Viscous hydrodynamic model of non-linear plasma oscillations in two-dimensional gated conduction channels and application to the detection of terahertz signals.

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Abstract. We study the non-linear plasma oscillations in a semiconductor conduction channel controlled by a gate. The analysis is based on the hydrodynamic equations derived from the Boltzmann equation, and includes the effects of viscosity, finite mobility, and temperature gradients in the channel. The conduction channel of a heterostructure High Electron Mobility Transistor (HEMT) can act as a plasma wave resonator for charge density oscillations at frequencies significantly higher than the transistor cut-off frequency in a short channel device. In the Dyakonov-Shur detector a short channel HEMT is used for the resonant tunable detection of electromagnetic radiation in the low terahertz range. Within the hydrodynamic approximation we evaluated the resonant nonlinear response to a small signal, and obtained the temperature dependence of the quality factor Q of the plasma resonance. We find that in high mobility gated semiconductor conduction channels the quality of the resonance is limited by the temperature dependent viscosity of the electron fluid.

The conduction channel of a semiconductor Field Effect Transistor (FET) or a heterostructure High Electron Mobility Transistor (HEMT) can act as a plasma wave resonator for density oscillations in quasi-two-dimensional electron gas, at frequencies significantly higher than the transistor cut-off frequency in a short channel device. The hydrodynamic model predicts a resonance response to electromagnetic radiation at the plasma oscillation frequency which can be used for detection, mixing, and frequency multiplication in the terahertz range [1]. In particular, the hydrodynamic nonlinearities produce a constant source-to-drain voltage when gate-to-channel voltage has a time-harmonic component. In the Dyakonov-Shur detector a short channel HEMT is used for the resonant tunable detection of terahertz radiation. The non-linear plasma response has been observed in InGaAs [2] and GaN [3] HEMTs, in the frequency range from 0.2 to 2.5 THz. The results show that short channel FETs can be used both for tunable resonant and broadband detection of electromagnetic radiation in THz and sub-THz range.

The analysis based on hydrodynamic model [1] shows that the detector response ΔU, the constant source-to-drain voltage induced by the incoming ac signal of amplitude U_a and circular frequency ω, is given by

$$\frac{\Delta U}{U_0} = \left(\frac{U_a}{U_0}\right)^2 f(\omega) \qquad (1)$$

where $U_0=U_g-U_{th}$, U_g is the gate voltage and U_{th} is the threshold voltage for the formation of the conduction channel. The plasma waves in the gated two-dimensional channels have linear dispersion law $\omega_{pl}(q) = sq = q(eU_0/m)^{1/2}$, where m is the electron effective mass and e is electron charge. In a FET channel with length L the eigen-frequencies of the plasma standing waves are odd multiples of the fundamental plasma frequency given by $\omega_0 = \pi s/2L$. If the momentum relaxation time τ, determined by electron-phonon and electron-impurity collisions is such that $\omega_0\tau >> 1$, the HEMT can operate as a resonant detector tunable by the gate voltage. The width of the resonance is determined by the momentum relaxation rate $1/\tau$ that limits the electron mobility, and by the hydrodynamic viscosity in the channel.

We evaluated the electron-electron scattering rate $1/\tau_{ee}(p)$ using quasi-classical approximation [4] for the temperature dependent dielectric function of two-dimensional gated channel. The Fourier transform of the electron-electron interaction is $v(k) = e^2[\varepsilon_0\varepsilon_s(1+\coth(kd))]^{-1}$, where d is the distance from the gate to the channel and $\varepsilon_0\varepsilon_s$ is the dielectric constant. The mean free path for an electron with wave-vector k is obtained as $\lambda(k) = v_k\tau_{ee}(k)$ where $v_k = \hbar k/m$ and τ_{ee} is the inverse of the e-e scattering rate.

The hydrodynamic equations can be derived from the quasi-classical Boltzmann equation as the balance equations, starting with a drifted Fermi-Dirac distribution as a zero order term in the expansion of the distribution function in orders of the Knudsen number [4]. Using the calculated $\tau_{ee}(k)$ in the relaxation time approximation for the first order correction to collision integrals, we obtained the pressure tensor and the heat flux vector, and the temperature dependence of the hydrodynamic transport coefficients, i.e. viscosity ν and heat conductivity κ. For a parabolic conduction band, the hydrodynamic variables are plasma density $n(\mathbf{r},t)$, macroscopic (drift) velocity $\mathbf{u}(\mathbf{r},t)$, and electron temperature $T(\mathbf{r},t)$. Defining the temperature in energy units as $\theta \equiv k_BT$,

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we find that in the case of one-dimensional flow uniform in the transverse direction the hydrodynamic equations are

$$\frac{\partial n}{\partial t}+\frac{\partial (nu)}{\partial x}=0 \tag{2}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+\frac{e}{m}\frac{\partial U}{\partial x}+\frac{1}{n}\frac{\partial P}{\partial x}+\frac{u}{\tau}-\nu\frac{\partial^2 u}{\partial x^2}=0 \tag{3}$$

$$\frac{\partial \theta}{\partial t}+\frac{\partial (\theta u)}{\partial x}-\frac{\chi}{c_V}\frac{\partial^2 \theta}{\partial x^2}-\frac{m\nu}{c_V}\left(\frac{\partial u}{\partial x}\right)^2 =\frac{1}{c_V}\left(\frac{\partial W}{\partial t}\right)_c-\frac{mu^2}{c_V\tau} \tag{4}$$

where W is electron total energy, P is pressure, and c_v is the heat capacity. Electric potential U is a functional of n(x), and if L >> d we can approximate [1] U = en/C where C is gate to channel capacitance per unit area The relaxation time τ in the friction term in Eq. (3) can be related to the mobility η in the channel, $\eta = e\tau/m$, and the energy relaxation time τ_ε can be calculated from the electron-phonon scattering rate. In Eq. (4) we used modified heat conductivity coefficient $\chi \equiv \kappa/n$ which has the same units as kinematic viscosity.

The temperature dependence of the friction time τ was obtained from the temperature dependence of mobility in GaAs and GaN semiconductor heterostructures. The temperature dependence of the viscosity and heat conductivity is shown in Fig. 1 for GaAs and GaN channels, with U_0 set to 0.5 V and 1 V respectively, and the gate to channel distance d = 35 nm. The values of the Fermi temperature for the two cases are 405 K and 195 K.

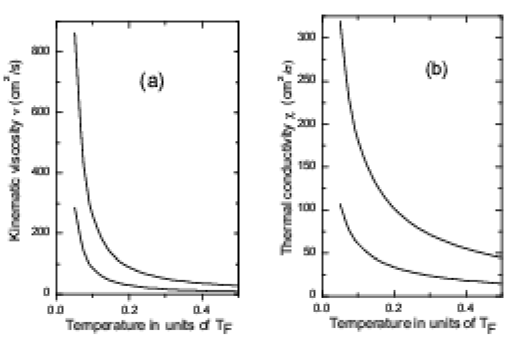

Fig. 1. Coefficient of (a) kinematic viscosity ν and (b) heat conductivity $\chi \equiv \kappa/n$ are shown as functions of temperature for GaAs (upper curves) and GaN (lower curves) channels.

Below 200 K, $1/\tau \approx 1/\tau_0 + aT$ where values of a can be deduced from the temperature dependence of mobility at low temperatures. Applying the small signal analysis to the hydrodynamic equations, we obtain the detector response in the form given in Eq. (1), and function f(ω) at given temperature. Near the resonant frequency ω_0 the function f(ω) is approximately a Lorentzian with the width Δω determined by the friction and viscosity. In case of the GaAs channel with with L = 0.5 μm at U_0 = 0.5 V the resonant frequency $f_0 = \omega_0/2\pi \approx 0.5$ THz. We define the quality factor Q of the resonance at $\omega = \omega_0$ as $Q \equiv \omega_0/\Delta\omega$. Then

$$\frac{1}{Q}=\frac{2L}{\pi s_0 \tau}+\frac{2\pi\nu}{s_0 L} \tag{5}$$

For the case when the T = 0 value of τ is τ_0 = 10 ps, the resonator quality factor Q is shown in Fig. 2 as a function of temperature at low temperatures for GaAs and GaN submicron channels. We see that the quality factor is limited to values below Q = 10, which agrees with the experimental studies [2,3].

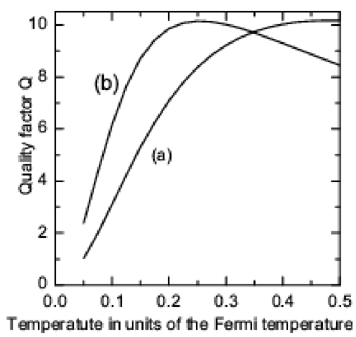

Fig. 2. Plasma resonator quality factor is shown as function of temperature for (a) GaAs and (b) GaN channels with length L = 0.5 μm. The resonance is at $f_0 \sim 0.5$ THz.

We find that the viscosity effects limit the quality of the resonator at low temperatures, reducing the advantage of higher mobility achieved by lowering the temperature. Our treatment extended the theory of Dyakonov-Shur plasma resonator and detector to account for the temperature dependence of viscosity, and included the energy balance equation into the analysis. In the examples considered here we showed that the quality of the plasma resonance in the high mobility channels at low temperature is strongly limited by the effects of viscosity.

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