Terahertz Electronics

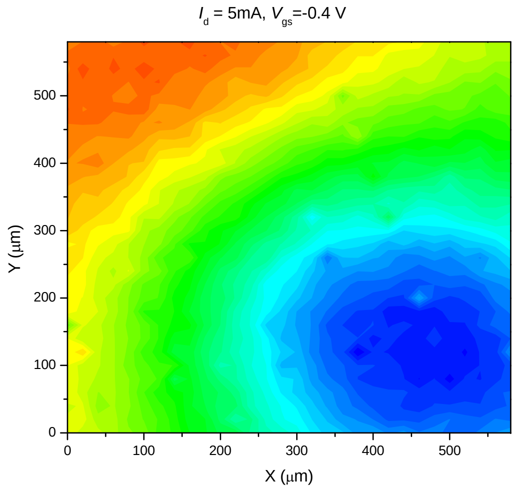
Michael S. Shur

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/

Presented at Nano and Giga Challenges in Electronics,
Photonics, and Renewable Energy Conference
McMaster University
August 14, 2009

Outline

- **THz applications and “THz gap”**
- **State-of-the-art of THz electronics and THz transistor**
- **Ballistic transport -> unavoidable in modern transistors**
  - Ballistic “mobility”
  - Ballistic admittance
- **Plasma wave THz electronics**
  - Instability and THz generation
  - Resonant and non-resonant THz detection
  - Subwavelength imaging
  - Plasma wave THz arrays



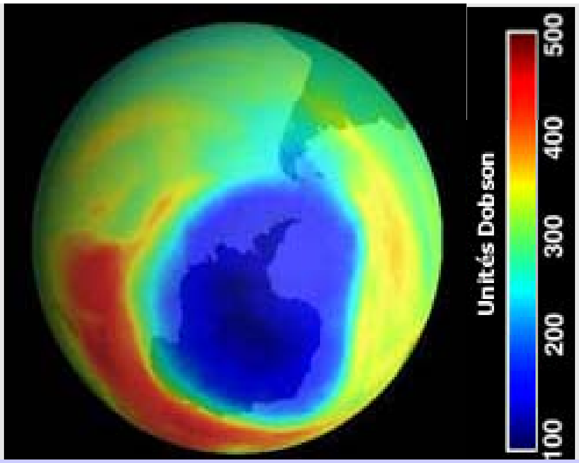
From Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging,
International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

- **Conclusions and future work**

THz applications

THz detection of concealed weapons. [1] IEEE©(2007)

Hidden art revealed by Terahertz.[2]



THz image of ozone hole.[3] IEEE©(2007)

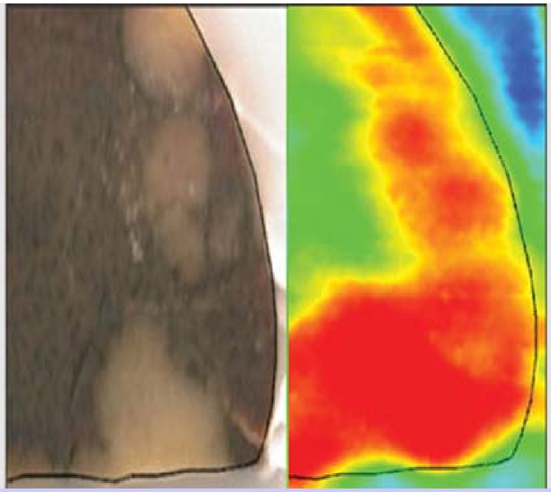
---

[1] R. Appleby and H.B. Wallace, “Standoff detection of weapons and contraband in 100 GHz to 1 THz Region”, IEEE Trans. Antennas Prop. Vol. 55, p. 2944 (2007).

[2] ScienceDaily (Feb. 5, 2008), http://www.sciencedaily.com/releases/2008/02/080204111732.htm.

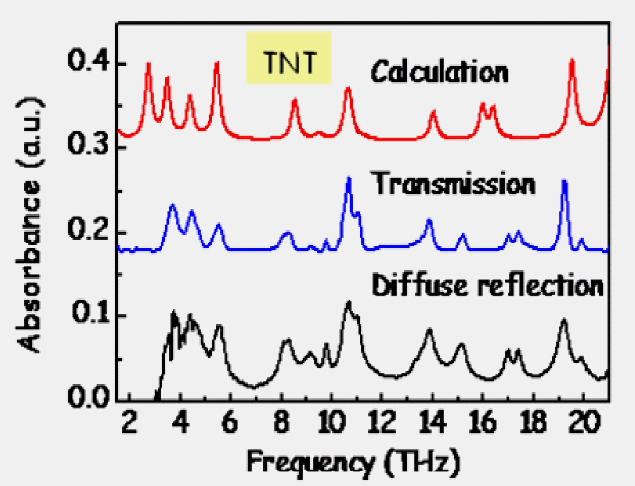
[3] F. Pieternel, E. Levelt, G. W. Hilsenrath, C.H.J. Leppelmeier, P.K. van den Oord, J. Bhartia, J. F. Tamminen, J.P. de Hann, and J.P. Veefkind, “Science objectives of the ozone monitoring instrument”, IEEE Trans. On Geoscience And Remote Sensing, Vol. 44, No. 5, pp. 1199-1208 (2006).

THz Applications



THz cancer detection.[1]

THz applications in dentistry.[2]



Explosive detection using THz radiation.[3]

---

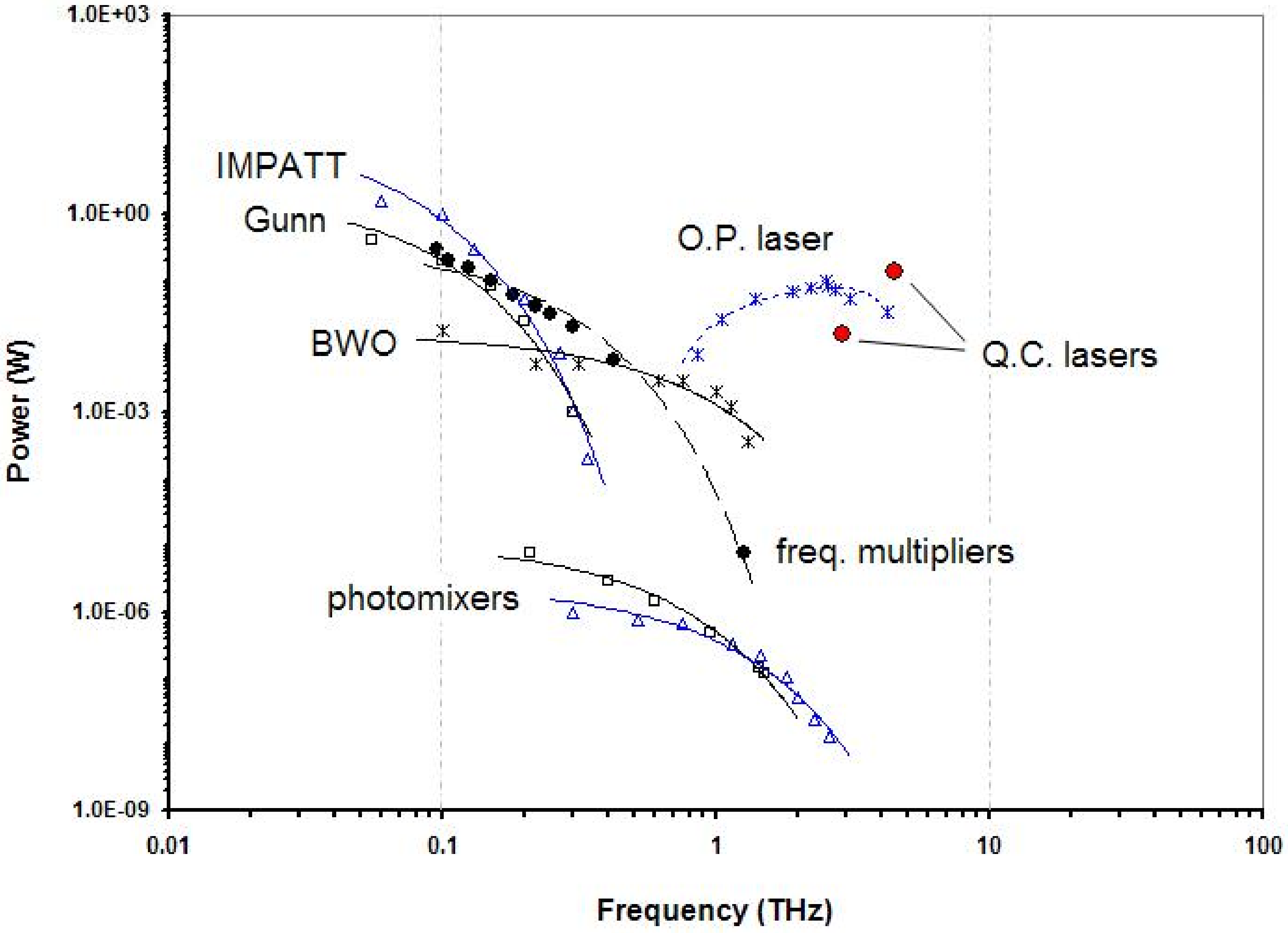
[1] PTBnews: http://www.ptb.de/en/publikationen/news/html/news021/artikel/02104.htm.

[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).

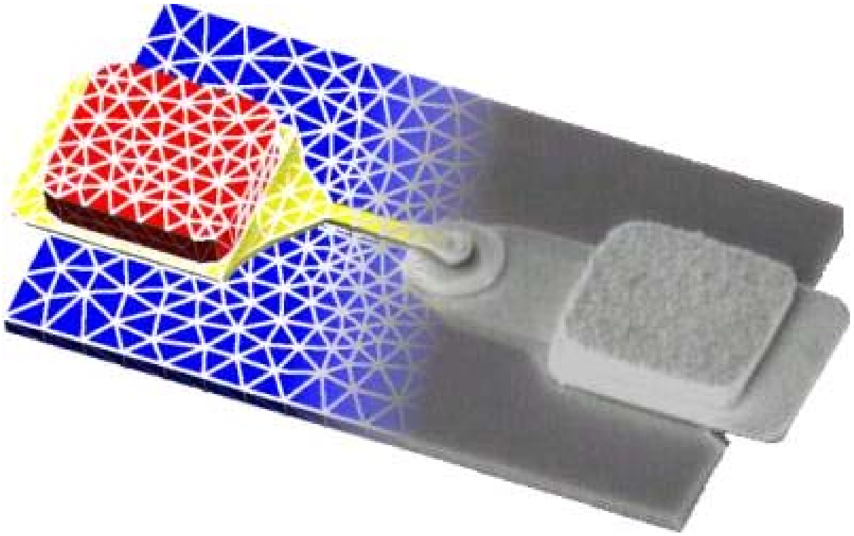
THz gap

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



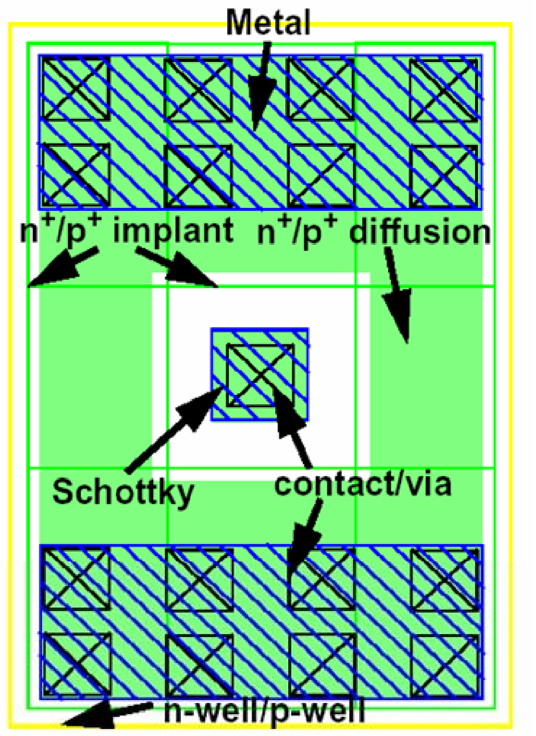
THz Schottky Diode

100 GHz – 2.5 THz

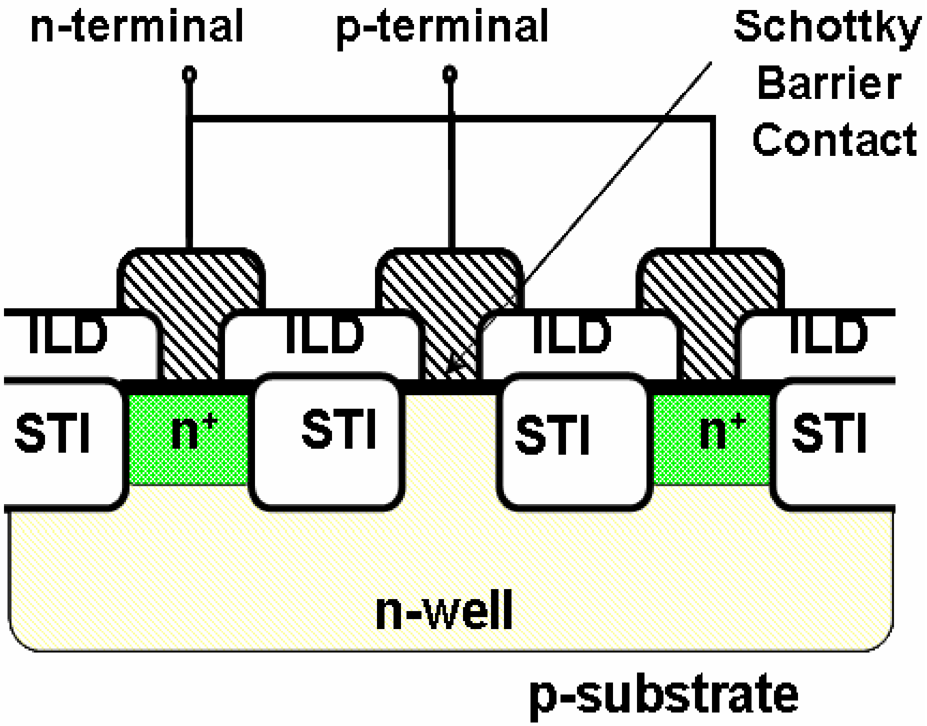


From http://www.acst.de/images/company_diode.jpg

Mm wave Schottky diode in 0.13 micron process



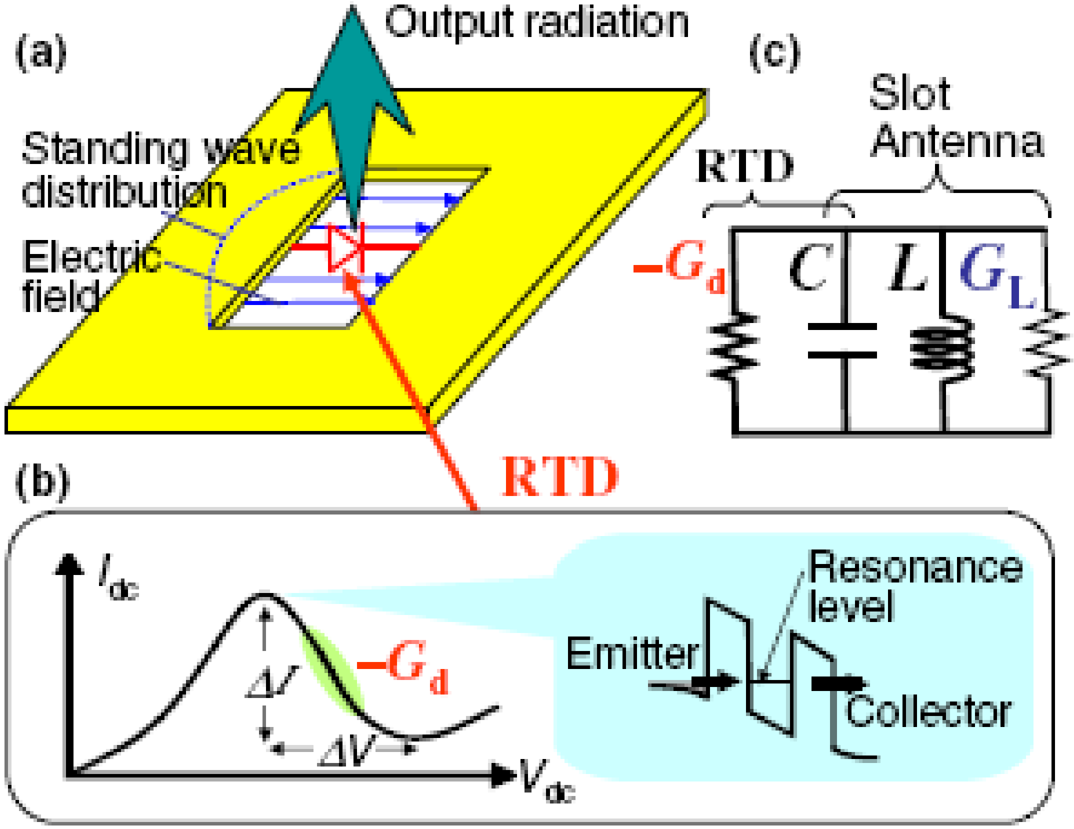
One cell layout



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

Resonant Tunneling Diodes



(Color online) Fundamental structure of the RTD oscillator

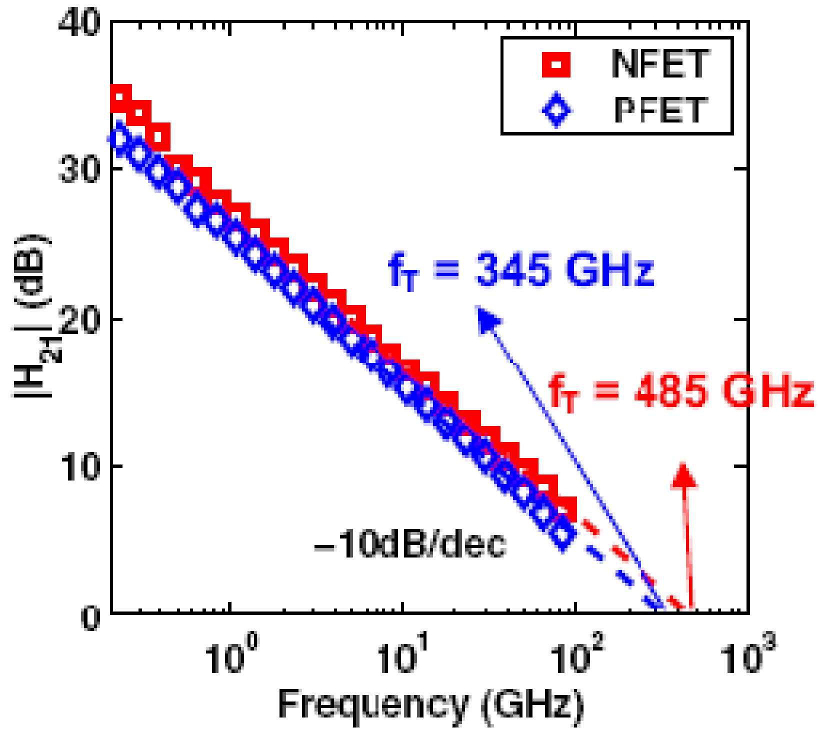
. (a) Slot resonator and RTD, (b) potential profile and current–voltage characteristics of RTD, and (c) equivalent circuit of (a).

Fundamental oscillation up to 0.65 THz and harmonic oscillation up to 1.02 THz

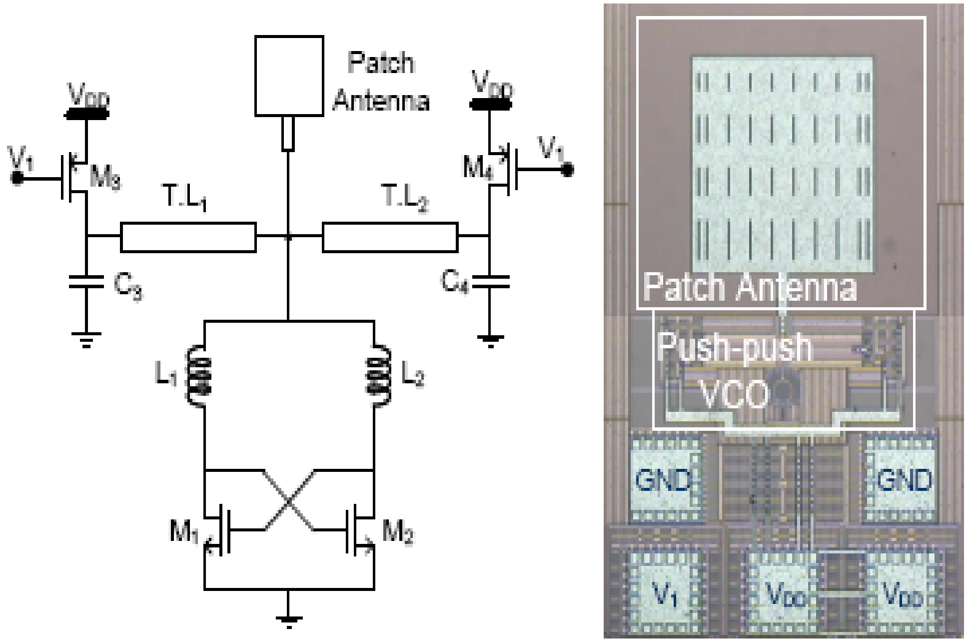
From Masahiro ASADA, Safumi SUZUKI, and Naomichi KISHIMOTO
“Resonant Tunneling Diodes for Sub-Terahertz and Terahertz Oscillators”
Japanese Journal of Applied Physics. Vol. 47, No. 6, 2008, pp. 4375–4384

Expected up to 60 microwatt at 2 THz

0.41 THz Si 45 nm CMOS VCO

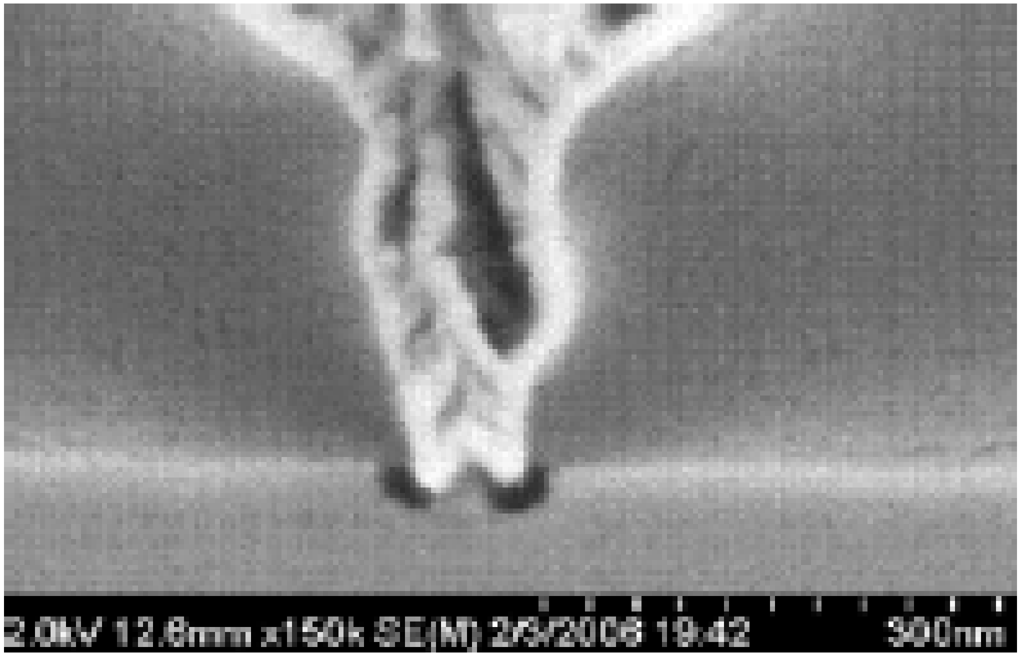


From S. Lee, B. Jagannathan, S. Narasimha, Anthony Chou, N. Zamdmer, J. Johnson, R. Williams, L. Wagner, J. Kim, J.-O. Plouchart, J. Pekarik, S. Springer and G. Freeman, IEDM Technical Digest, p. 225 (2007)



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

Northrop Grumman f_{max} is higher than 1 THz

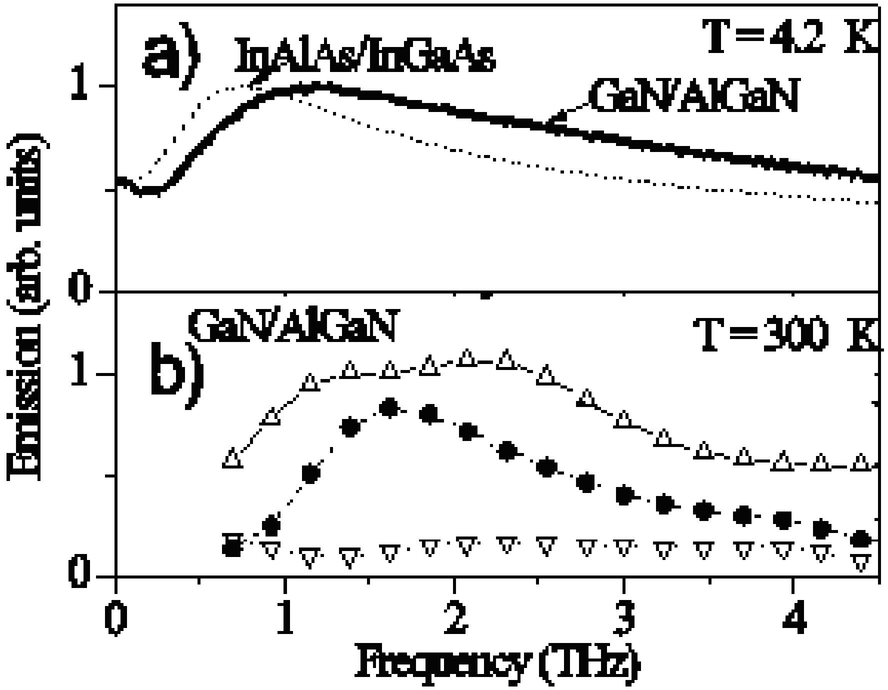


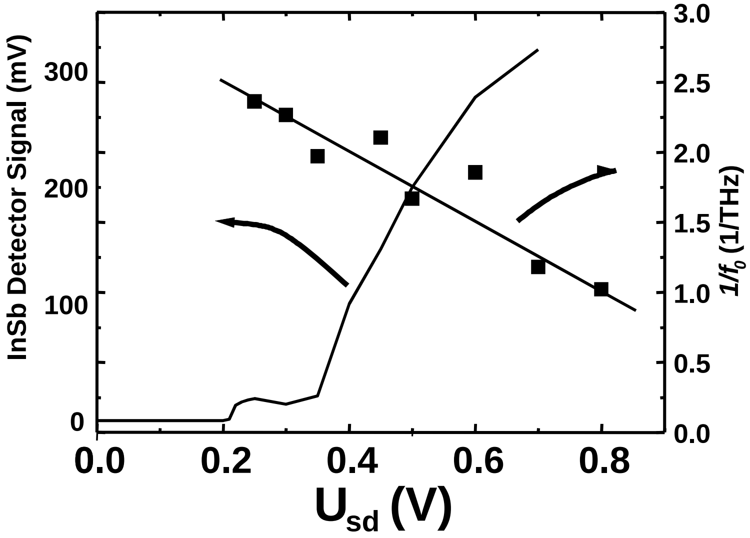
From R. Lai, X. B. Mei, W.R. Deal, W. Yoshida, Y. M. Kim, P.H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, A. Fung, Sub 50 nm InP HEMT Device with Fmax Greater than 1 THz, IEDM Technical Digest, p. 609 (2007)

InGaAs/InP Based HEMT

35 nm gate device cross section

Room Temperature Tunable Emission





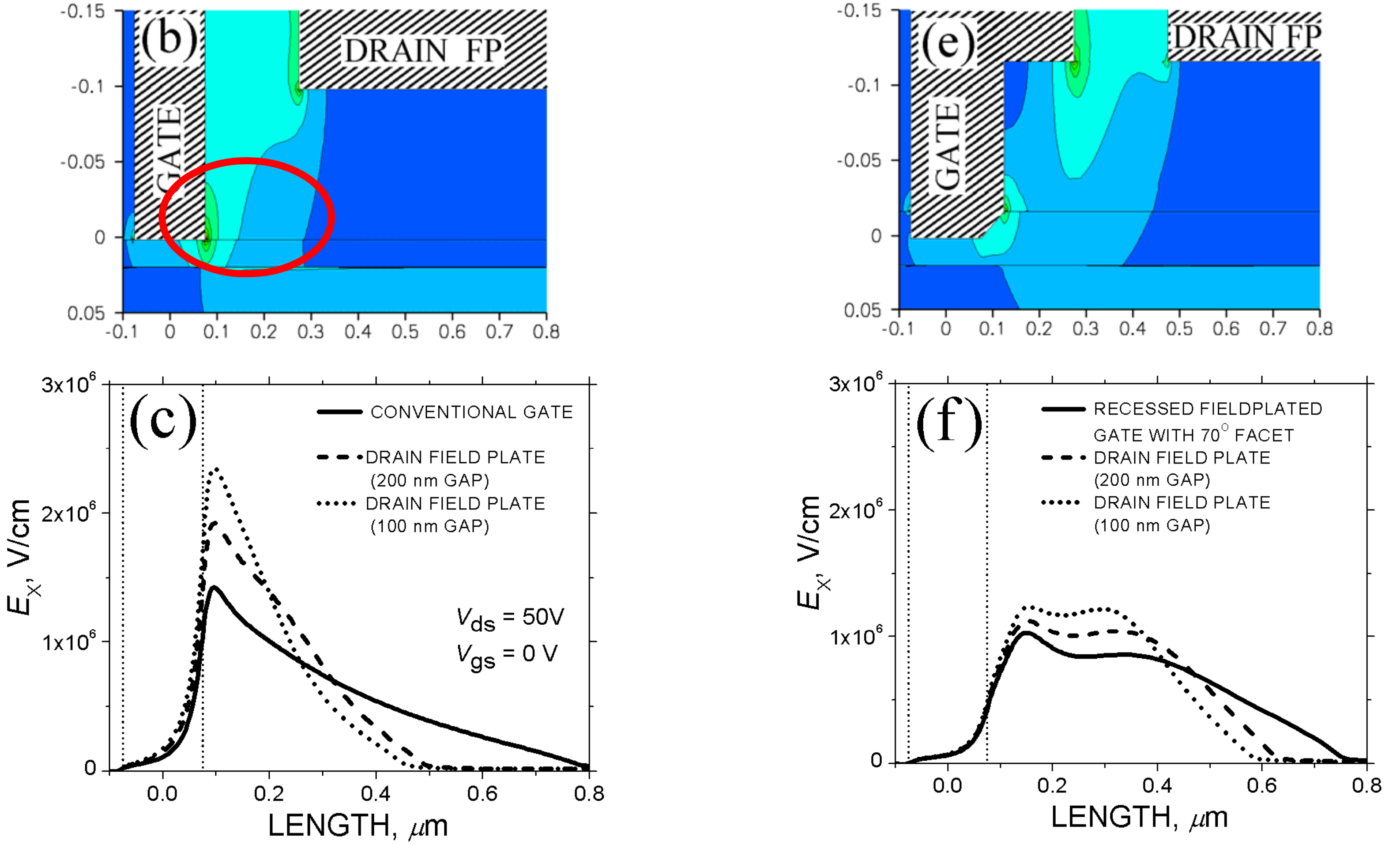
From D. B. Veksler, A. El Fatimy, N. Dyakonova, F. Teppe, W. Knap, N. Pala, S. Rumyantsev, M. S. Shur, D. Seliuta, G. Valusis, S. Bollaert, A. Shchepetov, Y. Roelens, C. Gaquiere, D. Theron, and A. Cappy, in Proceedings of 14th Int. Symp. "Nanostructures: Physics and Technology" St Petersburg, Russia, June 26-30, 2006, pp 331-333

From W. Knap, J. Lusakowski, T. Parenty, S. Bollaert, A. Cappy, V. Popov, and M. S. Shur,
Appl. Phys. Lett. 84, No 13, 2331-2333, March 29 (2004)

THz transistors: issues

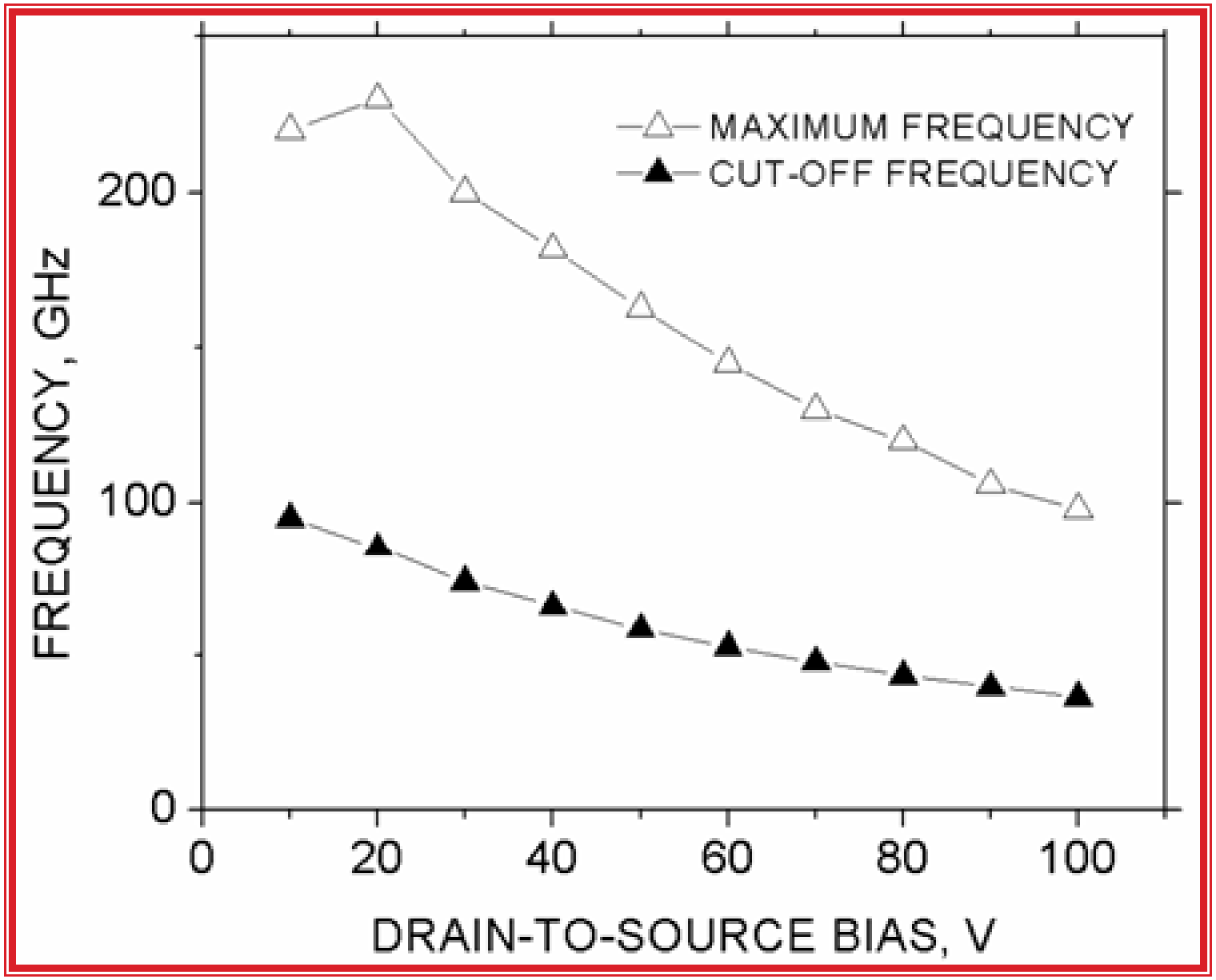
- Effective gate length is longer
- Parasitics are important
- Matching is difficult
- Device physics is different
  - In THz transistors, electrons experience very few collisions
  - Electron inertia is very important
  - Electrons behave as a fluid

Effective gate length



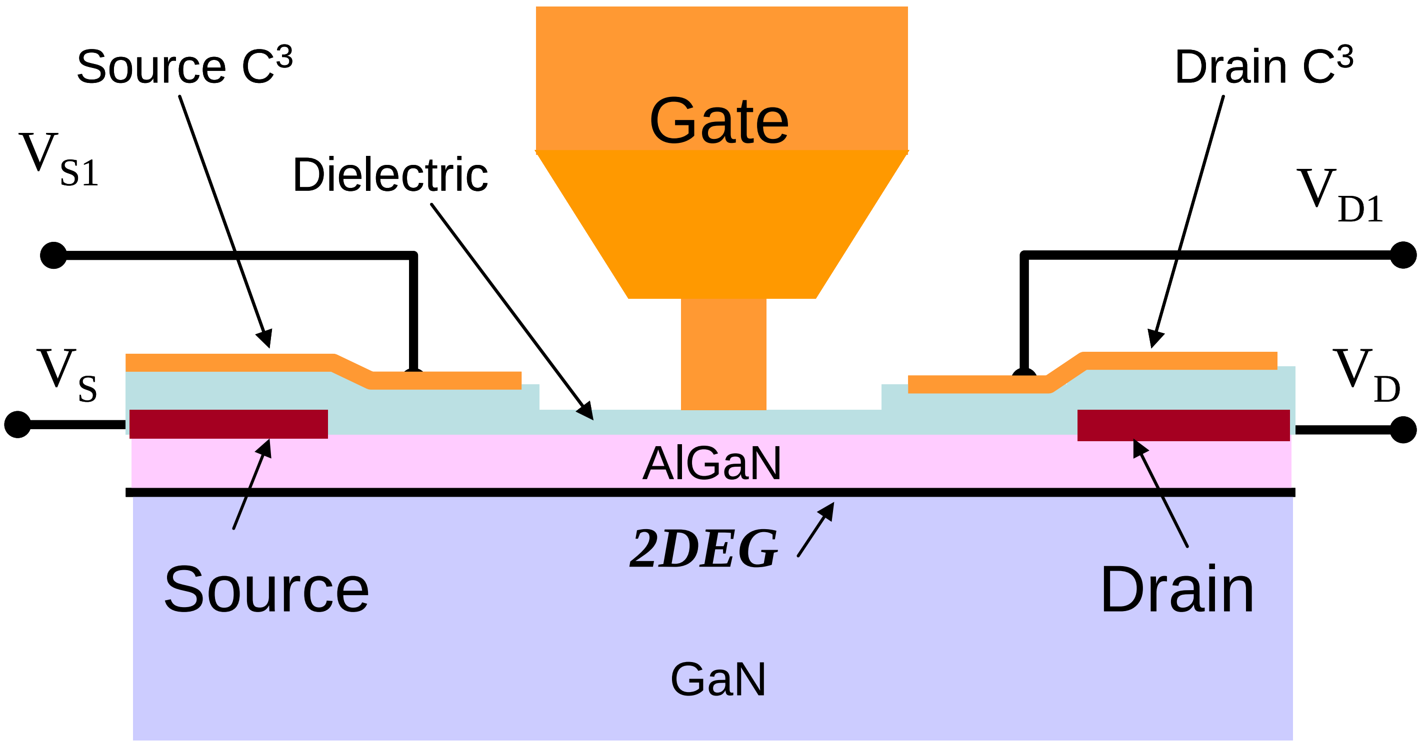
From V. O. Turin, M. S. Shur, and D. B. Veksler, IJHSES, vol. 17, No. 1 pp. 19-23 (2007)

Effect of gate extension



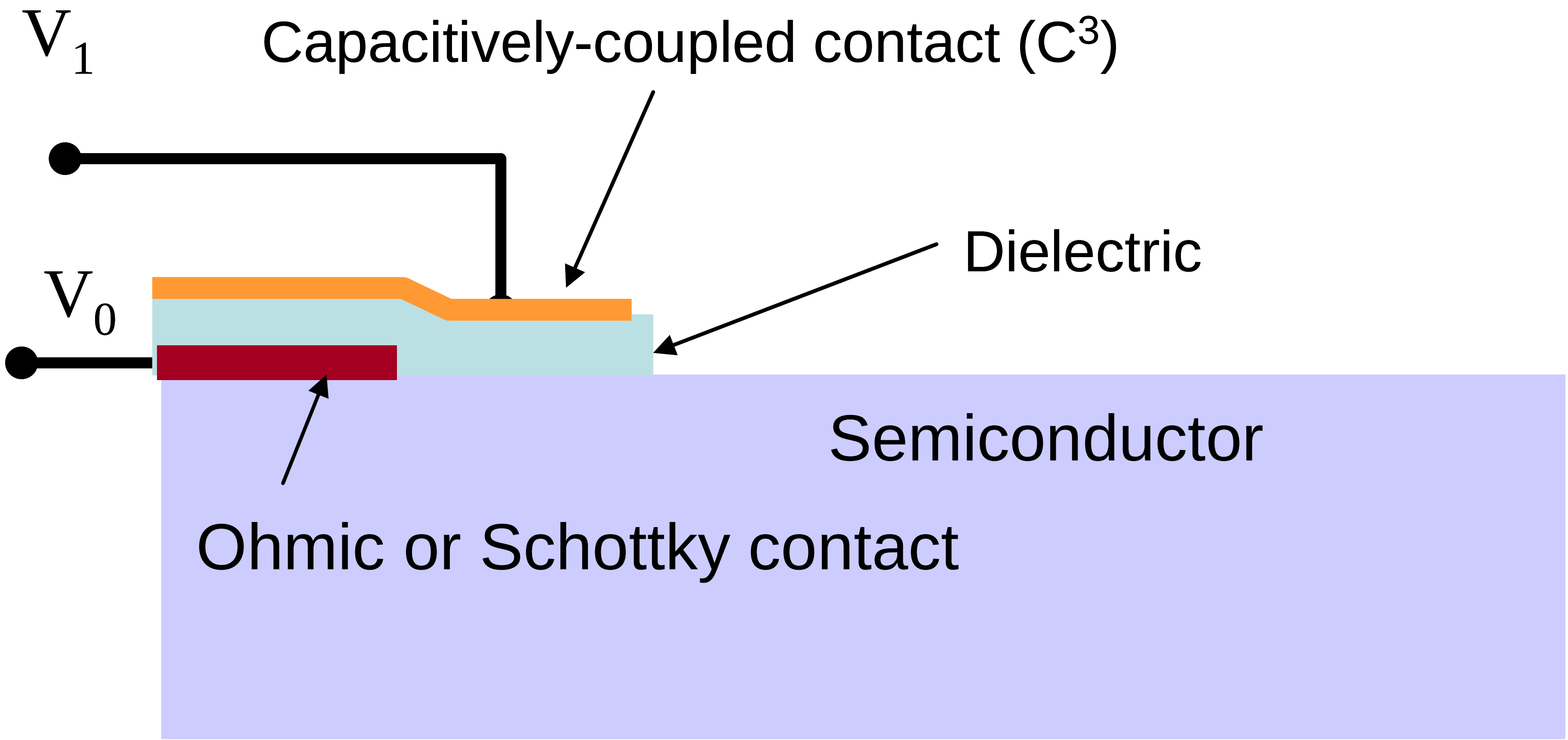
From V. O. Turin, M. S. Shur, and D. B. Veksler, IJHSES, vol. 17, No. 1 pp. 19-23 (2007)

Five-terminal HFET with additional biased capacitively coupled contacts



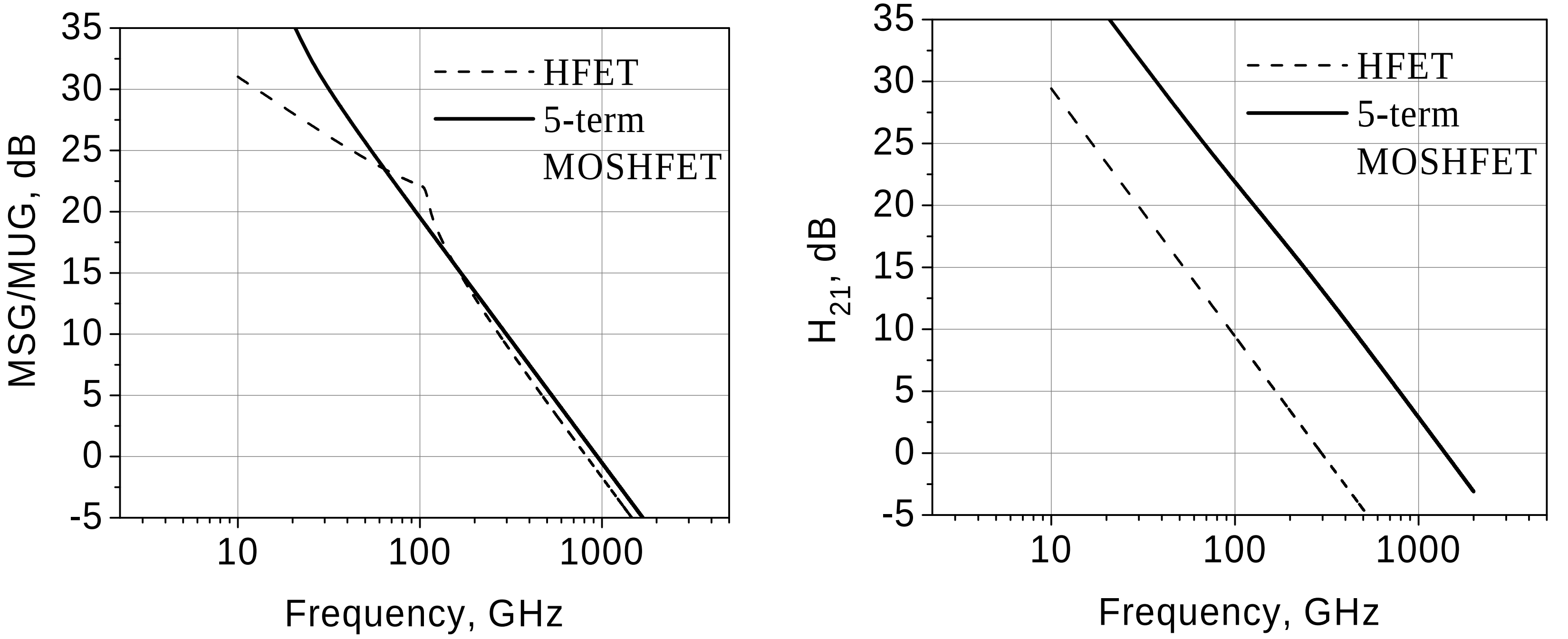
From G. Simin, M. Shur and R. Gaska, IJHSES Vol. 19, No. 7–14, 1 (2009)

Capacitively coupled contact with additional DC bias



After G. Simin, M. Shur, R. Gaska, Patent pending 2/12/2007

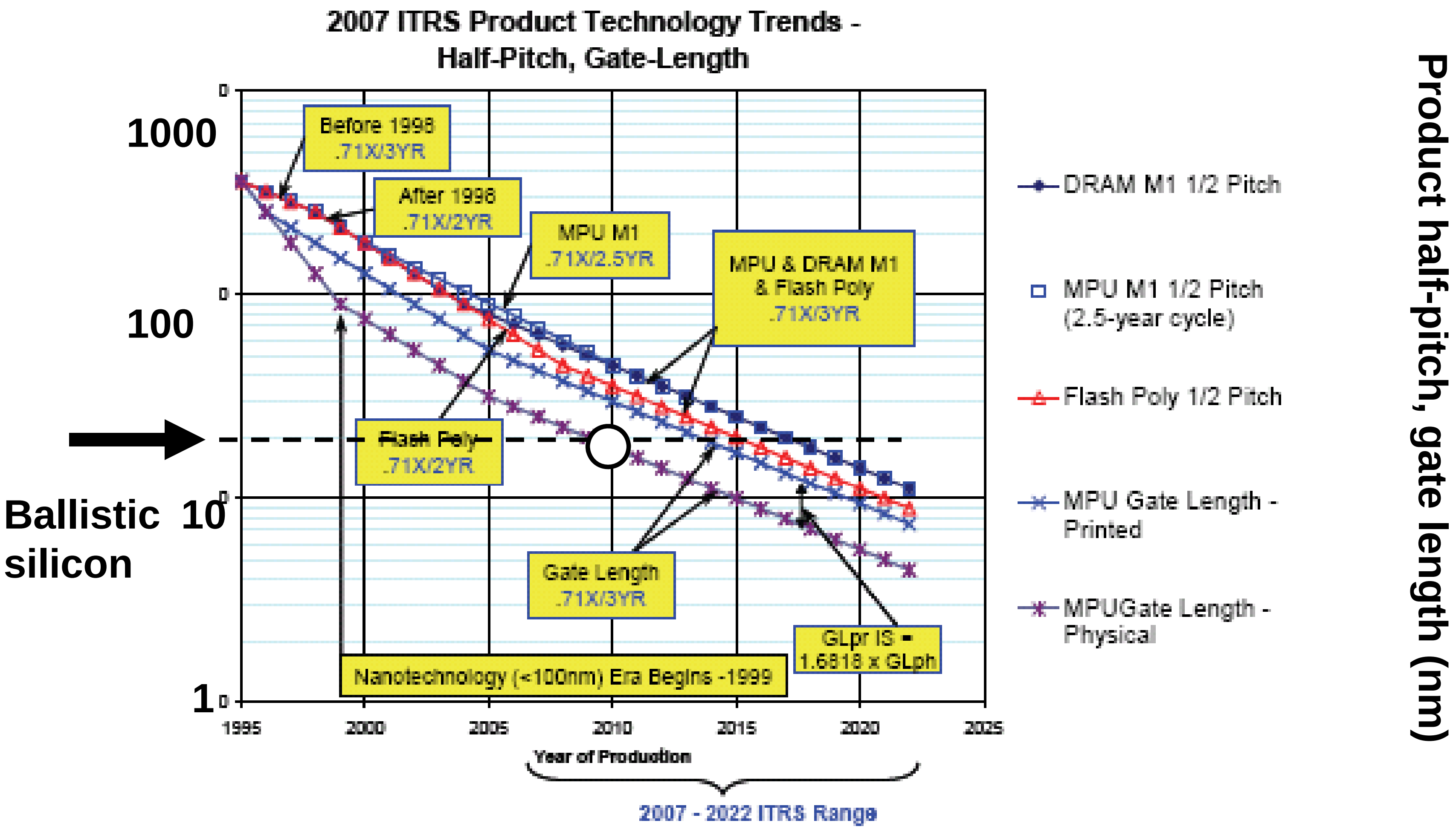
Novel THz Device design:
5-terminal THz GaN HFET



Cut-off frequencies for regular (dash) and 5-terminal (solid) GaN HFETs with 30-nm long gate (ADS simulations).

G. Simin, M. Shur and R. Gaska, ISDRS, accepted for publication (2009)

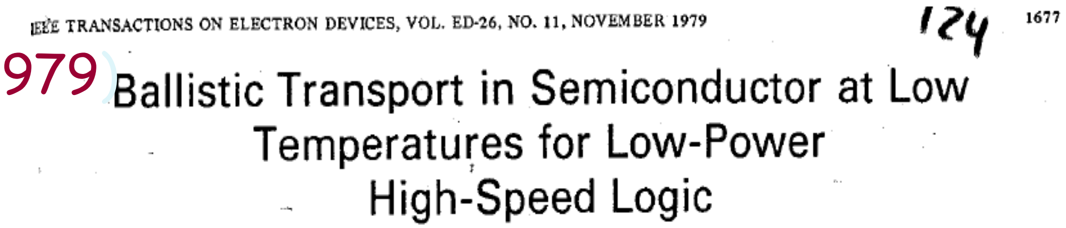
Product Half Pitch, Gate length (nm)



FROM INTERNATIONAL TECHNOLOGY ROADMAP FOR SEMICONDUCTORS
2007 EDITION EXECUTIVE SUMMARY

THz Performance Using 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

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

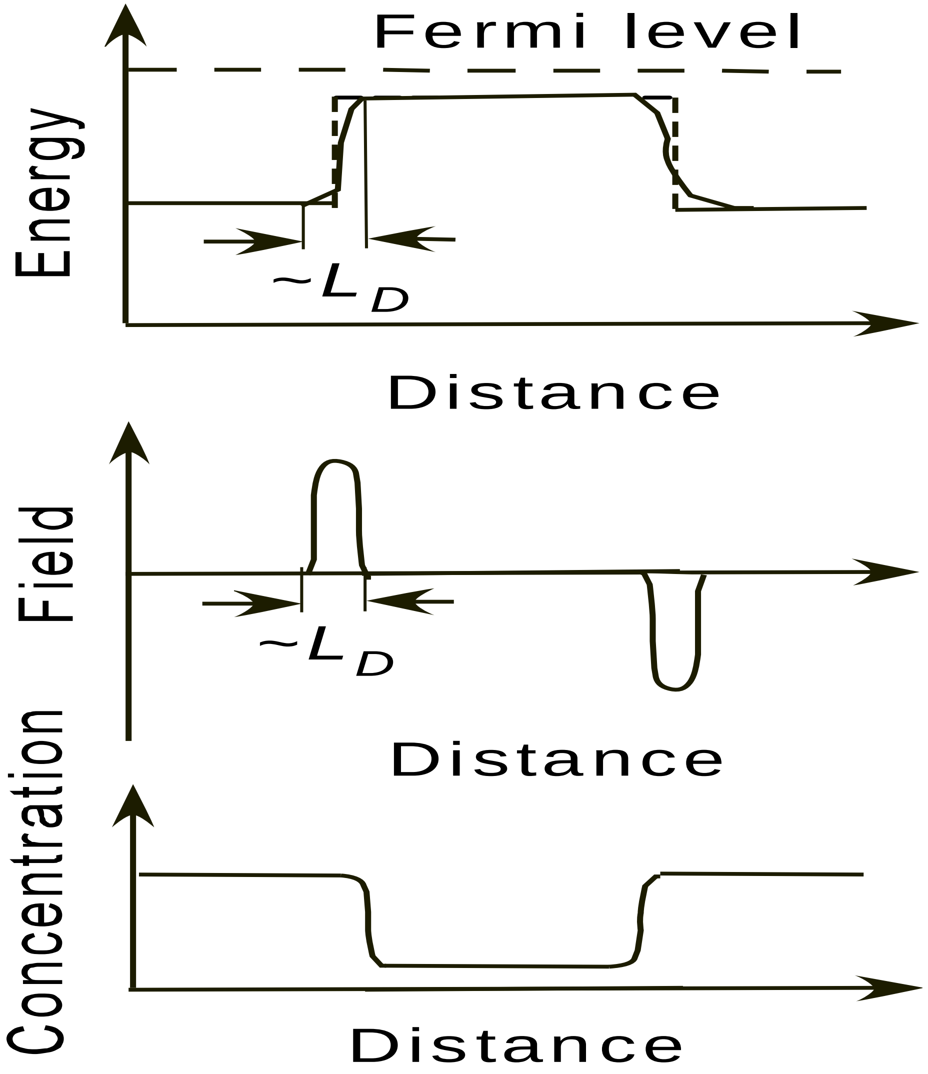
Ballistic Transistor Has Virtually Unimpeded Current Flow (Dec. 6, 1999)

Intel Itanium 'leapfrog' to 32-nm

Colleen Taylor, Contributing Editor -- Electronic News, 6/14/2007

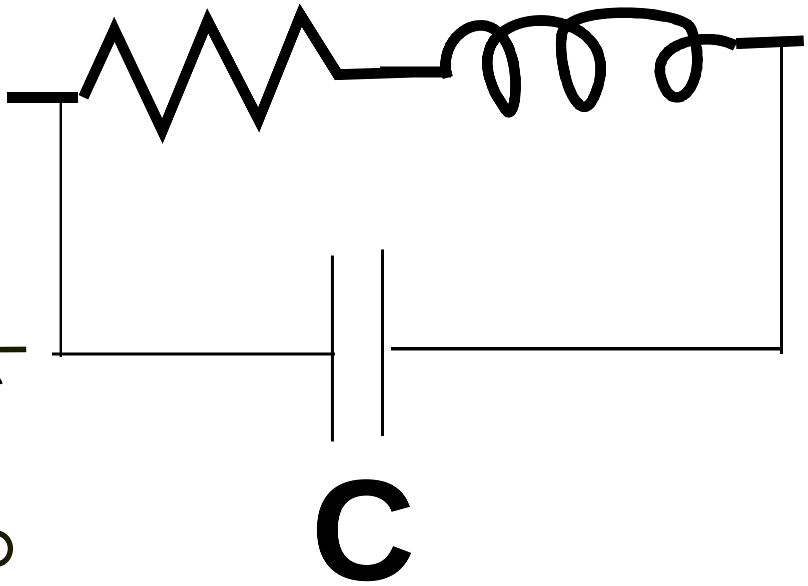
If the 25 nm node predicted by ITRS is reached in 2009 - 2010, all transistors will be ballistic

Energy band, field, and concentration profiles of n^+-n-n^+ sample in equilibrium

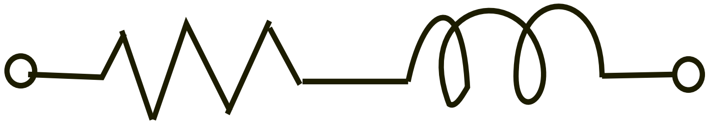


Drude Equation and Equivalent Circuit

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

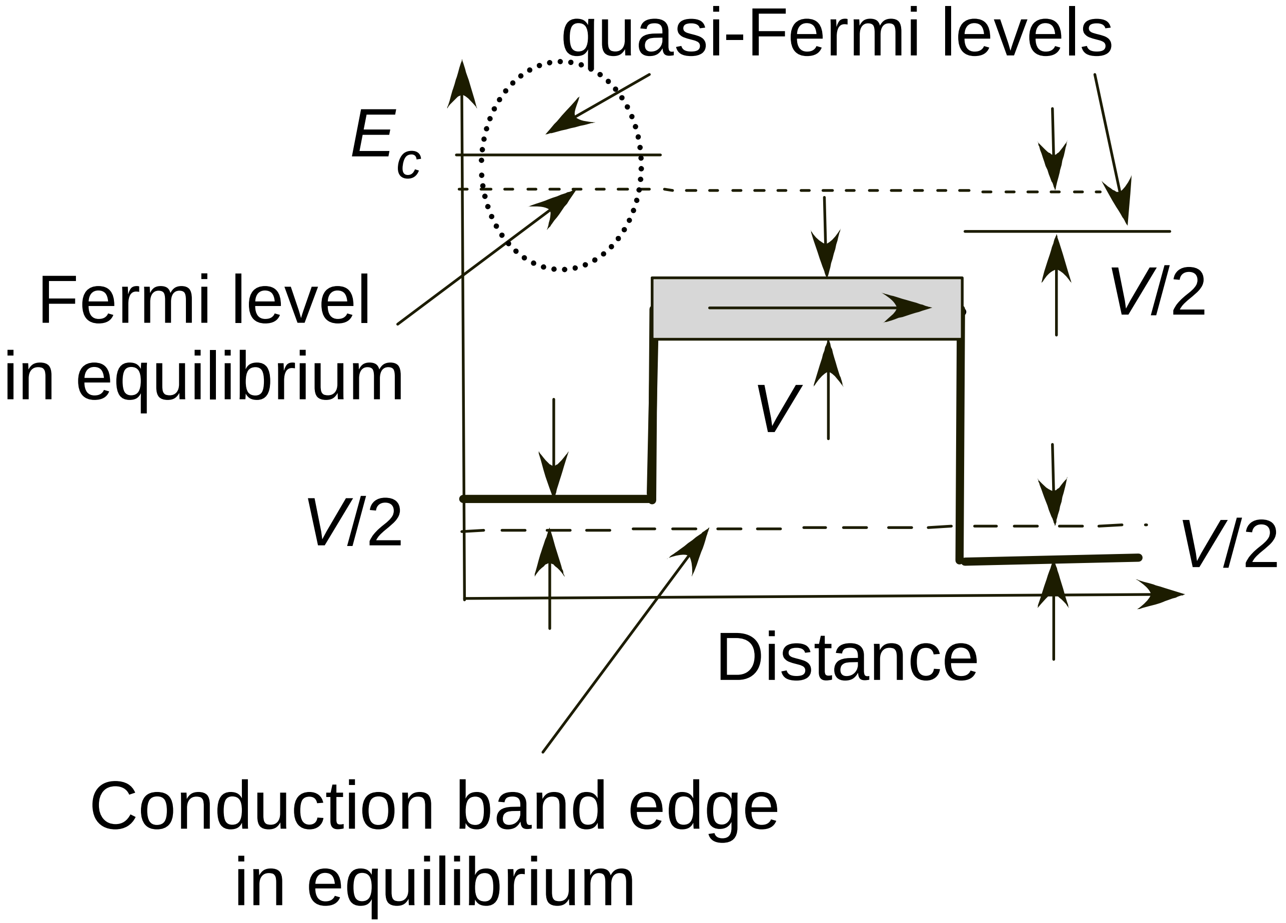


3D $\sigma_o = \frac{e\,\mu\, n\, S}{L}$ $\quad \mathbf{L} = \frac{L\, m}{e^2\, n\, S}$



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

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

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

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).

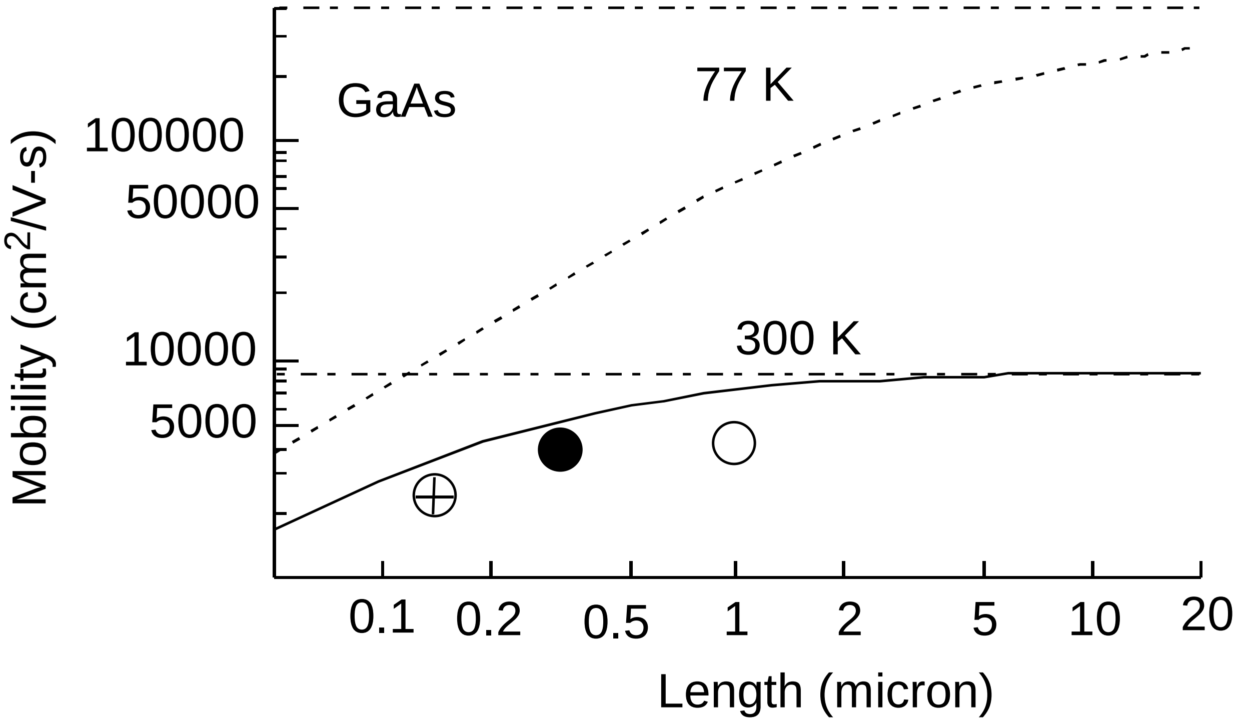
Geometry	Degenerate	Non-degenerate
2D	$\alpha = \frac{2}{\pi}$ $v_F = \frac{\hbar}{m}\sqrt{2\pi n_s}$ [8]	$\alpha = \frac{1}{2}$ $v_{th} = \left(\frac{\pi k_B T}{2m}\right)^{1/2}$ [4]
3D	$\alpha = 3/4$ $v_F = \frac{\hbar}{m}\left(3\pi^2 n_s\right)^{3/4}$	$\alpha = \frac{2}{\pi}$ $v_{th} = \left(\frac{8k_B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

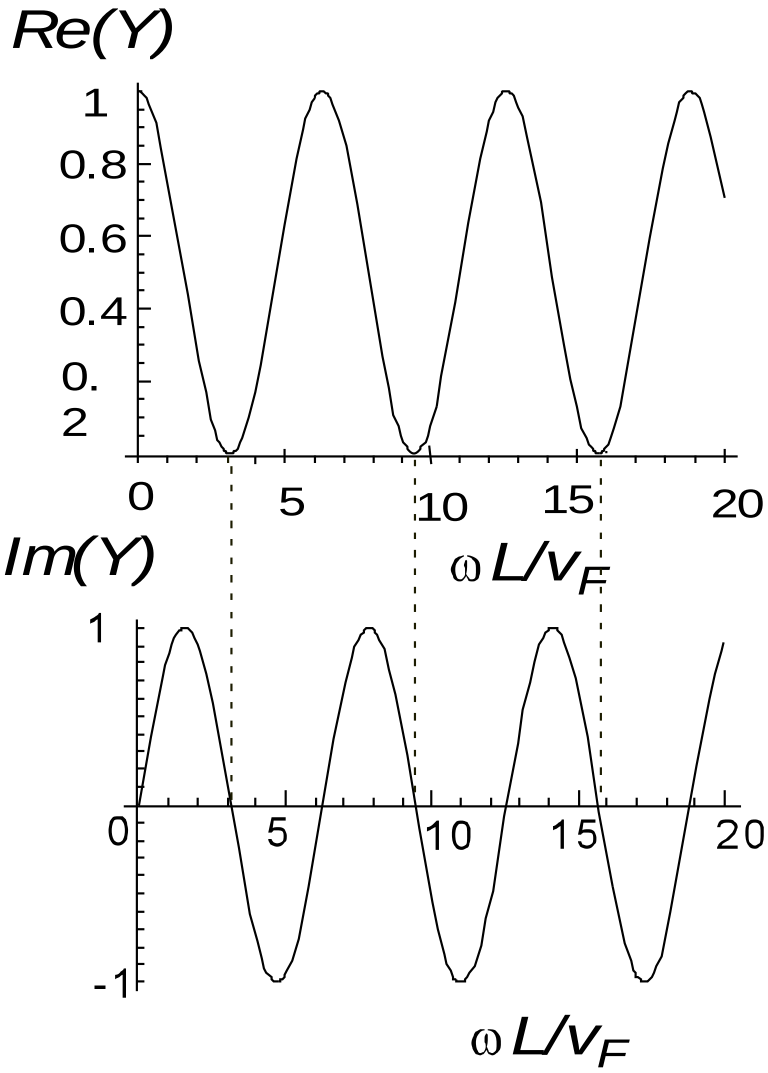
Experimental Evidence for Ballistic Mobility (after Shur (2002)



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

Ballistic Admittance in Quantum Wires

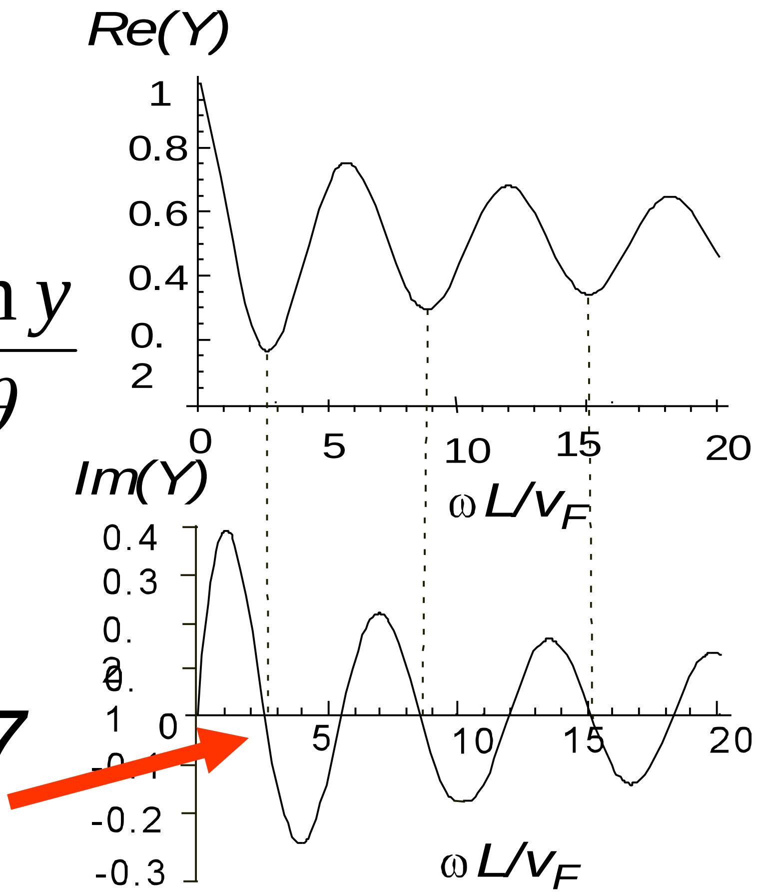
However in 1D systems e-e interaction might completely destroy these oscillations



After M. Buttiker, J. Phys. Cond. Matter, vol. 5, 93-61 (1993)

Ballistic Admittance versus Frequency

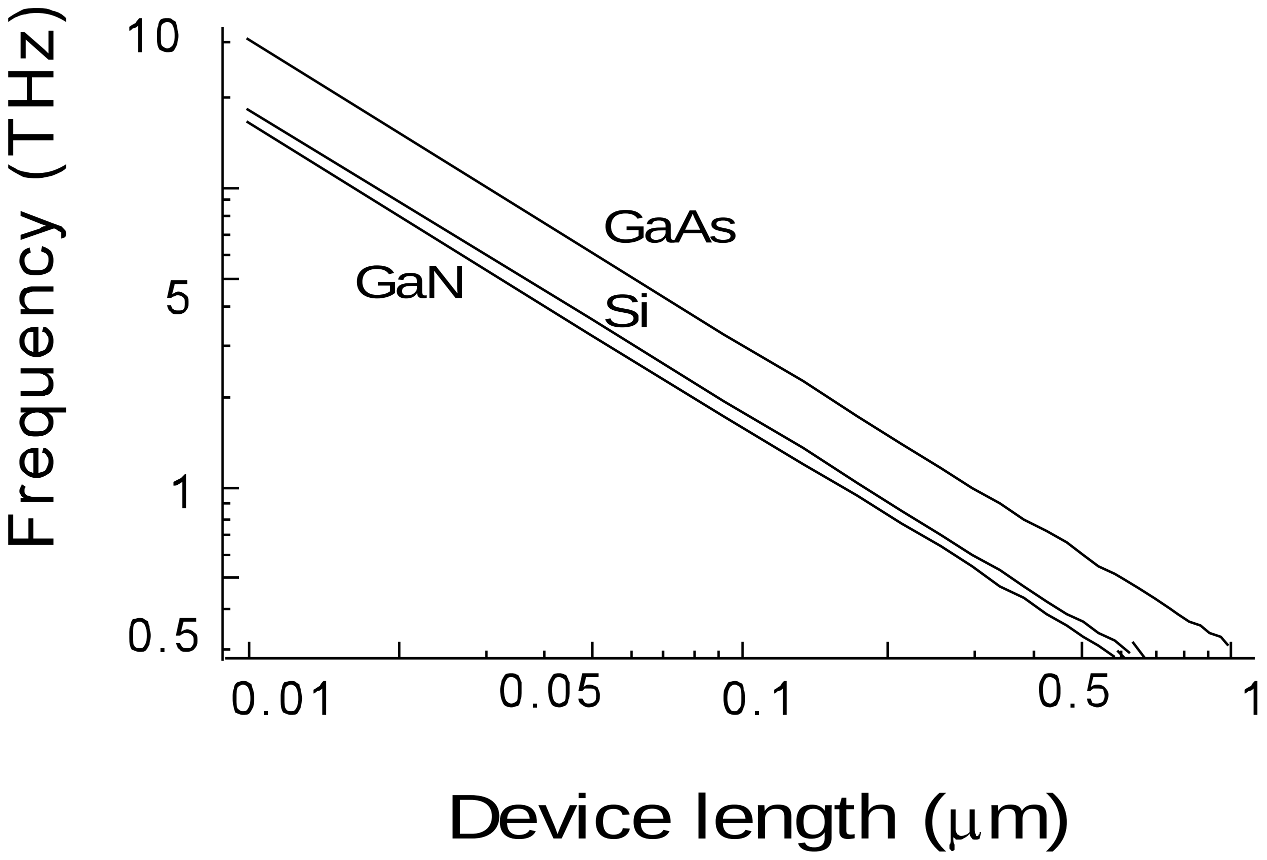
$$Q = \frac{\omega}{\mathrm{Re}\,Y}\frac{d\,\mathrm{Im}\,Y}{d\omega} = \frac{\theta}{\mathrm{Re}\,y}\frac{d\,\mathrm{Im}\,y}{d\theta}$$



Q ~ 7

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

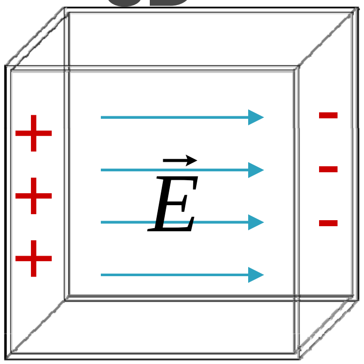
Oscillation frequency



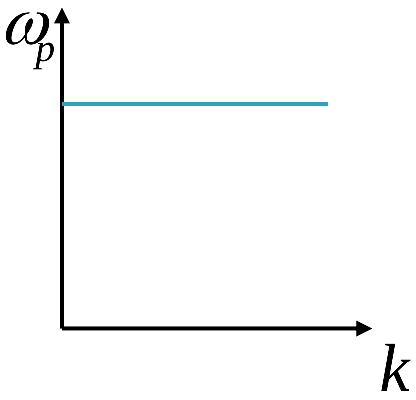
After A. P. Dmitriev and M. S. Shur, Appl. Phys. Lett., 89, 142102, (2006)

Dispersion of Plasma Waves

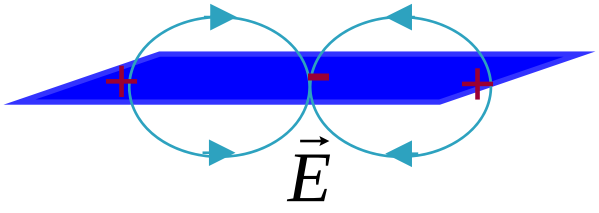
3D



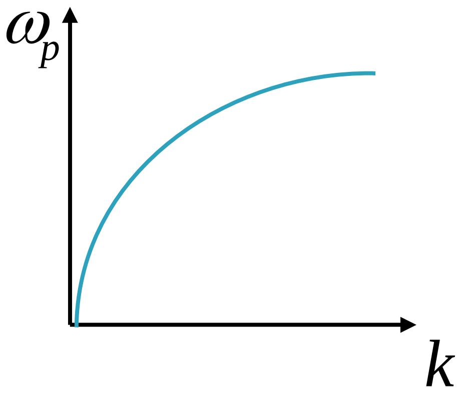
$$\omega_p = \sqrt{\frac{e^2 N_{3D}}{\varepsilon\varepsilon_0 m}}$$



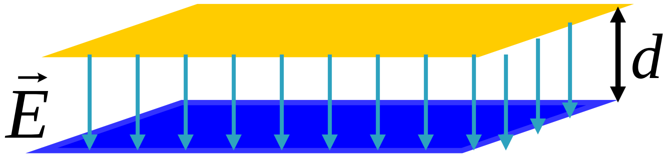
2D ungated



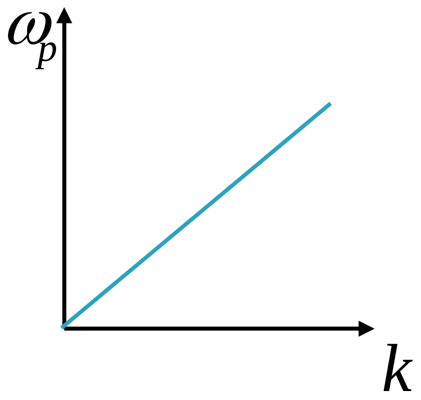
$$\omega_p = \sqrt{\frac{e^2 N_{2D}}{2\varepsilon\varepsilon_0 m}k}$$



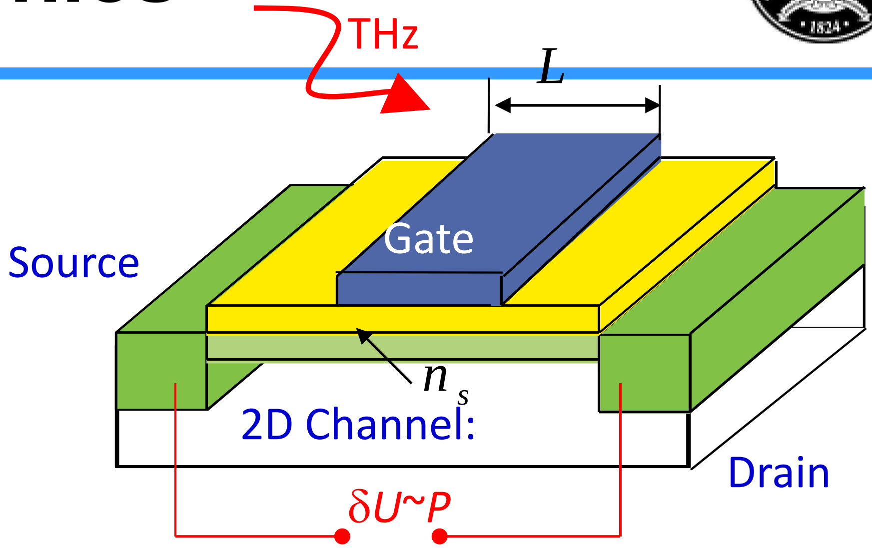
2D gated



$$\omega_p = \sqrt{\frac{e^2 N_{2D} d}{\varepsilon\varepsilon_0 m}}\,k \quad kd<<1$$



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*)

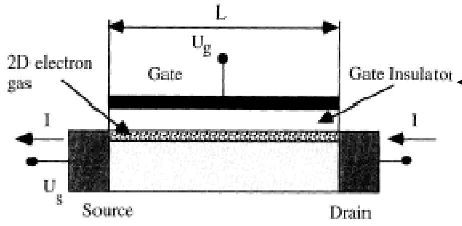
Water wave analogy

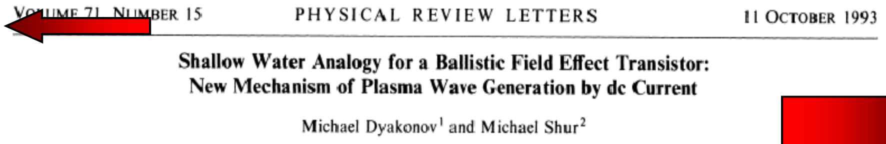
---

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

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

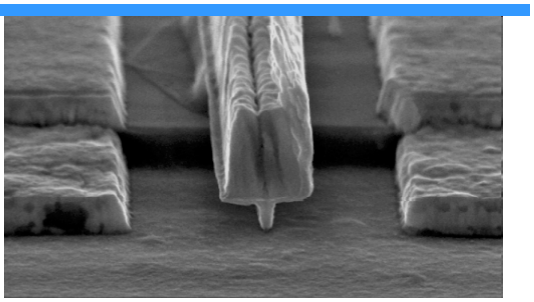
Plasma Wave THz Electronics

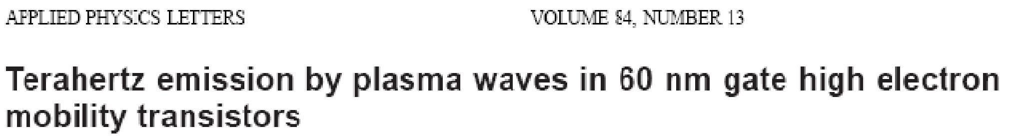



VOLUME 71, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1993

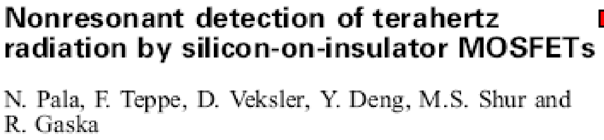
Shallow Water Analogy for a Ballistic Field Effect Transistor: New Mechanism of Plasma Wave Generation by dc Current

Michael Dyakonov[1] and Michael Shur[2]

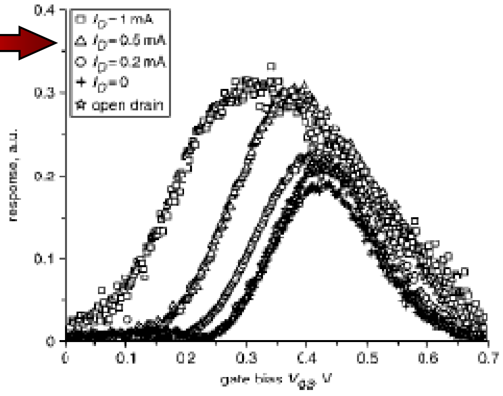

(Courtesy of W. Knap)

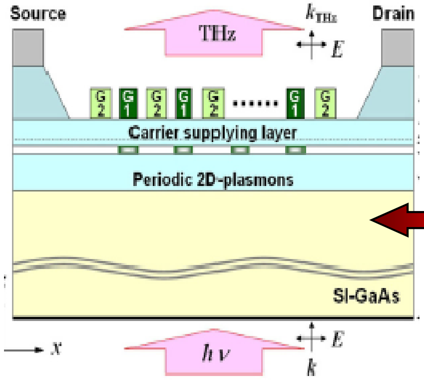

APPLIED PHYSICS LETTERS VOLUME 84, NUMBER 13 29 MARCH 2004

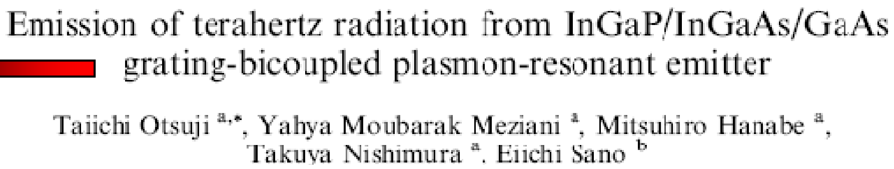
Terahertz emission by plasma waves in 60 nm gate high electron mobility transistors


Nonresonant detection of terahertz radiation by silicon-on-insulator MOSFETs

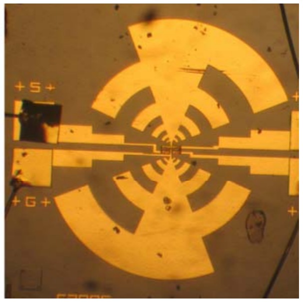
N. Pala, F. Teppe, D. Veksler, Y. Deng, M.S. Shur and R. Gaska

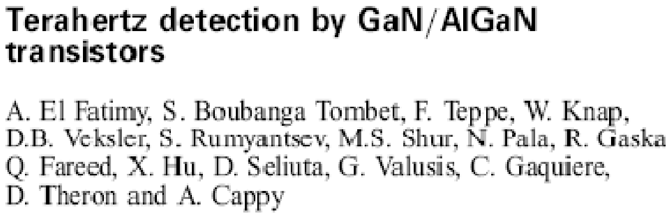




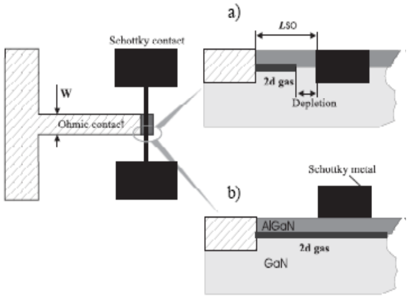

Emission of terahertz radiation from InGaP/InGaAs/GaAs grating-bicoupled plasmon-resonant emitter

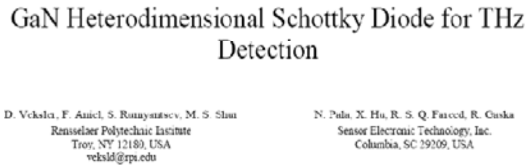
Taiichi Otsuji [a,*], Yahya Moubarak Meziani [a], Mitsuhiro Hanabe [a], Takuya Nishimura [a], Eiichi Sano [b]




Terahertz detection by GaN/AlGaN transistors

A. El Fatimy, S. Boubanga Tombet, F. Teppe, W. Knap, D.B. Veksler, S. Rumyantsev, M.S. Shur, N. Pala, R. Gaska Q. Fareed, X. Hu, D. Seliuta, G. Valusis, C. Gaquiere, D. Theron and A. Cappy




GaN Heterodimensional Schottky Diode for THz Detection

D. Veksler, F. Aniel, S. Rumyantsev, M. S. Shur
Rensselaer Polytechnic Institute
Troy, NY 12180, USA
veksld@rpi.edu

N. Pala, X. Hu, R. S. Q. Fareed, R. Gaska
Sensor Electronic Technology, Inc.
Columbia, SC 29209, USA

2D Plasmonic Devices for THz Applications

THz Detectors and Mixers

- M. Dyakonov and M. Shur, IEEE T-ED (1996)
- K. Guven et al., PRB (1997)
- V. Ryzhii et al., JAP (2002)
- W. Knap et al., APL, JAP (2002)
- X.G. Peralta et al., APL (2002)
- A. Satou et al., SST (2003)
- V.V. Popov et al., JAP (2003)
- V. Ryzhii et al., JAP (2003)
- F. Teppe et al., APL (2005)
- I.V. Kukushkin et al., APL (2005)
- D. Veksler et al., PRB (2006)
- Knap et al APL (2008)
- Stillman et al (2008)

THz Generators

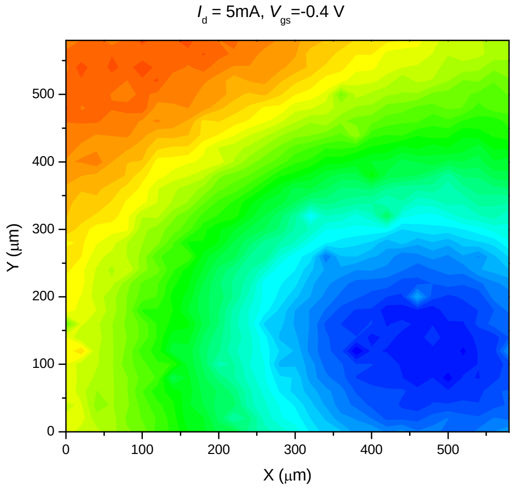
- M. Dyakonov, M. Shur, PRL (1993)
- K. Hirakawa, APL (1995)
- K. D. Maranowski, APL (1996)
- V.V. Popov et al., Physica A (1997)
- S.A. Mikhailov, PRB (1998); APL (1998)
- P. Bakshi et al., APL (1999)
- N. Sekine at al., APL (1999)
- R. Bratshitsch et al., APL (2000)
- Y. Deng at al., APL (2004)
- W. Knap et al., APL (2004)
- M. Dyakonov and M.S .Shur, APL (2005)
- N. Dyakonova et al., APL (2006)
- Otsuji APL (2006) DRC 2007
- Otsuji LEC (2008)

Plasma THz Electronics Advantages

- Small size (easy to fabricate matrixes/arrays)

- Compatible with VLSI technology

- For detectors:
  - High sensitivity
  - Broad spectral range
  - Band selectivity and tunability
  - Fast temporal response



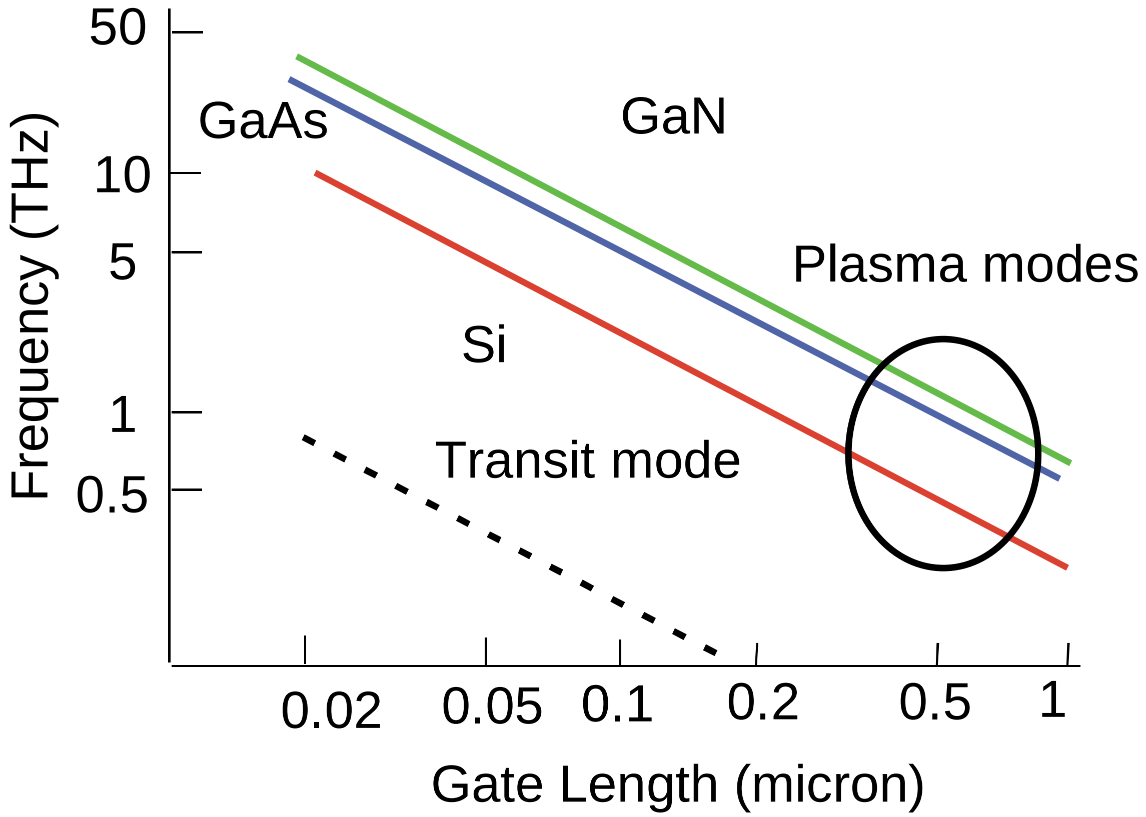
Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging,
International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Plasma Waves in a Field Effect Transistor

- •Plasma frequency can be tuned by gate-to-channel voltage

- •FET channel plays a role of a resonant cavity for plasma waves

- •Plasma waves can propagate much faster than electrons

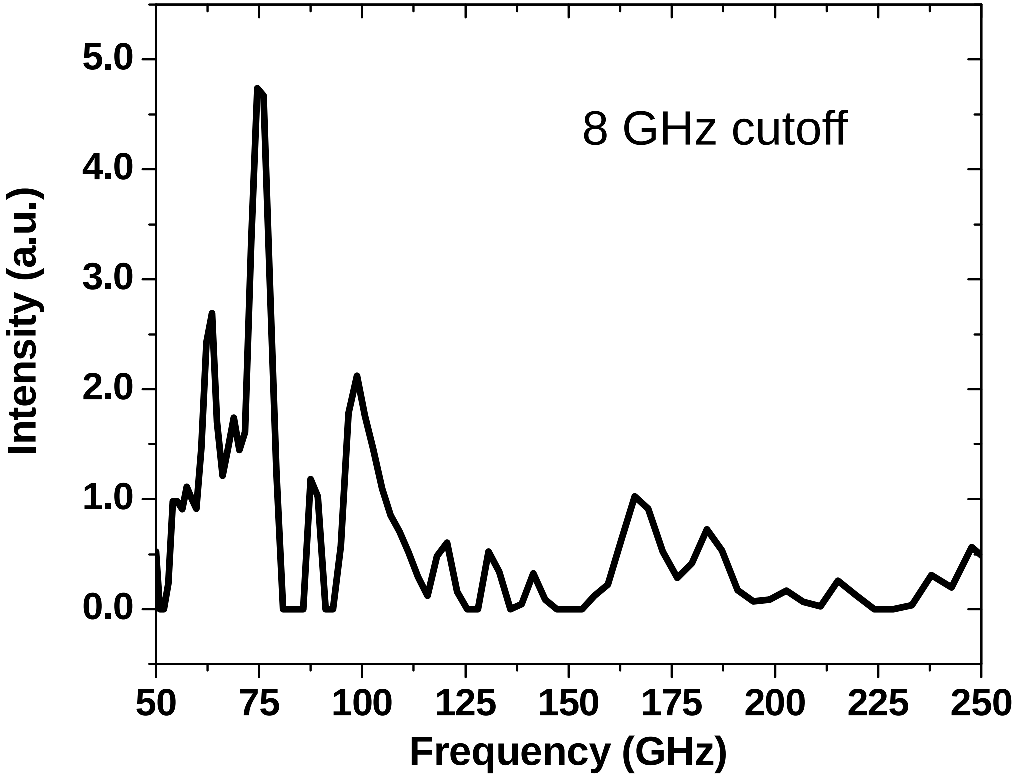


From V. Ryzhii and M.S. Shur, Plasma Wave Electronics Devices, ISDRS Digest, WP7-07-10, pp 200-201, Washington DC (2003)

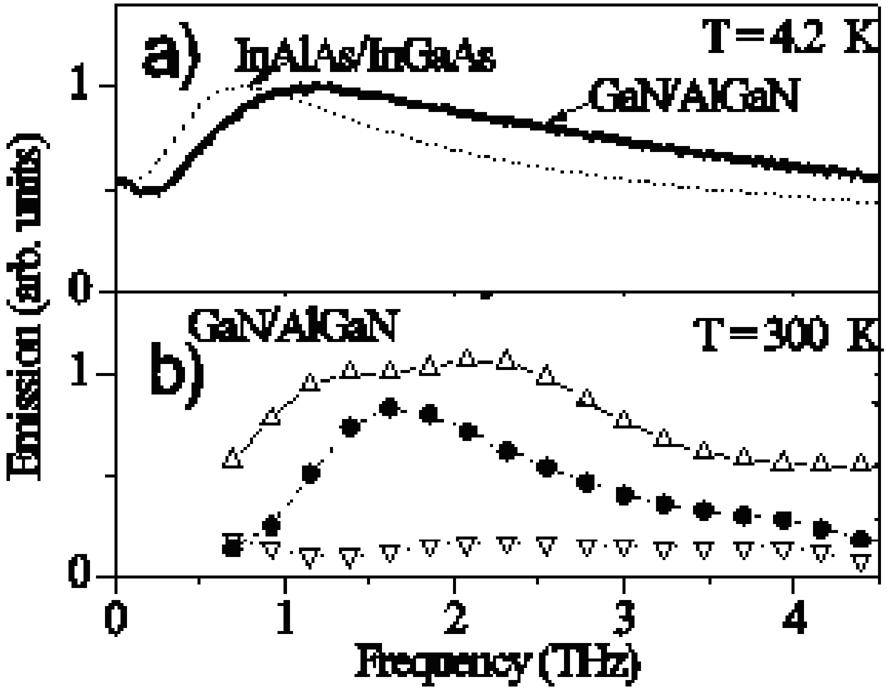
Radiation intensity from 1.5 micron GaN HFET at 8 K

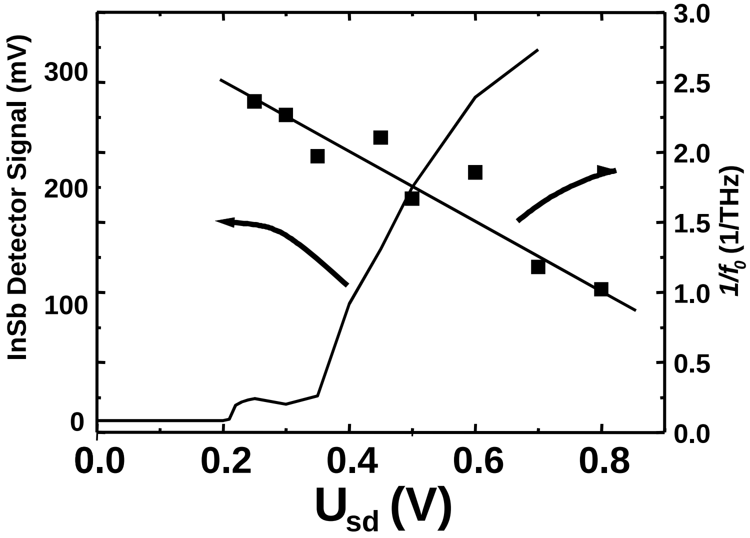
-

From Y. Deng, R. Kersting, J. Xu, R. Ascazubi, X. C. Zhang, M. S. Shur, R. Gaska,
G. S. Simin and M. A. Khan, and V. Ryzhii, Millimeter Wave Emission from GaN HEMT,
Appl. Phys. Lett. Vol. 84, No 15, pp. 70-72, January 2004



Room Temperature Tunable Emission

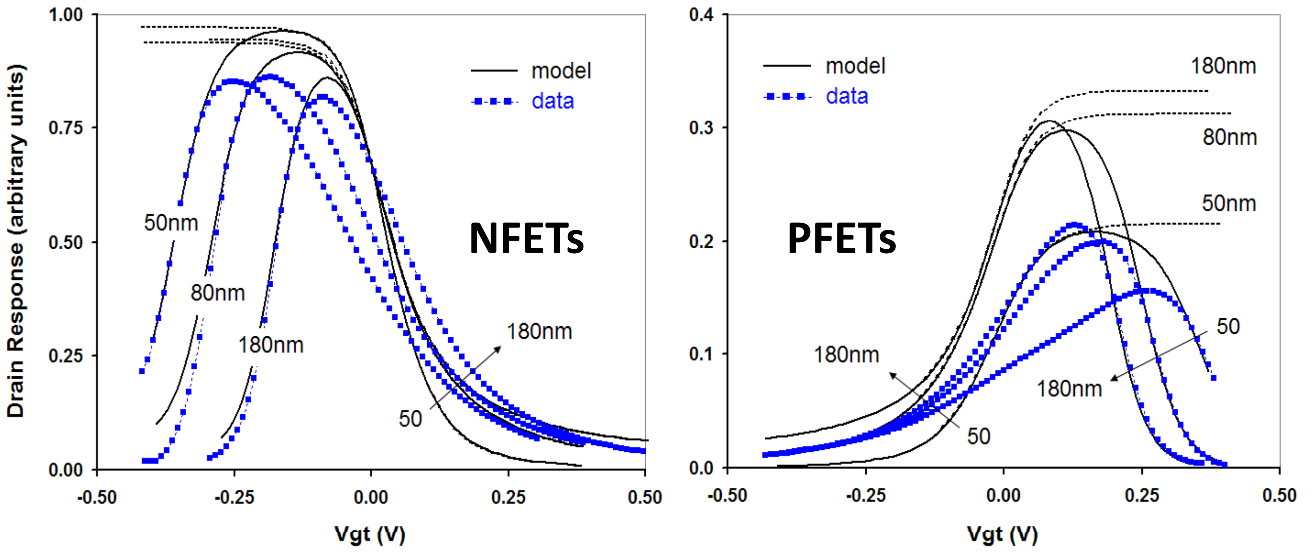




From D. B. Veksler, A. El Fatimy, N. Dyakonova, F. Teppe, W. Knap, N. Pala, S. Rumyantsev, M. S. Shur, D. Seliuta, G. Valusis, S. Bollaert, A. Shchepetov, Y. Roelens, C. Gaquiere, D. Theron, and A. Cappy, in Proceedings of 14th Int. Symp. "Nanostructures: Physics and Technology" St Petersburg, Russia, June 26-30, 2006, pp 331-333

From W. Knap, J. Lusakowski, T. Parenty, S. Bollaert, A. Cappy, V. Popov, and M. S. Shur,
Appl. Phys. Lett. 84, No 13, 2331-2333, March 29 (2004)

THz response of CMOS (non-resonant)



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

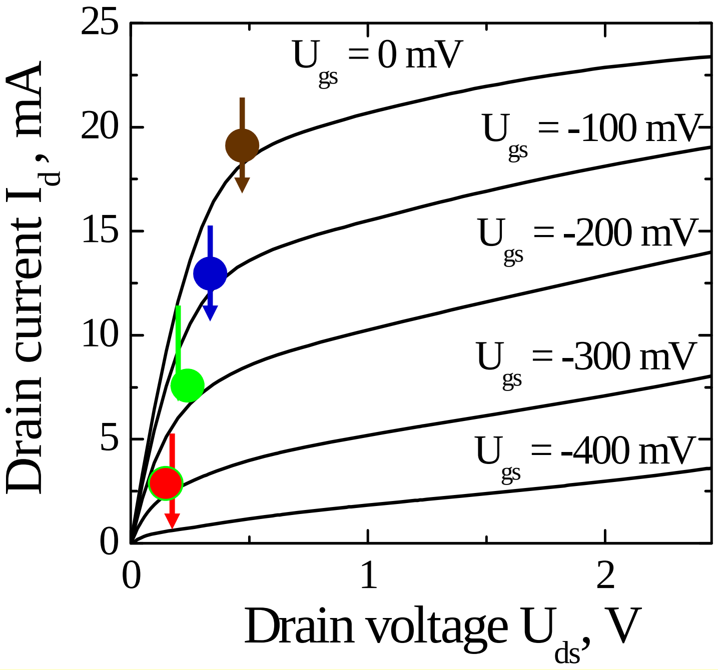
- ***Extension earlier work on n-channel Si FET response to p-channel devices.***
- ***Compare and contrast n and p-channel responsivity, detectivity and response speed in open drain and drain current enhanced response configurations.***

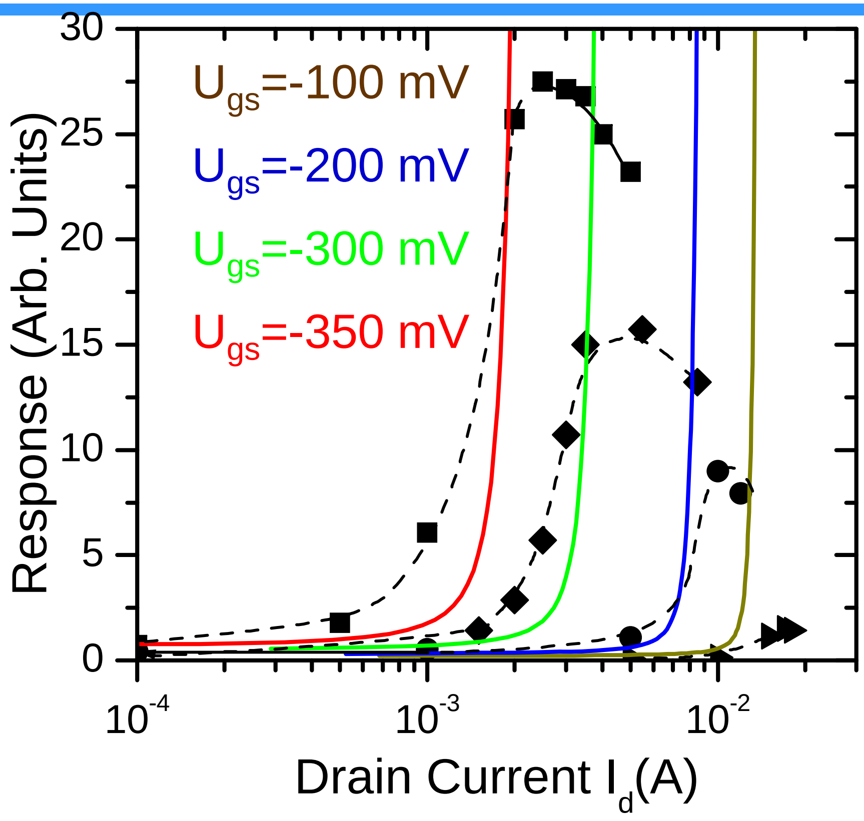
From W. Stillman, F. Guarin, V. Yu. Kachorovskii, N. Pala, S. Rumyantsev, M.S. Shur, and D. Veksler, Nanometer Scale Complementary Silicon MOSFETs as Detectors of Terahertz and Sub-terahertz Radiation, in Abstracts of IEEE sensors Conference, Atlanta, GA, October 2007, pp. 479-480

Non-resonant detection (ωτ<<1)

f = 0.2 THz; T=300 K

250 nm GaAs FET





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

$$j_d \ll j_{sat}$$

Symbols – experiment

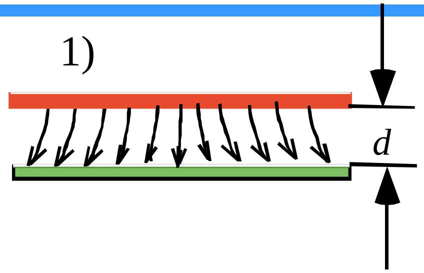
Colored curves - theory

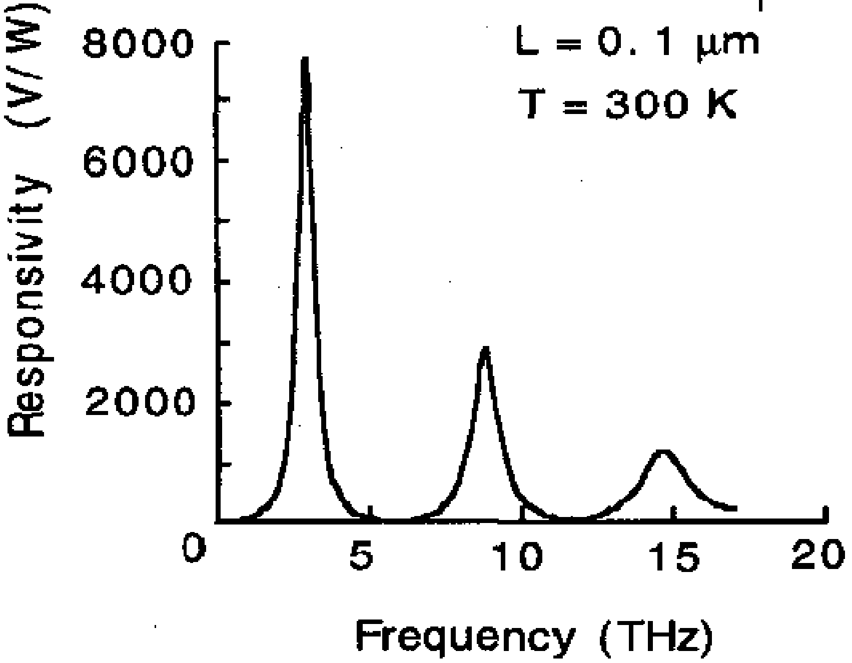
D. Veksler *et al , Phys. Rev. B 73, 125328 (2006).*

HEMT for Resonant THz detection

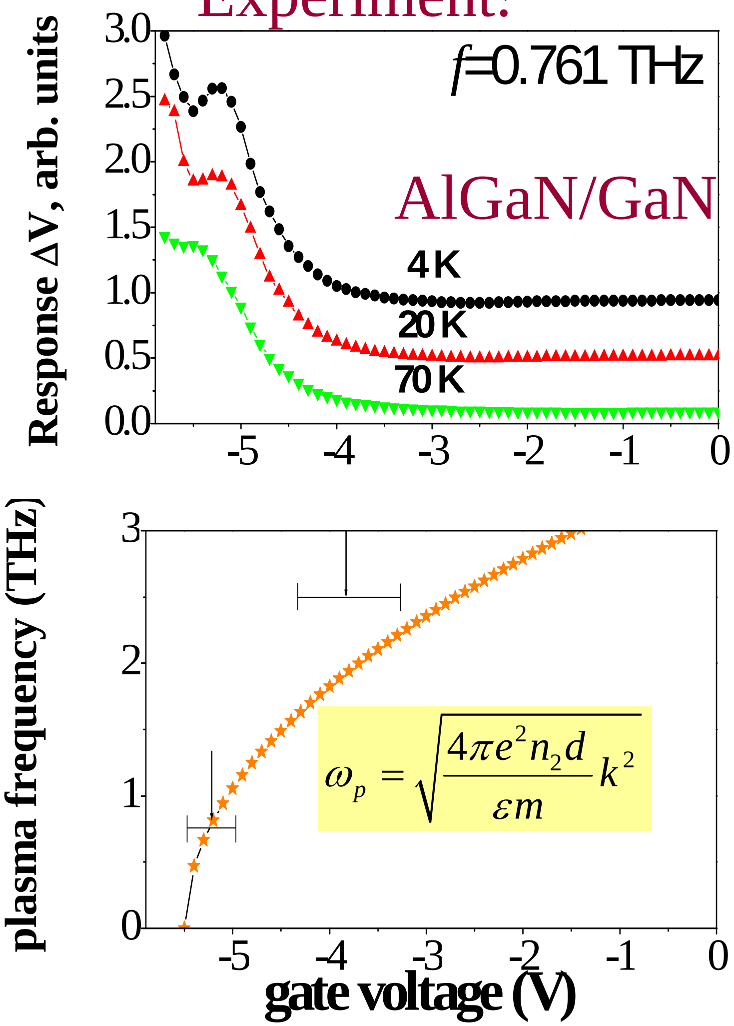
Theory:

1)





Experiment:2)

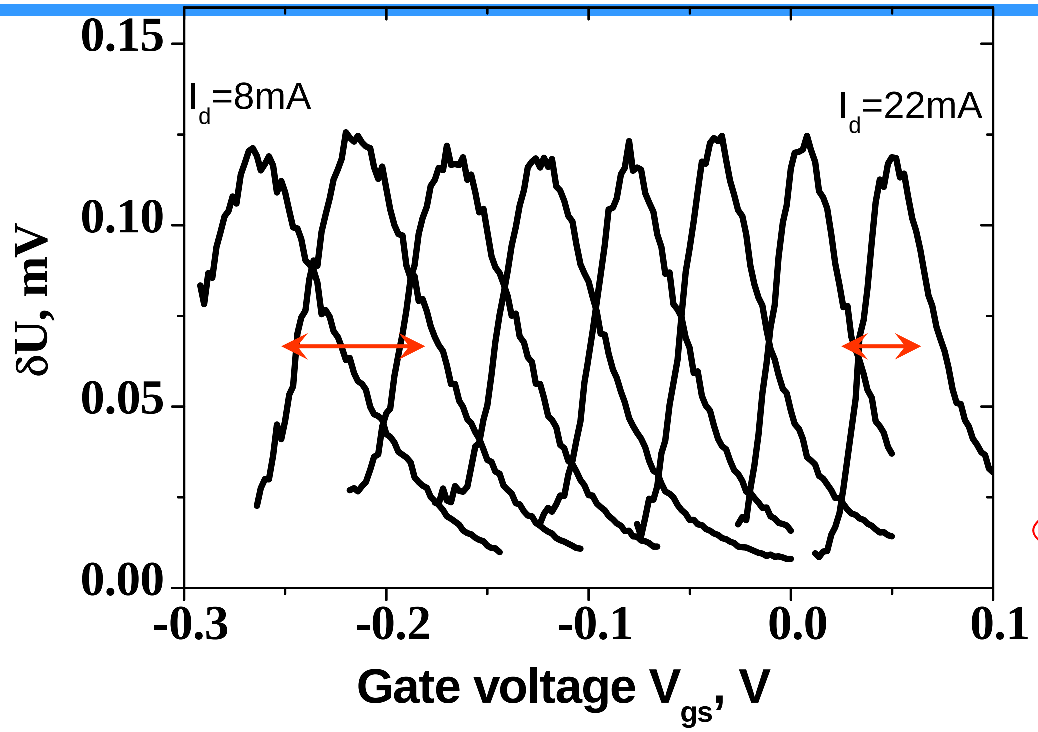


$$\omega_p = \sqrt{\frac{4\pi e^2 n_2 d}{\varepsilon m} k^2}$$

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

2) A. El Fatimy, N. Dyakonova, F. Teppe, W. Knap, N. Pala, R. Gaska, Q. Fareed, X. Hu, D. B. Veksler, S. Rumyantsev, M. S. Shur, D. Seliuta, G. Valusis, S. Bollaert, A. Shchepetov, Y. Roelens, C. Gaquiere, D. Theron, and A. Cappy, Electronics letters, Vol. 42 No. 23, 9 November (2006)

Resonant detection near instability threshold



f = 0.6 THz; T=300 K

***GaAs FET* 250 nm**

$$\omega_0\tau < 1, \text{ but } \omega_0\tau_{eff} >> 1$$

Instability increment

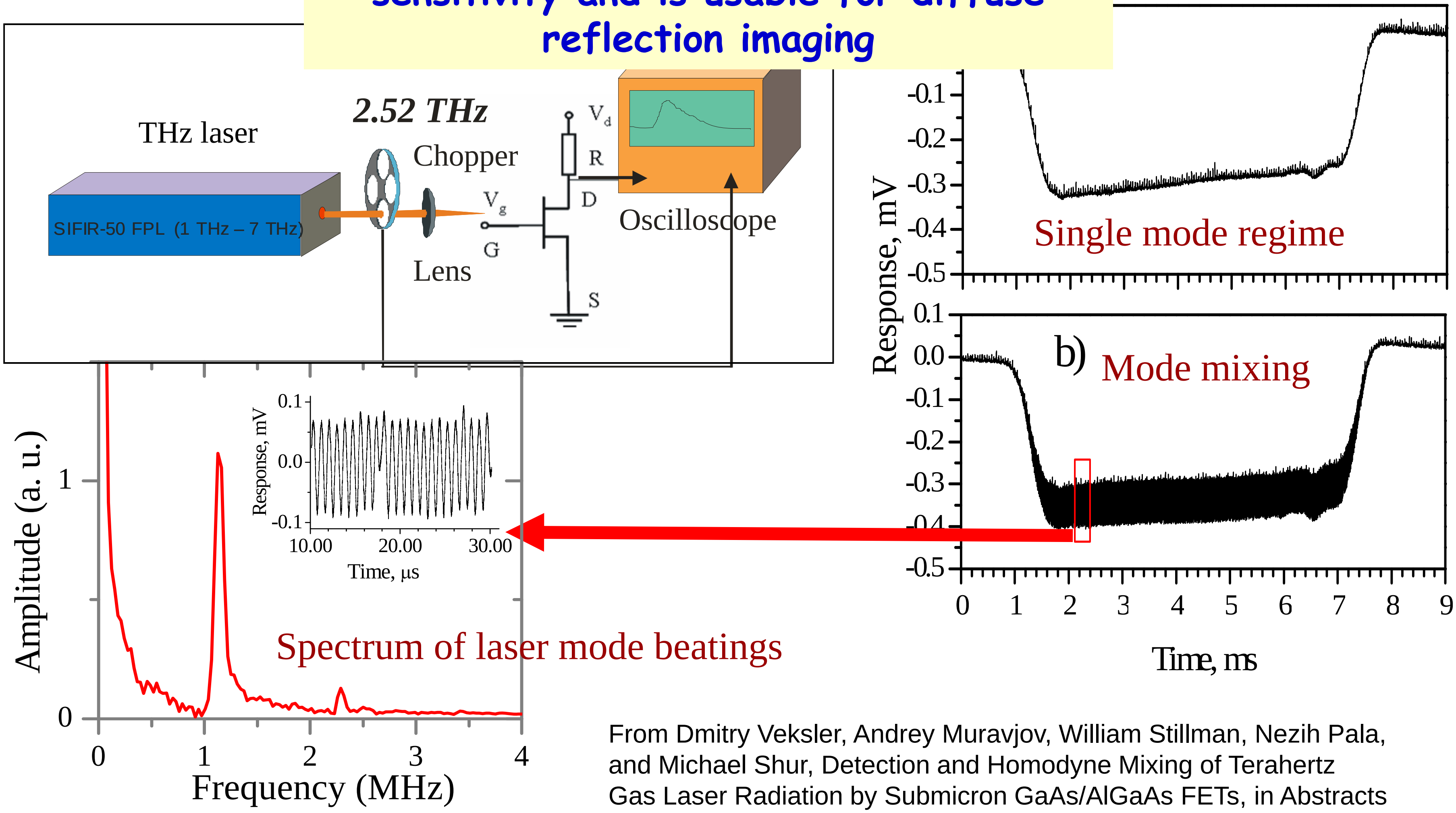
$$\frac{1}{2\tau_{eff}} = \left(\frac{1}{2\tau} - \frac{v_d}{L}\right)$$

The decrement decreases with electron velocity or drain current due to approaching to the threshold of the plasma wave instability.

F. Teppe, W. Knap, D. Veksler, et al, Appl. Phys. Lett. **87**, 052107 (2005)

Homodyne detection by plasma FET: Mixing of laser modes

Heterodyne detection has a much higher sensitivity and is usable for diffuse reflection imaging

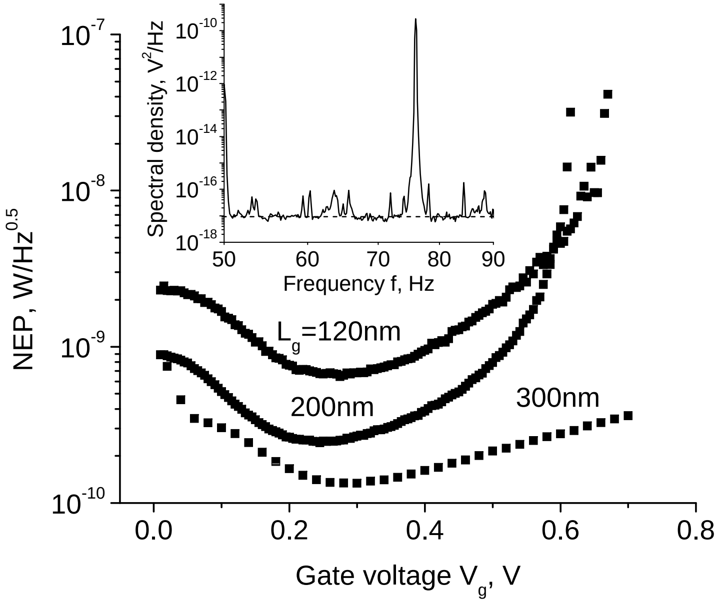


From Dmitry Veksler, Andrey Muravjov, William Stillman, Nezih Pala, and Michael Shur, Detection and Homodyne Mixing of Terahertz Gas Laser Radiation by Submicron GaAs/AlGaAs FETs, in Abstracts of IEEE sensors Conference, Atlanta, GA, October 2007

Comparison of THz Detection Devices (300 K)

Detector	NEP (W/Hz½)	Response time (Hz)
Microbolometer	Not tunable	
Pyroelectric	Not tunable	
Schottky Diode	Not tunable	
Plasma Wave Detector	Tunable	

Si MOS



El Fatimy, N. Dyakonova, F. Teppe, W. Knap,D. B. Veksler, S. Rumyantsev, M. S. Shur, N. Pala, R. Gaska, Q. Fareed, X. Hu, D. Seliuta, G. Valusis, C. Gaquiere, D. Theron, and A. Cappy, IElec. Lett. (2006).

Advantages of Plasma wave detector:

- Band selectivity and tunability (**resonant detection**)
- Fast temporal response
- Small size (easy to fabricate matrixes/arrays)
- Compatible with VLSI technology
- Broad spectral range

Table courtesy of D. Veksler, RPI

Achieved Detector Performance

GaAs :

1 THz detection demonstrated

R ~ 10 - 10^3 V/W

n = 2×10^{11} cm^{-2} L = 0.2 μm.

Detection 120 GHz - 2.5 THz

GaN :

1 THz detection demonstrated

n = 2×10^{13} cm^{-2} & L =2 μm

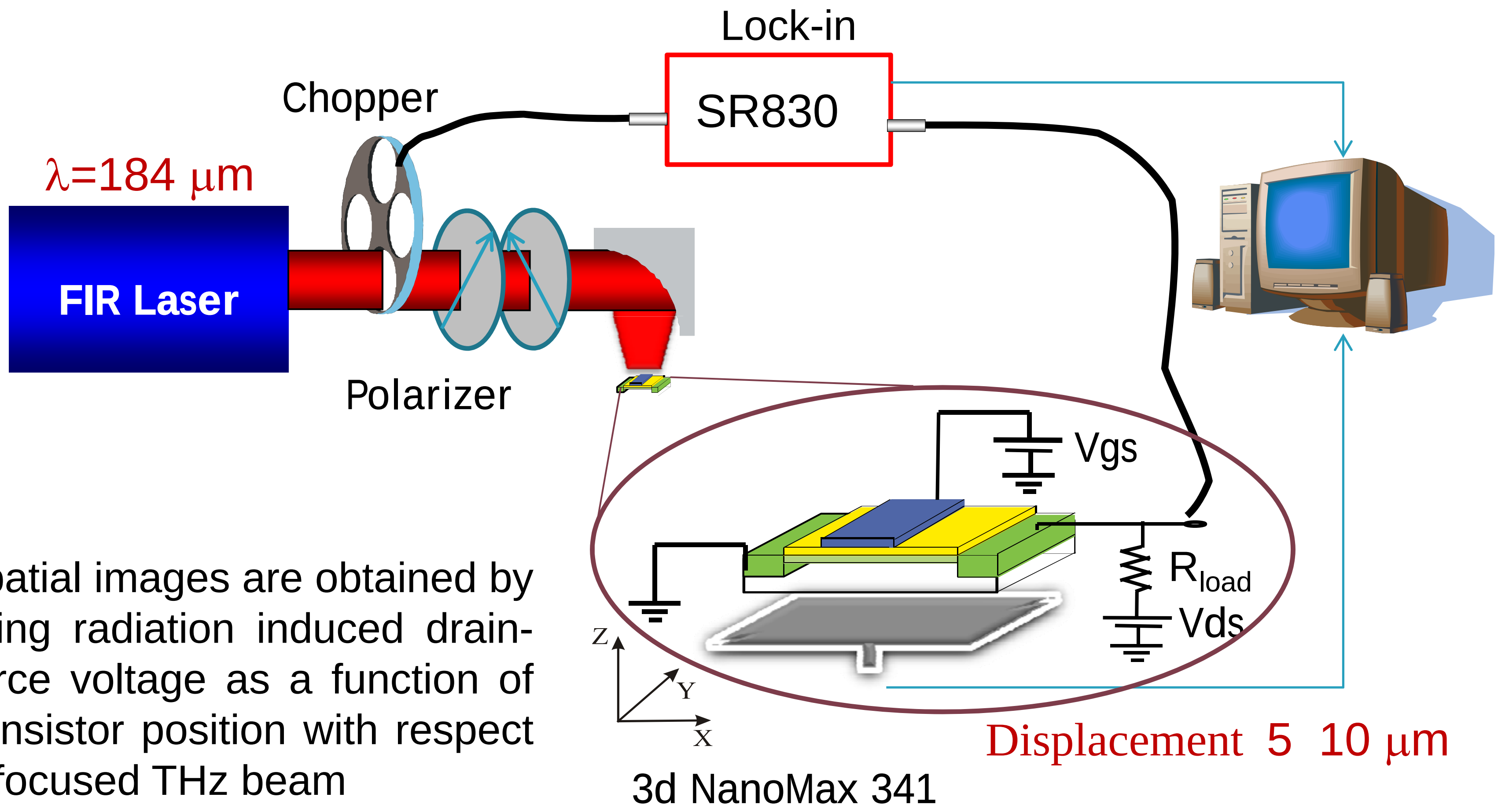
Room temperature generation

(Knap et al Veksler et al (2006)

Si : 120 GHz – 3 THz detection demonstrated

NEP ~ 10^{-10} W/Hz

Subwavelength Imaging: coupling of THz radiation into transistor

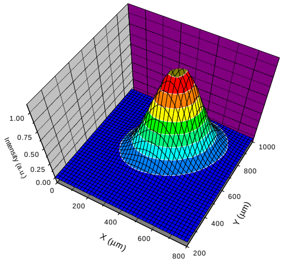


The spatial images are obtained by recording radiation induced drain-to-source voltage as a function of the transistor position with respect to the focused THz beam

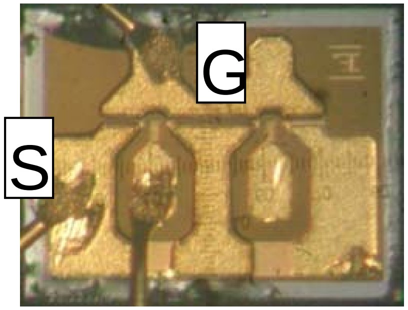
Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Transistor responsivity pattern exhibits two spots of maximum response with different signs

Beam profile in the focal spot:

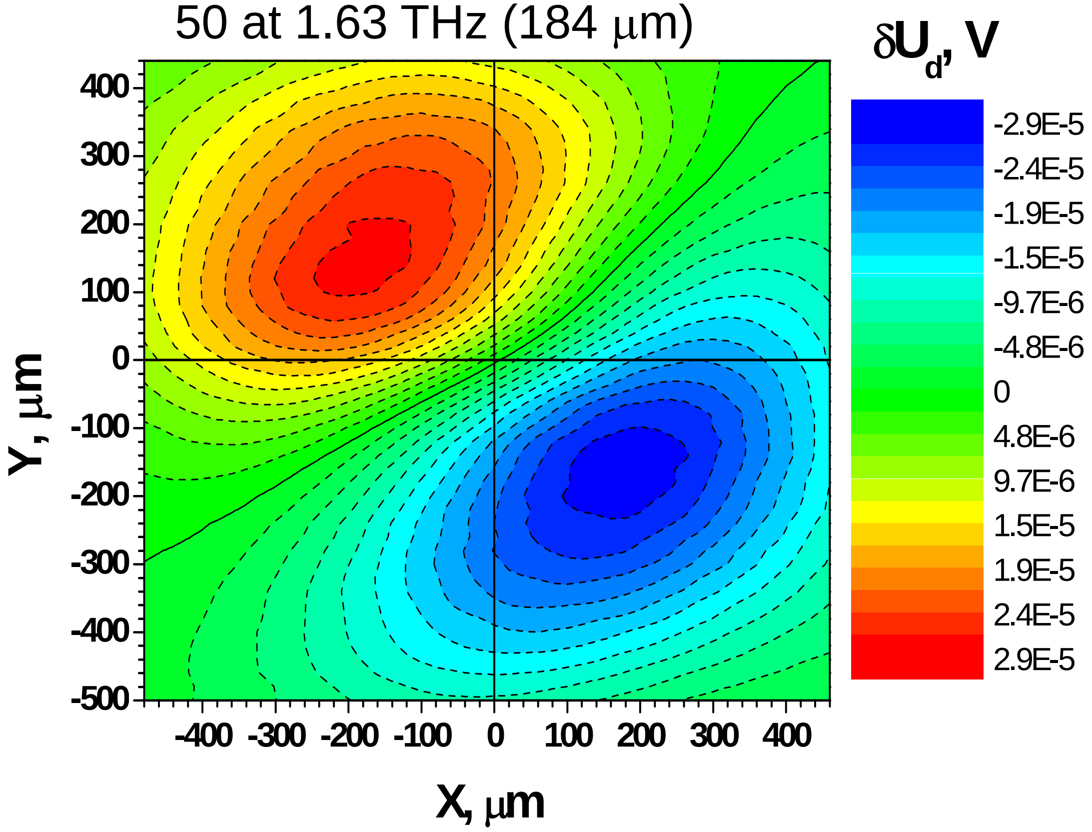


$V_{gs} = 0.45\,V,\ j_d = 0$



Fujitsu FHX06X
GaAs/AlGaAs HEMT
L_g=0.25μm
W=200μm

Source: Terahertz gas laser SIFIR-50 at 1.63 THz (184 µm)

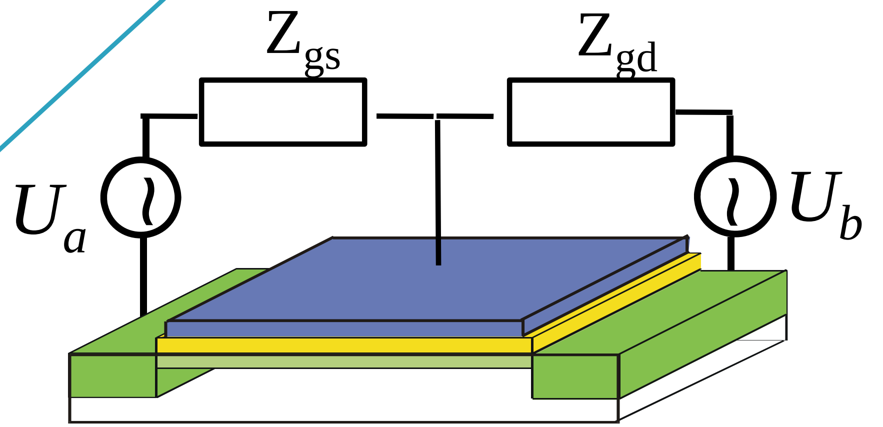


Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Theory

Hydrodynamic equations for 2D gas in the FET channel:

$$\begin{cases} \dfrac{\partial v}{\partial t} + v\dfrac{\partial v}{\partial x} + \dfrac{v}{\tau} + \dfrac{e}{m}\dfrac{\partial U}{\partial x} = 0 \\ \dfrac{\partial n}{\partial t} + \dfrac{\partial (nv)}{\partial x} = 0 \\ en = CU \end{cases}$$



Boundary conditions:

$$U_\omega(0) - j_\omega(0)Z = U_a, U_\omega(L) + j_\omega(L)Z = U_b.$$

We see that the response might have different signs depending on the ratio $|U_a|^2/|U_b|^2$

$$\delta V = -\frac{1}{4U_{gs} - U_{th}}\left(\frac{\omega_0}{\omega}\right)^3\left(\frac{|U_a|^2}{\left(1 - j_d/j_{sat}\right)^{1/2}} - \frac{|U_b|^2}{\left(1 - j_d/j_{sat}\right)^{3/2}}\right)$$

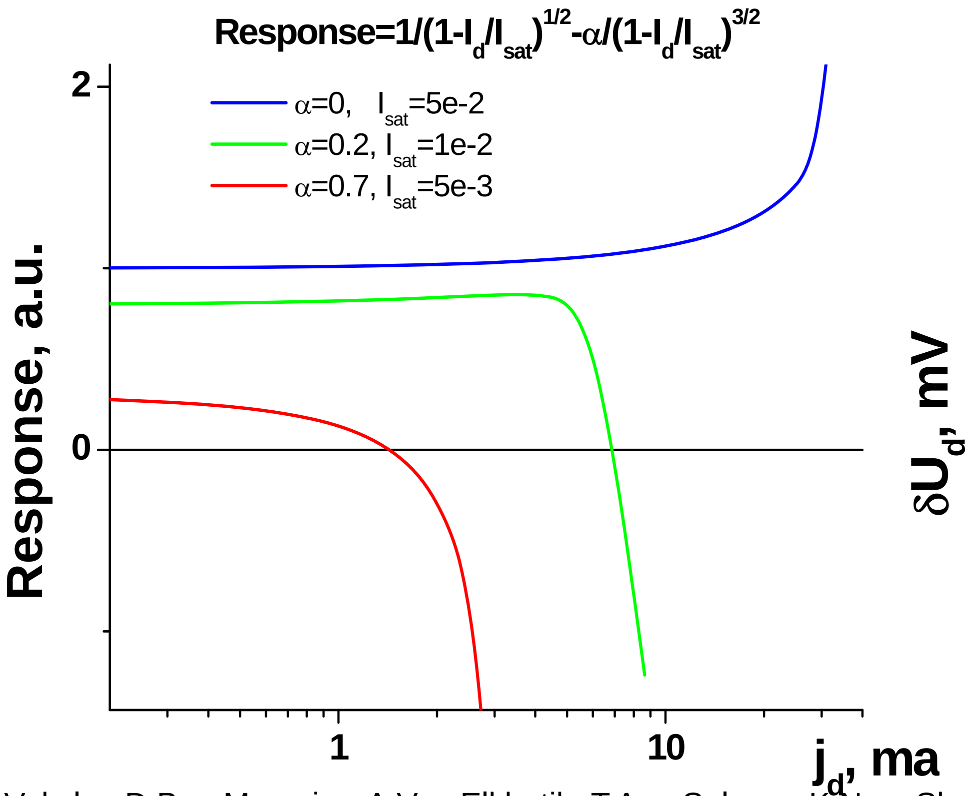
$$\omega_0 = (\mu U_g)^{-1/3}(CL^*)^{-2/3}$$

$$Z \approx -i\omega L^*$$

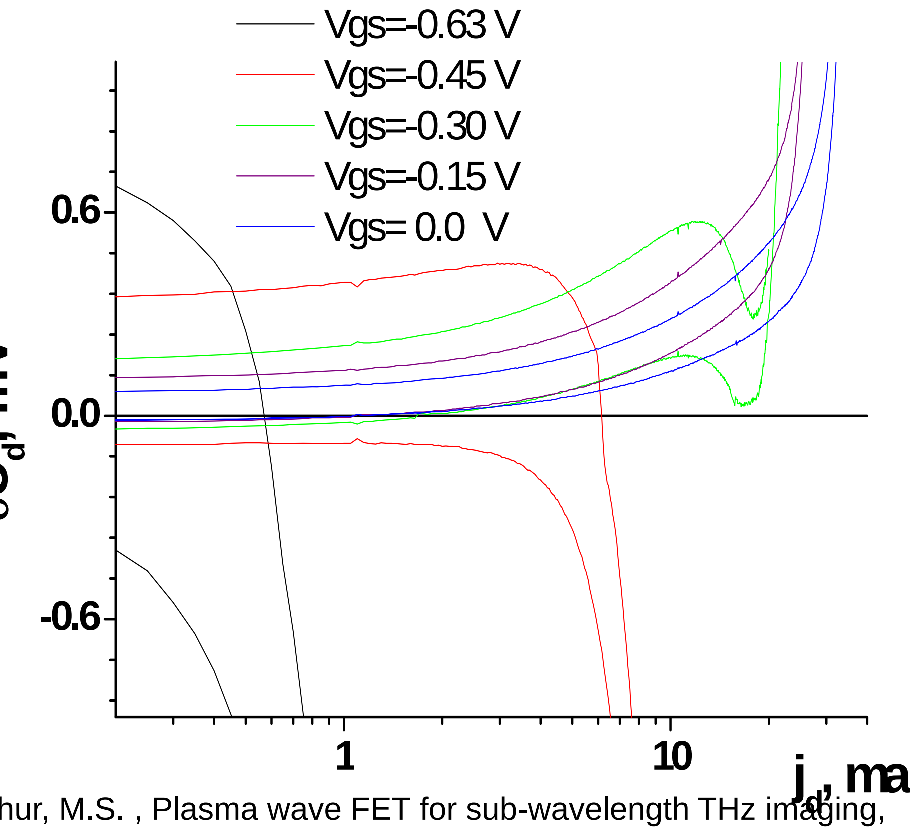
Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

Transistor THz responsivity vs. drain current and gate voltage

Theory:

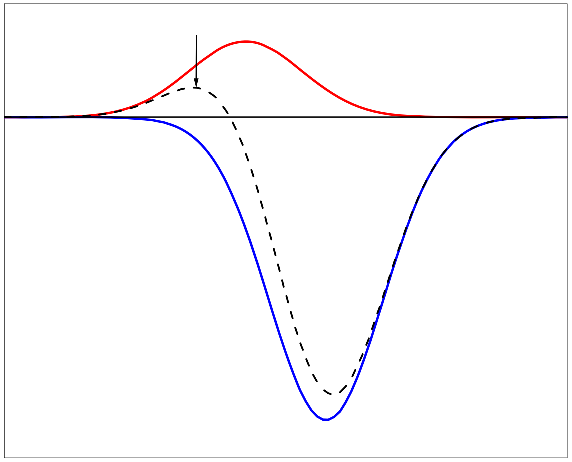


Experiment:



Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

THz Imaging with plasma FET



- THz image is a result of superposition of the responses from different parts of the transistor.

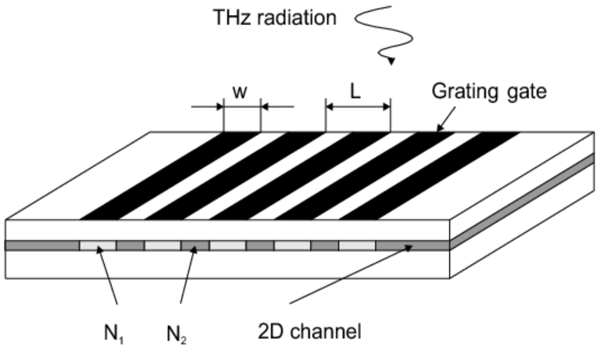
- Drain current leads to increase in the ratio between negative and positive responses. As a result the maximum of the response shifts in XY plane.

Sub-wavelength THz resolution is typically reached using a needle or sub-wavelength diaphragms and optically induced diaphragms

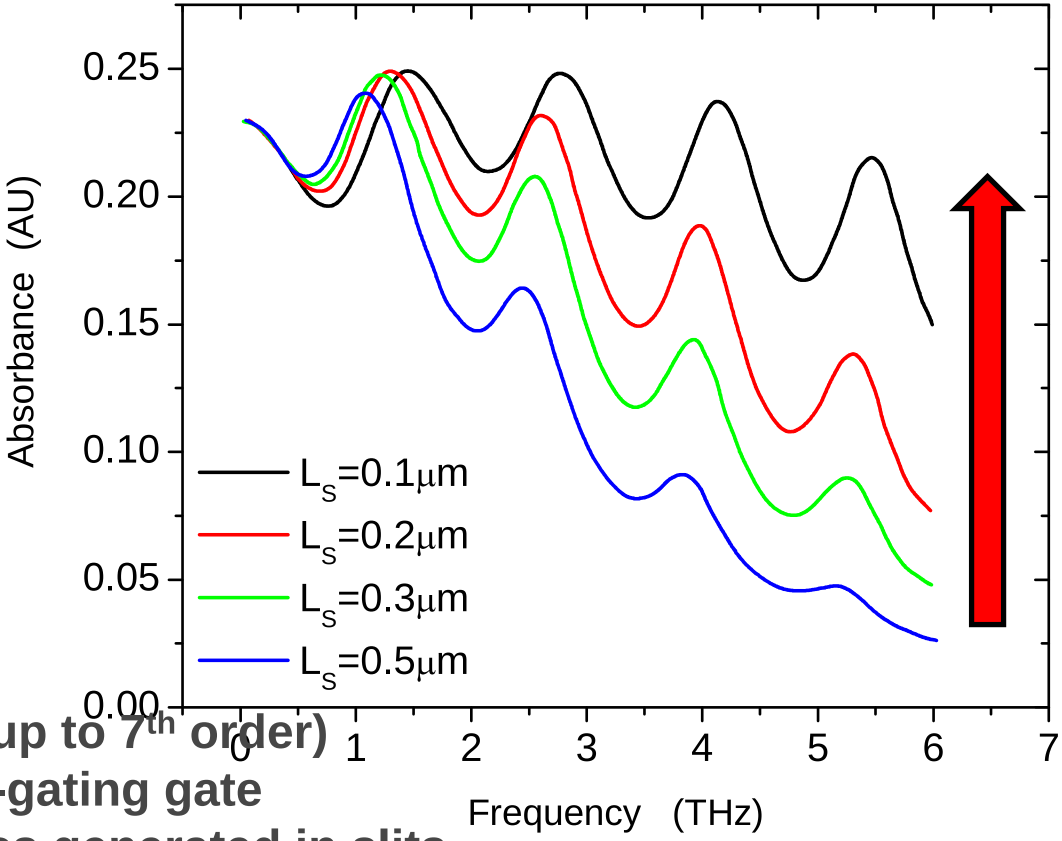
Here sub-wavelength resolution might be achieved due to variation of the responsivities driving the transistor with the drain current

Veksler, D.B. Muraviev, A.V. Elkhatib, T.A. Salama, K.N. Shur, M.S. , Plasma wave FET for sub-wavelength THz imaging, International Semiconductor Device Research Symposium December 12-14, 2007 College Park, Maryland, USA

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

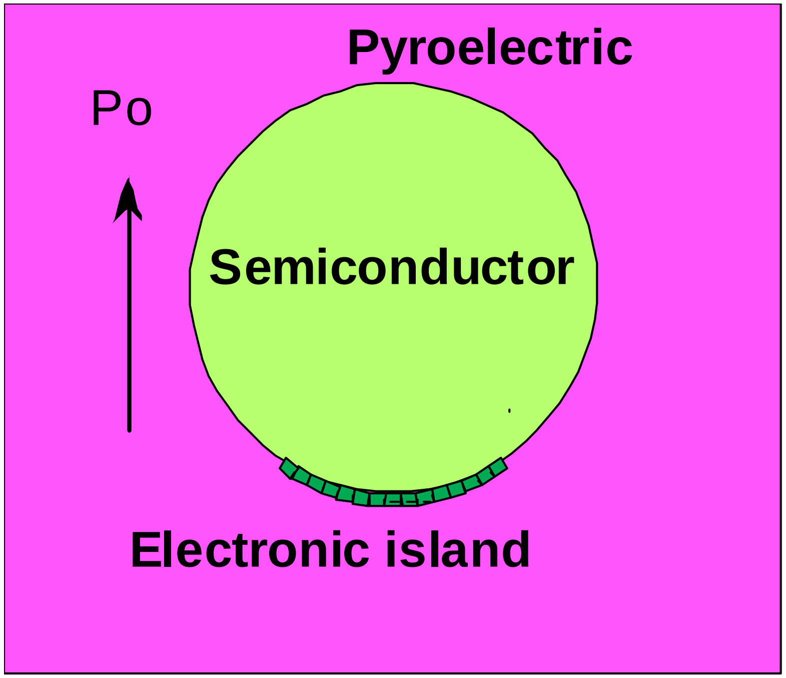


Plasmon absorption in a slit-grating gate device is 10^3 times stronger than in array of non-interacting FET units

V. Popov, M. Shur, G. Tsymbalov, D. Fateev, IJHSES, September 2007

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

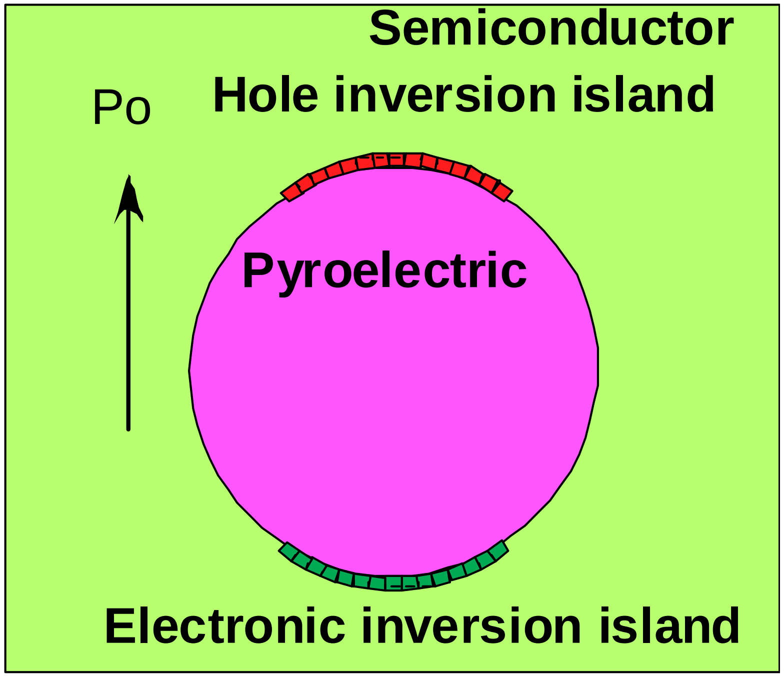


Pyroelectric

Po

Semiconductor

Electronic island



Semiconductor

Po

Hole inversion island

Pyroelectric

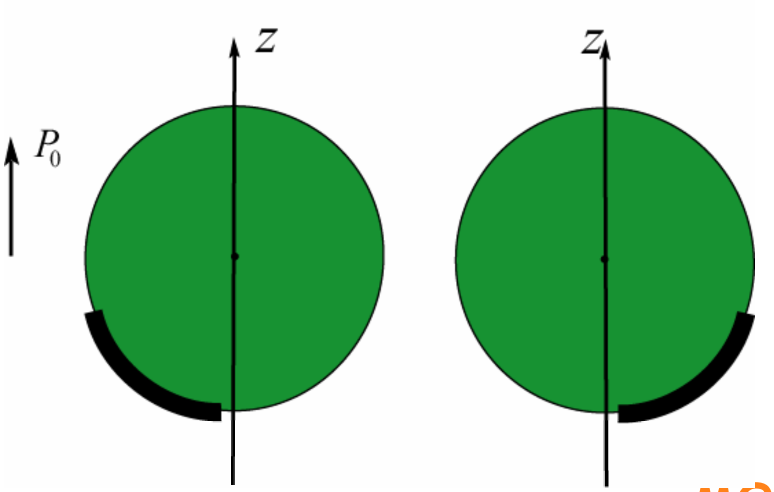
Electronic inversion island

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

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

MOVABLE QUANTUM DOTS (MQD)

Oscillation frequency is of the order of a terahertz

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

CAN SWITCH OR SHIFT FREQUENCY
BY EXTERNAL FIELD OR BY LIGHT

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

Conclusions

- Silicon penetrated THz range
- C^3 contacts reduce parasitics in THz transistors
- Transport is ballistic in submicron transistors, and the physics is very different
- Ultra short channel transistors support plasma waves in THz range with the channel acting as a resonance cavity
- Plasma waves can be used for detection and generation of THz radiation
- A plasma wave FET can achieve THz resolution at nanometer scale
- Arrays of THz plasma wave transistors promise x1,000 increase in performance

I am grateful to my THz colleagues for their hard work, inspiration, and contributions

Dr. Dyakonova and
Prof. Dyakonov

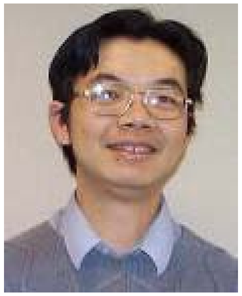
Dr. Veksler

Dr. Kachorovskii

Prof. Pala

Dr. Knap

Dr. Rumyantsev



Dr. Deng

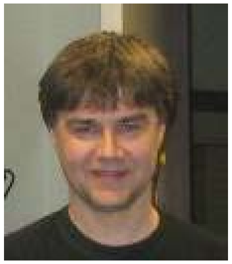
Prof. M. Ryzhii

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)