

ANALYSIS OF STEP-VELOCITY DEPENDENCES OF CARBON CONCENTRATION IN c- AND m-PLANE GaN HOMOEPITAXIAL LAYERS

Mishima, Tomoyoshi / Ohta, Hiroshi / Mochizuki, Kazuhiro
/ Horikiri, Fumimasa

(出版者 / Publisher)

法政大学イオンビーム工学研究所

(雑誌名 / Journal or Publication Title)

PROCEEDINGS OF THE 39th SYMPOSIUM ON MATERIALS SCIENCE AND ENGINEERING
RESEARCH CENTER OF ION BEAM TECHNOLOGY HOSEI UNIVERSITY (December 16,
2020)

(巻 / Volume)

39

(開始ページ / Start Page)

25

(終了ページ / End Page)

28

(発行年 / Year)

2021-02-26

(URL)

<https://doi.org/10.15002/00025847>

ANALYSIS OF STEP-VELOCITY DEPENDENCES OF CARBON CONCENTRATION IN *c*- AND *m*-PLANE GaN HOMOEPITAXIAL LAYERS

Kazuhiro Mochizuki[#], Fumimasa Horikiri¹, Hiroshi Ohta, Tomoyoshi Mishima
*Research Center of Ion Beam Technology, Hosei University, 3-7-2, Kajino-cho,
Koganei, Tokyo 184-8584, Japan*

¹*SCIOCS Co. Ltd., 880, Isagozawa-cho, Hitachi, Ibaraki 319-1418, Japan*

Reported step-velocity dependences of carbon concentration in *c*- and *m*-plane GaN homoepitaxial layers were successfully reproduced based on a step-edge segregation model with the following assumptions: 1) the diffusion coefficient of carbon in GaN is 2×10^{-13} cm²/s (@ 1000°C–1100°C); 2) the length of time before the carbon concentration at the step-edge site reaches its equilibrium value is sufficiently shorter than the meantime until a carbon atom incorporated at the kink site moves through the step-edge site to the surface site.

I. Introduction

Toward the realization of an advanced energy-saving society, group-III-nitride semiconductors have been used for highly efficient electronic^{1,2)} and optical devices.³⁾ For the performance improvement of such devices, it is necessary to reduce the carbon impurity, which is known to create deep levels.⁴⁻⁹⁾ In the case of GaN power devices with breakdown voltage exceeding 1 kV, the carrier concentration in the n-type drift layer has to be lower than 1×10^{16} cm⁻³.¹⁰⁾ Metalorganic vapor-phase epitaxy (MOVPE) under unoptimized growth conditions, however, results in carbon concentration on the order of 10^{16} cm⁻³ in GaN layers.¹¹⁾ In the case of green laser diodes, on the other hand, the growth temperature T_g for p-type (Al)GaN layers has to be low (about 900°C) to avoid thermal degradation of high-In content InGaN/GaN multi-quantum wells.¹²⁾ Such low T_g during MOVPE induces severe carbon incorporation, resulting in high-resistivity p-(Al)GaN.¹³⁾

With respect to the understanding of impurity segregation, MOVPE growth on vicinal surfaces should be effective on the basis that an impurity can segregate not only at the surface site,¹⁴⁾ but also at the step-edge sites (Fig. 1). In the case of nitrogen segregation during liquid-phase epitaxy of GaP, Nishinaga et al. proposed a step-edge segregation model in which part of the impurity atoms incorporated at the kink site is assumed to escape from the step-edge site.^{15,16)} They expressed the

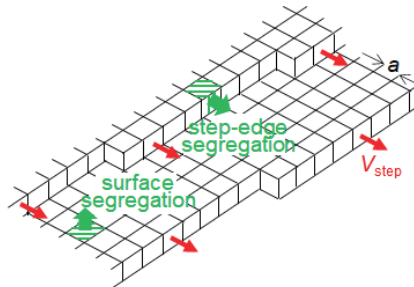


Fig. 1. Schematic illustration of step-edge and surface segregation on a growing stepped surface. V_{step} : average step velocity; a : lattice constant.

[#] e-mail: kazuhiro.mochizuki.66@hosei.ac.jp

segregation coefficient, k , as

$$k = k_{\text{surf}} + (k_{\text{step}} - k_{\text{surf}}) \exp(-D/V_{\text{step}} a), \quad (1)$$

where k_{surf} and k_{step} are the equilibrium segregation coefficients at the surface and step-edge sites, respectively, D is the diffusion coefficient in the solid, V_{step} is the average step velocity, and a is the lattice constant. Equation (1) holds when the length of time before the impurity concentration at the step-edge site reaches its equilibrium value, τ_{step} , is sufficiently shorter than the meantime until an impurity incorporated at the kink site moves through the step-edge site to the surface site, τ .

Considering a large strain around the carbon occupying a gallium site (C_{Ga}) in GaN (because of the bond length of C_{Ga} being 18%–26% shorter than the GaN bulk bond length),^{4,17-19} Mochizuki et al. assumed that the segregation coefficient of C_{Ga} is less than unity.²⁰ They also assumed that the concentration ratio of carbon adatoms to gallium adatoms in the vicinity of the step-edge site was about the same as the concentration ratio of carbon adatoms to gallium adatoms at the surface site and rewrote Eq. (1) as²⁰

$$N = N_{\text{surf}} + (N_{\text{step}} - N_{\text{surf}}) \exp(-D/V_{\text{step}} a), \quad (2)$$

where N is the carbon concentration in GaN layers, N_{surf} is the equilibrium carbon concentration at the surface site, and N_{kink} is the equilibrium carbon concentration at the kink site. In the case of polar c -plane GaN homoepitaxial layers [Fig. 2(a)], they reproduced the reported experimental results²¹⁻²³ using Eq. (2) with $D = 2 \times 10^{-13}$ cm²/s and $a = 0.30$ nm.²⁰

In the case of non-polar m -plane GaN homoepitaxial layers [Fig. 2(b)], on the other hand, Yamada et al. experimentally reported the dependence of N on V_{step} . Accordingly, in this report, the reported V_{step} dependence of N in m -plane GaN layers is analyzed and compared to the reported analysis for the V_{step} dependence of N in c -plane GaN layers.²⁴

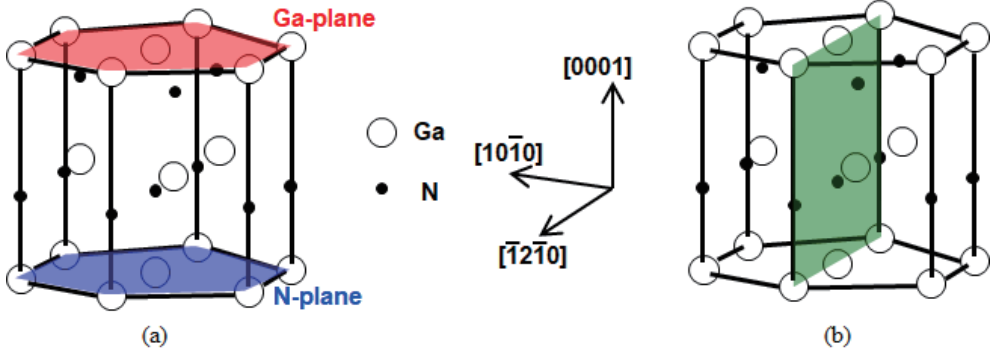


Fig. 2. (a) Polar c -plane and (b) nonpolar m -plane in the GaN wurtzite crystal unit cell.

II. Analysis

The surface atomic density in the solid, n , is 0.61×10^{15} cm⁻² on an m -plane and 1.14×10^{15} cm⁻² on a c -plane.²⁵ By simply assuming the simple cubic lattice shown in Fig. 1, a ($= n^{-0.5}$) is calculated to be 0.40 nm on an m -plane and 0.30 nm on a c -plane. As shown in Fig. 3, D of 2×10^{-13} cm²/s well reproduces the results for c - (i.e., Ga-, N-) and m -plane growths.

III. Discussion

Cao et al. measured the concentration–depth profiles of carbon implanted into GaN at doses of $3\text{--}5 \times 10^{14} \text{ cm}^{-2}$ and found that D is less than $2 \times 10^{-13} \text{ cm}^2/\text{s}$ even after annealing at 1450°C .²⁶⁾ Judging from the similar D fitted in the case of T_g of 1000°C ²⁴⁾– 1100°C ²¹⁾ (Fig. 3), we consider the step-edge segregation model is adequate for describing carbon segregation during MOVPE of GaN.

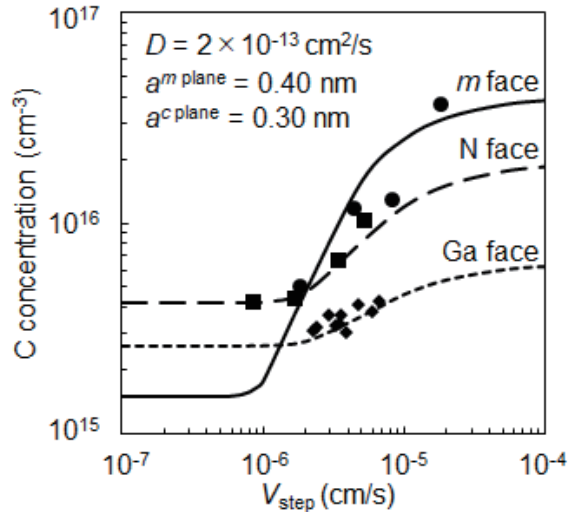


Fig. 3. Step-velocity dependences of carbon concentration fitted to the reported results.^{21–24)}

IV. Conclusions

Based on the step-edge-segregation model, the reported step-velocity dependences of carbon concentration in c - and m -plane GaN homoepitaxial layers were reproduced by assuming $D = 2 \times 10^{-13} \text{ cm}^2/\text{s}$ (@ 1000°C – 1100°C) and $\tau_{\text{step}} \ll \tau$.

References

- 1) B. J. Baliga, Gallium Nitride and Silicon Carbide Power Devices (World Scientific, Singapore, 2017).
- 2) K. Mochizuki, Vertical GaN and SiC Power Devices (Artech House, Boston, 2018).
- 3) S. Nakamura and G. Fasol, The Blue Laser Diode: GaN Based Light Emitters and Lasers (Springer, Berlin, 1997).
- 4) J. L. Lyons, A. Janotti, and C. G. Van de Walle, Appl. Phys. Lett. 97, 152108 (2010).
- 5) M. A. Reshchikov, D. O. Demchenko, A. Usikov, H. Helava, and Y. Makarov, Phys. Rev. B 90, 235203 (2014).
- 6) N. Sawada, T. Narita, M. Kanechika, T. Uesugi, T. Kachi, M. Horita, T. Kimoto, and J. Suda, Appl. Phys. Express 11, 041001 (2018).
- 7) F. Horikiri, Y. Narita, T. Yoshida, C. Ito, V. Gupta, and A. Somanchi, Dig. Int. Conf. Compound Semiconductor Manufacturing Technology (Austin), 2018 paper 7.2.
- 8) K. Kojima, F. Horikiri, Y. Narita, T. Yoshida, H. Fujikura, and S. F. Chichibu, Appl. Phys. Express 13, 012004 (2020).
- 9) K. Shiojima, F. Horikiri, Y. Narita, T. Yoshida, and T. Mishima, Phys. Status Solidi B, 1900561 (2019).
- 10) T. Kachi, Jpn. J. Appl. Phys. 53, 100210 (2014).
- 11) Y. Inatomi, Y. Kangawa, A. Pimpinelli, and T. L. Einstein, Phys. Rev. Mater. 3, 013401 (2019).
- 12) D. Queren, M. Schillgalies, A. Avramescu, G. Brüderl, A. Laubsch, S. Lutgen, and U. Strauß, J. Cryst. Growth 311, 2933 (2009).
- 13) J. Yang et al., J. Appl. Phys. 115, 163704 (2014).
- 14) A. A. Chernov, in Modern Crystallography III Crystal Growth, ed. A. A. Chernov

- (Springer, Berlin, 1984), p. 187.
- 15) T. Nishinaga, C. Sasaoka, and K. Pak, *Jpn. J. Appl. Phys.* 28, 836 (1989).
 - 16) T. Nishinaga, K. Mochizuki, H. Yoshinaga, and M. Washiyama, *J. Cryst. Growth* 98, 98 (1989).
 - 17) P. Boguslawski and J. Bernhol, *Phys. Rev. B* 56, 9496 (1997).
 - 18) A. F. Wright, *J. Appl. Phys.* 92, 2575 (2002).
 - 19) L. Bellaiche, S.-H. Wei, and A. Zunger, *Phys. Rev. B* 56, 10233 (1997).
 - 20) K. Mochizuki, F. Horikiri, H. Ohta, and T. Mishima, *Jpn. J. Appl. Phys.* 59, 068001 (2020).
 - 21) K. Nagamatsu, Y. Ando, T. Kono, H. Cheong, S. Nitta, Y. Honda, M. Pristovsek, and H. Amano, *J. Cryst. Growth* 512, 78 (2019).
 - 22) F. Horikiri, Y. Narita, T. Yoshida, T. Kitamura, H. Ohta, T. Nakamura, and T. Mishima, *Jpn. J. Appl. Phys.* 56, 061001 (2017).
 - 23) F. Horikiri, Y. Narita, T. Yoshida, T. Kitamura, H. Ohta, T. Nakamura, and T. Mishima, *IEEE Trans. Semicond. Manuf.* 30, 486 (2017).
 - 24) H. Yamada, H. Chonan, T. Takahashi, and M. Shimizu, *Jpn. J. Appl. Phys.* 57 (2018) 04FG01.
 - 25) S. C. Cruz, S. Keller, T. E. Mates, U. K. Mishra, S. P. DenBaars, *J. Cryst. Growth* 311 (2009) 3817.
 - 26) X. A. Cao et al., *J. Electron. Mater.* 28, 261 (1999).