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Active Control of Nitride Plasmonic Dispersion in the Far Infrared

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SAND2014-19512
Unlimited Release
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Abstract

We investigate plasmonic structures in nitride-based materials for far-infrared (IR) applications. The two dimensional electron gas (2DEG) in the GaN/AlGaN material system, much like metal-dielectric structures, is a patternable plasmonic medium. However, it also permits for direct tunability via an applied voltage. While there have been proof-of-principle demonstrations of plasma excitations in nitride 2DEGs, exploration of the potential of this material system has thus far been limited. We recently demonstrated coherent phenomena such as the formation of plasmonic crystals, strong coupling of tunable crystal defects to a plasmonic crystal, and electromagnetically induced transparency in GaAs/AlGaAs 2DEGs at sub-THz frequencies. In this project, we explore whether these effects can be realized in nitride 2DEG materials above 1 THz and at temperatures exceeding 77 K.

CONTENTS

NOMENCLATURE

GaN	Gallium Nitride
IV	Current-Voltage
SEM	Scanning Electron Microscope
THz	Terahertz
2DEG	Two-dimensional electron gas

1. INTRODUCTION

Over the past 10 years we have developed a thorough understanding of Terahertz (THz) plasmonic excitations in high mobility two-dimensional electron gas (2DEG) material. All of this work has primarily been at frequencies ranging from 0.1 to 1 THz using the GaAs/AlGaAs material system. While plasmonics can offer interesting tunable circuit elements, this frequency region lacks integrated gain. By moving to much higher frequencies from 1 to 5 THz, quantum cascade lasers become accessible. Developing plasmonic technology in this higher frequency range can enable on chip sensing and high speed modulators and possibly improve heterodyne mixer performance.

Nitrides are a relatively immature plasmonic material system, and fundamental questions concerning their potential as a reconfigurable plasmonic medium remain open. In comparison to mature III-V materials such as GaAs/AlGaAs structures, electron scattering rates are higher in nitride 2DEGs. Electron scattering contributes significantly to plasmon damping. We anticipate that the capability of operation above 1 THz will compensate for the contributions from electron scattering mechanisms to plasmon damping. However, this needs to be demonstrated conclusively. During this program we simulated plasmon dispersion in this material system, fabricated devices, and initial electrical characterization of the devices was performed. Full photoresponse tests were beyond what we could accomplish under this effort.

2. SIMULATION OF PLASMA MODES

Our primary simulation efforts were done in collaboration with researchers at Florida International University and Rensselaer Polytechnic Institute. The work is detailed in "Dispersion Studies in THz Plasmonic Devices with Cavities" [1] (Karabiyik etal. SPIE Vol. 9102, 9102K-05, 2014). To summarize that work, we can say that numerical and analytical calculations predict plasmonic bandgaps and crystal defect mode in modulated GaN HEMT systems using realistic material parameters.

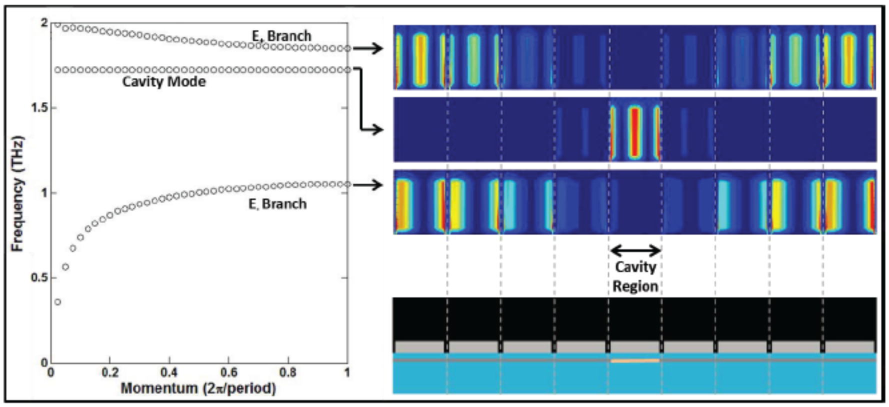

Fig. 1: From Ref[1], Dispersion curves of grating gated GaN 2DEG plasmonic devices with cavities. Grating gate device geometry has 900 nm gate length and 100 nm slit length. Electric field distributions ($|E|^2$) of the corresponding branches are shown. Red indicates the high electric fields and blue indicates the low electric field. Cavity mode is localized on the cavity region while resonant modes are localized on off-cavity regions.

While it is one thing to predict plasmon excitations and cavity behavior, experimental verification of those properties require a mechanism to convert the high frequency excitation into a measureable response. Beyond that, a localized probe of plasmon resonances is clearly advantageous in light of the simulations in Fig. 1. In section 4 we will detail the enabling device behavior for such measurements and demonstrate that our GaN based devices have the desired IV characteristics needed for successful plasmon detection.

3. FABRICATION

The wafer used for this work was Sandia growth GNC3096. The room temperature 2DEG had a carrier density of approximately 9 x 10^{12} cm^{-2}/vs.

GNC3096A

Material	Å
Al_xGaN (x=0.27)	220
GaN	9700
AlN	1600

Substrate: (-A)SiC-SI development DSP II-VI A4-227-03 387um thick

The process flow below was used for GaN device fabrication:

1. Mesa Definition
a. Rinse wafer with acetone, methanol, and isopropanol for 15 seconds each, rinse, dry
b. Mesa Lithography
i. Apply/spin HMDS
ii. Apply/spin AZ P4330 @ 5k rpm for 30 s, soft bake @ 90 C for 90 s
iii. Expose with soft contact for 70 s using EBR pattern
iv. Develop MF300 for 120 s
v. Expose with vacuum contact for 8.5 s (170 mJ/cm2) using mesa litho pattern
vi. Develop using MF300 for 65 s
vii. Descum photo resist, LFE barrel plasma clean, O2, 20 W, 5 min
c. Mesa etch
Trion Chlorine ICP Etch Tool
i. Etch 47 sec for 800 A
ii. Rinse, DI H20
iii. LFE plasma clean, O2, 850 mTorr, 200 W, 10 min
iv. Strip PR with acetone soak and airbrush spray, then rinse in methanol and dry with N2
v. LFE plasma clean, O2, 850 mTorr, 200 W, 10 min
vi. Measure mesa height

2. Ohmic Contacts
a. Ohmic Lithography
i. Apply/spin HMDS
ii. Apply/spin on AZ 5214 @ 5k rpm for 30 s, soft bake @ 90 C for 90 s
iii. Expose for 60 s using EBR pattern
iv. Develop using MF300 for 60 s
v. Expose for 5.4 s (108 mJ/cm2) vacuum contact using ohmic contact pattern
vi. Develop using MIF300 for 45 s
b. Metal Deposition
i. Descum photoresist, LFE plasma clean, 20W, 5 min

ii. Remove oxide, 1:1 (HCl:DI H2O), dip for 10 s, rinse, dry, load into E-beam evaporator without delay
iii. Metal Deposition using E-beam evaporation:
1. 250 A Ti
2. 1000 A Al
3. 150 A Ni
4. 500 A Au
iv. Metal Pattern Lift-Off : Soak substrate(s) upside down in 90 C NMP for 30 min with stir bar agitation
v. Soak and rinse with acetone, isopropanol, and dry
c. Anneal
i. RTA @ 850 C for 30 s in flowing Argon @ atmosphere

3. Gate Contacts
a. E-beam Lithography
i. Dehydration bake, 150 C for 5 min, then cool
ii. Apply PMMA C9 495 e-beam resist.
iii. Spin at 5k rpm for 45 seconds.
iv. Hotplate bake 180 C for 15 min
v. Coat with 10nm thermal Au (charge dissipation)
vi. E-beam lithography: expose gate pattern with 1150 uC/cm2
vii. Remove Au charge layer with KI/I2 solution.
viii. Develop exposed resist in 1:3 MIBK:Isopropanol for 75 seconds
vii. LFE plasma clean, O2, 20W, 5 min

b. Metal Deposition
i. Remove substrate oxidation using 1:1 (HCl:DI H2O) 10 s dip, DI H2O rinse until 10 MOhm reading, dry w/ N2. Load sample(s) into e-beam evaporator without delay.
ii. Metal Deposition, using E-beam evaporation:
1. 200 A Ni
2. 4500 A Au
iv. Metal pattern lift-off: Soak wafers upside down in 90 C NMP for 20 min
v. Rinse with acetone, IPA, N2 dry.

4. Dielectric Passivation Layer
a. Silicon Nitride Deposition
i. Plasma clean substrate(s) using O2 plasma tool, 20W for 5 min
ii. Deposit 1000A CVD Silicon Nitride

b. Passivation Lithography
i. Apply HMDS
ii. Apply/spin on AZ P4330 @ 5k rpm for 30s
iii. Bake @ 110 C for 90 s
iv. Expose using EBR pattern for 70 s, soft contact
v. Develop using MF 300 for 240 s
vi. Expose passivation dielectric pattern for 9 s (180 mJ/cm2), vacuum contact

vii. Develop using MF 300 for 120 s
c. SiN Etch:
i. Descum photoresist using LFE O2 plasma clean, 20W for 5 min
ii. Etch 1000 A Silicon Nitride with Fluorine ICP Etch tool (105 seconds with Trion Tool and recipe)
iii. LFE Resist clean, O2, 200 W, 10 min
iv. Rinse substrate(s) with acetone, methanol, and isopropanol for 15 seconds each, rinse, dry

5. Antenna and Bond Pads
a. Antenna & Bond Pad Lithography
i. Apply/spin HMDS
ii. Apply/spin AZ P4330 @ 5k rpm for 30 s, soft bake @ 90 C for 90 s
iii. Expose for 70 s using EBR pattern, soft contact
iv. Develop using MIF300 for 120 s
v. Expose for 8.5 s (170 mJ/cm2) using antenna/bond pad pattern
vi. Develop using MF300 for 65 s
b. Metal deposition
i. Descum photoresist pattern, LFE O2 plasma, 20W, 5 min
ii. Deposition using E-beam evaporation:
1. 200 A Ni
2. 4500 A Au
iii. Soak wafers upside down in 90 C NMP for 10 min with stir bar agitation
iv. Soak and rinse with acetone, rinse with isopropanol, and dry.

An example device fabricated using this process is shown in Fig. 2. The fine gate detail is emphasized in Fig. 2 (b) and Fig. 2(c). A variety of gate line widths ranging from 0.3 microns to 2 microns were fabricated.

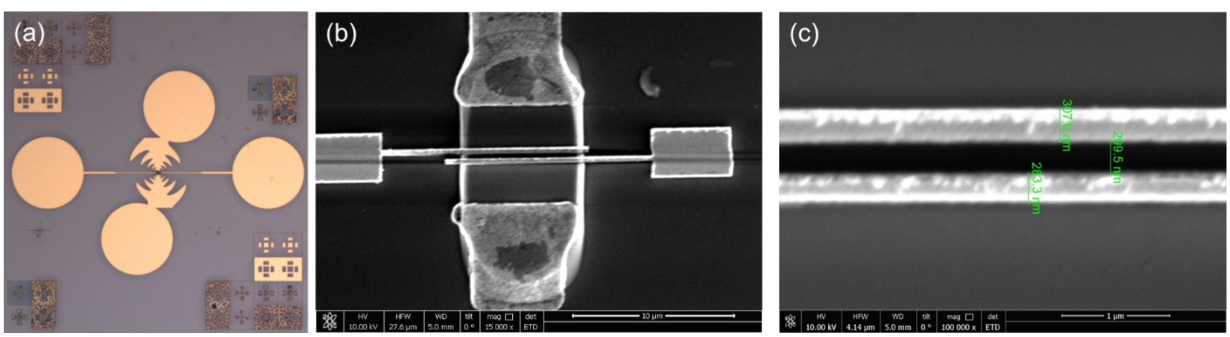

Fig. 2: Fabricated THz GaN HEMT devices. (a) Full view of complete device including THz antenna. (b) SEM of plasmonic transistor located at antenna vertex. (c) SEM image of narrowest gate lines of device.

4. ELECTRICAL CHARACTERIZATION

In 2006 we first realized that nearly depleted gated regions could act as either an integrated plasmon rectifier or local bolometer depending on biasing conditions [2]. This observation launched years of work leading to direct tunable THz detectors with competitive performance to the recent observation of Tamm states in THz plasmonic crystals [3]. The electrical characteristics that lead to this novel detection behavior are shown in Fig. 3 for a high mobility transistor device fabricated in GaAs. When a single gate line in the device is biased near depletion, a tunnel barrier is formed between the source and drain. In the negative IV quadrant, the gated section of the transistor channel acts as a plasmon rectifier. In the positive IV quadrant, the gated channel section has a bolometric response.

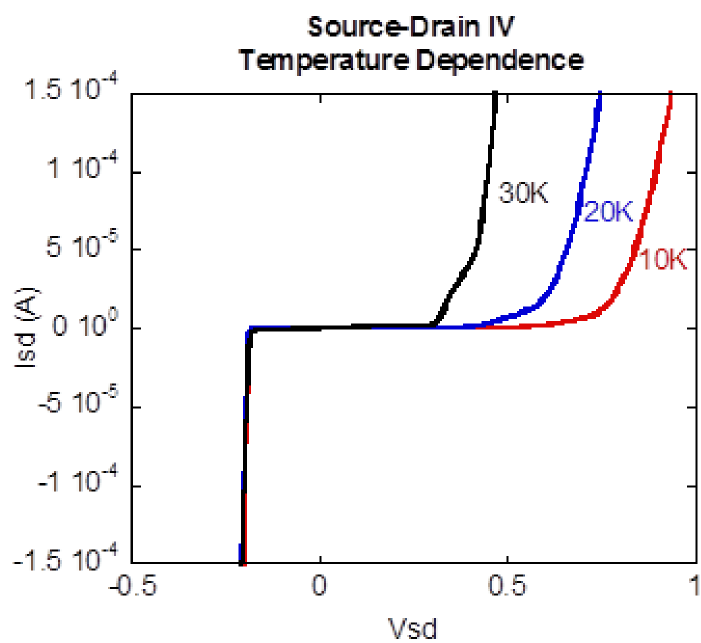

Fig. 3: IV characteristics of GaAs based plasmonic transistor. A single gate line is operated near depletion creating a tunnel barrier between the source and drain. In the negative IV quadrant, this gate line acts as a plasmonic rectifier sensing any adjacent plasma excitation. In the positive IV quadrant, the gated region of channel provides a bolometric response.

The bolometric nature of the positive IV quadrant is made clear by the temperature dependence shown in Fig. 3. As temperature is increased, eventually this IV feature loses contrast and the device loses sensitivity. Knowing this general behavior is critical to GaN device performance, we performed basic IV characterization of devices at room temperature. Results from those measurements are shown in Fig. 4. First, the pinchoff point for the channel is characterized in Fig. 4(b) in order to ascertain approximate operating points for rectifier/bolometer operation. In Fig. 4(c), the device is biased in a similar way as the GaAs device used for Fig. 3. Clearly, the negative quadrant IV characteristics are in line with rectifier behavior. The positive IV quadrant was not completely explored as the measurement was set to 2 V compliance in order to protect the device. As these are preliminary measurements, it was satisfactory to simply verify the barrier was intact at room temperature. In our experience, when sufficient voltage is applied eventually tunneling occurs leading to a bolometric response having high responsivity. At this stage, the IV characteristics of the GaN device indicate that elevated temperature operation of our preferred detection mechanisms using the rectifier/bolometer element should be possible.

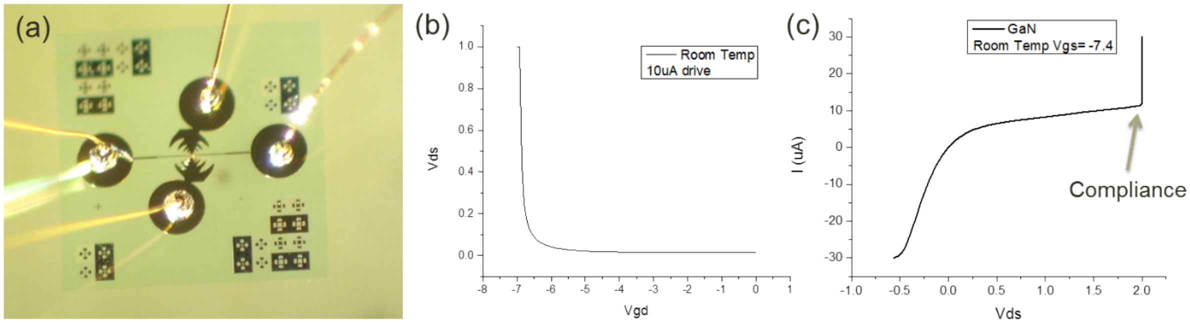

Fig. 4: IV Characterization of GaN based plasmonic transistors. (a) Fully packaged device. (b) Drain-Source voltage vs. Gate-Source voltage with source grounded. Pimchoff of the channel occurs near 7V. (c) Drain-Source current vs. voltage with single gate line pinched biased to -7.4 V. The compliance of the measurement unit was set to 2 V in order to protect the device.

5. CONCLUSION

This effort sought to investigate the tailorability of plasmonic structures in nitride-based (GaN) materials for far-infrared (IR) applications. While there have been proof-of-principle demonstrations of plasma excitations in nitride 2DEGs, exploration of the potential of this material system has thus far been limited. Our initial goal was to demonstrate theoretically and experimentally that GaN could support coherent phenomena, such as the formation of plasmonic crystals, strong coupling of tunable crystal defects to a plasmonic crystal, and electromagnetically induced transparency. During this program, simulations were performed that predict the desired performance, including the existence of plasmonic defect cavities using reasonable GaN material properties, and devices were fabricated and characterized. However, the characterization was limited to IV testing in order to determine if the gate defined barriers could be used as plasmonic detection elements as we have done in previous work on GaAs. Initial results are promising; however, full photoresponse testing was not performed and is left as future work to be performed.

6. REFERENCES

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