PLASMONIC NANOSENSORS FOR THz COMMUNICATION AND SENSING FOR IoT APPLICATIONS

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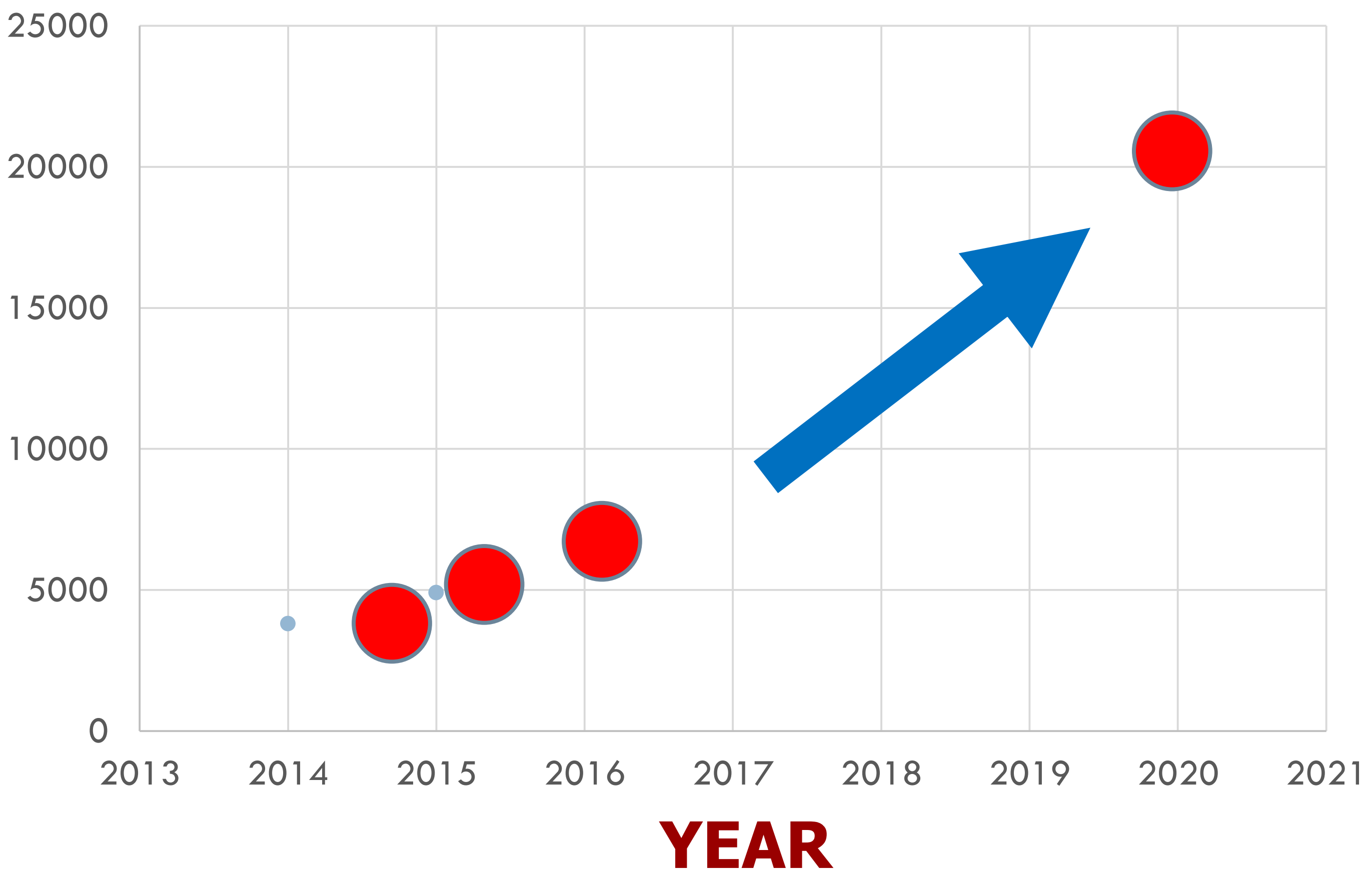
The 14th U.S.-Korea Forum on Nanotechnology: Internet of Things (IoT) including Nanosensors and Neuromorphic Computing

Outline

- Motivation
- Scaling issues for VLSI
- THz communications on nanoscale
- Plasmonic Nanosensors
- CNT and graphene plasmonics on Si
- Future work
- Conclusions

INTERNET OF THINGS INSTALLED BASE (MILLIONS OF UNITS)

More aggressive estimates over 50 billions by 2020



DATA FROM http://www.gartner.com/newsroom/id/3165317

IoT needs

- **LOW POWER WIDE AREA (LPWA) wireless technology**
- **Bandwidth**

IoT NEEDS

REQUIRE ADVANCED NANOSCALE VLSI TECHNOLOGY for ULTRA-LOW POWER

INTEL: 10 nm iPhone should be announced today

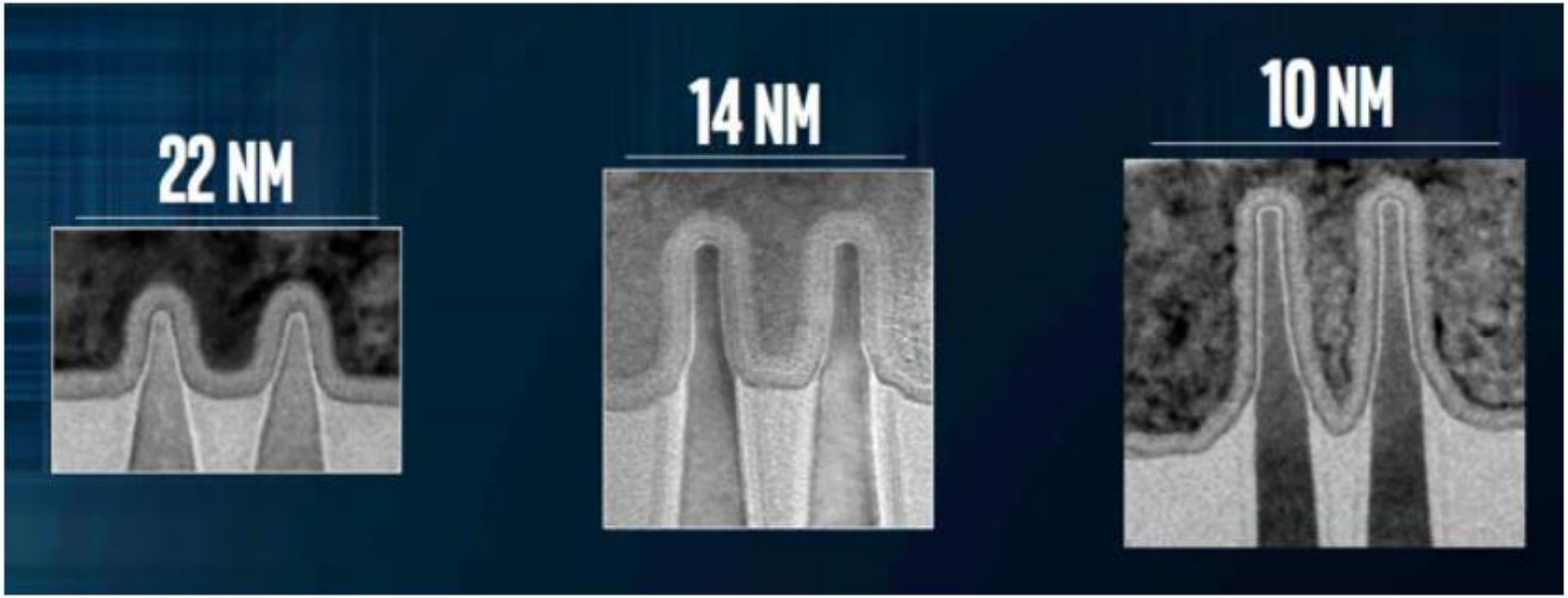
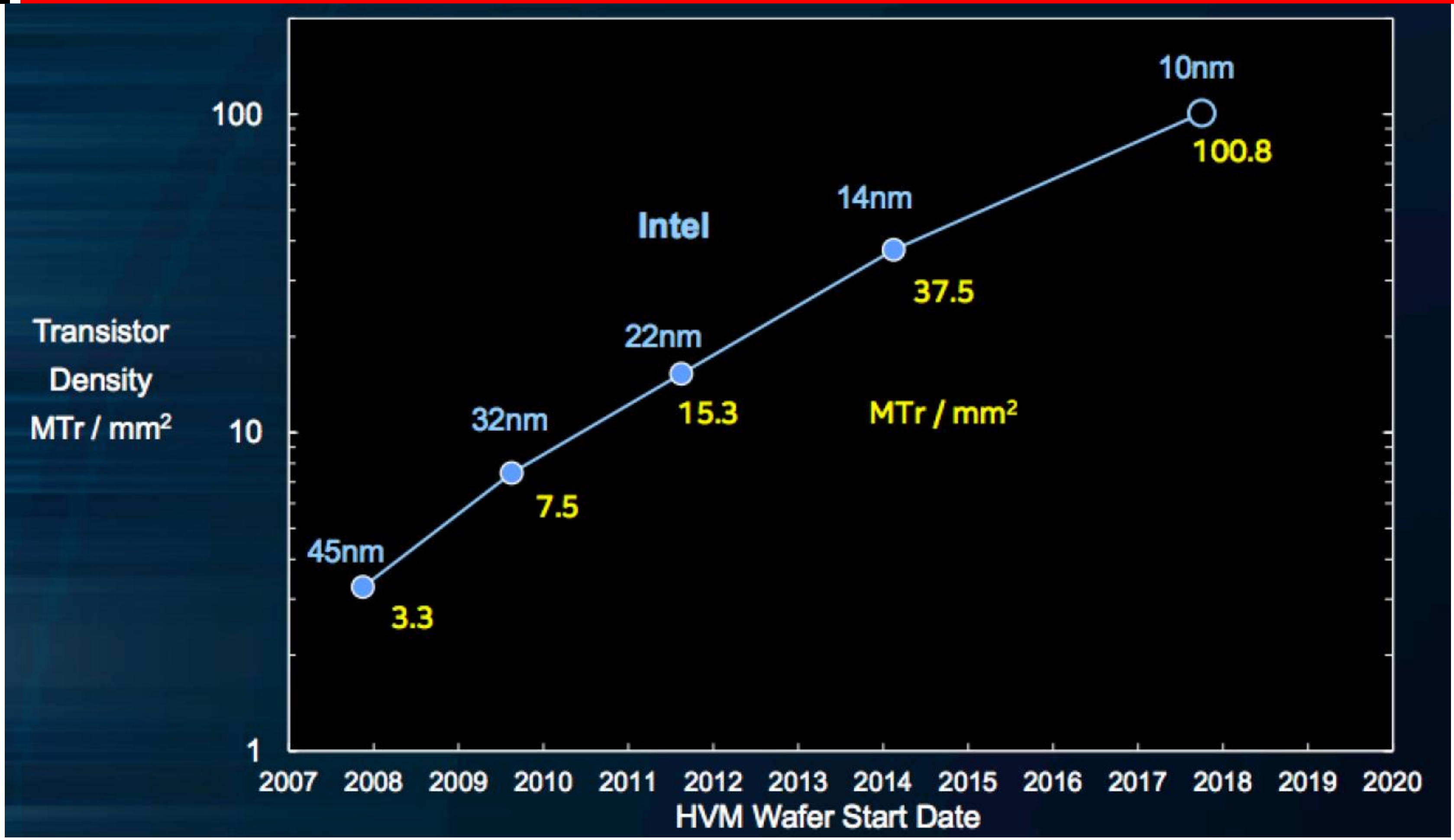


Image: Intel

From Rachel Cortland, posted 30 March 2017
https://spectrum.ieee.org/nanoclast/semiconductors/processors/intel-now-packs-100-million-transistors-in-each-square-millimeter

0.1 billion transistors per mm^2



From Rachel Cortland, posted 30 March 2017
https://spectrum.ieee.org/nanoclast/semiconductors/processors/intel-now-packs-100-million-transistors-in-each-square-millimeter

5 nm?

Metrology Research Engineer

GLOBALFOUNDRIES

Albany, NY, US

Posted 60 days ago

Essential Responsibilities :

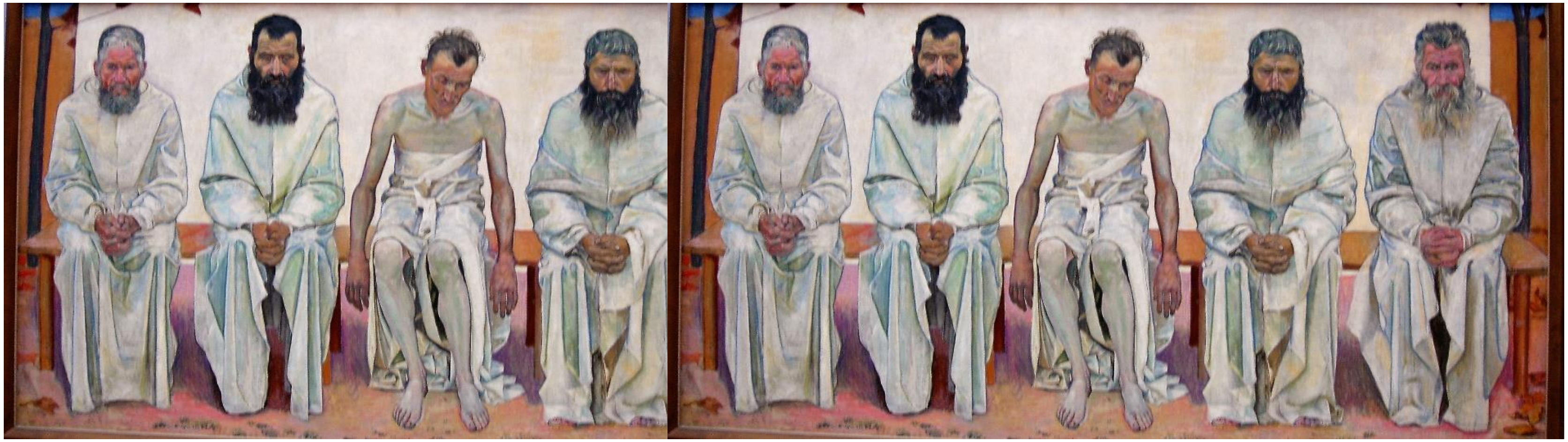
- **Establishing overlay and CD measurement capabilities for the <u>7-nm node and beyond</u>**

Minimum Transistor size

Silicon unit cell 0.543 nm (9 unit cells for 5 nm)

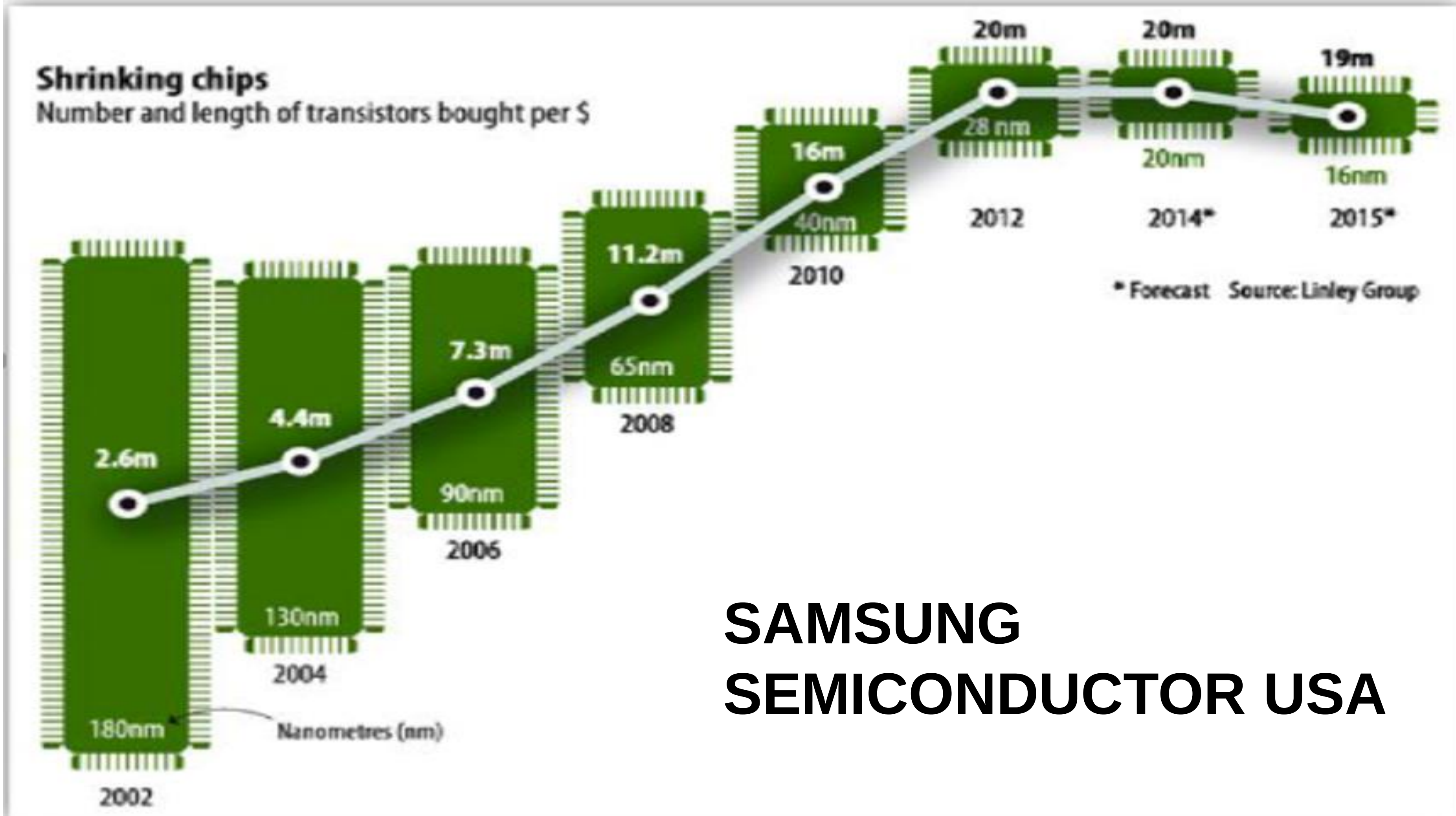
Silicon –Silicon Dioxide interface 0.7 nm

Silicon-Silicon Dioxide layer 1 nm



Ferdinand Hodler, Swiss (March 14, 1853 – May 19, 1918)

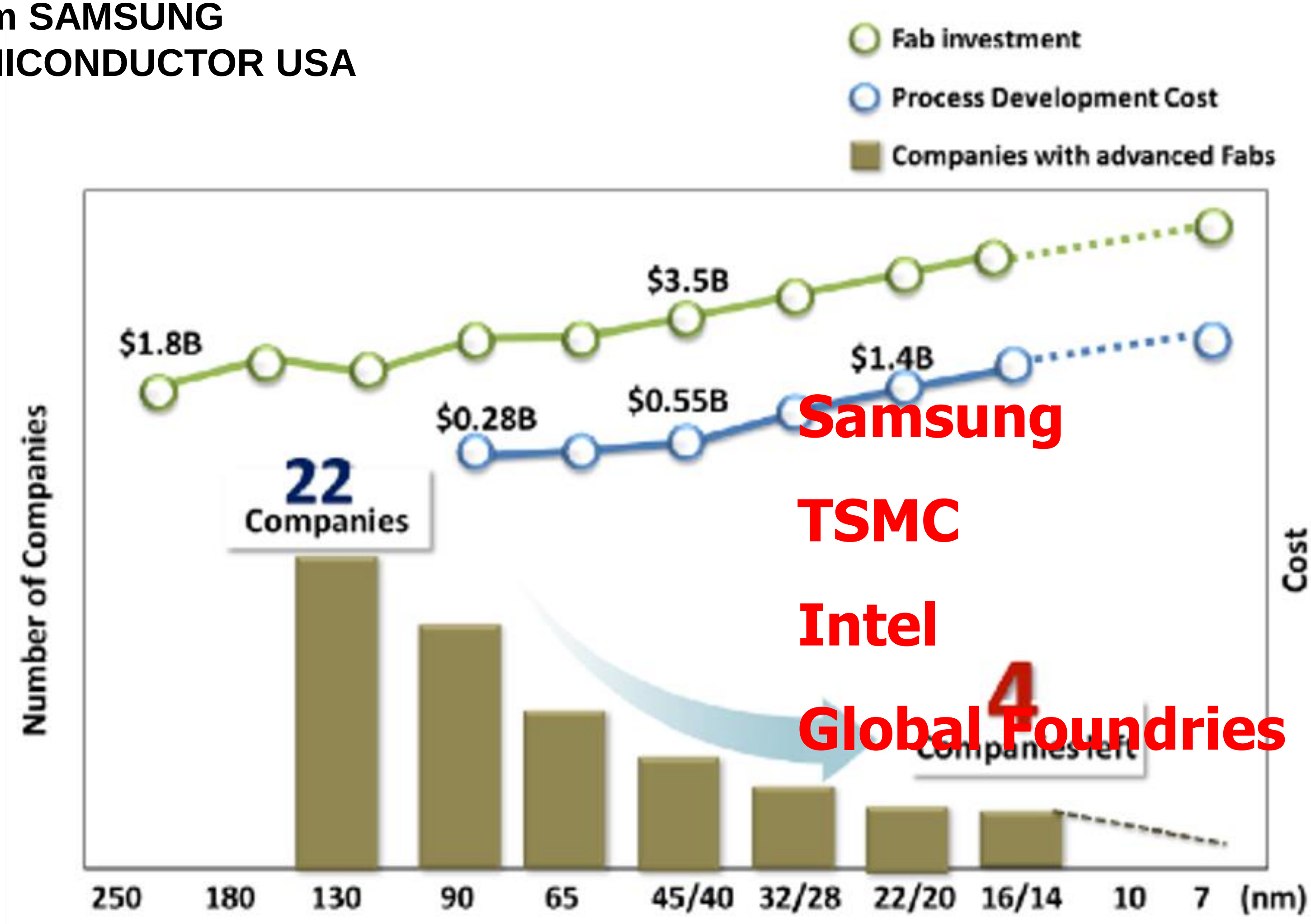
Cost technology rising after 28 nm



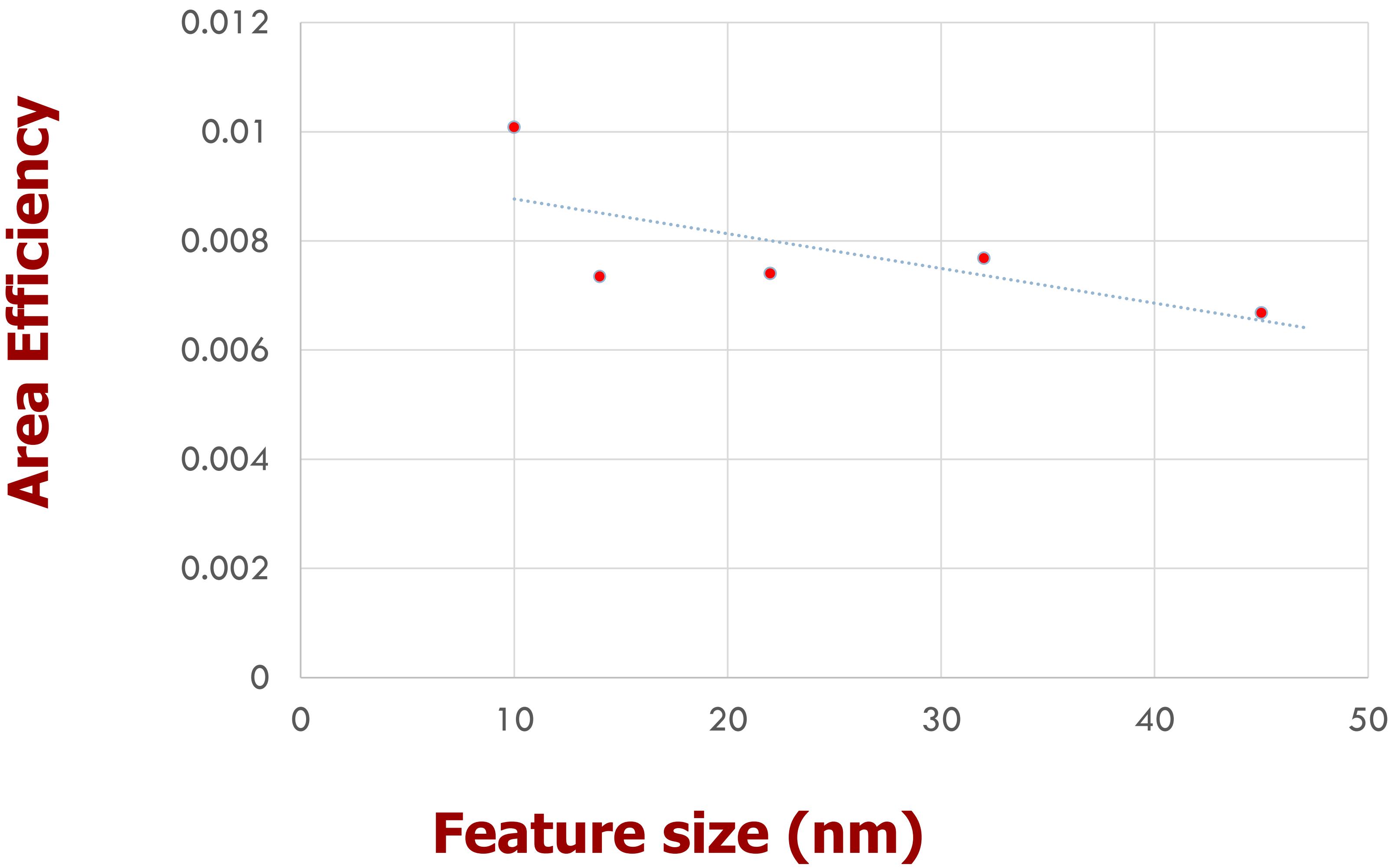
SAMSUNG SEMICONDUCTOR USA

Companies dropping out

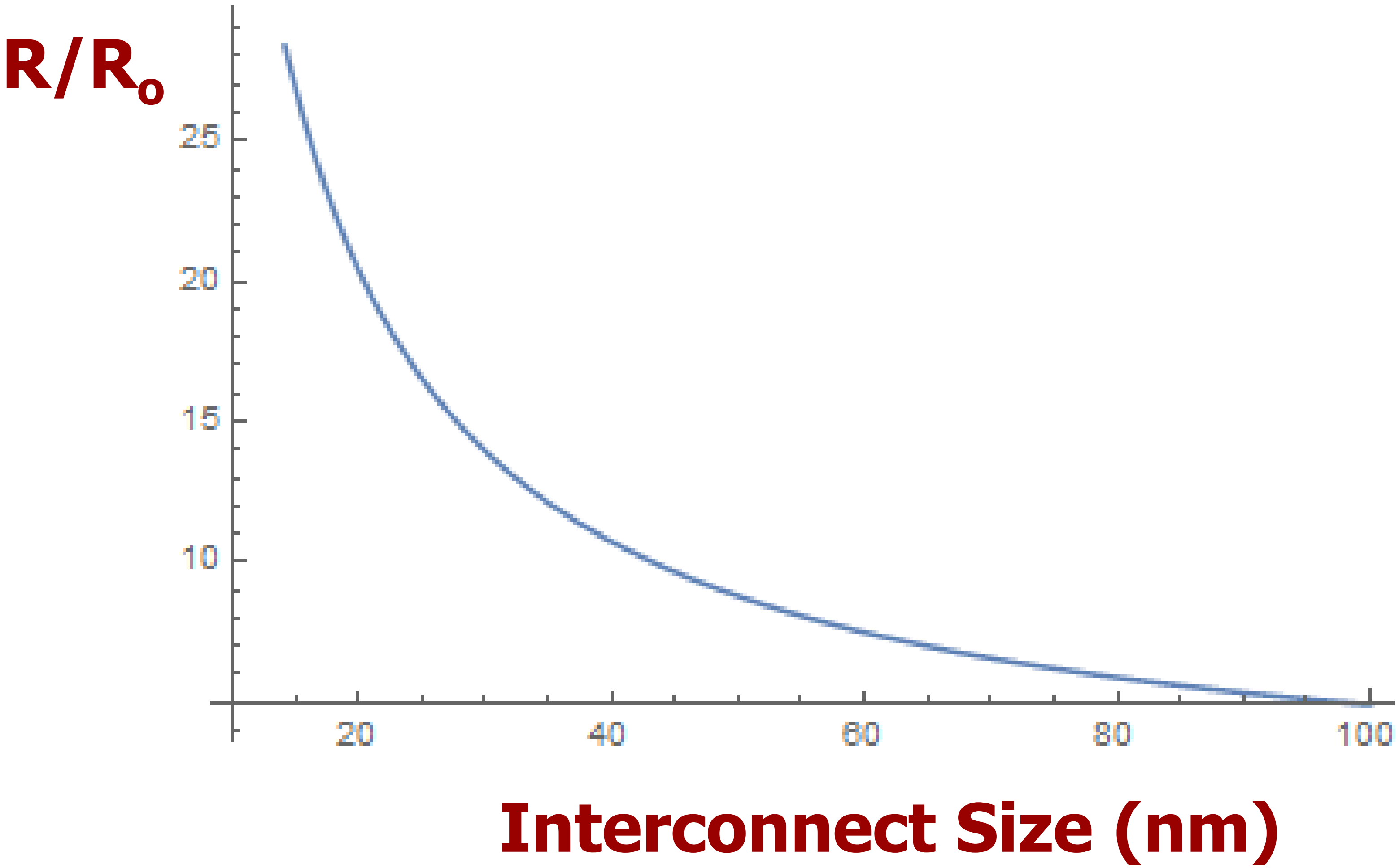
From SAMSUNG SEMICONDUCTOR USA



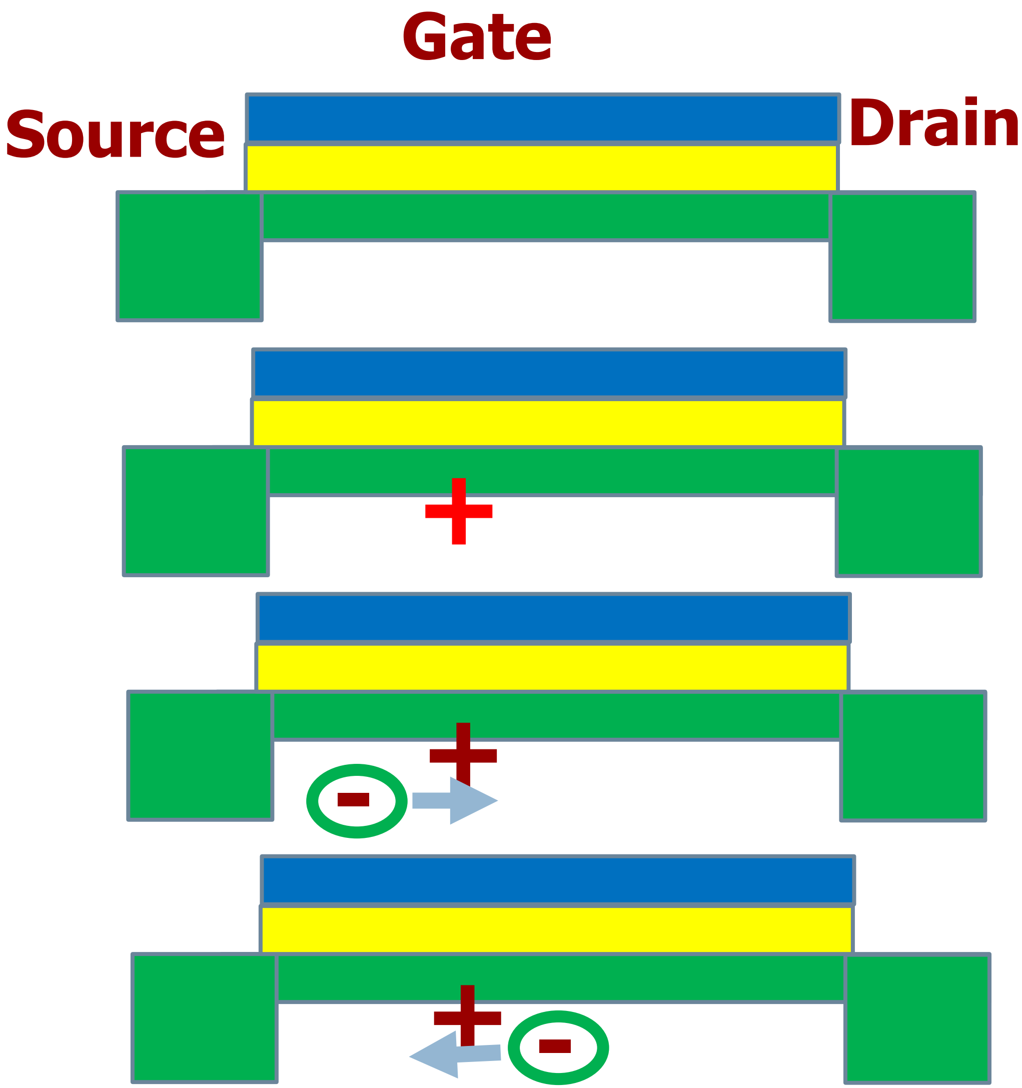
Area Efficiency for INTEL technology

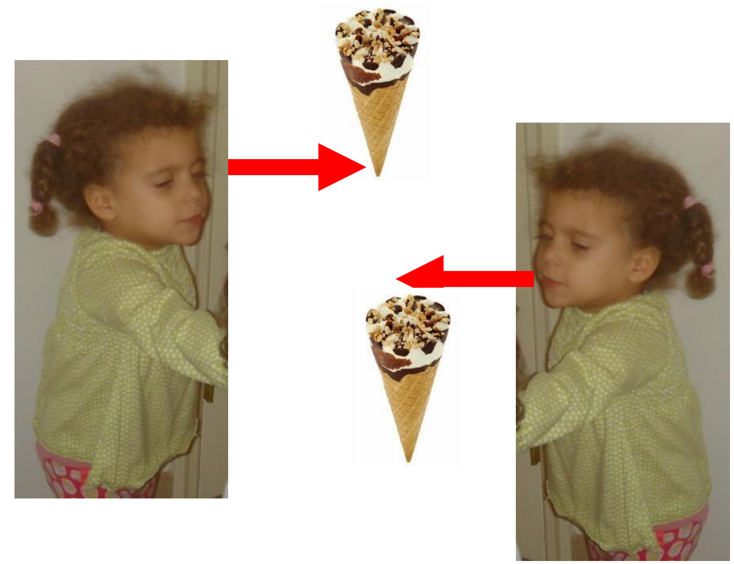


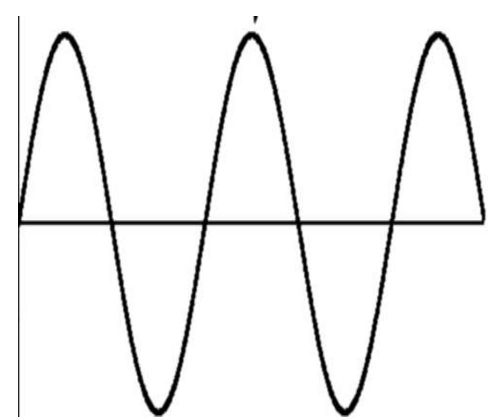
Interconnect Resistivity



Plasma Waves

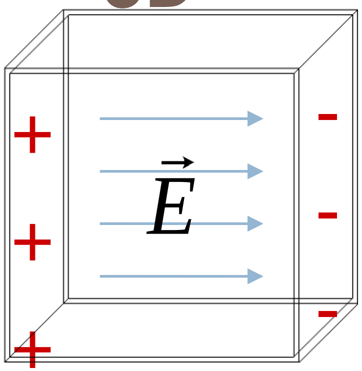




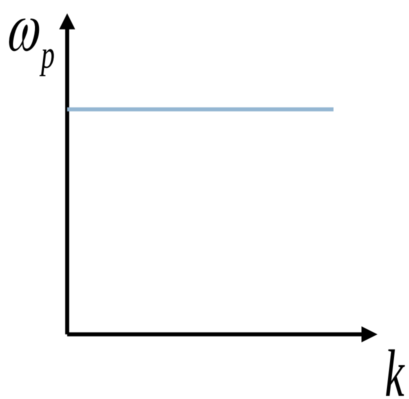


Dispersion of Plasma Waves

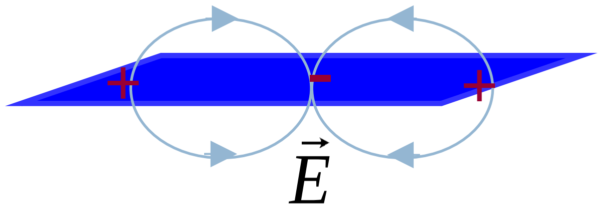
3D



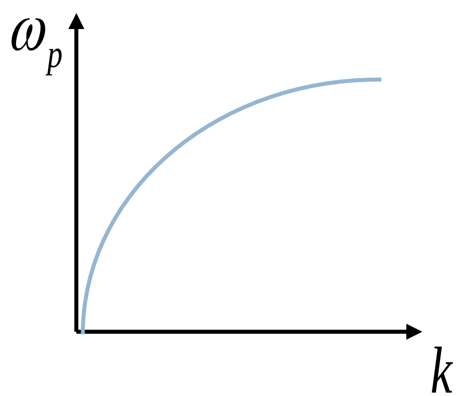
$$\omega_p = \sqrt{\frac{e^2 N_{3D}}{\varepsilon\varepsilon_0 m}}$$



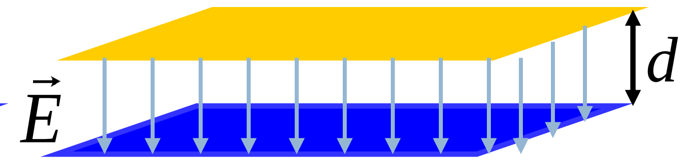
2D ungated



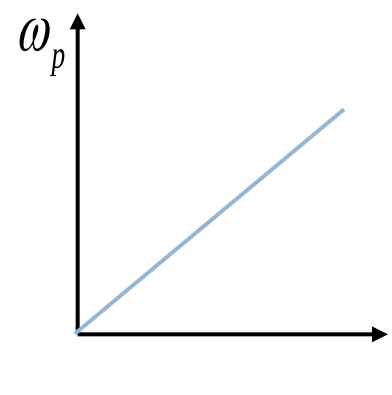
$$\omega_p = \sqrt{\frac{e^2 N_{2D}}{2\varepsilon\varepsilon_0 m} k}$$



2D gated

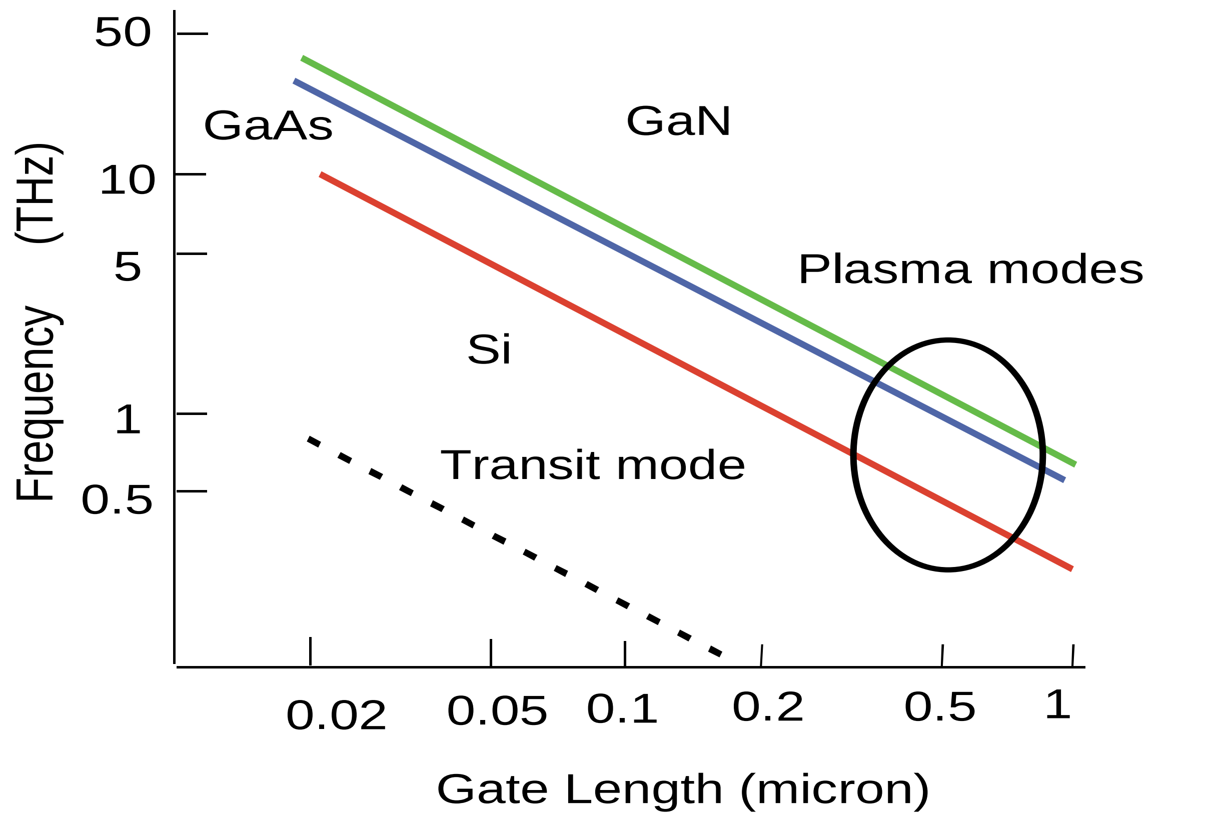


$$\omega_p = \sqrt{\frac{e^2 N_{2D} d}{\varepsilon\varepsilon_0 m} k} \quad kd << 1$$

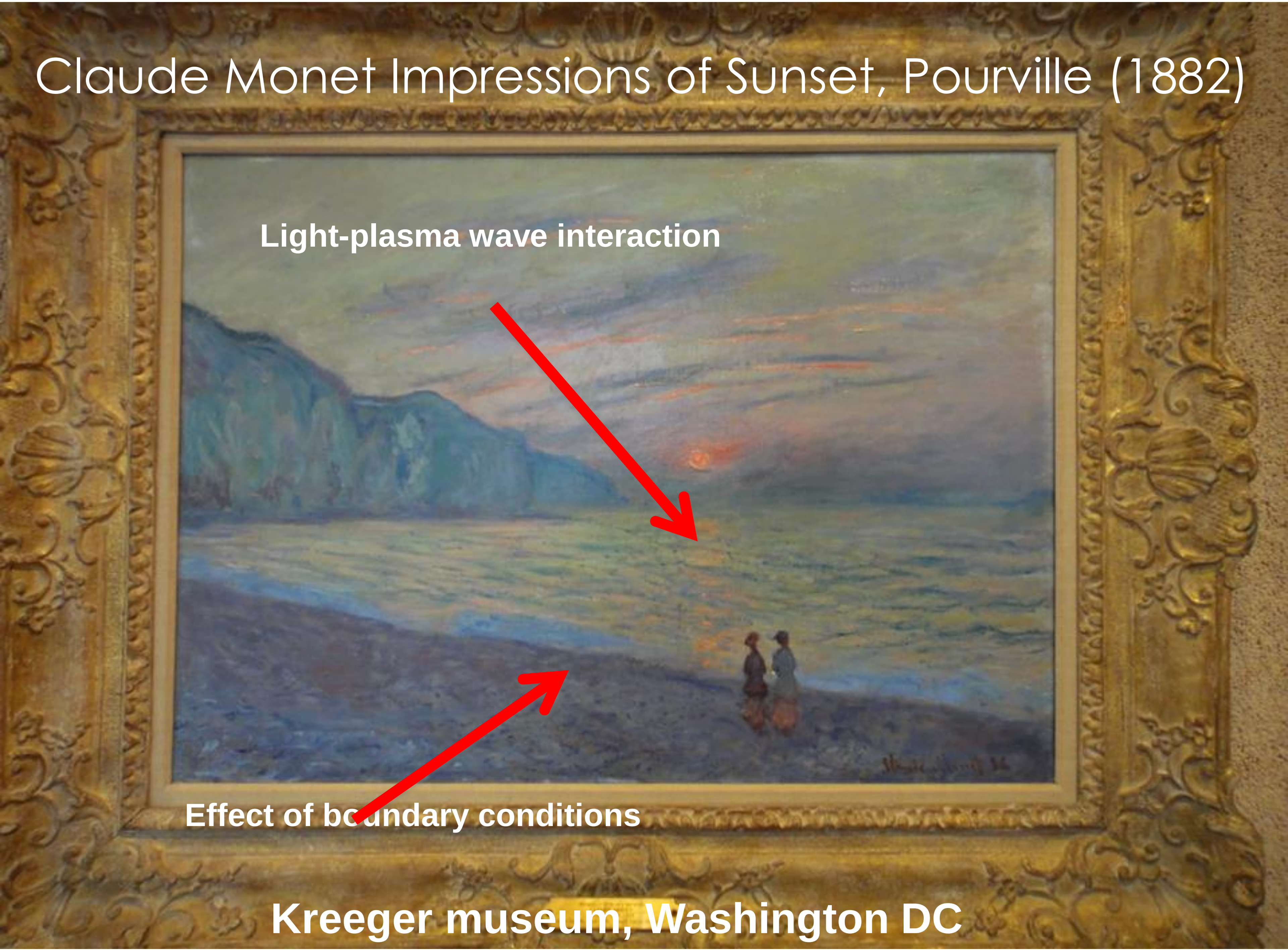


Plasma Waves in a Field Effect Transistors

- 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)


Claude Monet Impressions of Sunset, Pourville (1882)
Light-plasma wave interaction
Effect of boundary conditions
Kreeger museum, Washington DC

Shock Plasma Waves (Hokusai 1760-1849)

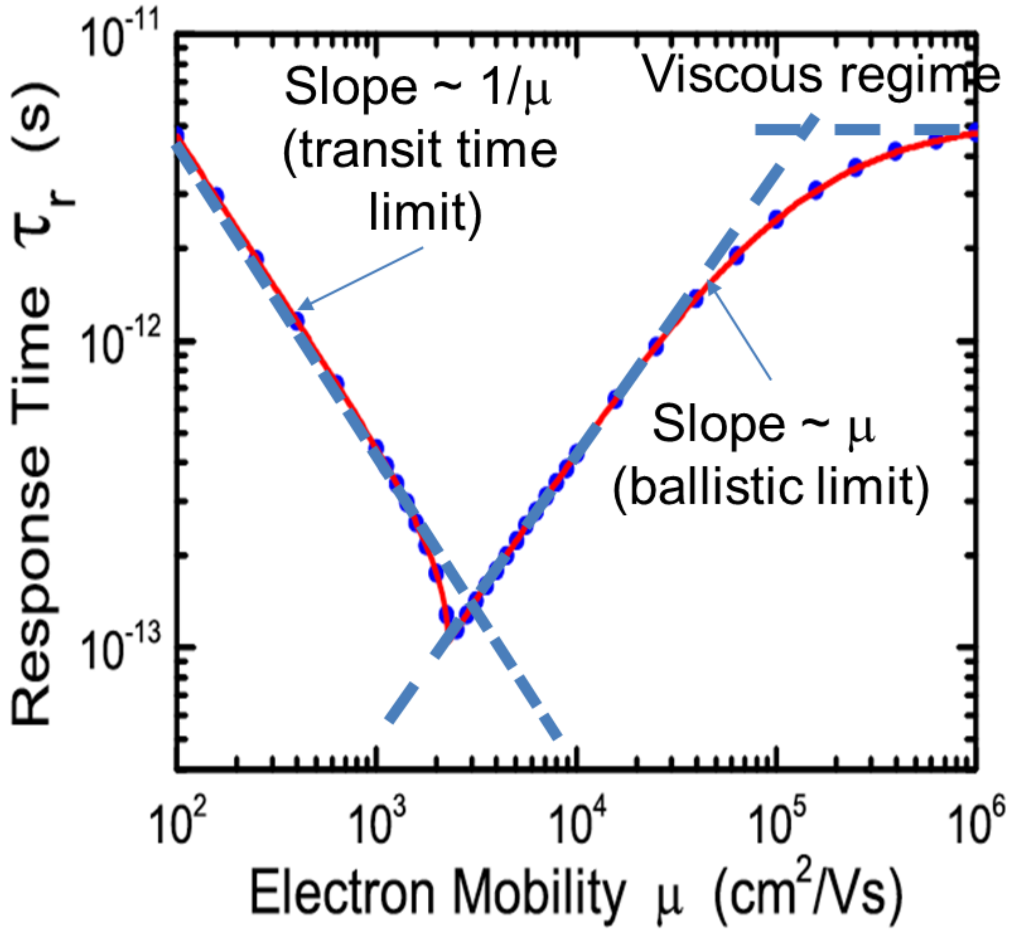
Plasma THz Electronics Advantages

- Small size (easy to fabricate arrays)
- High sensitivity
- Broad spectral range
- Band selectivity and tuneability
- Fast temporal response

- Si plasmonic FETs compatible with VLSI technology

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

Physics of High Speed

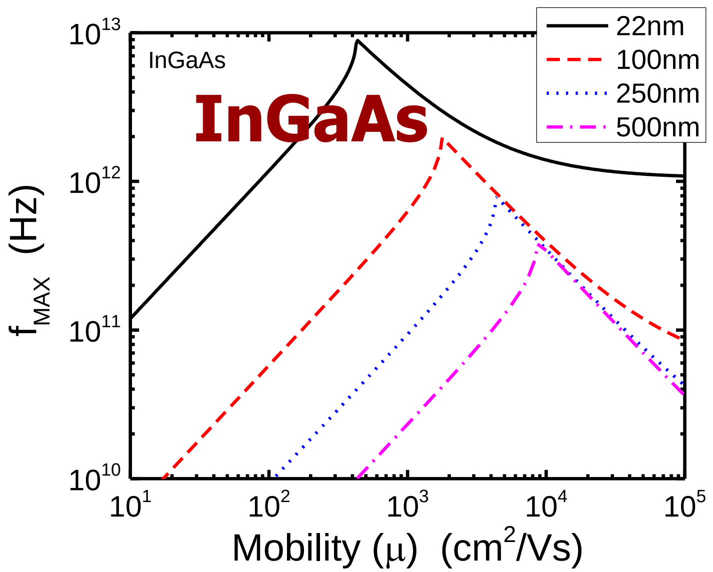


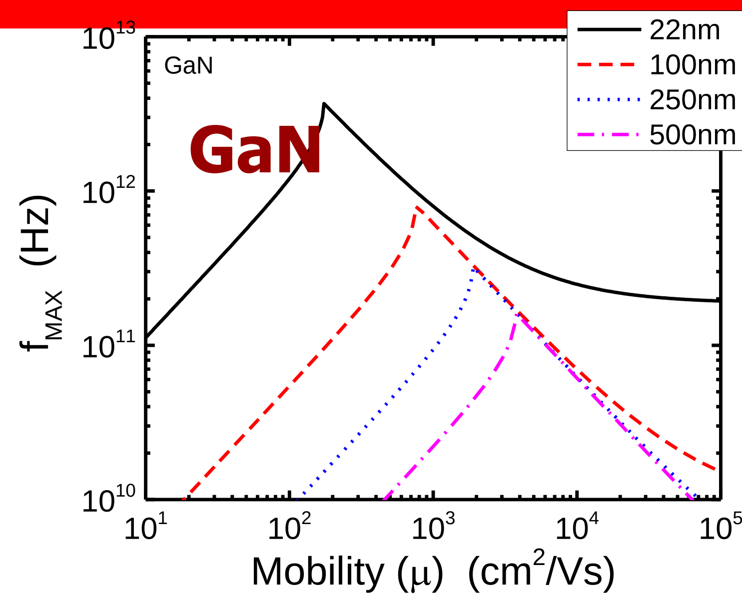
ELECTRON TRANSPORT

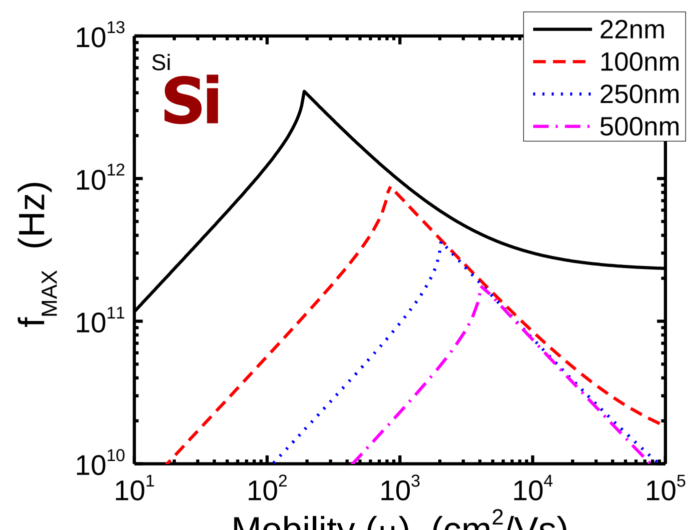
- **Collision dominated**
- **Ballistic**
- **Viscous regime**

M. Shur, A. Muraviev, G. Rupper, and S. Rudin, THz Pulse Detection by Photoconductive Plasmonic High Electron Mobility Transistor with Enhanced Sensitivity, Device Research Conference (DRC) 2016

Modulation frequency

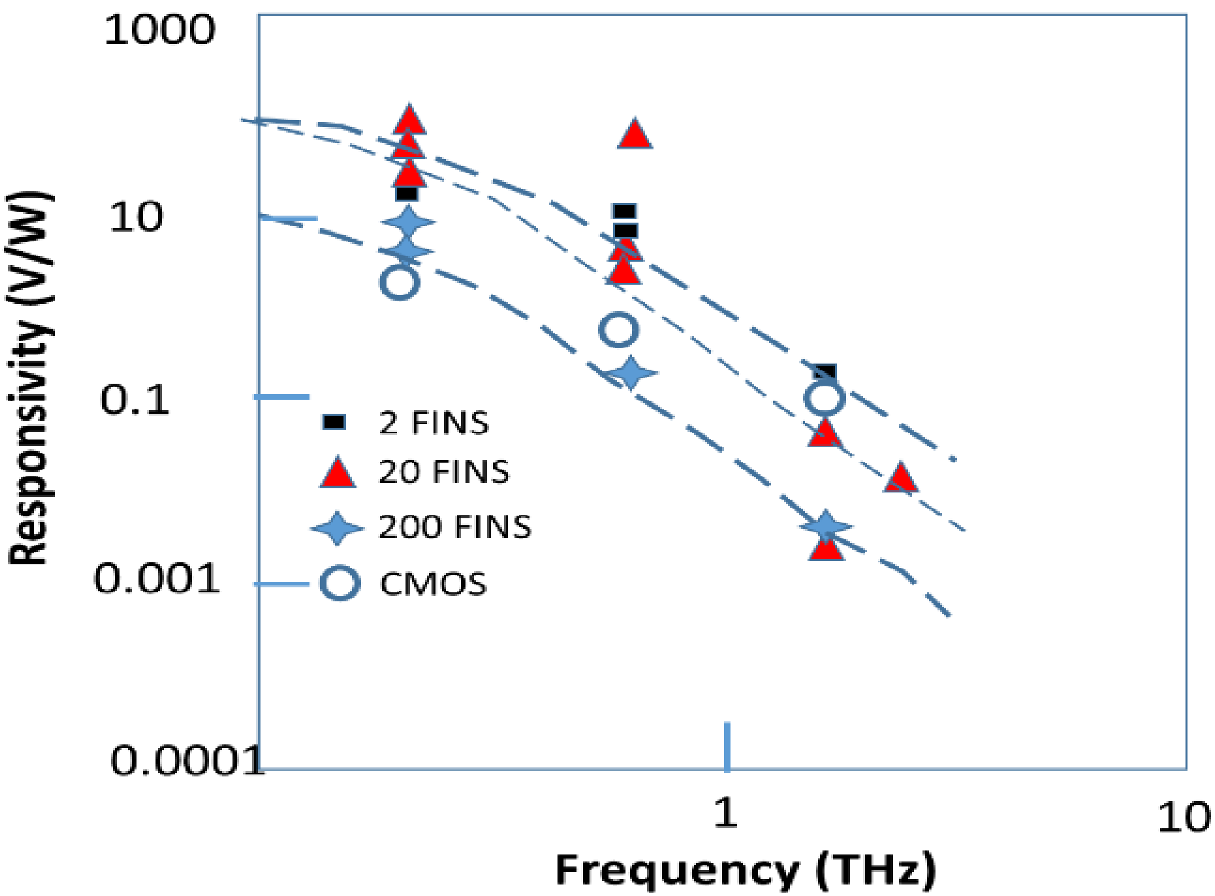






From M. Shur, G. Rupper and S. Rudin, " Ultimate limits for highest modulation frequency and shortest response time of field effect transistor ", Proc. SPIE 10194, Micro- and Nanotechnology Sensors, Systems, and Applications IX, 101942M (May 18, 2017); doi:10.1117/12.2261105; http://dx.doi.org/10.1117/12.2261105

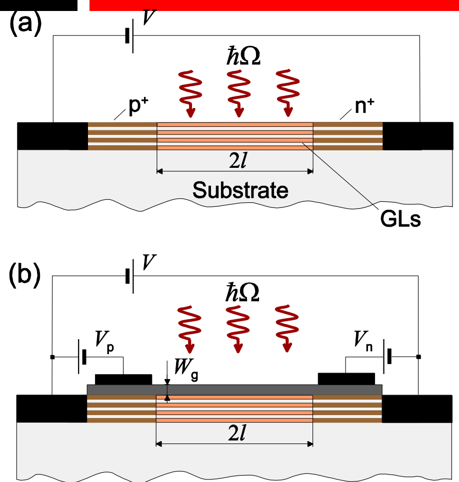
Plasmonic detectors work up to 5 THz



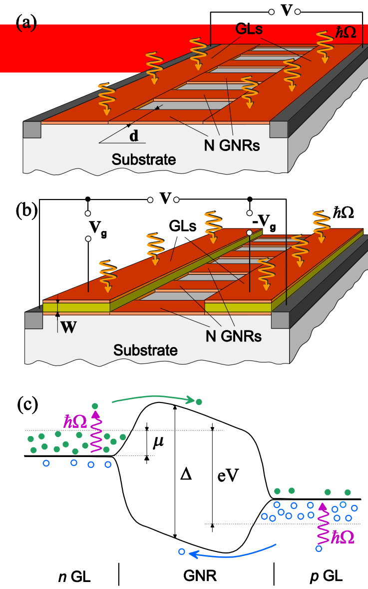
After W. Stillman, C. Donais, S. Rumyantsev, M. Shur, D. Veksler, C. Hobbs, C. Smith, G. Bersuker, W. Taylor and R. Jammy, Silicon FIN FETs as detectors of terahertz and sub-terahertz radiation, International Journal of High Speed Electronics and Systems, vol. 20, No. 1, pp. 27-42 March (2011)

Graphene photodetectors concepts

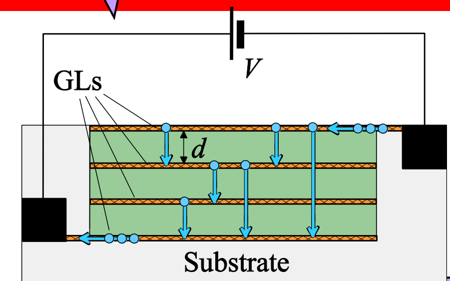
GL p-i-n photodiodes



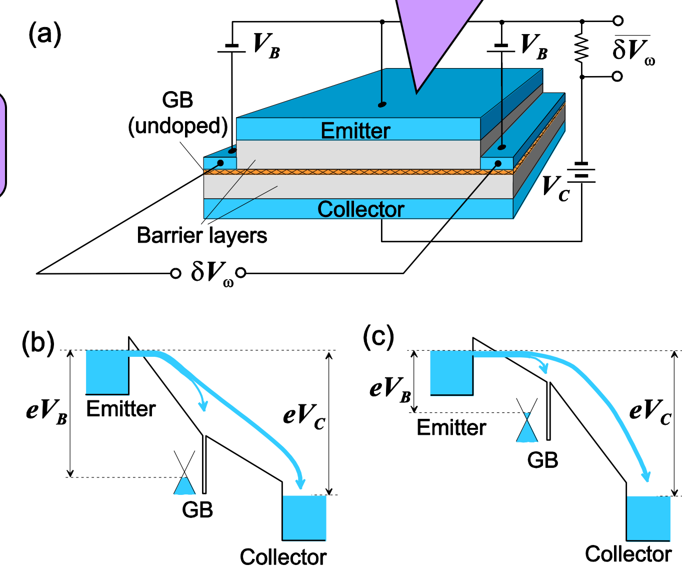
GNR hot-electron bolometers



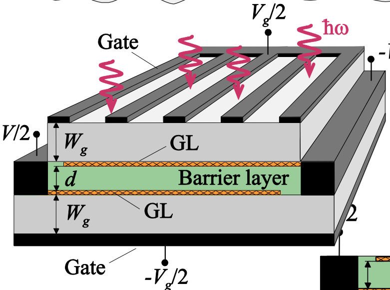
Vah der Waals hot-electron bolometer



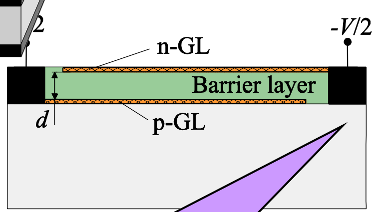
Hot-electron transistor with GL base as plasmonic THz detector

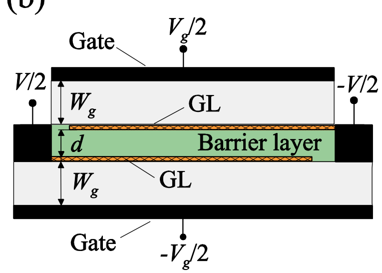


Interband double-GL photodetector



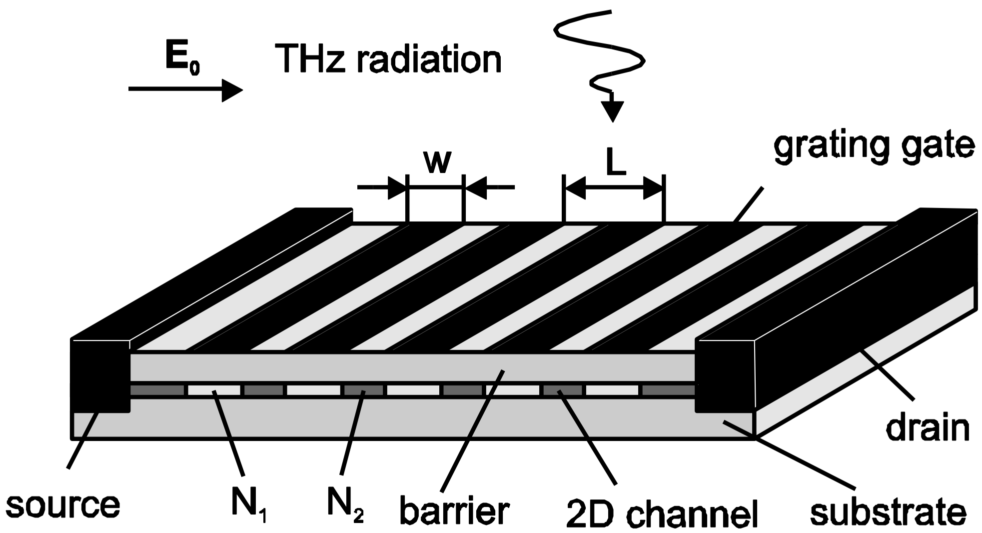
Double-GL plasmonic THz detectors

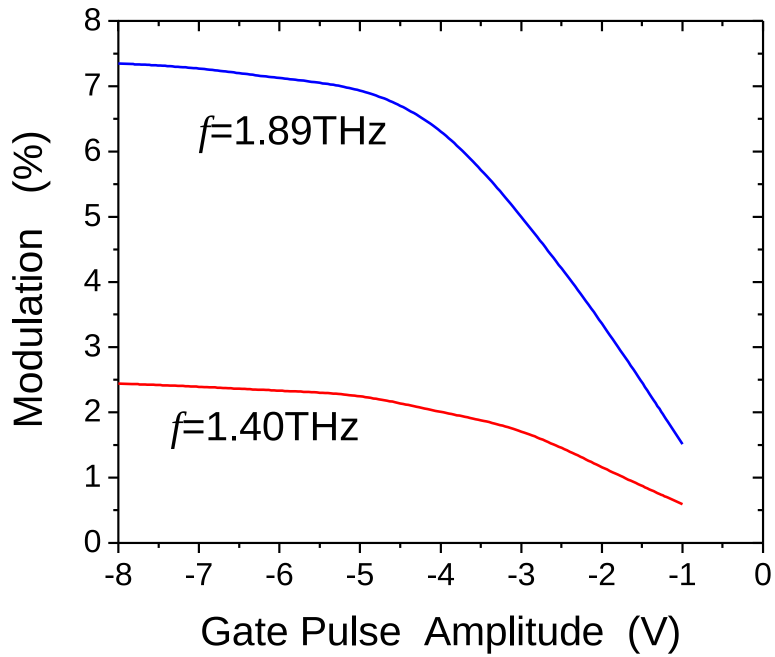




V. Ryzhii, T. Otsuji, M. Ryzhii, V. E. Karasik, V. Ya. Aleshkin, A. A. Dubinov, V. Leiman, D. Svintsov, V. Mitin, and M. S. Shur, International Symposium on Hybrid Quantum System 2017 (HQS 2017), Zao, Miyagi, Japan, Sept. 10—13, 2017

Modulator

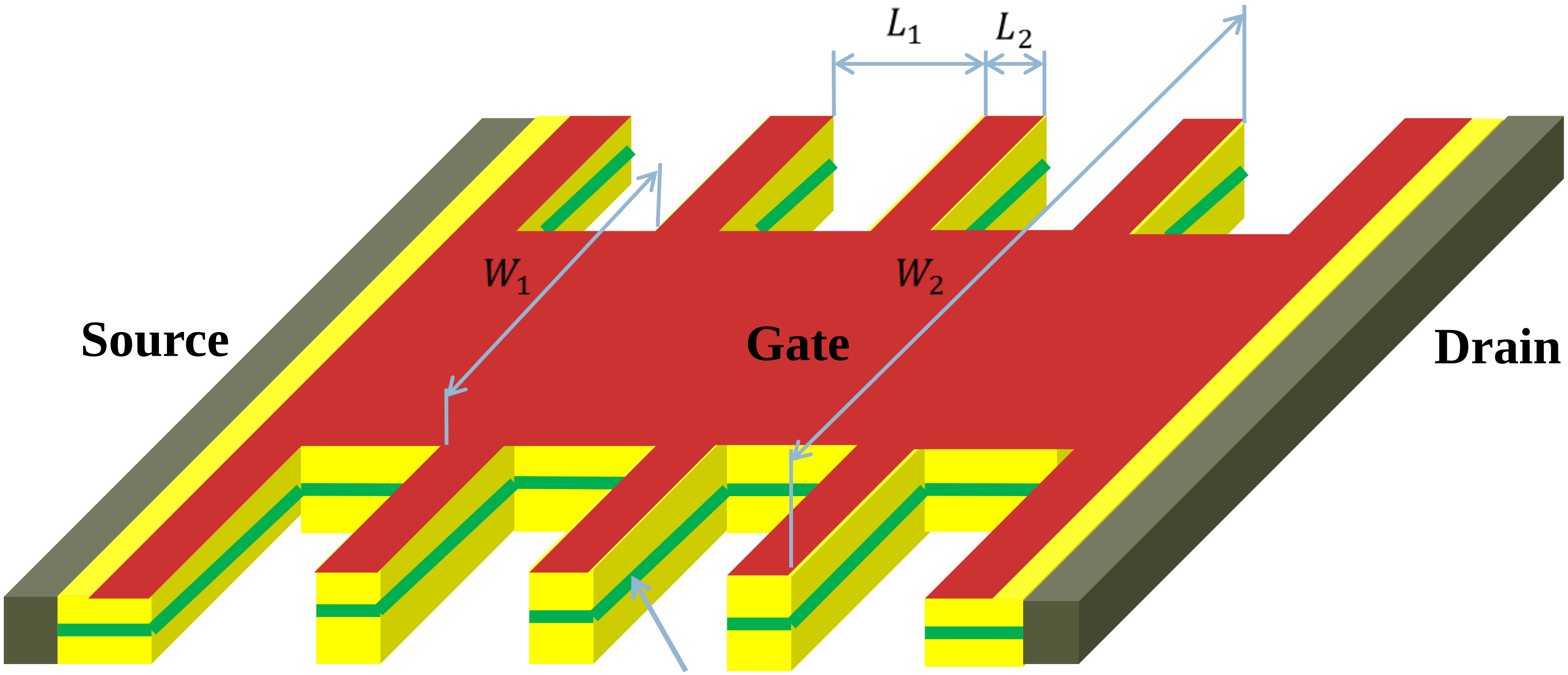




N. Pala, D. Veksler, A. Muravjov, W. Stillman, R. Gaska, and M. S. Shur, Resonant Detection and Modulation of Terahertz Radiation by 2DEG Plasmons in GaN Grating-Gate Structures, in Abstracts of IEEE Sensors Conference, Atlanta, GA, October 2007, pp. 291-292

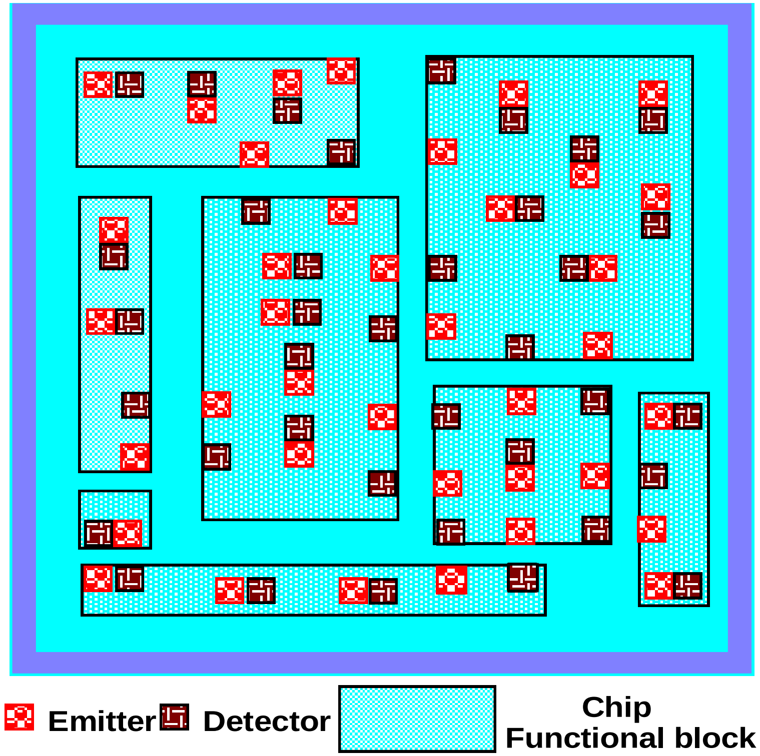
Plasmonic Boom THz Source

100 mW @ 1 THz



G. R. Aizin, J. Mikalopas, M. Shur. Current driven" plasmonic boom" instability in gated periodic ballistic nanostructures, Phys. Rev. B 93, No 19, 195315, May 2016

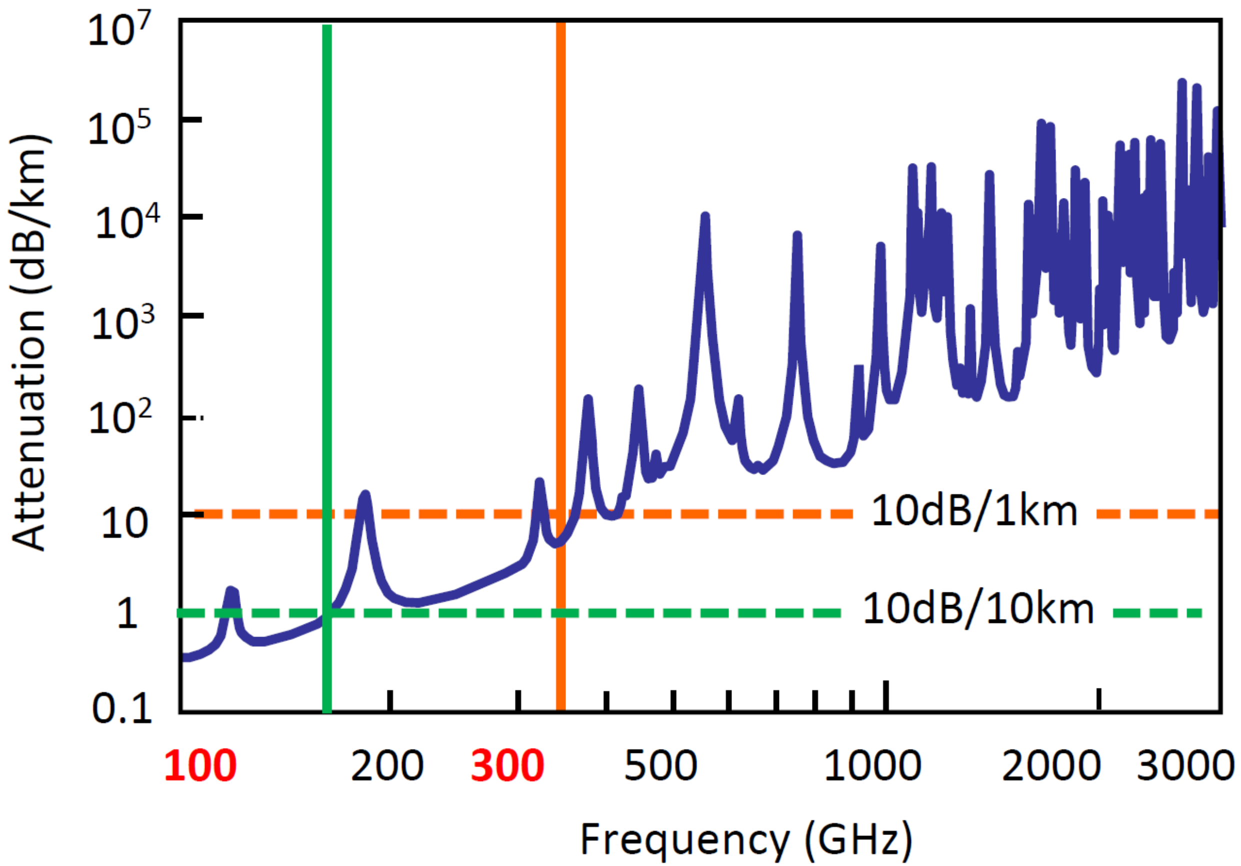
THz Communication on Nanoscale



From Y. Deng and M. S. Shur, Electron Mobility and Terahertz Detection using Silicon MOSFETs, Solid-State Electronics, Vol. 47, Issue 9, pp. 1559-1563, September 2003

Large VLSI chip using terahertz emitter-detector pairs for wireless interconnect

THz attenuation in atmosphere



From Tadao Nagatsuma, Present and Future of Terahertz Communications "TeraHertz: New opportunities for industry, EPFL, FEB 11-13, 2013

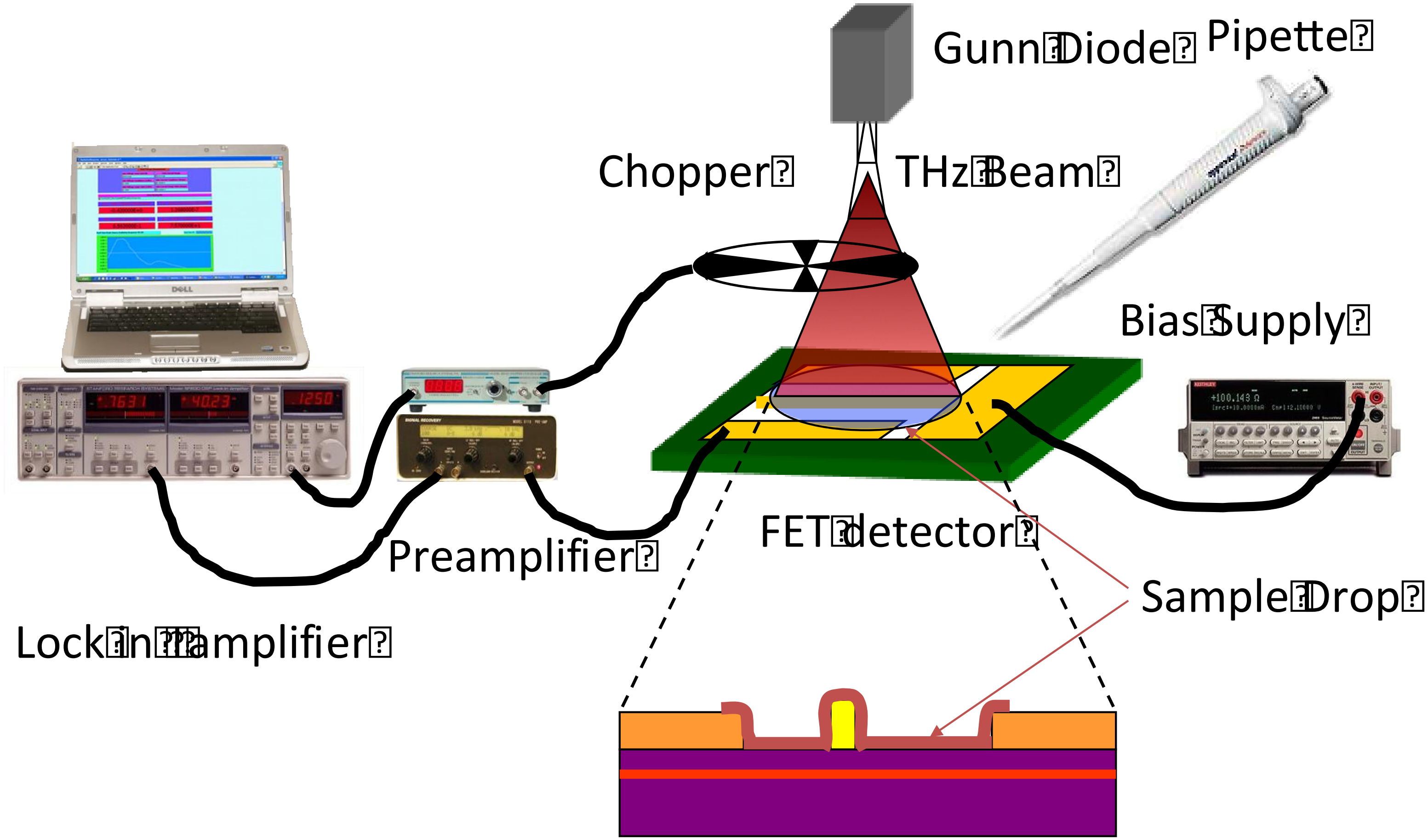
THz communication (0.1 THz to 30 THz)

- Goes through fog and dust
- Goes through walls
- LOS and NLOS with reflections
- Very secure
- Hard to jam
- Unique for next generation WLAN
- Unique for next generation WPAN (biomedical)
- Range from 1000's km in space to submicron communications on chip
- Data rates up to Tbps predicted
- Excellent for frequency spreading

APPLICATIONS of THz SENSING TECHNOLOGY

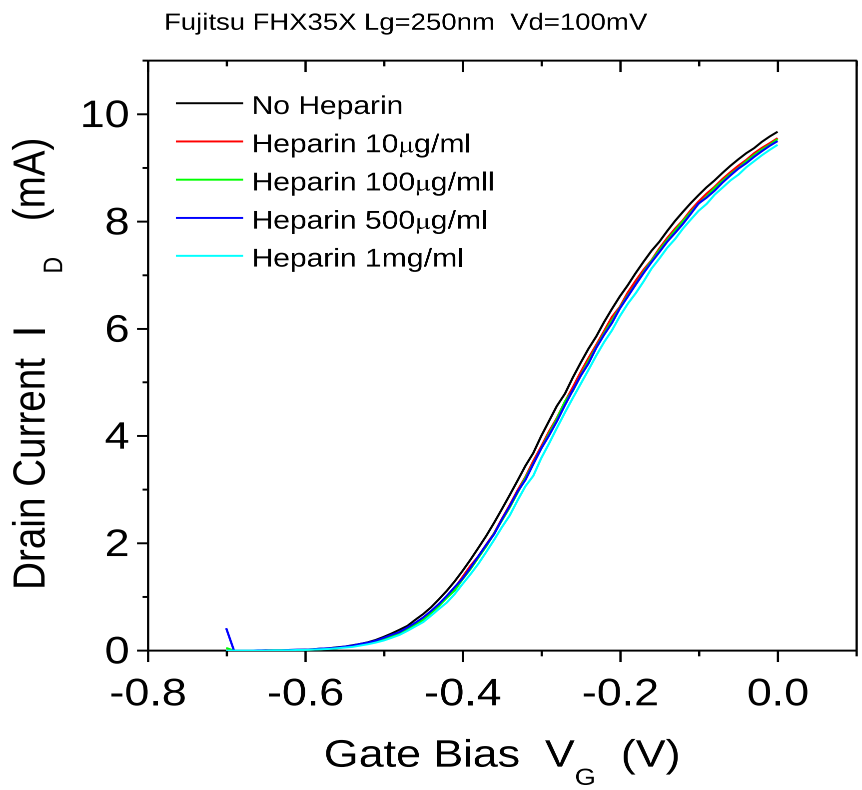
- Radio astronomy and Earth remote sensing
- Vehicle radars and compact radars
- Non-destructive VLSI testing
- Chemical sensors
- Explosive detection sensors
- Gasoline and oil quality testing
- Moisture content sensing
- Coating thickness control
- Film uniformity determination
- Structural integrity testing
- Medical diagnostics, sensing, and imaging
- Concealed weapons and object detection
- Detection of Chemical Warfare Agents

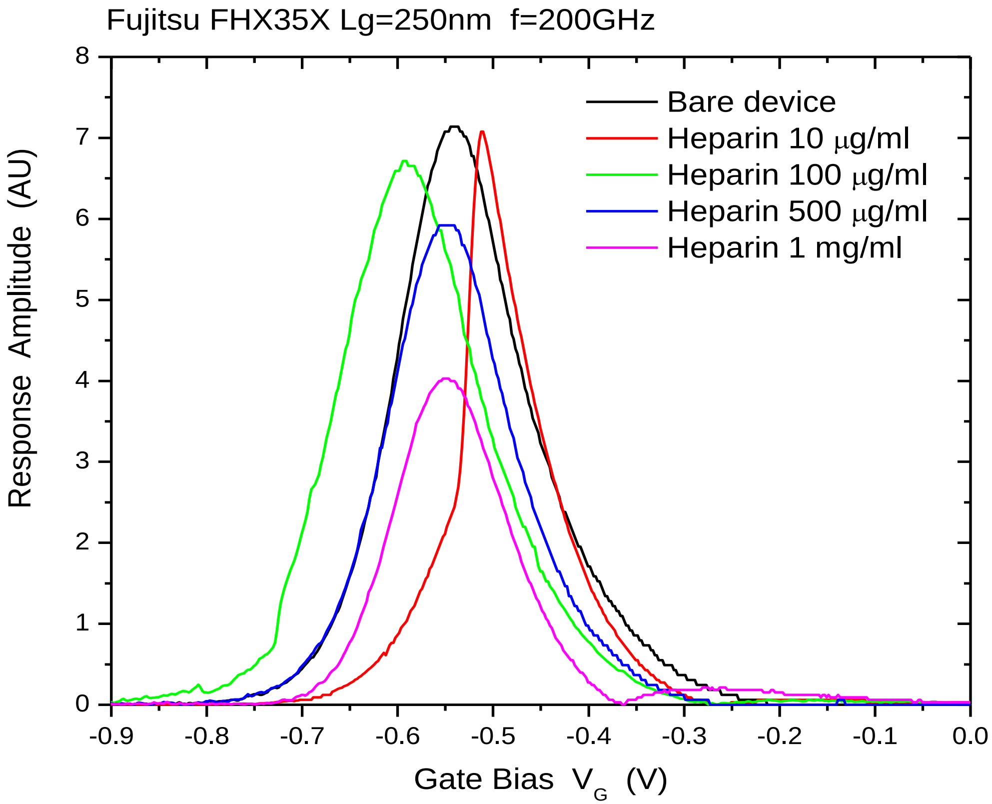
THz Sensing of Biofluids



N. Pala and M. Shur, Plasmonic THz detectors for biodetection, Electronics Lett,, Vol. 44, No24, p. 1391 (2008)
N. Pala, M. S. Shur, and R. Gaska, Plasma Wave-based THz Bio Detectors, presented at SPIE Optics East (2007)

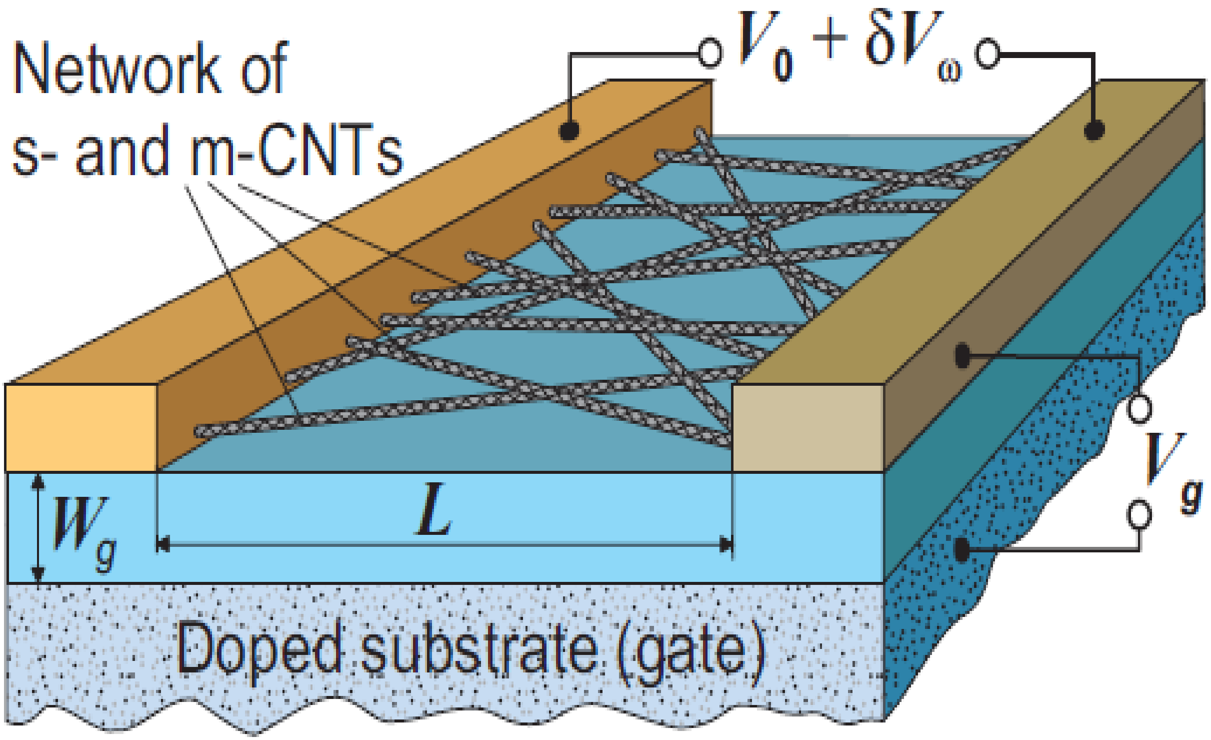
Transfer Characteristics With and Without Heparin and Response of the Plasma Wave Detector





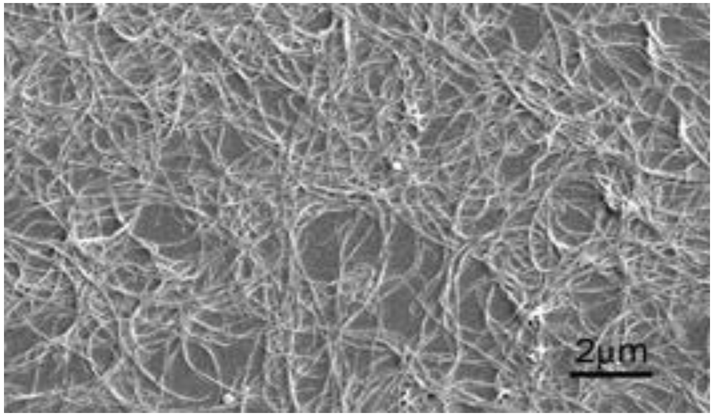
N. Pala and M. Shur, Plasmonic THz detectors for biodetection, Electronics Lett,, Vol. 44, No24, p. 1391 (2008)
N. Pala, M. S. Shur, and R. Gaska, Plasma Wave-based THz Bio Detectors, presented at SPIE Optics East (2007)

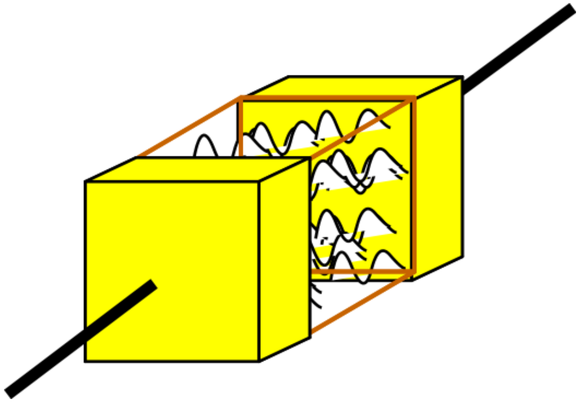
Plasmonic sensor using 2D and 3D percolating CNTs



V. V. Ryzhii, T. Otsuji, M. Ryzhii, V. G. Leiman, G. Fedorov, G. N. Goltzman, I. A. Gayduchenko, N. Titova, D. Coquillat, D. But, W. Knap, V. Mitin, and M. S. Shur, "Two-dimensional plasmons in lateral carbon nanotube network structures and their effect on the terahertz radiation detection", J. Appl. Phys. 120(4) (2016) 044501.

CNT supercapacitors for IoT





M. Shur, 3D Carbon Nanotube Energy Storage and Sensors Devices and Systems, Provisional Patent Application, EFS ID: 29868227. Application Number: 62536092, Confirmation Number: 5173, July 24 (2017).

A. Vijayaraghavan, S. Kar, S. Rumyantsev, A. Khanna, C. Soldano, N. Pala, R. Vajtai, O. Nalamasu, M. Shur, and P. Ajayan, Effect of Ambient Pressure on Resistance and Resistance Fluctuations in Single-Wall Carbon Nanotubes, J. Appl. Phys. 100, 024315 (2006),

Conclusions

- **Low power and band width requirements of IoT demand ultra small feature sizes**
- **Scaled interconnects become a dominant factor**
- **Plasma waves electronics approach could enable THz communication and sensing from nanoscale on chip to LPWA wireless network scale**
- **CNT, graphene and CNT supercapacitors integrated wit Si VLSI have potential for IoT applications**
- **Future work: plasmonic THz sources**

Acknowledgment

This work was made possible by Army Research Laboratory under ARL MSME Alliance (Project Manager Dr. Meredith Reed) and by Office of Naval Research (Project Manager Dr. Paul Maki)