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Terahertz Plasmon Amplification in RTD-gated HEMTs with a Grating-gate

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ABSTRACT

We analyze amplification of terahertz plasmons in a grating-gate semiconductor hetero-structure. The device consists of a resonant-tunneling-diode gated high-electron-mobility transistor (RTD-gated HEMT), i.e. a HEMT structure with a double-barrier gate stack enabling resonant tunneling from gate to channel. In these devices, the key element enabling substantial power gain is the coupling of terahertz waves into and out of plasmons in the RTD-gated HEMT channel, i.e. the gain medium, via the grating-gate itself, part of the active device, rather than by an external antenna structure as in previous works, enabling amplification with associated power gain >> 30 dB at room temperature.

Keywords: terahertz, amplification, plasmons

1. INTRODUCTION

The terahertz (THz) frequency range is the region of the electromagnetic spectrum lying between radio-frequency and the infrared. Although much progress has been made in recent years, technology accessing the THz band is still remarkably underdeveloped. The THz band was once unexplored and untapped to such an extent that it was often referred to as the "THz-gap"; however, recent progress in sources and detectors is closing this "THz-gap" and turning THz technology into one of the most rapidly growing technological fields [1]. Over the past decades, the terahertz range has become the subject of much attention due to its wide range of applications including astronomy, imaging, spectroscopy, communications, and so on [2-3]. Although significant progress has been accomplished, there is still a need for devices efficiently operating at these frequencies, for instance, devices enabling power amplification. In this context, resonant-tunnel-diode gated high-electron-mobility transistors (RTD-gated HEMTs) [4-6] have been recently been discussed capable of enabling power gain at terahertz frequencies [7]. In these devices, the power gain originates due to interplay between electron plasma waves, which are excited in the HEMT two-dimensional electron gas (2DEG), and resonant tunneling, which occurs when electrons tunnel from the gate-electrode to the 2DEG because of the device gate-stack being a double-barrier hetero-structure. This resonant-tunneling hetero-structure can effectively operate as a gain medium providing gain to the terahertz plasmons excited in the channel. Previous theoretical work on these devices, employing antenna fed configurations, predicted the potential of achieving gain exceeding 5 dB in the GaN materials system (see Fig. 1) [7]. Theoretical work on the graphene materials system [8] predicts a slightly larger gain levels [9].

In this work we discuss GaN-based grating-gate structures. In these structures, incoming terahertz radiation is coupled into plasmons [10-12] in the active region of the device via the grating-gate itself [13], rather than by an antenna structure as in our previous work [7]. These plasmons are then amplified as they travel through the 2DEG and eventually re-radiated as amplified terahertz radiation. When analyzing, by means of numerical simulations, this re-radiated terahertz radiation we observe that terahertz power amplification with gains >> 30 dB are possible in optimized device configurations.

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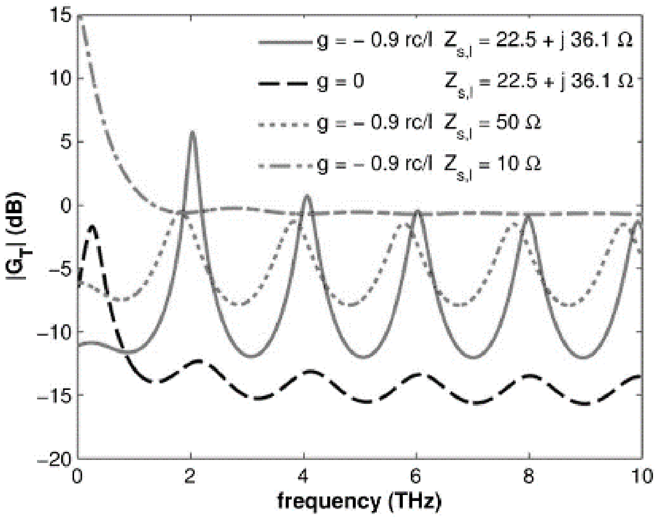

Figure 1. Simulated gain spectra in optimized GaN-based RTD-gated HEMTs using antenna coupling (Figure extracted from Ref. [7]).

2. MODEL AND METHODS

The analyzed RTD-gated HEMT epitaxial structure is depicted in Fig. 2. The grating gate topology couples in and out an incoming, normally-incident, terahertz beam into plasmons in the HEMT channel. As mentioned in the introduction, these plasmons are then amplified as they travel through the RTD-gated channel, which is owed to the negative differential resistance taking place from the gate to the channel. In our work simulations are performed employing Ansys HFSS. For this purpose each layer in the RTD-gated HEMT hetero-structure is modelled employing appropriate constitutive parameters.

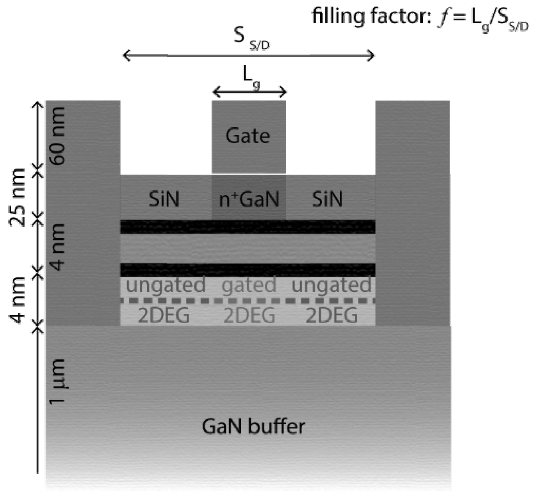

Figure 2. Unit cell epitaxial structure of the analyzed RTD-gated HEMT. All layers are modeled employing Drude models for their frequency dependent electrical conductivities, the two layers depicted in black color correspond to AlN barriers.

In the simulation models, the dynamic-conductivity of the AlGaN/GaN/AlGaN double-barrier tunneling region is modeled through an anisotropic-material tensor (i.e. σx = σy = 0, σz < 0), since electron-tunneling occurs along zdirection. The z-component of this conductivity (σz) is varied in our simulations, and it is considered uniform along space; distributed effects are not considered in our study and will be the subject of attention in future studies. Due to the symmetry of the device structure, periodic boundary conditions are set along x- and y-directions. All other material layers are modeled following Drude models; DC conductivities of $2.4\text{x}10^4$ and 230 S/m, and electron momentum relaxation times of 75 and 150 fs are assumed for the n+GaN region above the tunneling region and for the GaN buffer layer below the HEMT channel, respectively. We considered devices with a gate-length of 100 nm. The thicknesses of various material layers as well as the relevant geometric dimensions of the metallic layers are depicted in Fig. 2.

The gated 2DEG (channel region), as well as the ungated 2DEG (access region), were modeled as 4 nm thick conductive layers following a Drude-dispersion where electron momentum relaxation time was set to 130 fs; and the source/drain electrode contact length was fixed to 500 nm. The addition of source and drain contacts allows for proper biasing of each individual RTD-gated HEMT. The filling factor is defined as the ratio between the gate length (Lg) and the source-to-drain separation ($S_{S/D}$), as pictured in Fig. 1. The gated/ungated 2DEG conductivity as well as the filling factor were also varied in our simulations. Finally, Power gain is calculated as the ratio (in dB) between: (i) the sum of the powers of the reflected (P1) and transmitted waves (P2) through the structure, and (ii) the power of the incoming terahertz excitation (P0), i.e. (P1+P2)/P0.

3. RESULTS

At this end we proceed to perform numerical simulations for the structure described in the previous section. Results from the simulations are shown in Fig. 2. As depicted in Fig. 2a, maximum gain versus negative differential conductance for two values of ungated region conductivity (0 and 3mS), it is observed that a finite access region (ungated 2DEG) conductivity is required so to excite plasmons in the gated 2DEG thus observe gain. Moreover > 40dB gain is observed, when optimizing the structure for maximum gain. In general, we observed that: (a) the gate conductivity along with (b) the geometry of the device and (c) the materials dielectric parameters, initially set the electron palsma wave resonance frequency. Moreover, as the gate-to-channel negative differential conductance is increased the resonance red-shifts and the attainable gain varies, as shown in Fig. 2b. We conclude that there is an optimal negative differential conductance level capable of maximizing the attainable gain, in agreement with the discussion in [7] as pictured in Fig. 2.

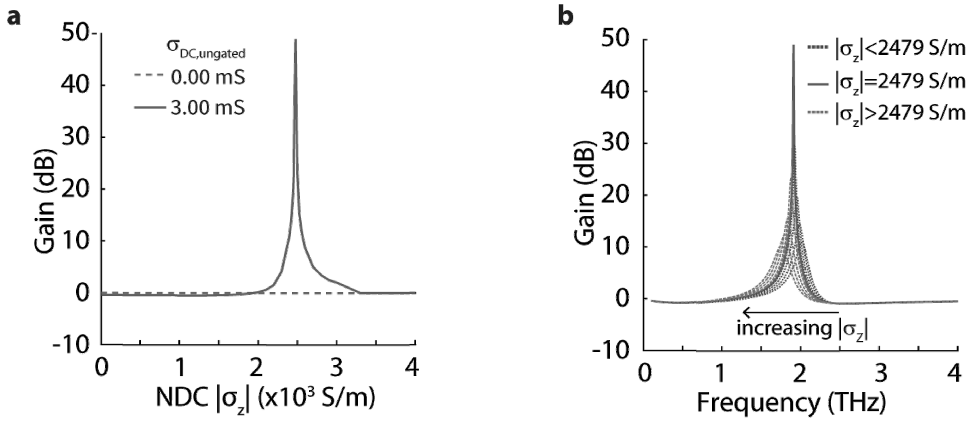

Figure 3. (a) Extracted maximum gain (from the calculated gain spectra) for a configuration with 2 mS gated conductivity, and 0 (dashed) and 3 mS (continuous) ungated conductivity, as a function of the negative differential conductance $|\sigma z|$. (b) Corresponding gain spectra used to extract the maximum gain shown in (a). The RTD negative differential conductance is swept and the conductivities of the gated and ungated regions are fixed to 2mS and 3mS, respectively

4. CONCLUSION

In conclusion, this work predicts terahertz power amplification in grating-gate RTD-gated HEMTs. Terahertz radiation in these devices is coupled into 2DEG channel plasmons via the grating-gate itself, rather than by an antenna structure. The potential of achieving power amplification with gain >> 30 dB at 2 THz is predicted. The electrical conductivities of the gated and ungated regions, the negative differential conductance level achievable from the RTD are identified as key parameters affecting the attainable power gain levels.

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