REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

<table>
<thead>
<tr>
<th>1. REPORT DATE (DD-MM-YYYY)</th>
<th>2. REPORT DATE</th>
<th>3. DATES COVERED (From - To)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb., 14 2004</td>
<td></td>
<td>Final 1999-2003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. TITLE AND SUBTITLE</th>
<th>5a. CONTRACT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid State THz Sources</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5b. GRANT NUMBER</th>
<th>5c. PROGRAM ELEMENT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>G N00014-99-1-0915</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. AUTHOR(S)</th>
<th>5d. PROJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimitris Pavlidis</td>
<td>PR 00PR04186</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>5e. TASK NUMBER</th>
<th>5f. WORK UNIT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</th>
<th>8. PERFORMING ORGANIZATION REPORT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRDA, The University of Michigan</td>
<td></td>
</tr>
<tr>
<td>3003 South State Street</td>
<td></td>
</tr>
<tr>
<td>Ann Arbor, MI 48109-1274</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</th>
<th>10. SPONSOR/MONITOR'S ACRONYM(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Sponsor: US DOD Navy Department</td>
<td></td>
</tr>
<tr>
<td>Prime Sponsor: US Dep Advanced Research Projects Agency</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>11. SPONSORING/MONITORING AGENCY REPORT NUMBER</th>
<th>12. DISTRIBUTION AVAILABILITY STATEMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Approved for public release distribution unlimited</td>
</tr>
</tbody>
</table>

13. SUPPLEMENTARY NOTES

14. ABSTRACT
High layer quality GaN NDR layers have been grown in house by newly set up MOCVD facility. Record quality A1N layers were grown for high thermal conductivity substrateless diodes with improved thermal management. GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation. Liquid Nitrogen Characterization of GaN NDR diodes manifested clear increase of current handling as necessary for establishment of NDR conditions. Planar GaN NDR diodes have been investigated as an alternative to vertical designs. InGaN/GaN superlattice designs have been theoretically and experimentally investigated for THz signal generation. Pulse generation setups have been developed to respond to high power, nssec time needs of GaN NDR diodes. On wafer probe techniques with built-in resonators have been investigated for high frequency testing of NDR diodes. Experimental micromachining technology was developed for silicon. Waveguide, probes, transitions and flanges developed and tested in W band. Excellent experimental results were obtained in W band. Nearly finished with corresponding GaAs process technology. Technology demonstration was made with complete W band multiplier.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON

20040219 197
Solid State THz Sources

FINAL REPORT
September 23, 2003
The University of Michigan

Dimitris Pavlidis
Professor of EECS
The University of Michigan
Department of Electrical Engineering
and Computer Science
1301 Beal Ave.
Ann Arbor, MI 48109-2122
Tel:(734) 647-1778, Fax:(734) 763-9324
e-mail: pavlidis@umich.edu
URL: www.eecs.umich.edu/dp-group

Goals, Objectives and Main Technical Approach
Develop solid-state THz sources using GaN NDR (Negative Differential Resistance) diode oscillators and micromachining.
The NDR devices can further be integrated using low-cost power combining networks and cavities operating at Terahertz frequencies.
Silicon micromachining has been selected as the enabling technology of building blocks for circuits and systems at THz frequencies. Micromachining technology is used for the fabrication of scalable THz structures.

Major Impact of Technology and Accomplishments
The use of wide bandgap GaN-based semiconductors is expected to result in increased operating frequency of Gunn-effect enabling for the first time, THz signal generation using solid-state Gunn diode oscillators. Micromachined structures are low cost alternatives that can batch produce a variety of components needed at submillimeter frequencies. The major impact of this research will be to greatly reduce the cost and development time of THz circuits.

GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation.
Deep RIE technology has been optimized for waveguide and probe fabrication. Initial results show excellent insertion and return loss over W band.

The University of Michigan — SSEL

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited
Program Objective and Strategy

Develop solid-state THz sources using GaN NDR (Negative Differential Resistance) diode oscillators and micromachining.

The NDR devices can further be integrated using low-cost power combining networks and cavities operating at Terahertz frequencies. GaN bulk NDR devices are explored as possible THz sources and other alternatives such as SL and Schottky tunnel designs are evaluated.

Silicon micromachining has been selected as the enabling technology of building blocks for circuits and systems at THz frequencies. Silicon and GaAs technology is used to micromachine THz structures. W band multipliers are used as a proof of concept and extension of the technology to submillimeter wave and THz frequencies is envisaged.

Technical Challenges

• Transport properties and Negative Differential Resistance Properties of GaN and Nitride-Based Compounds
• Low defect concentration of nitride surfaces exposed to deep etching.
• Efficient thermal dissipation in GaN-based NDR devices
• Substrate removal, packaging and testing of high power GaN NDR devices.
• Combination of micromachined structures with sources
• Process development for DRIE depths deep enough to allow waveguide fabrication
• First demonstration of deep etch technology in GaAs for submillimeter applications
• Design and development of circuit elements limited by technology geometries
Key Milestones

- High layer quality GaN NDR layers have been grown in house by a newly set up MOCVD facility.
- Record quality AlN layers were grown for high thermal conductivity substrateless diodes with improved thermal management.
- GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation.
- Liquid Nitrogen Characterization of GaN NDR diodes manifested clear increase of current handling as necessary for establishment of NDR conditions.
- Planar GaN NDR diodes have been investigated as an alternative to vertical designs.
- InGaN/GaN superlattice designs have been theoretically and experimentally investigated for THz signal generation.
- Pulse generation setups have been developed to respond to high power, nsec time needs of GaN NDR diodes. On wafer probe techniques with built-in resonators have been investigated for high frequency testing of NDR diodes.
- First DRIE fabricated waveguides in WR10 and WR3
- Fully micromachined transitions covering full waveguide band in WR10
- Fabrication of state of the art planar monolithic W band multipliers
- GaAs deep etch technology

Technology Transition/Insertion/Commercialization Plan

- We have established various collaborations with government and industry laboratories for advancing, testing and using the developed technology. This includes manufacturers of Gunn diodes and government/academic laboratories.
- Proposals to NASA Glenn and NASA JPL for further work at THz frequencies
- ARO MURI research program to develop low cost sources for chemical and biological sensing applications
Outline

- Introduction
- THz GaN NDR diode oscillators
- THz Micromachined Structures
- Conclusions

THz GaN NDR diode oscillators

The University of Michigan — SSEL
Outline

- Introduction
- Operation of GaN NDR diode oscillators
- Development and optimization of fabrication technology
- Fabrication of GaN NDR diodes
- Si wafer thinning technology
- Electrical characterization of NDR diodes
- Packaging and RF testing of GaN NDR diodes
- Conclusions

Solid-State Terahertz Sources (The UofM Approach)

GaN NDR Diodes for THz signal Generation
Micromachined Resonator; Filter/Multiplier
= Solid-State Terahertz Source

- Unique approach combining new semiconductor and micromachined concepts
- Semiconductor device potential for high-power fundamental or harmonic sources
- Possibility to apply micromachined concept to other sources developed under this program
Use of GaN for Signal Generation

- Theoretical and experimental studies of electron transport in GaN predict critical field >150KV/cm and peak velocity >2×10^7 cm/s.
- Maximum frequency of oscillations in NDR devices is limited by the energy-relaxation and intervalley relaxation time.
  - Frequency of GaAs Gunn diodes is limited by electron scattering at ~100GHz, while in GaN this limit is at ~800GHz.

The University of Michigan — SSEL

GaN NDR Diode Fabrication
Mask Set for Small Size Diodes

The University of Michigan — SSEL
ICP Etching

- Unlike RIE that uses parallel plate reactor, ICP utilizes inductively coupled plasma
- ICP has several advantages over RIE:
  * Operation over wider range of pressures (1 – 500 mTorr)
  * Plasma density increases linear with power up to high power levels
  * ICP can produce more anisotropic etches compared to RIE
  * Plasma is usually more dense leading to chemical etching enhancement
    → Less surface damage
  * ICP allows better selectivity between the etched and the masking materials

Etching of GaN:
Sample UMTS125 with 100 nm n+ GaN (1e19 cm-3) cap layer,
1 micron n- GaN active layer (1e17 cm-3), 500 nm n+ GaN bottom
contact layer (8e18 cm-3), 1.96 microns u-GaN (4e16 cm-3) and a 20
nm LT-NL (nucleation layer?).

Sample description:
A-type: mesa etching with 5 microns thick AZ4562 resist mask (targeted etch depth:
about 1300 nm)
B-type: mesa etching with a combination of Ti/Al/Ti/Au-metallization
(22nm/78nm/22nm/83nm) and 1.5 microns thick HiPR6517 resist as mask.

Test samples: AZ4562 on glass, the B-structures with and without photoresist on Glass
(possibility to determine the etching rate of photoresists and metallisations)

Etching machine: Oxford Instruments Plasmalab 80+plus RIE system
Gas: SiCl4, 5 sccm
Base pressure: 8E-6 mbar
rf power: 200 W
measured self-bias: between...
Etching procedure: 15 min etching, 10-25 min break for the pressure to recover

Test results: 3x15 min etching + 2x10 min break
  - etch depth of AZ4562: 1500 nm
  - etch depth of glass: 100 nm
  - etch depth of GaN: 760 nm (17 nm/min)
2d Batch: 76 min etch + breaks, etch depth of GaN: 800nm (11 nm/min)
  - expected etch depth: about 1300nm. Reason: silicide formation slowing down the process.
3d Batch to continue the etching, after cleaning of the chamber !!, 15+10+10 min etching and 25+15 min break, etching depth 1600-1700 nm. After cleaning the chamber higher etching rate was observed.

PEC Etching of GaN

- Etching of GaN occurs due to Photo-electrochemical reaction at sample surface
  - Arc lamp induces photo-generated e-h pairs in GaN
    - Excitation provided by newly acquired 200W Oriel Hg arc lamp
  - Photo-generated holes assist Redox reaction in KOH solution
  - KOH etches the oxidized gallium products
  - HgXe bulb produces a smooth and uniform etch compared with Hg. Etch rate also is different. Rate was Hg) 67 nm/min and HgXe) 150 nm/min.

- Parameter Space for PEC etching
  - Sample Carrier Conc.
  - UV light intensity
  - Solution type
  - Solution conc.
  - Temp.
  - Agitation
### Thomas Swan 3x2” CCS Reactor

- Vertical GaN Reactor
- Water cooled stainless steel outer chamber
- Quartz inner chamber
- Rotating susceptor to improve uniformity
- "Showerhead" injection for efficient gas delivery and mixing
- 3-zone heater for uniform temperature distribution
- Dry Nitrogen purged glovebox enclosure

### Interferometer Trace

- Interferometer trace shows smooth LT GaN growth then subsequent roughening during the ramp to 1040C.
- After ~1200 sec of 3D growth, HT GaN material is recovered and growing with smooth surface and constant growth rate
- Growth Rate ~ 1.7 μm/hr, consistent with XSEM
UID Hall Results

- Cut 6 300x300 mil (7.5x7.5 mm²) square for Hall
- Background doping reduced to ~4x10¹⁹ cm⁻³ with corresponding mobility of ~300 cm²/Vs.
- Background and mobility appear uniform across the wafer.

Gunn Diode Structures

- Calibration of doping for silane flows of 4 sccm=1.0e19 cm⁻³ and 0.05 sccm=1.2e17 cm⁻³. Curve was generated and silane flow calculated for doping of 1e17, 8e18, and 1e19 cm⁻³.
- Growth of three Gunn diode structure. Sample 125 is traditional vertical structure with 1 μm active layer. Sample 126 is vertical but with a 2 μm active layer. Sample 128 is a planar Gunn structure with a 3 μm active layer.
Suppression of Yellow luminescence deep centers of GaN

- **Yellow luminescence center**: a universal feature of GaN located around 2.3 eV.
- **YL source**: electrons from conduction band or a shallow donor to a deep state.
- **Deep state**: Ga vacancy or complex of Ga vacancy with impurity.
- **Effects**: YL centers may influence GaN based device performance → high quality GaN layers evidenced by small FWHM/XRC, low noise and large carrier lifetime constants are associated with small YL.
- Use YL to optimize GaN device quality.

RT Photoluminescence of GaN

![Graph showing intensity vs. energy with peaks labeled YL and BE.]

Typical PL shows a narrow band edge (BE) peak (~3.4 eV) and broad yellow luminescence (YL) band (~2.3 eV).
Integrated Yellow to Band edge Luminescence (YL/BE) ratio

- The experimental data and Shockley-Read-Hall Model calculation agree well at low and high excitation density.
- SRH lifetime can be extracted from low excitation region (1.25 ns).

YL of Si doped GaN

Buffer layer growth conditions were changed to study impact on Si-GaN quality

<table>
<thead>
<tr>
<th></th>
<th>Grow time (s)</th>
<th>Ramp time (s)</th>
<th>Re-crystallize time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>230</td>
<td>300</td>
<td>60</td>
</tr>
<tr>
<td>B</td>
<td>230</td>
<td>300</td>
<td>150</td>
</tr>
</tbody>
</table>

- SRH lifetime of YL centers can be extracted using Hall carrier density $N_d$ and YL to BE ratio.
- The lifetime of YL increases nearly linearly with Si doping density.
- Si substitutes the deep-level Ga vacancy → formation of shallow donor levels decreases YL band (deep level density) → improved material quality ($\tau_{\text{SRH}}$).
- Si-GaN lifetime increases for high quality buffer layer A.

At low excitation density:

$1/\tau_{\text{SRH}} = \sigma_0 v_0 N_d \cdot (\text{YL/BE}) \cdot B \cdot N_d$

$B = 4.7 \times 10^{11} \text{ cm}^3/\text{s}$ (Constant related to band-to-band recombination)
Growth Pressure and V/III Ratio Effects YL Deep Center

<table>
<thead>
<tr>
<th>sample</th>
<th>Si-doped Carrier density (cm⁻²)</th>
<th>V/III ratio</th>
<th>Pressure (Torr)</th>
<th>SRH lifetime (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.73x10¹⁸</td>
<td>1400</td>
<td>100</td>
<td>0.34</td>
</tr>
<tr>
<td>B</td>
<td>4.33x10¹⁸</td>
<td>800</td>
<td>100</td>
<td>0.15</td>
</tr>
<tr>
<td>C</td>
<td>8.93x10¹⁸</td>
<td>1000</td>
<td>200</td>
<td>7.0</td>
</tr>
<tr>
<td>D</td>
<td>8.43x10¹⁸</td>
<td>1000</td>
<td>100</td>
<td>0.75</td>
</tr>
</tbody>
</table>

- High V/III ratio suppresses the Ga vacancy
- Increase of reactor pressure also reduces V/III ratio
- SRH lifetime is good indication for growth optimization.
  (high V/III and high pressure needed for improved GaN layer quality)

High Quality AlN Growth by MOCVD on Sapphire

1. Growth of AlN (0.4–1 μm) on low temperature (530°C) buffer layer:

   - FWHM-XRD increases with growth pressure.
   - AlN layer quality is not acceptable (min. FWHM=610°) if AlN is grown on sapphire using LT-buffer; Same feature expected using LT-GaN buffer.
2. Direct growth of AlN on sapphire:

- High quality AlN (0.4 μm) layer was grown on sapphire.
- X-ray rocking curve with excellent FWHM value of 95 arcsec.
- FWHM of x-ray rocking curve is strongly dependent on nitridation time.

---

Low Temperature PL of GaN Layers Used in NDR-Diodes

- The main peak is neutral donor bound exciton with FWHM=10 meV.
- Two electron transitions (D0, Xn) at 3.1 eV; One phonon and two phonon replica were observed.
- The above features indicate high quality samples.
NDR-GaN Diodes Using AlN for Substrateless Design

- The obtained high quality AlN could be used as base for growth of substrateless NDR-GaN Diodes ➔ improved handling of thermal issues.
- Growth of high quality GaN-diode layers on AlN buffer would require following studies for reduced AlN surface roughness.
  - ALE-like initial AlN growth on sapphire with excess NH₃ flow for reduced layer roughness.
  - Growth of low XRD FWHM bulk AlN using reduced NH₃ flow.

Sample 0B Measurement Results

Room Temperature Pulsed Measurements
Sample 0B

- Linear Fit: 0 - 12 V
- Linear Fit: 15 - 22 V

Device burned at ~ 30 V

Rise and Fall Times: <50 ns (variable)
Average Pulse Width: 200 ns
Maximum Pulse Width: 300 ns
Period: 10 ms - 1 s

- RT pulsed IV measurements were performed under following pulse conditions:
  - period: >10 ms; rise/fall time: <50 ns; width: 200 ns; max width: <300 ns
  - Slight current saturation begins to onset at > 20 V (100 kV/cm)
  - After a sudden spike at ~30 V device is burned and left open.
Measurements Under Different Pulse Conditions

- RT measurements under long pulse conditions (~300 μs) showed saturation at ~300 mA
- Same measurement but at LN2 temperature demonstrated higher peak current at ~600 mA and more pronounced NDR
- Under short pulse conditions (pulse width ~200 ns) current begins to saturate at ~24 V corresponding to 120 kV/cm even at room temperature

SEM of the Tested Diodes

- Anode contacts burn at high fields
Measured Test Structures of 00B1. The cathode metallisation is not wide enough for the probes. After some measurements the contacts deteriorate.

Diodes Mounted on Diamond Heat Sink

- Collaboration with Quinstar
- Mounting with diamond heat sink improves heat dissipation
  ⇒ reduction of thermal limitation
DC Characteristics of Small Gunn Diodes

Sample MICH 01106-1A. Diode diameter: ~15 µm  
Device burned

- Previous measurements of GaN on SiC Gunn diodes with ~ 50-100µm diameter showed onset of NDR at \( V \approx 12 \text{V} \) (\( Ec \approx 24 \text{kV/cm} \)) with dissipated power \( ~3-4\text{W} \)
- The critical field for GaN on SiC diodes is well below the predicted values for GaN.
  NDR effect is severely affected by thermal issues.
- Smaller thickness, 0.5µm, diodes on Si have better heat dissipation through the substrate.
  Possibility to observe NDR effects which are less affected by thermal issues.
- Onset of NDR was observed at \(-15-16\text{V}}
- Corresponding value of the critical field, \( Ec = 300 \text{kV/cm} \)

Charged line configuration (Blumlein) for pulse generation

The DC supply \( V_{ch} \) is varied between 2 and 500V. The switch is triggered with a period of 100 ms and the trigger pulse of 12V amplitude and 10 ms width (possible to go down to 10 and 2 ms for the period and the width, respectively) is provided by the 8114A pulse generator.

The scope is a 50 Ohm terminating load. With a 50 Ohm DUT the scope waveform is a pulse of negative polarity and \( V_{ch}/2 \) amplitude.

The University of Michigan — SSEL
Pulse waveforms with connected diode (00B1) for different pulse widths. The reflected amplitude of the 88 ns pulse is too low, possibly due to poor contacts. There is a 20db atten. Before the scope (max input rms 5V). A factor 10 is to be considered for the voltage scale. The input impedance of the scope is set to 50 Ohm. Pulse waveform @ 100V charge voltage, for 21, 44 and 84 ns pulse width.

I-V curves of the 00B1 structures (2 micron thick layer) for 2 pulse widths.
Oscillator layout for 4.6 GHz
(Simulation including S-parameters of connections to the diode)

rf output

To diode connection

1954 micron

Bias input

---

GaAs Gunn Diodes (DC Measurement)

<table>
<thead>
<tr>
<th>LAYER NR.</th>
<th>MATERIAL</th>
<th>THICKNESS (nm)</th>
<th>DOPING (cm⁻³)</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>InGaAs</td>
<td>50</td>
<td>N (&gt;1 E19)</td>
<td>Cap</td>
</tr>
<tr>
<td>3</td>
<td>InGaAs</td>
<td>50</td>
<td>N (5 E18)</td>
<td>In Graded</td>
</tr>
<tr>
<td>2</td>
<td>GaAs</td>
<td>10000</td>
<td>N (2 E15)</td>
<td>Gunn layer</td>
</tr>
<tr>
<td>1</td>
<td>GaAs Substrate</td>
<td>N (1-3 E18)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

The University of Michigan — SSEL
Spectrum analysis of a GaAs Gunn Diode with a resonator

Sampling-Oscilloscope measurement of a GaAs Gunn Diode with a resonator
On-wafer measurement setup for Gunn oscillations in GaAs and GaN diodes

Setup for GaAs Gunn-diode testing (10 microns active layer, 150x200 sq. Microns area, Oscillations at 3.9GHz with 200 ns pulses and 100 us repetition rate.

GaN NDR Diode Fabrication

**Vertical NDR Structure**
- Non-planar approach
- Good thermal dissipation
- Substrate thinning
  ⇒ Integrated heat sink

**Horizontal NDR Structure**
- Easy integration
- Reduced heat dissipation

*The University of Michigan — SSEL*
**v-F Measurements**

**Velocity – Field Measurement Results**

- Velocity saturation is revealed but no real overshoot prior to breakdown ($F_b \approx 180$ kV/cm)
- Test structures burned even under pulsed conditions ($t_{pulse} = 200$ ns)
- Breakdown is likely due to localized high field in the constriction (< 10 μm)
- Breakdown field is reduced to < 50 kV/cm without passivation
- Transport is along a-axis vs. c-axis in our diode design

**Planar Diode Measurements**

- DC measurements of planar TLM-like structures for 3 (black), 6 (purple), 10 (yellow) μm spacing between pads
- The critical voltage is dependent on the diode length; increases with separation

*The University of Michigan — SSEL*
Measurements with planar structures:
3 microns spacing, 40 ns and 200 ns pulses. Saturation tendency, probably due to thermal effects, reached at lower voltage and current for longer pulses independent of the repetition rate. Saturation field about half of corresponding vertical structures (with 2 microns active layer). Beyond 25V important heat development leading to non reproducible results (shift of the saturation current and voltage to lower values), and destruction of the contact metallization.

AlGaN Calibration

- The TMGa and TMAI flows were selected to give a molar ratio of ~25% Al content. A thick AlGaN layer was grown to facilitate XRD and X-SEM measurements
- Optical micrograph shows AlGaN is cracking due to lattice mismatch induced strain in the thick layer. This is typical for AlGaN grown direct on GaN.
- X-SEM
  - Cross-Section shows AlGaN/GaN interface very clearly. Growth rate was determined to be ~0.9 μm/hr.
AlGaN/GaN Uniformity

- Mobility and sheet charge are uniform across the wafer
  - Mobility uniformity less than 5%
  - Charge uniformity less than 10%

Study of Al Incorporation

- Al incorporation into solid AlGaN shows a super-linear trend
  - We expect reduced Al-NH3 pre-reactions due to use of low pressure, low ammonia flow, and close-coupled showerhead reactor design
  - In absence of pre-reaction, quasi-thermodynamic models predict preferential Al incorporation when using high growth temperature and low V/III ratio.
- To verify our data, we are currently studying Al incorporation under various other growth temperature and V/III ratio.

The University of Michigan — SSEL
InGaN Calibration

<table>
<thead>
<tr>
<th>Material</th>
<th>InGaNP1 (851)</th>
<th>InGaNP2 (854)</th>
<th>Low Temp. GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth Temp</td>
<td>730°C</td>
<td>730°C</td>
<td>730-750°C</td>
</tr>
<tr>
<td>Carrier Gas</td>
<td>N₂</td>
<td>N₂</td>
<td>N₂</td>
</tr>
<tr>
<td><a href="%5BTMIn%5D+%5BTMGall%5D">TMIn</a></td>
<td>0.86</td>
<td>0.86</td>
<td>0</td>
</tr>
<tr>
<td>Growth Rate</td>
<td>40 mm/hr</td>
<td>80 mm/hr</td>
<td>40-80 mm/hr</td>
</tr>
<tr>
<td>XRD-In content</td>
<td>21%</td>
<td>17%</td>
<td>-</td>
</tr>
<tr>
<td>NH3</td>
<td>2.5 s/min</td>
<td>2.5 s/min</td>
<td>2.5 s/min</td>
</tr>
<tr>
<td>Growth Pressure</td>
<td>200-500 Torr</td>
<td>200-500 Torr</td>
<td>200 Torr</td>
</tr>
</tbody>
</table>

• Thick InGaN was grown directly on GaN to determine growth rate, In content, and layer quality.
  - In content not sensitive to input gas ratio due to In volatility temperature above 500°C
  - Must change growth temperature or pressure to tune the In content
• LT-GaN also optimized for use in FET to avoid change of growth temperature that could lead to interface degradation

InGaN/GaN SL Growth for Negative Differential Resistance

<table>
<thead>
<tr>
<th>SL #1: without n-GaN caps</th>
<th>SL #2: with n-GaN caps</th>
<th>SL #3: without n-InGaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 nm n-InGaN (4e18 cm⁻³)</td>
<td>50 nm HT n-GaN (4e18 cm⁻³)</td>
<td>50 nm HT n-GaN (4e18 cm⁻³)</td>
</tr>
<tr>
<td>2.5 nm u-InGaN (4e18 cm⁻³)</td>
<td>2.5 nm n-GaN (4e18 cm⁻³)</td>
<td>2.5 nm u-InGaN (4e18 cm⁻³)</td>
</tr>
<tr>
<td>2.5 nm GaN barrier</td>
<td>2.5 nm u-InGaN (4e18 cm⁻³)</td>
<td>2.5 nm u-InGaN (4e18 cm⁻³)</td>
</tr>
<tr>
<td>2.5 nm u-InGaN (4e18 cm⁻³)</td>
<td>2.5 nm GaN (4e18 cm⁻³)</td>
<td>2.5 nm u-InGaN (4e18 cm⁻³)</td>
</tr>
<tr>
<td>160 nm n-InGaN (4e18 cm⁻³)</td>
<td>160 nm n-InGaN (4e18 cm⁻³)</td>
<td>160 nm n-InGaN (4e18 cm⁻³)</td>
</tr>
<tr>
<td>500 nm u-GaN transition</td>
<td>500 nm u-GaN transition</td>
<td>500 nm u-GaN transition</td>
</tr>
<tr>
<td>LT-GaN N.L.</td>
<td>LT-GaN N.L.</td>
<td>LT-GaN N.L.</td>
</tr>
<tr>
<td>400 μm Sapphire</td>
<td>400 μm Sapphire</td>
<td>400 μm Sapphire</td>
</tr>
</tbody>
</table>

*Nominal In concentration for all InGaN layers ~ 5%*
Characterization of InGaN/GaN superlattices

- The I-V characteristic for different structures
- SL2: 10 QWs InGaN/GaN; SL3: 10 QWs GaN/InGaN; SL4: same as SL3 high Ip%
- All samples processed in parallel and annealed at 750 C

Breakdown Mechanism

A possible breakdown mechanism between n+ and n- layers is of concern: Apart from a soft recovery, it is necessary that the diode can withstand a high $dl/dt$, which may result in dynamic avalanche well below the static breakdown voltage. Dynamic avalanche is caused by a current controlled increase of the effective doping level $N_{eff}$ [see Eq. (1)]. $J_p$ is the hole and $J_S$ the electron current density, $v_{sat}$ the carrier saturation velocity, and $N_D$ the $n$-base doping.

$$N_{eff} = N_D + \frac{J_p - J_S}{q \times v_{sat}}$$  \hspace{1cm} (1)

Diode destruction by dynamic avalanche during reverse recovery has been reported in Refs. 1-3, but a considerably
Ohmic Contact Considerations

- At high power the Ti/Al/Au ohmic contacts suffer from severe degradation
- First the contact metal begins to melt around the perimeter of the contacts
- When pushed higher in power the top Au "shoots" across the separation between anode and cathode, eventually violently burning the diode under test
- To remedy this problem a new metallization scheme was used:
  - Ti/Al/Ni/Au contacts were used in recent runs
  - Ni serves as a barrier preventing Au from diffusing into the Ti/Al/GaN contact
  - 10-100 times better quality contacts were achieved (Rsc = 4.4 x 10^-6 Ohm/cm²; previous Rsc = 1.3 x 10^-4 Ohm/cm²)
- However, at high powers the top Au layer still melts destroying the diode as described above
- Another approach is currently being tested with introduction of refractory metals into the ohmic metallization scheme (Mo, Pt, W, etc.)
- Although refractory metal contacts have usually higher resistance compared with Ti/Al contacts their power handling capability is much higher

Conclusions I

- High layer quality GaN NDR layers have been grown in house by a newly set up MOCVD facility
- Record quality AlN layers were grown for high thermal conductivity substrateless diodes with improved thermal management.
- GaN Gunn diodes were designed and fabricated on Si substrates with high thermal conductivity. Combined with the use of small size devices they allowed to bias GaN NDR diodes under electric fields suitable for oscillation.
- Liquid Nitrogen Characterization of GaN NDR diodes manifested clear increase of current handling as necessary for establishment of NDR conditions.
- Planar GaN NDR diodes have been investigated as an alternative to vertical designs.
Conclusions II

- InGaN/GaN superlattice designs have been theoretically and experimentally investigated for THz signal generation.
- Pulse generation setups have been developed to respond to high power, nsec time needs of GaN NDR diodes. On wafer probe techniques with built-in resonators have been investigated for high frequency testing of NDR diodes.

THz Micromachined Structures

Yongshik Lee, Jack East and Linda Katehi
The University of Michigan
Outline

- Overview & Background
- Thz micromachined structures
- Summary

THz Micromachined Structures

- Goal is to develop silicon and GaAs micromachining technology
- The resulting processes can be used to realize low cost batch fabricated structures from 100 GHz to several THz
- Probes, waveguides, transitions and flanges have been developed and tested
- Continuing efforts will focus on WR10, WR5 and WR3 circuits and systems
Deep RIE (DRIE) Technology

- Goal is to realize micromachined elements that can be scaled to THz frequencies
- Design based on HFSS
- Technology based on conventional lithography and a STS deep etch tool
- Example WR 10 waveguide and transition

DRIE (continued)

- Complex structures such as coupling probes positioned with integral backshunts can be fabricated
- Excellent control of dimensions possible
- Assembly and alignment will be critical at higher frequencies
- Batch techniques will be needed to reduce cost
DRIE (continued)

- Assembly and alignment will be critical at higher frequencies
- Batch techniques will be needed to reduce cost
- Alignment "pins" and "holes" can be easily included as part of the design

Transition Results

FGC-to-DRIE Waveguide Transition
Waveguide Transitions

- We also need transitions to external waveguide assemblies
- Batch fabrication and accurate low cost alignment and assembly will be critical

WR3 DRIE Waveguides

- Nearly vertical walls with slightly curved bottom
- Excellent cross section dimensional control
- Initial surface roughness reasonable, can be improved with slower etching and oxidation smoothing
- CST analysis shows excellent return loss with expected misalignment
Flange Alignment & Assembly

The University of Michigan — SSEL

GaAs Etched Chemistry Development

- New effort this year to micromachining GaAs structures
- Etching chemistry and masking requirements from silicon
- Initial results good for W band multiplier chips
- Additional optimization needed for thinned chips and substrateless waveguide transitions

The University of Michigan — SSEL
Project Summary

- Experimental micromachining technology developed for silicon
- Waveguide, probes, transitions and flanges developed and tested in W band
- Excellent experimental results in W band
- Nearly finished with corresponding GaAs process technology
- Technology demo with complete W band multiplier
- Ongoing efforts to use technology up to 325 GHz