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THz Devices Based on 2D Electron Systems

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Abstract

In two-dimensional electron systems with mobility on the order of 1,000 – 10,000 cm^2/Vs, the electron scattering time is about 1 ps. For the THz window of 0.3 – 3 THz, the THz photon energy is in the neighborhood of 1 meV, substantially smaller than the optical phonon energy of solids where these 2D electron systems resides. These properties make the 2D electron systems interesting as a platform to realize THz devices. In this paper, I will review 3 approaches investigated in the past few years in my group toward THz devices. The first approach is the conventional high electron mobility transistor based on GaN toward THz amplifiers. The second approach is to employ the tunable intraband absorption in 2D electron systems to realize THz modulators, where I will use graphene as a model material system. The third approach is to exploit plasma wave in these 2D electron systems that can be coupled with a negative differential conductance element for THz amplifiers/sources/detectors.

1. GaN based HEMT devices toward THz

GaN HEMTs provide a high two-dimensional electron gas (2DEG) density in the order of 10^{13} cm^{-2} due to strong polarization effects and a modest electron mobility up to 2200 cm^2/V·s, which results in an output current density over 4.0 A/mm [1] and in turn a high output power density at a large supply voltage. Moreover, the GaN-on-SiC integration manifests an excellent substrate thermal conduction, which is beneficial to reduce packaging and cooling costs. These features of GaN enable promising power amplifications with high power added efficiency in cellular devices, base stations, wireless networks and defense systems.

Based on the definition of f_T, the frequency when the short circuit current gain h_{21} reaches unity, and the device small signal equivalent circuit analysis (Fig. 1), one can extract an analytical expression for f_T or the total delay time τ_{tot} as a function of equivalent circuit parameters as follows:

$$f_T = \frac{1}{2\pi\tau_{tot}} = \frac{g_m / 2\pi}{(C_{gs}+C_{gd})[1+(R_s+R_d)/R_{ds}]+g_m C_{gd}(R_s+R_d)},$$

in which g_m represents the intrinsic transconductance, C_{gs}/C_{gd} the gate-to-source/drain capacitance (the sum of both intrinsic denoted as $C_{gs,int}$ and extrinsic as $C_{gs,ext}$, same for C_{gd}), R_s/R_d the source/drain resistance, and R_{ds} of the channel output resistance. The total delay time τ_{tot} can be further divided into two components: intrinsic delay time τ_{int} and parasitic delay time τ_{par}, expressed as:

$\tau_{int}=(C_{gs,int}+C_{gd,int})/g_m=L_g/v_e$,

$\tau_{par}=(C_{gs,ext}+C_{gd,ext})/g_m+C_{gd}(R_s+R_d)+(C_{gs}+C_{gd})(R_s+R_d)g_{ds}/g_m$,

in which L_g represents the gate length, and v_e the effective electron velocity.

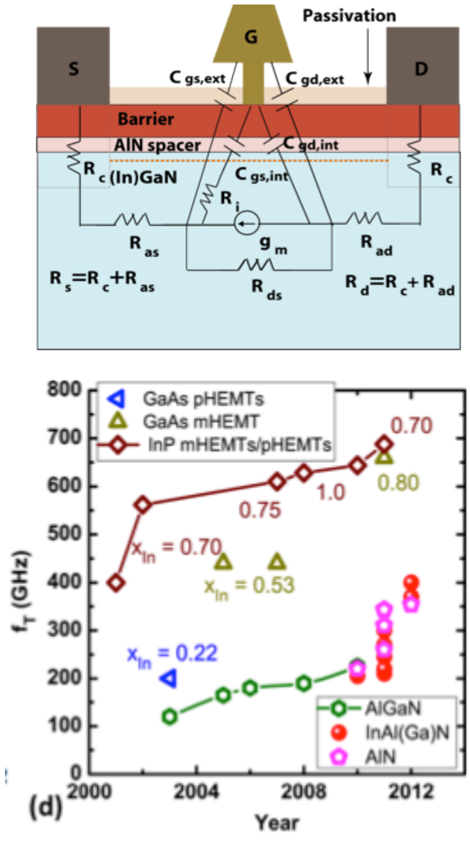

Fig. 1 Schematic of GaN HEMT structure with small-signal equivalent circuit components. the evolution of f_T in the last one decade for both III-V pHEMTs and GaN HEMTs [reproduced from Ref.10].

To improve the device speed, the first intuitive way is to reduce the τ_{int} by scaling down the gate length thus the intrinsic capacitance assuming a constant v_e/g_m. The gate-length scaling in GaN HEMTs much benefitted from the Si CMOS and III-V pHEMTs technologies [2,3]. With decananometer L_g, the parasitic delay can reach 30-50% of the total delay. The devices speed is ultimately limited by the first term of the f_T equation associated with the extrinsic capacitance ($C_{gs,ext}$+$C_{gd,ext}$) and g_m [4]. Therefore, maximizing g_m is key to obtaining terahertz transistors. This is consistent with the observation that InGaAs-channel HEMTs exhibit higher speed than GaN or Si based FETs. To further improve the GaN HEMT speed, it is paramount to seek approaches that enhance injection velocity thus $g_{m,int}$, such as the use of InGaN [5] or isotope-disordered channels [6].

2. Graphene based THz modulators

Another physical phenomenon we explored is intraband transition (photon absorption) in 2D electron systems. We showed the terahertz (THz) wave transmission through the graphene layer can be electrically tuned by varying its Fermi levels [7]. It is amazing that a layer of carbon atoms with the thickness 1000,000 times smaller the wavelength can so efficiently modulate the electromagnetic waves. In visible range, graphene exhibits flat transmission spectrum of 97%, which is almost independent its Fermi levels. On the contrary, in THz range, intra-band carrier transition dominates due to the low incident photon energy, resulting in a Fermi level dependent transmittance. As shown in Fig. 2, the available states that could induce THz absorption are larger while the Fermi level stays further from the Dirac point. Therefore, such intraband absorption based THz modulation could be readily realized by tuning graphene's Fermi level with various approaches.

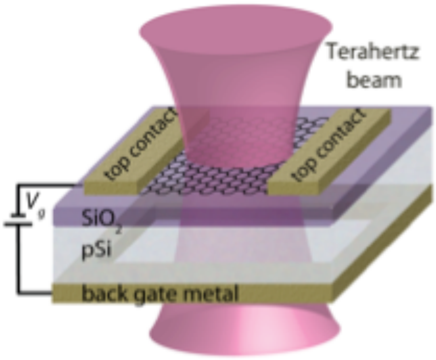

Fig. 2 The structure of electro-absorption THz modulator based on graphene.

3. Plasmons in 2D electron systems

Two-dimensional (2D) electron systems formed in the channel of sub-micrometer transistors enable the propagation of electron-density oscillations for frequencies laying in the THz region of the spectrum. These so-called plasma waves are generated when individual electrons in the channel are not able to follow high frequency oscillations and lag behind. The delay exhibited by the electrons presents an inductive behavior, which in turn couples with the gate-channel capacitor to give rise to a resonator of electron-density waves. The dynamics of these waves and their non-linear effects can be exploited to realize detectors, mixers and multipliers for frequencies inside the THz band [8]. However, all plasmons are intrinsically lossy. To engineer a gain medium in the THz region, which can couple with a plasmon THz waveguide, is a possible approach to realize loss THz transmission lines, amplifiers and oscillators. Toward this end, we proposed resonant tunnel diode (RTD) gated HEMTs, where the negative differential conductance cancels the conductive loss in plasmons [9,10].

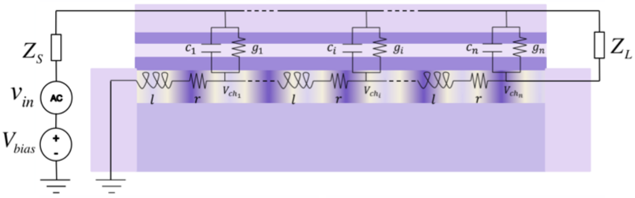

Fig. 3 Distributed high frequency transmission line model for a RTD-gated plasma wave HEMT.

Acknowledgements

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