PLASMA WAVE ELECTRONICS FOR TERAHERTZ APPLICATIONS

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Abstract

A channel of a field effect transistor might act as a resonance cavity for the plasma waves. For micron or sub-micron gate lengths, the fundamental frequency of this cavity is in the terahertz range and can be easily tuned by changing the gate bias. The quality factor of this plasma wave resonator depends on the momentum relaxation time and on the plasma frequency determined by the device length. A short field effect transistor can be used as a basic device for resonant detection, mixing, multiplication, and even generation of terahertz radiation.

Introduction

The difficulty in generating and detecting terahertz radiation using solid state devices is related to the fact that on one hand the carrier transit times in semiconductor devices are typically much longer than the period of the terahertz oscillations and, on the other hand, the quanta of terahertz radiation are much smaller than room or even liquid nitrogen temperature. However, the plasma waves in a gated two dimensional electron gas (2DEG) might propagate with a much larger velocity than the electron drift velocity and their excitation is not linked to any type of intersubband or interband electronic transitions. Hence, they can be excited at room or even at elevated temperatures.

As we discuss below, a channel of a field effect transistor is, in fact, a resonant cavity for the plasma waves. For micron or sub-micron gate lengths, the fundamental frequency of this cavity is in the terahertz range and can be easily tuned by changing the

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gate bias. If the quality factor of this plasma wave resonator is high or, at least, larger than unity (which might be achieved in High Electron Mobility Transistors as we discuss below), a FET can be used as a basic device for resonant detection, mixing, multiplication, [1] and even generation [2] of terahertz radiation.

Plasma waves are the oscillations of electron density in space and time, and their properties depend on the electron density and on the dimensions and geometry of the electronic system. Unlike in a three dimensional case, where the plasma oscillation frequency is nearly independent of the wave length, in a gated two-dimensional electron gas (2DEG), the plasma wave have a linear dispersion law similar to that of sound waves or light in vacuum. In this case, the plasma wave velocity, s, is proportional to the square root of the electron sheet density. The velocity of the plasma waves can be easily tuned by the gate bias that controls the 2DEG density.

We will start from a general discussion of plasma waves, in particular, of the plasma waves in a FET channel, and of the boundary conditions that determine the frequencies of the plasma modes in a FET. We will then consider a hydrodynamic approach to the analysis of plasma waves and invoke the shallow water wave analogy. This discussion will be followed by the review of possible devices applications, including a terahertz tunable detector, mixer, multiplier, and oscillator. In conclusion, we will consider problems and challenges to be overcome in the plasma wave electronics field.

Plasma waves in a FET channel

The dispersion relations for plasma waves in the systems of different dimensions can be derived in a simple manner by neglecting collisions and considering only the average drift velocity, v. In this case, the small signal equation of motion and the continuity equation are:

$$\frac{\partial \mathbf{j}}{\partial t} = \mathbf{E}\frac{e^2 n}{m} \tag{1}$$

$$\frac{\partial \rho}{\partial t} + div\mathbf{j} = 0 \tag{2}$$

where $\mathbf{j} = en\mathbf{v}$ is the current density, e is the electronic charge, n is the electron density, m is the electronic effective mass, and ρ is a small-signal charge density related to a deviation of n from its equilibrium value, $\mathbf{E}$ is the small signal electric field. Eq. (1) follows from the Newton Second Law of Motion, where the electron scattering is neglected. These equations are valid for any dimensionality of the problem. However, for the 3D case, the $\mathbf{j}$, n, and ρ are current per unit area, electron concentration, and electric charge per unit volume, respectively, whereas in the 2D case, the $\mathbf{j}$, n, and ρ are current per unit length, electron concentration per unit area, and the electric charge per unit area, respectively.

Differentiating Eq. (2) with respect to time and using Eq. (1), we obtain:

$$\frac{\partial^2 \rho}{\partial t^2} + \frac{e^2 n}{m} div\mathbf{E} = 0 \tag{3}$$

In the 2D case, the electric field vector, **E**, in Eqs. (1) and (3) should be understood as the in-plane electric field having only two components, E_x and E_y, since the third component of the electric field (which is perpendicular to the plane, *xy*, of the 2DEG) does not contribute to the in-plane current and, hence, does not enter into Eq. (1).

The specific relation between **E** and ρ, which should augment Eq. (3) for the complete set of equations, depends on the dimensionality and/or geometry of the problem. In a three-dimensional case, this equation is obviously:

$$div\mathbf{E} = \frac{4\pi\rho}{\varepsilon}, \tag{4}$$

where ε is the dielectric constant. Substituting Eq. (4) into Eq. (3), we obtain a harmonic oscillator equation for the charge density and the well-known expression for the bulk plasma frequency

$$\omega_p = \sqrt{\frac{4\pi e^2 n}{m\varepsilon}} \tag{5}$$

or, in the SI system of units,

$$\omega_p = \sqrt{\frac{e^2 n}{\varepsilon\varepsilon_o m}}, \tag{5a}$$

where ε_0 is the dielectric permittivity of vacuum.)

In the case of a gated two-dimensional electron gas (i.e. of a FET), the relation between the electron concentration and electric potential is given by

$$en = CU \tag{6}$$

where $U = U_g - U_c - U_T$, U_T is the threshold voltage, $U_g - U_c$ is the potential difference between the gate and the channel, $C = \varepsilon/4\pi d$ is the gate-to-channel capacitance per unit area, and d is the gate-to-channel separation. This equation is valid when U changes along the channel on the scale large compared to d (so-called gradual channel approximation). Hence, the in-plane electric field is given by

$$\mathbf{E} = -\frac{1}{C}\nabla\rho \tag{7}$$

Eq. (7) replaces Eq. (4), which is valid in the 3D case. Substituting Eq. (7) into Eq. (3), we finally obtain the two-dimensional wave equation for the surface charge ρ

$$\frac{\partial^2 \rho}{\partial t^2} - s^2 \Delta\rho = 0 \tag{8}$$

where Δ is the two-dimensional Laplace operator, and

$$s = \sqrt{\frac{4\pi e^2 nd}{m\varepsilon}} \tag{9}$$

is the velocity of the surface plasma waves. The solution of Eq. (8) corresponds t waves with a linear dispersion law:

$$\omega = sk, \tag{10}$$

where ω and k are the frequency and the wave vector of the plasma waves, respectively. Using Eq. (6) and (7), we can express the plasma wave velocity in terms of the gate voltage swing:

$$s = \sqrt{\frac{eU}{m}} \tag{11}$$

In a similar way, using Eq. (4) and the relation between the in-plane electric field and surface charge density for ungated 2D electron gas, one can obtain the dispersion law for the plasma waves in this system.

$$\omega = \sqrt{\frac{2\pi e^2 n}{m\varepsilon} k} \tag{12}$$

In the same way, we can obtain the dispersion law for the plasma waves propagating a along a one-dimensional wire:

$$\omega = s_1 k \left(\ln \frac{1}{kr} \right)^{1/2} \tag{13}$$

Here r is the radius of the wire, s_1 is the velocity of the one-dimensional plasma waves given by

$$s_1 = \sqrt{\frac{ne^2}{m\varepsilon}} \tag{14}$$

We note that the equations for the ungated 2D gas are valid when $kd \ll 1$ (in the opposite limiting case $kd \gg 1$ the existence of the metallic gate is irrelevant, and one obtains the dispersion relation given by Eq. (12)). For the 1D case Eq. (13) holds when $kr \ll 1$.

Fig. 1 gives the summary of the plasma wave frequencies and dispersion relations for systems of different dimensions and geometry. We note the similarity between the dispersion relations for the gated 2DEG case and ungated 1DEG case. This similarity means that the results discussed below for the gated 2DEG should equally apply to ungated quantum wires.

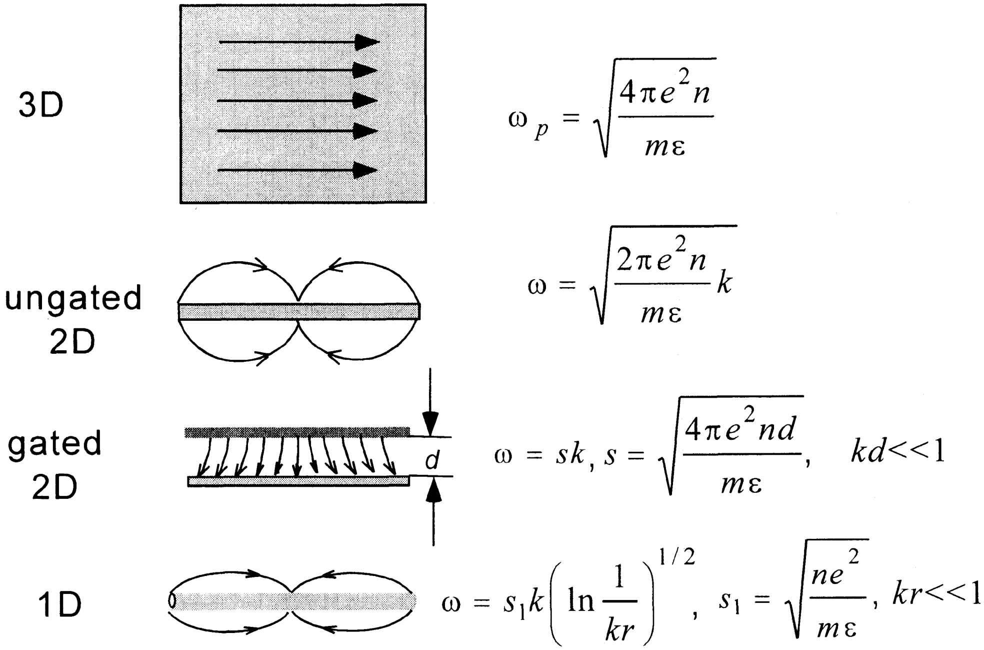

Fig. 1. Plasma wave frequencies for different sample geometries.

The fundamental frequency, f_l, of the FET plasma wave resonator is

$$f_l = const\ s/L \tag{15}$$

where *const* is a numerical constant, s is the plasma wave velocity given by Eqs. (9) or (11), and L is the gate length. The constant numerical factor, const, in Eq. (15) depends on the boundary conditions (see the following section, where we show that $const = 1/4$ for a certain type of the boundary conditions). Since s is on the order of 10^8 cm/s, we obtain and $f_l \sim 1$ THz for L=1 μm. Thus, a sub-micron FET would serve a resonator cavity for terahertz oscillations.

Plasma waves in a gated 2D electron gas were first considered by Chaplik [3] for electrons on the surface of liquid helium. For the case of a FET, they were considered by Nakayama. [4] Allen et al. [5] observed infrared absorption and Tsui et al. [6] observed weak infrared emission related to such waves in silicon inversion layers. Results of a recent study by Burke et al. [7] are presented in Figs. 2 and 3.

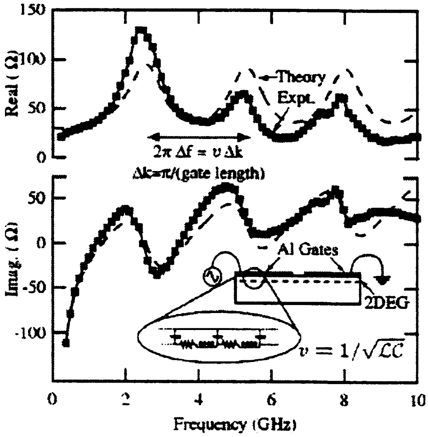

Fig. 2. Impedance of gated sample with 2D electron gas versus frequency. For this sample, $\omega_p\tau = 1$ at 1.25 GHz (where τ is the momentum relaxation time). [7]

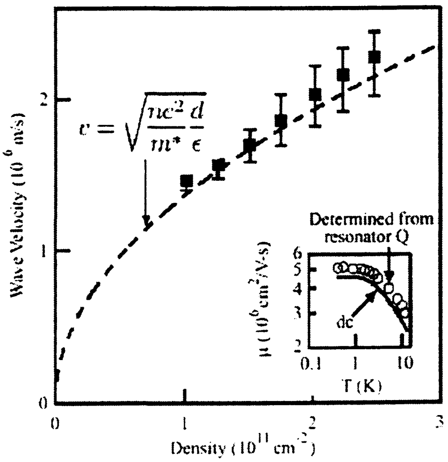

Fig. 3. Plasma wave velocity versus electron density. [7]

Burke et al. measured the impedance of a high mobility gated 2D electron gas in a gated GaAs/AlGaAs heterojunction at low temperatures. The gate length was ~ 0.4 mm, and the electron scattering time was on the order of 100 ps. In Fig. 2, one can see well-defined resonance peaks, corresponding to several plasma wave modes with frequencies in the gigahertz range. Results for the plasma wave velocity, deduced from such measurements at different gate biases, are presented in Fig. 3.

From Fig. 2 and Eq. (15) we conclude that a device with the same mobility and a gate length, L=1 μm would have the fundamental frequency of 1 THz and a quality Q=100!

Boundary conditions

The frequencies of the plasma waves depend on the boundary conditions. As discussed above, the channel of a FET works as a resonator for the plasma waves. This resonator is analogous to a segment of a transmission line. In this analogy, the role of the distributed capacitance is played by the gate-to-channel capacitance, while the equivalent inductance is related to the electron inertia. Therefore, it is natural to specify the boundary conditions in terms of the terminating impedances, Z_s and Z_d, at the source and drain side of the channel. Hence, the boundary conditions are

$$\begin{aligned} Z_s j_s &= U_s \\ Z_d j_d &= U_d \end{aligned} \tag{16}$$

where j_s, j_d, U_s, and U_d are the AC gate-to-channel current densities and potentials U at the source and drain sides of the channel, respectively (see Fig. 4).

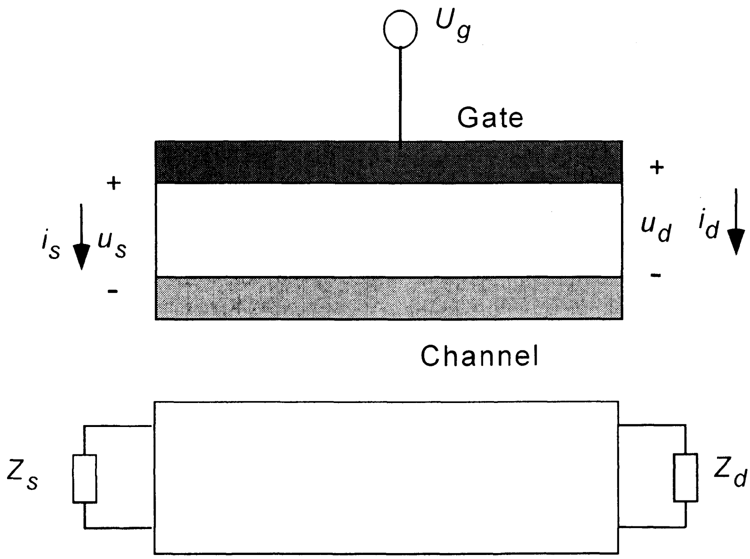

Fig. 4. Boundary conditions and transmission line analogy for plasma waves in field effect transistor.

We can understand these boundary conditions by considering the external capacitances connecting the gate contact to the source and drain contacts, respectively. A characteristic scale for these capacitances is the gate-to-channel capacitance, C, of the device. Obviously, if the terminating capacitance is much smaller then C, the terminating impedance corresponds to an open circuit at the plasma wave frequency. In the opposite limiting case, when the terminating capacitance is much larger then C, the terminating impedance corresponds to a short circuit at the plasma wave frequency. The former limiting case corresponds to the situation when the ac gate-to-channel current density is zero at the contact, while the latter limiting case corresponds to the zero ac potential at the contact.

We note that FETs are normally designed and operated in such a way that there is a natural asymmetry in these boundary conditions for several reasons. First, the high frequency transistor layout must minimize the parasitic drain-to-gate capacitance compared to the parasitic gate-to-source capacitance, since the drain-to-source capacitance is the Miller capacitance that strongly degrades the microwave transistor operation. Second, the flowing drain-to-source current caused an asymmetry in the channel potential distribution with a smaller charge in the channel toward the drain side and, as a consequence, the drain-to-gate capacitance decreases and the gate-to-source capacitance increases with the drain bias.

Having this in mind, we will adopt below the following simplified boundary conditions for the ac channel currents and gate-to-channel voltages:

$$U = 0 \quad \text{at the source,}$$
$$j = 0 \quad \text{at the drain,} \tag{17}$$

which corresponds to a short circuit at the source and an open circuit at the drain. For such boundary conditions, the plasma wave frequencies are given by

$$f_n = sn/4L, \quad n = 1,2,3... \tag{18}$$

Hydrodynamic approach and shallow water wave analogy

As was shown above, the plasma waves are a very general phenomenon that exists in systems with different geometry and dimensions and with different electron concentrations. However, in the special case when the concentration is large enough but the electrons are still not strongly degenerate, the electron-electron collisions are more frequent than electron collisions with impurities and/or lattice vibrations. In this case the electrons actually behave not as a gas, but rather like a fluid, and should be described using the hydrodynamic approach. [2]

As was discussed in [2], for a highly non-ideal electron gas in an AlGaAs/GaAs heterostructures with the electron surface concentration, n, on the order of 10^{12} cm^{-2} at 77 K, the thermal energy, the Fermi energy, and the Bohr energy are of the same order. Under such conditions, the mean free path for electron-electron collisions is on the order of the mean distance between electrons (~ 100 Å), which is much smaller than both the mean free path and a typical gate length, and the hydrodynamic approach should be adopted.

The basic equations describing the two dimensional electronic fluid are the relationship between the surface carrier concentration and gate voltage swing, the hydrodynamic equation of motion, and the continuity equation. The surface concentration, n, in the FET channel is related to the local gate-to-channel voltage swing, $U = U_{gc}(x) - U_T$, by Eq. (4). Here $U_{gc}(x)$ is the local gate-to-channel voltage. As discussed above, Eq. (19) represents the usual gradual channel approximation (see, for example, [8]), which is valid when the characteristic scale of the potential variation in the channel is much greater than the gate-to-channel separation.

The equation of motion (the Euler equation) is

$$\frac{\partial \mathrm{v}}{\partial t}+\mathrm{v}\frac{\partial \mathrm{v}}{\partial x}+\frac{e}{m}\frac{\partial U}{\partial x}+\frac{\mathrm{v}}{\tau}=0 \qquad (19)$$

where $\partial U/\partial x$ is the longitudinal electric field in the channel, $\mathrm{v}(x,t)$ is the local electron velocity, and m is the electron effective mass. The last term accounts for electronic collisions with phonons and/or impurities. (Here we neglect the viscosity of the electronic fluid.) Eq. (2) has to be solved together with the usual continuity equation, which (taking Eq. (1) into account) can be written as:

$$\frac{\partial U}{\partial t}+\frac{\partial (U\mathrm{v})}{\partial x}=0 \qquad (20)$$

Equations (19) and (4) coincide with the equations describing the so-called shallow water in conventional hydrodynamics [9] if U is replaced by the water level, h, and e/m is replaced by the free fall acceleration, g.

The term "shallow water" in hydrodynamics refers to the situation when the scale of spatial variations is large compared to the water depth, h. Plasma waves in the FET channel for $kd<<1$ correspond to shallow water waves with $kh<<1$. The velocity of shallow water waves is $(gh)^{1/2}$, which is analogous to the plasma wave velocity $s=(eU/m)^{1/2}$. This exact shallow water analogy [2] gives a deeper insight in the processes occurring in the FET channel under different conditions. We note that the hydrodynamic analogy goes even further, since plasma waves in the limit $kd>>1$ with the $\omega\sim k^{1/2}$ dispersion law (see Eq. (12)) exactly correspond to deep-water waves $(kh>>1)$.

An important parameter in hydrodynamics is viscosity. The viscosity of the 2D electronic fluid is of the order of $\mathrm{v}_F\lambda_{ee}$ where v_F is the Fermi velocity and λ_{ee} is the mean free path for the electron-electron collisions, which is on the order of the inter-electronic distance, $n^{-1/2}$. Then we obtain the following estimate for the viscosity of the electron fluid: $\nu=\hbar/m \approx 15$ cm^2/s for GaAs. For comparison, the viscosity of air is about 0.15 cm^2/s. For wavelengths that are short enough the electron viscosity may provide the dominant mechanism for damping of plasma oscillations.

FET as a detector of terahertz radiation

Electromagnetic radiation can excite plasma waves, and, therefore, a FET has a resonance response at the plasma wave frequency. As we discussed in [1], this effect can be used for the resonance detection and mixing of electromagnetic radiation at terahertz frequencies. The half width of the resonance curve is determined by the damping of plasma waves, i.e. by the electron momentum relaxation time and by the electron viscosity.

The detection is based on the nonlinearity of the electron fluid (the main source of non-linearity is the dependence of the plasma wave velocity on the electron concentration), which is, in fact, the usual effect of rectification of the ac radiation field. Thus, a constant drain-to-source voltage should develop in response to incoming electromagnetic radiation. Certainly, an asymmetry of the drain and source contacts should exists, in order to have this effect. Such an asymmetry can be caused by the following reasons:

a) The radiation could be fed in (by an external antenna) to one side of the transistor, e.g. between the source and the gate

b) As discussed above, the boundary conditions might be different at the source and at the drain (e.g. short circuit at the source and open circuit at the drain)

c) A dc source-drain current could be applied, depleting the drain end of the channel

As we showed in Ref. [1] at low frequencies, such that $\omega\tau << 1$, the HEMT should work as a non-resonant broad band detector with the responsivities, which are comparable to those of Schottky diode detectors. In the low frequency limit, our theory predicts that the responsivity, R, of such a HEMT detector is given by

$$R = \alpha\, L^4\omega^2/(6s^4\tau^2) \qquad (21)$$

The pre-factor α in Eq. (18) depends on the boundary conditions.

Recently, we fabricated a prototype non-resonant detector (operating in the microwave range) using an AlGaAs/GaAs 0.15-micron gate HEMT. [10] The measured dependencies of the detector responsivity on the gate bias and frequency were in good agreement with our theory (see Fig. 5).

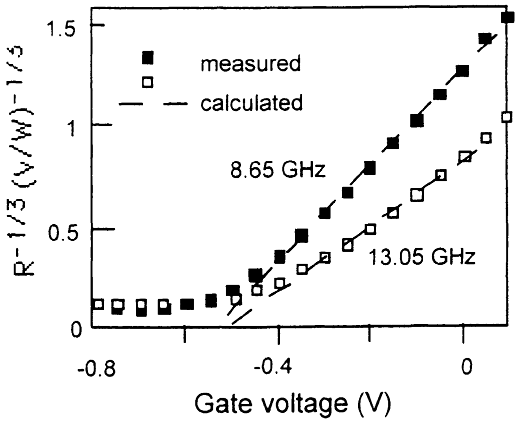

Fig. 5. Comparison of measured and predicted responsivities for an AlGaAs/GaAs HEMT. [10]

Fig. 6 shows a schematic diagram and an equivalent circuit of a HEMT subjected to terahertz radiation [11, 12]. In the case that is the most appropriate for the resonant detector, the incoming electromagnetic radiation induces an ac voltage at the source side of the channel. The drain side of the channel is an open circuit. (A coupling with a terahertz radiation might be enhanced using an appropriate antenna structure.) This ac voltage excites the plasma waves.

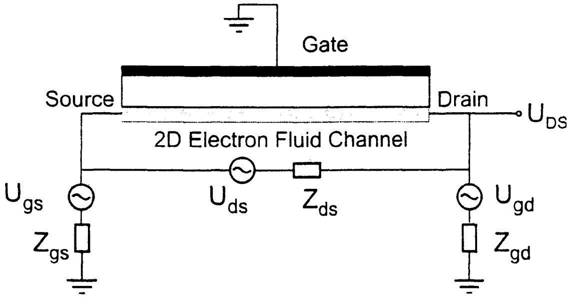

Fig. 6. Schematic diagram and an equivalent circuit of a HEMT subjected to terahertz radiation. [12]

As mentioned above, the dc gate-to-source voltage determines the velocity, s, of these waves. Because of the nonlinear properties of the electron fluid and the asymmetry in the boundary conditions, a FET biased only by the gate-to-source voltage and subjected to electromagnetic radiation develops a constant drain-to-source voltage, which has a resonant dependence on the radiation frequency with maxima at the plasma oscillation frequency and its odd harmonics. For the frequencies, such that $|\omega - n\,\omega_1| << \omega_1$, and for $s\tau/L >> 1$ where τ is the momentum relaxation time and L is the channel length, we obtain [19, 31]

$$\frac{\Delta U}{U_o} = \left(\frac{U_a}{U_o}\right)^2 \left(\frac{s\tau}{L}\right)^2 \frac{1}{4(\omega - n\omega_1)^2 \tau^2 + 1} \tag{22}$$

Here where n = 1, 3, 5, 7..., ΔU is the dc voltage difference between the drain and source potentials, U_o is the gate-to-source gate voltage swing, and U_a is the amplitude of the ac source-to-gate voltage induced by the incoming radiation. The half width of the resonance curve is determined by the damping of the plasma oscillations caused by the electron momentum relaxation and/or the electron fluid viscosity. Thus, the FET acts as a tunable resonance quadratic detector of electromagnetic radiation. As can be seen from Figs. 6 and 7, the resonance responsivity of a FET can exceed typical responsivities of standard Schottky barrier detectors (which are on the order of 1000 V/W) by many orders of magnitude, if the quality factor, Q, is high enough (the responsivity is proportional to Q^2.)

Recently, we reported on the implementation of a terahertz detector utilizing 2D electronic fluid in a High Electron Mobility Transistor (HEMT). [32] To our knowledge, this is the first plasma wave terahertz detector ever demonstrated.

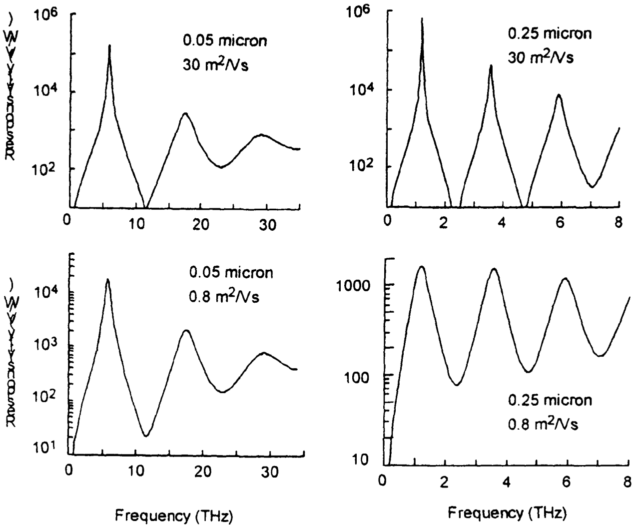

Fig. 7. Detector responsivity versus frequency for 0.05 μm and 0.25 μm gate HEMTs at 77 K and 300 K. Parameters used in the calculation: $U_o = 0.5$ V, $G = 1.5$, $\nu = 15$ cm^2/s, $m = 0.063$ m_o, $\mu = 30$ m^2/V-s at 77 K, $\mu = 0.8$ m^2/V-s at 300 K. Here G is the antenna gain and ν is viscosity of the electronic fluid. [1, 17], © IEEE, 1996

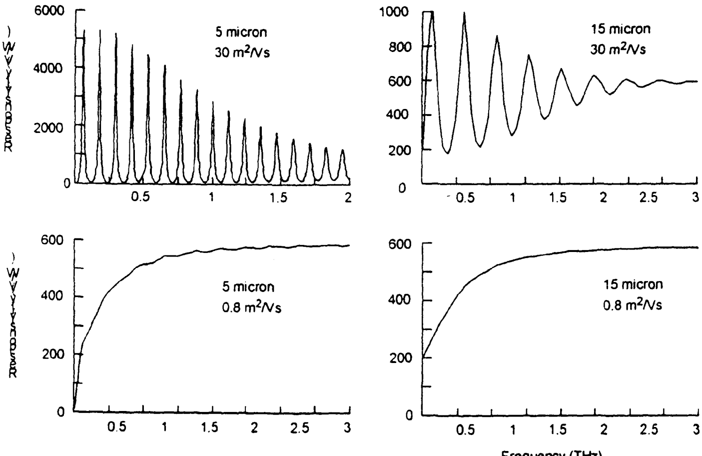

Fig. 8. Calculated responsivity of 2 μm and 15-μm gate HEMTs at 77 K and 300 K. The devices behave as resonant detectors at 77 K and as broadband detectors at 300 K. Parameters used in the calculation: $U_o = 0.5$ V, $G = 1.5$, $\nu = 15$ cm^2/s, $m = 0.063$ m_O, $\mu = 30$ m^2/V-s at 77 K, $\mu = 0.8$ m^2/V-s at 300 K. [1, 17], © IEEE, 1996

The detector was fabricated using a *Fujitsu* FHR20X HEMT mounted on a quartz substrate. The device operated at a frequency of 2.5 THz, which is about 30 times higher than the transistor cutoff frequency. A CO_2-pumped far-infrared gas laser served as a source of terahertz radiation. The laser beam was chopped and focused on the sample with the electric field polarization oriented in the drain-to-source direction. The drain was open, thus the drain current is zero. The gate current is in the order of nano-ampere for the measurement range of gate bias.

In agreement with the predictions of our terahertz detector theory [19, 31], the radiation induced a negative DC drain-to-source bias proportional to the radiation intensity. This voltage was measured using a lock-in amplifier.

The device characteristics were fitted using the HEMT model implemented in AIM-Spice. [13], [14] The parameters were extracted from measured DC characteristics and from the elements of the small-signal microwave equivalent circuit.

The measured dependencies of the detector responsivity on the gate bias are in good agreement with the gate bias dependence of the normalized responsivity predicted by the detector theory [1, 17] (see Fig. 9).

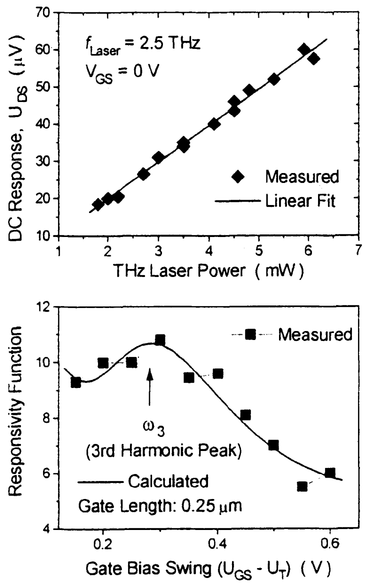

Fig. 9. Measured (symbols) response versus incident power at zero gate bias. Also shown gate bias dependence of the detector dimensionless responsivity function, which is proportional to $U = V_{gs} - V_T$, measured (symbols) at the laser frequency of 2.5 THz and the laser power of 5.7 mW. The solid line is predicted by the theory and is normalized for comparison. The peak corresponds to the third harmonic of the fundamental plasma frequency, ω_3. [11], © IEEE, 1998

The responsivity increases at smaller gate voltage swings as predicted by the theory. The dimensionless responsivity function displays a rather broad resonant peak corresponding to the third harmonic of the fundamental plasma frequency.

Since the drain current was zero, and the gate current in the measurement range was also nearly zero, the heating effect should be entirely independent of the gate bias. Hence, it could not have been responsible for the measured effect. Beside that, the wavelength of the terahertz radiation was nearly two orders of magnitude larger than the gate length. Therefore, the temperature rise, if any, would be uniform over the device, and can in no way result in the measured drain voltage response that was proportional to the terahertz radiation intensity.

More recent results showed a large increase in the detector detectivity in the regime with an applied drain-to-source bias. [15] Since the drain bias decreases the drain-to-source capacitance and increases the gate-to-source capacitance, this result is consistent with the expected impact of asymmetrical boundary conditions as discussed above.

FET as a mixer and multiplier

In practical systems, mixing of weak incoming signal, $U_a \cos(\omega t)$ with a strong local oscillator signal, $U_{loc}\cos(\omega_{loc}t)$, is often more desirable because of a much higher sensitivity. For $|\omega - n\,\omega_{loc}|\tau << 1$, the equation describing the electron fluid mixer response coincides with Eq. (`22), where U_a^2 should be replaced with U_aU_{loc}.

Nonlinear properties of the 2D electronic fluid not only lead to the rectification of the incoming electromagnetic radiation but also to the appearance of a signal at the second and higher harmonics of the incoming radiation with the resonance response at the fundamental plasma frequency (see Fig. 10).

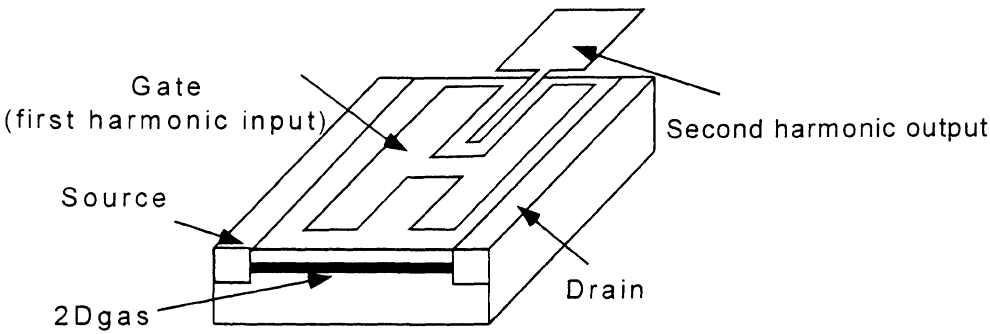

Fig. 10. Schematic design of HEMT doubler with two gates. An alternative design may utilize a single gate and an additional contact to the 2D channel at approximately 0.35 L from the source. (From [1,17], © IEEE, 1996.)

As expected, the second harmonic has a larger magnitude than higher harmonics. For the second harmonic, the voltage has a maximum closer to the source end of the device channel, which should be accounted for in the multiplier design.

The amplitude of the second harmonic is roughly of the same order as the dc voltage developed in the resonance detector.

Generation: terahertz whistle and electronic flute

In Ref. 2 we have found that under certain conditions the steady state with a dc current in the FET channel is unstable against spontaneous generation of plasma waves. This instability is the consequence of asymmetric boundary conditions at the source and the drain. The simplest asymetric conditions are the ones discussed above: short curcuit at the source and open curcuit at the drain. If, for a moment, we neglect dissipation, this instability immediately follows from Eqs. (19) and (20). These equations should be linearized with respect to small deviations of U and v from their steady state values, and the temporal evolution of these small perturbations should be studied, taking account of the boundary conditions given by Eq. (17). Such calculation yields the following expression for the growth increment [2]:

$$\omega'' = \frac{s^2 - v_o^2}{2Ls} \ln\left|\frac{s+v_o}{s-v_o}\right| \tag{23}$$

where v_o is the steady state velocity of the electrons in the channel. The dependence of the increment on the ration v_o/s is presented in Fig.11.

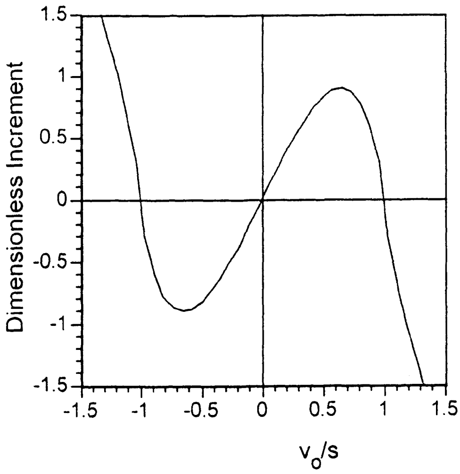

Fig. 11. Dimensionless plasma wave increment, $2\omega'' L/s$, as a function of Mach number, $M = v_o/s$. The steady electron flow is unstable when $0 < v_o < s$ and $v_o < -s$.[2]

One can see that the instability exists for any arbitrary small v_o (small current). This, of course, is the consequence of neglecting losses, caused by collisions. In reality, there would be a threshold current, at which the calculated increment exceeds the losses (see Fig. 12 which shows the net increment and threshold velocities).

The origin of this instability can be understood if one considers reflections of a plasma wave from the two boundaries. With our boundary conditions, it is easy to calculate that for a small amplitude wave of potential U the amplitude reflection coefficient at the source is equal to -1, while the reflection coefficient at the drain is equal to $(s+v_o)/(s-v_o)$, i.e. is greater than unity! Thus one could say that plasma waves are amplified during reflection at the drain contact. However, this is not quite accurate. As it was pointed out by Cheremisin [16] if one consideres the current rather than voltage wave, the reflection coefficients are reversed, but the product of the two reflection coefficients remains the same. The products of the reflection coefficients at the source and at the drain are greater than unity, if a dc electron flow exists. This is the origin of the wave amplification during a round trip, and this mplification leads to an instability of the steady state with respect to generation of plasma waves.

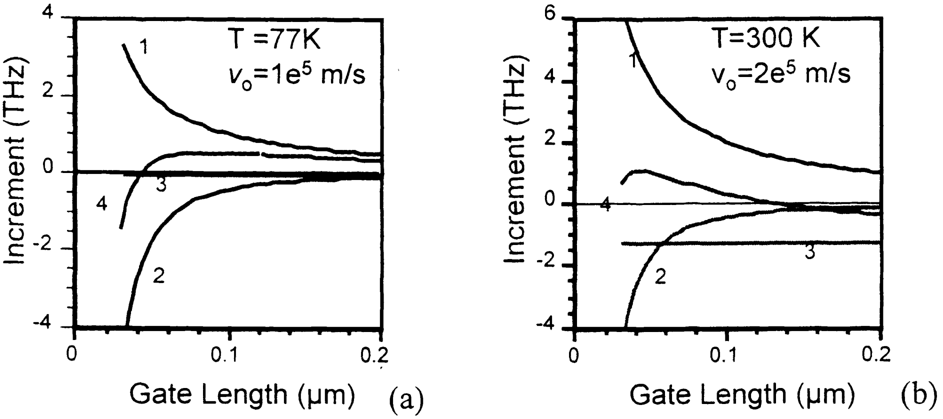

Fig. 12. Growth increment and decrements of plasma waves versus channel length for AlGaAs/GaAs HEMT at 77 K (a) and 300 K (b). 1 -growth increment, 2 - decrement caused by electron viscosity, 3 - decrement caused by electron scattering, 4 - net increment (positive values correspond to the wave growth). [17]

The precise form of the boundary conditions used above is not crucial for the instability. It can be shown, that a positive growth increment can be obtained for arbitrary terminating impedances Z_s and Z_d (see Eq. (16)), provided that the imaginary part of Z_s is greater than the imaginary part of Z_d, in other words that the gate-to-source capacitance, C_{gs}, is greater than the gate-to-drain capacitance, C_{gd}. Of course, if there are apreciable losses at the contacts, described by the real parts of Z_s and Z_d, this would increase the instability theshold or might even completely suppress the instability.

Actually, this type of instability is well known in acoustics: this is the mechanism responsible for the performance of the ordinary whistle, excitation of organ pipes and a great variety of wind musical instruments. [18] In all of these cases, if the velocity of the air flow exceeds a certain threshold (determined by dissipation), sound waves are generated in a resonant cavity. From the theoretical point of view, the problem can be devided into two: a) given the terminating (acoustic) impedances, calculate the growth increment and the threshold flow velocity, and b) calculate the terminating impedances. The latter task is difficult, since it requires consideration of the two or three dimensional flow at the pipe ends. The former problem was solved in Reference [2].

In this regard, we would like to stress that plasma waves are similar not only to shallow water waves but also to sound waves since they have a linear dispersion law. In turn, shallow water behavior is similar to the dynamics of a gas with pressure proportional to the square of the density, (see, for example, [9]). Thus, the nonlinear hydrodynamic equations for the 2D electron fluid are similar to (but not identical with) the equations for a real gas, such as air. However, the linearized equations describing small-amplitude plasma waves in a FET and sound waves in a gas are identical. Since the linearized equations determine the instability threshold for a steady flow (i. e. the wave generation threshold), the instability conditions for a real gas and for a 2D electron fluid should be similar provided that the Reynolds numbers and quality factors of resonance cavities are the same.

Hence, in principle, one can design a device, which we called an "electronic flute" [19]. As was shown in Reference [19], these dimensionless parameters for a HEMT structure might be of the same order of magnitude as for a conventional wind musical instrument (Re ~ 50 and Q ~ 1 - 100), see Table 1.

Table. 1. Parameter comparison for conventional and electronic flutes. [33]

Parameter	Conventional Flute	Electronic Flute
relevant dimension	1 cm	10^{-4} cm
flow velocity	10 cm/s	10^7 cm/s
wave velocity	3×10^4 cm/s	10^8 cm/s
viscosity	0.15 cm^2/s	15 cm^2/s
frequency	10 - 10^3 Hz	10^{11} - 10^{13} Hz
Reynolds number	60	60
Quality factor	3-100	10

Thus, a complete similarity between the plasma waves in a FET and sound waves led us to believe in the possibility of realizing an electronic flute based on the excitation of plasma waves by a direct current in gated modulation doped structures (see Fig. 13). This electronic flute should operate in the terahertz range of frequencies and emit far infrared radiation.

As a consequence of the instability, the amplitude plasma oscillations grows in time, reaching a stationary state of nonlinear oscillations with an amplitude determined by sheet carrier concentration in the channel, momentum relaxation time, and device length.[2,19] This stationary state was examined by computer simulation in Refs.[20], [21] revealing a complex behavior involving traveling shock waves. Such oscillations should result in a periodic variation of the channel charge and the mirror image charge in the gate contact, i. e. to the periodic variation of the dipole moment. This variation should lead to electromagnetic radiation. The device length is much smaller than the wavelength of the electromagnetic radiation, λ at the plasma wave frequency. (The transverse dimension, W, may be made comparable to λ.). Hence, the Ballistic FET operates as a point or linear source of electromagnetic radiation. Many such devices can be placed into a quasi-optical array for power combining.

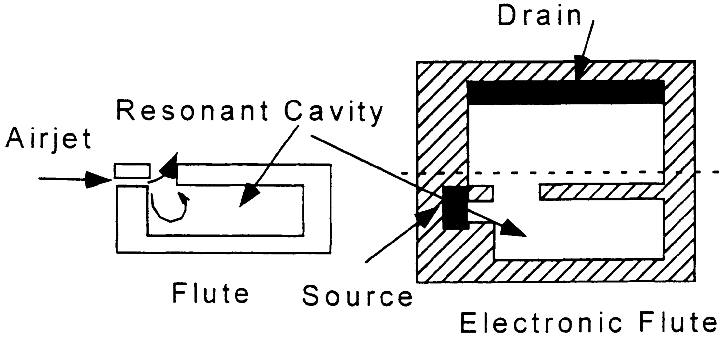

Fig. 13. Simplified diagrams of a jet driven pipe musical instrument of a flute family and of electronic flute. Arrows show the direction of airflow and streamlines of electric current. White area of the electronic flute is the gated region with the 2D-electron fluid in the channel. The part of this device shown below the dashed line is the electronic flute. The top gated portion of the device connected to the drain is similar to the outside air space for a jet driven musical instrument. The streamlines of the electron flow near the cavity opening excite the plasma waves in the cavity, just like the air jet penetrating the resonant cavity in a flute excites sound waves in the flute resonance cavity.[19]

Conclusions.

Plasma wave electronics opens up intriguing opportunities for implementing solid-state tunable generators and tunable resonant and non-resonant detectors and mixers of terahertz radiation. Such development might open up many new exciting applications. However, several theoretical and experimental problems have to be solved in order to make this dream a reality.

The theoretical challenges involve the analysis of the two-dimensional and three-dimensional problems, a more detailed understanding of the boundary conditions [22], [23], and the analysis of non-linear regimes of the plasma wave devices. [24]

Also, the predicted increment of the plasma wave instability is relatively weak, and one would need a ballistic transistor in order to obtain generation at low currents. (Some preliminary evidence of such generation was reported in [17].) We should mention, however, that recent work by Ryzhii et al. offers the solution for this problem by implementing a double barrier resonant tunneling structure between the gate an the channel. As shown in [25], [26], [27], [28], this should dramatically increase the plasma wave instability increment and make a room temperature terahertz generation possible.

Another intriguing solution of this problem (still quite speculative) might be related to the recently predicted negative differential mobility in silicon 2DEG that might be used in order to enhance the growth of plasma wave oscillations. [29]

Another problem is that of enhancing coupling between the terahertz radiation and plasma waves. This problem is common for all types of solid-state terahertz devices, and can be solved by using arrays of FETs (electronic flute) or appropriate antenna structures. Evidently, more theoretical and experimental work is required in order to solve all these problems.

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