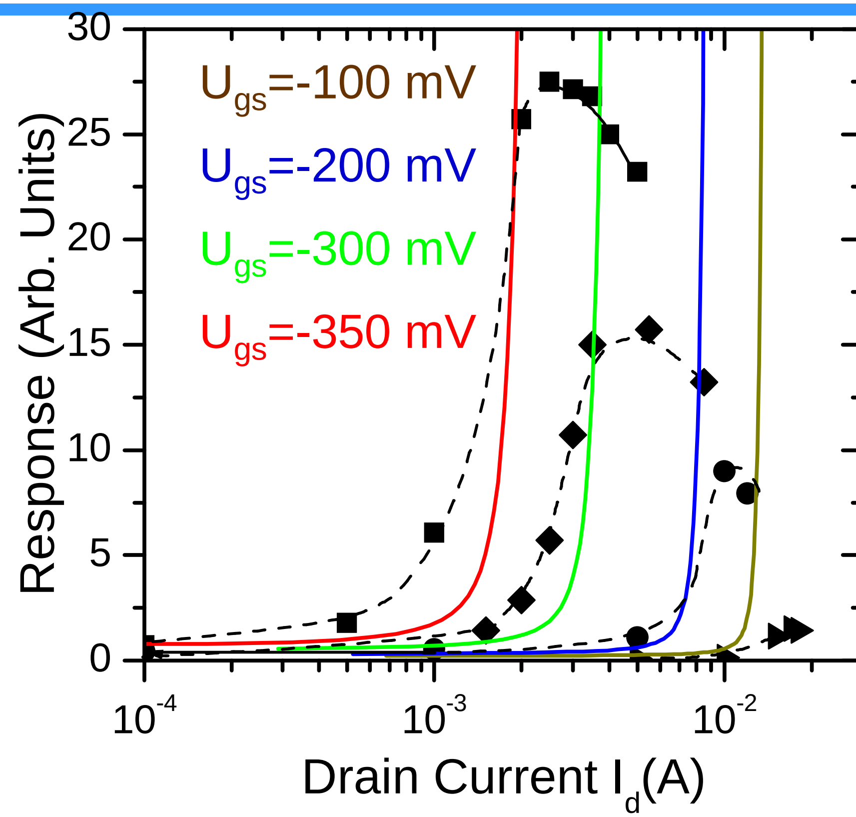
M. S. Shur, Ballistic and Collision Dominated Transport in a Short Semiconductor Diode, IEDM Technical Digest, pp. 618-621, Washington, DC (1980)

Non-resonant detection (ωτ<<1)

f = 0.2 THz; T=300 K

250 nm GaAs FET





$$V_{response} = \frac{U_a^2}{4(U_{gs} - U_{th})(1 - j_d / j_{sat})^{1/2}}$$

$$j_d << j_{sat}$$

Symbols – experiment

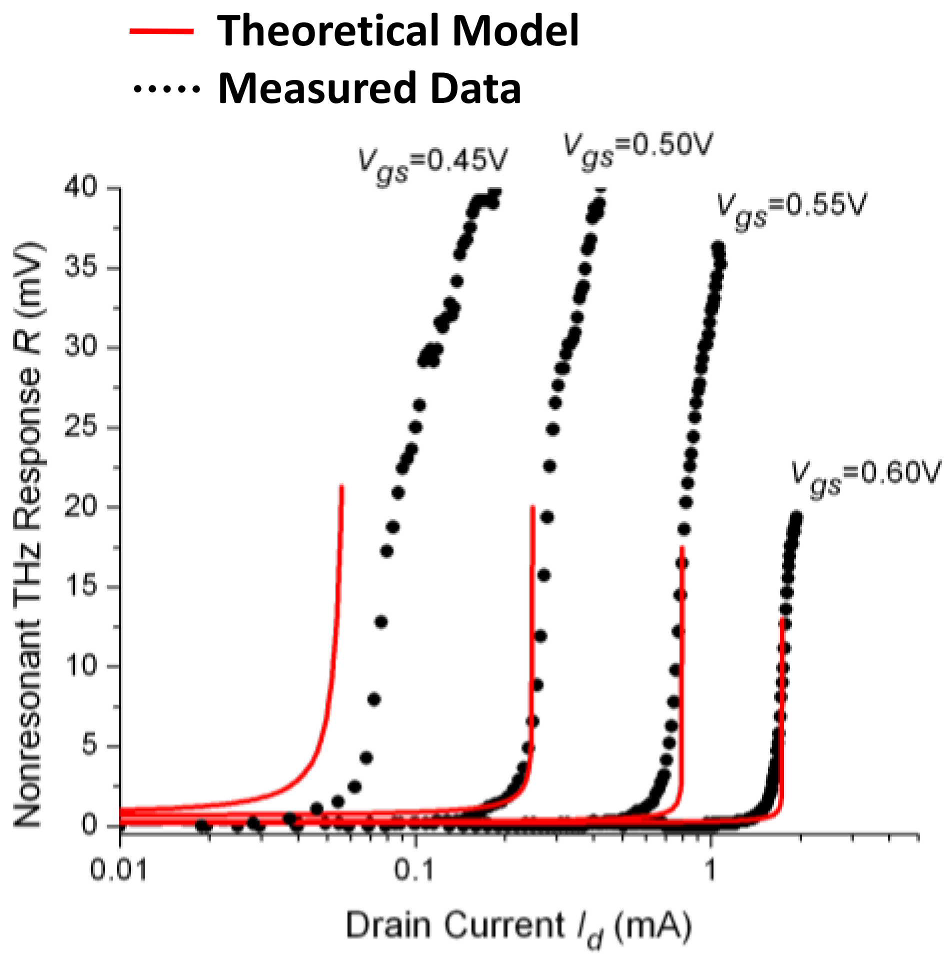
Colored curves - theory

***D. Veksler** et al , Phys. Rev. B 73, 125328 (2006).*

THz response in deep saturation regime

- We discovered that THz response is increasing with drain current in the deep saturation regime. The early results was an artifact of the experimental setup.

Hokusai Print



T. A. Elkhatib, V. Y. Kachorovskii, W. J. Stillman, D. B. Veksler, **K. N. Salama**, X.-C. Zhang, and M. S. Shur, "**Enhanced Plasma Waves Detection of Terahertz Radiation using Multiple High-Electron-Mobility Transistors Connected in Series**," *IEEE* Transactions on *Microwave Theory and Techniques. (Accepted)*

Conclusions

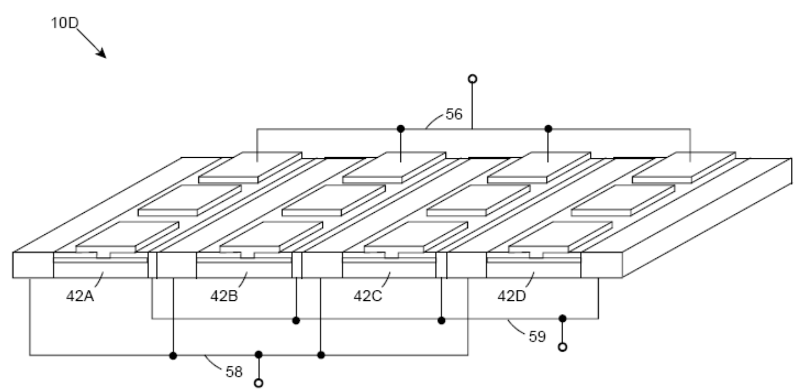
•Arrays of THz plasma wave transistors promise x1,000 increase in performance

•Sharp plasma resonances have been observed in grating gate structures at T<170 K

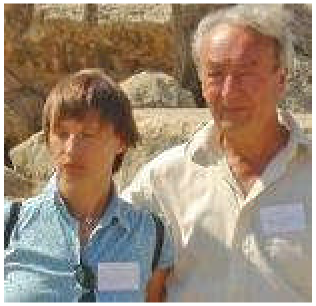
•Response from several transistor in series ~ N

•Problems to understand and resolve

- •Coupling
- •Matching
- •Ballistic effects
- •Contacts
- •High field plasmonics

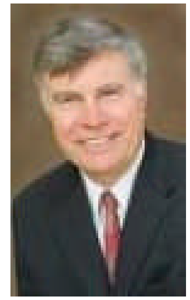


Acknowledging
my colleagues and collaborators


Dr. Dyakonova and
Prof. Dyakonov


Dr. Veksler


Dr. Kachorovskii


Prof. Mitin


Dr. Knap


Dr. Rumyantsev


Prof. Otsuji


Prof. M. Ryzhii

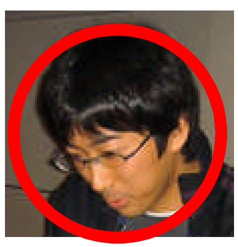

Dr. Dmitriev


Prof. Zhang


Prof. V. Ryzhii


Dr. Stillman


Dr. Muraviev


Dr. Satou


Dr. Levinshtein


Dr. Popov


T. Elkhatib


Prof. Xu

Acknowledgment

This work has been supported by NSF, ONR, and DARPA (MTO)