# Plasma Wave Electronics: Terahertz Detectors and Sources Using Two Dimensional Electronic Fluid in High Electron Mobility Transistors.

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**Abstract.**

We discuss applications of plasma waves in High Electron Mobility Transistors for detectors and sources operating in millimeter and submillimeter range. A short channel High Electron Mobility Transistor (HEMT) has a resonance response to electromagnetic radiation at the plasma oscillation frequencies of the two dimensional electrons in the device. The devices, which use this resonance response should operate at much higher frequencies than conventional, transit-time limited devices, since the plasma waves propagate much faster than electrons. The responsivities of such devices may greatly exceed the responsivities of Schottky diodes currently used as detectors and mixers in the terahertz range. A long channel HEMT has a nonresonant response to electromagnetic radiation and can be used as a broad band detector for frequencies up to several tens of terahertz. Recently, a prototype non-resonant detector (operating in the microwave range) was fabricated using an AlGaAs/GaAs 0.15 micron gate HEMT. The measured dependencies of the detector responsivity on the gate bias and frequency are in good agreement with our theory.

## Introduction.

In this paper, we review our recent work [1-6] on the applications of plasma waves in High Electron Mobility Transistors for detectors and sources operating in microwave, millimeter and submillimeter range. Plasma waves in a FET have a linear dispersion law, just like sound waves. The plasma wave velocity in a FET can easily exceed $10^8$ cm/s (about an order of magnitude higher than the electron saturation velocity in GaAs or Si). That is why plasma wave electronics will operate at much higher frequencies than conventional electronics (for a 0.1 micron FET the operating frequency will be in a terahertz range). A field effect transistor channel acts as a resonance cavity for plasma waves. The quality factor of such a cavity is on the order of $Q = sL/\tau$ where $L$ is the channel length, and t is the momentum relaxation time. In a high mobility, short channel FET, this quality factor can easily exceed 10. In a FET with a small DC current, plasma waves may grow and this leads to the emission of far infra-red radiation. A plasma wave instability may occur due to the boundary conditions typical for a FET, which lead to plasma wave amplification due to reflections from the drain

The nonlinear hydrodynamic properties of the electron fluid may be used for new types of detectors, mixers, and amplifiers. A short channel High Electron Mobility Transistor (HEMT) has a resonance response to electromagnetic radiation at the plasma oscillation frequencies of the two dimensional electrons in the device. A long channel HEMT has a nonresonant response to electromagnetic radiation and can be used as a broad band detector for frequencies up to several tens of terahertz. Our estimates show that the sensitivity of the resonant HEMT detector should exceed the sensitivity of conventional Schottky diode detectors by a factor of $Q^2$, that is by several orders of magnitude. The sensitivity of the non-resonant, broad band HEMT detector is comparable to the sensitivity of conventional Schottky diode detectors (approximately 600 V/W).

## Basic equations

As was discussed in [4], for a highly non-ideal electron gas in an AlGaAs/GaAs heterostructures with the electron surface concentration, $n_s$, 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 ($\approx$ 100 Å) 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, $n_s$, in the FET channel is related to the local gate-to-channel voltage swing, $U = U_{gc}(x) - U_T$, by

$$n_s = CU / e \tag{1}$$

where $C$ is the gate capacitance per unit area and $U_{gc}(x)$ is the local gate-to-channel voltage. Eq. (1) represents the usual gradual channel approximation [7] 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

$$\frac{\partial \mathrm{v}}{\partial t} + \mathrm{v}\frac{\partial \mathrm{v}}{\partial x} + \frac{e}{m}\frac{\partial U}{\partial x} + \frac{\mathrm{v}}{\tau} = 0 \tag{2}$$

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 :

$$\frac{\partial U}{\partial t} + \frac{\partial (U\mathrm{v})}{\partial x} = 0 \tag{3}$$

Equations (2) and (3) coincide with the equations describing the shallow water in conventional hydrodynamics if $U$ is replaced by the water level and e/m is replaced by the free fall acceleration.

Another important parameter is viscosity. The viscosity of the 2D electronic fluid is of the order of $\mathrm{v}_F\lambda_{ee}$ where $\mathrm{v}_F$ is the Fermi velocity and $\lambda_{ee}$ is the mean free path for the electron-electron collisions, which is on the order of the inter-electronic distance, $n_s^{-1/2}$. 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.

**Electronic Flute and Terahertz Sources.**

It is well known that plasma waves with a linear dispersion law, $\omega = sk$, may propagate in a Field Effect Transistor channel. [8-10] Here $\omega$ is frequency, $s = (eU/m)^{1/2}$ is the wave velocity, $e$ is the electronic charge, $m$ is the electron effective mass, $U$ is the gate-to channel voltage swing, and $k$ is the wave vector. Allen et al. observed infrared absorption [11] and Tsui et al. observed weak infrared emission [12] related to such waves in silicon inversion layers.

As discussed in [13], 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, [14]). 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, one can design a device, which we called an "electronic flute" [3]. In [3], we showed that these dimensionless parameters for our "electronic flute" should be of the same order of magnitude as for a conventional flute.

In a short field effect transistor where electrons experience practically no collisions with

phonons and/or impurities during the transit time (we call such a device a Ballistic FET). However, the high electron concentration results in many electron-electron collisions. In this case, individual electrons cannot be considered as ballistic particles but the two dimensional (2D) electron gas as a whole will exhibit interesting hydrodynamic behavior. As we showed in [4], the steady state of a current-carrying Ballistic FET is unstable for appropriate boundary conditions.

As a consequence of the instability, the amplitude plasma oscillations grows in time, reaching a steady-state amplitude determined by sheet carrier concentration in the channel, momentum relaxation time, and device length. [15] This results 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, $\lambda_R$ at the plasma wave frequency. (The transverse dimension, $W$, may be made comparable to $\lambda_R$.). 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. The maximum modulation frequency is still limited by the transit time ($\approx$ 2 ps in our example).

**Detection and Mixing of Terahertz Radiation by Two Dimensional Electronic Fluid**

As we discussed above, plasma waves may be coupled to electromagnetic radiation. Conversely, electromagnetic radiation can excite plasma waves, and, therefore, a FET has a resonance response at the plasma wave frequency. The half width of the resonance curve is determined by the inverse momentum relaxation time. As we discussed in [1, 2], this effect can be used for the resonance detection and mixing of electromagnetic radiation at terahertz frequencies.

We also showed that at low frequencies, $\omega$, such that $\omega\tau << 1$, where $\tau$ is the momentum relaxation time, the HEMT works as the detector of electromagnetic radiation 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

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

The pre-factor $\alpha$ depends on the boundary conditions.

Recently, we fabricated a prototype non-resonant detector (operating in the microwave range) using a AlGaAs/GaAs 0.15 micron gate HEMT. [6] The measured dependencies of the detector responsivity on the gate bias and frequency were in good agreement with our theory (see Fig. 1).

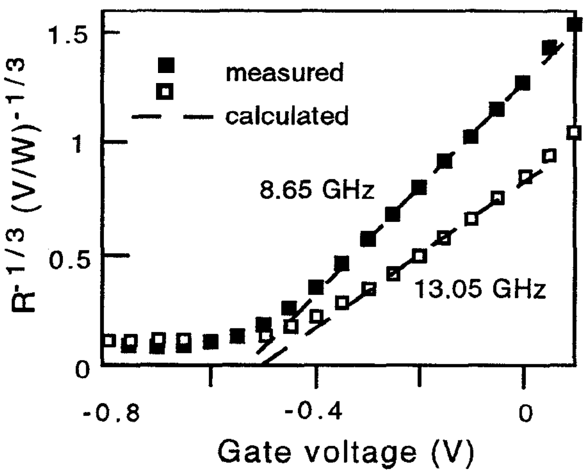


Fig. 1. Comparison of measured and predicted responsivities for an AlGaAs/GaAs HEMT. [6]

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