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Numerical hydrodynamic modeling of non-linear plasma oscillations in the conduction channels of FETs and application to non-linear transformation of harmonic signals

S. Rudin† and G. Samsonidze‡§

† U.S. Army Research Laboratory, Adelphi, Maryland 20783, USA

‡ Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia

§ University of Maryland, College Park, Maryland 20742, USA

Plasma excitations have been of considerable interest in recent studies of semiconductor quantum wells and quasi-two-dimensional (2D) conduction channels in FETs and HEMTs. The intrasubband plasmons that are associated with a single electron subband can be studied as collective excitations in a two-dimensional electron fluid. When the electron-electron collision time is much smaller than the collision times with impurities and phonons the hydrodynamic model should be applicable to the carriers in MOS-FET and HEMT channels. Various non-linear wave phenomena were predicted for the electron fluid [1]. Recently, Shur and Dyakonov [2] analyzed new effects related to plasma oscillations and proposed novel electronic devices operating in terahertz frequency range. The velocity of linear plasma waves s_0 is determined by the gate voltage swing U_0 , $s_0 = (eU_0/m)^{1/2}$ where m is the electron effective mass, e is electron charge. In the case of GaAs HEMT for the gate lengths from $1 \mu\text{m}$ to $0.1 \mu\text{m}$ at $U_0 = 1 \text{ V}$ the fundamental plasma resonance frequency ω_0 varies from 0.5 to 5 THz [2]. It was shown in ref. [1, 2] that under asymmetric boundary conditions on the source and drain contacts the linear plasmons become unstable and new non-linear effects in the device response appear.

In this work we consider a non-linear device response to harmonic signals applied as AC electric potentials at the source and drain contacts. We consider one dimensional fluctuation of 2D density along the channel (x axis). Let n_0 be an equilibrium 2D density of electrons in the channel, determined by the gate voltages. We write the time and space dependent 2D density as $n(x, t) = n_0 + \delta n(x, t)$. The basic equations are [2]

$$\frac{\partial n}{\partial t} + \frac{\partial(nv)}{\partial x} = 0 \quad (1)$$

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = -\frac{e}{m} \frac{\partial U}{\partial x} - \frac{v}{\tau} \quad (2)$$

where $\partial U/\partial x$ is the electric field component along the channel, $v(x, t)$ is local velocity of the electron fluid, τ is an electron collision time with phonons and impurities. If the distance d from the channel to the gate is small compared to the channel length L and the edge effects are neglected the Poisson equation which relates U and n can be treated in gradual channel approximation resulting in a linear local relation:

$$n(x, t) = \frac{C}{e} U(x, t) \quad (3)$$

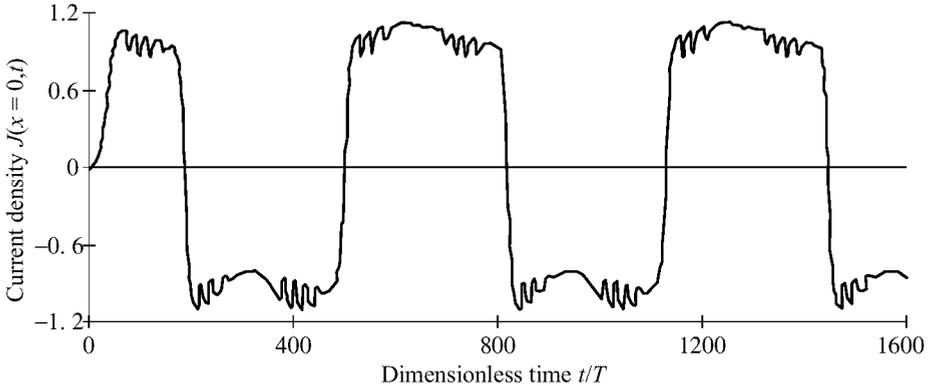


Fig 1. Dimensionless source current density.

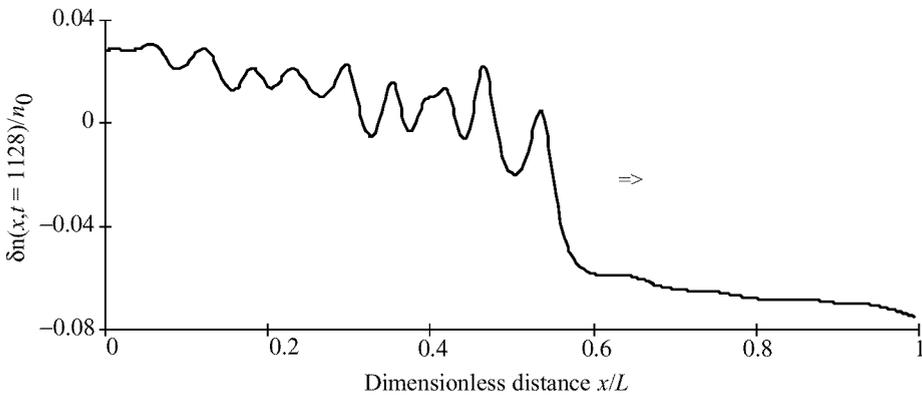


Fig 2. Electron density profile at $t/T = 1128$.

where C is the gate capacitance per unit area. The deviations from this approximation in higher orders of d/L lead to the non-linear dispersion effects in plasma waves [3] and are not included here.

In our numerical solution we introduce dimensionless variables: length x/L , time t/T where $T = L/s_0$, density n/n_0 , velocity v/s_0 , frequency ω/ω_0 . We also introduce a dimensionless friction coefficient $\gamma = L/s_0\tau$. The τ itself can be determined from a known mobility in the channel. We take boundary conditions corresponding to the application of harmonic signals at the source and the drain. We want to see how the high frequency plasma oscillations lead to a non-linear response when applied signals are of much lower frequency. From equation (3) the boundary conditions for applied electric potentials can be stated in terms of density variations: $\delta n(0, t)/n_0 = A_s \cos(\omega_s t)$, $\delta n(1, t)/n_0 = A_d \cos(\omega_d t)$. From the numerical solution of equations (1)–(3) we find the source (or drain) current density as $j_s(t) = n(0, t)v(0, t)$. It is shown in Fig. 1 as a function of time for $A_s = A_d = 0.1$, $\omega_s/\omega_0 = 0.01$, $\omega_d/\omega_0 = 0.03$, $g = 0.001$. We see that after a short transition a periodic regime is attained. In the Fourier analysis of $j(t)$ many harmonics besides those of the applied signals are generated. The form of $j(t)$ is found to be determined by the non-linear plasma waves in the channel. In particular during the time intervals corresponding to large drops and raises of the source current

a shock wave propagates in the channel, reflecting a few times between the contacts. The corresponding density profile is shown in Fig. 2.

We find that the non-linear wave propagation leads to the interesting non-linear response in the terminal current even though the applied signal is of much lower frequency than the fundamental plasma frequency. Similar response is found when the frequencies of applied signals are equal but their amplitudes are different or if there is a phase shift between applied signals. This may allow for the experimental demonstration of the non-linear plasma response and some novel device applications.

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References

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