

Plasma Wave Electronics for Generation and Detection of THz Radiation

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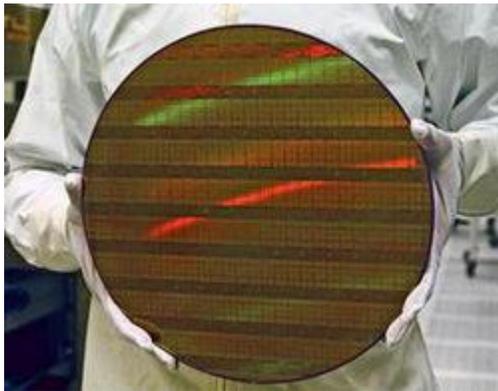
ABSTRACT

Scaling down the minimum feature size of integrated circuits is pushing the operation of field effect transistors into a ballistic regime, where electron inertia and plasma wave effects start playing a dominant role. In this paper, we review detection and generation of sub-terahertz and terahertz radiation by plasma waves. Both resonant and non-resonant detection has been demonstrated in Si,-based, III-V based, and AlGaIn/GaN field effect transistors, and the results are in reasonable agreement with theory. These devices expect to find applications for terahertz detection at high operating frequencies. Weak tunable terahertz emission has been observed at cryogenic temperatures but the plasma wave mechanism still needs to be explored to be proven responsible for this emission. Further improvements are expected by using field effect transistor arrays both for terahertz detection and emission.

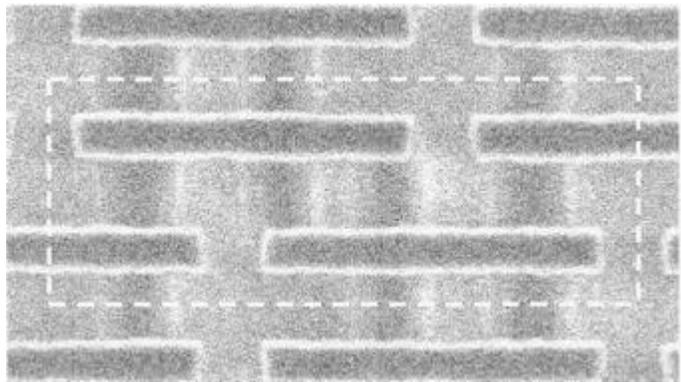
Keywords: plasma wave electronics; terahertz emission, terahertz detection, ballistic transport

1. INTRODUCTION

In 2006, Intel, IBM, TI, and Samsung all announced plans for a 45 nm CMOS technology¹. In January 2006, Intel announced a working 45 nm chip (see Figure 1). The next goal (and, possibly, the shortest silicon MOS with planar design, is to develop 32 nm technology by 2010.



(a)



(b)

Figure 1. Intel 45 nm wafer (a) and 45 nm six transistor SRAM cell. (from www.physorg.com/news10230.html).

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The effective channel length is shorter than the minimum feature size and is expected to reach 17 nm for the 32 nm node. Hence, it will drop below the mean free path in silicon (see Figure 2) causing ballistic or quasi-ballistic transport to be a dominant mode of electron transport not only in deep submicron high mobility semiconductor devices but also in mainstream silicon field effect transistors, at least at low drain-to-source voltages.

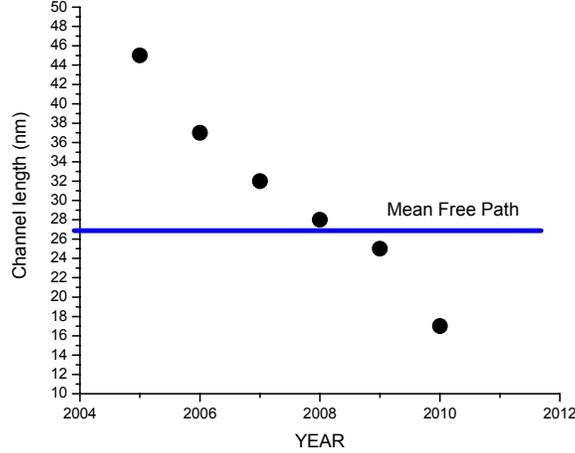


Figure 2. Effective channel length projections and mean free path in silicon at room temperature.

For this mode of transport (first predicted in 1979² and experimentally observed in 1999³), the electron inertia plays a very important or even a dominant role making resonant plasma wave effects to be very pronounced in short channel devices. These waves are the waves of electron density propagating in the device channels. The oscillations of the electron density can be explained as follows. A decrease of the electron density in a certain region due to a fluctuation causes an excess of positive charge, and electrons in the vicinity of this fluctuation will rush into the fluctuation attracted by this positive charge. However, because of the electron inertia, they will overshoot and will have to come back, overshooting again, and, hence, support the oscillations of the electron density (i.e. plasma waves). From the mathematical point of view, these oscillations are very similar to shallow water waves and deep water waves, for the gated and ungated two dimensional electron gas, respectively.⁴ In the gated channel, plasma waves propagate with the velocity

$$s_o = \sqrt{qU_o / m} \quad (1)$$

Here m is the effective electron mass, q is the electronic charge, $U_o = U_{gs} - U_T$ is the gate voltage swing, U_{gs} is the gate bias, and U_T is the threshold voltage [5]. Their dispersion law is $\omega = sk$, where ω is the radian plasma frequency and k is the wave vector. Eq. (1) is valid when $S \gg v_{th}$, where v_{th} is the effective thermal velocity defined as

$$v_{th} = \sqrt{\frac{\eta k_B T}{m}} \quad (2)$$

and which should be replaced by the Fermi velocity for the degenerate two dimensional (2D) electron gas). Here η is the ideality factor for the subthreshold current, k_B is the Boltzmann constant, and T is temperature. A more accurate expression for the plasma wave velocity is given by⁶

$$s^2 = v_{th}^2 \left(1 + \exp\left(-\frac{qU_0}{\eta k_B T}\right) \right) \ln \left(1 + \exp\left(\frac{qU_0}{\eta k_B T}\right) \right) \quad (3)$$

In the limiting cases, Eq. (1) yields

$$s^2 = \frac{eU_0}{m}, \text{ for } qU_0 > \eta k_B T; \quad s^2 = v_{th}^2, \text{ for } U_0 < 0 \text{ and } q|U_0| > \eta k_B T.$$

A short FET channel acts as a resonant "cavity" for the plasma waves with the eigen frequencies

$$\omega_N = \omega_0(1 + 2N) \quad (4)$$

Here

$$\omega_0 = \frac{\pi s}{2L} = \frac{\pi v_{th}}{2L} \left\{ \left[1 + \exp\left(-\frac{qU_0}{\eta k_B T}\right) \right] \ln \left(1 + \exp\left(\frac{qU_0}{\eta k_B T}\right) \right) \right\}^{1/2} \quad (5)$$

is the fundamental plasma frequency that can be tuned by changing the gate voltage swing, U_0 .

Figures 3 and 4 show the calculated plasma velocity and fundamental plasma frequency for a 50 nm effective channel length for GaAs, Si, and GaN.

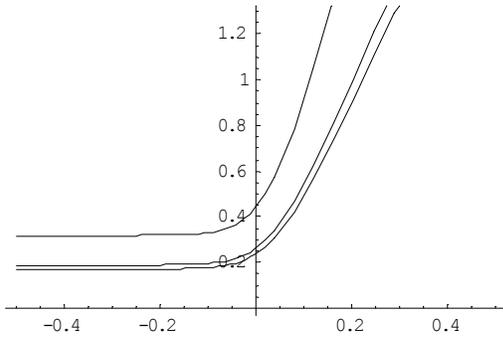


Figure 3. Plasma wave velocity (in 10^6 m/s) versus gate voltage swing U_0 (V) for GaAs, Si, and GaN (top, middle, and bottom lines, respectively)..

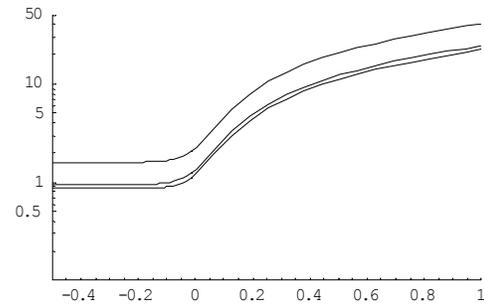


Figure 4. Plasma wave fundamental frequency (THz) versus gate voltage swing U_0 (V) GaAs, Si, and GaN (top, middle, and bottom lines, respectively).

As seen, the plasma frequency is in the terahertz range of frequencies. Dyakonov and Shur⁴ predicted that a current flowing through a ballistic field effect transistor should lead to the instability (generation) of plasma waves and, as a consequence, to the emission of an electromagnetic radiation at the plasma wave frequencies. Below the instability threshold, the excitation of the plasma waves could be used for detection or mixing of electromagnetic radiation at terahertz frequencies.⁷ Hence, the plasma wave electronic effect have potential for pushing the operation of short channel field effect transistors into the terahertz range, far above their operating frequencies in conventional modes of operation.

2. PLASMA WAVE THZ DETECTION

Figure 5 (from⁸) shows an equivalent circuit of a plasma wave THz detector using a short channel FET. Electromagnetic radiation induces small voltage variations between the transistor terminals. The voltage magnitude, phase and which terminals it drops across all depend on the electromagnetic polarization and incidence angle as well as

the transistor orientation and geometry of the contact pads that couple this radiation with the plasma waves. The mechanism of THz coupling to an individual device is not well understood but recent work⁹ showed that coupling to a FET array could be very effective. Nonlinearities related to the nonlinear terms in the transport equations or strong transistor nonlinearity near and below threshold lead to the rectification of the plasma waves inducing a voltage drop between the source and drain, which represents the detector response. The nonlinear properties of such waves and asymmetric boundary conditions at source and drain lead to the radiation-induced constant voltage drop along the channel ΔU ⁴, which is the detector response. The key parameter is the plasmon decay time τ . When $\omega\tau \ll 1$, where ω is the radiation frequency, the plasma wave are overdamped and detector response is a rising function of radiation frequency and decreasing function of the gate voltage swing (broadband detector). (The frequency dependence of coupling might affect the dependence of the detector responsivity on frequency.¹⁰) When $\omega\tau \gg 1$, the FET can operate as a resonant detector⁴ (see Figure 6).

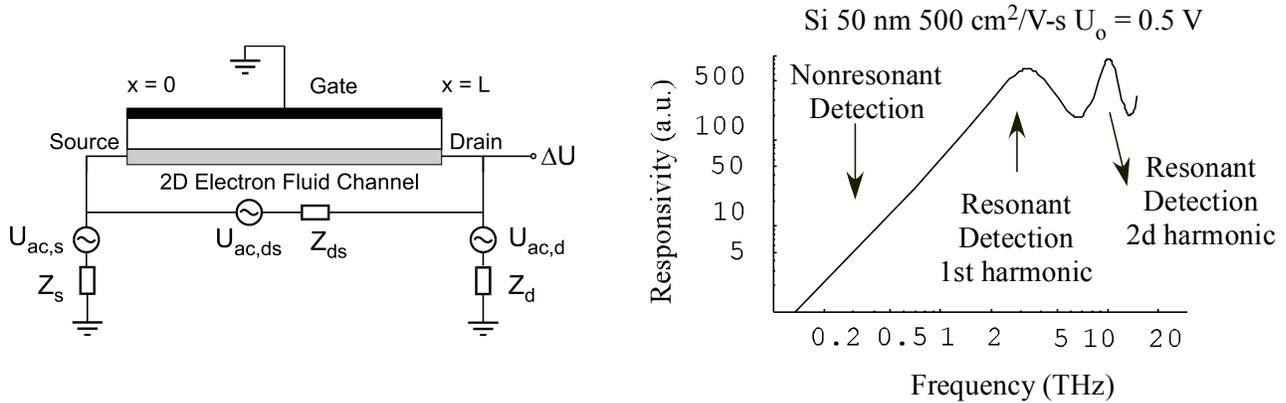


Figure 5. Equivalent circuit of plasma wave FET THz detector.

Figure 6. Calculated responsivity (arbitrary units) of Si FET with 50 nm effective channel length as a function of frequency. At low frequencies, the response is non-resonant. At higher frequencies, responsivity has tunable resonant peaks.

However, this resonant behavior might be barely noticeable in the dependencies of the responsivity on the gate bias, since the responsivity is proportional to $1/U_o$ at positive U_o .⁴ This is illustrated by Figure 7 that shows the calculated dependencies of the responsivity for the same silicon FET on the gate voltage swing for frequencies 2.5 THz, 3.5 THz, and 5 THz. As suggested in⁸ (where the resonant response was observed for the first time), the resonant response is much more noticeable in the dependencies of $R \times U_o$ (see Figure 8).

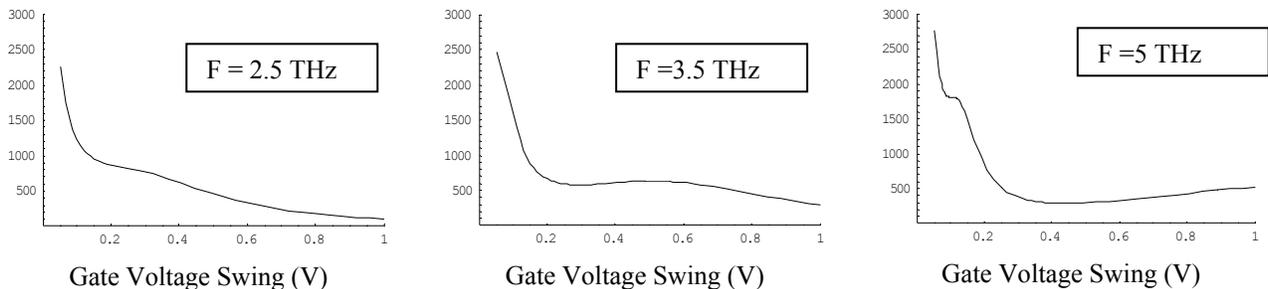


Figure 7. Calculated dependencies of the responsivity R (arbitrary units) on the gate voltage swing for frequencies 2.5 THz, 3.5 THz, and 5 THz.

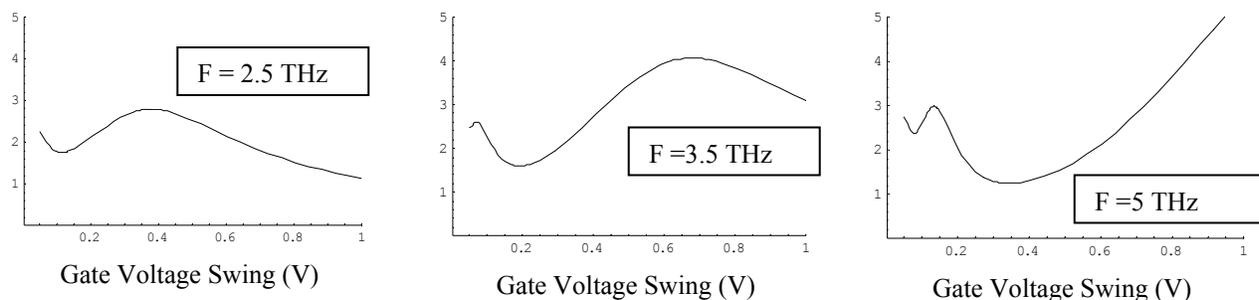


Figure 8. Calculated dependencies of $R \times U_o$ (arbitrary units) on the gate voltage swing for frequencies 2.5 THz, 3.5 THz, and 5 THz.

In these calculations, the plasmon decay time was taken to be equal to the momentum relaxation time. In fact, other decay mechanisms related to the effects of contacts on the ballistic transport¹¹, viscosity of the electron fluid due to the electron-electron collisions⁴, and a possible effect of oblique plasma modes¹² might further dampen the resonant response. Therefore, we conclude that, at least for Si FET detectors, the distinction between resonant and non-resonant detection at zero applied bias is not overly important, except, possibly, at fairly high frequencies. More important from the application point of view is an increase in the responsivity below threshold predicted in⁶. At zero drain bias, the maximum of the responsivity is always in the subthreshold regime. The theory of the non resonant response developed in⁶ is in good agreement with experimental data.¹⁰

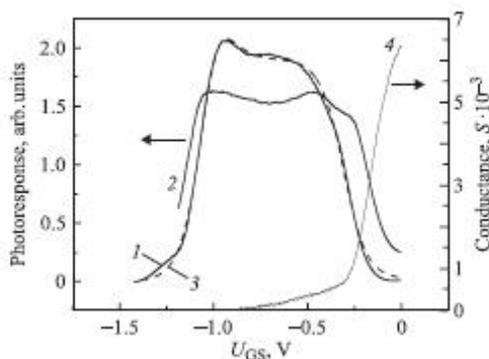


Figure 9. Measured (solid line 1) and calculated (dashed line 3) response of AlGaAs/GaAs HEMT to 329 GHz radiation, response to 229 GHz radiation (curve 2) and FET conductance (curve 4).¹⁰

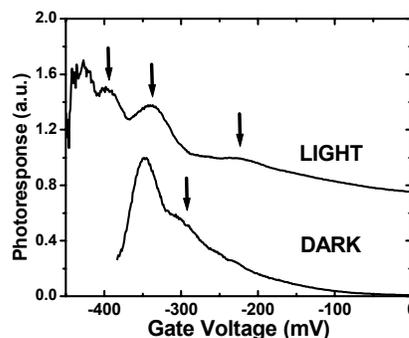


Fig.10. Photoresponse of 15 μ m gate length AlGaAs/GaAs FET versus gate voltage in dark and under illumination. The peaks under illumination correspond to the resonant detection at 600 GHz, 800 GHz, and 1200 GHz.¹³

The resonant response at zero drain bias has been observed in AlGaAs/InGaAs transistors¹³ at cryogenic temperatures, see Fig. 11. The resonant detection is clearly seen under light, when the device mobility is higher.

As was first shown in¹⁴, the application of drain bias can increase the plasma wave detector responsivity by orders of magnitude. In¹⁴, this was effect was explained by the increase in the asymmetry of the boundary conditions. This asymmetry definitely increases the responsivity, which is the largest when the gate-to-source circuit is shorted and the drain-to-gate circuit is open⁴. However, the non-linearity of the electric field distribution in the FET channel induced by the electric current¹⁵ and the effect of the drift velocity on the plasma decay¹⁶ are even more important for the non-resonant and resonant detection, respectively.

Figure 12 shows the response of an AlGaAs/InGaAs HEMT to 200 GHz radiation (characters), as a function of drain current at different gate biases. The peaks of the response correspond to the drain current saturation when the electric field in the channel becomes very non-uniform enhancing the device non-linearity. (All of our experimental data starting from the first observation of the effect of the drain current agree with this result.) Figure 13 shows how the resonant detection becomes visible at room temperature at higher drain currents.

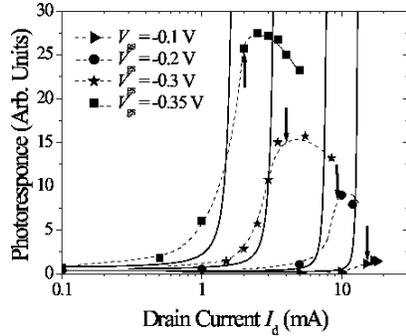


Fig. 12: Photoresponse of GaAs HEMT to 200 GHz radiation (characters), as a function of drain current at different gate biases. Dashed lines are drawn to guide an eye. Solid curves represent the theoretical dependencies. Arrows show the values of the current, corresponding to the velocity saturation.¹⁶

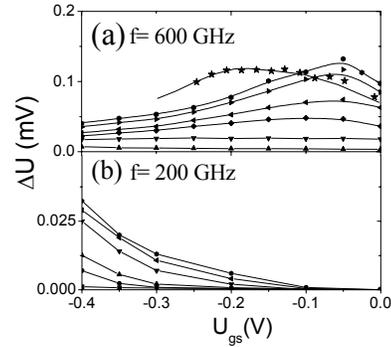


Fig. 13: Photo-induced drain-source voltage as a function of gate bias for 600 GHz (a) and 200 GHz (b) sources for different drain-source voltages. (a) – drain voltages from the bottom to the top: 100mV, 250mV, 400mV, 500mV, 750mV, 1V, 1.2V. (b) – drain voltages from the bottom to the top: 10mV, 50mV, 100mV, 250mV, 500mV, 1V.¹⁷

This enhancement of the resonant response is due to the effect of the electron drift velocity on the plasmon decay time¹⁷:

$$\frac{1}{\tau_i} = \frac{1}{\tau} - \frac{2v_o}{L} \quad (6)$$

Here is the plasmon decay time affected by the electron drift velocity v_o . This expression coincides with that for the increment of the plasma wave instability⁴. If v_o is high enough and $1/\tau$ is low enough, the resonant detection should evolve into the plasma wave instability leading to the terahertz emission (see the next Section).

3. PLASMA WAVE THZ EMISSION

Deng et al were first to observe the sub-THz emission from GaN/AlGaIn HEMT at cryogenic temperatures.¹⁷ Knap et al observed tunable THz emission an AlGaAs/InGaAs HEMT with a 60 nm long gate at 4.2 K.¹³ (see Fig. 14).

The emission was tuned by the drain bias. The resonant frequency value shifted from 0.42 THz up to 1 THz with increasing source-to-drain voltage in agreement with the theory accounting for the effective channel length decrease with the drain bias. More recently, room temperature THz emission from AlGaIn/GaN HEMTs was reported¹⁸.

4. CONCLUSIONS

Numerous experiments on detection [] and mixing of THz radiation have established the role of plasma wave effects in short FETs. From the application point of view, Si-based plasma wave detectors seem to be most promising. Recent studies reveal relatively high responsivities¹⁰ and low Noise Equivalent Power comparable to that of commercial detectors but with a great advantage of a much higher speed (up to tens or hundred GHz operating frequencies compared to 10 Hz for commercial pyroelectric detectors.)

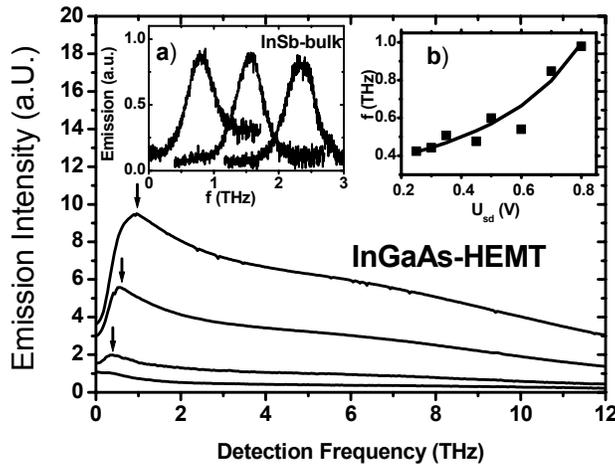


Fig. 14. Emission spectra of the emission from InGaAs HEMT. The arrows mark the maxima position for emission at drain-source voltages of 0.3V, 0.6V and 0.8V. Insert a) shows the calibration curves of the InSb detector in different magnetic fields; right). Insert b) represents the resonant frequencies of the emission from InGaAs HEMT versus source-drain voltage.¹³

The plasma wave mechanism is involved in the observed THz emission still has not been fully established, since as pointed out in^{16,18}, other mechanisms, such as electron "run-away" phenomena, transit time effects, enhanced emission of optical phonons, and stratification of electron flow might lead to the terahertz emission.

The key improvements in the emitted power are expected from using HEMT arrays rather than individual devices and improving the device designs and operating regimes to use electron tunneling^{19,20} and transit time effects^{21,22,23} to boost the increment of plasma wave instability.

ACKNOWLEDGMENTS

The work at RPI was supported by the STTR grant by ARO (subcontract from SET, Inc.) and by CRDF. I am grateful to my colleagues Drs. M. Dyakonov, N. Dyakonova, S. Rumyantsev, A. Dmitriev, V. Kachorovskii, F. Teppe, M. Levinshtein, V. Ryzhii, V. Popov, N. Pala, and Y. Deng and my students, D. Veksler and W. Stillman for their pioneering contributions to plasma wave THz electronics.

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