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Coordinated B diffusion Gaussian distribution AlGaN/GaN HEMT device by quasi-van der Waals epitaxy

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AlGaN/GaN high electron mobility transistors (HEMTs) have excellent electron mobility, breakdown voltage, and power density, making them integral to radio frequency (RF) technology. However, lower switching ratios lead to signal delay and distortion under high-frequency conditions [1–4]. This study introduces an innovative mechanism based on coordinated B diffusion Gaussian distribution based on quasi-van der Waals epitaxy to achieve an AlGaN/GaN HEMT with a high $I_{\rm on}/I_{\rm off}$ ratio. h-BN layer pretreated via ion implantation served as the boron source, enabling a two-stage coordinated distribution in the back barriers. This approach prevented threading dislocations from propagating upward and effectively increasing the barrier height. The $I_{\rm on}/I_{\rm off}$ ratio was improved by three orders of magnitude, reaching 10^{10}. These findings advance the development of high-performance electronic components, supporting innovations in 5G communications, the Internet of Things, and intelligent transportation systems.

Experimental results. As illustrated in Figure 1(a), this study presents an HEMT device with a SiC/h-BN/AlN/GaN/AlGaN structure, where the Al component in the AlGaN layer accounts for 25%. The TEM image on the left side of Figure 1(b) reveals numerous penetrating dislocations in the GaN film without B diffusion. Conversely, the TEM image on the right side demonstrates that with coordinated B diffusion, the dislocation annihilation depth in the GaN film is as low as 168 nm. This is because boron atoms accumulate in the dislocation regions, converting vertical dislocations into lateral stacking faults, effectively preventing dislocation extension.

Figure 1(c) compares the output curves of devices on two different structures, with the gate voltage ranging from −9 to 1 V in 2 V steps. The maximum saturation current of the HEMT device without B diffusion is 1103 mA/mm, while the device with B diffusion achieves an increased maximum saturation current of 1448 mA/mm. Figure 1(d) presents the transfer curves in linear coordinates, demonstrating a 33.4% increase in saturation current at a drain bias of 5 V. Figure 1(e) displays the transfer curves of the device in logarithmic coordinates over a test range of −14 to 2 V in steps of 1 V. The HEMT device with B diffusions achieved an $I_{\rm on}/I_{\rm off}$ ratio as high as 10^{10}, attributed to coordinated B diffusion, which increased the back barrier of the channel.

As shown in Figure 1(f), the HEMT devices fabricated in this study demonstrated industry-leading switching ratio performance, along with superior electron transport properties. These findings underscore the effectiveness of h-BN films in enhancing the quality of nitride films and improving device performance through coordinated B diffusion and quasi-van der Waals epitaxy. The schematic diagram of the two-stage boron diffusion process in the coordinated B diffusion Gaussian distribution, as shown in Figures 1(g) and (h), clearly illustrates the characteristics of these two phases through graphical representation. Phase one: boron atoms diffuse along defect pathways into the deeper regions of the AlN layer, accumulating to form enrichment zones within the highly defective AlN nucleation layer. Phase two: the boron atoms undergo outward diffusion from these enriched zones. This diffusion process exhibits a certain time lag relative to the epitaxial growth process, resulting in significantly reduced boron concentration within intact crystal lattices. This mechanism effectively prevents the detrimental effects of high-concentration doping on epitaxial layer quality.

Conclusion. Based on the mechanisms of quasi-van der Waals epitaxy and coordinated B diffusion Gaussian distribution, we have developed a novel AlGaN/GaN high electron mobility transistor (HEMT). The h-BN interlayer serves dual functions in this process: as a stress-relief mediator through quasi-van der Waals epitaxy to mitigate interlayer stress and promote thin film

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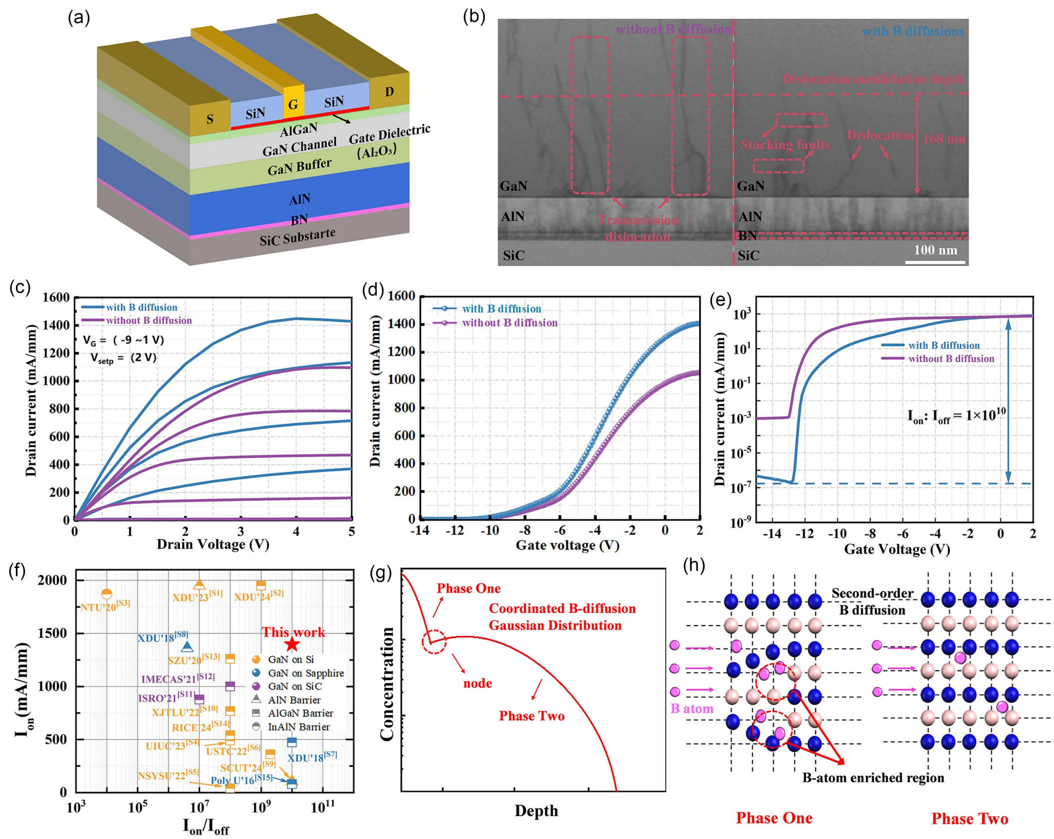

Figure 1 (Color online) (a) Schematic of the AlGaN/GaN HEMT structure; (b) cross-sectional STEM of the full HEMT structure grown on SiC (without B diffusion and with B diffusion); (c) output characteristic curve of the device; (d) DC transfer characteristic curve of the device; (e) DC transfer characteristic in a semi-logarithmic coordinate system; (f) comparison of the saturation output current and switching ratio performance for different HEMT devices; (g) fitting curve of the co-modulated Gaussian distribution of B diffusion; (h) schematic diagram of two-stage B atom diffusion in the coordinated B diffusion Gaussian distribution.

growth while providing nucleation sites, and as a boron source when pre-treated with ion implantation to enable two-stage coordinated B diffusion Gaussian distribution within the heterojunction back barrier. These findings highlight significant advancements in GaN HEMT technology, providing robust support for future high-performance radio frequency and power electronic applications.

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Supporting information Appendix A. 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.

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