Terahertz Electronics

Michael Shur
ECSE, Physics, and Center for Integrated Electronics, Rensselaer Polytechnic Institute, Troy NY 12180
shurm@rpi.edu (518) 276 2201

Keywords: Terahertz, Plasmons, FETs, HBTs, SOI, Gunn, IMPATT

Abstract

Applications of terahertz technology include detection of biological and chemical hazardous agents, explosive detection, applications in building and airport security, radio astronomy and space research, and in biology and medicine, for example, in cancer diagnostics. These applications have stimulated a lot of interest in terahertz electronics technologies that have potential to replace or augment more traditional terahertz photonics techniques, such as Time Domain Spectroscopy, Fourier Transform Infrared Spectroscopy and THz dielectric spectroscopy. In addition to THz electronics technologies relying on the frequency multiplication using mostly Schottky diodes, THz transistor technology has emerged, since the device feature sizes have shrunk to the point, where ballistic mode of electron transport becomes important or even dominant. Both Heterostructure Bipolar Transistors (HBTs) and High Electron Mobility Transistors (HEMTs) have reached cutoff frequencies approaching 1 THz. Recently, THz emitters based on the excitation of two-dimensional electron gas (2DEG) plasmons at semiconductor heterointerfaces have been demonstrated opening up a new paradigm in the terahertz electronics. These sources are tunable and can be used together with THz plasmonic resonant and non-resonant detectors using the same technology. The challenge here is to increase efficiency and output power by orders of magnitude.

Applications of terahertz technology [1-4] include detection of biological and chemical hazardous agents, explosive detection, applications in building and airport security[5] , earth and ozone hole [6,7] ’ monitoring, radio astronomy and space research [8,9] ’, in biology and medicine [10] , for example, in cancer diagnostics. These applications have stimulated a lot of interest in terahertz electronics technologies [11] that have potential to replace or augment more traditional terahertz photonics techniques, such as Time Domain Spectroscopy [12] , Fourier Transform Infrared Spectroscopy [13] and THz dielectric spectroscopy [14] .

In addition to THz electronics technologies relying on the frequency multiplication mostly using Schottky diodes [15] , Gunn diodes, and IMPATT diodes (see Figures 1 and 2), THz transistor technology has emerged, since the device feature sizes have shrunk to the point, where ballistic mode of electron transport [16] becomes important or even dominant. Heterostructure Bipolar Transistors (HBTs) and High Electron Mobility Transistors (HEMTs) are capable of operation in the sub-terahertz region [17] , and recently have reached cutoff frequencies approaching 1 THz. University of Illinois group has recently reported on Type-II GaAsSb/InP HBTs with Record fT = 670 GHz and Simultaneous fT, fmax > 400 GHz (see Fig. 3) [18]. In these devices, the compositional grading was used to enhance the electron velocity, hence, increase speed.

The Northrop Grumman group reported on Sub a 50 nm InP HEMT Device with fmax greater than 1 THz (see Figure 4). [19] They also demonstrated an amplifier with a 15 dB gain at 340 GHz and predicted that their technology will allow building MMIC amplifiers operating up to 600-700 GHz. The Seoul National University group reported on 610 GHz InAlAs/$In_{0.75}$GaAs Metamorphic HEMTs with an Ultra-Short 15-nm-Gate and extracted ballistic velocity of 4.3×10^7 cm/s. [20]

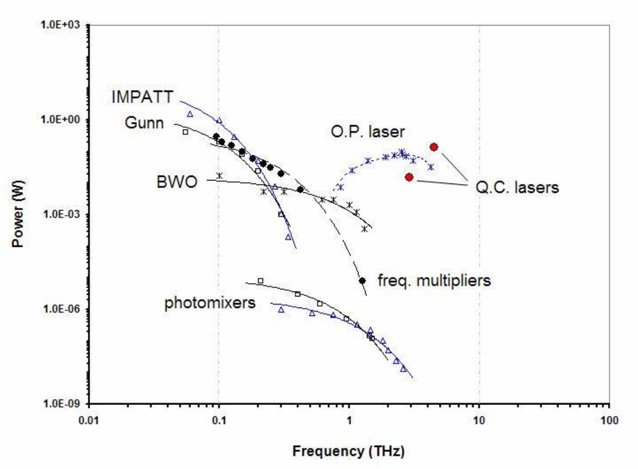

Figure 1: Power output versus frequency of available Continuous Wave (CW) Terahertz and Sub-terahertz sources. (From [21]). References: IMPATT, Gunn oscillators [22], BWO [23], frequency multipliers [24], photomixers [25,26] , OP laser [27] and QC lasers [28,29]

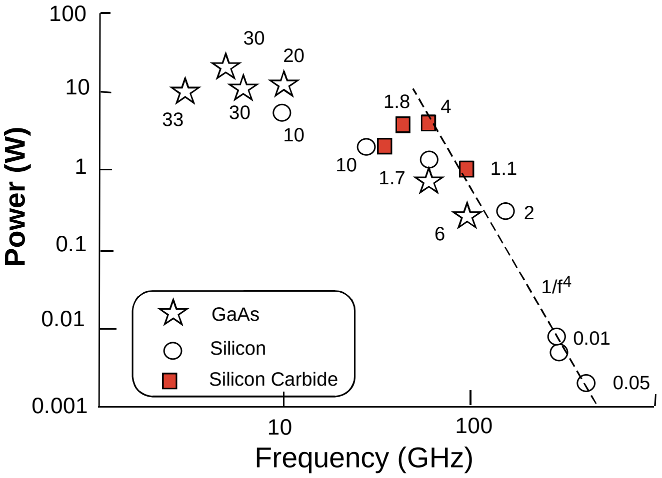

Figure 2: IMPATT power versus frequency. Data points from R. J. Trew, Transit time microwave devices, p. 7-32. In The RF and Microwave Handbook, M. Golio, Editor, CRC Press (2001)

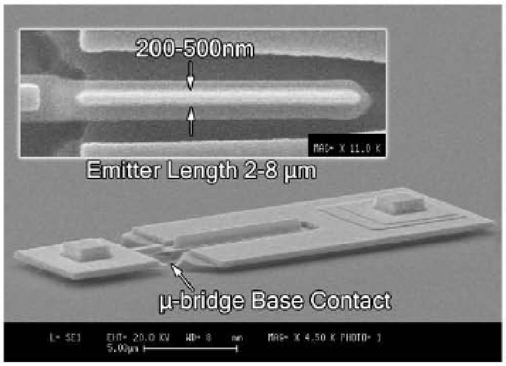

Figure 3: SEM image ultra-high frequency HBT from UIUC.[18] © IEEE 2007

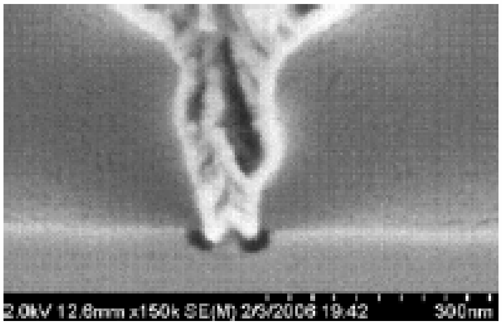

Figure 4: Cross section of 35 nm InP HEMT T-gate from Northrop Grumman.[19] . © IEEE 2007

In 2007, IBM demonstrated record RF performance of silicon SOI achieving the cutoff frequency 485GHz with a 45nm NMOS transistor. Using a notched body contact reduced the parasitic capacitance. Even the IBM PMOS transistors reached the cutoff frequency of 345GHz (see Fig. 5).

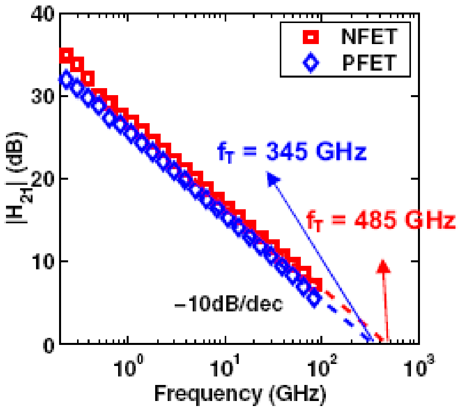

Figure 5: Current gain |*H*21| for 30 μm wide SOI NFET (Lpoly =29 nm) and SOI PFET (Lpoly =31 nm) with relaxed poly pitch at *VGS* = 0.6 (-0.6) V, *VDS* =1.0 (-1.0) V. From [30] ©IEEE (2007)

A new and different approach to THz electronics relies on using wave of electron density (called plasma oscillations) for detection and generation of THz radiation. This approach (first proposed in [31,32]) was recently used to demonstrate THz detection by Si CMOS [33-36], (see Fig. 6). THz emitters based on the excitation of two-dimensional electron gas (2DEG) plasmons at semiconductor heterointerfaces have been also demonstrated. These sources are tunable and can be used together with THz plasmonic resonant and non-resonant detectors using the same technology. The challenge here is to increase efficiency and output power by orders of magnitude, and we discuss the design approaches for achieving this goal.

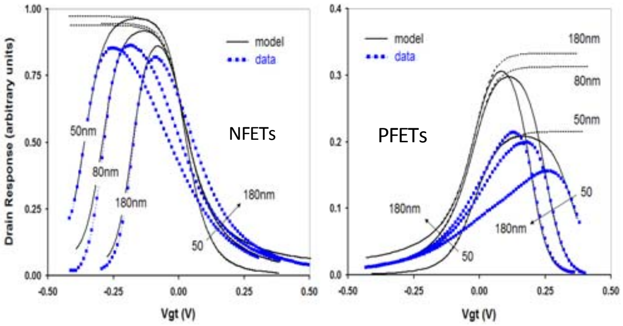

Figure 6: Sub-THz response of CMOS Si detectors (from [37]) ©IEEE 2007

ACRONYMS

FET's: Field Effect Transistor
HBT's: Heterostructure Bipolar Transistors
HEMT's: High Electron Mobility Transistors
SOI: Silicon on Insulator
IMPATT: Impact Avalanche Transit Time
THz: Terahertz
MMIC: Monolithic Microwave Integrated Circuit
SEM: Scanning Electron Microscope
RF: Radio Frequency
NMOS: N-Type Metal Oxide Semiconductor
PMOS: P-Type Metal Oxide Semiconductor
CMOS: Complimentary Metal Oxide Semiconductor

REFERENCES

[1] Masayoshi Tonouchi Cutting-edge terahertz technology, Nature Photonics 1, 97 - 105 (2007)

[2] Siegel, P.H. Terahertz technology, IEEE Transactions on Microwave Theory and Techniques, Volume: 50, Issue: 3, pp. 910-928 Mar 2002

[3] D. Woolard, W. Loerop, and M. S. Shur, and, Editors, Terahertz Sensing Technology, Volume I. Electronic Devices & Advanced Technology, World Scientific (2003) ISBN 981-238-334-4

[4] D. Woolard, W. Loerop, and M. S. Shur, and, Editors, Terahertz Sensing Technology, Volume I. Electronic Devices & Advanced Technology, Volume II. Emerging Scientific Applications and Novel Device Concepts, World Scientific (2003)

[5] D. L Woolard, J. O Jensen, R J. Hwu, and M. S Shur, Editors, Selected Topics in Electronics and Systems - Vol. 46, Terahertz science and technology for military and security applications (2007), also in International Journal of High Speed Electronics and Systems, Vol. 17, No 2 (2007)

[6] Farman, J. C., Gardiner, B. G. and Shanklin, J. D. Nature 315, 207−210 (1985).

[7] M. L. Santee et al., Geophys. Res. Lett., vol. 32, no. L12817, 2005

[8] G. L. Pilbratt, Herschel Space Observatory mission overview, in IR Space Telescopes and Instruments. Edited by John C. Mather. Proceedings of the SPIE, Volume 4850, pp. 586-597 (2003).

[9] M. S. Shur, Terahertz Technology for Space Exploration and for Data Communication, Proceedings of SPIE -- Volume 6776, Broadband Access Communication Technologies II, Raj Jain, Benjamin B. Dingel, Shozo Komaki, Shlomo Ovadia, Editors, 67760D (Sep. 10, 2007)

[10] Siegel, P.H. Terahertz technology in biology and medicine. IEEE Transactions on Microwave Theory and Techniques, Volume: 52, Issue: 10, pp. 2438- 2447, Oct. 2004

[11] M. S. Shur, Terahertz technology: devices and applications, Proceedings of ESSDERC 2005, 35th European Solid-State Device Research Conference, pp. 13 – 21, Grenoble, France, 12-16 September 2005, edited G. Ghibaudo, T. Skotnicki, S. Cristoloveanu, and M. Brillouet

[12] P Y Han1 and X-C Zhang , Free-space coherent broadband terahertz time-domain spectroscopy, Meas. Sci. Technol. 12 1747-(2001)

[13] Brian C. Smith, Fourier transform infrared spectroscopy, CRC Press 1996

[14] Friedrich Kremer (Editor), Andreas Schönhals (Editor), Broadband Dielectric Spectroscopy (Hardcover) Springer (2002)

[15] Crowe, T.W. Mattauch, R.J. Roser, H.P. Bishop, W.L. Peatman, W.C.B. Liu, X. GaAs Schottky diodes for THz mixing applications, Proceedings of the IEEE, Volume: 80, Issue: 11, pp. 1827-1841, Nov 1992

[16] M. S. Shur and L. F. Eastman, Ballistic Transport in Semiconductors at Low-Temperatures for Low Power High Speed Logic, IEEE Transactions Electron Devices, Vol. ED-26, No. 11, pp. 1677-1683, November (1979)

[17] J.-S. Rieh, B. Jagannathan, D. R. Greenberg, M. Meghelli, A. Rylyakov, F. Guarin, Z. Yang, D. C. Ahlgren, G. Freeman, P. Cottrell, and D. Harame, SiGe heterojunction bipolar transistors and circuits toward terahertz communication applications, IEEE Transactions on Microwave Theory and Techniques, vol. 52, 2390, (2004).

[18] William Snodgrass, Bing-Ruey Wu, K. Y. Cheng, and Milton Feng Type-II GaAsSb/InP DHBTs with Record fT = 670 GHz and Simultaneous fT, fmax > 400 GHz, IEDM Technical Digest, p. 623 (2007)

[19] 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)

[20] Seong-Jin Yeon, Myonghwan Park, JeHyuk Choi1, and Kwangseok Seo, 610 GHz InAlAs/In0.75GaAs Metamorphic HEMTs with an Ultra-Short 15-nm-Gate, IEDM Technical Digest, p. 613 (2007)

[21] 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

[22] G. I. Haddad, J. R. East, and H. Eisele, Two-terminal active devices for terahertz sources, *International Journal of High Speed Electronics and Systems*, vol. 13, 395, (2003)

[23] MicroTech Instruments, Terahertz Spectrometers, Imaging Systems and Accessories Catalog, http://mtinstruments.com/downloads/Microtech%20Product%20Catalog.pdf, (2007).

[24] T. W. Crowe, D. W. Porterfield, J. L. Hesler, W. L. Bishop, D. S. Kurtz, and H. Kai, Terahertz sources and detectors, Proceedings of SPIE - The International Society for Optical Engineering, Orlando, FL, USA, (2005)

[25] S. Verghese, K. A. McIntosh, and E. R. Brown, Optical and terahertz power limits in the low-temperature-grown GaAs photomixers, *Applied Physics Letters*, vol. 71, 2743 (1997).

[26] M. Mikulics, E. A. Michael, R. Schieder, J. Stutzki, R. Gusten, M. Marso, A. van der Hart, H. P. Bochem, H. Luth, and P. Kordos, Traveling-wave photomixer with recessed interdigitated contacts on low-temperature-grown GaAs, *Applied Physics Letters*, vol. 88, 41118, (2006)

[27] Coherent, SIFIR-50 Stabilized Integrated FIR (THz) Laser System, http://www.cohr.com/downloads/SIFIR50_DSrevB.pdf, (2007)

[28] B. S. Williams, Q. Qin, S. Kumar, Q. Hu, and J. L. Reno, High-temperature and high-power terahertz quantum-cascade lasers,

Proceedings of SPIE - The International Society for Optical Engineering, San Jose, CA, United States, (2007).

[29] S. Barbieri, J. Alton, H. E. Beere, J. Fowler, E. H. Linfield, and D. A. Ritchie, 2.9 THz quantum cascade lasers operating up to 70 K in continuous wave, *Applied Physics Letters*, vol. 85, 1674, (2004)

[30] Sungjae Lee, Basanth Jagannathan*, Shreesh Narasimha*, Anthony Chou*, Noah Zamdmer*, Jim Johnson, Richard Williams, Lawrence Wagner*, Jonghae Kim*, Jean-Olivier Plouchart*, John Pekarik, Scott Springer and Greg Freeman, Record RF performance of 45-nm SOI CMOS Technology, IEDM Technical Digest, p. 225 (2007)

[31] M. Dyakonov and M. Shur, Shallow water analogy for a ballistic field effect transistor: New mechanism of plasma wave generation by dc current, *Physical Review Letters*, vol. 71, 2465, (1993).

[32] M. Dyakonov and M. Shur, Detection, mixing, and frequency multiplication of terahertz radiation by two-dimensional electronic fluid, *IEEE Transactions on Electron Devices*, vol. 43, 380, (1996)

[33] W. Knap, F. Teppe, Y. Meziani, N. Dyakonova, J. Lusakowski, F. Boeuf, T. Skotnicki, D. Maude, S. Rumyantsev, and M. S. Shur, Plasma wave detection of sub-terahertz and terahertz radiation by silicon field-effect transistors, *Applied Physics Letters*, vol. 85, 675, (2004).

[34] F. Teppe, Y. M. Meziani, N. Dyakonova, J. Lusakowski, F. Boeuf, T. Skotnicki, D. Maude, S. Rumyantsev, M. S. Shur, and W. Knap, Terahertz detectors based on plasma oscillations in nanometric silicon field effect transistors, *Physica Status Solidi C: Conferences*, vol. 2, 1413, (2005).

[35] N. Pala, F. Teppe, D. Veksler, Y. Deng, M. S. Shur, and R. Gaska, Nonresonant detection of terahertz radiation by silicon-on-insulator MOSFETs, *Electronics Letters*, vol. 41, 447, (2005).

[36] 23 W. Stillman, M. S. Shur, D. Veksler, S. Rumyantsev, and F. Guarin, Device loading effects on nonresonant detection of terahertz radiation by silicon MOSFETs, *Electronics Letters*, vol. 43, 422, (2007)

[37] W. Stillman, F. Guarin, V. Y. Kachorovskii, N. Pala, S. Rumyantsev, M. S. Shur, and D. Veksler, Nanometer Scale Complementary Silicon MOSFETs as Detectors of Terahertz and Sub-terahertz Radiation, 6th Annual IEEE Conference on Sensors, Atlanta, Ga., (2007)