



Status of Structural Analysis of Substrates and Film Growth Inputs for GaN Device Development Program

by Kevin Kirchner

ARL-TR-5427

January 2011

Approved for public release; distribution unlimited.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory

Adelphi, MD 20783-1197

January 2011

Status of Structural Analysis of Substrates and Film Growth Inputs for GaN Device Development Program

Kevin Kirchner Sensors and Electron Devices Directorate, ARL

Approved for public release; distribution unlimited.

Index constructions and		REPORT DO	CUMENTATI	ON PAGE		Form Approved OMB No. 0704-0188
1. REPORT DATE (DP-MM-YVYY) 2. REPORT TYPE 3. DATES COVERED (From - To) January 2011 Interim 5. CONTRACT NUMBER Status of Structural Analysis of Substrates and Film Growth Inputs for GaN 5e. CRART NUMBER Status of Structural Analysis of Substrates and Film Growth Inputs for GaN 5e. CRART NUMBER Status of Structural Analysis of Substrates and Film Growth Inputs for GaN 5e. CRART NUMBER 6. AUTHOR(S) 5d. PROGRAM ELEMENT NUMBER Kevin Kirchner 5e. TASK NUMBER 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION RAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTI: RDRL:SED-E 2800 Powder Mill Road Adelphi, MD 20783-1197 5. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 13. SUPPLEMENTARY NOTES 11. SPONSOR/MONITOR'S ACRONYM(S) 14. ASTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and S* semis for cach quadrant of the 18 wafers. Data comparisons made include the figures of marti (FOM) for GaN semis for cach quadrant of the 18 wafers. Data comparisons made include the figures of marti (FOM) for GaN states compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs comfared vit	Public reporting burden data needed, and comple burden, to Department o Respondents should be a valid OMB control numb PLEASE DO NOT	for this collection of informat tring and reviewing the collect of Defense, Washington Headd aware that notwithstanding ar ber. RETURN YOUR FORM	ion is estimated to average 1 ho tion information. Send commer quarters Services, Directorate fo ny other provision of law, no pe 1 TO THE ABOVE ADD	ur per response, including th tts regarding this burden esti r Information Operations ar erson shall be subject to any RESS.	he time for reviewing i imate or any other aspe- d Reports (0704-0188 penalty for failing to	instructions, searching existing data sources, gathering and maintaining the ect of this collection of information, including suggestions for reducing the s), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, comply with a collection of information if it does not display a currently
January 2011 Interim 4. TTLE AND SUBTILE Sa. CONTRACT NUMBER Status of Structural Analysis of Substrates and Film Growth Inputs for GaN Sb. CANT NUMBER Device Development Program Sb. GRANT NUMBER 6. AUTHOR(\$) Sb. GRANT NUMBER Kevin Kirchner Sc. TASK NUMBER 9. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) Sc. TASK NUMBER 9. Status of Structural Analysis of Substrates and Pilm Growth Inputs Sc. TASK NUMBER 9. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) Sc. TASK NUMBER 9. Structural Analysis of Substrates and Pilm Growth Inputs Sc. TASK NUMBER 9. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) Sc. TASK NUMBER 9. STRUCTURAL SUBJECT Sc. TASK NUMBER 9. SPONSORINONIORING AGENCY NAME(\$) AND ADDRESS(E\$) Sc. TASK NUMBER 9. SPONSORINONIORITING AGENCY NAME(\$) AND ADDRESS(E\$) 10. SPONSORINONIOR'S ACRONYM(\$) 11. SPONSORINONIOR'S REPORT NUMBER(\$) 12. DISTRIBUTIONIAVARIABILITY STATEMENT ARL-TR-5427 Approved for public release; distribution unlimited. 11. SPONSORINONITOR'S REPORT 13. SUPPLEMENTARY NOTES 11. SPONSORINONITOR'S REPORT 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis o	1. REPORT DATE	(DD-MM-YYYY)	2. REPORT TYPE			3. DATES COVERED (From - To)
4. TITLE AND SUBTITLE Sa. CONTRACT NUMBER Status of Structural Analysis of Substrates and Film Growth Inputs for GaN Sa. CONTRACT NUMBER 6. AUTHOR(5) Sc. GRANT NUMBER 6. AUTHOR(6) Sd. PROJECT NUMBER 7. PERFORMING ORGANIZATION NAME(5) AND ADDRESS(ES) Sd. PROJECT NUMBER 9. VORK UNIT NUMBER Sd. PROJECT NUMBER 7. PERFORMING ORGANIZATION NAME(5) AND ADDRESS(ES) Se. TASK NUMBER 2800 Powder Mill Road Addelphi, ND 20783-1197 7. SPONSORING/MONITORING AGENCY NAME(5) AND ADDRESS(ES) II. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(5) 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT 14. ABSTRACT Sea Cond Science and quadrant of the 18 wafers. Data comparisons made include the figures of mareit (FOM) for GaN substrates congrad with those of GaN films grown on the substrates, and the bomoepitaxial GAN film with the development of novel faw substrates. The manalysis produced the best FOMs for GaN for our lab to date: 39'' (are seconds) symmetric and 58'' asymmetric. The good homoepitaxial GAN film quality was shown to be substrate for any lab trate. Seconds yammetric and systematic and 58'' asymmetric. The good homoepitaxial GAN film quality was shown to be substrate for GaN for our lab to date: 39'' (are seconds) symmetric and 58'' asymmetric. The good homoepitaxial GAN film quality was 3 to 8 titmes bet	January 2011		Interim			
Status of Structural Analysis of Substrates and Film Growth Inputs for GaN Device Development Program 5GRANT NUMBER 5PROGRAM ELEMENT NUMBER 5TSK NUMER 5TSK NUMBER 5TSK NU	4. TITLE AND SUE	BTITLE				5a. CONTRACT NUMBER
Device Development Program	Status of Struc	tural Analysis of S	Substrates and Film	Growth Inputs f	or GaN	
E. AUTHOR(6) Sc. PROGRAM ELEMENT NUMBER Kevin Kirchner Sd. PROJECT NUMBER Se. TASK NUMBER Sd. PROJECT NUMBER U.S. Army Research Laboratory St. MORK UNIT NUMBER ATTN: RDRL-SED-E ARL-TR-5427 2800 Powder Mill Road Artl-TR-5427 Adelphi, IND 20783-1197 In. SPONSORING/MONITORING AGENCY NAME(5) AND ADDRESS(ES) S. SPONSORING/MONITORING AGENCY NAME(5) AND ADDRESS(ES) Io. SPONSOR/MONITOR'S ACRONYM(5) 11. SPONSOR/MONITORING AGENCY NAME(5) AND ADDRESS(ES) Io. SPONSOR/MONITOR'S ACRONYM(5) 13. SUPPLEMENTARY NOTES 11. SPONSOR/MONITOR'S REPORT NUMBER(5) 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric and films grown on the substrates, and the homoepitaxial GaN films 'FOMs compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial GAN film guality was -34 to 58 times better than that of good heteroepitaxial films. The eanalysis produced the best FOMs for GaN for our lab to date: 39'' (arc seconds) symmetric and S8'' asymmetric. The good homoepitay was how to be suited for our experimentia needs. At a 59% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural analysis, GAN Device Program, Schottky Devic	Device Develo	pment Program			or Guilt	5b. GRANT NUMBER
6. AUTHOR(S) 5d. PROJECT NUMBER Kevin Kirchner 56. TASK NUMBER 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 56. TASK NUMBER U.S. Army Research Laboratory 51. WORK UNIT NUMBER ATTN: RDRL-SED-E 2800 Powder Mill Road Adelphi, MD 20783-1197 ARL-TR-5427 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 12. DISTRIBUTIOWAVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT 14. ABSTRACT CGAN flux grown on the substrates, and the homooptitaxial GAN flux's POMS CGAN substrates compared with those of GAN flux grown on the substrates, and the homooptitaxial GAN flux's POMS Comparisons made include the figures of merit (FOM) for GAN flux grown on the substrates, and the homooptitaxial GAN flux's POMS compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for grown GAN substrates. The microstructural quality of the water quadrants of the Hydride Vapor Phase epitaxially grown GAN substrates. The microstructural quality of the water quadrants of the Hydride Vapor Phase epitaxially grown GAN substrates. The microstructural quality of the water quadrants of the Hydride Vapor Phase epitaxially grown GAN substrates. The microstructural quality of the water quadrants of the Hydride Vapor Phase epitaxi						5c. PROGRAM ELEMENT NUMBER
Kevin Kirchner 5e. TASK NUMBER 7. PERFORMING ORGANIZATION NAME(5) AND ADDRESS(E5) 5. PERFORMING ORGANIZATION REPORT NUMBER U.S. Army Research Laboratory ATTN: RDL-SED-E 2800 Powder Mill Road ARL-TR-5427 Adelphi, MD 20783-1197 10. SPONSORMONITOR'S ACRONYM(5) 5. SPONSORINGMONITOR'S ACRONYM(5) 11. SPONSORMONITOR'S ACRONYM(5) 12. DISTRIBUTION/AVAILABILITY STATEMENT 10. SPONSORMONITOR'S REPORT Approved for public release; distribution unlimited. 11. SPONSORMONITOR'S REPORT 13. SUPPLEMENTARY NOTES 14. ABSTRACT 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric and asymmetric and fills "rOMs" compared with those of GaN fills grown on the substrates, and the homoepitaxial GaN fills "FOMs compared with those form heteroepitaxial fills. The analysis produced the best FOMs for GaN for our lab to date: 39" (are seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN fills quality was -3 to 8 times better than that of good heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the the aterial injuts as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 15. SUBJECT TEMS GaN, homoepitaxial, x-ray diffraction, micro structural an	6. AUTHOR(S)					5d. PROJECT NUMBER
5 TASK NUMBER 5 TASK NUMBER 5 TASK NUMBER 5 TASK NUMBER 5 WORK UNIT NUMBER 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION ATTN: RDR.JSED-E 2800 Powder Mill Road Adelphi, MD 20783-1197 8. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 11. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER 13. SUPLEMENTARY NOTES 14. ABSTRACT 17. Dist report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GAN films 'FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39' (arc seconds) symmetric and Sa' saymmetric. The good homoepitaxial GAN films 'FOMs confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxiall grown GAN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxial grown GAN substrates. The interostructural analysis, GaN Device Program, Schottky Devices, HEMT, film <	Kevin Kirchne	r				
Sec. TASK NUMBER 5. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) 5. WORK UNIT NUMBER U.S. Army Research Laboratory ATTN: RDRL-SED-E 2800 Powder Mill Road ARL-TR-5427 Adelphi, MD 20783-1197 4. PEPORTNOMBER 5. SPONSORING/MONITORING AGENCY NAME(\$) AND ADDRESS(E\$) 10. SPONSOR/MONITOR'S ACRONYM(\$) 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 11. SPONSOR/MONITOR'S REPORT NUMBER(\$) 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GAN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GAN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of meril (FOM) for GaN substrates compared with those of GAN films grown on the substrates, and the bonocpitaxial GAN film guality was -3 to 8 times better than that of good heteroepitaxial films. The analysis produced the best FOMs for GAN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homocpitaxial GAN film quality was -3 to 8 times better than that of good heteroepitaxial grown GAN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GAN substrates. The microstructural analysis, GAN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION CHARER PAGE 17. LIMITATION LABSTRACT 1.MISTRACT		1				
5. WORK UNIT NUMBER 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRSED-E 2800 Powder Mill Road Adelphi, MD 20783-1197 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 11. SPONSOR/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GAN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of CGAN films grown on the substrates, and the homoepitaxial GAN films 'FOMs' compared with those of CGAN films grown on the substrates, and the homoepitaxial GAN films' FOMs' confidence elbevel, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxial films. The heteroepitaxial films. The heteroepitaxial GAN film quality was shown to be suited for our experimental needs. At a 95% confidence elvel, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSFIGATION						5e. TASK NUMBER
5f. WORK UNIT NUMBER 7. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) 8. PERFORMING ORGANIZATION U.S. Army Research Laboratory REPORT NUMBER ATTN: RDRL-SED-E 2800 Powder Mill Road Adelphi, MD 20783-1197 Interpretation of the second sec						
7. PERFORMING ORGANIZATION NAME(\$) AND ADDRESS(E\$) 8. PERFORMING ORGANIZATION U.S. Army Research Laboratory REPORT NUMBER ATTN: RDRL-SED-E 2800 Powder Mill Road Adelphi, MD 20783-1197 a.RL-TR-5427 9. SPONSORING/MONITORING AGENCY NAME(\$) AND ADDRESS(E\$) 10. SPONSOR/MONITOR'S ACRONYM(\$) 11. SPONSOR/MONITOR'S ACRONYM(\$) 11. SPONSOR/MONITOR'S REPORT 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films 'FOMs compared with those of Max films. The analysis produced the best FOMs for GaN for our lab to date: 39° (arc seconds) symmetric and S8" asymmetric. The good homoepitaxial GaN film quality was -30 to 8 times better than that of good heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39° (arc seconds) symmetric and S8" asymmetric. The good homoepitaxial GAN film quality was -30 to 8 times better than that of good heteroepitaxial films. The materostructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural analysis, GAN Device Program, Schottky Devices, HEMT, film </td <td></td> <td></td> <td></td> <td></td> <td></td> <td>5f. WORK UNIT NUMBER</td>						5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) 8. PERFORMING ORGANIZATION U.S. Army Research Laboratory ATTN: RDRL-SED-E 2800 Powder Mill Road ARL-TR-5427 Adelphi, MD 20783-1197 10. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 11. SUPPLEMENTARY NOTES 11. SPONSOR/MONITOR'S REPORT 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films 'FOMs compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films 'FOMs compared with those firm heteroepitaxial GaN film quality was shown to be suited for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was -3 to 8 times better than that of good heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 49.5% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the material inputs as measured by x-ray diffraction is currently on track						
U.S. Army Research Laboratory ATTN: RDRL-SED-E 2800 Powder Mill Road ARL-TR-5427 Adelphi, MD 20783-1197 10. SPONSORINOMONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 3. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S ACRONYM(S) 12. DISTRIBUTIONAVAILABILITY STATEMENT Approved for public release; distribution unlimited. 11. SPONSOR/MONITOR'S REPORT 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GAN films 'FOMs compared with those form heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was shown to be suited for our experiment needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxiall fyms. The heteroepitaxial GAN film quality was shown to be suited for our experiment needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GAN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its	7. PERFORMING (ORGANIZATION NAM	E(S) AND ADDRESS(ES	5)		8. PERFORMING ORGANIZATION REPORT NUMBER
ATTN: KDRC-SED-E 2800 Powder Mill Road Adelphi, MD 20783-1197 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those form heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was -3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: a REPORT b ABSTRACT C THIS PAGE Unclassified Unclassified Unclassified C THIS PAGE UNC	U.S. Army Res	search Laboratory				
2000 FOWDER MIN KOAD Adelphi, MD 20783-1197 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) 10. SPONSOR/MONITOR'S REPORT NUMBER(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S) 12. DISTRIBUTIOW/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those of mometric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial GaN film quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The development of novel GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF BASTRACT c. THIS PAGE UU 36	ATTN: KDKL	-SED-E				ARL-TR-5427
9. SPONSORING/MONITORING AGENCY NAME(\$) AND ADDRESS(E\$) 10. SPONSOR/MONITOR'S ACRONYM(\$) 11. SPONSOR/MONITOR'S ACRONYM(\$) 11. SPONSOR/MONITOR'S ACRONYM(\$) 12. DISTRIBUTION/AVAILABILITY STATEMENT 11. SPONSOR/MONITOR'S REPORT Approved for public release; distribution unlimited. 11. SPONSOR/MONITOR'S REPORT 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those for bhetroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF PAGES	2800 Powder N Adelphi MD 2	00783_1107				
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those of the to show a bias between the quality was shown to be suited for our caperimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxial gan metric to play its part in the development of novel GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION UP as the structure of the structure of associated was and the structure of the structu	9 SPONSORING/		Y NAME(S) AND ADDR	ESS(ES)		10 SPONSOR/MONITOR'S ACRONYM(S)
11. SPONSOR/MONITOR'S REPORT NUMBER(S) 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner 18. REPORT b. ABSTRACT C. THIS PAGE Unclassified 19a. HAMEER (Include area code) (301) 394-0093				200(20)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (are seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 16. SEURITY CLASSIFICATION OF: 17. LIMITATION OF PAGE UU 18. NUMBER (Include area code) (301) 394-0093						11. SPONSOR/MONITOR'S REPORT
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SEURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT OF ABSTRACT Unclassified 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT Unclassified b. ABSTRACT Unclassified UU 36 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner						NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 16. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE <td></td> <td></td> <td></td> <td></td> <td></td> <td></td>						
Approved for public release; distribution unlimited. 13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT Unclassified 18. NUMBER OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE 19. 19. Number (Include area code) (301) 394-0093	12. DISTRIBUTION					
13. SUPPLEMENTARY NOTES 14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE UU 36 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner	Approved for p	public release; dist	tribution unlimited.			
14. ABSTRACT This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: a. REPORT b. ABSTRACT c. THIS PAGE UU Unclassified Unclassified		ADV NOTES				
This report covers the x-ray diffraction crystallographic analysis of semiconductor wafers involved in our team's project to produce gallium nitride (GaN) wide bandgap devices. The wafers were examined for crystal quality by symmetric and asymmetric GaN scans for each quadrant of the 18 wafers. Data comparisons made include the figures of merit (FOM) for GaN substrates compared with those of GaN films grown on the substrates, and the homoepitaxial GaN films' FOMs compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our lab to date: 39" (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices.17. LIMITATION OF ABSTRACT18. NUMBER PAGES19a. NAME OF RESPONSIBLE PERSON Kevin Kirchnera. REPORT Unclassifiedb. ABSTRACT Unclassifiedc. THIS PAGE Unclassified19b. TELEPHONE NUMBER (<i>Include area code</i>) (301) 394-0093	14 ABSTRACT	ARTNOTES				
compared with those from heteroepitaxial films. The analysis produced the best FOMs for GaN for our fab to date: 39 (arc seconds) symmetric and 58" asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices.15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film16. SECURITY CLASSIFICATION OF:17. LIMITATION OF ABSTRACT Unclassifieda. REPORT Unclassifiedb. ABSTRACT UnclassifiedC. THIS PAGE UUUU36	This report cov produce galliun asymmetric Ga GaN substrates	vers the x-ray diffi m nitride (GaN) w aN scans for each s compared with the	raction crystallographide bandgap device quadrant of the 18 hose of GaN films g	phic analysis of s es. The wafers we wafers. Data com grown on the sub	emiconductor ere examined parisons mad strates, and the	r wafers involved in our team's project to for crystal quality by symmetric and le include the figures of merit (FOM) for he homoepitaxial GaN films' FOMs
seconds) symmetric and 38 asymmetric. The good homoepitaxial GaN film quality was ~3 to 8 times better than that of good heteroepitaxial films. The heteroepitaxial GaN film quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices.15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film16. SECURITY CLASSIFICATION OF:17. LIMITATION OF ABSTRACT Unclassified18. NUMBER OF PAGES19a. NAME OF RESPONSIBLE PERSON Kevin Kirchnera. REPORT Unclassifiedb. ABSTRACT UnclassifiedC. THIS PAGE Unclassified10.13. NUMBER OF PAGES19a. NAME OF RESPONSIBLE PERSON (Go1) 394-0093	compared with	those from heter	pepitaxial films. Th	e analysis produc	the best F	OMs for GaN for our lab to date: 39" (arc
Interforepriaxial ministic file neteroepriaxial GaN mini quality was shown to be suited for our experimental needs. At a 95% confidence level, we were able to show a bias between the quality of the wafer quadrants of the Hydride Vapor Phase epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE UU 36 19b. TELEPHONE NUMBER (Include area code) (301) 394-0093	seconds) symmetry	films The hetero	enitarial GaN film	nomoepitaxial G	an nim quai	Ity was ~ 3 to 8 times better than that of good
epitaxially grown GaN substrates. The microstructural quality of the material inputs as measured by x-ray diffraction is currently on track to play its part in the development of novel GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION 17. LIMITATION 18. NUMBER 19. NAME OF RESPONSIBLE PERSON 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. ABSTRACT 19. TELEPHONE NUMBER (Include area code) 19. JOINT 10. JO	confidence lev	el we were able to	o show a bias betwe	en the quality of	the wafer ou	adrants of the Hydride Vanor Phase
currently on track to play its part in the development of novel GaN-based devices. 15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF ABSTRACT 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE Unclassified UU 36 19b. TELEPHONE NUMBER (Include area code) (301) 394-0093	epitaxially gro	wn GaN substrate	s. The microstructu	ral quality of the	material inpu	its as measured by x-ray diffraction is
15. SUBJECT TERMS GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF PAGES 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE Unclassified UU 36 19b. TELEPHONE NUMBER (Include area code) (301) 394-0093	currently on tra	ack to play its part	t in the developmen	t of novel GaN-b	ased devices.	
GaN, homoepitaxial, x-ray diffraction, micro structural analysis, GaN Device Program, Schottky Devices, HEMT, film 16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF ABSTRACT 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE Unclassified UU 36 19b. TELEPHONE NUMBER (Include area code) (301) 394-0093	15. SUBJECT TER	MS				
16. SECURITY CLASSIFICATION OF: 17. LIMITATION OF ABSTRACT 18. NUMBER OF ABSTRACT 19a. NAME OF RESPONSIBLE PERSON Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE UU 36 19b. TELEPHONE NUMBER (Include area code) (301) 394-0093	GaN, homoepi	taxial. x-rav diffra	action, micro struct	ural analysis. Gal	N Device Pro	gram. Schottky Devices, HEMT, film
16. SECURITY CLASSIFICATION OF: OF ABSTRACT OF PAGES OF PAGES Kevin Kirchner a. REPORT b. ABSTRACT c. THIS PAGE UU 36 19b. TELEPHONE NUMBER (Include area code) (301) 394-0093	Sur , nomoopi			17. LIMITATION	18. NUMBER	19a. NAME OF RESPONSIBLE PERSON
a. REPORT b. ABSTRACT c. THIS PAGE UU 36 19b. TELEPHONE NUMBER (Include area code) (301) 394-0093	16. SECURITY CL	ASSIFICATION OF:		OF	OF	Kevin Kirchner
Unclassified Unclassified Unclassified UU 36 (301) 394-0093	a. REPORT	b. ABSTRACT	c. THIS PAGE	ABOIRACI	I AGEO	19b. TELEPHONE NUMBER (Include area code)
	Unclassified	Unclassified	Unclassified	UU	36	(301) 394-0093

Standard Form 298 (Rev. 8/98) Prescribed by ANSI Std. Z39.18

Contents

List of Figures	iv
List of Tables	iv
Acknowledgments	v
1. Introduction and Background	1
2. Kyma GaN Substrates	3
3. SUNY Heteroepitaxial GaN Films on Sapphire Substrates	11
4. GaN Substrates vs. GaN Films Grown On Them	16
5. Homoepitaxial vs. Heteroepitaxial GaN Films	18
6. Observations and Conclusions	21
Appendix. Statistical Bias between Kyma GaN Wafer Quadrants	23
List of Symbols, Abbreviations, and Acronyms	27
Distribution List	28

List of Figures

List of Tables

Table 1. GaN substrates vs. GaN films grown on them	16
Table A-1. Two factor ANOVA without replication	24
Table A-2. Paired sample T- test for QI and QIII.	25

Acknowledgments

I would like to acknowledge the members of my team: Dr. Ken Jones, Dr. Randy Tomkins, Dr. Tim Walsh, Mike Derenge, and Cuong Nguyen for their help, support, and collaboration throughout the year. Additional thanks go to Dr. Walsh for his help with the statistical analysis contained within this report.

INTENTIONALLY LEFT BLANK.

1. Introduction and Background

Solid-state devices based on gallium nitride (GaN) have the potential to have superior electronic properties. After the type of material used, the quality of that material is critical. However growing and processing better materials is a laborious and very expensive process. An extremely useful way of tracking the material improvement process is through the use of x-ray diffraction. The wavelengths of the x-rays used are dimensionally on the scale of the smallest component (unit cell) of the atom's long range order. It is because of this relationship that x-ray diffraction is able to tell us how repeatable a group of unit cells are with respect to their neighbors. The higher the degree of repeatability in a crystalline solid, the higher the quality. The x-ray diffraction unit of measure of a material's quality is the full width at half maximum (FWHM) value.

This report covers the crystallographic analysis, by x-ray diffraction, of 18 recent wafers involved in our team's project to produce GaN-based wide bandgap (WBG) devices. The substrate and film inputs for the project came from Kyma, Crystal Systems, Mike Derenge, and our State University of New York (SUNY) partners. Some additional enabling collaborations during this period were with Georgia Institute of Technology, Pennsylvania State University, and Sandia National Laboratory. The wafers were examined by symmetric (sym) GaN (002) and asymmetric (asym) GaN (102) scans for each of the sub regions of the 18 wafers.

Besides the analysis of the basic crystalline quality of the project's inputs, many comparisons were made. For example, the figures of merit (FOMs) for GaN substrates were compared with the FOMs of GaN films that were grown on those substrates. Some comparisons between different FOMs are given in terms of percentage of improvements. So for example, if sample A had a FWHM value of 100" (arc seconds) and sample B had a FWHM value of 60", that comparison could be expressed as there being a 40% improvement between sample A and B. Also, it is worth noting that smaller FWHM values indicate better crystalline quality of a material.

Heteroepitaxially grown GaN films are still, relatively speaking, immature; and homoepitaxial GaN films, and the GaN substrates that make their existence possible, have even shorter analysis baselines. Because of the small number of good GaN homoepitaxial films currently available to us, this report is somewhat interim in nature. That said, my work has uncovered many encouraging material attributes. For example, the x-ray work includes the best FWHM numbers that I have measured for the GaN (002) peak, 39". FWHM values correlate with lower defect densities, and lower defect densities have been shown to correlate with better device characteristics.

With new material systems there are always challenges. The asymmetric x-ray scans seem to have revealed in plane, material quality issues. Many of these problems are conjectured to be caused by small angle grain boundaries (SAGBs).* SAGBs are thought to be formed by an amassing of line defects.

This work, besides documenting the overall quality of the material, also differentiates between multiple technologies, different material processing, and interactions between inputs. Additionally this work constitutes an initial investment in being able to make "before and after" comparisons in the future.

At this stage of the project, I am not sure of what and how patterns in the data will show up, so I employ a number of different methods of organizing the data in this report, i.e., graphical, chart form, grouping levels, and overlays. Each section of the report includes a short section-specific introduction.

This report contains six sections:

- 1. Introduction and Background
- 2. Kyma GaN substrates
- 3. SUNY heteroepitaxial GaN films
- 4. GaN substrates and film comparisons
- 5. Homoepitaxial vs. heteroepitaxial GaN films
- 6. Observations and Conclusions

^{*}Callister, W. D. *Material Science and Engineering An Introduction*, Fourth Edition, John Wiley & Sons: New York 1997, p.77.

2. Kyma GaN Substrates

Twelve of Kyma's novel hydride vapor phase epitaxy (HVPE) GaN substrates, enabling homoepitaxial growth of GaN films, were analyzed. For analytical purposes, the twelve 1x1 cm wafers were divided into a total of 48 quadrants (Cartesian coordinate nomenclature). Each plot and major chart entry is labeled with the sample number from which it came. The plot's abscissa values are the quadrant number from which the data was taken; the ordinates are the FWHM values.

Notes:

- The plots of the x-ray scans were grouped by similarities of pattern. Patterns varied from having both sym (GaN 002) and asym (GaN 102) scans matching their counterparts to only having one of the pairs possess some similarity. There were also a couple of mirror image pairings between scans.
- The sym scans contained the best GaN FWHM value (39") I have seen to date. The asym values ranged from decent to poor. Sample 15691 (figure 1) had the best symmetric scans, averaging 40" across the four quadrants of its wafer. Quadrant I, for both sym and asym scans, had the best results across all samples. This could be caused by an inhomogeneity in the wafer's growth conditions. If an examination of the growth conditions turned up a difference it could potentially mean a significant improvement in the quality of the sample output as a whole. To be sure, we ran a statistical analysis and there is a statistically significant bias between the wafer quarters across the wafers (see the appendix). A level of detail of the scans that is not made clear by either the charts or the plots is the effect of an amassing of material defects, which create what are called SAGBs (figure 2).

Ranking of Kym	na's GaN	l Substr	ates by	X-ray D	iffraction	
Kyma Subs	trates, Svn	nmetric Sca	an (002), Ui	nits: Arc Se	econds	Wafer
Wafer#	, QI*	QII	QÍÍ	QIV	Row Ave	Rank
6921	82	84	173	114	113	10
6942	56	61	54	54	56	2
7041	56	69	93	82	75	5
7286	76	119	130	69	99	8
8183	49	83	65	54	63	4
8184	74	70	132	69	86	6
8185	167	154	157	154	158	11
8186	58	60	66	57	60	Tie 3
8187	72	157	85	72	97	7
12932	100	101	104	120	106	9
15691	39	39	40	41	39.75	Best 1
15994	54	60	61	65	60	Tie 3
Averages	(4	88	97	79		
Quad Ranking	1st (Best)	3rd	4th	2nd		
Kyma Subs	trates. Asv	mmetric So	can (102). L	Jnits: Arc S	Seconds	Wafer
Wafer #	QI	QII	QIII	QIV	Row Ave	Rank
6921	525+204	402+342	551+321	624+164	858	5
6942	700	1033	995	993	930	6
7041	830	1225	1279	843	1044	8
7286	823	1172	1344	962	1075	9
8183	414	484	426	402	431	2
8184	477	564	670	545	564	3
8185	356	372	355	364	361	Best 1
8186	967	1217	1202	946	1083	10
8187	1008	1385	1263	937	1149	11
12932	1094	1756	1727	1172	1437	12
15691	544	648	656	542	598	4
15994	930	1161	1123	881	1024	7
A				70.1		
Averages	/39	980	993	/81		
Quad Ranking	ist (Best)	3rd	4th	2nd		

Figure 1. Ranking of Kyma's GaN substrates by x-ray diffraction.

In figure 1, the following apply:

• QI through QIV stand for the different wafer quadrants. They are in Cartesian coordinates as follows

	QII	QI
s:	QIII	QIV

- There are 96 data points over 48 sample regions across 12 wafers. •
- The asymmetric rocking curves (RCs) of sample 692.1 consisted of two distinct regions. ٠ The FWHM for each are included.

- For row and column averages, it is the sum of the two values that are used for sample 692.1.
- The row averages are also the sample average.

In addition to the rankings shown in the charts, the following was observed:

- The sym scans show a remarkable improvement over the industry standard.
- Up to their point in the sample stream, samples 8183, 8184, and 8185 were the 2nd, 3rd, and 1st, respectively, in in-plane (parallel to surface to sample) crystal quality. With sample 8186, the quality changed abruptly. Interestingly, the rankings of the quadrants across all samples are the same for both the sym and asym scans.

Figure 2 shows four scans (A through D). Scans A and B, although having similar FWHM numbers, show the start of a move from a monolithic to a multifaceted "flat topped" peak. With their flat-topped multifaceted peaks, scans C and D show the progression of the effect due to a further increase in the density of the SAGB.

Figure 3 presents a thumbnail overview of the GaN substrate plots.

Figures 4–6 show the enlarged individual plots.

The data from these x-ray scans of freestanding GaN substrates provides the first sets of data that allow subsequent comparisons between substrates and films and a more complete analysis between homoepitaxial and heteroepitaxial film growth. Eventually, the information will be carried forward into the analysis space where the processing and performance of devices is analyzed.



Figure 2. Scans of the monolithic and facetted GaN peaks. The plots are of intensity vs. position.

	Microsoft E	xcel -	Shaffer	r5_10_K	/ma	_thumbs2.	kls																	_ 8 ×
)e	Eile Edit	⊻iew	Insert	Format]	ools	<u>D</u> ata <u>Win</u>	dow <u>H</u> elp																	-8×
) 🚅 🖬 ,	8	3 R	5.		Σ f* 2	1 🛍 😨	» A	Arial		• 10	•	B /	U				\$ %	, .00	.00 •.•	律律		- 3	• 🔺 • .
Û.	P39	-		=																				
	C		D	E		F	G	Н	1		J		K		L	М		N	0)	Р		Q	
1	Kuma	-			-		Over	view c	ofX-ra	y Sc	ans of]	Kyn	na's	Ga	N W	afers	-		-			_		
3	6921Svn	692	1Asvm		F	942Svm	6942Asvm		70415	wm 7	/041Asvm	-25.77		728	36Svm	7286A	svm		8183	Sym	8183A	svm		
4	8	2	729			56	700			56	830	li –			76	1200.1	323			49	-	414		
5	8	4	744			61	1033			69	1225				119	1	172			83		484		
6	17	3	872			54	995			93	1279				130	13	344			65	-	426		
7	11	4	788			54	993			82	843		-	-	69		362	_	-	54		402	-	<u> </u>
10 11 12 13 14 15 16		1	i	→ m 			•		-	• • • •	••••••••••••••••••••••••••••••••••••••	- HI - HI - HI - HI - HI - HI - HI - HI				2 2		11 5		•		-11 0	-##- 	
18	8184Syn	1 818	4Asym	1	8	3185Sym	8185Asym		81865	Sym 8	3186Asym	1		818	37Sym	8187A	sym		12932	2Sym	129324	Asym		
19	7	4	477			167	356			58	967				72	10	800			100	1(094		
20	7	0	564			154	372			60	1217	_	_		157	13	385		_	101	17	756		
21	13	2	670		-	157	355		_	66	1202		_	-	85	12	263		_	104	17	727		-
23 24 25 26 27 28 29 30 31 31 32 33 34 ▲	Plots: X Valuesi	Axis n the	Wafer Tables	Quadra are the l	nt N WH	um bers (C	artesian Co	ordinate	es); Y Axi are in rec	s, FW	HM V alu symmetri	344 10 11 es c are	in blu	ie.			943 • 11 • 1	1937 27 5		*	0181 014 2)	477	1472	
D	aw • 13 (2 4	utoshap	es • \			ना 🖭	N • - D	• 4 •		- = •				11	_								





Figure 4. Kyma GaN substrates, FWHM vs. quadrant plots. The grouping shows data pattern A.

Note: The sym scans are blue and the asym scans are red.



Figure 5. Kyma GaN substrates plots, FWHM vs. quadrant. The grouping of the plots shows data pattern B. Sym scans are blue and asym are red.



Figure 6. Kyma GaN substrates, FWHM vs. quadrant plots. The grouping of x-ray plots shows data pattern C.

Note: The sym scans are blue and the asym scans are red.

3. SUNY Heteroepitaxial GaN Films on Sapphire Substrates

Sym and asym scans were taken of the heteroepitaxial GaN films that were grown on five 2" sapphire wafers by our partners at SUNY. There is one x-ray plot per wafer containing both sym and asym scans (figure 8). Groupings of x-ray scans were again made on the basis of plot similarities (figure 9 and 10). Sample 2093N1 is one-half of a 2" wafer, having Quads I and IV. The collected data is also presented in chart form (figure 7). The chart shows rankings of the wafers and the quadrants across all SUNY wafers. The best wafer in terms of sym x-ray scans is 2093N. There was a tie for the best sample in terms of the asym scans, between samples 2079 and 2088. The best quadrant across all the wafers, in sym terms is QII. The best in terms of the asym scan analysis across all wafers is QI.

Note: Samples 2080 and 2088 were grown to be high electron mobility transistors (HEMTs) structures while the remaining samples were prepared to be Schottky devices. This means that the GaN films on 2080 and 2088 are thinner than those on the remaining samples. In heteroepitaxial growth, thicker films often show better structural quality than thinner films. Therefore if the two HEMT samples have similar or slightly worst FOMs this still signifies films of good quality in my opinion. Overall, sample 2080 had the second best scan out of the five samples for both sym and asym scans, and sample 2088 was the third best for sym scans and was tied for first for asym scans. Therefore, the HEMT samples echo the Schottky data, i.e., all our SUNY samples are of good microstructural quality.

These x-ray scans of the heteroepitaxial films are part of my group's analysis and documentation of the input streams for our GaN Device Program. In this report additional analyses are presented, for example, I compare the Kyma homoepitaxial films with these heteroepitaxial films in section 4. Over time, as we learned the quality of the samples and our expectations for the project grew, we increased the number of scans from 8 scans per 2" sample to 32. Our team has been developing GaN Schottky diodes and HEMTs with segments of these wafers.

	200			Ir	- 16	۰.	F f.	. 41	40 12	a	» Ar	al	- 10	61	B J	. 11	I I III I	= = 53	¢	%	+,0 .00			- 1	2
			7 42	-		æ •	- Ja	Z		e	<]	u.	1 10					= = m	Ψ	/0 1	.00 +.0	37- 37			
	A		В	-	C		D		F		F	G	Н		1		d	K		1	M	N		()	0
5	SUNY		-				-		-														_		-
F	anking o	of Gal	V/Sap	ophir	e San	ples	s Usi	ng X-	ray Diffra	action	Ê.														_
		1		1		1																			
														Ave	rages			Wafer Ran	k		Notes				
		Wat	ier#			QI	*	(JII	QII		QIV	l	Syn	n	As	ym	Sym	Asyr	n					
			2079	Sy	n		3	313	30	2	335	5 342			323	1		4			8 data pts	(dps),	4 & 4	£	
		-		As	m	_	4	113	43	4	459	9 459				_	441			1a		-			_
Į.		-		-	54150	-				-				-		_				_			_		_
ŀ		-	2080	Sy	n			266	25	0	269	277		-	268	-		2				<u></u>	_		
		-		As	m		4	111	43	2	47.	2 462		-		-	444			2	8 dps, 4 &	4	-		
		-	2000	0		-		71	25		27	1 200		-	270			2		-	22 dea	-			_
			2000	Ag	n	-	- 1	1 12	25	4	214	200		-	212		441	3		16	32 aps				_
		-		MS	m	+		+05	40	4	40	4/4		-		-	441			10	-	+	-		_
8		-	20031	Su	~	+		230	22	2	23(243		-	231	-		1	-		32 dae		-		_
		-	2000	Ac	m	-	- 1	137	45	3	450	450		-	201	-	450			3	oz upo				_
7		-		1.10		-		1.51	40		-154	400		-			400				-	-	-		_
3			2093N	1Svi	n	-	2	227				237			232						1/2 wafer.	16 dat	apts		_
3				As	m	1	2	125		-		416				-	421				16 dps, 88	48			_
1		Ave	rages	Sy	n	1	2	261	20	6	22	2 277													
				As	m		4	118	43	1	468	3 452													
8		1																							
}		Qua	d Ran	k Sy	m			3		1		2 4													
		1		As	m	1		1	-	2		1 3				_									
				_				_						_											_
i		Note	BS													_						<u> </u>			_
		* QI	- QIV	star	ds for	qua	drant	s, u	sing Cart	esiar	coord	inates		-		-							_		_
		Tab	le unit	s are	arc s	ecor	nds							-							-				_
		Syn	nmetri	c sc	an valu	les \	were	in th	e good ti	o exc	ellent	range							_	_					_
		Asy	mmet	ric p	aks a	ISO	snow	red v	good F	UM, I	had a r	narrow range,	and the p	eaks	were	mon	nolitic			_				_	_
1		Tor	half of	amp	ing st	rate	gies i	over	ume mai	the h	inemic	holf	113	-		-			-	-		-	-		_
		Lot	nair of	fica	ers we	~ 2	s% b	y De	then riel	the b	f for a	nalí.	ny cloce f	or ac		ake	eliebt	dvantage E) oldo			-			_
		Leit	side (n sa	nhies	23	J 70 D	ener	man ngi	n rial	nor sy	miscans, ve	iy close i	oras	ym pe	ans,	, siigint a	auvantage P	SIGE			+			_

Figure 7. Ranking of SUNY GaN/sapphire samples using x-ray diffraction. 12



Figure 8. Graphical overview of SUNY heteroepitaxial GaN data. The sym scans are blue and the asym scans are red.



Figure 9. SUNY GaN/sapphire heteroepitaxial films, showing grouping of x-ray plots by data pattern A. The sym scans are blue and the asym scans are red.



Figure 10. SUNY GaN/sapphire heteroepitaxial films, showing grouping of x-ray plots by data pattern B. The sym scans are blue and the asym scans are red.

4. GaN Substrates vs. GaN Films Grown On Them

This section presents a comparison of the structural quality of HVPE-grown GaN substrates and the metalorganic chemical vapor phase deposition (MOCVD) grown homoepitaxial GaN films produced on them. The data is represented in both table (table 1) and graphic (figure 11) forms. The following summary provides an additional examination of the data:

- The graphical output highlights the relationship between the substrates and films.
- The sym substrate and film scans track each other for both samples, but for the asym scans, they do not track for either sample.
- The sym values for both substrate and film of sample 8183 are excellent (table 1).
- The film values for the asym scans of 8184 contain an extraordinary value of 58".
- The asym scans for the films are significantly lower than the substrate values, particularly for sample 8184.

These were the only homoepitaxial GaN films measured to date until a couple of weeks ago. Since then we have received a few samples from Lumilog/SUNY; however, they are not up to the level of quality of the Kyma samples examined here. The Lumilog/SUNY film's sym values averaged ~200" and the film's asym values averaged ~400".

Table 1. GaN	substrates vs.	GaN films	grown or	n them.
--------------	----------------	-----------	----------	---------

SAMPLE 8183	SAMPLE 8184
Sym Scan Values	Sym Scan Values
Substrate: 49, 83, 65, 54 Film :50, 89, 66, 53	Substrate: 74, 70, 132, 69 Film : 69, 62, 109, 59
Notes	
Note: Very close match between substrate and film average values Sub 63", Film 65"	Note: Similar average values, substrate and film: Sub 86", Film 75".
Asym Scan Values	Asym Scan Values
Substrate: 414, 484, 462, 402 Film : 268, 276, 291, 283	Substrate: 477, 564, 670, 545 Film : 58, 106, 86, 71
Notes	



Figure 11. Graphical comparison of Kyma GaN Substrates and the GaN films grown on them, FWHM vs. quadrant plots

5. Homoepitaxial vs. Heteroepitaxial GaN Films

Two plots (sym and asym) containing eight scans were used to compare the homoepitaxial film data with the very good quality heteroepitaxial films we received, primarily, from our SUNY partners. Our team's principle grower, Mike Derenge, grew the homoepitaxial and heteroepitaxial films on the Kyma and the Crystal System's substrates, respectfully. All the SUNY and our principal grower's films were grown by MOCVD.

The comparisons for the sym scans show the homoepitaxial films improving over their heteroepitaxial counterparts by from 73% to 77% (figures 12 and 13). For the asym scans, the homoepitaxial films improved over their heteroepitaxial films by from 42% to 94%. It is very promising having two sym homoepitaxial FWHM values in the 50s, having an asym value in the 50s is extraordinary (i.e., sample 8184's 94% improvement). Good FWHM values correlate with lower defect densities, and lower defect densities are thought by the technical community to correlate with better device characteristics.

The homoepitaxial films show some remarkable improvements in crystal quality, unfortunately the devices that were fabricated on them had some performance issues. However, we do have initial data pointing to a solution for the device performance problems. Our group is currently in the process of implementing that solution.



Figure 12. Comparison of homoepitaxial and heteroepitaxial films using sym scans.





Figure 13. Comparison of homoepitaxial and heteroepitaxial films using asym scans.

6. Observations and Conclusions

In this interim report, I have presented the results of the microstructural analysis using x-ray diffraction of substrate and film inputs to the GaN WBG Device Program of the Power Components Branch.

We have observed the following:

- Our best GaN (002) FWHM value to date 39". This is important because good FWHM numbers correlate with lower defect densities and lower defect densities are thought by the technical community to correlate with better device characteristics.
- We documented the quality of Kyma's novel HVPE GaN substrates by wafer and wafer quarters (figures 1, 4, 5, and 6).
- We provided a composite thumbnail overview of the sample plots of Kyma's novel GaN substrates (figure 3).
- We showed an example of the effect of peak broadening in x-ray output by SAGB (figure 2).
- Asym scans of 12 HVPE GaN substrate wafers show a broad range of FWHM values, ~350" to 1750" (figure 1).
- We had excellent asymmetric scan results of the homoepitaxial films (sample 8184) with FWHM values of 58" to 106" (table 1).
- We documented the good input quality of SUNY's heteroepitaxial films by wafer and wafer quarters (figure 7).
- The composite thumbnail plots of SUNY scans provided an overview of heteroepitaxial film's sym and asym scans to illustrate the relationships between them (figure 8).
- Homoepitaxial film quality showed improvement over the substrate it was grown on, in some cases by 5 to 7 times (Sample 8184, asym peaks, table 1).
- In sections 2, 3, and 4, we saw the variation in tracking between the sym and asym scans.
- We presented graphical comparisons between good quality GaN heteroepitaxial films and novel GaN homoepitaxial films from Kyma (figures 12 and 13).
- Kyma substrates' micro-structural quality showed a bias across their 12 wafers in favor of quadrants I and IV (figure 1 and tables A-1 and A-2). This could be useful information for our Kyma partners.

There has been a steep learning curve in our team, and the technical community at large, regarding GaN quality. Recently, we have also obtained data suggesting we are overcoming a major hurdle involving carbon's negative role in the low-doped GaN films, which we use in fabricating some of our devices.

As we are able to obtain additional good homoepitaxial films to use for device fabrication, and our fabrication techniques and understanding matures, there will likely be additional useful and instructive correlations.

One group in the GaN device community has recently, after five years of hard work, achieved the technical community's target 600-V breakdown voltage. We have also attained 600-V breakdown on Kyma substrates and we are working to duplicate these results in our films.

While x-ray diffraction can help us rate our material input streams, it can also help inform us about issues like the material imperfections behind the material consistency issues we are working through. Going forward using x-ray diffraction along with scanning electron microscopy (SEM), Atomic Force Microscopy (AFM), cathodoluminescence (CL), and etch pit techniques, we will try to better understand and control the number and types of material defects in our devices to a degree that will help us have good device yields.

Appendix. Statistical Bias between Kyma GaN Wafer Quadrants

The present data was examined to determine if the findings present in the report are statistically significant. Specifically, our goal was to determine if the mean FWHMs of the 002 (symmetric) reflections differed between quadrants of the Kyma samples. Two separate analyses were undertaken. First, the four quadrants were compared with the use of a two-factor analysis of variance (ANOVA). Second, the quadrants with the largest difference in mean, QI and QIII, were compared with a paired sample T-test.

The ANOVA analysis comparing the four quadrants is shown on table A-1. The 002 FWHM data are contained in the top table and are organized by wafer (row) and quadrant (column). Below the FWHM data is a tabulation of statistics on the individual columns (quadrants) which are used in the ANOVA calculation. For each column, the sum (T_a) , sum squared (T_a^2) , number of observations (n_a) , mean, and standard deviation are calculated. Likewise, statistics are calculated by row (wafer) and tabulated to the right of the main data table. Below the table, the calculation steps are outlined, including calculation of the grand total T and total number of observations n. Sum of squares variation due to factor A (that is, due to variation by column, or equivalently by quadrant of the wafer) SS_A is calculated, along with the mean square variation due to factor A, MS_A . Likewise, the sum of squares and mean square variation SS_B and MS_B are calculated for variation due to factor B (that is, variation by row, or equivalently by wafer). The sum of squares due to interaction between the two factors SS_{AB} is shown, along with the mean square variation *MS*_{AB} (also known as error variance). Finally, the total sum of squares is given. Below these, the F value is given for variation due to factor A (data column or quadrant) and factor B (data row or wafer). The F value is given by $F_x = MS_x/MS_{AB}$, where x is A or B. Next to the F value for both factors, the probability (from the F distribution) is given. The probability P_A for factor A is interpreted as the probability that the four columns share the same mean. The value is 0.053, or equivalently there is a $1 - P_A = 0.947$ probability that the four columns (quadrants) do not have the same mean. Thus we have rigorously shown that there is a statistically significant difference in the mean value of the 002 FWHM depending on the quadrant of the wafer for these Kyma wafers.

Wafer #	QI	QII	QIII	QIV	Ть	T _b ²	n _b	Mean	Std. dev
6921	82	84	173	114	453	205209	4	113.25	42.44
6942	56	61	54	54	225	50625	4	56.25	3.30
7041	56	69	93	82	300	90000	4	75.00	16.02
7286	76	119	130	69	394	155236	4	98.50	30.49
8183	49	83	65	54	251	63001	4	62.75	15.06
8184	74	70	132	69	345	119025	4	86.25	30.58
8185	167	154	157	154	632	399424	4	158.00	6.16
8186	58	60	66	57	241	58081	4	60.25	4.03
8187	72	157	85	72	386	148996	4	96.50	40.80
12932	100	101	104	120	425	180625	4	106.25	9.32
15691	39	39	40	41	159	25281	4	39.75	0.96
15994	54	60	61	65	240	57600	4	60.00	4.55
Ta	883	1057	1160	951					
T _a ²	779689	1117249	1345600	904401					
n _a	12	12	12	12					
Mean	72 5 8 2	00 000	06 667	70.050					
	/ 3.003	00.003	90.007	79.250					
Std. dev	4051	37.744	42.934	33.251					
Std. dev T n SS _A MS _A SS _B MS _B SS	4051 4051 48 3690.7 1230.2 46388.2 4217.1	37.744	Grand tota 70tal num. Sum of sq Mean squa Sum of sq Mean squa	79.230 33.251 ber of obse uares varia are variation uares varia are variation	ervations tion due n due to tion due n due to	to factor A factor A (b to factor E factor B (b	(by colu by colu 3 (by r by colu	column) umn) ow) umn)	
Std. dev T n SS _A MS _A SS _B MS _B SS _{AB} MS	4051 4051 48 3690.7 1230.2 46388.2 4217.1 14270.5 432.4	37.744	Grand tota Total num Sum of sq Mean squa Sum of sq Mean squa Interaction	33.251 33.251 ber of obse uares varia are variation uares varia are variation usum of squ	ervations ation due n due to ition due n due to uares are varia	to factor A factor A (b to factor E factor B (b	(by c by colu 3 (by r by colu	column) umn) ow) umn)	iance)
Std. dev F 1 SS _A VIS _A SS _B VIS _B SS _{AB} VIS _{AB}	4051 4051 48 3690.7 1230.2 46388.2 4217.1 14270.5 432.4	37.744	Grand tota Total num Sum of sq Mean squa Sum of sq Mean squa Interaction Interaction	33.251 33.251 ber of obse uares varia are variation uares varia are variation sum of squ mean squ	ervations Ition due n due to Ition due n due to uares are varia	to factor A factor A (b to factor E factor B (b tion (also d	(by colu ay colu (by r ay colu called	column) umn) ow) umn) I error var	iance)
Std. dev T n SS _A MS _A SS _B MS _B SS _{AB} MS _{AB} SS _{total}	4051 4051 48 3690.7 1230.2 46388.2 4217.1 14270.5 432.4 64349.5	37.744	Grand tota Total num Sum of sq Mean squa Sum of sq Mean squa Interaction Total sum	33.251 33.251 ber of obse uares varia are variation uares varia are variation uares varia of squares	ervations n due to n due to n due to uares are varia	to factor A factor A (b to factor E factor B (b tion (also d	(by colu by colu 3 (by r by colu called	column) umn) ow) umn) I error var	iance)
Std. dev T n SS _A MS _A SS _B MS _B SS _{AB} MS _{AB} SS _{total}	4051 4051 48 3690.7 1230.2 46388.2 4217.1 14270.5 432.4 64349.5 F 2.845 9.752	р 0.053 1E-07	Grand tota Total num Sum of sq Mean squa Sum of sq Mean squa Interaction Interaction Total sum	79.230 33.251 ber of obse uares varia are variation uares varia are variation uares varia of squares of squares <i>P is the pro</i>	ervations n due to n due to n due to uares are varia	to factor A factor A (b to factor E factor B (b tion (also o that the dij	ر (by colu y colu dy colu y colu callec fferen	column) umn) ow) umn) I error var I error var	riance) s share the same me
Std. dev T n SS _A MS _A SS _B MS _B SS _{AB} MS _{AB} SS _{total} A (column) B (row)	4051 4051 48 3690.7 1230.2 46388.2 4217.1 14270.5 432.4 64349.5 F 2.845 9.752 2.845	P 0.053 1E-07	Grand tota Total num Sum of sq Mean squa Sum of sq Mean squa Interaction Interaction Total sum	79.230 33.251 ber of obse uares varia are variation uares varia are variation uares varia of squares <i>P is the pro</i> for variation	ervations n due to n due to n due to uares are varia obability	to factor A factor A (b to factor E factor B (b tion (also o that the dij that the dij	(by colu y colu) (by r y colu callec (qua	column) umn) ow) umn) I error var It columns drants)	riance) s share the same me
Std. dev T n SS _A MS _A SS _B MS _B SS _{AB} MS _{AB} SS _{total} A (column) B (row)	4051 4051 48 3690.7 1230.2 46388.2 4217.1 14270.5 432.4 64349.5 F 2.845 9.752 2.845 0.053	р 0.053 1Е-07	Grand tota Total num Sum of sq Mean squa Sum of sq Mean squa Interaction Interaction Total sum	79.230 33.251 al ber of obse uares varia are variation uares varia are variation sum of squ of squares <i>P is the pro</i> for variation that differe	ervations n due to n due to uares are varia obability n betwee	to factor A factor A (b to factor E factor B (b tion (also o that the dii that the dii on columns rants have	(by colu y colu) (by r y colu callec callec callec	column) umn) ow) umn) I error var It columns drants) e mean	iance) s share the same me

Table A-1. Two factor ANOVA without replication.

Table A-2 shows the T-test analysis. The two quadrants were chosen because they have the largest difference in mean value, 73.58 (QI) compared with 96.67 (QIII). The table shows the 002 FWHMs organized by wafer (row) and quadrant (column). To the right of the FWHM data, the mean for each row is given, as well as the difference *d* between the QI and QIII values for

each wafer. Below the table, statistics are calculated for each column (quadrant), including the mean, standard deviation, variance, and total number of observations n. The test statistic t is given by

$$t = \frac{d_{avg}}{s_d / \sqrt{n}} \tag{A.1}$$

where d_{avg} is the average difference between QI and QIII, s_d is the standard deviation of the difference, and *n* is the number of observations. From the test statistic, the t-distribution yields a probability of 0.024 that the two samples (quadrants I and III) have the same mean, that is, there is a 97.6% chance that they come from populations with different means. Thus, we can rigorously conclude that there is a significant difference in the means of the 002 FWHMs for quadrants I and III in the Kyma-grown GaN samples. Furthermore, from the *t* value corresponding to a probability of 0.05, the 95% confidence interval for the mean difference between QI and QIII is found to be 19.34. Thus, we can say at a 95% confidence level that the difference between the mean values of QI and QIII is 23.08 ± 19.34. Further testing should help to narrow down the confidence window allowing us to more precisely determine the mean difference between the 002 FWHM of QI and QIII.

/afer #	QI*	QII	QIII	QIV	Mean d (QI - QIII)	
6921	82	84	173	114	113.25	-91
6942	56	61	54	54	56.25	
7041	56	69	93	82	75.00	-3
7286	76	119	130	69	98.50	-5
8183	49	83	65	54	62.75	-10
8184	74	70	132	69	86.25	-54
8185	167	154	157	154	158.00	1
8186	58	60	66	57	60.25	-
8187	72	157	85	72	96.50	-1
12932	100	101	104	120	106.25	-
15691	39	39	40	41	39.75	-
15994	54	60	61	65	60.00	-
Mean:	73.583	88.083	96.667	79.250		-23.08
Standard dev:	33.776	37.744	42.934	33.251		30.44
Variance:	1140.811	1424.629	1843.333	1105.659		926.8
n:	12	12	12	12		1
aired test, two tai	led					
-2.627		Test statisti	С			
0.024		Probability f	he two sam	iples have th	ie same mea	n
0.976		Probability f	he two sam	ples do not	have the sam	ie mean
Mean c	lifference:	-23.083				
95% confidenc	e interval:	19.343				

Table A-2. Paired sample T- test for QI and QIII.

INTENTIONALLY LEFT BLANK.

List of Symbols, Abbreviations, and Acronyms

ANOVA	analysis of variance		
Asym	asymmetric x-ray scan		
CL	cathodoluminescence		
FOM	figure of merit		
FWHM	full width at half maximum		
GaN	gallium nitride		
HEMT	high electron mobility transistors		
HVPE	hydride vapor phase epitaxy		
MOCVD	metalorganic chemical vapor phase deposition		
SAGB	small angle grain boundary		
SEM	scanning electron microscopy		
SUNY	State University of NY		
Sym	symmetric x-ray scan		
WBG	wide bandgap		

No. of

Copies Organization

- 1 ADMNSTR ELEC DEFNS TECHL INFO CTR
 - ATTN DTIC OCP 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
- 1 HC US ARMY RSRCH LAB ATTN RDRL CIM G T LANDFRIED BLDG 4600 ABERDEEN PROVING GROUND MD 21005-5066
- 3 HCS US ARMY RSRCH LAB ATTN IMNE ALC HRR MAIL & RECORDS MGMT ATTN RDRL CIM L TECHL LIB ATTN RDRL CIM P TECHL PUB ADELPHI MD 20783-1197
- 10 HCS US ARMY RSRCH LAB
- 1 CD ATTN RDRL SED ED SHAFFER ATTN RDRL SED E BRUCE GEIL PAUL BARNES KEN A JONES TIM WALSH RANDY TOMPKINS CUONG NGUYEN KEVIN KIRCHNER (1 CD, 3 HCS)

TOTAL: 16 (1 ELEC, 1 CD, 14 HCS)