Experimental demonstration of enhanced terahertz coupling to plasmon in ultra-thin membrane AlGaN/GaN HEMT arrays

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Introduction

THz technology offers multiple applications in areas such as remote sensing, spectroscopy, biomedical imaging, and ultra-wide bandwidth communications [1]. However, obtaining high-frequency performance at THz frequencies has proven challenging in conventional electronic devices. This difficulty motivated the exploration of unconventional transport mechanisms such as electron plasma waves. Two dimensional electron gases (2DEGs) in semiconductor heterostructures can allow for collective motion of electrons, i.e. plasma waves, whose group velocity is >10X larger than typical electron drift velocities (i.e. $v_g > 10^8$ cm/s) [2-3]. Devices based on electron plasma waves have attracted significant attention during recent years for THz generation, detection and amplification [4]. In this context, efficient coupling of external THz radiation into and out of plasmons in semiconductor heterostructures is essential for the operation of these devices. A conventional approach to excite plasmons in a 2DEG is via a grating gate coupler as illustrated in Fig. 1(a). In a grating gate configuration, adjacent unit-cells interact with each other making this a *coupled resonant system*. In contrast, via addition of source (*S*) and drain (*D*) electrodes, in a HEMT array configuration as depicted in Fig. 1(b), every unit cell becomes effectively independent. In this configuration, the THz to plasmon coupling is enhanced due to a cooperative effect by synchronizing the electron plasma waves in each unit-cell of the array as theoretically discussed by Popov *et al* [5]. *Here we present the first experimental demonstration of enhanced THz coupling to electron plasma wave or plasmon in ultra-thin membrane HEMT arrays via plasmon synchronization*. A thin-membrane configuration enables us to remove substrate effects and further enhance the coupling. The proposed approach allows: (*i*) more efficient excitation of high order plasmonic modes, and (*ii*) superior overall coupling -even in configurations having less number of devices per unit area-. Our results reveal a simple way to enhance the THz to plasmon coupling and thus improve the performance of electron plasma wave based devices; this effect can be exploited, for example, to improve the response of HEMT THz detectors.

Device fabrication

Devices were fabricated in MOCVD-grown epitaxial structures consisting of a 4.5 µm thick AlN buffer layer, followed by a 200 nm GaN layer and a 20 nm AlGaN barrier, which were grown on Si (111) [6]. In this structure, which is illustrated in Fig. 1(c), a 2DEG with charge density ~1×10^{13} cm^{-2} and μ ~1,400 cm^2/V.s is formed at the AlGaN/GaN interface. Since $\omega_p \propto (d^{1/2} . k)$, where ω_p is the plasmonic resonance frequency, d is the gate-to-2DEG barrier thickness, and k is the wave vector, a 30 nm SiO_2 spacer was deposited on the top of the HEMT structure in order to push the plasmonic resonances towards higher frequencies without the need to reduce lateral dimensions. *S*/*D* contacts (Ti/Al/Ti/Ni/Au) and gate fingers (Ti/Au) were defined in successive lithography and lift-off steps in a periodic-pattern through direct writing using a Heidelberg PG 101 pattern generator. TLM measurements, shown in Fig. 2(a), indicate a contact resistance of 1.3 Ω.mm and a sheet conductivity of 1.5 mS; this agrees well with our results from THz spectroscopy, see Fig. 2(b). The center area of the Si substrate was etched from the backside by DRIE (Oxford ICP 100). *The resulting samples are ultra-thin HEMT membranes (thickness ~5 µm) and therefore do not exhibit any substrate-related effects*; an optical image of an example device is depicted in Fig. 2(c).

Results and Discussion

To analyze the effect of synchronized excitation as a way to enhance THz to plasmon coupling, we fabricated two samples of similar gate length and unit-cell dimensions with and w/o *S*/*D* electrodes. In both samples plasmonic resonances were observed at 77K. As depicted in Fig. 2(a) the sample with *S*/*D* electrodes presented three well-defined resonances at ~0.4, ~0.8, and ~1.2 THz, respectively; this is in close agreement with predictions from full-wave electromagnetic simulations by HFSS. In contrast, the sample w/o *S*/*D* electrodes exhibited just one clear but much weaker resonance as shown in Fig. 3(b). In the sample with *S*/*D* electrodes the *S*/*G* and *D*/*G* separation (0.8 µm) was limited by the lithographic resolution of our pattern generator; numerical simulations, depicted in Fig. 3(c), show that by reducing this separation it is possible to further improve the resonance strength.

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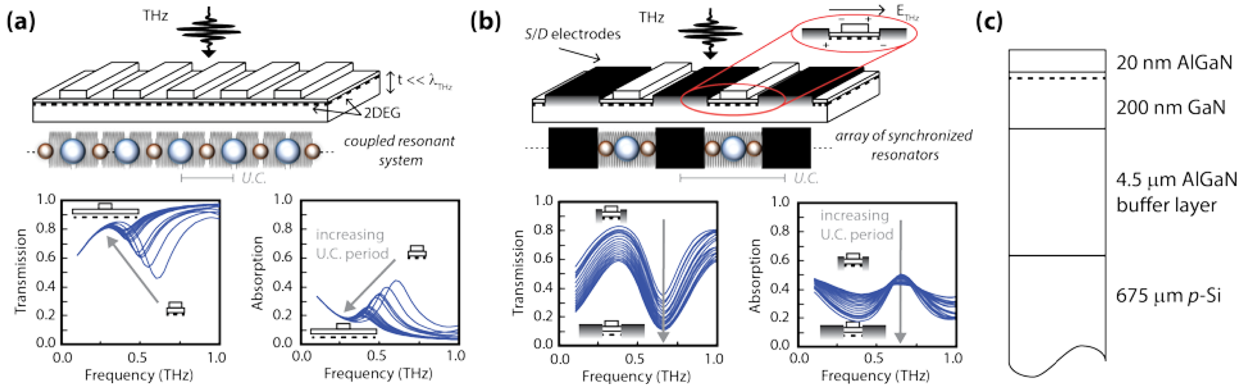

Fig. 1. (a) Sketch of a grating gate HEMT structure along with simulated THz transmission/absorption. Ultra-thin membranes (thickness ~5 μm) are used to minimize substrate-related effects in both simulations and experiments. This configuration operates as a *coupled resonant system* where the unit-cell (*U.C.*) period defines ω_p. **(b)** Sketch of a HEMT array configuration; the addition of *S*/*D* electrodes enhances the THz to plasmon coupling by properly synchronizing electron plasma waves in each unit-cell. This configuration operates as an *array of independent resonators*; ω_p is defined by both the gated 2DEG and the access region 2DEG rather than by the unit-cell period. When increasing the unit-cell period by increasing the *S*/*D* electrode length, stronger confinement of THz radiation occurs. As a result, THz radiation is more likely to excite plasmons and the overall coupling into the active region is enhanced in each unit-cell, i.e. the same total absorption is observed with less number of HEMTs in the array. **(c)** Layer structure of the analyzed AlGaN/GaN HEMT wafer.

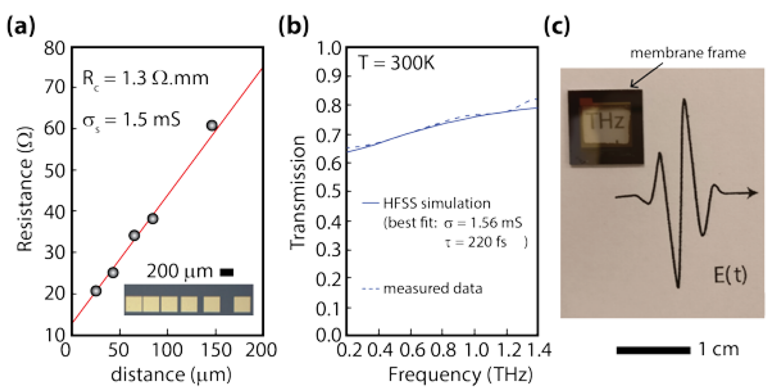

Fig. 2. (a) TLM measurements. A reduction in sheet conductivity from 2.3 to 1.5 mS is observed after SiO_2 deposition. This is attributed to a decrease in charge density. **(b)** Measured THz transmission through a control sample; the measured data fits well to simulations employing a Drude model with 1.56 mS zero-frequency conductivity and 220 fs scattering time. **(c)** Optical image of a fabricated sample, the structure is transparent at visible wavelengths owing to its ultra-thin thickness (~5 μm).

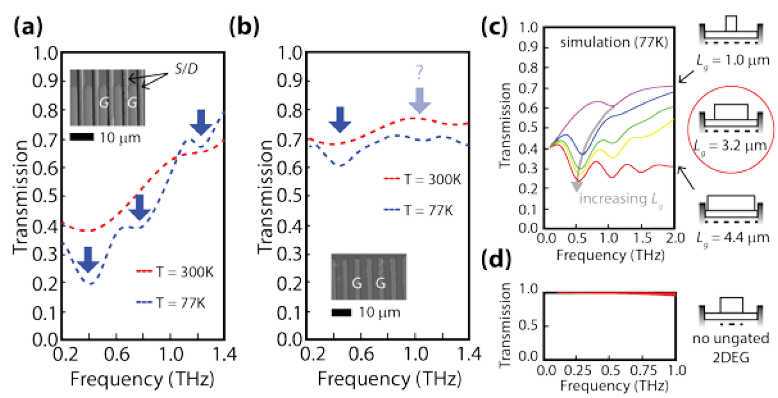

Fig. 3. (a) Measured transmission spectra through a sample with *S*/*D* electrodes; although weak resonant features are observed at room temperature, which is a result of the short relaxation time for electrons in GaN at 300K, three well defined resonances are present at 77K. **(b)** Measured transmission spectra through a sample w/o *S*/*D* electrodes; much weaker resonances are observed in this sample. **(c)** Simulated transmission spectra (77K) for the HEMT array structures with various gate lengths. The unit-cell periodicity and *S* to *D* separation were set to 6 μm and 4.8 μm, respectively. By reducing the spacing between the *S*/*D* electrodes and the gate, it is possible to improve the resonance strength. **(d)** Simulated transmission spectra for the same HEMT array structure in (c) but without access region 2DEGs; poor coupling is observed as evidenced with near unity transmission. This results from the gated 2DEG, i.e. gated plasmons, being screened by the metal gate electrode. In general, the external THz excitation is coupled into the gated plasmon via the access region 2DEG.