Development of Microwave and Terahertz Detectors Utilizing AlN/GaN High Electron Mobility Transistors

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Abstract—**We report our work on development of microwave and terahertz detectors using AlN/GaN high electron mobility transistors. Microwave measurements (f = 10 – 40 GHz) using AlN/GaN HEMTs as detectors have been performed and the results have shown that the device work in non-resonant mode at room temperature with a responsivity roughly proportional to f^2 at low frequencies. Measured responsivity as a function of gate bias also shows reasonable agreement with theory and published results. Initial calculation results show that an AlN/GaN HEMT with 0.15 um gate length works in the resonant mode when it is cooled down to 77K. The fundamental resonant frequency increases from 200 GHz to 3.2 THz with gate-to-source voltage swing of 0.01 V to 2.0 V. The drain-to-source voltage response also increases with increasing of the gate-to-source voltage swing. We plan to integrate the AlN/GaN HEMT devices broadband lens-coupled antennas and low-pass filters for tunable plasma wave THz detectors.**

I. Introduction

High sensitivity, cost-effective and frequency-tunable terahertz (THz) detectors have many applications in astronomy, imaging, spectroscopy and biosensing. Current solid-state all-electronic THz detectors are mainly based on bolometers, Schottky diodes, and pyroelectric or photoconductive devices, and these detectors either have fixed operation frequencies and narrow band, or are 'broadband' but require spectrometers or equivalent for spectrum analysis. Frequency-tunable detectors are desired in many systems for realizing all-electronic tunability instead of using gratings or moving mirrors that are bulky and prone to mechanical failure.

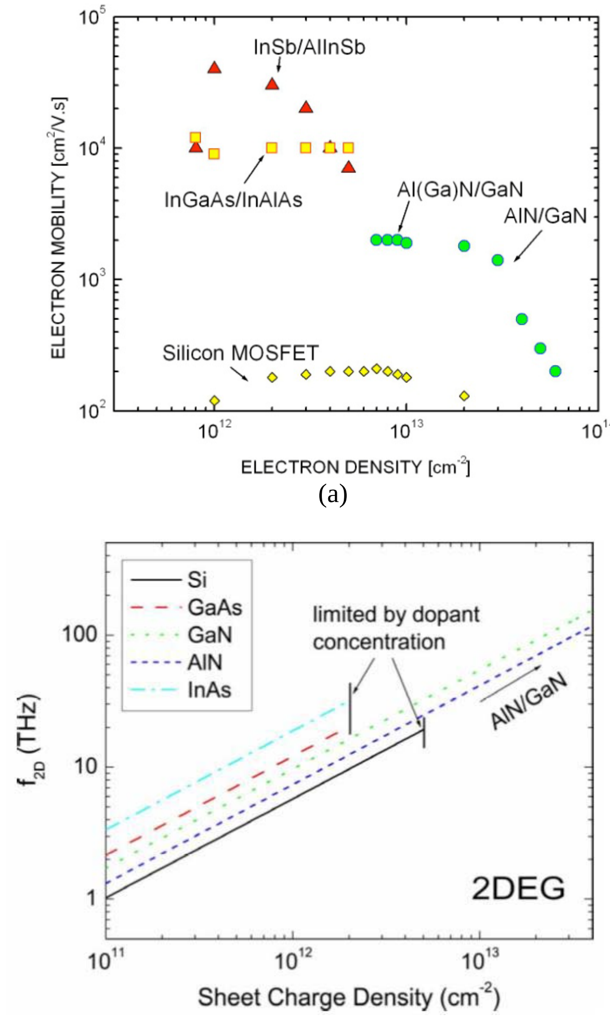
Dyakonov and Shur [1] have shown that plasma waves in a high electron mobility transistor (HEMT) channel have nonlinear properties, and can be utilized for tunable terahertz detection. A HEMT, when biased with gate-to-source voltage (V_{gs}-V_{th}, V_{th} is the threshold voltage) and illuminated by electromagnetic radiation, can generate a constant drain-to-source voltage due to the asymmetry boundary conditions at the drain and source. For a HEMT (with effective electron mass, m) with an effective gate length L, the plasma wave resonates at,

$$f = \frac{1}{4L}\sqrt{e(V_{gs} - V_{th})/m} \tag{1}$$

and its odd harmonic frequencies. The quality factor of the resonance is determined by $s\tau/L$, where s is the plasma wave velocity, and τ is the momentum relaxation time. If $s\tau/L > 1$, the HEMT works in the resonant mode, and the detection frequency can be tuned by the gate-to-source biasing, according to (1). If $s\tau/L < 1$, the HEMT then works as a non-resonant broadband THz detector.

To date, THz detectors using HEMTs have been demonstrated in various GaAs and GaN based devices [2, 3]. However, in most of the experiments performed, THz radiation was directly focused on devices without any coupling antennas, resulting in limited detector responsivity. In addition, the plasma wave in an GaAs HEMT corresponds to a plasma resonant frequency up to ~ 10 THz. AlN/GaN nano-scale heterojunctions offer better structures with very large tunable frequency range up to ~ 100 THz due to their extraordinarily high carrier concentration and high carrier mobility. Thus, THz detectors using AlN/GaN HEMTs can have much broader tunable frequency range and better sensitivity.

In this work, we report our initial work on development of microwave and THz detectors using AlN/GaN HEMT devices. We have performed microwave measurements (10-40 GHz) using AlN/GaN HEMTs as detectors. The results have shown that the device works in non-resonant mode at room temperature with a responsivity roughly proportional to f^2 at low frequencies, which agrees well with the theoretical prediction. Measured responsivity as a function of gate bias also shows reasonable agreement with the theory and published results [4]. Measurements at W-band using Agilent 110 GHz vector network analyser (VNA), and at 200 GHz and 600 GHz using VDI (Virginia Diodes, Inc.) solid-state source will be performed to characterize the device behaviours at higher frequencies. Initial calculation results show that an AlN/GaN HEMT with 0.15 um gate length works in the resonant mode when it is cooled down to 77K. The fundamental resonant frequency increases from 200 GHz to 3.2 THz with the gate-to-source voltage swing (V_{gs}-V_{th}) varies from 0.01 V to 2.0 V. The drain-to-source voltage



(b)

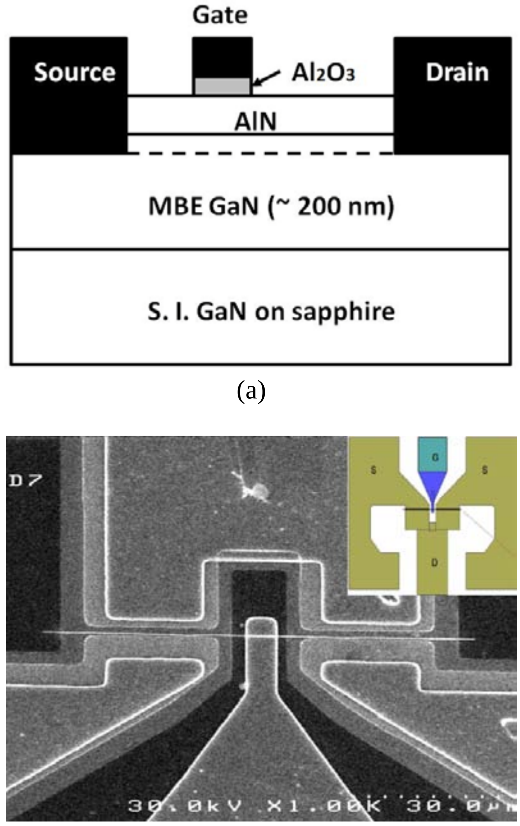
Fig. 1 (a) Carrier density and mobilities measured on AlN/GaN structures grown at Notre Dame in comparison with other 2DEG system [5], and (b) calculated corresponding plasma wave frequency in AlN/GaN HEMT devices and other semiconductors.

response also increases with increasing of the gate-to-source voltage swing.

II. AlN/GaN HEMT Devices

High performance HEMT devices are desired in realizing tunable THz detectors. AlN/GaN HEMTs offer the advantages including simultaneously high 2-D electron-gas density (2DEG) and high carrier mobility, high current density, low sheet resistance and high tranconductance [5-7].

As shown in Fig. 1 (a), nitride-based heterostructures have the extremely high 2DEG densities compared to other HEMT technologies. The fundamental upper limit of the polarization-induced 2DEG density at Al(Ga)N/GaN heterojunctions is nearly $6\times10^{13}/cm^2$, which is achievable only when the barrier layer is AlN, due to the maximum polarization (spontaneous and piezoelectric) difference between the AlN barrier and the underneath GaN layer [6]. At such a high 2DEG density, the carrier mobility is usually degraded. However, a window is observed in which the



(b)

Fig. 2 (a) Schematic of the AlN/GaN HEMT structure, and (b) SEM image of the device contact geometry.

AlN/GaN heterostructures have both high mobility (1600 $cm^2/V{\cdot}s$) and high 2DEG density, resulting in highly sensitive THz detectors in a wide frequency range. According to (1), the resonant frequency is proportional to the square rood of the 2DEG electron concentration. Fig. 1(b) shows the calculated plasma resonant frequencies in various semiconductors. The 2DEG formed at an AlGaAs/GaAs HEMT corresponds to a frequency up to 10 THz, while an AlN/GaN HEMT can attain much higher frequency up to 100 THz.

Fig. 2(a) shows the typical schematic of the AlN/GaN HEMT structure. The ultrathin AlN/GaN heterojunctions were grown at the University of Notre Dame using the process described in [6] using a Vecco Gen 930 plasma-assisted MBE system. The process starts from the growth of a 200 nm unintentionally doped (UID) GaN buffer layer, followed by a 3.5 nm UID AlN barrier. The device isolation mesa is fabricated using a BCl_3/Cl_2 reactive ion etch (RIE) process and Ti/Al/Ni/Au stacks were deposited to obtain ohmic contacts. The gates were defined using e-beam lithography. A 3 nm Al_2O_3 gate dielectric was deposited followed by a Ni/Au gate metal layer. Fig. 2(b) shows the SEM image of the device contact geometry for RF probing measurement. The fabricated AlN/GaN HEMT devices resulted in a typical carrier concentration of $2.75\times10^{13}/cm^2$, a

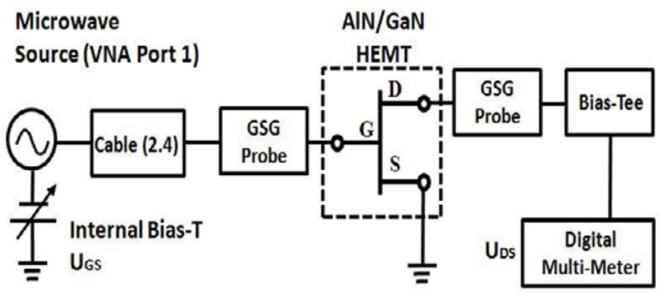


Fig. 3 AlN/GaN Detector measurement setup for microwave frequencies from 0.1 GHz to 40 GHz, the microwave power is provided by an Agilent 8722D vector network analyser.

carrier mobility of 1367 cm^2/V·s, and a device sheet resistance of ~ 166 Ω/□.

III. Microwave Measurement

On the basis of the Dyakonov and Shur theory [1], a 2D electron fluid detector operates in a non-resonant regime at low frequencies when $f \to 0$. The detector responsivity, R, is determined by [1]:

$$R = \frac{|U_{ac}|^2}{P} \frac{\pi^2 L^4}{6u^2} \frac{f^2}{(U_{gs} - U_{th})^3} \quad , \tag{2}$$

where U_{ac} is the microwave amplitude applied to the gate, P is the available microwave power, and u is the channel electron mobility.

To verify this, we have performed microwave measurement using AlN/GaN HEMTs as detectors, in the frequency range of 0.1 GHz to 40 GHz. The device for this study has a nominal gate length of 2 μm, a gate width of 25 μm, a measured threshold voltage of -3 V, and a carrier mobility of ~1300 cm^2/V·s. Fig. 4 shows the microwave measurement setup where the microwave power was provided by an Agilent 8722D vector network analyser. This allowed the input reflection coefficient to be measured when the incident RF frequency was swept from 0.1 to 40 GHz. The HEMT device was placed on a microwave probe station platform and fed by a GSG (Ground-Signal-Ground) microwave probe (see inset of Fig. 2 (b)), where the device gate was connected to the S-finger and the source was connected to the ground. The gate-to-source voltage was applied through the Agilent 8722D internal bias-T (Port 1). The device drain was connected to another GSG probe followed by the second bias-T (external), and the device DC response (i.e. the drain-to-source voltage, U_{ds}) was measured using a digital multimeter at the bias-port of the second bias-T. In this measurement, the output RF power from the VNA Port 1 (P_0) was fixed at -10 dBm, and the detector responsivity, R, is defined as $R = U_{\mathrm{ds}}/P_0$. The intrinsic responsivity of the detector can be corrected on the basis of the reflection measurement (S_{11}) at Port 1.

Fig. 4 shows the initial microwave measurement results using AlN/GaN HEMTs as detectors. Impedance matching was not performed for this initial test, and the input reflection coefficient of the detector was found to be quite large (S_{11} average -0.05 dB) and a strong function of frequency over the entire frequency range (10-40 GHz). The cable loss of the measurement system was first measured, and then the device response was taken with gate biasing of -1 V. After cable loss (0-4 dB, depends on frequency) correction, the detector responsivity as a function of frequency is shown in Fig. 4(a). From nearly 15 GHz, the measured responsivity increases from 0 to 1 V/W (at 26 GHz) and then becomes relatively flat, with an average around 0.5 V/W. The responsivity is roughly proportional to f^2 at low frequencies (15-26 GHz), which agrees well with theoretical prediction. The behaviour at frequencies higher than 26 GHz will be discussed in the later section. At frequencies lower than 15 GHz, negative responsivities were measured, which is not well understood at this time. Taking into account of the large reflection at the input port, the intrinsic responsivity of the AlN/GaN HEMT as a microwave detector will be in the

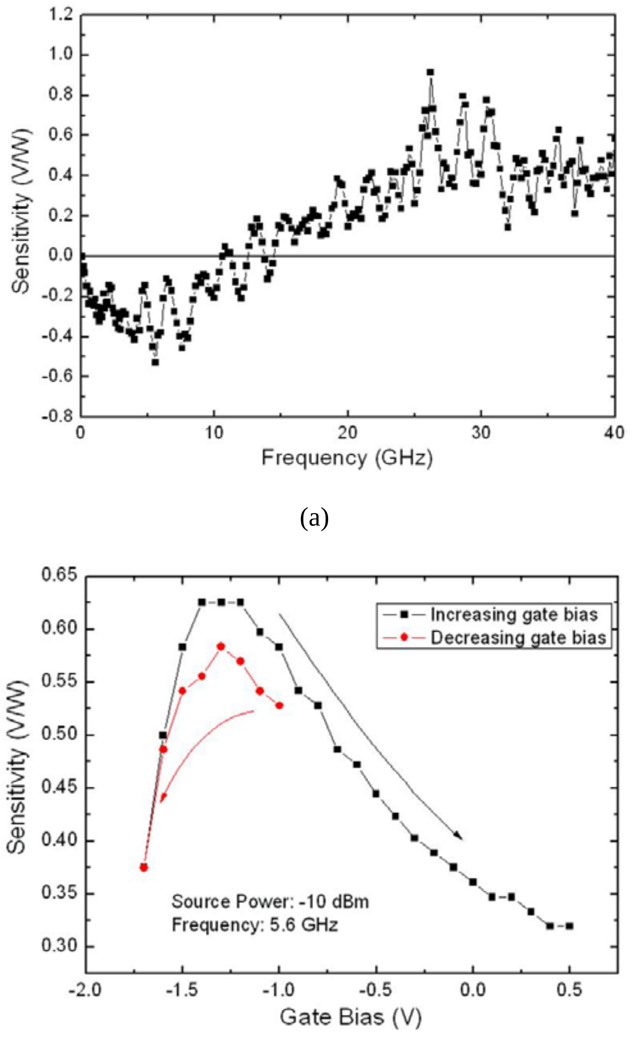


Fig. 4 Microwave measurement results: (a) measured frequency dependence of detector responsivity (gate-to-source voltage swing -1 V), and (b) measured gate bias dependence of detector responsivity.

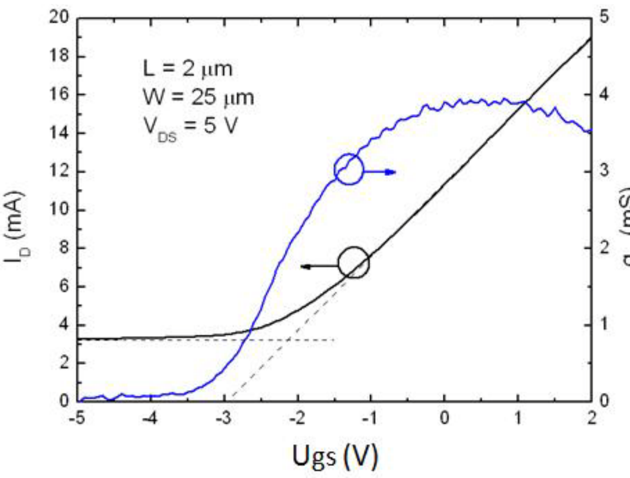


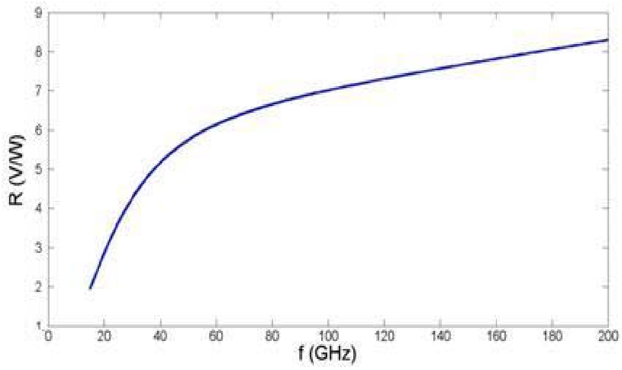
Fig. 6 DC I-V transfer curves for the AlN/GaN HEMT device under test.

range of 0-10 V/W. Measured responsivity as a function of gate bias at 5.6 GHz is shown in Fig. 4 (b). The responsivity increases with decreasing gate biasing voltage when $U_{gs} > -1.6$ V, and decreases rapidly when $U_{gs} < -1.4$ V. The detector theory in (2) and [1] only valid at $U_{gs} > -1.4$ V. The gate bias dependence of the responsivity shows reasonable agreement with the theory and published results [4]. We attribute the discrepancy to the relatively low quality of the device in this study. As shown in Fig. 5, the DC I-V transfer curves for the AlN/GaN HEMT device under test show relatively large drain current leakage (~ 3 mA) after pinch-off (i.e. $U_{gs} < -3$ V), and relatively small transconductance. Better devices will be utilized in the future measurement.

IV. AlN/GaN HEMT THz Detectors

At terahertz frequencies, the plasma wave in a HEMT device resonates at fundamental frequency and its odd harmonics (see equation (1)). If $s\tau/L > 1$, the HEMT works in the resonant mode, and the detection frequency can be tuned by the gate-to-source biasing, according to (1). If $s\tau/L < 1$, the HEMT then works as a non-resonant broadband THz detector. On the basis of the Dyakonov and Shur theory [1], we have solved the 2D electron fluid equations in an AlN/GaN HEMT channel.

Nonresonant THz Detectors: For the AlN/GaN HEMT device under test in this study, we use $m_e = 0.2\ m_0$ (where m_e is the effective mass and m_0 is the electron mass), gate length $L = 2\ \mu m$, and carrier mobility $u = 1300$ cm^2/V·s (room temperature). Fig. 6 (a) shows the calculated detector responsivity (gate biasing -1 V) over the frequency range of 0 to 200 GHz. The responsivity increases rapidly at frequencies lower than 80 GHz, and then increases much slower at higher frequencies. The curve is quite smooth and no resonance is observed, demonstrates that the device works in a nonresonant mode ($s\tau/L$ ~0.02 << 1). We compare the calculated results with the measurement data from 15 GHz to 40 GHz by taking into account of the large reflection at port 1, as shown in Fig. 6 (b). The agreement between theory and measurement is quite good at this microwave frequency range.



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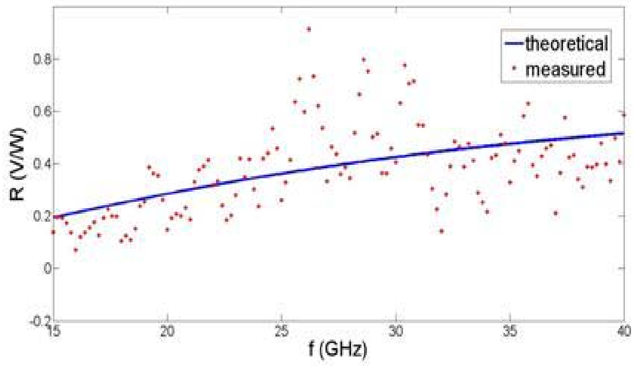


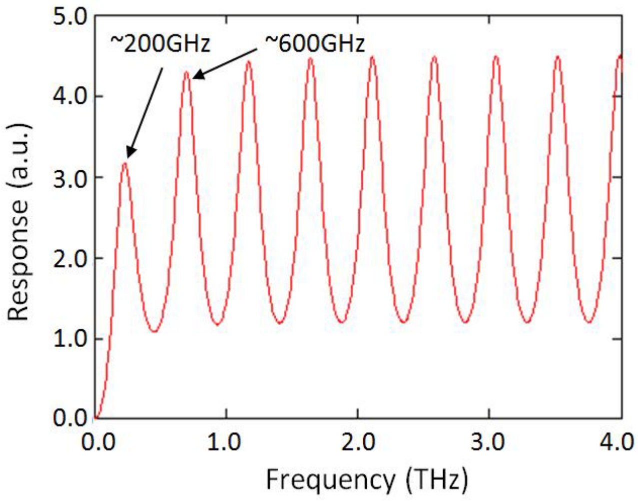
(b)

Fig. 6 Nonresonant AlN/GaN HEMT detector: (a) calculated detector responsivity, and (b) comparison between theory and measurement. The HEMT device under study (theory) has a gate length of 2 μm, and a carrier mobility of 1300 cm^2/V·s (room-T). In addition, we use $m_e = 0.2\ m_0$ for GaN systems.

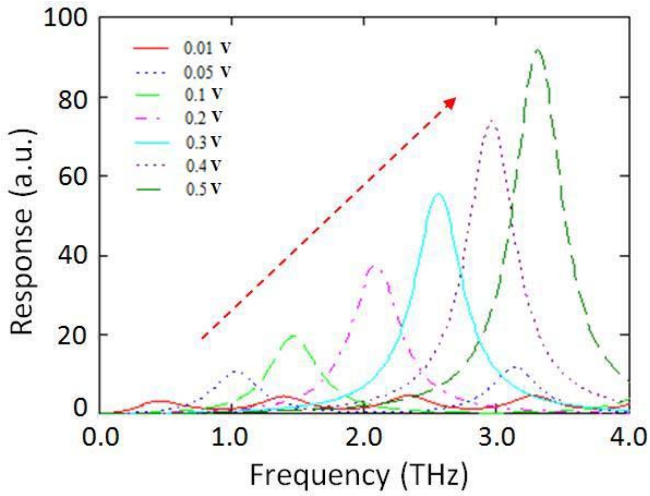
Resonant THz Detectors: A THz HEMT detector is predicted to have much higher responsivity when it works in the resonant mode [1]. In order to have a resonant mode THz AlN/GaN detector, the value of $s\tau/L$ must be greatly increased. Since the momentum relaxation time τ is determined by,

$$\tau = u m_e / e \quad , \tag{3}$$

the device can be cooled down to lower temperatures for higher carrier mobility. For GaN systems, u can be significantly increased from ~1000 cm^2/V·s at room-T to ~ 6500 cm^2/V·s at 77 K. In addition, the device effective gate length L should be decreased. Our calculation shows that an AlN/GaN HEMT with 0.15 μm gate length at 77 K has resonant features on its frequency dependent responsivity curves. As shown in Fig. 7 (a), the fundamental resonant frequency of an cooled AlN/GaN HEMT (77 K, 0.15 μm gate length) with 0.01 V gate-to-source voltage swing (V_{gs}-V_{th}) is nearly 200 GHz, and its third harmonic frequency is 600 GHz. As shown in Fig. 7 (b), the fundamental resonant frequency increases from 200 GHz to 3.2 THz with the gate-to-source voltage swing varies from 0.01 V to 2.0 V. The drain-to-source voltage response also increases with increasing of the gate-to-source voltage swing. These



(a)



(b)

Fig. 7 Resonant AlN/GaN HEMT detector: (a) calculated detector response (V_{gs}-V_{th} = 0.01 V) as a function of frequency, and (b) the detector response at various gate-to-source voltage swing. The HEMT device under study (theory) has a gate length of 0.15 μm, and a carrier mobility of 6300 $cm^2/V\cdot s$ (77 K). We use $m_e = 0.2\ m_0$ for GaN systems in this calculation.

features are very attractive at THz region. Measurements at 180-220 GHz and 570-630 GHz are currently under way. The AlN/GaN HEMT devices will soon be integrated with broadband lens-coupled antennas [8] and low-pass filters for tunable plasma wave THz detectors.

V. Conclusions

We have performed microwave measurement (0.1-40 GHz) using AlN/GaN HEMTs as detectors. The results have shown that the device works in non-resonant mode at room temperature with a responsivity agrees well with the theoretical prediction. Measured responsivity as a function of gate bias also shows reasonable agreement with the theory and published results. Room temperature responsivity measurement at W-band using Agilent 110 GHz vector network analyser (VNA), and at 200 GHz and 600 GHz using VDI (Virginia Diodes, Inc.) solid-state source are currently underway. Initial calculation results show that an AlN/GaN HEMT with 0.15 um gate length works in the resonant mode when it is cooled down to 77K. The fundamental resonant frequency increases from 200 GHz to 3.2 THz with the gate-to-source voltage swing (V_{gs}-V_{th}) varies from 0.01 V to 2.0 V. The drain-to-source voltage response also increases with increasing of the gate-to-source voltage swing. The AlN/GaN HEMT devices are planned to be integrated with broadband lens-coupled antennas and low-pass filters for tunable plasma wave THz detectors.

Acknowledgment

The authors would like to thank their colleagues in the Nano Materials and Devices Laboratory and the High Speed Electronic Devices and Circuits Laboratory at the University of Notre Dame. This work is funded by the Office of Naval Research (Dr. Paul Maki).

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