发 光 学 报
CHINESE JOURNAL OF LUMINESCENCE

Article ID: 1000-7032(XXXX)XX-0001-09

Space-Confined Chemical Vapor Deposition of Exfoliable γ-Ga_2O_3 Thin Films

ZHAO Xufeng[1#], LI Xianxu[2#], ZHANG Dong[1], JIANG Nengdong[1], WANG Wenjie[1*]

(1. *School of Mathematics and Physics, North China Electric Power University, Beijing* 102206, *China*;
2. *School of Physics and Astronomy, Beijing Normal University, Beijing* 100875, *China*)
* *Corresponding Author, E-mail: wwj*2008@ncepu. edu. cn

Abstract: To address the challenges of poor thermodynamic stability and difficult high-temperature preparation of metastable γ-Ga_2O_3, this paper proposes an innovative space-confined chemical vapor deposition (SCCVD) strategy. This method takes advantage of the surface energy and chemical potential differences between the amorphous precursor powder and the crystalline film. By generating a high saturated vapor pressure inside the micron-scale confined space, we can precisely control the deposition rate difference in a reducing atmosphere. The study shows that the γ-Ga_2O_3 thin film epitaxially grown on a fluorophlogopite mica substrate exhibits a pronounced (111) preferred orientation, following a pyramidal step-flow growth mode, with an optical bandgap of 5. 3 eV. With the in-situ auxiliary doping of substrate elements Mg and Al, the film remains phase-stable at 1200 °C. This represents the highest temperature tolerance achieved for γ-Ga_2O_3 to date. Furthermore, leveraging the van der Waals layered characteristics of fluorophlogopite mica, the epitaxial film was successfully delaminated without damage and transferred to a flexible substrate, demonstrating excellent mechanical flexibility and high-curvature bending resistance. This work not only overcomes the bottleneck of high-temperature preparation of metastable phases but also provides an ideal material platform for the development of flexible solar-blind detection and wearable optoelectronic devices.

Keywords: γ-Ga_2O_3; CVD; Metastable phase
CLC number: **Document code**:
DOI: 10. 37188/CJL. 20260163 **CSTR**: 32170. 14. CJL. 20260163

空间限域-化学气相沉积法外延生长可剥离γ-Ga_2O_3薄膜

赵旭锋[1#], 李现旭[2#], 张东[1], 蒋能东[1], 王文杰[1*]

(1.华北电力大学 数理学院 北京 102206;
2.北京师范大学 物理与天文学院 北京 100875)

摘要: 针对亚稳态γ-Ga_2O_3热力学稳定性差、高温制备困难等挑战,本文提出了一种创新的空间限域化学气相沉积策略。该方法巧妙利用非晶前驱体粉末与晶态薄膜之间的表面能及化学势差异,通过在微米级限域空间内构建高饱和蒸气压环境,实现了在还原性气氛下对沉积速度差的精准调控。研究表明,在氟金云母衬底上外延生长的γ-Ga_2O_3薄膜呈现显著的(111)面择优取向,遵循金字塔状台阶生长模式,其光学禁带宽度为5.3eV。得益于衬底元素Mg和Al的原位辅助掺杂,该薄膜在1200℃下仍能保持相结构稳定,刷新了目前γ-Ga_2O_3所能耐受的最高温度记录。此外,依托氟金云母的范德华层状特性,成功将外延薄膜无损剥离并转移至柔性基底,薄膜展现出优异的机械柔韧性与大曲率弯折耐受力。本工作不仅突破了亚稳相高温制备的瓶颈,更为柔性日盲探测及可穿戴光电器件的研发提供了理想的材料平台。

收稿日期: XXXX-XX-XX; **修订日期**: XXXX-XX-XX
基金项目:

关 键 词：γ-Ga_2O_3；CVD；亚稳相

1 Introduction

Gallium oxide, as a highly promising ultra-wide bandgap semiconductor material, exists in five polymorphs: α, β, γ, ε, and δ[1-4]. Among these, β-Ga_2O_3 with a monoclinic crystal structure is the most thermodynamically stable phase and has been widely applied in cutting-edge fields such as solar-blind deep ultraviolet detectors and high-power field-effect transistors[5-12]. However, compared to the relatively well-developed β phase, the metastable γ-Ga_2O_3 with a spinel structure suffers from its inherent thermodynamic instability[13-18]. This significantly hinders the preparation of high-quality thin films, and as a result, related research remains limited. Recent studies have confirmed that incorporating heterovalent elements such as Mg, Al, and Cu for lattice doping can effectively alter the local coordination environment of the system, thereby inducing a phase transformation from the stable β phase to the metastable γ phase and substantially broadening the thermodynamic stability window of the latter[17, 19-21]. Achieving efficient and stable doping of heterovalent elements to further enhance the phase stability of γ-Ga_2O_3 remains a major challenge in this field.

Addressing the above challenges, finding an epitaxial platform that combines "in-situ composition control" and "advanced device compatibility" has become key. Fluorophlogopite mica ($KMg_3(AlSi_3O_{10})F_2$), with its natural van der Waals layered structure, abundant Mg/Al elements, and atomically flat surface obtainable via mechanical exfoliation, is an ideal substrate for the epitaxial growth of γ-Ga_2O_3 thin films. The weak interlayer van der Waals forces also mean that films epitaxially grown on this substrate can be lifted off intact, which is a clear advantage for fabricating flexible, self-supported gallium oxide-based optoelectronic devices[22, 23]. However, from a kinetic perspective, inducing the cross-interface diffusion of Mg and Al atoms from the substrate into the epitaxial layer typically requires very high growth temperatures. In conventional chemical vapor deposition processes, to maintain growth by reducing the precursor with hydrogen, the film is often exposed to a high-temperature reducing atmosphere, which causes severe decomposition and desorption of Ga_2O_3, thereby compromising the integrity of the epitaxial layer. The central challenge, therefore, is to suppress film decomposition in a reducing environment while keeping the temperature high enough to drive effective doping from the substrate elements, so as to realize high-quality γ-Ga_2O_3 epitaxy on fluorophlogopite mica.

Motivated by the above issues, this work presents a space-confined chemical vapor deposition (SC-CVD) approach. In terms of crystal growth energetics, the method makes use of the physical benefits that single-crystal structures offer relative to polycrystalline or amorphous systems, such as lower surface energy, reduced defect density, and greater structural stability. By confining the reaction area on a micron scale, a locally high saturated vapor pressure environment is systematically constructed. This allows precise control over the kinetics of precursor reduction and the difference in film epitaxy deposition rate under a reducing atmosphere. Using this approach, we successfully achieved Mg and Al-assisted in-situ doped heteroepitaxy of γ-Ga_2O_3 on fluorophlogopite mica substrates, followed by exfoliation onto flexible tape. Microscopic growth kinetics indicate that the deposition process follows a typical step-mediated pyramidal growth mode. Initially, discrete crystalline nuclei with regular step structures form, which then gradually merge and evolve into a continuous, dense film. This film exhibits excellent high-temperature thermal stability.

2 Experiment

The substrate used in the experiment was fluorophlogopite mica produced by Changchun Taiyuan Fluorophlogopite Mica Co., Ltd. Before use, the mica sheet was exfoliated with a mica knife to ensure an atomically flat, impurity-free surface. Gallium ox-

ide powder with a purity of 99.99% (produced by Macklin Inc.) was used as the precursor. For the preparation of γ-Ga_2O_3 thin films, 2 g of gallium oxide powder was evenly spread at the bottom of an alumina boat. A U-shaped support frame was placed on top of the powder, and a 1 cm × 1 cm fluorophlogopite mica substrate was placed on the support frame. A gas mixture containing 10% hydrogen in argon was introduced at a flow rate of 200 sccm. The temperature profile was set to ramp from room temperature to 1100 °C in 40 minutes, held at 1100 °C for 40 minutes, and then naturally cooled to room temperature. This sample was named γGa-1. Repeating the above procedure twice gave sample γGa-2, three times gave γGa-3, four times gave γGa-4, five times gave γGa-5, and six times gave γGa-6. For the preparation of β-Ga_2O_3 thin films, 0.2 g of gallium oxide powder was placed in an alumina boat, and the 1 cm × 1 cm fluorophlogopite mica substrate was placed 16 cm away from it. The temperature at this position, measured using a thermocouple, was approximately 700 °C. A gas mixture containing 10% hydrogen in argon was introduced at a flow rate of 150 sccm. The temperature profile was set to ramp from room temperature to 1100 °C in 40 minutes, held at 1100 °C for 40 minutes, and then naturally cooled to room temperature. This sample was named βGa-1. After film growth, commercial blue tape was used as the transfer medium. The tape was uniformly applied to the surface of the γ-Ga_2O_3/fluorophlogopite mica sample, and moderate pressure was applied to expel air bubbles and ensure intimate contact. Taking advantage of the weak van der Waals bonding between mica layers, a slow peel from one side caused the γ-Ga_2O_3 film to separate completely with the tape, achieving a damage-free transfer to a flexible substrate. XRD (SmartLab SE) was used to obtain the lattice constants. Raman spectra were acquired using a Raman spectrometer (ihr550, excitation wavelength 532 nm). SEM (Hitachi S-4800) and AFM (Park XE7, resolution 1024) were used to characterize the surface morphology of the samples.

3 Results and Analysis

During the heteroepitaxy of gallium oxide thin films on fluorophlogopite mica substrates using conventional chemical vapor deposition (CVD), introducing hydrogen to reduce the Ga_2O_3 powder effectively lowers the reaction temperature but introduces new kinetic challenges. Under high-temperature reducing conditions, the adsorption – desorption equilibrium on the substrate surface shifts strongly toward desorption, hindering stable deposition of the gas-phase species. Consequently, conventional CVD processes often fail to achieve effective growth of gallium oxide films under high-temperature reducing environments. To address this issue, this study developed a space-confined chemical vapor deposition (SCCVD) technique. As shown in Figure 1, the core of this setup lies in using a custom-made 500 μm thick sapphire three-sided surrounding mold to create a micron-scale confined space with the substrate. The physical advantage of this design is that the confined space restricts the precursor molecules generated by reduction to a very small area, rapidly establishing a locally high saturated vapor pressure environment, which significantly enhances the adsorption probability of molecules. Owing to its numerous voids, defects, and high surface energy, the amorphous precursor powder is reduced by hydrogen far more rapidly than the well-crystallized epitaxial film, enabling selective reduction by hydrogen. Protected by the abundant amorphous precursor, the deposition rate on the epitaxial film surface always exceeds the rate of reduction/etching by hydrogen, overcoming the theoretical limitation of heteroepitaxial growth of oxide thin films in high-temperature reducing environments. Furthermore, using this high-temperature SCCVD process, Mg, Al, and Si ions

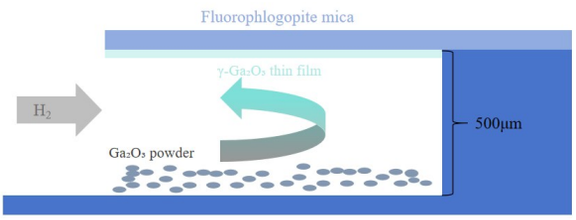

Figure 1 Schematic diagram of space-confined chemical vapor deposition.

from the fluorophlogopite mica substrate undergo cross-interface diffusion under thermal activation, achieving in-situ doping of the film. This auxiliary composition control from the substrate is key to successfully obtaining the high-temperature metastable γ-Ga_2O_3 thin film.

Figure 2(a) shows the XRD patterns of samples γGa-1 to γGa-6. The results indicate that all samples only exhibit three strong diffraction peaks corresponding to the (111), (222), and (333) planes of γ-Ga_2O_3, confirming a pronounced [111] preferred growth orientation. As the growth cycle increases, the peak intensities steadily improve, and no impurity phases or additional orientations are detected, indicating that the film maintains a high degree of epitaxial consistency and phase stability during SCCVD growth. In contrast, the XRD pattern of the βGa-1 sample in Figure 2(c) shows typical diffraction features of β-Ga_2O_3 corresponding to the (-201), (-402), and (-603) planes[5, 24]. This suggests that at the lower temperature of around 700 °C, due to insufficient thermal activation energy, the Mg and Al elements from the fluorophlogopite mica substrate cannot effectively diffuse across the interface into the epitaxial layer, thus losing their ability to regulate the Ga_2O_3 crystal phase. This inference is further confirmed by the cross-sectional EDS mapping in Figure 5: The Mg and Al atomic percentages in the epitaxially grown γ-Ga_2O_3 film reach as high as 9.79% and 3.71%, respectively, successfully achieving in-situ auxiliary doping. Conversely, in the β-Ga_2O_3 film region, the Al content is only 1.32%, insufficient to support the stable existence of the metastable phase. Figures 2(b) and (d) show the Raman spectra of the fluorophlogopite mica substrate and the γ-phase and β-phase films epitaxially grown on it. The results show that the characteristic scattering peaks of the two films perfectly match their respective standard phases, and no characteristic vibrational modes of other polymorphs are found, fully verifying that the obtained γ-Ga_2O_3 and β-Ga_2O_3 films possess high phase purity.

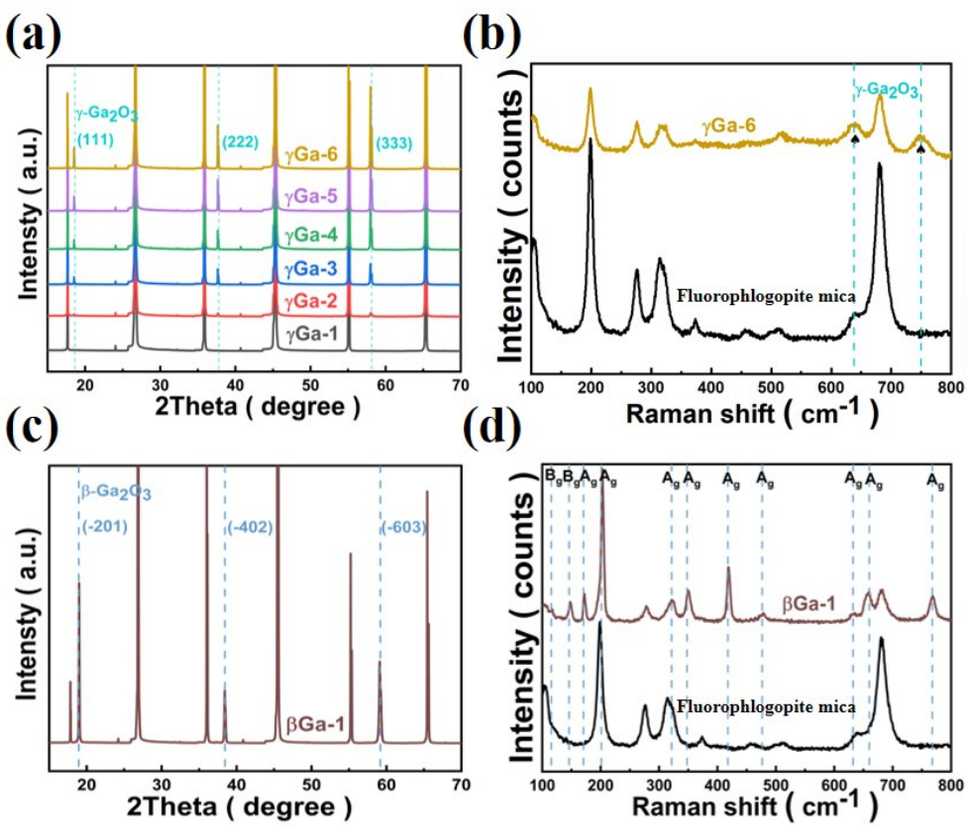

Figure 2 (a) XRD patterns of γGa-1 to γGa-6. (b) Raman spectrum of γGa-6. (c) XRD pattern of the β-Ga_2O_3 thin film. (d) Raman spectrum of the β-Ga_2O_3 thin film.

Figure 3(a) shows an optical microscopy image of the γ-Ga_2O_3 film grown for 40 minutes. To evaluate the film's coverage quality, part of the sample area was deliberately scratched. The result clearly shows that a uniformly distributed continuous film has formed on the substrate surface. Although the macroscopic surface is relatively flat, the SEM image in Figure 3(b) reveals that the microstructure consists of discrete islands approximately 1 μm in size. As the growth cycle increases to 2 cycles (about 80 minutes), the island features on the film surface become more pronounced. Notably, all triangular islands exhibit a high degree of preferred orientation consistency. This is attributed to the monoclinic crystal system characteristics of the fluorophlogopite mica substrate: its surface provides an anisotropic interfacial lattice potential field, allowing the γ-Ga_2O_3 crystal nuclei to have only a single orientation with the lowest interfacial energy, thereby macroscopically inducing the regular alignment of island orientations. Combined with the AFM analysis in Figure 3 (f), two typical types of triangular islands exist on the film surface: "plateau-shaped islands" with smooth tops and steep step edges, and "pyramidal islands" with layered step edges and gentle slopes. This morphological differentiation originates from complex growth kinetic competition. The enhanced diffusion rate of surface molecules at high temperatures induces step merging to form flat plateaus. However, the ultra-high saturated vapor pressure in the space-confined environment leads to a very high flux of adatoms. When hydrogen partially passivates the step edges, it significantly increases the Ehrlich-Schwoebel barrier for adatoms, limiting their attachment to lateral steps, forcing atoms to undergo secondary nucleation at the intersection areas on the island tops, eventually evolving into pyramidal structures. When adjacent islands gradually grow and approach each other, the channel regions formed expose many dangling bonds, possessing a high coordination number, which provides strong binding energy sites for adatoms, promoting rapid molecular filling and inducing island coalescence (Figure 3d). After 5 growth cycles, the film shows a clear trend towards connectivity. Although coalescence might introduce dislocations, the in-situ annealing effect generated by the high-temperature environment enhances dislocation mobility, allowing them to annihilate through interactions or migration to grain boundaries, thereby effectively improving the crystalline quality of the film. After 6 cycles (240 minutes), the film becomes fully continuous. Secondary nucleation, triggered by the non-equilibrium adsorption – desorption at very high vapor pressure, generates a

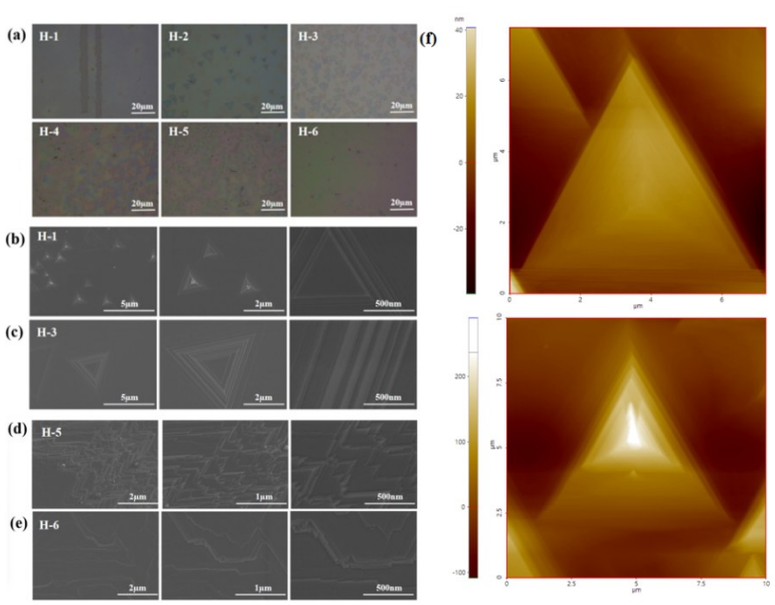

Figure 3 (a) Optical image of gallium oxide (γGa-1 to γGa-6). (b)-(e) SEM images of gallium oxide after 1, 3, 5, and 6 cycles (γGa-1, 3, 5, 6). (f) AFM image of islands on the gallium oxide thin film.

small number of particles on the surface. Even so, the AFM result in Figure 3(f) confirms that the step height variation of the continuous film is significantly reduced compared to the initial islands, and the overall surface smoothness is greatly optimized.

The cross-sectional SEM image in Figure 4(a) shows that the thickness of the grown γ-Ga_2O_3 film is approximately 1.2 μm, from which an average growth rate of about 300 nm/h is estimated. Notably, a transition layer approximately 2 μm thick is observed between the thin film and the fluorophlogopite mica substrate. This transition layer exhibits a mixed morphology of layered and blocky structures and has a clear physical interface with both the upper film and the underlying substrate. The formation of this thick transition layer is primarily attributed to significant cross-interface diffusion and permeation of Ga ions with high chemical potential into the substrate under the high-temperature growth environment. Furthermore, Figure 4(b) compares the UV absorption spectra and calculated optical bandgaps of the γ-Ga_2O_3 film and the β-Ga_2O_3 control film. The results show that the bandgap of the prepared γ-Ga_2O_3 reaches 5.3 eV, significantly wider than the 4.9 eV of β-Ga_2O_3. This significant bandgap widening effect originates from a combination of physical and chemical mechanisms: the intrinsic band-structure difference that arises from the unique spinel crystal structure of γ-Ga_2O_3; on the other hand, it benefits from the diffusion doping of Al from the substrate into the film during growth, introducing an alloying modulation effect[21, 25].

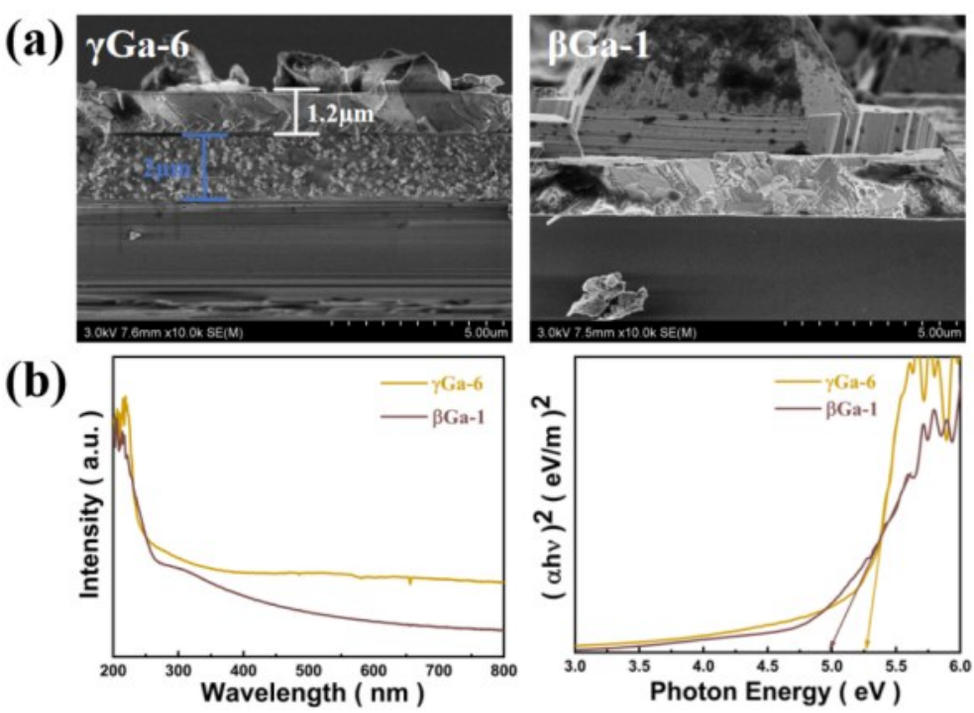

Figure 4 (a) Cross-sectional schematic of γGa-6 and βGa-1. (b) Absorption spectra and optical bandgaps of γGa-6 and βGa-1.

The cross-sectional energy dispersive spectroscopy (EDS mapping) image in Figure 5(a) clearly reveals the in-situ doping distribution characteristics of Mg and Al ions in the γGa-6 film. Notably, the abundance of Mg and Al elements within the interfacial transition layer is significantly lower than in its adjacent substrate and epitaxial film regions. This abnormal compositional distribution indicates that the transition layer is essentially formed by the reverse diffusion of Ga ions with high chemical potential into the fluorophlogopite mica substrate. Quantitative elemental analysis further confirms that compared to the unaffected pure substrate region, the Mg and Si element content in the transition layer is reduced by about 5%, Al by 2%, while the Ga content increases dramatically by about 13%. Combining this significant elemental concentration gradient distribution, the microscopic kinetic mechanism can be

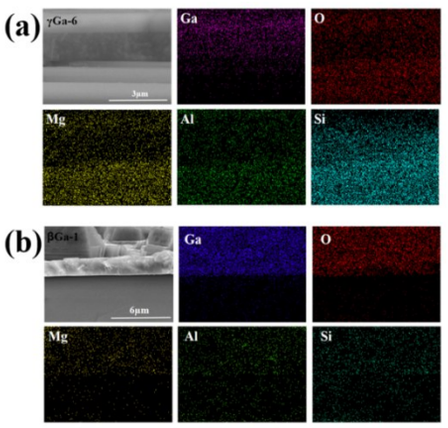

Figure 5 (a) Cross-sectional EDS image of γ-Ga_2O_3. (b) Cross-sectional EDS image of β-Ga_2O_3.

deduced: under high-temperature thermal activation, Mg, Al, and Si elements on the substrate surface diffuse outward, segregate, and participate in the doping growth of the upper film. This drives a substantial backward flux of Ga ions that fills the resulting cation vacancies. As a control experiment, the cross-sectional EDS analysis of βGa-1 shown in Figure 5 (b) indicates that although trace amounts of Mg, Al, and Si elements also diffuse into the film under lower temperature growth conditions, their overall incorporated concentrations are significantly lower than those in the γGa-6 system (detailed data mentioned before). This compositional comparison further confirms that sufficient high-temperature-driven interdiffusion of interfacial elements is the key factor for achieving effective doping and stabilizing the γ crystalline phase.

To evaluate the ultra-high temperature thermal stability of the γ-Ga_2O_3 thin film, it was annealed in air at 1200 °C for 60 minutes. The XRD pattern in Figure 6(a) shows no obvious shift or intensity change of the diffraction peaks after annealing, and no indication of a transition to the β phase or any impurity phases. This indicates that the film possesses excellent phase stability, maintaining its crystal structure integrity in the extreme environment of up to 1200 °C. To the best of our knowledge, this is the highest phase stability temperature reported for γ-Ga_2O_3 thin films to date. Benefiting from the natural van der Waals layered structure of fluorophlogopite mica, epitaxial films grown on it can be mechanically exfoliated using specialty tape or organic polymers, enabling nondestructive transfer to any flexible substrate. As shown in Figure 6(b), the γ-Ga_2O_3 film successfully exfoliated with blue tape demonstrates excellent mechanical flexibility, capable of withstanding macroscopic bending at high curvatures without cracking. This characteristic lays an important material foundation for developing flexible solar-blind ultraviolet detectors and wearable optoelectronic devices based on metastable gallium oxide.

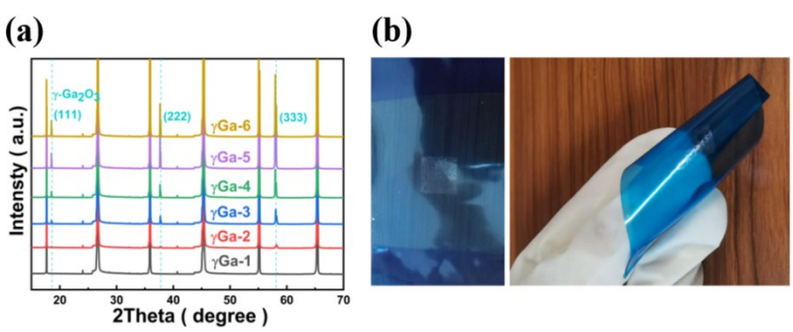

Figure 6 (a)XRD pattern of γ-Ga_2O_3 after annealing at 1200 °C. (b)γ-Ga_2O_3 thin film exfoliated using blue tape.

4 Conclusion

In this paper, high-quality heteroepitaxy of (111)-oriented γ-Ga_2O_3 thin films was successfully achieved under a high-temperature reducing environment using an innovative space-confined chemical vapor deposition (SCCVD) method. The study deeply reveals the regulatory effect of high saturated vapor pressure within the confined microspace on nucleation kinetics, as well as the rate competition mechanism between precursor reduction and film deposition. It also systematically demonstrates the critical role of in-situ doping from substrate elements Mg/Al in stabilizing the metastable phase structure. The experimental results show

that the film not only exhibits excellent optical properties but also achieves a breakthrough in phase stability temperature reaching 1200 °C, setting a new record for the highest thermal stability known for γ-Ga_2O_3 systems. Furthermore, we confirmed that the epitaxial film can be transferred intact to flexible substrates and exhibits remarkable macroscopic flexibility. This work provides a solid theoretical foundation and experimental support for developing Ga_2O_3-based high-performance optoelectronic devices for extreme environments, particularly flexible wearable solar-blind detection systems.

References:

[1] BOSI M, MAZZOLINI P, SERAVALLI L, *et al*. Ga_2O_3 polymorphs: tailoring the epitaxial growth conditions [J]. *Journal of Materials Chemistry C*, 2020, 8(32): 10975-10992.

[2] KANEKO K, UNO K, JINNO R, *et al*. Prospects for phase engineering of semi-stable Ga_2O_3 semiconductor thin films using mist chemical vapor deposition [J]. *Journal of Applied Physics*, 2022, 131(9).

[3] ZHENG X-Q, ZHAO H, FENG P X-L. A perspective on β-Ga_2O_3 micro/nanoelectromechanical systems [J]. *Applied Physics Letters*, 2022, 120(4).

[4] WANG J, GUO H, ZHU C-Z, *et al*. ε-Ga_2O_3: a promising candidate for high-electron-mobility transistors [J]. *IEEE Electron Device Letters*, 2020, 41(7): 1052-1055.

[5] LU C, LI M, GAO L, *et al*. Freestanding crystalline β-Ga_2O_3 flexible membrane obtained via lattice epitaxy engineering for high-performance optoelectronic device [J]. *ACS nano*, 2024, 18(7): 5374-5382.

[6] HE J, JIAO S, NIE Y, *et al*. Research Progress of p-type Doping of-GaO [J]. *Chinese Journal of Luminescence*, 2024, 45(4): 557-567.

[7] WANG Y, LI J, ZHANG T, *et al*. Optimization quality for indium pulse-assisted of β-Ga_2O_3 thin film on sapphire surface [J]. *Ceramics International*, 2023, 49(23): 37506-37512.

[8] NANDI A, CHERNS D, SANYAL I, *et al*. Epitaxial growth of (−201) β-Ga_2O_3 on (001) diamond substrates [J]. *Crystal Growth & Design*, 2023, 23(11): 8290-8295.

[9] KUSABA T, SITTIMART P, KATAMUNE Y, *et al*. Heteroepitaxial growth of β-Ga_2O_3 thin films on single crystalline diamond (111) substrates by radio frequency magnetron sputtering [J]. *Applied Physics Express*, 2023, 16(10): 105503.

[10] CHEN W, JIAO T, DIAO Z, *et al*. Selective-area growth of β-Ga_2O_3 nanowire films on nano-patterned Si (111) substrate by metal-organic chemical vapor deposition [J]. *Ceramics International*, 2023, 49(13): 22170-22176.

[11] MONDAL A K, DEIVASIGAMANI R, PING L K, *et al*. Heteroepitaxial growth of an ultrathin β-Ga_2O_3 film on a sapphire substrate using mist CVD with fluid flow modeling [J]. *ACS omega*, 2022, 7(45): 41236-41245.

[12] JIAO T, LI ZM W Q. Growth of β-Ga_2O_3 thin films on Ga_2O_3/GaN/sapphire template [J]. *Chinese Journal of Luminescence*, 2020, 41(3): 281-287.

[13] PICHORIM A, NECKEL I T, DE OLIVEIRA A J A, *et al*. Theoretical approach to defect-induced magnetism in oxygen-deficient γ-Ga_2O_3 films [J]. *Materials Chemistry and Physics*, 2024, 314: 128877.

[14] LU Q, XU L, HAN K, *et al*. Effect of surface modification on the photoluminescent properties of γ-Ga_2O_3 nanocrystals [J]. *Materials Letters*, 2023, 344: 134437.

[15] GARCíA-FERNáNDEZ J, KJELDBY S, NGUYEN P, *et al*. Formation of γ-Ga_2O_3 by ion implantation: Polymorphic phase transformation of β-Ga_2O_3 [J]. *Applied Physics Letters*, 2022, 121(19).

[16] TAN X, GENG S, JI Y, *et al*. Closest packing polymorphism interfaced metastable transition metal for efficient hydrogen evolution [J]. *Advanced Materials*, 2020, 32(40): 2002857.

[17] LIU Q, GUO D, CHEN K, *et al*. Stabilizing the metastable γ phase in Ga_2O_3 thin films by Cu doping [J]. *Journal of Alloys and Compounds*, 2018, 731: 1225-1229.

[18] MITOME M, KOHIKI S, NAGAI T, *et al*. A rhombic dodecahedral honeycomb structure with cation vacancy ordering in a γ-Ga_2O_3 crystal [J]. *Crystal growth & design*, 2013, 13(8): 3577-3581.

[19] ZHAO L, WU W, GAO B, *et al*. CO2 Stress-Driven Room Temperature Ferromagnetism of Ultrathin 2D Gallium Oxide [J]. *Small*, 2024, 20(16): 2308187.

[20] HUANG H-L, JOHNSON J M, CHAE C, *et al.* Atomic scale mechanism of β to γ phase transformation in gallium oxide [J]. *Applied Physics Letters*, 2023, 122(25).

[21] CORA I, FOGARASSY Z, FORNARI R, *et al.* In situ TEM study of κ→β and κ→γ phase transformations in Ga_2O_3 [J]. *Acta Materialia*, 2020, 183: 216-227.

[22] GAO Y, ZHOU K, LIU Z, *et al.* Wafer-Scale Manufacturing and Crack-Free Transferring of GaN-Based Membranes for Flexible Optoelectronics [J]. *Advanced Science*, 2025, 12(46): e12193.

[23] CHEN R, SONG Y, HE R, *et al.* III-nitride semiconductor membrane electronics and optoelectronics for heterogeneous integration [J]. *Progress in Quantum Electronics*, 2024, 98: 100536.

[24] LU Y, ZOU X, KRISHNA S, *et al.* Thermal mismatch engineering induced freestanding and ultrathin Ga_2O_3 membrane for vertical electronics [J]. *Materials Today Physics*, 2023, 36: 101181.

[25] GOTTSCHALCH V, MERKER S, BLAUROCK S, *et al.* Heteroepitaxial growth of α-, β-, γ-and κ-Ga_2O_3 phases by metalorganic vapor phase epitaxy [J]. *Journal of Crystal Growth*, 2019, 510: 76-84.

赵旭锋(2000–),女,山西晋中人,硕士研究生,2023年于太原师范学院获得学士学位,主要从事宽禁带半导体与卡西米尔力的研究。

E-mail: zxf13994562957@163.com

王文杰(1979–),男,山西人,博士,讲师,硕士生导师,2007年在中科院半导体所超晶格实验室获凝聚态物理专业博士学位,主要从事宽禁带半导体和二维材料研究。

E-mail: wwj2008@ncepu.edu.cn

李现旭(1997–),男,山东东营人,博士研究生,2025年与华北电力大学获得硕士学位,主要从事宽禁带半导体与铁电材料的研究。

E-mail: 19862509809@163.com