AlGaN/GaN plasmonic terahertz electronic devices

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Abstract. A very large electron sheet density and a relatively long momentum relaxation time of the two-dimensional electron gas in III-N heterostructures makes this materials system to be very attractive for plasmonic electronics applications.

1. Introduction

Terahertz (THz) plasmonic devices [1],[2], are getting close to being commercialized. Efficient room temperature detectors implemented in AlGaAs/GaAs, AlGaN/GaN heterostructures [3] and Si CMOS terahertz cameras [4] have been reported. Graphene transistors exhibited overdamped plasmonic response, and graphene plasmonic detectors are expected to achieve superior performance. While most of the device efforts focused on THz plasmonic detectors, terahertz radiation emitted by short channel InGaAs [5] and AlGaN/GaN [6],[7] devices at cryogenic and room temperatures has been reported. Using "plasmonic crystals" [8], which are one-dimensional [9], two-dimensional or three-dimensional plasmonic arrays [10], could boost performance by orders of magnitude. The vast majority of the results deal with overdamped response related to nonlinearities in the device response. But the resonant plasmonic detection has also been reported [11],[12]. Recent results on extremely high sheet two-dimensional electron gas (2DEG) densities in AlInN/GaN structures [13], predictions of extremely high overshoot electron velocities in InN [14], and resonant terahertz response in AlGaN/GaN grating gate structures [15],[16] make this materials system very attractive for further development of plasma wave electronic devices. In this paper, we discuss how transport properties of short-channel III-N plasmonic devices and their performance.

2. Collision dominated and ballistic electron transport in III-N 2DEG

Figure 1 shows the measured [17] and calculated temperature dependence of 2DEG mobility, μ, in AlGaN/GaN heterostructure. (The mobility calculations accounted for optical phonon, acoustic phonon, and ionized impurity scattering.) Also shown is the ballistic mobility [18],[19] (i.e. the electron mobility limited by the device contacts given (for the degenerate 2DEG) by [20]
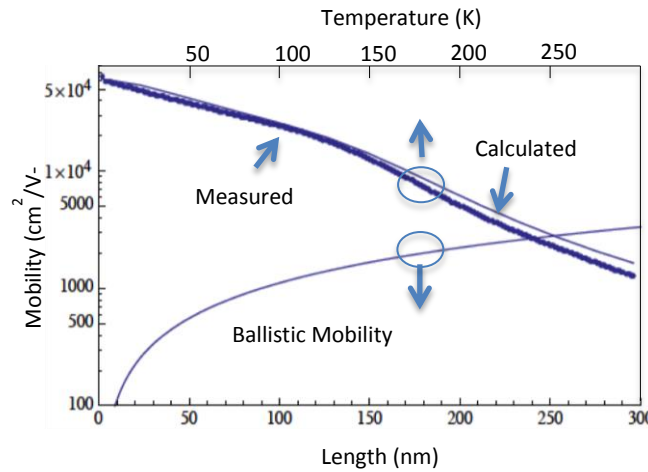
$$\mu_{bal} = \frac{2}{\pi} \frac{qL}{m_n v_F}$$

Here q is the electronic charge, L is the gate length, m_n is the electron effective mass, $v_F = \frac{\hbar}{m_n} \sqrt{2\pi n_s}$ is the Fermi velocity, and n_s is the electron sheet density. As seen, the overall effective mobility
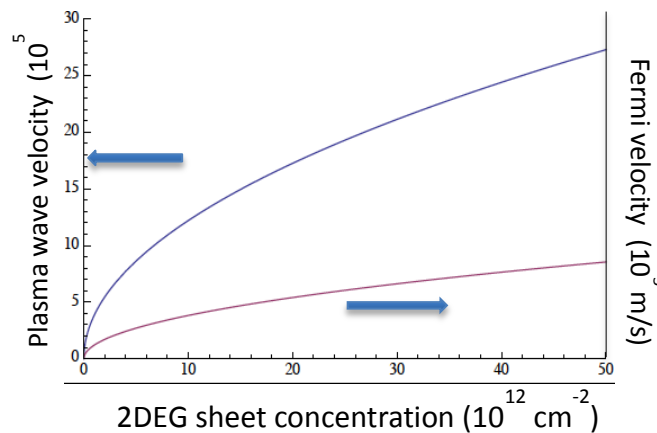
$$\mu_{eff} \approx \frac{\mu_{bal}\mu_{eff}}{\mu_{bal} + \mu_{eff}}$$

at temperatures below 250 K.

Figure 1. Measured and calculated temperature dependence of two-dimensional electrons in AlGaN/GaN heterostructure and ballistic mobility versus gate length.

Figure 2 shows the electron plasma $S = \sqrt{\dfrac{q^2 n_s d}{\varepsilon_0 \varepsilon}}$ and Fermi velocities as functions of the 2DEG sheet density in GaN.

Figure 2. Plasma and Fermi velocities versus 2DEG sheet density.

As was shown in [21], the ratio of the decrement related to the Landau damping to the real part of the plasma frequency is given by

$$\frac{Im\,\omega}{Re\,\omega} = \frac{\sqrt{\pi}}{2} \frac{E_S^{3/2}}{E_F (k_B T)^{1/2}} \exp\left[\frac{E_F - E_S}{k_B T}\right]$$

As seen, the plasma wave velocity is much larger than the Fermi velocity in the III-N 2DEG Fermi velocity and, therefore, the Landau damping is relatively small.

Figure 3 shows the fundamental plasma frequency

$$f = \frac{S}{4L}$$

for III-N 2DEG FETs for short circuit boundary condition at the source side of the gated channel and open circuit condition at the drain side.
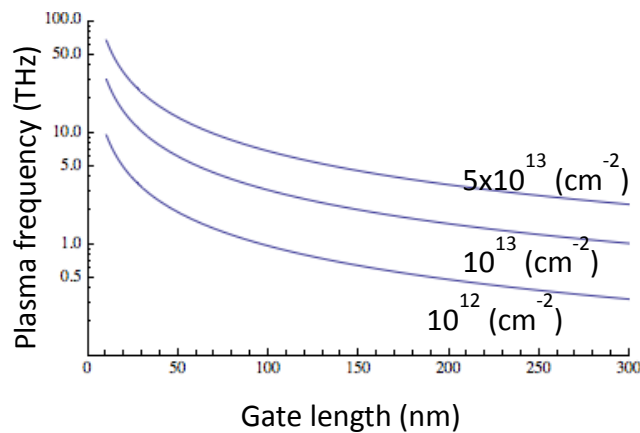
Figure 3. Fundamental plasma frequency versus gate length for different 2DEG densities.

Figure 4 shows the plasma wave quality factor calculated using the momentum relaxation time extracted from the measured mobility data shown in Figure 1 for frequencies of 1 THz and 5 THz.
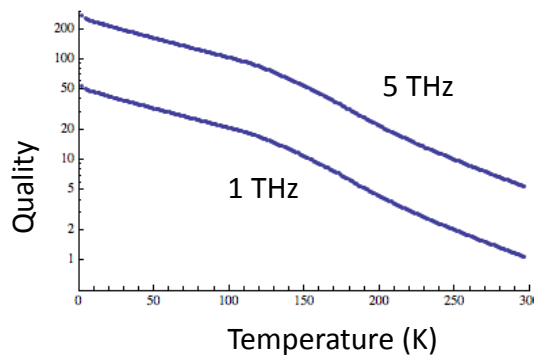
Figure 4. Plasma wave quality factor versus temperature for 1 THz and 5 THz plasma frequencies for III-N FETs.

These results show that the resonant detection and THz emission are possible at room temperature using short channel devices with the gate length below 50 to 70 nm and operating at frequencies of the order of 5 THz or above. Longer devices are expected to operate as broadband THz plasmonic detectors or in the intermediate regime with the quality factor on the order of 1.

In the broadband detection regime, THz radiation couples to the device at the gate edges and excites an overdamped plasma mode that propagates into the channel along the distributive RC transmission line formed by the channel resistance and the gate-to-channel capacitance (see Figure 5).
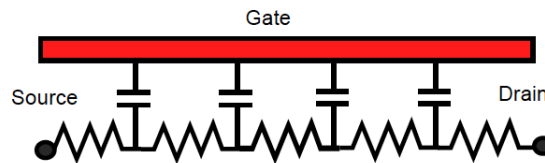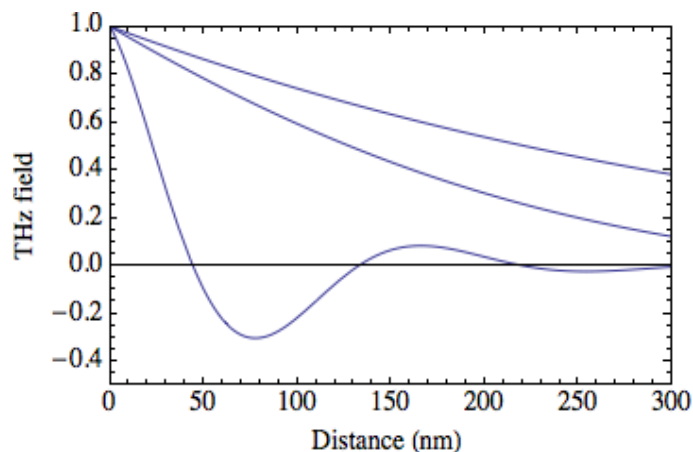

Figure 5. Lossy transmission line representation of FET channel for overdamped plasma wave propagation.

The characteristic scale of the decay depends on the field effect mobility μ and signal frequency ω (see figure 6).

$$L_0 = \sqrt{\frac{\mu V_{GT}}{\omega}}$$

Here V_{GT} is the gate voltage swing.

Figure 6. Plasmonic decay. Top, middle, and bottom curves are for f =0.2 THz, 0.5 THz, and 5 THz for GaN 2DEG.

Kachorovski et al. [22] calculated the conversion efficiency   of a GaN-based FET defined as the ratio of the power dissipated by radiation-induced dc current to the THz dissipated power. And predicted the maximal value of the conversion efficiency on the order of 10%.

3. Experimental data

El Fatimy et al. reported on both resonant and non-resonant plasmonic detection GaN HEMTs with 150 nm gates (see figure 7) [23]. They reported on the minimum Noise Equivalent power of 5×10^{-9} W/Hz$^{0.5}$.

Taginawa et al. [3] achieved the responsivity of 1100 V/W using a GaN plasmonic detectors matched to 1 THz radiation.

Muravjov et al. [24] observed strong plasmon resonances in the terahertz transmission spectra in the range between 1 and 5 THz of large-area slit-grating-gate AlGaN/GaN-based FET structures at temperatures from 10 to 170 K. The resonance frequencies corresponded to the excitation of plasmons

with wave vectors equal to the reciprocal lattice vectors of the metal grating, which coupled plasmons and incident terahertz radiation. The resonances tunable by the applied gate voltage were observed up to 170 K. The results were in a good agreement with the theoretical predictions [25].
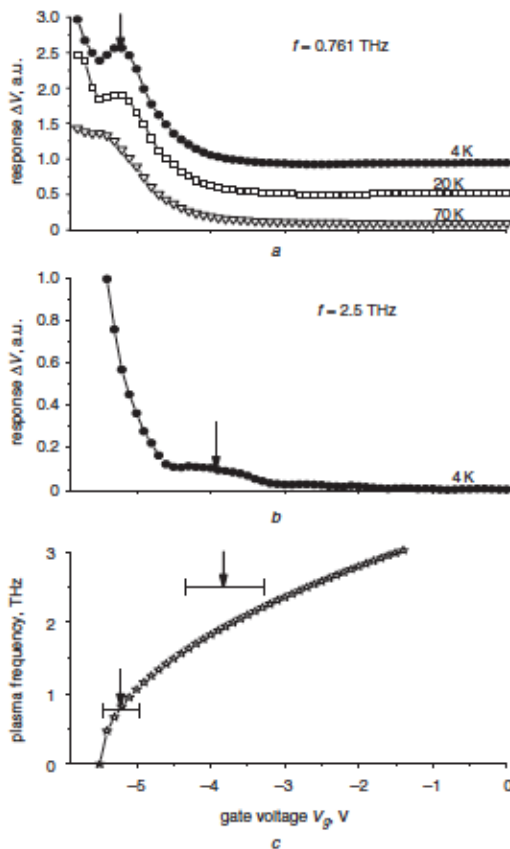
Figure 7. Plasmonic response of GaN/AlGaN -based FET to THz radiation. Bars show the position and width of resonant maxima. Line shows the calculated dependence of fundamental plasma frequency versus gate voltage (From [22]).

4. Conclusion

Exceptional transport properties of III-N 2DEG make GaN-based FETs uniquely suitable for applications in advanced plasmonic electronic devices for detection, mixing, and generation of THz radiation.

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