Rapid, non-destructive detection of defects in Thick-GaN bulk

Contract Number: 35488
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Project Period: FY2020

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Topic: Wide Bandgap Semiconductors for Power Electronics
Subtopic: Wide-Bandgap Power Electronics Substrates & Processing

U.S. DOE Advanced Manufacturing Office Virtual Program Review Meeting
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Rapid, GaN defect Non-Destructive Evaluation (*GaNDE*)

GaNDE Project Overview

Timeline

GaNDE award issued July 2019
Projected end date June 2022
Project 30% complete (TRL2/3-TRL6)
COVID19 delays expected

Budget

	FY19 Actual Costs	FY20 Actual Costs (4/30/20)	F21 Planned Costs	Total Planned Funding (FY22 Project End Date)
DOE Funded	$202K	$647K	$1,314K	$3,960K

Barriers

- *Key barrier to harness GaN wide bandgap semiconductor outstanding properties for increasing **power electronics** energy **efficiency**, **reliability**, **performance** is availability of **low cost**, **low defect GaN** substrates.*
- *"True bulk" GaN growth and GaN fabrication require **metrology tools validated** (in this project) **at the device-level** to inform improvements in the manufacturing process of power electronics.*

Partners

- ***Academic***: Ohio State University (OSU, OH) and Georgia Tech (GT, GA) – **device fab./epi**
- ***Industry***: SixPoint Materials, Inc., CA and Nexgen (CRADA),CA/NY. **GaN growth, fab.**
- ***GaNDE (LLNL lead)*** engaged in **Research and Development of novel industrial metrology tools** for next gen. semiconductors, GaN growth & devices, involving 4 faculty, 5 PhD students, 2 US startups, 6 *LLNL* Nat. Lab scientists, engineers supports **PowerAmerica mission**

GaNDE is meeting Consortia Objective as it supports efficient US manufacturing of high energy efficiency GaN based power devices

Problem: *broad deployment of high efficiency, high performance GaN-based power electronics is limited by availability of low defects, low cost wide bandgap (WBG) GaN semiconductor substrates & GaN growth seeds*

- ***Solution:*** *We are developing, testing, and validating new multi-modal optical metrology approaches for wafer-level detection of device-relevant defects in GaN*
- ***Impact:*** *New metrology will inform improvements manufacturing costs, device reliability, and performance of next generation power electronic devices* ***beyond Silicon technology***

GaNDE Alignment with AMO mission, goals, and multi-year planning*

- Seeks technological competitive advantage for US semiconductor and device manufacturers
- Collaborative effort 1 National Lab (LLNL), 2 industry (1 CRADA) and 2 academic institutions
- Supports workforce development: 5 new PhD students and 1 new hire National Lab engineer
- Can harness **WBG semiconductors** grown **with low defects** from **bulk GaN substrates**
- Can **improve device reliability** by detecting sparse device-relevant "killer-defects"
- Can impact **2/3 of overall manufacturing costs** of power electronics
- Can **reduce inefficiencies** in manufacturing at bulk growth and device fabrication stages

*Supports ***PowerAmerica*** *goals & planning*: Next Generation Power Electronics National Manufacturing Innovation Institute

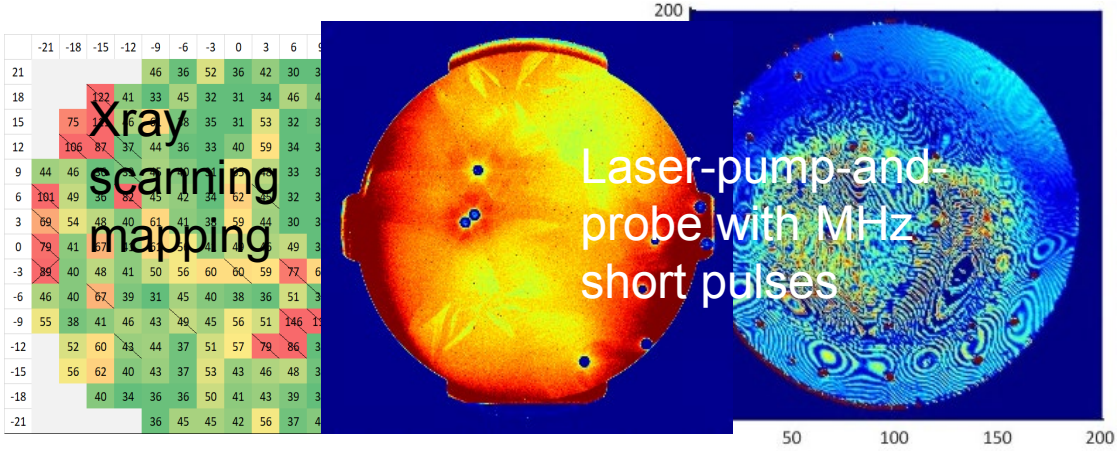
We propose a novel approach for highly integrated GaN defect detection with multiple-imaging validated at device level

State of the Art GaN defect detection

- ***Can be slow (e.g. Xray, AFM, SEM wafer/day), low resolution (mm) & sensitivity, mostly surface***
- ***Possibly detects non-relevant GaN defects***
- ***Low specificity from low level of detection modalities and lack of validation data***
- ***Most sensitive are destructive evaluation (e.g. etching, sections)***

Proposed defect detection in GaN (*GaNDE*)

- ***Rapid 3D, Non-Destructive Evaluation (10's wafers/hr)***
- ***Wafer-level detection sub-µm defects, ppm levels at µm's resolution***
- ***Yields device-relevant defects***
- ***High levels of integrated detection modalities to derive true signatures of "killer defects"***
- ***device-level validation data***



A rapid, reliable tool for defect detection in GaN will inform bulk growth conditions optimization, and downstream device fabrication eliminating wasted processing and improving reliability, which reduces manufacturing costs

GaN defect signatures are mapped throughout power electronic device production cycle to validate metrology approach at device level

vendors

HVPE GaN seed 2”

HVPE GaN substrate (industry reference)

SixPoint

bulk “NEAT” GaN Ammonothermal bulk growth

growth

SixPoint

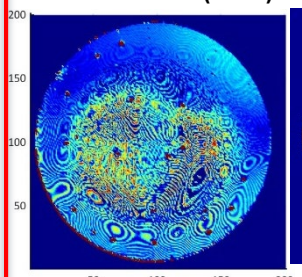
slicing and polish Substrates (2”)

substrate

multimodal metrology

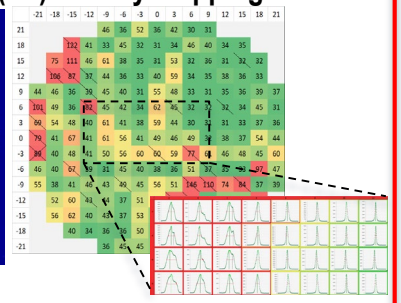
LLNL

Photothermal (PTM) Photoluminescence (PL)



SixPoint

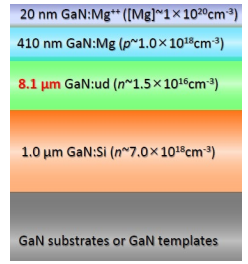
X-ray mapping



device growth

OSU/GT

epi-growth

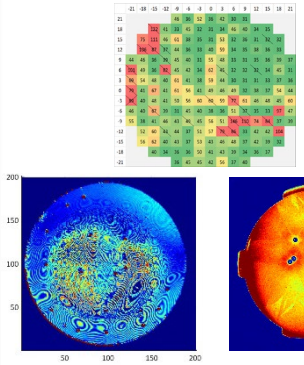


On wafer testing:

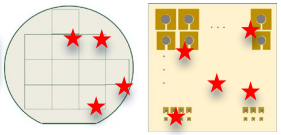
- I-V, I-C
- Characterization

metrology

LLNL / SixPoint



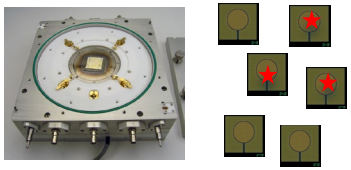
OSU/GT/Nexgen



pn diode (1.2kV)
Device fab & packaging

★ Detection device-relevant defects

LLNL

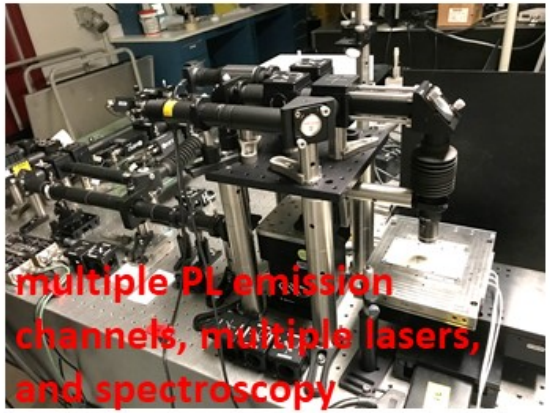


- Accelerated lifetime
- forensics
- Microscopy
- Validation & science

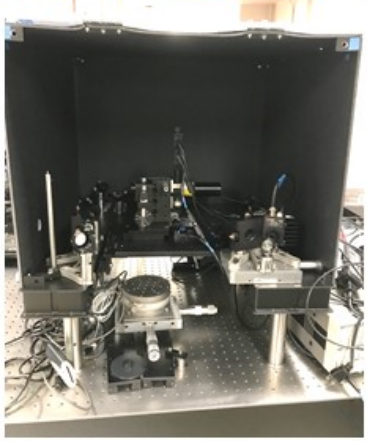
- SixPoint Materials, unique US industry expertise in commercial scale ammonothermal bulk GaN growth
- LLNL, decades experience in extreme high-power laser materials defect mitigation and analysis
- OSU and GT, world class faculty, facilities, depth in development of semiconductor materials, power devices

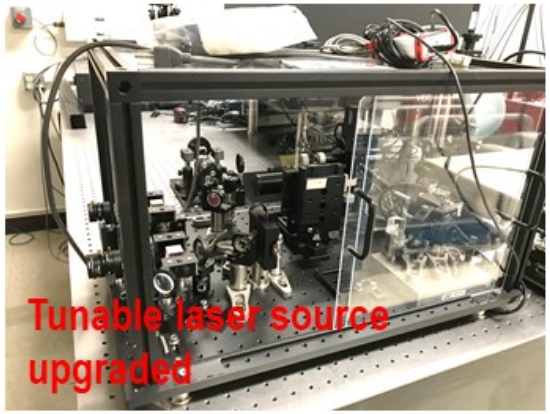
We developed mostly in-house LLNL detection of GaN defects across multiple imaging modalities forming a signature when registered to device data

Photoluminescence (PL) setup 1

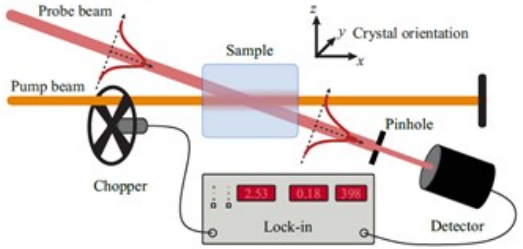


Photothermal (PTM) setup 1





PhotoThermal laser pump-probe scheme



Signal modality	GaN signature relevant defects
PL intensity	✓
PL spectra	✓
PL lifetime	✓
PL backscatter	✓
PTM intensity	✓

Excited defects with sub-band gap light relax by radiative and non-radiative transitions that are mapped by a combination of high rep-rate, short pulse laser sources and spectroscopy scanned across industry-relevant wafers up to 4-inch diameter

Transition of *GaNDE* technology to industry includes multiple pathways, from licensing, to startup, to continued maturation

- Startup route (TRL>6):
  - Project PI completed UC Davis National Labs entrepreneurship program (FY19)
  - PI to submit Department of Energy's Energy I-Corps Full Team *GaNDE* Proposal for next Cohort with in-depth customers validation (FY20)
  - Small Business Innovation Research (SBIR) program/prototyping (FY22)

- Technology maturation route (TRL6 – TRL8):
  - CRADA with US industry and partners (FY22)
  - Use-case demonstration on commercially viable devices (Nexgen FY20)
  - Demonstration built-in project from 2 independent universities fabs

- Licensing to US industry (TRL6 –TRL9)
  - Spin-off SixPoint Materials (project partner/LLNL PI entrepreneurial leave)
  - KLA-Tencor, or others….

Management approach: includes quarterly reviews milestones, tasks, peer-reviewed publications, monthly multi-institutional remote conferences, joint sessions

Major tasks and milestones (36 months project)

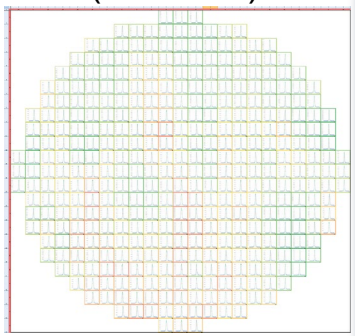
Tasks	Description	Milestones	Description	status
FY2020*				
High power GaN diode devices development	Develop 1.2kV diode test platform @100A/cm²	Device test platforms with GaN intrinsic failures only	Device GaN failure modes only, no artifact >1.2kV	COVID DELAYED ECD FY20
Baseline multi-modal *GaNDE* metrology development	Develop basic components of GaN imaging systems PL/PTM	Integrated GaNDE measurements with device and Xray data	mm resolution, 1 wafer/hr, predicts device failures	DELAYED PENDING COVID
Accelerated power devices lifetime tests development	implement multichannel device lifetime testing	Working testbed for devices accelerated testing	Fast, hi temperature bias, operational lifetime testing	DELAYED PENDING COVID
FY2021				
Growth of low defect bulk GaN	Grow low oxygen, dislocations bulk GaN	Low defects bulk GaN wafers	10^{18} O/cm²; $<10^4$/cm² dislocations	On track
Develop sped-up multimodal GaN imaging	Develop more integrated, faster *GaNDE* detection	Faster, higher resolution *GaNDE* defect detection	sub-mm, 1-10 wafers/hr, predicts device failure	On track
FY2022				
GaNDE full demonstration on low defects with miscut angles substrates	Fast GaNDE tested at device-level for multiple GaN propagated defects	Validated and integrated *GaNDE* with actionable detection of device-relevant defects	GaN defect imaging predicts with high level confidence device reliability from signature	On track

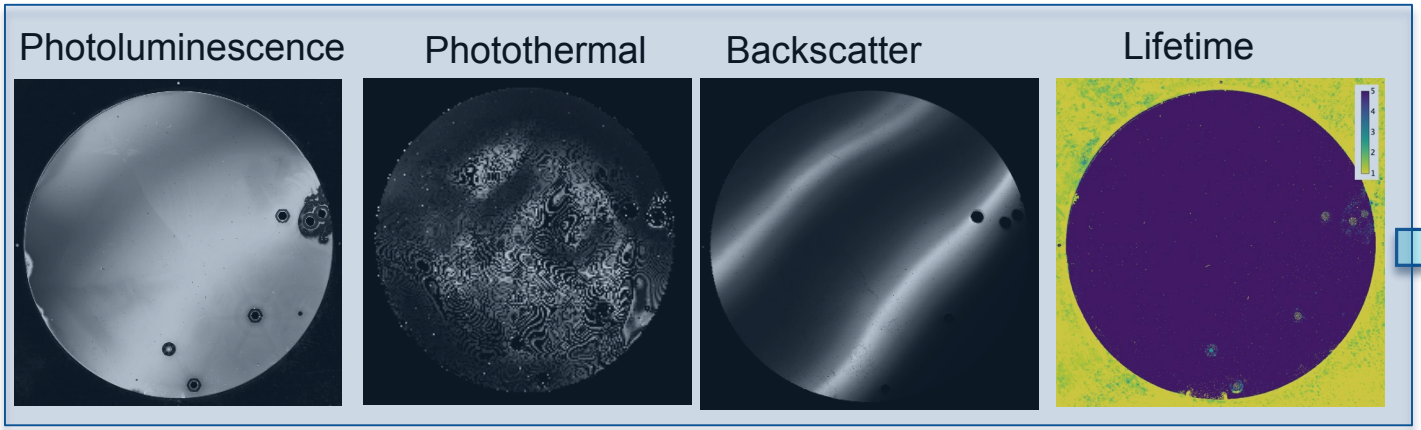
*New staff hire at LLNL, 5 new graduate students at GT and OSU, identifying GT/OSU students for LLNL summer internships. Project is fully staffed.

Detection of device-relevant defects will begin validation using power diodes test devices accelerated lifetime testing (Q3, Q4 FY20)

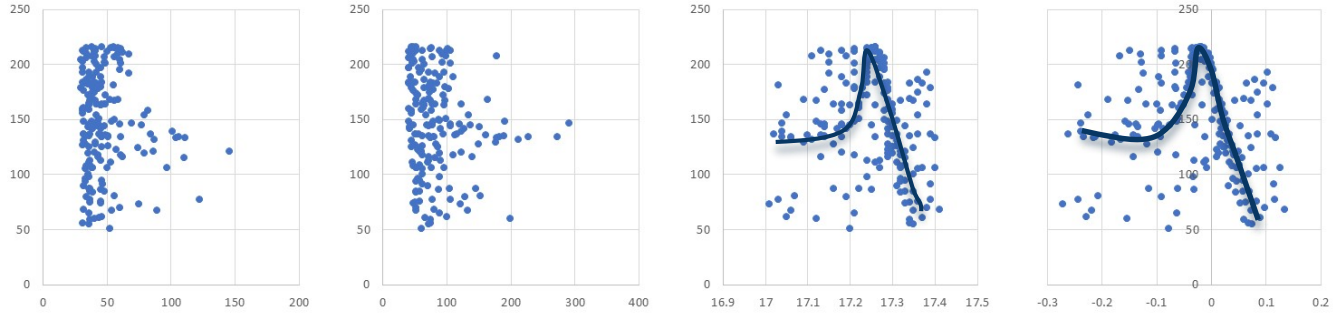
Illustration of some *GaNDE* wafer-level imaging modalities

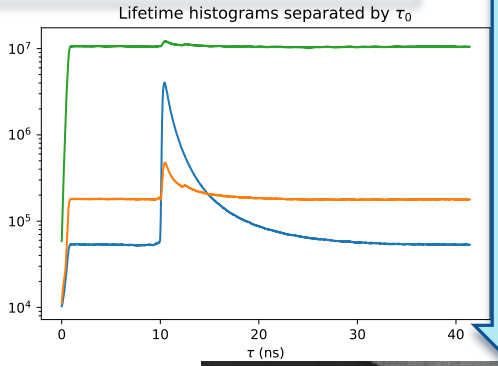
Xray mapping (standard)



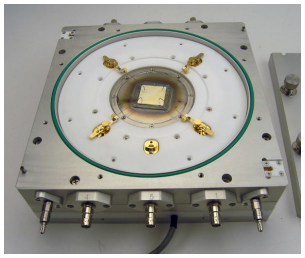


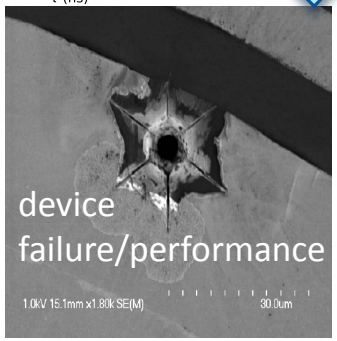
Photoluminescence intensity versus Xray mapping data:





- We have completed bulk GaN growth cycles (2) and wafer preparation
- *Seed, substrate growth,* and *post* epi-wafer growth were fully scanned for first batch of devices prep.
- First analysis of *GaNDE* detection pending fabricated devices availability for accelerated lifetime testing (right)
- COVID delay device fabrication to register *GaNDE* data to device data





Measure of Success For *GaNDE*

SUCCESS

- *GaNDE* validation: detecting defect signature that predict > 90% of diode power devices GaN failures, up to 10 wafers/hour, at μm resolution and ppm defect detection levels in a commercially viable package
- *GaNDE* tracks defects propagating throughout device manufacturing

KEY CHALLENGES

- *GaNDE* generates gigabytes of multidimensional wafer-datasets that need to be spatially registered with μm precision and analyzed with computationally intensive tools (opportunity for Machine Learning)
- Attribution of defects causing device failures requires labor intensive *post-mortem* microscopy and spectroscopy for peer-review publications
- Designing devices with intrinsic GaN failure modes without artifacts
- Low defect bulk GaN growth remains a challenge we expect *GaNDE* to help by providing timely, and relevant feedback on growth conditions