Towards Manufacturing Large Area GaN Substrates from QST® Seeds

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Abstract

This paper summarizes recent developments in the hydride vapor phase epitaxy (HVPE) growth of thick crystalline GaN on 150 mm diameter QST® seeds followed by removal of the seed to create 100 mm diameter freestanding GaN substrates. A roadmap to manufacturing 200 mm freestanding GaN from 300 mm QST® is also presented in support of the manufacturing of GaN devices in large volume 200 mm diameter wafer fabs.

INTRODUCTION

Realization of a cost-effective high-quality large-diameter GaN substrate is an important goal for the high-volume GaN device industry. Large diameters are required for insertion into device manufacturers' fabs which currently are forced to use non-native substrates (including Si, sapphire, and SiC) which present lattice constant and thermal expansion mismatches with GaN that result in high defect densities and yield losses due to wafer bow and film cracking. With the exception of a few laboratory demonstrations, freestanding GaN substrate technology is effectively limited to diameters of 100 mm and smaller due to lattice lensing in the freestanding GaN crystal, an effect thought to be related to the use of non-native seeds with differing thermal expansion coefficients for bulk GaN growth [1]. Such realities have motivated Kyma and Qromis, Inc. to partner to apply Kyma's large diameter HVPE GaN process to Qromis' Qromis Substrate Technology (QST®) to leverage the large diameter and the close thermal match of the QST® to GaN. Recently Kyma and Qromis reported [2] on the realization of 10 micron thick 200 mm diameter GaN on QST® templates and in this paper Kyma and Qromis report on demonstration of 500 micron thick 100 mm diameter freestanding GaN as well as the path forward to realizing 150 mm and 200 mm diameter freestanding GaN.

TECHNICAL APPROACH

1) **Overall approach:** A schematic diagram of our technical approach is shown in Fig. 1. The basic process is HVPE growth of thick GaN on the 150 mm 5 µm thick GaN-on-QST® MOCVD template (or seed), followed by seed removal, followed by wafering, to create an epi-ready 100 mm freestanding GaN substrate. Following are some details about the seed material, growth tool, growth approach, and the seed removal process.

2) **QST® substrates:** Qromis has fabricated thousands of 150 mm QST® substrates and high performance LED device wafers based on those during the 2010-2013 period and recently reported [3,4] on its partnership with Vanguard International Semiconductor (VIS) to manufacture 200 mm diameter QST® substrates, GaN-on-QST® epi wafers, and GaN-on-QST® based device wafers at VIS in Taiwan. Qromis reported on these developments at the 2017 Compound Semiconductor International Conference [3] and 2017 International Conference on Nitride Semiconductors [4]. Currently, 200 mm QST® and GaN-on- QST® templates are commercially available products. The GaN on QST® template is shown schematically in the lower left portion of Fig. 1. It consists of a ceramic core which is closely thermal expansion matched to GaN and surrounded by a special passivation coating on which the thin (111) Si layer film is formed followed by an MOCVD GaN layer. The close thermal match of the QST® to GaN provides a unique substrate on which thick GaN can be deposited for freestanding GaN substrate production.

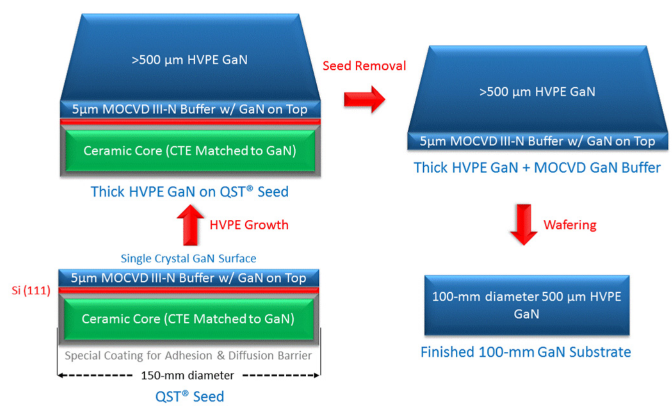

Fig. 1. Schematic of the process beginning with a 150 mm QST® substrate as the seed (bottom left), followed by growth of thick HVPE GaN, then removal of the seed, then wafering to create a 100 mm diameter freestanding GaN substrate. The process can be applied to 200 mm QST® substrates to produce 150 mm diameter freestanding GaN substrates.

3) **HVPE growth:** Kyma's HVPE growth tool and process technology was applied to Qromis' 150 mm diameter 5 µm thick high quality MOCVD GaN-on-QST® templates, which served as an epi-ready seed to nucleate and carry out thick GaN overgrowth. Kyma's patented and proprietary methods were used to control the surface morphology and GaN strain state throughout the growth. Kyma's HVPE tool & process have undergone a number of in-house improvements over the past decade, including hardware modifications and special techniques to minimize the frequency and the cost of maintenance events and to provide uniform and stable precursor flows up to and exceeding 15 mm of GaN growth before a maintenance event is needed. Until recently Kyma employed HVPE to produce 2 inch, 3 inch, and 100 mm substrates; recently Kyma expanded an existing tool to support 150 mm growths – that tool was used in the current study. Growth rates can be controlled from < 10 microns/hour to > 250 microns/hr without sacrificing crystalline purity or structural quality. As suggested in Fig. 1, HVPE growth of thick GaN under conditions that created the highest quality freestanding GaN leads to a narrowing of the growth surface diameter with thickness. This means the current process applied to 150 mm seeds do not enable a 150 mm freestanding substrate, which is why a 100 mm diameter substrate was targeted. Recently, however, Kyma has further expanded its diameter capabilities to grow GaN on 200 mm QST® templates (see Fig. 2) [2], which in the future will be used to create 150 mm freestanding GaN.

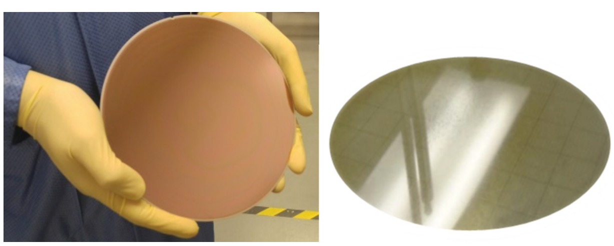

Fig. 2. (Left) Image of a 200 mm GaN on QST® template and (right) image of a 100 mm freestanding GaN substrate (after polishing) produced from a 150 mm QST® seed.

4) **QST® seed removal process:** A special technique was developed at Kyma that enables post-growth removal of the seed from the GaN crystal, the latter including both the MOCVD GaN buffer layer and the thick HVPE GaN layer. This results in a freestanding GaN crystal with a diameter between 100 mm and 150 mm and relatively smooth top and bottom surfaces. This crystal is suitable for subsequent wafering and polishing in order to produce an epi-ready GaN substrate.

5) **Wafering:** Once the seed is removed, the GaN crystal is put through Kyma's wafering processing, which is a combination of slicing, grinding, cutting, thinning, and polishing, with the goal of creating a 100 mm freestanding GaN substrate. The process for generating an epi-ready surface is similar that that which was developed over many years at Kyma for its commercial freestanding GaN (2" and smaller) substrate products and results in a surface finish that is without any evidence of scratching or subsurface damage. An image of a polished 100 mm substrate is shown in Fig. 2.

RESULTS & DISCUSSION

1) **Materials characterization:** X-ray diffraction (XRD) rocking curves of the GaN substrates showed full-width half-maximas < 150 arcsec for the symmetric {002} and asymmetric {102} peaks, consistent with high structural quality. Cathodoluminescence (CL) images were also obtained which corroborated the high structural quality and showed that defect densities are around $2x10^7$ cm^{-2}, which is similar to existing freestanding GaN substrates in the market and 10x to 100x lower than GaN buffer layers in GaN devices grown on non-native substrates (see Fig. 3). Large lattice radii of curvature, corresponding to > 35 meters of lensing, were measured through the central 60 mm of the 100 mm substrate which compares very well to the typical results from sapphire substrates which are never above 10 meters for 2" wafers [1] (see Fig. 4). Evidence of lensing at the wafer edge stems from a mounting issue.

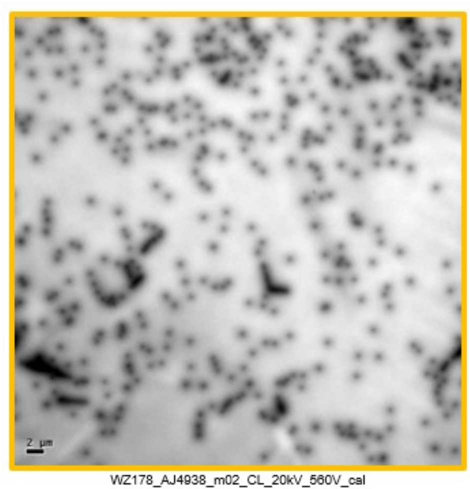

Fig. 3. CL image from a 100 mm freestanding GaN substrate produced from a QST® seed. Average defect density measured in 4 spots was 2E7 cm^{-2} with measurements ranging from 1.61E7 to 2.74E7 cm^{-2}.

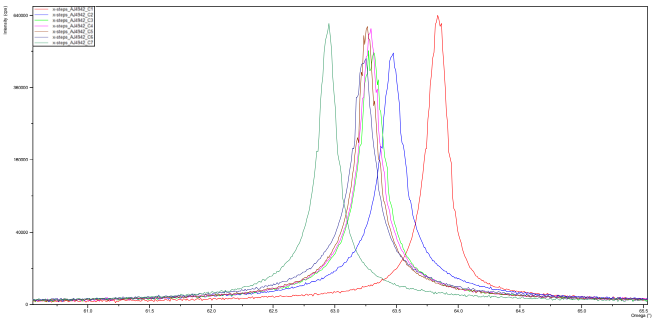

Fig. 4. Omega scans across 90 mm of polished freestanding GaN (AJ4938) showing good potential within the inner 60 mm (average curvature > 35 meters corresponding to 9 µm of bow over 2" or 35 µm of bow over 4") and lensing at the edge (with local curvature ~ 3 meters). The edge lensing stems from a polishing-induced mounting issue.

2) **Wafering/Polishing:** Utilizing the standard polishing processes developed for 2" freestanding GaN wafer production, we were able to achieve very smooth surfaces, suitable for carrying out device epitaxy. A Wyko white-light interferometer image spanning a region of 117 x 156 µm is shown in Fig. 5, exhibiting R_q and R_a roughnesses of < 1 nm. Further development of the polishing processes are likely necessary to enhance the material removal rates of the large substrates in order to minimizing the cost associated with polishing of these substrates, but the standard polishing processes appear to be satisfactory for producing low volumes of such substrates.

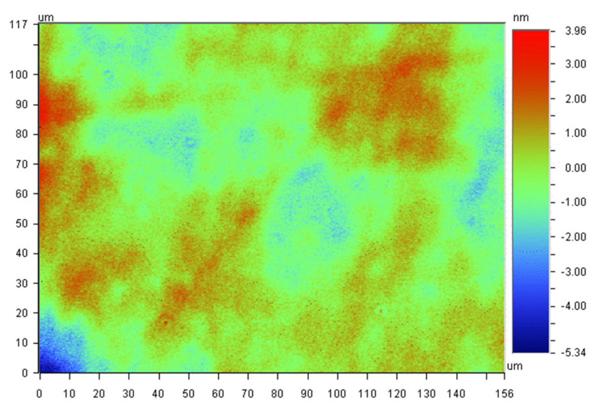

Fig. 5. Wyko image of a the GaN surface after CMP, showing an R_q roughness of < 1 nm.

3) **Manufacturing cost structure**: The manufacturing cost structure has been analyzed and the forecast for volume manufacturing scenarios is found to support a sub-$1,000 manufacturing cost for 100 mm and 150 mm freestanding GaN substrates based on GaN-on-QST® seeds. Our analysis is based on Kyma's current raw materials, labor, and indirect costs, and our analysis does not include the cost of the QST® seed. Cost vs. volume (per year) for 150 mm freestanding GaN substrates produced using this technique and assuming 100% yield is shown in Fig. 6. The $1000/wafer mark is met at a modest volume of about 100 wafers per month.

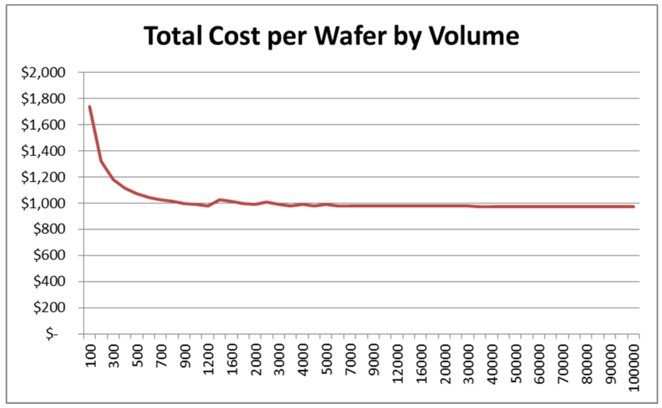

Fig. 6. Cost of 150 mm freestanding GaN wafers by volume (per year) using the GaN-on-QST® seed approach.

Closer analysis of the wafer cost can be understood by breaking the costs down further into those associated with crystal growth vs. those associated with polishing. These breakouts are given in Fig. 7. While crystal growth costs constitute a larger portion of the cost, we believe that polishing costs can potentially be easily reduced by further optimization of the polishing processes to increase the removal rates during lapping and polishing. Furthermore, if we were to move into a scenario in which we were producing such quantities of substrates we could presumably command better pricing than we currently garner from our raw materials suppliers (e.g. gallium, NH_3, quartzware, polishing slurries, etc.). As such, we believe that the 100 mm and 150 mm freestanding GaN substrates based on GaN-on-QST® seeds represent a potentially game-changing approach to realizing large-diameter freestanding GaN substrates.

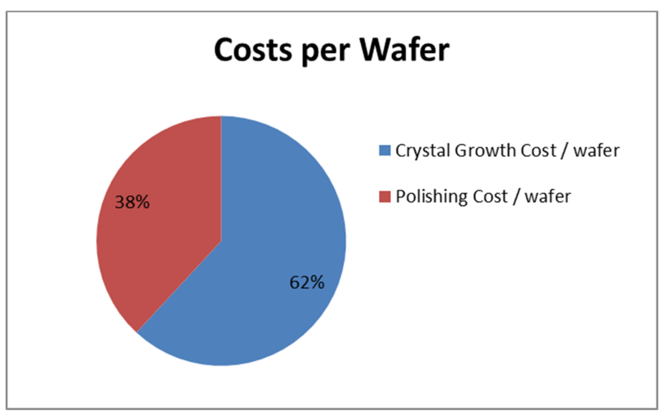

Fig. 7. Breakout of 150 mm wafer costs in terms of crystal growth vs. polishing costs.

CONCLUSIONS

Kyma and Qromis report on an exciting new demonstration of the manufacturing of 100 mm freestanding GaN substrates by applying Kyma's HVPE process to Qromis' CTE-matched 150 mm GaN-on-QST® seeds and employing a special technique for seed removal. The structural quality and defect density appears encouraging for device manufacturers to utilize such substrates for high performance GaN-based electronics. We additionally show the potential for a low manufacturing cost structure and the ability of the technique to extend to larger-yet diameters. This demonstrates that this technology has excellent commercialization potential.

ACKNOWLEDGEMENTS

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ACRONYMS

QST®: Qromis Substrate Technology
HVPE: Hydride Vapor Phase Epitaxy
VIS: Vanguard International Semiconductor