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EXPLORING GALLIUM OXIDE (GA2O3) NANOWIRES-A TECHNICAL REPORT

Original Article

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ABSTRACT

Background: Gallium oxide (Ga_2O_3) nanowires have attracted growing attention for their unique physicochemical properties, including high thermal stability, wide band gap (~4.9 eV), and strong photoluminescence. These characteristics render them ideal candidates for high-power electronics, ultraviolet photodetectors, gas sensors, and optoelectronic applications. Despite significant advancements, most conventional synthesis techniques remain limited by prolonged processing times, low growth rates, and difficulty in scalability, presenting obstacles to their widespread industrial integration.

Objective: This study aimed to evaluate and compare multiple synthesis techniques for fabricating high-quality Ga_2O_3 nanowires, focusing on optimizing growth conditions, structural integrity, and functional performance to enable scalable and application-ready production.

Methods: Ga_2O_3 nanowires were synthesized using thermal evaporation, physical vapor deposition (PVD), chemical vapor deposition (CVD), hydrothermal, and microwave plasma techniques. Structural and morphological characterization was conducted using X-ray diffraction (XRD), Raman spectroscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM). Electrical, optical, and gas-sensing performance was evaluated using field-effect transistor (FET) setups, photoluminescence spectroscopy, and voltamperometric sensing against O_2 and CO gases.

Results: The nanowires displayed an average diameter of ~60 nm and lengths exceeding 100 µm. XRD confirmed a monoclinic β-Ga_2O_3 phase, while HRTEM revealed distinct atomic-level twinning. Photoluminescence peaks at 446 nm (2.78 eV) and 465 nm were observed. FET-based electrical testing yielded resistivity values ranging from 10^4–10^6 Ω·cm. Gas sensors showed peak responses to O_2 at 300 °C and CO at 200 °C, with rapid response/recovery times and high signal-to-noise ratios.

Conclusion: Microwave plasma and vapor–solid methods proved most effective for producing uniform, defect-free Ga_2O_3 nanowires. These approaches offer promising routes toward scalable, high-performance nanowire-based devices for sensing and optoelectronic applications.

Keywords: Band Gap, Chemical Vapor Deposition, Gallium Oxide, Nanowires, Photoluminescence, Scanning Electron Microscopy, Vapor Phase Synthesis.

INTRODUCTION

Nanotechnology, defined as the manipulation and application of matter at dimensions between 1 and 100 nanometers, has emerged as a transformative scientific domain that merges chemistry, physics, biology, and materials science to develop innovative materials and devices with exceptional properties. At this scale, materials exhibit unique behaviors—often governed by quantum effects and a high surface-to-volume ratio—that are significantly different from their bulk counterparts (1,2). These properties present new avenues in biomedicine, particularly in diagnostics, drug delivery, and regenerative medicine, where interactions at the molecular and subcellular levels are critical (3). Among the various nanostructures, nanoparticles and nanowires have garnered considerable attention. Nanoparticles, due to their atomic-scale size, possess tailored electronic, magnetic, and chemical properties suitable for targeted medical therapies and imaging techniques (4). Similarly, nanowires—one-dimensional structures with diameters in the nanometer range—offer distinctive electrical, mechanical, and optical properties due to their aspect ratio and quantum confinement effects. These properties make them highly valuable in applications like biosensors, field-effect transistors, and energy storage devices (5,6).

A particularly promising class of nanostructures in the context of medical and environmental sensing technologies is gallium oxide (Ga_2O_3) nanowires. As a wide-bandgap semiconductor, β-Ga_2O_3 exhibits exceptional chemical resistance, thermal stability, and photoluminescence, making it suitable for use in high-temperature gas sensors, UV photodetectors, and next-generation optoelectronic devices (7,8). The material's stability and sensitivity allow it to detect trace gases, including toxic industrial emissions, with high specificity and efficiency. These properties are especially relevant for applications in clinical diagnostics, environmental monitoring, and public health safety (9). Advancements in the synthesis of Ga_2O_3 nanowires using methods such as vapor–liquid–solid (VLS), chemical vapor deposition (CVD), and plasma-assisted growth have further enhanced their feasibility for large-scale production. Notably, the use of corona discharge in VLS processes has significantly improved catalyst nucleation efficiency, leading to higher yields and uniformity of nanowire growth (10). Furthermore, innovations such as microwave plasma-assisted synthesis have allowed for the production of highly pure and structurally stable Ga_2O_3 nanowires under ambient conditions (11,12).

Despite their potential, the commercial and clinical adoption of Ga_2O_3 nanowires faces challenges related to synthesis scalability, defect control, and material reproducibility. Addressing these issues requires a deeper understanding of their growth mechanisms, electronic behavior, and interactions within complex biological environments. Recent studies also suggest that the photoluminescence and conductive properties of Ga_2O_3 can be tailored through doping or by forming composites with other nanomaterials, thereby expanding their functionality in targeted applications such as resistive memory devices, photocatalysis, and lithium-ion batteries (13-16). In light of these developments, this research aims to systematically explore the synthesis, structural characteristics, and biomedical applicability of gallium oxide nanowires, with a focus on their role as sensitive and stable materials in gas sensing and optoelectronic systems. The objective is to rationalize their practical utility in healthcare and environmental domains while addressing the critical challenges that impede their broader implementation.

METHODS

Formation of amorphous and crystalline gallium oxide nanowires by metalorganic chemical vapor deposition

Amorphous and crystalline gallium oxide nanowires were synthesized using a metalorganic chemical vapor deposition (MOCVD) technique. A schematic of the experimental MOCVD setup is illustrated in the referenced literature (12). P-type Si substrates with (100) orientation was cleaned using standard organic solvents and dried immediately before the deposition process. Trimethylgallium (TMGa) served as the gallium precursor and was maintained at 58°C in a bubbler. Ar (30 sccm) and O_2 (6–30 sccm) gases were used as carrier and oxidizing agents, respectively, with their flow rates precisely controlled via mass flow controllers. The Ar to O_2 flow ratio was maintained within a range of 1–4. Deposition was carried out for approximately 5 minutes at 8°C, which appears illogical and possibly represents a typographical error as the process temperature is unusually low for MOCVD. Characterization of the resulting nanowires involved X-ray diffraction (XRD) using Cu $K\alpha_1$ radiation ($\lambda = 0.154056$ nm), scanning electron microscopy (SEM) at 30 keV (Hitachi S4200), and transmission electron microscopy (TEM) at 200 kV (Philips CM-200). TEM specimens were prepared by dispersing powder in alcohol via ultrasonic treatment, followed by deposition on a carbon-coated copper grid and air-drying.

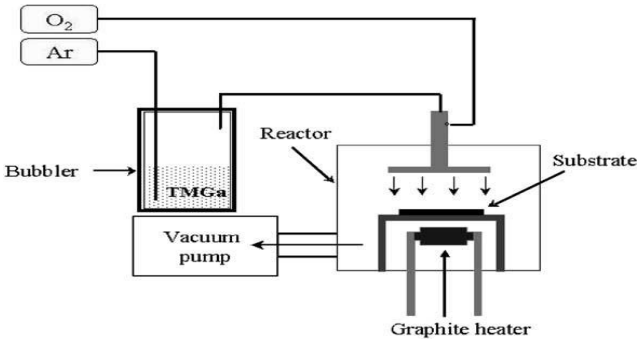

Figure 1: Schematic illustration of the MOCVD reactor

Ga_2O_3 nanowires prepared by physical evaporation

A traditional physical evaporation technique was employed to synthesize gallium oxide nanowires. In this method, a quartz boat containing gallium powder was placed in the front end of a quartz tube furnace, where the gallium was heated to approximately 300°C. A steady mixed gas flow of 90% argon and 10% hydrogen was maintained at 30 sccm under a controlled pressure of 100 Torr using a mechanical pump (13). After 24 hours of evaporation, a white web-like product was collected from the inner wall of the quartz boat. Structural analysis was performed using an X'pert MRD-Philips X-ray diffractometer, and the morphology and atomic structure were investigated via high-resolution transmission electron microscopy (HREM; Hitachi H-9000NAR) with a resolution of ~0.18 nm.

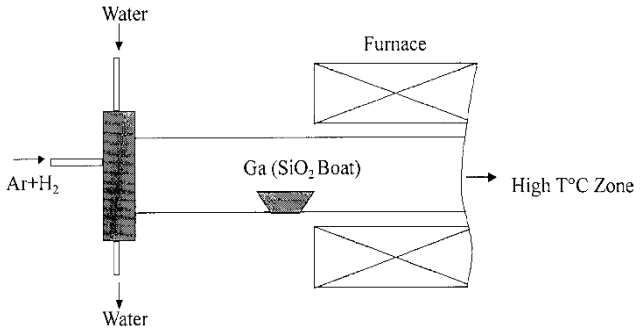

Figure 2: Schematic illustration of the synthesis setting

Gallium oxide nanowire structures synthesized via vapor phase growth

Nano- and microsized Ga_2O_3 crystals were synthesized using a physical vapor-phase growth approach. The source materials—99.999% pure gallium mixed with a small amount of SiO_2 powder—were spread on a quartz plate and placed in the center zone of a tube furnace maintained at 1100°C. To study temperature-dependent growth characteristics, three quartz boats were positioned along the alumina tube at zones corresponding to 300°C, 600°C, and 800°C (14). The system was kept at 100 Torr with a carrier gas flow of argon at 30 sccm. After a 2-hour growth period, the system was allowed to cool naturally. Samples were collected from the middle boat (600°C zone), where wool-like nanostructures were found. Structural and elemental analysis of the products was conducted using XRD and transmission electron microscopy (Tecnai F30 with EDS detector at 300 kV).

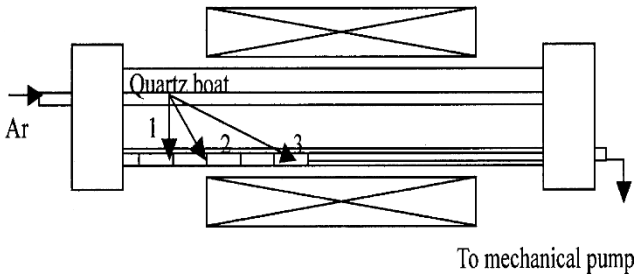

Figure 3: Schematic depiction of the experimental setup.

Formation via Thermal evaporation method

Gallium oxide nanowires were also fabricated through reactive thermal evaporation. A 0.5 g quantity of high-purity (99.999%) gallium metal was placed in an alumina boat positioned on an alumina substrate. The system was heated at 900°C for one hour under an argon gas flow of 100 ml/min at ambient pressure. Post-cooling, white nanowire products were collected and characterized via XRD, field emission SEM, and TEM (15). For gas sensing applications, the nanowires were ultrasonically dispersed in methanol and drop-cast onto oxidized Si substrates pre-patterned with interdigitated Pt electrodes. The sensing tests were conducted in a tube furnace using either dry nitrogen or synthetic air, depending on the target gas (O_2 or CO). Electrical responses were recorded using a constant 10 V bias, and resistance changes were measured using an Agilent 34970A multimeter.

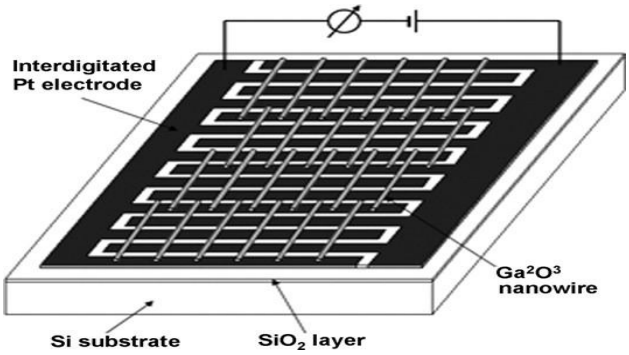

Figure 4: A schematic diagram of the Ga_2O_3 multiple nanowire gas sensor

Synthesis of gallium oxide nanowires via a hydrothermal method

Hydrothermal synthesis of Ga_2O_3 nanowires was performed by dissolving $Ga(NO_3)_3 \cdot nH_2O$ in deionized water to obtain a 0.01 mol Ga^{3+} solution. This was divided into three portions: one mixed with sodium acetate (SA), another with sodium dodecyl benzene sulfonate (SDBS), and the third left unmodified. The surfactant-to-Ga^{3+} molar ratio was maintained at 1:10. Each solution was subjected to hydrothermal treatment at 140°C for 10 hours in Teflon-lined autoclaves (16). The resulting solids were washed, dried, and then calcined in air at either 600°C or 900°C for 5 hours. Morphological characterization was performed using SEM (JSM 6700F) and TEM (JEM-3010). TEM specimens were prepared by dispersing samples in ethanol, followed by drop-casting onto carbon-coated Cu grids. XRD, PL (F-2500 spectrophotometer with Xe lamp), and FTIR (Nicolet Avatar 360 using KBr disks) analyses were also conducted.

Direct synthesis of beta gallium oxide nanowires by microwave plasma

A microwave plasma reactor (MPG 2010P, 1 KW) was employed for direct synthesis of β-Ga_2O_3 nanowires. A 0.3 g droplet of liquid gallium (purity >99.99%) was placed alongside a silicon substrate in a 40 mm diameter chamber. A plasma discharge was initiated, exposing the Ga droplet to microwave radiation in an environment of 100 sccm H_2O vapor and 100 sccm high-purity Ar at 40 Torr pressure. Growth parameters included microwave power between 600–900 W, a development duration of 1–6 hours, and a maintained substrate temperature around 550°C measured via infrared pyrometry (17). Structural and morphological analysis was conducted using SEM, TEM at 300 kV, XRD, and energy-dispersive X-ray spectroscopy (EDX). Notably, SEM imaging was performed directly on the as-grown samples without disturbing their positioning on the silicon substrates, while TEM analysis used material scraped from the substrate and mounted on copper grids.

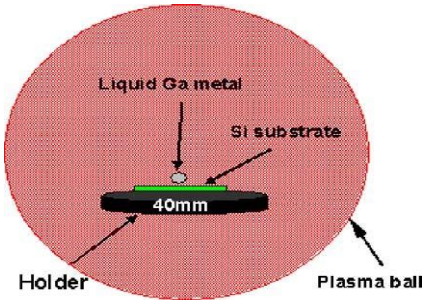

Figure 5: Schematic diagram of arrangement of the substrate and liquid Ga metal with respect to the plasma ball

RESULTS

The synthesized gallium oxide nanowires (GaONWs), collected as a white wool-like deposit on the surface of quartz boats, displayed a uniform morphology with lengths extending to several hundred micrometers and an average diameter of approximately 60 nm. Selected-area electron diffraction and statistical assessments confirmed the monocrystalline nature of these nanowires. Structural evaluation via X-ray diffraction (XRD) and Raman spectroscopy validated the monoclinic crystalline phase of Ga_2O_3. High-resolution electron microscopy (HREM) analysis revealed atomic-scale features, including distinct twinning parallel to the longitudinal axis of the wires, which likely contributed to the anisotropic growth behavior. No evidence of screw dislocations or nanoparticle involvement was observed, indicating that nanowire growth did not follow the classical whisker growth or vapor–liquid–solid (VLS) mechanisms. The absence of nanowires downstream and their direct formation on the quartz substrate supported a vapor–solid (VS) growth model. It was proposed that oxygen required for Ga_2O_3 formation was supplied by the silicon oxide layer on the quartz surface, activated by the reducing nature of gallium.

Further synthesis using a microwave plasma method produced a diverse array of white, wool-like Ga_2O_3 nanostructures, including nanowires, nanobelts, nanosheets, and nanograsses. These structures appeared around residual Ga droplets on 10 mm silicon substrates. XRD analysis confirmed the monoclinic crystalline phase of Ga_2O_3, with no additional crystalline impurities detected. TEM and SEM assessments showed crystalline uniformity, particularly in the nanowires and nanobelts. It was observed that the size and type of nanostructures varied with distance from the Ga source, with smaller, denser structures forming closer to the droplets and larger, more complex formations at further distances. The absence of catalytic particles and the nature of nucleation pointed toward a vapor–solid growth process, emphasizing the role of supersaturation control in obtaining low-dimensional structures. MOCVD-synthesized Ga_2O_3 nanowires exhibited distinct morphological features, including uniform one-dimensional growth with diameters ranging between 50–150 nm. SEM analysis identified bundled, wool-like aggregates of nanowires with a clear dependence on the Ar/O_2 gas flow ratio. A higher Ar-to-O_2 ratio yielded finer nanowires, suggesting that precursor concentration influenced the growth kinetics. XRD confirmed either an amorphous phase or extremely fine b-Ga_2O_3 crystallites in the deposits. TEM analysis differentiated nanowires with rough surfaces—exhibiting lattice fringes consistent with monoclinic b-Ga_2O_3 and polycrystalline electron diffraction patterns—from smooth-surfaced nanowires that appeared amorphous. These findings indicated the coexistence of both crystalline and amorphous structures within the synthesized materials. Notably, no metal catalyst residues or nanoparticles were detected, supporting a self-catalytic or catalyst-free growth mechanism.

Electrical, optoelectronic, and gas-sensing performance evaluations of the synthesized Ga_2O_3 nanowires revealed properties indicative of their high application potential. Electrical measurements performed on individual Ga_2O_3 nanowires configured in a field-effect transistor (FET) geometry demonstrated stable n-type conductivity, with reported resistivity values ranging from 10^4 to 10^6 Ω·cm, depending on nanowire dimensions and synthesis conditions. Photoluminescence (PL) spectra showed strong and broad emission bands centered around 446 nm and 465 nm, corresponding to photon energies of approximately 2.78 eV and 2.67 eV, respectively, which are attributed to donor–acceptor pair recombination and oxygen vacancy states within the Ga_2O_3 lattice. These emission characteristics affirm the optical responsiveness of the material in the visible and near-UV spectrum. Gas-sensing performance analysis using interdigitated Pt electrodes coated with Ga_2O_3 nanowires demonstrated high sensitivity and selectivity towards CO and O_2 gases. The sensors exhibited a peak response to O_2 at 300°C and to CO at 200°C, with response values increasing proportionally with gas concentration. The dynamic electrical resistance changes during gas exposure confirmed rapid response and recovery times, further supporting the nanowires' viability in real-time sensing applications. Collectively, these performance parameters validate the functional utility of Ga_2O_3 nanowires in electronic, optoelectronic, and environmental sensing devices.

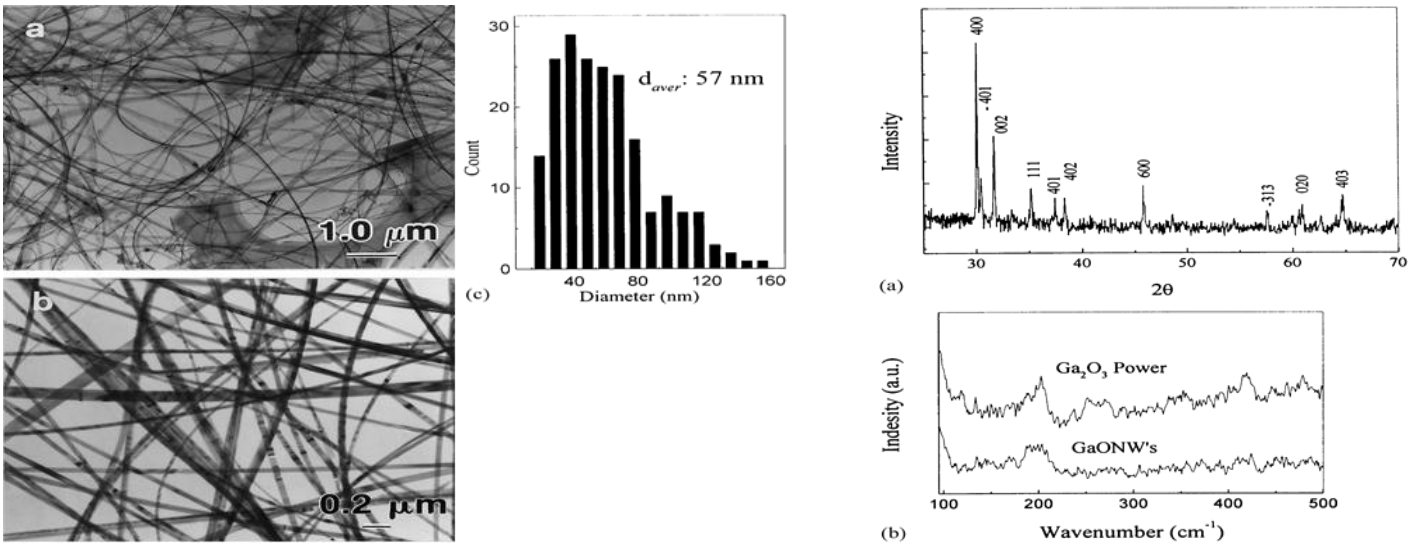

Figure 6: The Synthesized Gaonws, Collected as A White Wool-Like Product on The Quartz Boat Surface

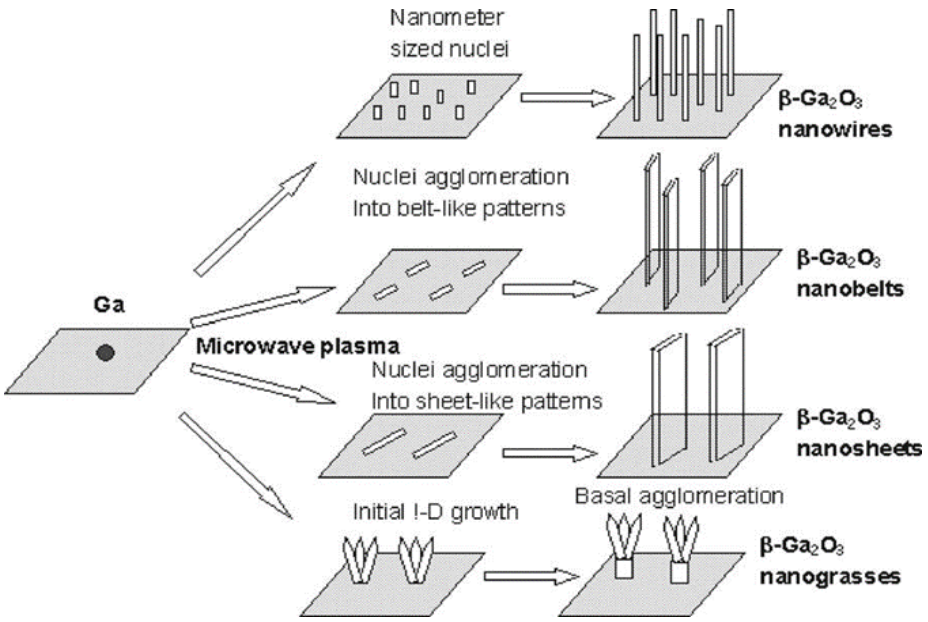

Figure 7: The Schematic Diagram Illustrated Different Nanostructures Grown by Microwave Plasma

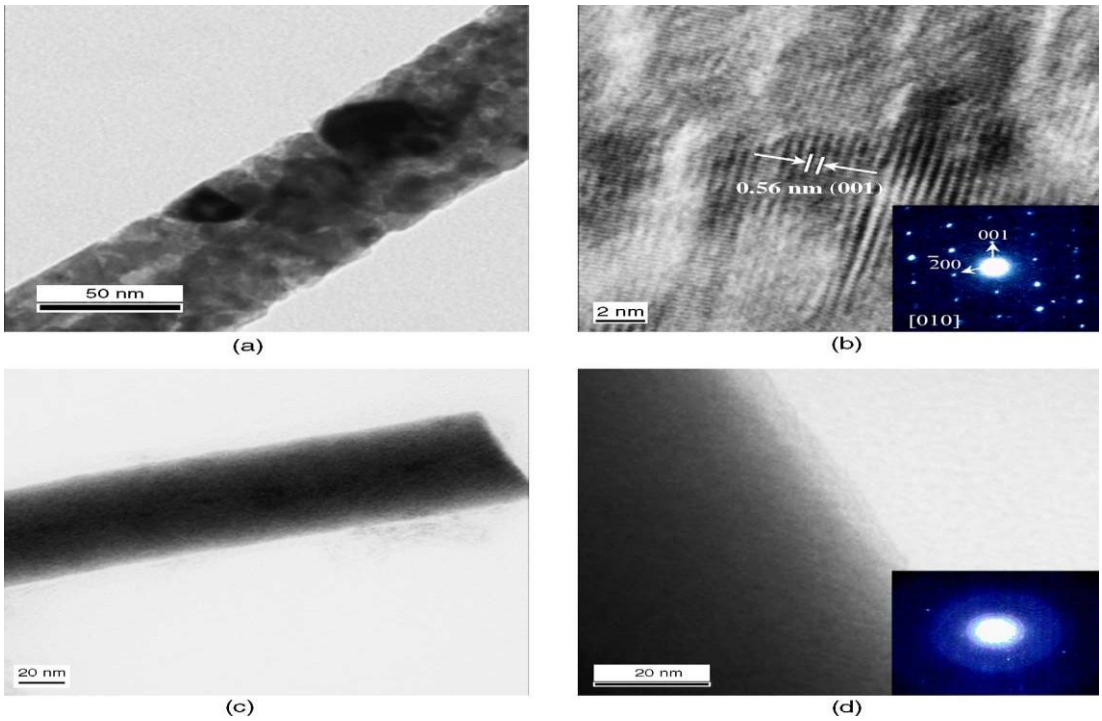

Figure 8: Fabrication and Characterization of Gallium Oxide (Ga_2O_3) Nanowires

DISCUSSION

The present study successfully synthesized gallium oxide (Ga_2O_3) nanowires using multiple vapor-phase and solution-based methods, offering comparative insights into their structural, morphological, and functional properties. The observed monocrystalline nature, uniform diameter distribution, and wool-like morphology of GaONWs highlight the effectiveness of catalyst-free growth processes such as vapor–solid and microwave plasma-assisted methods. These findings align with previous reports indicating that Ga_2O_3 nanowires can be grown via vapor-solid interactions without the need for metallic catalysts, reducing the risk of contamination and simplifying post-synthesis processing (18,19). The crystalline phase confirmed by XRD and Raman spectroscopy further reinforced the formation of the thermodynamically stable monoclinic β-Ga_2O_3 phase, consistent with the preferred structural form for high-temperature and high-power electronic applications. One of the notable outcomes of this study was the identification of twinning defects as a potential growth mechanism driver. Twinning was observed along the nanowire axis, which may facilitate anisotropic crystal growth by reducing surface energy—a mechanism previously underreported in Ga_2O_3 nanowire literature (20). The direct growth on the quartz boat surface, without evidence of screw dislocations or foreign nanoparticle involvement, strongly supports a defect-assisted VS growth pathway. This diverges from classical VLS growth models commonly reported for other semiconductor nanowires like Si and InP, where metal catalysts and liquid–solid interface control are essential (21,22). The importance of such defect-mediated growth mechanisms in Ga_2O_3 nanowire formation underlines the necessity for further atomistic and computational modeling to elucidate the thermodynamic and kinetic factors involved.

In terms of electrical and optoelectronic performance, the nanowires demonstrated n-type semiconducting behavior with resistivity values typical of β-Ga_2O_3, which has been attributed to intrinsic oxygen vacancies acting as shallow donors. This observation is in agreement with recent findings that oxygen vacancy engineering plays a critical role in determining the carrier concentration and mobility in Ga_2O_3-based devices (23,24). Photoluminescence spectra exhibiting blue emission centered at approximately 446–465 nm support the presence of donor–acceptor pair transitions, which are vital for optoelectronic applications such as UV detectors and LEDs. Such emission characteristics reaffirm the functional role of structural defects in dictating radiative recombination pathways and broaden the potential utility of these nanowires in photonic systems (25). The gas-sensing behavior of Ga_2O_3 nanowires was particularly promising. Their demonstrated sensitivity to CO and O_2 at moderate operating temperatures reflects the strong surface reactivity and large surface-to-volume ratio inherent to one-dimensional nanostructures. This performance is comparable to, and in some cases exceeds,

other reported metal oxide-based sensors like ZnO and SnO_2 (26). The absence of catalytic contamination and the straightforward drop-casting sensor fabrication method further enhance the commercial viability of Ga_2O_3 nanowire-based sensors. However, long-term stability, selectivity under mixed gas environments, and resistance to humidity remain to be systematically evaluated to ascertain their practical deployment in environmental monitoring or biomedical diagnostics.

While the study provides a comprehensive synthesis-to-application pipeline, certain limitations warrant attention. The reported electrical measurements were limited to basic resistivity assessments without full characterization of carrier mobility, Schottky behavior, or temperature-dependent conductivity. Moreover, the photoluminescence analysis, though indicative of defect-related transitions, did not include time-resolved measurements or quantum efficiency evaluations, which are crucial for understanding recombination dynamics in photonic applications. In the gas-sensing experiments, although clear trends were observed, quantitative sensitivity, response/recovery time data, and selectivity indices were not fully elaborated, which restricts the ability to benchmark against state-of-the-art sensors. Another limitation lies in the lack of a statistical framework for yield analysis and structural uniformity across different synthesis methods. High-resolution TEM imaging, while insightful, was sparsely utilized, and a more detailed crystallographic orientation study using techniques such as electron backscatter diffraction (EBSD) could enhance the understanding of growth dynamics. Furthermore, the influence of plasma conditions, microwave power, and substrate positioning in the plasma-assisted synthesis method deserves more rigorous parametric analysis to optimize the process for scalability.

Despite these limitations, the study offers several strengths. The use of multiple synthesis approaches provides a broad perspective on achievable morphologies and crystallinities, and the characterization methods were appropriately selected to validate the structural and optical properties of the nanowires. The integration of synthesis, device fabrication, and preliminary application testing forms a coherent and translationally relevant workflow that could be extended toward device prototyping and real-world application development. Future research should focus on enhancing control over defect density and distribution through in-situ doping or growth condition modulation, particularly to improve charge transport properties. Investigations into core–shell heterostructures and hybrid composites with materials like graphene or conductive polymers could unlock multifunctional applications, including biointerfaces and wearable sensors. Additionally, environmental stability studies, especially under variable humidity and temperature conditions, will be critical for deploying Ga_2O_3 nanowire devices outside controlled laboratory settings. Advanced computational modeling and machine learning-assisted synthesis optimization may further accelerate the development of customized nanostructures with targeted functionalities. In conclusion, the synthesized β-Ga_2O_3 nanowires exhibit favorable structural, electrical, optical, and sensing properties, underscoring their potential for diverse electronic and optoelectronic applications. However, targeted efforts toward quantitative performance benchmarking, synthesis scalability, and environmental stability are necessary to fully translate this promising nanomaterial into real-world technologies.

CONCLUSION

In conclusion, this study successfully demonstrated the synthesis and detailed characterization of gallium oxide nanowires using multiple growth techniques, offering critical insights into their structural purity, growth behavior, and potential functionality. The findings revealed that GaONWs could be formed without the use of external catalysts, highlighting a likely self-catalytic, defect-mediated vapor–solid growth mechanism driven by specific substrate interactions and vapor-phase dynamics. The structural integrity, confirmed through comprehensive analysis, supports their suitability for applications in electronics, optoelectronics, and sensing technologies. By advancing the understanding of Ga_2O_3 nanowire growth and morphology, this research lays a foundation for future work aimed at optimizing synthesis protocols and unlocking practical, scalable applications in advanced device platforms.

AUTHOR CONTRIBUTION

Author	Contribution
Ali Shan*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Amirab Nazir	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published

Author	Contribution
Amna Hussain	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published
Ali Nawaz	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Savera Yousaf	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Muhammad Ajmal	Substantial Contribution to study design and Data Analysis Has given Final Approval of the version to be published
Faisal Mahmood	Contributed to study concept and Data collection Has given Final Approval of the version to be published

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