SCIENCE CHINA
Information Sciences

• LETTER •

November 2023, Vol. 66 219403:1–219403:2
https://doi.org/10.1007/s11432-022-3668-0

Defect evolution in GaN thin film heterogeneously integrated with CMOS-compatible Si(100) substrate by ion-cutting technology

Hangning SHI[1,2], Ailun YI[1,2], Jiaxin DING[1,2], Xudong LIU[1,2], Qingcheng QIN[1,3], Juemin YI[4], Junjie HU[4], Miao WANG[4], Demin CAI[5], Jianfeng WANG[4,5], Ke XU[4,5], Fengwen MU[6], Tadatomo SUGA[7], René HELLER[8], Mao WANG[8,9], Shengqiang ZHOU[8], Wenhui XU[1,2], Kai HUANG[1,2], Tiangui YOU[1,2*] & Xin OU[1,2*]

[1] *State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai* 200050*, China;*
[2] *University of Chinese Academy of Sciences, Beijing* 100049*, China;*
[3] *School of Materials and Chemistry, University of Shanghai for Science and Technology, Shanghai* 200093*, China;*
[4] *Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, Suzhou* 215123*, China;*
[5] *Suzhou Nanowin Science and Technology Co., Ltd., Suzhou* 215123*, China;*
[6] *SABers Co., Ltd., Tianjin* 300451*, China;*
[7] *Collaborative Research Center, Meisei University, Hino-shi, Tokyo* 191-8506*, Japan;*
[8] *Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Bautzner Landstrße 400, Dresden* 01328*, Germany;*
[9] *College of Physics and Electronic Engineering, Sichuan Normal University, Chengdu* 610101*, China*

Received 3 August 2022/Revised 29 September 2022/Accepted 25 December 2022/Published online 20 October 2023

Citation Shi H N, Yi A L, Ding J X, et al. Defect evolution in GaN thin film heterogeneously integrated with CMOS-compatible Si(100) substrate by ion-cutting technology. Sci China Inf Sci, 2023, 66(11): 219403, https://doi.org/10.1007/s11432-022-3668-0

Ion-cutting technology is an ingenious solution to the high-quality heterogeneous integration of GaN thin films with CMOS-compatible Si(100) substrate, which provides a platform to combine GaN-based optoelectronics, high-frequency and high-power electronics with digital signal processing, logic computation, and control of Si(100) CMOS [1]. Previously, we reported the fabrication of 2-inch GaN film on SiO_2/Si(100) substrate (GaNOI) by the ion-cutting technology [2]. In this study, we further study the defect evolution in the transferred GaN films, which is needed to promote the practical applications of the GaNOI material platform.

Experiments. The detailed fabrication process of GaNOI was previously reported [2]. The free-standing GaN bulk wafer was implanted with hydrogen (H) ions and then bonded with a SiO_2/Si(100) handle wafer by the surface activated bonding technology. The GaN film was transferred onto the handle wafer after annealing at 450°C (marked as GaNOI-AT), and some of the GaNOI pieces were post-annealed at 800°C (marked as GaNOI-PA). See Appendix A for the detailed introduction and experiments.

Results and discussions. Scanning transmission electron microscopy (STEM) was used to evaluate the defect evolution and to characterize the microstructures of the GaN films. Figures 1(a)–(c) and (d)–(f) show the HAADF-STEM images of GaNOI-AT and GaNOI-PA, respectively. The high-magnification images shown in Figures 1(b) and (c) suggest that the GaNOI-AT near the surface layer was heavily damaged by H ion implantation, which was filled with point-like nano-cavity defects and clusters as marked by the red circles in Figure 1(b). Figure 1(c) shows the distorted and chaotic GaN lattice caused by the H ions. After post-annealing at 800°C, plenty of larger-volume cavity defects were formed in the near surface region of the GaNOI-PA as shown in Figure 1(e), while the lattice of GaN shown in Figure 1(f) was recovered. Most of the residual H ions from the ion-slicing process were released from the lattice of the as-transferred GaN film during the post-annealing process, which can be absorbed by the nano-cavity defects and clusters via the migration-coalescence (MC) mechanism as the precursor of larger cavity defects. The cavity defects evolve and grow up continuously due to the effect of the Ostwald ripening (OR) mechanism in which the small cavities dissolve and merge into large cavity defects [3]. In the meantime, the GaN lattice was recovered.

The optical properties of the GaN films were investigated by temperature-dependent photoluminescence (PL) spectra from 5 K to 300 K as shown in Figure 1(g). For the GaNOI-AT, extremely weak near-band-edge (NBE) emission peaking at 357 nm was detected only at a low temperature of 5 K as marked by the red box of the magnified spectrum, while

* Corresponding author (email: t.you@mail.sim.ac.cn, ouxin@mail.sim.ac.cn)

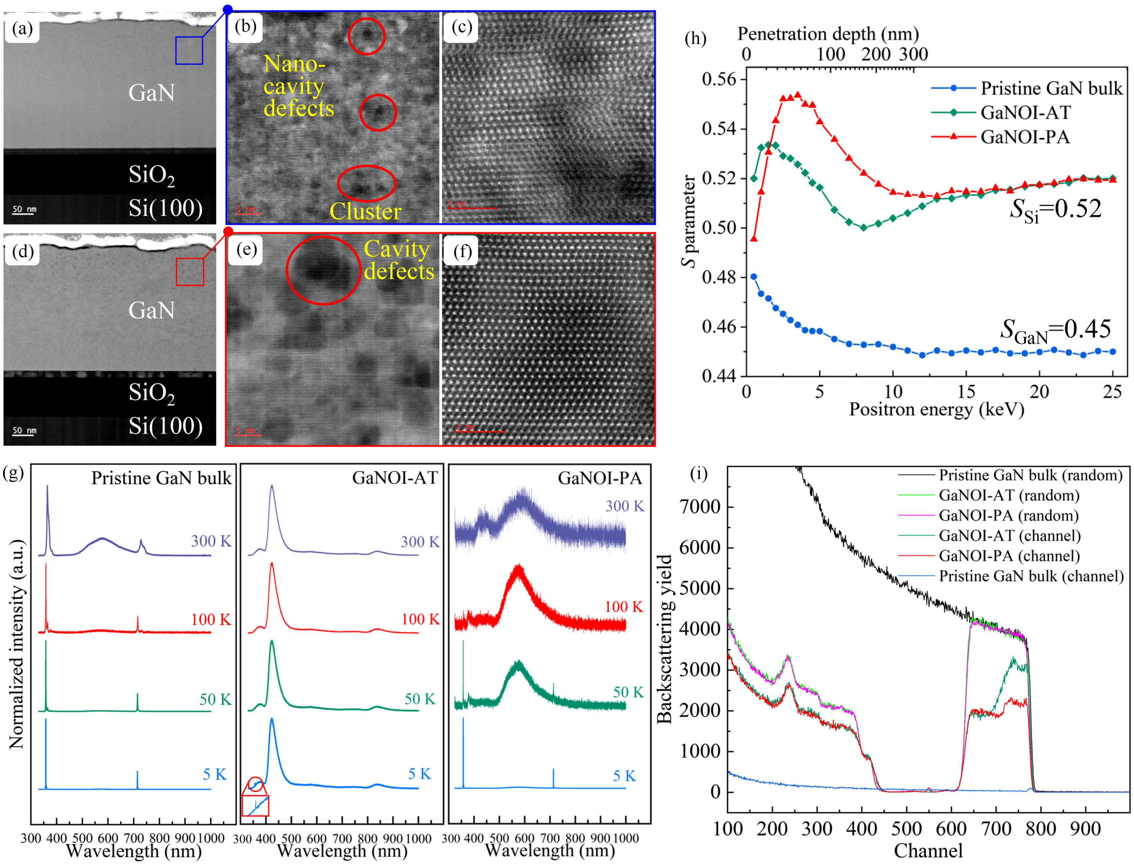

Figure 1 (Color online) (a) High-angle annular dark-field (HAADF)-STEM image of the GaNOI-AT. (b) High-magnification and (c) atomic-resolution HAADF-STEM images of the GaNOI-AT near the surface layer. (d) HAADF-STEM image of the GaNOI-PA. (e) High-magnification and (f) atomic-resolution HAADF-STEM images of the GaNOI-PA near the surface layer. (g) Normalized temperature-dependent PL spectra. (h) S parameter as a function of incident positron energy. (i) Results of Rutherford backscattering in channeling mode (RBS/C) and in random mode.

the NBE emission disappeared immediately as the temperature increased due to the severe lattice damage caused by H ion implantation leading to the annihilation of exciton transitions. After the post-annealing process, the NBE emission peaking at 357 nm at the temperature below 100 K was recovered due to the recovery of the GaN lattice.

The positron annihilation spectroscopy (PAS) of Doppler broadening S parameter depth profile measurements were carried out to identify the dominant vacancy-related defect type as shown in Figure 1(h). In the energy range of 2 to 10 keV, the S parameter for the GaNOI-AT is significantly greater than that of GaN bulk, which is further increased for the GaNOI-PA. The greater S parameter indicates the bigger open-volume defects [4], indicating that the dominating defects are nano-cavities for the GaNOI-AT and larger size cavity defects for the GaNOI-PA. The defect distribution and lattice disorder of the GaN films were investigated utilizing RBS/C measurement as shown in Figure 1(i). See Appendix B for the detailed results and discussion.

Conclusion. The defects and their thermo-evolution in the hetero-integrated GaN films on Si(100) substrate were thoroughly studied. The nano-cavity defects and residual H ions in the as-transferred GaN film evolved into larger size cavity defects due to the OR mechanism and MC mechanism, while the GaN lattice was recovered and the NBE emission of the post-annealed GaN film at low temperature reappeared. The results of PAS and RBS also confirmed the evolution of defects and the recovery of GaN lattice.

Acknowledgements This work was supported by National Key Research and Development Program of China (Grant No. 2021YFB3601900), National Natural Science Foundation of China (Grant Nos. 62174167, 62293520, 62293521), Shanghai Rising-Star Program (Grant No. 22QA1410700), Shanghai Basic Research Project (Grant No. 22JC1403300), and K. C. Wong Education Foundation (Grant No. GJTD-2019-11).

Supporting information Appendixes A and B. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Then H W, Radosavljevic M, Jun K, et al. Gallium nitride and silicon transistors on 300 mm silicon wafers enabled by 3-D monolithic heterogeneous integration. IEEE Trans Electron Dev, 2020, 67: 5306–5314
2 Shi H, Huang K, Mu F, et al. Realization of wafer-scale single-crystalline GaN film on CMOS-compatible Si(100) substrate by ion-cutting technique. Semicond Sci Technol, 2020, 35: 125004
3 Huang K, You T, Jia Q, et al. Defects induced by MeV H+ implantation for exfoliating of free-standing GaN film. Appl Phys A, 2018, 124: 118
4 Moutanabbir O, Scholz R, Gösele U, et al. Experimental elucidation of vacancy complexes associated with hydrogen ion-induced splitting of bulk GaN. Phys Rev B, 2010, 81: 115205