Phys. Status Solidi A **207**, No. 6, 1348–1352 (2010) / **DOI** 10.1002/pssa.200983621

physica status solidi a
www.pss-a.com
applications and materials science

# AlInN HEMT grown on SiC by metalorganic vapor phase epitaxy for millimeter-wave applications

**Shiping Guo**[*,1], **Xiang Gao**[1], **Daniel Gorka**[1], **Jinwoork W. Chung**[2], **Han Wang**[2], **Tomas Palacios**[2], **Antonio Crespo**[3], **James K. Gillespie**[3], **Kelson Chabak**[3], **Manuel Trejo**[3], **Virginia Miller**[3], **Mark Bellot**[3], **Glen Via**[3], **Mauricio Kossler**[3], **Howard Smith**[3,4], **and David Tomich**[3]

[1] IQE RF LLC, Somerset, NJ 08873, USA
[2] Massachusetts Institute of Technology, Cambridge, MA 02139, USA
[3] AFRL Sensors Directorate, WPAFB, OH 45424, USA
[4] University of Dayton Research Institute, Dayton, OH 45424, USA

Received 8 October 2009, accepted 18 November 2009
Published online 17 May 2010

**Keywords** AlInN, MOVPE, heterojunction, high mobility electron transistor, 2DEG

* Corresponding author: e-mail sguo@iqep.com, www.iqep.com, Phone: +01 732 271 5990, Fax: +01 732 412 9325

In this work we present the epitaxial and device results of AlInN/GaN HEMTs grown on SiC by metalorganic vapor phase epitaxy. High quality AlInN/GaN HEMT structures with sub-10 nm AlInN barrier were grown with very low Ga background level (<1%). The low $R_{sh}$ of 215 Ω/sq was obtained with an excellent standard deviation of 1.1% across 3″ wafers. Lehighton RT contactless Hall tests show a high mobility of 1617 cm$^2$/V s and sheet charge density of $1.76 \times 10^{13}$/cm$^2$. DC characteristics of an AlInN/GaN HEMT with a gate length of 0.1 μm and 25 nm $Al_2O_3$ passivation show maximum drain current ($I_{DS,max}$) of 2.36 A/mm at $V_{GS} = 2$ V. Gate recessed devices with 0.15 μm gate length and 25 nm $Al_2O_3$ passivation resulted in maximum transconductance ($g_m$) of 675 mS/mm, the highest value ever reported in AlInN transistors. Excellent frequency response was obtained. The maximum $f_T$ is 86 GHz and $f_{max}$ is 91.7 GHz.



**1 Introduction** AlGaN/GaN HEMT transistors have been widely under development for high power high frequency device applications. Recent work at AFRL (air force research laboratory)/RYDD shows that virtually every non-gate recessed device with gate length shorter than 200 nm from $Al_xGa_{1-x}N$/GaN HEMTs exhibits significant frequency response degradation due to short channel effects that results from a thick AlGaN barrier, which is usually thicker than 17 nm in order to generate high current densities [1]. Higher Al content with thinner barrier has been pursued at the expense of a higher strain in the AlGaN/GaN interface [2].

$Al_xIn_{1-x}N$/GaN HEMT has the potential to push the performance beyond conventional $Al_xGa_{1-x}N$/GaN HEMT, with $x$ under 0.3, while reducing the strain in the AlInN/GaN interface [3]. AlInN/GaN HEMTs can assure superior performance at higher frequencies by eliminating short channel effects while maintaining or exceeding current densities of today's AlGaN/GaN HEMTs. $Al_{0.83}In_{0.17}N$ can be grown lattice matched to GaN buffer, thus reducing the stress in the barrier layer, which is expected to improve the device reliability [4, 5].

Due to the stronger polarization effects and a larger bandgap in AlInN, AlInN/GaN HEMTs can have higher two-dimensional electron gas (2DEG) charge density in the channel with a much thinner barrier layer than that in AlGaN/GaN HEMTs. Figure 1 shows the theoretical carrier concentration as a function of barrier thickness for various nitride-based HEMTs. It also illustrates that using the same thickness of a conventional AlGaN/GaN HEMT the AlInN/GaN HEMT would reach higher power performance or a thinner AlInN barrier could be used while maintaining the same power performance. This helps to improve the aspect ratio of the transistors for a given gate length and is very important for reducing short channel effects in high frequency HEMTs [1]. The higher 2DEG charge density in AlInN/GaN HEMTs also results in higher output current density, higher power density, and makes these devices more suitable for application in high temperature environments.

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**OCT 2009** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2009 to 00-00-2009** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**AlInN HEMT grown on SiC by metalorganic vapor phase epitaxy for millimeter-wave applications** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**IQE RF LLC,Somerset,NJ,08873** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 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
**See also ADM002356. Presented at the International Conference on Nitride Semiconductors (8th) (ICNS8) Held in Jeju, Korea on October 18-23, 2009. Sponsored by AOARD.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **5** | |

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

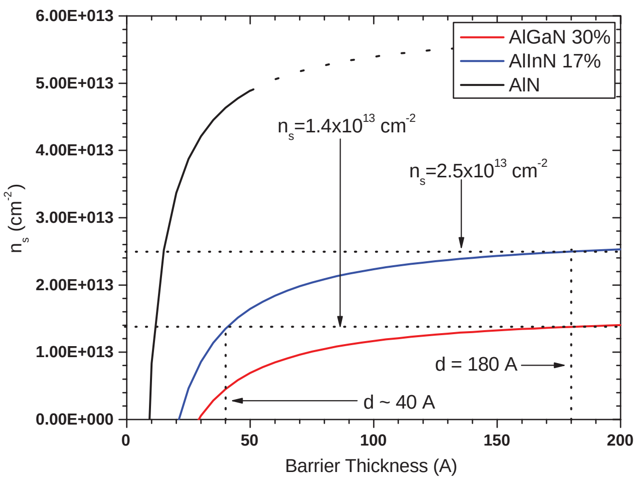


**Figure 1** (online color at: www.pss-a.com) Charge concentration for various nitride HEMTs as a function of barrier thickness.

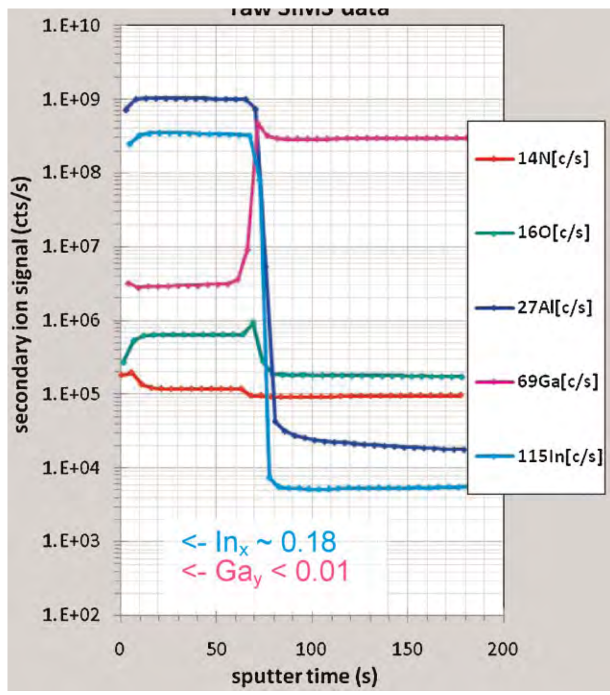


**Figure 2** (online color at: www.pss-a.com) SIMS profile of AlInN/GaN structure.

In spite of these promising capabilities, little reporting has been done with AlInN/GaN HEMTs. One of the problems is the difficulty of growing AlInN with low Ga incorporation and uniform In concentration across wafers [6, 7]. The Ga incorporation is concealed if XRD is used to determine composition. Therefore, other methods such as SIMS, XPS, or RBS need to be used to determine the presence of Ga.

**2 MOVPE growth** In this work, we report the epitaxial and device results of AlInN/GaN HEMTs grown on SiC by metalorganic vapor phase epitaxy (MOVPE). The AlInN films were verified by SIMS and have low ($<1\%$) Ga incorporation.

The AlInN epilayers were grown on 3″ semi-insulating SiC substrates by MOVPE using trimethylgallium (TMGa), trimethylaluminum (TMAl), and trimethylindium (TMIn) as group III precursors and ammonia ($NH_3$) for group V nitrogen. The AlInN/GaN HEMT structures consist of 2 μm of semi-insulating GaN buffer layer, a thin AlN spacer, and sub-10 nm of unintentionally doped AlInN barrier layer.

**3 Material characterization** Figure 2 shows a typical SIMS profile of an AlInN layer grown on GaN buffer. The Ga background level in AlInN layer is less than 1%. The exact amount was not established due to lack of calibration standards and current SIMS test limitation.

Figure 3 shows a sheet resistance ($R_{sh}$) map determined by a Lehighton Eddy current system, from an AlInN HEMT structure grown on SiC with a very thin total barrier thickness of $<10$ nm. The average $R_{sh}$ is 215 Ω/□ and the minimum $R_{sh}$ is 209 Ω/□, which matches the best-reported value by Europe's Ultragan project [8] with a 14 nm total barrier thickness. The standard deviation of $R_{sh}$ is 1.1% across 3″ wafers. Wafer level transport properties were determined by Lehighton contactless Hall system as shown in Fig. 4. The average mobility is measured to be 1576 $cm^2$/V s and the mobility uniformity is 2.3%. The maximum mobility is 1617 $cm^2$/V s, which is, to the best of our knowledge, the highest mobility reported for AlInN/GaN HEMTs [8]. The high mobility is believed to be related to the excellent interface between AlN interlayer and GaN buffer as well as the high aluminum content in the AlInN barrier. The average sheet charge density ($n_s$) measured using the same system is $1.71 \times 10^{13}$ $cm^{-2}$, which is lower than the $2.55 \times 10^{13}$ $cm^{-2}$ reported in Ref. [8]. On-wafer Hall tests at AFRL show an average mobility of 1317 $cm^2$/V s, almost 20% lower than that obtained from the contactless Hall test at

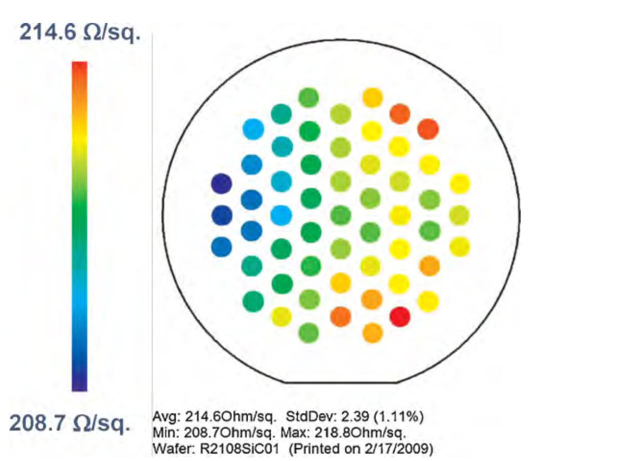


**Figure 3** (online color at: www.pss-a.com) Sheet resistance map of an AlInN HEMT measured by Lehighton Eddy current system.

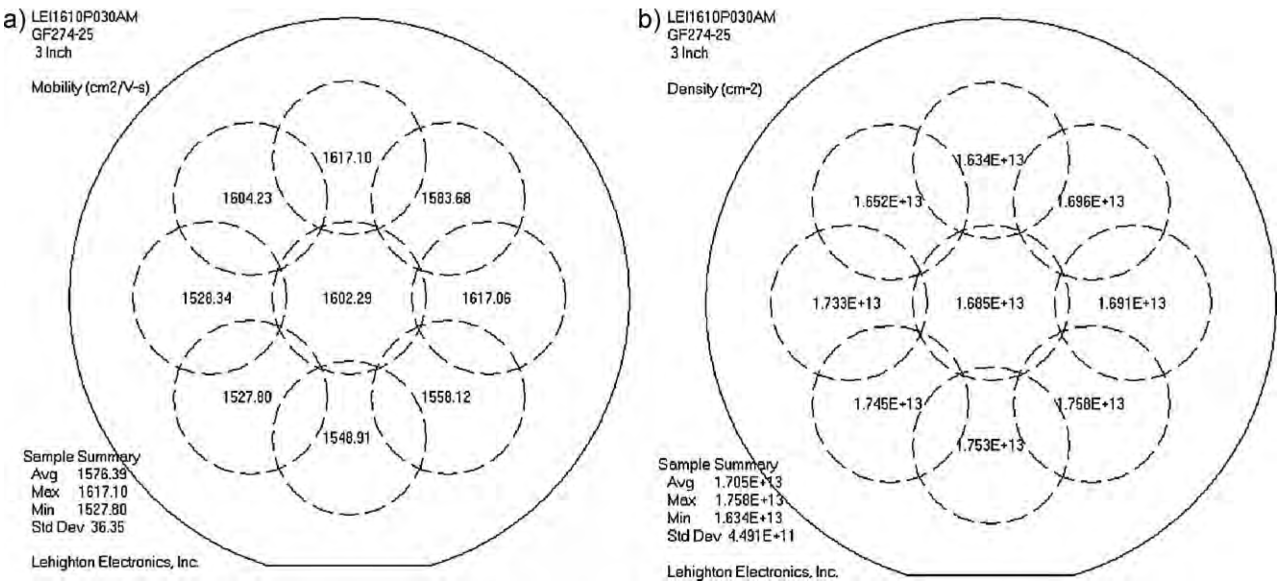


**Figure 4** (a) Mobility and (b) sheet charge density maps of an AlInN HEMT measured by Lehighton contactless Hall systems.

Lehighton. However, the average $n_s$ is $2.16 \times 10^{13}\,\mathrm{cm}^{-2}$, which is almost 20% higher than the contactless test value. Further study is under pursued to understand the test discrepancy between two measurements. The lower sheet charge density in this work is believed to be partially due to the thinner AlInN barrier thickness (13 nm in Ref. [8] *vs.* ~8 nm in this work). A similar sheet charge density value was recently reported by the same group with a thin barrier thickness [9].

Atomic force microscopic (AFM) image was taken from the AlInN terminated surface from an AlInN HEMT wafer, as shown in Fig. 5. The total surface roughness in terms of RMS is 0.31 nm measured from a 5 μm × 5 μm area. This value is around the same level measured from GaN terminated AlGaN/GaN HEMT wafers. However, the surface morphology of the AlInN terminated surface shows some nanostructures with a diameter of 10–100 nm and height of ~1 nm, which is significantly different comparing to the atomically smooth GaN terminated surfaces. It is possible that these nanostructures are associated with indium segregation similar to the same phenomenon observed in the thin InGaN layer grown on a GaN buffer. Detailed segregation mechanism needs further investigation.

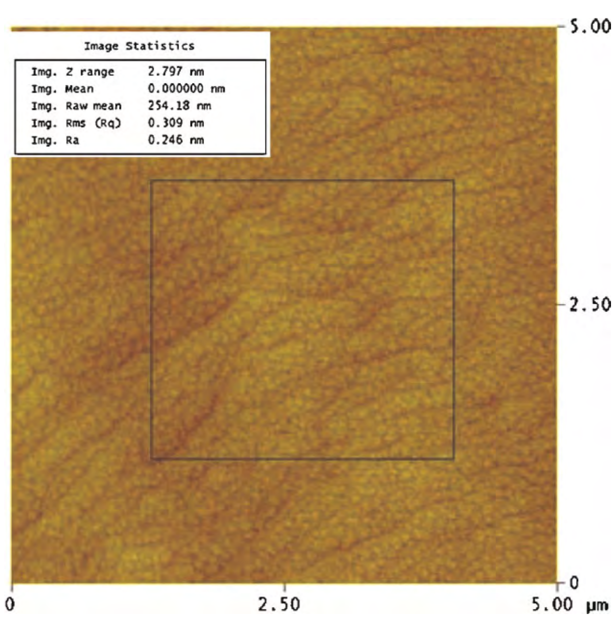


**Figure 5** (online color at: www.pss-a.com) AFM image from AlInN terminated HEMT (5 μm × 5 μm).

**4 Device fabrication and characterization** Device process was performed at both AFRL and MIT (Massachusetts Institute of Technologies). Details of the device process have been reported elsewhere at Refs. [10, 11]. The average contact resistance as measured by linear transmission line model (TLM) for the wafer was 0.47 Ω mm with a standard deviation of 0.12 Ω mm at AFRL. Similar contact resistance was obtained at MIT. The TLM measurements have a correlation coefficient of better than 0.999. Material sheet resistance measured by TLMs structures was 213 Ω/□ from the same wafer shown in Figs. 3 and 4, which was in good agreement with the Lehighton Eddy current measurements shown in Fig. 3.

Figure 6 shows the DC characteristics of an AlInN/GaN HEMT with a gate length of 0.1 μm and 25 nm $Al_2O_3$ passivation process at MIT. The maximum drain current ($I_{DS,max}$) at $V_{GS} = 2$ V is 2.36 A/mm, which is almost two times higher than that from conventional AlGaN/GaN HEMT. Figure 7 shows transconductance ($g_{m,max}$) at $V_{DS} = 5$ V of a gate recessed AlInN/GaN HEMT with a gate length of 0.15 μm and 25 nm $Al_2O_3$ passivation. Owing to the improvement by $Al_2O_3$ passivation as well as the low

 

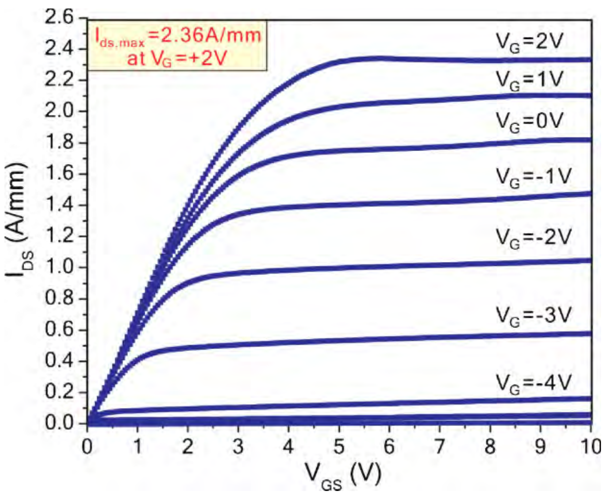


**Figure 6** (online color at: www.pss-a.com) DC current–voltage characteristics of an AlInN/GaN HEMT ($L_G = 0.1$ μm, 25 nm $Al_2O_3$ passivation) with a high maximum output current of 2.36 A/mm.

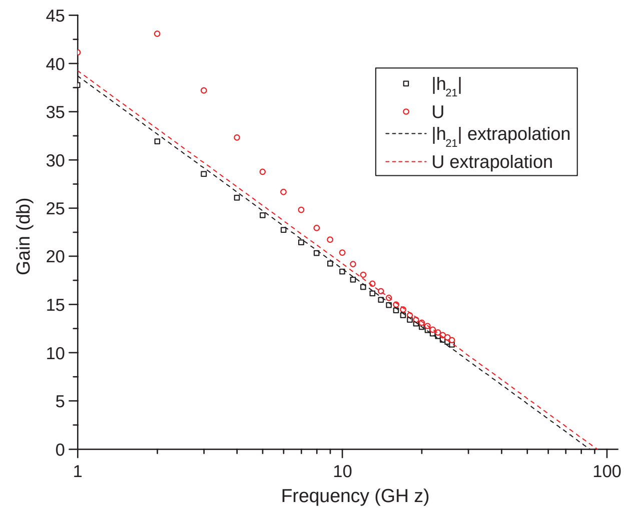


**Figure 8** (online color at: www.pss-a.com) Frequency response of the 9.8 nm total barrier height 2 × 150 AlInN/GaN HEMT.

damage gate recess (final AlInN barrier thickness: 3–4 nm), 0.15 μm gate length devices exhibited a high maximum output current density of $I_{d,max} = 1.5$ A/mm with a record peak extrinsic transconductance of $g_{m,ext} = 675$ mS/mm. The combination of high current density and transconductance in a single AlInN/GaN HEMT is very promising especially for high frequency high power applications.

Excellent frequency response was obtained from similar structure when processed with a gate length of 0.16 μm and 100 nm $Si_3N_4$ passivation at AFRL. Small signal *s*-parameter measurements were performed at $V_{DS} = 10$ V and $V_{GS} = 0$ V. The frequency was swept from 1 to 26 GHz in 1 GHz increments. These gave an extrapolated unity current gain cutoff frequency, $f_T$, of 86 GHz and the unilateral power gain maximum frequency of oscillation, $f_{max}$, of 91.7 GHz at $g_{m\text{-}peak}$, as shown in Fig. 8. Similar results were also observed at MIT.

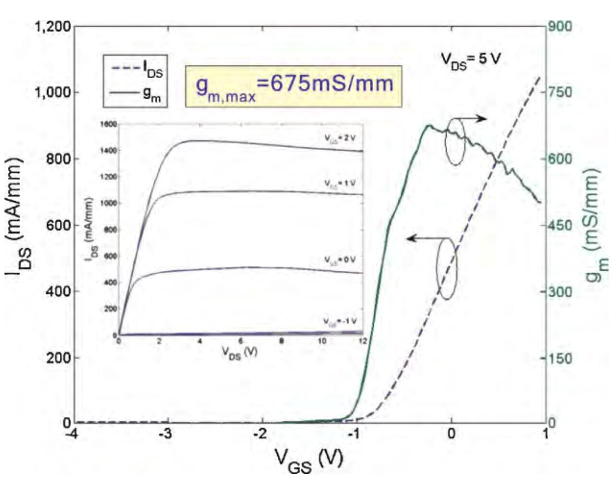


**Figure 7** (online color at: www.pss-a.com) Transconductance curve of a gate recessed AlInN/GaN HEMT ($L_G = 0.15$ μm, 25 nm $Al_2O_3$ passivation) with a record peak extrinsic transconductance of 675 mS/mm. The insets show $I_{DS,max}$ at different $V_{GS}$.

## 5 Conclusions

High quality AlInN/GaN HEMT structures with sub-10 nm AlInN barrier were grown on SiC substrates by MOVPE. The low $R_{sh}$ of 209 Ω/sq was obtained with an excellent standard deviation of 1.1% across 3″ wafers. RT Lehighton contactless Hall tests show a high mobility of 1617 $cm^2$/V s and sheet charge density of 1.76 × $10^{13}/cm^2$. Low ohmic contact resistance of 0.39 Ω mm was achieved. DC characteristics of an AlInN/GaN HEMT with a gate length of 0.1 μm and 25 nm $Al_2O_3$ passivation show maximum drain current ($I_{DS,max}$) of 2.36 A/mm at $V_{GS} = 2$ V. Gate recessed devices with 0.15 μm gate length and thin $Al_2O_3$ passivation from another AlInN HEMT wafer resulted in $g_m$ of 675 mS/mm, the highest value ever reported in AlInN transistors. Excellent frequency response was obtained with a maximum $f_T$ of 86 GHz and $f_{max}$ of 91.7 GHz.

**Acknowledgements** This project was supported in part by the AFRL contract FA8650-08-C-1443.

## References

[1] G. Jessen, R. Fitch, J. Gillespie, G. Via, A. Crespo, D. Langley, D. Denninghoff, M. Trejo, and E. Heller, IEEE Trans. Electron Devices **54**(10), 2589–2597 (2007).

[2] M. Higashiwaki, T. Mimura, and T. Matsui, Appl. Phys. Express **1**(2), 021103 (2008).

[3] F. Medjdoub, J.-F. Carlin, M. Gonschorek, E. Feltin, M. A. Py, D. Ducatteau, C. Gaquiere, N. Grandjean, and E. Kohn, International Electron Devices Meeting (IEDM 2006), 11–13 Dec. 2006, pp. 1–4.

[4] J. Joh, and J. A. del Alamo, International Electron Devices Meeting (IEDM, 2006), 11–13 Dec. 2006, pp. 415–418.
[5] J. Kuzmík, Semicond. Sci. Technol. **17**, 540–544 (2002).
[6] R. Butté, J.-F. Carlin, E. Feltin, M. Gonschorek, S. Nicolay, G. Christmann, D. Simeonov, A. Castiglia, J. Dorsaz, H. J. Buehlmann, S. Christopoulos, G. Baldassarri Höger von Högersthal, A. J. D. Grundy, M. Mosca, C. Pinquier, M. A. Py, F. Demangeot, J. Frandon, P. G. Lagoudakis, J. J. Baumberg, and N. Grandjean, J. Phys. D, Appl. Phys. **40**(20), 6328–6344 (2007).
[7] M. Trejo, G. H. Jessen, A. Crespo, J. K. Gillespie, D. Langley, D. Denninghoff, G. D. Via, J. Carlin, D. Tomich, J. Grant, and H. Smith, CS Mantech Conference, April 2008, pp. 129–132.
[8] M. Gonschorek, J.-F. Carlin, E. Feltin, M. A. Py, and N. Grandjean, Appl. Phys. Lett. **89**(6), 062106 (2006).
[9] M. Gonschorek, J.-F. Carlin, E. Feltin, M. A. Py, N. Grandjean, V. Darakchieva, B. Monemar, M. Lorenz, and G. Ramm, J. Appl. Phys. **103**(9), 093714 (2008).
[10] J. W. Chung, O. I. Saadat, J. M. Tirado, X. Gao, S. Guo, and T. Palacios, IEEE Electron Device Lett. **30**(9), 904–906 (2009).
[11] A. Crespo, M. M. Bellot, K. D. Chabak, J. K. Gillespie, G. H. Jessen, V. Miller, M. Trejo, G. D. Via, D. E. Walker Jr., B. W. Winningham, H. E. Smith, T. A. Cooper, X. Gao, and S. Guo, IEEE Electron Device Lett. **31**(1), 2–4 (2010).