High performance solar-blind AlGaN photodetectors

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NANOTAM Ozbay Group

• Research Associates
  – Dr. Gonca Ozkan (2005)

• Graduate Students
  – Koray Aydin (2002)
  – Irfan Bulu (2001)
  – Bora Alici (2004)
  – Bayram Butun (2001)
  – Turgut Tut (2001)
  – Atilla Ozgur Cakmak (2005)

• Research Engineers
  – Deniz Caliskan (2005)
  – Murat Erdogmus (2005)

• 2000-2005
  – ~70 SCI papers
  – ~45 invited international conference talks
  – ~1,100 SCI citations
NANOLab Building
New NanoLab Building

- 900 meter square
- 250 meter square clean rooms (class 10,000 and class 100)
- MOCVD lab
- 150 meter square nanoelectronics and nanophotonics laboratories
- 9 office rooms
- Conference room
- Completed during Jan-July 2004
Bilkent’s New GaN MOCVD System
Aixtron 200/4 RF-S
Device Fabrication

- Nanotechnology Research Center
  - Class 100 clean-room
  - Standard semiconductor process facilities
    - Photolithography
    - Thermal evaporator (metallization)
    - RF sputtering (thin film deposition)
    - Reactive ion etch (RIE) facility (dry etching of AlGaN layers)
    - Rapid thermal annealing (RTA) facility
    - Plasma-enhanced CVD (Dielectric material deposition)
    - Characterization: Profilometer, ellipsometer, SEM
AlGaN technology Photonics Applications

- Informatics
  - BluRay technology
  - 100 GByte DVD
  - Lightning
  - Traffic Lights
  - Biomedical
  - Automotive Industry
  - Cellular Phones

![Graph showing GaN sales over years with a note: 2010 > $5 B Market.](image)

Data Source: Strategies Unlimited 1997
Bilkent’s Blue LED from the MOCVD System
Bilkent’s Blue LED from the MOCVD System
**High Power AlGan/GaN HEMTs**

- **GaN**
  - Wide $E_g$
  - High $v_s$
  - High $V_{br}$
  - High $I_{max}$
  - High $n_s$
  - Low $R_{on}$ (low $V_{knee}$)
  - High Power Level
  - High Frequency ($f_t$)
  - High Efficiency (PAE)
  - High Operating Temp

**Why GaN Transistor?**
- High Outputpower
- Cellular communication
- Wireless Area Networks (WiMax)
- Satellite and radar systems
- Military Applications
- Analog RF systems
AlGaN/ GaN high power transistors
Collaborators

- **Iowa State University**
  - Costas Soukoulis
  - R. Moussa
  - Gary Tuttle
  - Thomas Koschny
  - Peter Markos

- **Boston University**
  - Selim Unlu

- **Massachusetts Institute of Technology**
  - Yoel Fink
  - Mehmet Bayindir

- **Aachen Technical University (Germany)**
  - Prof. Dr. Rolf H. Jansen
  - Prof. Dr. Michael Heuken

- **Instituto de Microelectronica de Madrid**
  - Pablo Aitor Postigo

- **Institute of Electronic Materials (ITME) Poland**
  - Wlodek Strupinski

- **FORTH (Crete, Greece)**
  - Costas Soukoulis
  - Maria Kafesaki
  - Nikos Katsarakis

- **Bilkent University**
  - Orhan Aytur
Introduction
Atmosphere & Solar UV Radiation

Most important UV source: Sun
Our UV shield: **Ozone layer** in atmosphere
- Strongly absorbs UV radiation with $\lambda < 280$ nm
- No UV ($\lambda < 280$ nm) radiation within the atmosphere

$\lambda < 280$ nm: **Solar-Blind** spectrum
Introduction
UV Detector Applications

- UV detectors
  - Fire alarms (flame detection)
  - Combustion and engine monitoring systems,
  - Environmental (ozone layer) monitoring
  - Detection of biological and chemical agents
  - Missile plume detection and early threat warning systems
  - Secure inter-satellite communications
  - Underwater/sub-marine communication systems

- Need for high-performance UV photodetectors!
Motivation
UV Detector Technologies

- Photomultiplier Tube (PMT)
  - High gain (>10^6)
  - Low noise, high detectivity
  - Expensive
  - Bulky, Physically fragile
  - High operation voltage (> 1 kV)
  - Susceptible to magnetic fields
  - Not solar-blind (need expensive/complex filter)

- Silicon (Si) based UV photodetector
  - Mature Si technology
  - Small-size, Low-cost
  - Device aging (subject to >> bandgap energy radiation)
  - Not solar-blind (need expensive/complex UV filter)

- Semiconductor-based intrinsic solar-blind detectors?
  - Wide Bandgap Semiconductors:
  - Diamond, Si, SiC, II-VI (ZnS, ZnSe), and III-Nitrides (Al_xGa_{1-x}N)
Motivation

Alternative Technology: Wide Bandgap Al$_x$Ga$_{1-x}$N

- Al$_x$Ga$_{1-x}$N (Wide bandgap III-V semiconductor)
  - Wide bandgap material ($>3.4$ eV)
  - Direct bandgap material
  - Efficient UV detection
  - Extremely low dark current (low thermal generation)
  - Bandgap engineering: heterostructures
  - Tunable cut-off: $360 \rightarrow 200$ nm as $x: 0 \rightarrow 1$
  - Intrinsic solar-blind for $x>0.38$
  - Can operate under high-power/temperature conditions
  - High-power/high-frequency electronics
- Lack of native substrate
- Material quality: high defect density
- Difficulty of high-quality p-type doping/contacts
- So far no good APD results (until our work)
Motivation

Why $\text{Al}_x\text{Ga}_{1-x}\text{N}$ UV Photodetectors?

- If properly constructed, $\text{Al}_x\text{Ga}_{1-x}\text{N}$-based photodetectors could offer significant advantages over PMT detectors in terms of:
  - Size
  - Cost
  - Robustness
  - Complexity
  - Dark current
  - Bandwidth
  - Solar-blind operation.

**Motivation:** Using the superior material properties of $\text{Al}_x\text{Ga}_{1-x}\text{N}$ material, design and fabricate high-performance UV photodetectors for visible/solar-blind applications.
Al_{0.38}Ga_{0.62}N/GaN Schottky Photodiode

- Designed for true **solar-blind** response (<280 nm)
- Al_{0.38}Ga_{0.62}N active layer
- GaN ohmic layer
- 0.2 µm thick Al_{0.38}Ga_{0.62}N diffusion barrier layer
- Sapphire substrate

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>n− Al_{0.38}Ga_{0.62}N</td>
<td>0.8 µm</td>
<td></td>
</tr>
<tr>
<td>n+ Al_{0.38}Ga_{0.62}N</td>
<td>0.2 µm</td>
<td></td>
</tr>
<tr>
<td>n+ GaN</td>
<td>0.6 µm</td>
<td></td>
</tr>
<tr>
<td>u.i.d GaN</td>
<td>0.5 µm</td>
<td></td>
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<tr>
<td>AlN nucleation layer</td>
<td></td>
<td></td>
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<tr>
<td>Sapphire Substrate</td>
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**Al$_{0.45}$Ga$_{0.55}$N/GaN p-i-n Photodiode**

- **Solar-blind** operation
- Al$_{0.45}$Ga$_{0.55}$N active (i) layer
- p+ ohmic layer: $>10^{17}$cm$^{-3}$

GaN/Al$_{0.45}$Ga$_{0.55}$N

- n+ ohmic layer: GaN
- p-type grading layer
- Sapphire substrate

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Material</th>
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<tbody>
<tr>
<td>30 nm</td>
<td>p+ GaN</td>
<td></td>
</tr>
<tr>
<td>15 nm grading (45%→0%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 nm</td>
<td>p+ Al$<em>{0.45}$Ga$</em>{0.55}$N</td>
<td></td>
</tr>
<tr>
<td>100 nm</td>
<td>i – Al$<em>{0.45}$Ga$</em>{0.55}$N</td>
<td></td>
</tr>
<tr>
<td>250 nm</td>
<td>n+ GaN</td>
<td></td>
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<tr>
<td>AlN Nucleation Layer</td>
<td></td>
<td></td>
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<tr>
<td>Sapphire Substrate</td>
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Al_{0.6}Ga_{0.4}N MSM Photodiode

- **Solar-blind** response
- Al_{0.6}Ga_{0.4}N active layer
- Low cut-off (<230 nm)
- Sapphire substrate (double-side polished)

```
~2 \mu m    u.i.d.    Al_{0.75}Ga_{0.25}N
```

```
AlN nucleation layer
```

```
Sapphire Substrate
```
Wafer Growth

- Metal-Organic-Chemical-Vapor-Deposition (MOCVD)
- High growth temperature: > 1000 °C
- Sapphire used as substrate material
- Started with thin AlN buffer layers
Fabrication Process

- Microwave compatible fabrication process
- 5-level process for Schottky and p-i-n devices
- 3-level process for MSM photodiode samples
- Different mask sets
- Device areas: 30–200 µm diameter
- Interdigitated fingers: 2–20 µm width/spacing
5. Interconnect metallization

- Thick (>0.8 µm) Ti/Au metal deposition & lift-off
- Microwave metal pads for on wafer measurements
Completed AlGaN Schottky Photodiodes (II)
AlGaN p-i-n Photodiode Fabrication

- Instead of Schottky $\Rightarrow$ p+ contact formation
- Annealed Ni/Au alloy for p-type ohmic contact
- Ring-geometry for high responsivity performance
AlGaN MSM Photodiode Fabrication

- Interdigitated Ti/Au Schottky (finger) metallization
- Surface passivation
- Interconnect metallization
**Device Characterization**

1 Spectral Transmission

- Fiber-optic based measurement setup
- Deuterium-tungsten light-source (200-850 nm)
- Reference: Air-transmission
- GPIB controlled measurement
Device Characterization

2. Current-Voltage

a) Hewlitt-Packard (HP) 4142B Modular DC Source/Monitor
   - Minimum detectable current > 100 fA
b) Keithley 6517A Electrometer/High-Resistance Meter
   - Measurement noise ~ 2 fA

- Probe-station and Low-noise triax probes/cabling
3. Spectral Photoresponse

- 175 W Xe UV-VIS light source
- Multimode UV-fiber
- Photocurrent recorded with Lock-in Amplifier
- Measurement range: 250-400 nm
Device Characterization

4. High-speed pulse response @ 267 nm

- 800 nm $\Rightarrow$ SHG+SFG $\Rightarrow$ UV pulses @ 267 nm
- 2 nonlinear BBO crystals utilized
- UV beam directed/focused onto samples via UV-grade mirrors and lenses
Device Characterization

5. Low-frequency Noise

- SR785 Dynamic Signal (FFT) Analyzer
- Measurement spectrum: 1 Hz – 100 KHz
- Noise floor: $3 \times 10^{-29} \text{ A}^2/\text{Hz}$ at 10 KHz
Results

$Al_{0.38}Ga_{0.62}N$ Schottky PD: I-V

- Dark current $< 3 \text{ fA} @ 12 \text{ V}$ reverse bias (setup limited)
- Dark current density: $4.2 \times 10^{-10} \text{ A/cm}^2 @ -12 \text{ V}$
- Breakdown voltage $> 50 \text{ V}$
Results

Al_{0.38}Ga_{0.62}N Schottky PD: Photoresponse

- **Au-Schottky sample**
  - Efficiency: 42% @ 267 nm, 50 V reverse bias
  - Responsivity: 89 mA/W @ 267 nm
  - Cut-off @ 274 nm, UV/VIS ~2x10^4 (True solar-blind)
Results

Al$_{0.38}$Ga$_{0.62}$N Schottky PD: Detectivity Analysis

- Background radiation ≪ Thermal noise in SB region
- Thermally limited detectivity: $D^* = R_0 \sqrt{\frac{R_0 A}{4kT}}$
- $R_0$ determined with curve fitting method: $R_0 = 4.01 \times 10^{17}$ Ω
- $D^* = 1.28 \times 10^{14}$ cmHz$^{1/2}$W$^{-1}$ at 250 nm
Results

$\text{Al}_{0.38}\text{Ga}_{0.62}\text{N}$ Schottky PD: High-speed

- **Bias dependence**
  - FWHM: 80 ps $\to$ 53 ps as $V_{\text{bias}}$: 5 V $\to$ 25 V
  - @ -25 V: Rise-time: 26 ps, Fall-time: 117 ps
  - 3-dB bandwidth: 4.1 GHz @ -25 V
Results

Al$_{0.38}$Ga$_{0.62}$N Schottky PD: Noise

- Good devices with low dark current: noise $\ll$ setup noise floor
- Several devices with high leakage measured
- $1/f$ characteristic at low frequencies
- Noise proportional to bias voltage

![Graph showing noise power density vs. frequency and bias voltage](image)
Results

Al_{0.45}Ga_{0.55}N p-i-n PD: I-V

- Leakage decreases after removal of GaN cap layer
- Dark current < 3 fA @ 6 V reverse bias
- Dark current density: $3.0 \times 10^{-11}$ A/cm² @ -6 V
- Breakdown voltage > 40 V
Results

Al$_{0.45}$Ga$_{0.55}$N p-i-n PD: Spectral Photoresponse

- Increases with reverse bias
- Max. QE=43% @ 271 nm (R=95 mA/W)
- Higher response after recess etch of p+ GaN cap layer:
  - QE=53% @ 261 nm, R=111 mA/W
  - Cut-off ~ 283 nm, UV/VIS ~ 10$^4$ (True solar-blind)
Results

Al$_{0.45}$Ga$_{0.55}$N p-i-n PD: Detectivity Analysis

- $R_0 = 9.52 \times 10^{15}$ Ω
- Thermally limited detectivity: $D' = 4.9 \times 10^{14}$ cmHz$^{1/2}$W$^{-1}$ at 267 nm
- PMT-comparable detectivity performance
Results

**Al\textsubscript{0.45}Ga\textsubscript{0.55}N p-i-n PD: High-Speed**

- Faster pulse response with reverse bias
- Faster response after recess etch
  - FWHM: 384 ps → 70 ps
  - 3-dB bandwidth: 160 MHz → 1.65 GHz

Before recess etch

After recess etch
Results
Al$_{0.75}$Ga$_{0.25}$N MSM PD: Spectral Transmission

- Double-side polished wafer
- Absorption edge (cut-off) @ $\sim$230 nm
Results

Al$_{0.75}$Ga$_{0.25}$N MSM PD: I-V

Low dark current at very high voltages:
- < 10 fA @ 100 V
- < 300 fA @ 150 V
- < 100 pA @ 350 V

Very high breakdown voltage:
> 300 V
Results

$\text{Al}_{0.6}\text{Ga}_{0.4}\text{N MSM PD: Spectral Photoresponse}$

- Photoconductive gain observed (low efficiency @ 0 bias)
- 250% efficiency @ 222 nm ($R=0.53$ A/W) under 50 V bias
- Cut-off @ 255 nm, UV/VIS $\sim 10^7$ (True solar-blind)
Recent Results: AlGaN Avalanche PDs
Gain Measurements of AlGaN Avalanche PDs
Photo Response of AlGaN Avalanche PDs

[Graphs showing quantum efficiency and responsivity as functions of wavelength for different voltages.]
Conclusion

Summary

- Designed, fabricated and tested high-performance UV Al$_x$Ga$_{1-x}$N photodetectors
- Solar-blind operation with Al$_x$Ga$_{1-x}$N($x>0.38$) layers
- High device performance
  - Low dark current
  - High breakdown voltage
  - High responsivity
  - High detectivity
  - Fast pulse response (high bandwidth)
  - Low noise
Conclusion
Achievements/Contributions

- **Solar-Blind Spectrum ($\text{Al}_x\text{Ga}_{1-x}\text{N}$):**
  - Record low dark current (density) (Schottky and p-i-n)
  - Record detectivity performance (p-i-n and Schottky)
  - Record bandwidth performance (Schottky, p-i-n, and MSM)
  - First Avalanche Photodetector Results
Conclusion
Publications

Acknowledgements

- FP5 EU-DALHM (Development and Analysis of Left Handed Metamaterials) 2002-2006
- FP6, EU-METAMORPHPOSE (MetaMaterials ORganized for radio, millimeter wave, and PHOtonic Superlattice Engineering) NoE, 2004-2008
- FP6, EU-PHOREMOST(Nanophotonics to realize Molecular-Scale Technologies) NoE, 2004-2008
- TUBITAK (GaN Based Light Sources for Informatics, Optoelectronics, and Nanophotonics Applications) (2005-2008)
- Turkish Defense Department (MSB ArGe) (2004-2007)
- ASELSAN and SSM (2004-2008)
Conclusion

Future Research Directions

- High-density $\text{Al}_x\text{Ga}_{1-x}\text{N}$ focal plane arrays (FPAs) for UV imaging applications
- $\text{Al}_x\text{Ga}_{1-x}\text{N}$-based avalanche photodiodes (APDs)
  - Higher detectivity $\Rightarrow$ replacing bulky/cooled PMT?
- $\text{Al}_x\text{Ga}_{1-x}\text{N}$-based phototransistors
- Alternative substrates (Si, SiC, native GaN)