New Concepts for Submillimeter-Wave Detection and Generation

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***Abstract* — Existing technology cannot adequately address growing needs of submillimeter wave applications. The emerging approaches, such as Quantum Cascade Lasers or terahertz sources using interband transitions operate involve photonics and are limited to cryogenic temperatures. Deep scaled down HEMTs, InP and SiGe HBTs, and even advanced Si MOSFETs are trying to reach the low frequency bound of this range. In this paper, we consider a plasma wave electronics approach for generation and detection of submillimeter wave radiation. This approach that relies on the excitation of electron density waves rather than on the electron drift shows great promise for submillimeter wave applications.**

I. INTRODUCTION

Submillimeter range of electromagnetic spectrum (100 µm to 1mm) roughly corresponding to frequencies from 300 GHz to 3 THz, presents a challenge for both electronic and photonic technologies. The sources of terahertz radiation come in two varieties: narrow band and wide band sources. Typical broadband terahertz sources use femtosecond lasers that excite charge carriers in a semiconductor sample with an antenna [1], or excite plasma oscillations [2]. Recent breakthrough technology of using relativistic electrons for exciting broadband terahertz radiation achieved terahertz power of 20 W [3].

The existing electronic narrow band terahertz sources have a fairly low power (see Figure 1), except for free-electron lasers that could reach 10^6 W of peak power [4].)

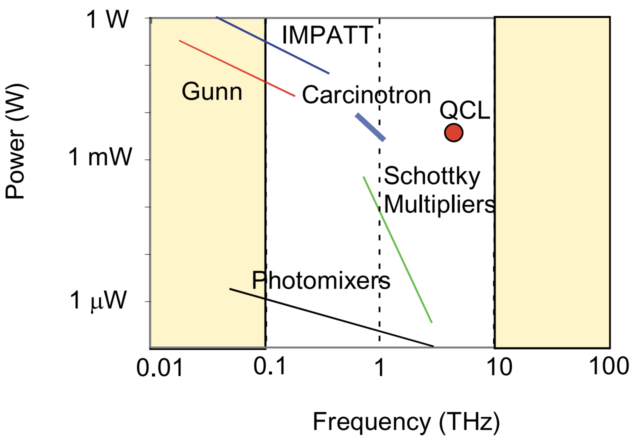

Fig. 1. Output power of existing narrow band submillimeter sources.

Emerging technologies for narrow band submillimeter sources include photonic sources, such as Quantum Cascade Lasers that demonstrated several milliwatt of power at wavelength close to 100 µm [5], emitters using intersubband transitions in SiGe quantum wells (~30 THz) [6], and emitters based on transitions between acceptor states in SiGe split by the built-in strain (~3 THz) [7], all operating at cryogenic temperatures. More conventional but deeply scaled down and innovative devices that might potentially reach this frequency range include a transferred substrate Heterojunction Bipolar Transistor (~1100 GHz f_{max}) [8], deep submicron InGaAs HEMT (~350 - 500 GHz f_T) [9], SiGe HBTs (~300 GHz f_T) [10], and even a silicon 50 nm Tri-Gate "terahertz" transistor from Intel [11]. All these devices struggle to overcome limitations related to the electron transit times and to parasitics that start playing a dominant role at subterahertz frequencies.

An alternative approach takes advantage of exciting the waves of electron density – plasma waves – in two dimension electron layers [12-15] (see Fig. 2).

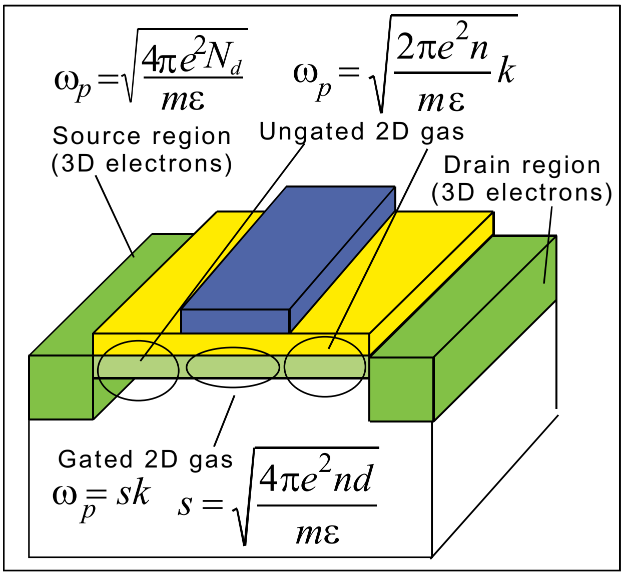

Fig. 2. Frequencies of plasma oscillations, ω_p, versus wave vector, k, in a field effect transistor. m is electron effective mass, e is dielectric constant, ε is electronic charge, N_d is bulk electron concentration for alloyed regions, and n is sheet electron density for channel regions.

A gated channel of a field effect transistor acts as a resonant cavity for these waves allowing for the resonant detection [16-19] or excitation [15, 20] of subterahertz or and terahertz radiation.

The resonant frequencies of the plasma oscillations are determined by the electron concentration in the channel and its length, as well as the electron concentration and geometrical parameters of the gate-to-source and gate-to-drain regions [21,22]. For HEMT structures with the submicron sizes, these frequencies fall in the THz range. The gate voltage changes the electron concentration under the gate and, therefore, can tune the resonant plasma frequencies.

II. Detection and Multiplication of Submillimeter Radiation Using Plasma Waves

Both resonant and non-resonant detection of terahertz and subterahertz radiation is possible based on the excitation of plasma wave in a FET channel [16]. The resonant detection takes places when $\omega_p\tau > 1$, where τ is the momentum relaxation time. If the opposite inequality holds ($\omega_p\tau > 1$), the detection is non-resonant. Figure 3 illustrates the transition from the non-resonant detection (at elevated temperatures) to the resonant detection at 8 K (indicated by an arrow.)

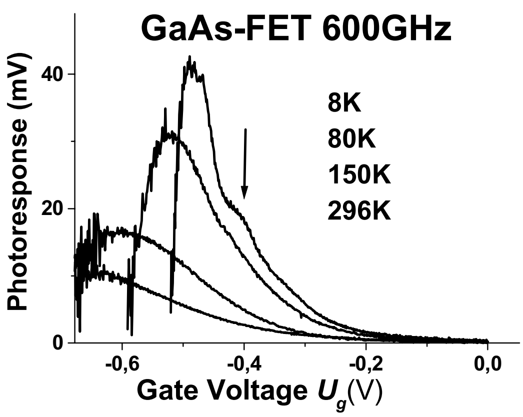

Fig. 3 Resonant and non-resonant detection [23].

Fig. 4 shows the resonant detection of the 600 GHz radiation by a GaAs/AlGaAs 0.15 micron gate HEMT.

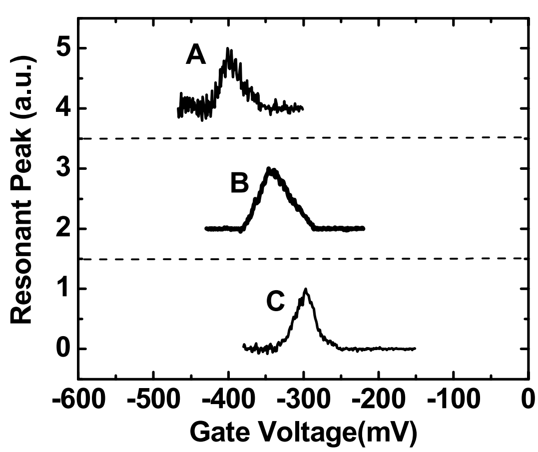

Fig. 4. Resonant peaks for three different electron sheet densities in 0.15 gate AlGaAs/GaAs HEMT showing that detection peaks shifting with threshold voltage (controlled by illumination) [18].

Fig. 5 presents the results of the resonant detection by a structure with two 2D high electron mobility electron layers with a metal grating serving as a gate [24,25].

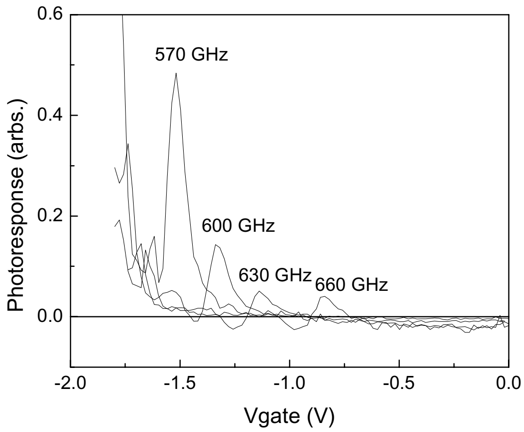

Fig. 5. Terahertz photoresponse as a function of gate voltage at four different frequencies. The temperature was T=25K and the source-drain current was I_{SD}=100μA. Grating period is 4μm [23].

The observed peaks are in agreement with the calculated frequencies of the plasma modes. These results illustrate the detection of subterahertz radiation associated with the excitation of plasma oscillations related to the intrinsic (hydrodynamic) nonlinearity of the electron transport along the channel [16].

The submillimeter wave detection can also use the nonlinear effects accompanying the electron injection from the channel into the gate (resulting in a gate current). The latter effects are due to a strong dependence of the leakage current on the local potential of the channel in the case of thermionic or tunneling injection. The utilization of such "transverse" nonlinearity in different transistor structures, in particular HEMTs, has been considered in Refs. [26-29]. Fig. 6 illustrates the detectivity peak at large gate bias that we associate with the effect of the gate leakage current [19].

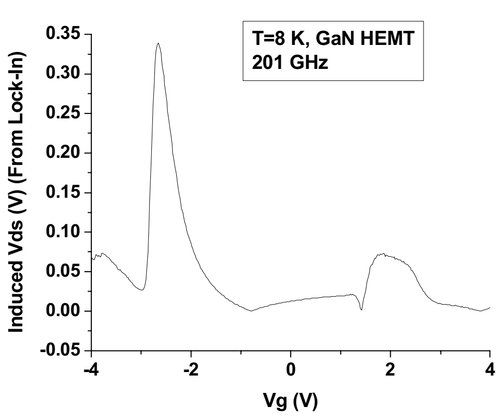

Fig. 6 Detection responsivity enhancement at high forward bias related to gate current [19].

The parameter characterizing the hydrodynamic nonlinearity can be estimated as $\eta_{II} = u_\omega/\pi s$, where u_ω is the amplitude of the ac component of the average (hydrodynamic) electron velocity in the channel and s is the plasma wave velocity (see Fig. 2). Taking into account that $u_\omega \sim e\varphi_\omega/(\pi ms)$, where φ_ω is the ac component of the potential and m is the electron effective mass, we obtain

$$\eta_{II} = \frac{e\varphi_\omega}{\pi^2 ms^2} \quad (1)$$

The estimate for the parameter characterizing the nonlinearity associated, for example, with thermionic injection yields

$$\eta_\perp = \frac{e\varphi_\omega}{2k_B T} \quad (2)$$

Comparing η_{II} and $\eta_\perp$ we arrive at [27]

$$\frac{\eta_{II}}{\eta_\perp} \sim \frac{2k_B Te\varphi_\omega}{\pi^2 ms^2} \sim \frac{v_T^2}{s^2} << 1 \quad (3)$$

This estimate shows that the detection related to the excitation of the plasma waves due to gate current could be more effective that the detection relying on the transport non linearity.

III. Plasma instabilities and self-excitation of THz plasma oscillations

A DC drain current flowing in the channel of a ballistic field effect transistor can lead to the instability of plasma waves, which could be used for generating subterahertz and terahertz radiation [15]. However, effects related to contacts [30-32] lead to a dramatic decrease of the effective “ballistic” mobility and might, in many cases, suppress this instability. Therefore, we proposed several new approaches for increasing the instability increment.

The current from the channel into the gate can cause instability of the stationary state of the electron system in the channel with respect to the excitation of the plasma oscillations. In transistor structures with the resonant-tunneling injection from the channel, the instability in question and self-excitation of the plasma oscillation can be associated with a negative differential conductivity of the double-barrier gate layer [33]. Such a device can be considered as a distributed resonant-tunneling diode (the region between the channel and the gate) integrated with a resonant "electron cavity" (its role is played by the gated channel). A negative dynamic conductivity of a single barrier gate layer can occur due the transit time effect exhibiting by the electrons injected into this layer from the channel [33, 34].

The self-excitation of plasma oscillations under consideration can lead to pronounced oscillations of the channel charge. This, in turn, results in the oscillations of the current induced in the external circuit (owing to the oscillations of the charge in the gate) connected with an antenna.

A negative dynamic conductivity of the gate layer is beneficial (even if its absolute value is insufficient for the self-excitation of plasma oscillation) in the HEMT operation as a THz detector, because such a conductivity suppresses the plasma oscillation damping, that leads to sharpening of the plasma resonances [26], [30]. The experimental observations of the plasma wave emission from a GaN-based HEMT were observed in the saturation regime [20], which is consistent with this excitation mechanism.

IV. Terahertz photomixing

The excitation of coherent plasma oscillations caused by the photoelectrons and photoholes generated by short optical pulses can be also used for the generation of THz radiation. However, relatively strong electron scattering on impurities in bulk structures with the electron system (resonant electron cavity) formed due to doping causes strong damping of the excited plasma oscillations. This damping results in the generation of only few-cycles of THz radiation [35].

Recently, a new concept of the generation of narrow-band THz signals in the structures akin to HEMT subjected to ultrashort optical pulses was proposed [36,37]. Such a device (referred in the following to as a HEMT-photomixer) can exhibit a strong resonant response to such pulses causing either intersubband [36] or interband [37] generation of mobile electrons (or electrons and holes). The excitation of the plasma oscillations in the device under consideration is associated with the pulse of the transient photocurrent induced in the absorption region by the photogenerated electrons and holes. These electrons and holes directly contribute to the current in the external circuit. However, the current induced by the oscillating electron component in the channel can substantially exceed the current induced by photocarriers if the amplitude of the plasma oscillations is sufficiently high.

In HEMT-photomixers utilizing the interband optical excitation, the photogenerated holes should be extracted from the absorption region. One of the possible options is to use a HEMT structure on heavily doped substrate of p+-type separated from the channel by an undoped absorption layer, so that this substrate serves as the hole sink. The thickness of the absorption layer should be optimized taking into account that it determines the fraction of absorbed optical power, the damping of the electron plasma oscillations due to the hole component in the substrate, and the gate-substrate capacitance. The latter can be crucial for matching of a HEMT-photomixer and an antenna.

The shape of the photocurrent peak (in particular, its height) is determined by the dynamic behavior of the photogenerated electrons and holes and geometry of the absorption region. The velocity overshoot being exhibited by the photocarriers due to their near-ballistic transport immediately after the photogeneration can significantly enhance the efficiency of the plasma oscillation excitation [38] and, therefore, the emitted THz power. The manifestation of the photoelectron velocity overshoot effect is possible if the electric field in the absorption region is sufficiently strong (large negative bias of the substrate) and the photon energy slightly exceeds the energy gap. The latter condition implies that photogenerated electrons have small energies and a significant portion of them can be markedly accelerated by the electric field (compare with Ref. [39]).

V. Conclusion

Plasma wave electronics holds promise of developing tunable powerful sources and tunable sensitive detectors of submillimeter wave radiation. The experimental results obtained so far [17-20] are limited to cryogenic temperatures (with a notable exception of the non-resonant detection [23]. However, new ideas of exciting the 2D plasma described in this paper hold promise of reaching higher temperature operation and much improved performance.

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References

[1] D. H. Auston, K.P. Cheung, J.A. Valdmanis, and D.A. Kleinman, D.A. *Phys. Rev. Lett.* **53**, 1555–1558 (1984)

[2] D. Hashimshony, A. Zigler, and D. Papadopoulos, *Phys. Rev. Lett.* **86**, 2806–2809 (2001)

[3] G. L. Carr *et al*. *Nature* **420,** 153–156 (2002)

[4] W. B. Colson et al. *Physics Today* **55** (1), 35–41 (2002)

[5] R. Kohler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi, *Nature* **417**, 156–159 (2002).

[6] G. Dehlinger, L. Diehl, U. Gennser, H. Sigg, J. Faist, K. Ensslin, D. Grützmacher, E. Müller, *Science* **290,** 2277 (2000)

[7] M. S. Kagan, I. V. Altukhov, E.G. Chirkova, K. A. Korolev, V. P. Sinis, R. T. Troeger, S. K. Ray, and J. Kolodzey, *Proc. 10th Int. Symp. "Nanostructures: Physics and Technology"*, St. Petersburg, Russia, 445 (2002)

[8] M. J. W. Rodwell et al, *International Journal of High Speed Electronics and Systems*, Vol. 11, No. 1 pp. 159-216 (2001)

[9]http://www.commsdesign.com/news/tech_beat/OEG20010419S0057

[10] J.-S. Rieh, et al., "SiGe HBTs with Cut-off Frequency Near 300 GHz," in *IEDM Tech. Dig.*, 2002

[11] R. Chau et. al., Advanced Depleted-Substrate Transistors: Single-Gate, Double-Gate, and Tri-Gate", *2002 International Conference on Solid State Devices and Materials (SSDM 2002)*, Nagoya, Japan

[12] S. J. Allen, D. C. Tsui and R. A. Logan, *Phys. Rev. Lett.* 38, 980 (1977)

[13] Tsui C D, Gornik E and Logan R A, *Solid State Comm.* 35 875 (1980).

[14] Burke P J, Spielman I B, Eisenstein J P, Pfeiffer L N, and West K W, *Appl. Phys. Lett.* 76, 745 (2000).

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

[16] Dyakonov M and Shur M, *IEEE Trans. Electron Devices* 43, 1640 (1996)

[17] W. Knap, Y. Deng, S. Rumyantsev, J.-Q. Lu, M. S. Shur, C. A. Saylor, L. C. Brunel, *Appl. Phys. Lett.* Vol. 80, No 18, pp. 3433-3435, 2002

[18] Knap W, Deng Y, Rumyantsev S, and Shur M S, *Appl. Phys. Lett.* 81, 4637 (2002)

[19] Y. Deng, W. Knap, S. Rumyantsev, R. Gaska, A. Khan, V. Ryzhii, E. Kaminska, A. Piotrowska, J. Lusakowski, and M. S. Shur, *2002 IEEE Lester Eastman Conference on High Performance Devices*, August 6-8, 2002, University of Delaware, Newark, DE 19716, IEEE Catalog Number 02CH37365, ISBN 0-7803-7478-9, pp. 135-142

[20] Y. Deng, R. Kersting, J. Xu, R. Ascazubi, X. C. Zhang, M. S. Shur, R. Gaska, G. S. Simin, M. A. Khan, and V. Ryzhii Millimeter Wave Emission from GaN HEMT, submitted for publication

[21] A. Satou, I. Khmyrova, V. Ryzhii, and M. S. Shur, *Semicond. Sci. Technol*., vol. 19, pp. 469-478, 2003

[22] V. Ryzhii, A. Satou, and M. S. Shur, *J. Appl. Phys.* vol. 93, pp. 10041-10045, 2003

[23] W. Knap, V. Kachorovskii, Y. Deng, S. Rumyantsev, J.-Q. Lu, R. Gaska, M. S. Shur, G. Simin, X. Hu and M. Asif Khan, C. A. Saylor, L. C. Brunel, *J. Appl. Phys*., vol. 91, No 11, 9346-9353 June (2002)

[24] X. G. Peralta, S. J. Allen, M. C. Wanke, N. E. Harff, J. A. Simmons, M. P. Lilly, J. L. Reno, P. J. Burke, J. P. Eisenstein, *Appl. Phys. Lett.*, vol. 81, No 9, pp. 1627-1629, August (2002)

[25] X. Peralta, S. J. Allen, M. C. Wanke, N. E. Harff, M. P. Lilly, J. A. Simmons, J. L. Reno, P. J. Burke, J. P. Eisenstein, W. Knap, Y. Deng, S. Rumyantsev, J.-Q. Lü, M. S. Shur, *International Journal of High Speed Electronics and Systems*, Vol. 12, No. 3 pp. 925-937 (2002)

[26] V. Ryzhii, *Jpn. J. Appl. Phys*., vol. 37, pp. 5937-5944, 1998.

[27] I. Khmyrova and V. Ryzhii, *Jpn. J. Appl. Phys*., vol. 39, pp. 4727-4732, 2000.

[28] V. Ryzhii, I. Khmyrova, and M. Shur, *J. Appl. Phys*., vol. 88, pp. 2868-2871, 2000

[29] V. Ryzhii and M. Shur, *Jpn. J. Appl. Phys*., vol. 40, pp. 546-550, 2001

[30] A. A. Kastalsky and M. S. Shur, *Solid State Comm.* Vol. 39, No. 6, p. 715 (1981);

[31] M. Dyakonov and M. S. Shur, in *the Physics of Semiconductors*. M. Scheffler and R. Zimmermann, Editors, World Scientific, Singapore, pp. 145-148, (1996))

[32] M. S. Shur, *IEEE EDL*, Vol. 23, No 9, pp. 511 -513, September (2002)

[33] V. Ryzhii and M. Shur, Jpn. *J. Appl. Phys.*, vol. 41, pp. 1922-1924, 2002

[34] V. Ryzhii and M. Shur, *Semicond. Sci. Technol.*, vol. 17, pp. 1168-1171, 2002.

[35] R. Kersting, K. Unterrainer, G. Strasser, H. F. Kauffmann, and E. Gornik, *Phys. Rev. Lett.*, vol. 79, pp. 3038-3041, 1997.

[36] V. Ryzhii, I. Khmyrova, and M. Shur, *J. Appl. Phys.*, vol. 91, pp. 1875-1881, 2002

[37] V. Ryzhii, I. Khmyrova, A. Satou, P. O. Vaccaro, T. Aida, and M. Shur, *J. Appl. Phys.*, vol. 92, pp. 5756-5760, 2002.

[38] V. Ryzhii, I. Khmyrova, and M. S. Shur, *Proc. SPIE*, vol. 5118, 2003 (in press)

[39] M. Ryzhii, M. Willander, I. Khmyrova, and V. Ryzhii, *J. Appl. Phys.* vol. 84, pp. 6419-6425, 1998