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Enhancing the Self-Heating Capability of AlGaN/GaN HEMT Gadgets with Fourth-Generation Semiconductor Components

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Abstract. GaN possesses numerous exceptional properties, such as wide bandgap and high thermal conductivity, which make it an ideal material for fabricating semiconductor devices. The high electric field and current in the channel, coupled with the high power density, make it inevitable that HEMT devices will generate a great deal of heat. Thus, an increase in temperature will unavoidably cause the DC and microwave characteristics of the device to deteriorate. At present, the fourth-generation semiconductor materials with new ultra-broad or ultra-narrow band gaps, mainly Ga_2O_3, GaSb, diamond and AIN, have emerged. In conventional situations, the substrate material will be Si, Sapphire, or the more advanced third-generation material SiC compared to the former, and the passivation layer will use SiN as the material. Our research is in progress to replace the traditional SiN and third-generation SiC with diamond and GaSb.

Keywords. GaN HEMT self-heating fourth-generation semiconductor

1. Introduction

Due to the perpetual advancement of modern technology, the semiconductor industry has become more and more irreplaceable as human society has entered the era of communication networks. In all aspects of our lives, semiconductors are indispensable[1]. The industry fields based on GaN materials, such as future smart grids, cloud computing and cloud native, industrial robots, as well as emerging industries such as HEMT and MESFET, have very broad prospects[2]. GaN has a bandgap of 3.39 eV, making it an ideal choice for producing high-power and devices[3]. Since most devices currently operate in higher temperature environments, conventional packaging and heat dissipation technology can no longer meet the needs of many high-power, high current, and high voltage working environments today. Therefore, the GaN HEMT device needs to be improved from its internal structure. In this article, we have decided to transform three aspects: substrate, passivation layer, and top layer[4]. We will use diamonds as the top and bottom layers. Research has revealed that epitaxial growth of the solid solution material, with GaSb as the substrate, can effectively reduce the stress, defects, and other issues caused by lattice misalignment[5].

By utilizing Silvaco TCAD software, this article has stimulated the GaN HEMT device, examining its self-heating effect, current collapse, current intensity, and transfer

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characteristics.

2. Device Structures and Models

GaN HEMT devices are simulated with Silvaco TCAD software, and Figure 1 displays conventional HEMT devices[6]. The base material is a 2.45 μm SiC layer, and it has a 50 nm AIN nucleation layer on the substrate, which serves to buffer lattice misalignment and thermal stress between the substrate and buffer, thereby creating a good separation and buffering effect[7-11]. Located above the 2.26 μm GaN buffer layer, the source and drain electrodes, measuring 0.6 μm and 0.352 μm respectively, are arranged in a sequence of layers that include a 22 nm AlGaN barrier layer, and a 4 nm GaN cap layer structure. The top layer is the SiN passivation layer[26-30]. The Gummel and Newton combination iterative method is employed for this iterative method[12-25]. Figure 2 displays the device designed by us for the application of fourth-generation semiconductor materials. Diamond is implemented as the substrate material instead of SiC[31]. In addition, GaSb is the passivation layer and diamond is the heat dissipation layer. All other parameters are the same as conventional materials.

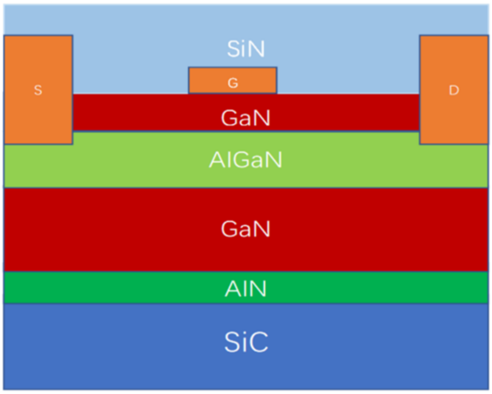

Figure 1. Traditional device structure

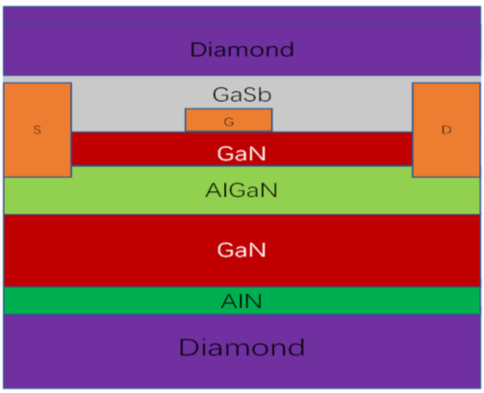

Figure 2. Novel device structure

3. Simulation Results and Discussion

3.1 Heat distribution

Figure 3 and Figure 4 respectively show the temperature distribution of traditional and new devices. From the pictures, we can see that under a gate voltage of 0 V, the heat distribution range of conventional devices is larger and the distribution area is wider. The portion of the device with a temperature of 400 K makes up approximately 13% of the total area[32]. Near the gate electrode, the temperature can reach a maximum of 456 K, while the average temperature near the channel is 420 K, thus diminishing and intensifying lattice scattering, thus diminishing carrier mobility of the channel. In Figure 4, the area where the maximum temperature is located is only 363 K, not exceeding 400 K. Compared to traditional device junctions, the average temperature in the channel region decreases by 24% to only 320 K. Therefore, the new structure has more advantages in heat control[33].

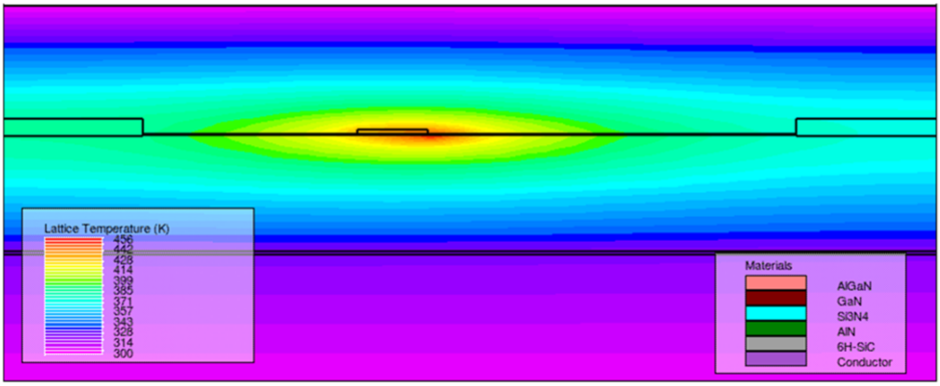

Figure 3. Temperature distribution of traditional device structure.

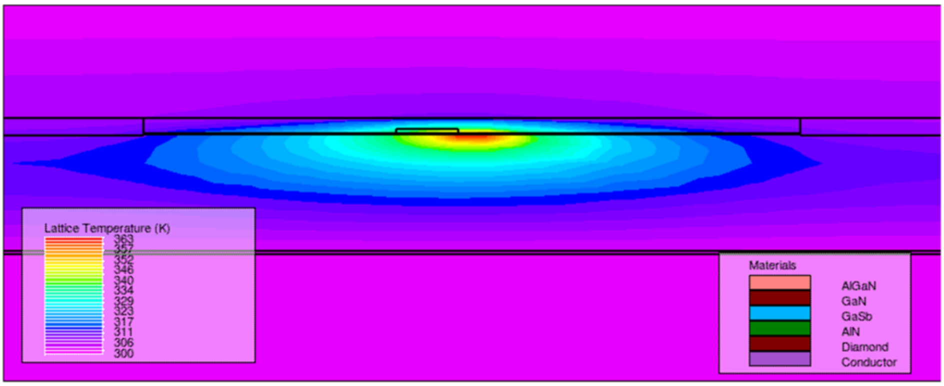

Figure 4. Temperature distribution of Novel device structure.

3.2 Current collapse and peak current

Figure 5 displays the output curves of both conventional and novel structures. The new structure's peak current can reach 1.907 A/mm^{-1}, while the conventional structure's peak current is 1.315 A/mm^{-1}, which is a 45% increase at a gate voltage of 0 V[34]. In the end, the immediate crash rate of the traditional structure is 20%, while the new structure is 3%, reducing it by 17% and achieving significant results.

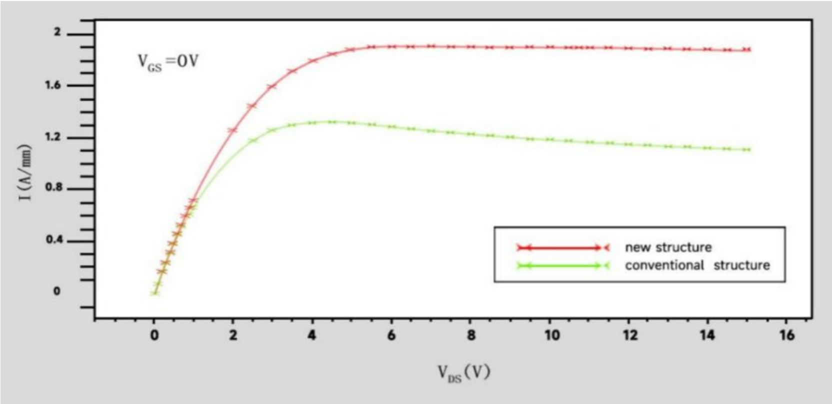

Figure 5. Output curves of traditional device structure and novel device structure.

3.3 Transfer characteristics of devices

The transfer characteristic curves for both the traditional and innovative structures are depicted in Figure 6. Upon examining the figure, it can be seen that the curve of the new structures is closer to the left. As temperature increases, this characteristic becomes more obvious[35]. The output current of the traditional structure drain is smaller than that of the new structure at the identical gate voltage, and it can be deduced that the new device has a more potent gate control capacity through the assessment of its transfer characteristics[36].

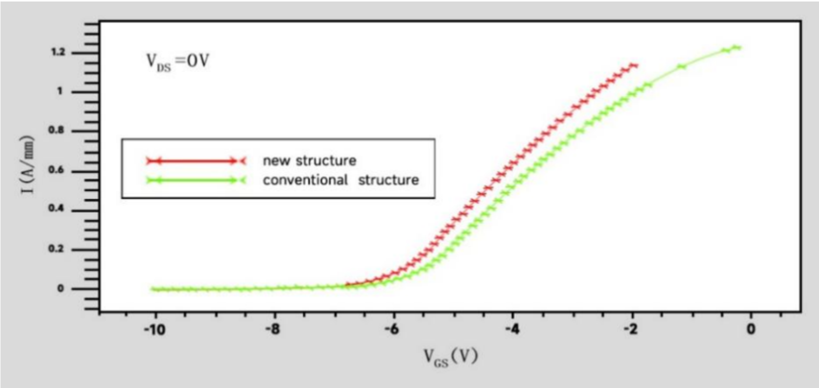

Figure 6. Transfer characteristic curves of traditional device structure and novel device structure.

4. Conclusion

The research into GaN HEMT devices has made tremendous strides, yet their self-heating capability causes a rise in channel temperature, thus making the thermal reliability issue more severe. This study focuses on the application of HEMT devices in high-power areas[37]. We replaced SiC substrate layer and SiN passivation layer with the fourth-generation semiconductor materials diamond and GaSb, respectively. Adding a diamond heat dissipation layer to the top of the device enhances its heat dissipation ability. The mean temperature declined by 24%, the maximum temperature slipped by 93 K, and the peak current slipped by 45%, due to the difference between traditional structures. Furthermore, the rate of current collapse improvement can reach 17% as well. As a result, the new structure proposed in this study improves the thermal and electrical properties of GaN HEMT[38]. Despite the fact that the fourth generation of semiconductors has yet to be extensively employed in many areas, and further evidence is needed to validate it, it is still in the realm of the third generation[39]. Nevertheless, the utilization of the fourth generation of semiconductors in HEMT devices has still been successful[40].

References

[1] Qing-ya Y ,Zhi-xing L ,Qing-ling C , et al.Fatty acid-binding protein gene is indispensable for molting process in Heortia vitessoides(Lepidoptera: Crambidae)[J].Journal of Integrative Agriculture,2023,22(02).

[2] Zhang H ,He C ,Shen L , et al.Membrane-targeting amphiphilic AIE photosensitizer for broad-spectrum bacteria imaging and photodynamic killing of bacteria[J].Chinese Chemical Letters,2023,34(09).

[3] Ding Y ,Wang C ,Pei L , et al.Mn~(4+) activated phosphors in photoelectric and energy conversion devices[J].Journal of Energy Chemistry,2023,86(11).

[4] ZHAO C,TANG W C,LAI B, et al.Low-efficiency-droop InGaN quantum dot light-emitting diodes operating in the “green gap”[J].Photonics Research, 2020,8(05):750-754.

[5] Sun C ,Xu X ,Gui C , et al.High-Quality Epitaxial N Doped Graphene on SiC with Tunable Interfacial Interactions via Electron/Ion Bridges for Stable Lithium-Ion Storage[J].Nano-Micro Letters,2023,15(11).

[6] Yong Liu, Qi Yu, Jiangfeng Du. A novel high breakdown voltage and high switching speed GaN HEMT with p-GaN gate and hybrid AlGaN buffer layer for power electronics applications[J]. Chinese Physics B, 2020,29(12):554-561.

[7] Hu Z ,Zhang F ,Zhou A , et al.Highly Reversible Zn Metal Anodes Enabled by Increased Nucleation Overpotential[J].Nano-Micro Letters,2023,15(10).

[8] SHI H ,YI A ,DING J , et al.Defect evolution in GaN thin film heterogeneously integrated with CMOS-compatible Si(100) substrate by ion-cutting technology[J].Science China(Information Sciences),2023,66(11).

[9] Hao H ,MingHui G ,CongYi W , et al.Lattice Boltzmann study on the effects of surface nanostructure on wettability with application in laser scanning fabrication of superhydrophobic surfaces[J].Science China(Technological Sciences),2023,66(11).

[10] Sun P ,Han S ,Liu J , et al.Introducing oxygen vacancies in TiO_2 lattice through trivalent iron to enhance the photocatalytic removal of indoor NO[J].International Journal of Minerals,Metallurgy and Materials,2023,30(10).

[11] Qian J ,Wen-jun J ,Cheng-xiu Y , et al.Inhibitory Effect of Jingui Shenqi Pills on Glucocorticoid-Enhanced Axial Length Elongation in Experimentally Myopic Guinea Pigs[J].Chinese Journal of Integrative Medicine,2023,29(11).

[12] Zhang Y ,Fan L ,Wang X , et al.Fabrication and luminescence of highly transparent C12A7:Tb~(3+) glass-ceramics via in-situ crystallization from aerodynamic levitation processed glasses[J].Journal of Rare Earths,2023,41(11).

[13] ZHANG Y ,ZHANG C ,YAO T , et al.Stability and Convergence Analysis of Unconditionally Energy Stable and Second Order Method for Cahn-Hilliard Equation[J].Journal of Mathematical Research with Applications,2023,43(06).

[14] Hao H ,MingHui G ,CongYi W , et al.Lattice Boltzmann study on the effects of surface nanostructure on wettability with application in laser scanning fabrication of superhydrophobic surfaces[J].Science China(Technological Sciences),2023,66(11).

[15] Gao T ,Sang X ,Huang X , et al.Macrophage-camouflaged epigenetic nanoinducers enhance chemoimmunotherapy in triple negative breast cancer[J].Acta Pharmaceutica Sinica B,2023,13(10).

[16] Zhang L ,Zheng X ,Liu X , et al.Toxic effects of three perfluorinated or polyfluorinated compounds(PFCs) on two strains of freshwater algae: Implications for ecological risk assessments[J].Journal of Environmental Sciences,2023,131(09).
[17] Hu H ,Yu L ,Ding Z , et al.Chemo–immunotherapy for chemo-resistance and metastasis of triple-negative breast cancer by combination of iron-oxide nanoparticles and dual-targeting doxorubicin liposomes[J].Chinese Chemical Letters,2023,34(10).
[18] Kluge N ,Reinehr S .Two become one:combination of two risk factors in a new glaucoma animal model[J].Neural Regeneration Research,2024,19(05).
[19] Wenye L ,Jianfeng Z ,Shuangshuang S , et al.Combination of artificial zeolite and microbial fertilizer to improve mining soils in an arid area of Inner Mongolia, China[J].Journal of Arid Land,2023,15(09).
[20] Li C ,Gu H ,Tang J , et al.A novel energetic framework with the combination of 5,6-fused triazolo-triazine and nitropyrazole-tetrazole for energy-stability balanced explosive[J].Defence Technology,2023,27(09).
[21] Adelia L A ,Nurainiwati A S ,Putra P Y P , et al.Efficacy, effectiveness, and safety of combination laser and tranexamic acid treatment for melasma: A meta-analysis[J].Chinese Journal of Plastic and Reconstructive Surgery,2023,5(03).
[22] YuHua S ,WenXiang Z ,JingHua J , et al.Torque production mechanism of switched reluctance machines with field modulation principle[J].Science China(Technological Sciences),2023,66(09).
[23] Ren Y ,Yin X ,Xiang L , et al.Layer stacked SiO_x microparticle with disconnected interstices enables stable interphase and particle integrity for lithium-ion batteries[J].Journal of Energy Chemistry,2023,86(11).
[24] JIANG Y ,TU J ,GAO S , et al.Randomly coupled trench-assisted multicore fibers with different arrangements for high tolerance of manufacturing errors[J].Science China(Information Sciences),2023,66(11).
[25] Jiamin S ,Zhongshu L ,Luyi Z , et al.Uniform Convergence Analysis of the Discontinuous Galerkin Method on Layer-Adapted Meshes for Singularly Perturbed Problem[J].Wuhan University Journal of Natural Sciences,2023,28(05).
[26] Jiang Y ,Huang P ,Jiang Z , et al.Gradient nanostructured tungsten and the thermal shock response[J].Tungsten,2023,5(04).
[27] Kuan S ,Ke-peng H ,Wen-wen H , et al.Optimizing slope safety factor prediction via stacking using sparrow search algorithm for multi-layer machine learning regression models[J].Journal of Mountain Science,2023,20(10).
[28] Wen-jun L ,Tong-hua L ,Xian-jun L , et al.Influence of thermal insulation layer schemes on the frost heaving force in tunnels[J].Journal of Mountain Science,2023,20(10).
[29] KUMARI C ,PARIDA K P .Ball Convergence Theorems for Chebyshev-Halley Method in B-Space[J].Journal of Mathematical Research with Applications,2023,43(06).
[30] BI H ,SONG Y ,YIN Y , et al.A novel sparse SAR unambiguous imaging method based on mixed-norm optimization[J].Science China(Information Sciences),2023,66(11).
[31] Chikkanna N, Krishnapillai S, Ramachandran V. In-plane and out-of-plane quasi-static compression performance enhancement of 3D printed re-entrant diamond auxetic metamaterial with geometrical tuning and fiber reinforcement[J]. Defence Technology, 2023,25(07):1-17.
[32] Weimin R, Baojiang L, Huanjun L, et al. Ground Penetrating Radar (GPR) Identification Method for Agricultural Soil Stratification in a Typical Mollisols Area of Northeast China[J]. Chinese Geographical Science, 2023,33(04):664-678.
[33] Chen X, Luo Q, Ma C. Inkjet-Printed Organic Solar Cells and Perovskite Solar Cells: Progress, Challenges, and Prospect[J]. Chinese Journal of Polymer Science,2023,41(08):1169-1197.
[34] Piemontese L .Historic recurrences in medicinal chemistry:nature-inspired structures as a new opportunity for novel multi-target anti-Alzheimer's drugs[J].Neural Regeneration Research,2023,18(12).
[35] Gu X, Qin Y, Sun S, et al. High-performance floating-gate organic phototransistors based on n-type core-expanded naphthalene diimides[J]. Chinese Chemical Letters, 2023,34(03):494-497.
[36] Wang W, Zhang Y, Guo X, et al. Rapid Conversion of Perhydropolysilazane into Thin Silica Coating at Low Temperature[J]. Chinese Journal of Polymer Science,2023,41(08):1198-1205.
[37] Lei W, ChangChun C, TianLong Z, et al. Mechanical-electrical synergy damage effect on GaN HEMT under high-power microwave[J]. Science China (Technological Sciences), 2023, 66(08):2373-2380.
[38] Lin D,Xiaofeng Y,Yang L, et al.Small-signal switch model of GaN HEMTs for MMIC applications[J].The Journal of China Universities of Posts and Telecommunications, 2016, 23(05):56-60.
[39] Abou-Senna H ,Radwan E ,Eldeeb H .A peer-to-peer logic environment to validate flashing yellow arrow decision support system[J].Journal of Traffic and Transportation Engineering(English Edition),2021,8(05).
[40] Komarala P E ,A.Alkhoori A ,Zhang X , et al.Design and synthesis of thermally stable single atom catalysts for thermochemical CO_2 reduction[J].Journal of Energy Chemistry,2023,86(11).