Gallium Oxide Techno-Economic Analysis for the Wide Bandgap Semiconductor Market

Preprint

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Gallium Oxide Techno-economic Analysis for the Wide Bandgap Semiconductor Market

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ABSTRACT

More than 30% of electrical energy passes through power electronics today with speculation that in the next decade this could grow to 80%. The wide bandgap semiconductor market is already approaching $1 billon USD in 2019 and is projected to be almost $7 billion USD in 2028. Even with its high cost, SiC, is starting to dislodge the incumbent Si technology in some applications, such as hybrid and electric vehicles, due to smaller size, and higher efficiency. We review and report the IHS Markit's market predictions for wide bandgap semiconductor technologies, and highlight the techno-economic analysis results for the manufacturing cost of Ga_2O_3 wafers. Specifically, we focus on the potential for Ga_2O_3 to be more economically advantageous than SiC using current manufacturing methods and then identify opportunities where research can further reduce the volume cost of Ga_2O_3 wafers.

Keywords: Ga_2O_3, gallium oxide, economics, market, techno-economic analysis, manufacturing

1. INTRODUCTION

Power electronics are playing an increasingly important role due to the rapid adoption of renewable energy technologies and the trend towards electrification of end-uses. More than 30% of electrical energy passes through power electronics today with speculation that in the next decade this could grow to 80%[1]. As a result, the wide bandgap market has the potential to grow from $1 billon USD in 2019 to $7 billion USD in 2028[2]. Silicon carbide (SiC) is the leading wide bandgap technologies but a barrier for additional adoption is its high cost when compared to the incumbent silicon technology. However, in applications where performance and size matter, such as hybrid and electric vehicles, SiC is starting to become the de facto technology used, even at its current cost. Wide bandgap power semiconductors account for less than 4% of the overall market in 2019. To achieve significant further adoption and market share lower prices will be required.

There are considerable advantages to using Ga_2O_3 in power electronics. For power electronics applications Ga_2O_3 provides a 4 - 10x higher performance limit than SiC or GaN, based on the widely-accepted Baliga's figure of merit (FOM), due to its wider bandgap (4.8 eV), as well as similar electron mobility (300 cm^2/Vs) and dielectric constant. However, one well-known challenge of Ga_2O_3 for power electronic applications: its 10x lower thermal conductivity compared to SiC and GaN. It has been shown that a Ga_2O_3 device will get much hotter than the conventional 150-200 °C operation temperature limit, necessitating aggressive thermal management[3]. Additionally further research is needed before p-tying Ga_2O_3 is available. Nevertheless, There is rapid progress being made on commercializing Ga_2O_3 wafers. At the beginning of 2020 it was possible to get purchase 4" Ga_2O_3 wafers as well as procure Ga_2O_3 wafers with epilayers.

With SiC technology already commercially available, the question arises regarding the value pursuing early stage research for gallium oxide (Ga_2O_3). As an answer to this question, our techno-economic analysis shows the potential for Ga_2O_3 to be more economically advantageous than SiC using current manufacturing methods while also providing the same reduction in size, increased efficiency, and higher operating temperature. The analysis further shows opportunities for research to make even greater advances in reducing the cost of Ga_2O_3 wafers produced at volume. Lowering the cost will further increase adoption of wide bandgap semiconductor based power electronics helping to meet the demand for increased electrical energy conversion, and facilitating wide bandgap technology capturing a significant share of this emerging market opportunity.

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2. WIDE BANDGAP SEMICONDUCTOR TECHNOLOGY MARKET

The wide bandgap market is poised for rapid growth in the next decade based on IHS Markit's market prediction. Figure 1 left shows the 2019 market for wide bandgap devices and modules achieved $1 billion USD. In the next decade the prediction is that it will top $7 billion USD. This growth is driven by the ability of the new technology to enable smaller systems; with the reduced size and weight, then leading to cost reductions, lower losses, higher switching frequencies, and higher operating temperatures. Wide bandgap semiconductors are still a tiny fraction of the overall power electronics market. Figure 1 right shows that in 2019 they only comprised 4% of the overall sales. The market remains dominated by incumbent silicon based technology.

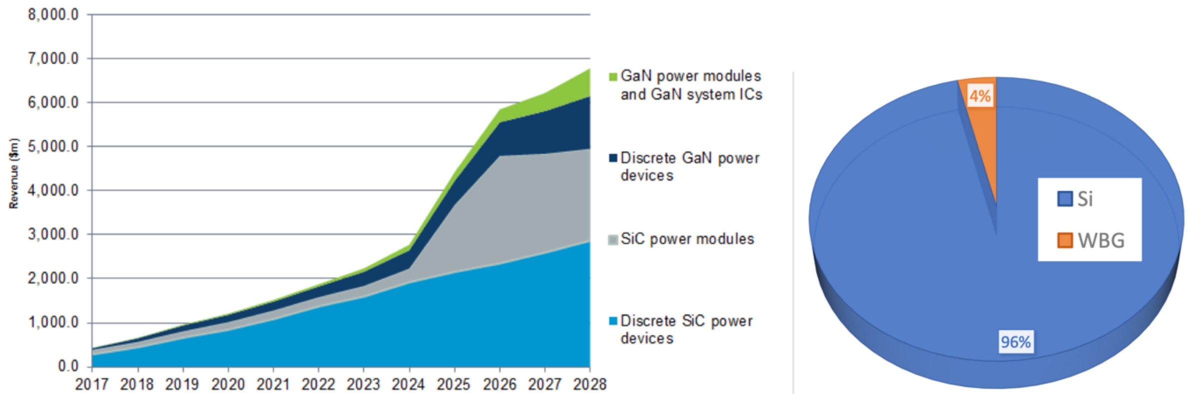

Figure 1. (left): 2019 IHS SiC and GaN market (Market data based on IHS Markit | Technology, now part of Informa Tech, SiC and GaN Power Semiconductors Report – 2019). (right): 2019 Power electronic market split between Si and WBG [4]

3. GALLIUM OXIDE WAFER TECHNO-ECONOMIC ANALYSIS

At an early stage of research on Ga_2O_3, it can be difficult to determine the new technology's potential against incumbent wide bandgap technology. Figures of merit can highlight Ga_2O_3's technical potential, but cost modeling is the only feasible method to determine whether it could compete with current state of art economically, assuming the necessary research breakthroughs are accomplished.

3.1. Methods

The process of manufacturing a Ga_2O_3 wafer was modeled using bottoms-up methodology[5]. This method is commonly used to understand the potential manufacturing cost of a technology at a volume similar to current state of art technology. The model for the Ga_2O_3 wafer was based on six process steps: Crucible charging; crystal growth; machine ingot; wafering and wafer clean; Polishing, final clean, and inspection; and lastly epitaxial growth using metal-organic chemical vapour deposition. The assumed parameters of the model include: 1m ingot length and 6in wafer diameter (similar to commercial SiC wafers), manufacturing volume of 5,000 wafers/month (allowing full equipment utilization), 10 times reuse of the Iridium crucible, and linear depreciation times of 7 years for equipment and 20 years for buildings. The cost show are for Ga_2O_3 wafers manufactured in the USA and do not include additional costs such as research & development and selling, general and administrative expenses (SG&A).

3.2. Results

Figure 2 shows the step by step cost for manufacturing a Ga_2O_3 wafer[5]. The total Ga_2O_3 wafer manufacturing cost comes to $283 USD. This is not market price, which may be higher due to profit margins and other factors such as those mentioned previously, such as SG&A. This compares to a cost of $916 USD for a similarly manufactured 6" SiC wafer[6].

The highest cost is in the crucible charging step. This cost is almost entirely materials. The materials costs are comprised of the substantial cost of the iridium crucible and the cost of the Ga_2O_3 powder. Research extending the usage of the crucible will have significant effect on driving down Ga_2O_3 wafer cost. The price used for the Ga_2O_3 was volume pricing given 2018 demand. The expectation is that the price would be reduced as demand for the Ga_2O_3 powder increased.

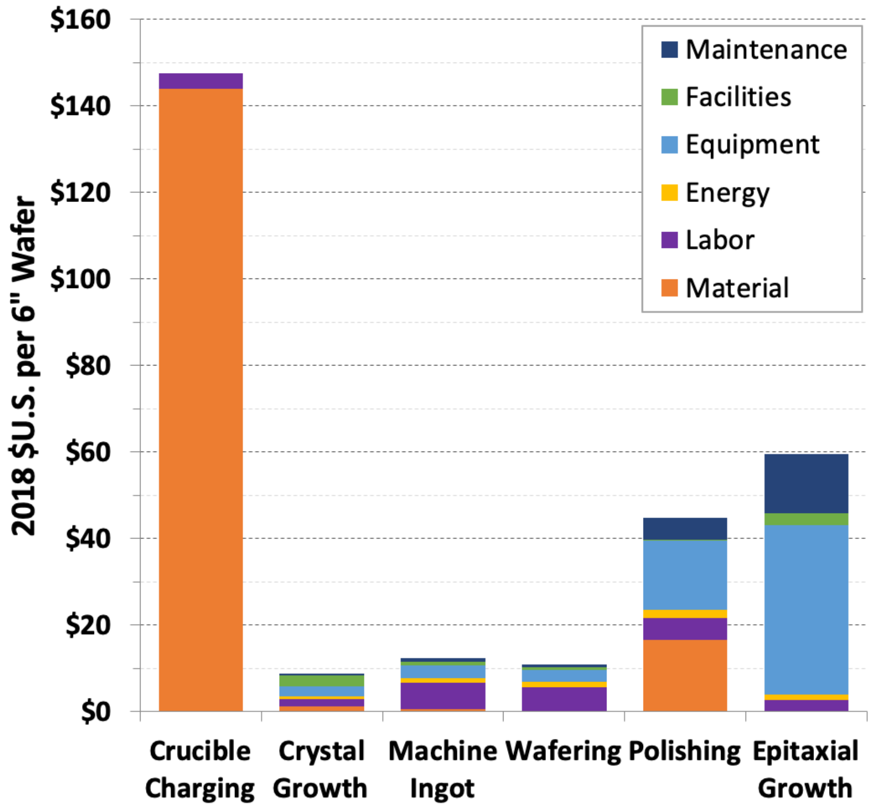

Figure 2. Ga_2O_3 6” 1m boule wafer manufacturing cost by each production step

4. GALLIUM OXIDE COST REDUCTION OPPORTUNITIES

Gallium Oxide 6in wafers manufactured at volume would be 3x less-expensive than a SiC wafer. Figure 3 compares the cost of $916 USD for a similarly manufactured 6” SiC wafer [6] (which is consistent with the market prices) to the projected cost for a Ga_2O_3 wafer manufactured in volume as described in section 3, which totaled $283. There is a 70% cost difference between the SiC and Ga_2O_3 wafers without any additional Ga_2O_3 wafer advances. The biggest driver of the cost difference between SiC and Ga_2O_3 is the inherent hardness of SiC requiring expensive diamond slurries and wire for the manufacturing process. For SiC manufacturing cost to further reduce, a cheaper alternative would have to be identified.

However, further cost reduction opportunities may be possible for Ga_2O_3 wafer manufacturing. The benefit of having bottom-up model is that the potential economic benefit of research advances can also be quantified. The furthest right bar in figure 3 shows even lower potential volume manufacturing cost of gallium oxide wafers. The figure shows that the wafer cost can be reduced from $283 to $195, a 31% reduction given 4 research advancements.

The first would be to double the crucible’s life. In 1974, Cockayne[7] documented the crucible could be used for a minimum of 10 uses. A literature search found allusions to advances that would increase the iridium crucible life, but not analytical numbers. There is indications that a crucible could actually be reworked to have a significantly longer life. For the purposes of a cost reduced Ga_2O_3 wafer a doubling of crucible life was conservatively chosen. Doubling the crucible life would further reduce cost 15%.

The second would to double the ingot length. Doubling the ingot length reduces the waste associated with each run. The waste is the pieces on each end of the boule that are cut off to make it the proper shape. Increasing the ingot length would provide a further 3% cost reduction.

The third proposed cost reduction would be to increase the polishing rate. By reducing polishing time by 50% a 4% cost reduction is realized.

Lastly, if the epitaxial deposition rate was 2X faster, a further 9% cost reduction would be achieved. This is achieved by allowing a higher utilization of equipment. The cumulative total if all these research advancements were achieved would be an additional $90 is savings, thus making a Ga_2O_3 wafer 80% cheaper than the projected SiC wafer.

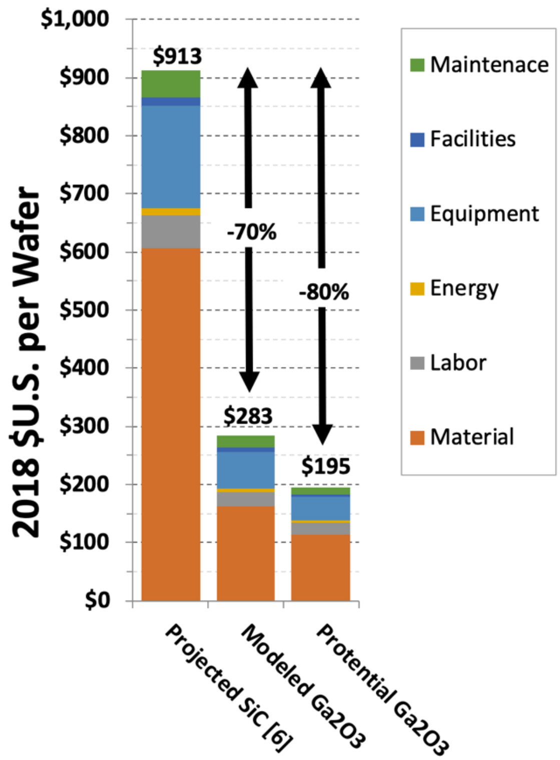

Figure 3. SiC cost compared to Ga_2O_3 with additional Ga_2O_3 cost down opportunities

5. CONCLUSION

The power electronics market is growing, with wide bandgap semiconductors capturing share in this Si-dominated market. With the wide bandgap market likely to grow 700% in the next decade the potential gallium oxide market is huge. The current cited roadblock to greater wide bandgap semiconductor adoption, is the high cost. Thus, gallium oxide's potential for lower cost and higher performance limit makes it an attractive alternative. While the technoeconomic analysis of the Ga_2O_3 wafer cost presented here is based on the future large-size and high-volume manufacturing scenarios, the estimated >3x cost advantage of Ga_2O_3 compared to SiC wafers can potentially translate to devices, and hold true once technical research and development advances move Ga_2O_3 devices into mainstream applications. In addition, the significant cost savings could help incentivize other cost-sensitive applications to switch to wide bandgap devices and realize the energy efficiency gains as well.

6. ACKNOWLEDGEMENT

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