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A Study on the Synthesis and Evaluation of Si/SiC Powders for SiC Wafers Fabrication and Si-Based Devices

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Abstract. This study delves into the synthesis of high-purity SiC powders utilizing two distinct silicon (Si) sources of recycled Si wafers and back-grind wastewater-both of which are abundant by-products in semiconductor manufacturing processes. The synthesis involved the high-temperature reaction of these Si sources with ultra-high-purity graphite (>6N) at temperatures exceeding 2100°C. The resulting α-phase SiC powders derived from previously used Si wafers demonstrated unparalleled quality, achieving a purity level surpassing 99.9999% and exhibiting particle sizes exceeding 500 µm. These characteristics render them highly suitable for the fabrication of SiC wafers, a cornerstone of advanced semiconductor applications. This research underscores the potential of leveraging industrial by-products as sustainable Si sources for SiC synthesis, highlighting the superiority of α-phase SiC produced from recycled Si wafers in high-purity applications.

1. Introduction

Silicon carbide (SiC) has cemented its position as a cornerstone material in modern power electronics, owing to its unparalleled electrical and thermal properties [1]. These attributes, including its wide bandgap, high thermal conductivity, and superior mechanical strength, make SiC an ideal candidate for high-performance power semiconductor devices, such as Schottky diodes, MOSFETs, and IGBTs[2, 3]. However, the success of SiC-based devices is intricately linked to the quality and consistency of SiC wafers, which are directly dependent on the purity and physical properties of the precursor materials used in their fabrication [4-7]. Achieving a stable supply chain for these precursors is critical to meeting the growing demand for SiC technology in electric vehicles (EVs), renewable energy systems, and other power electronics applications [8].

The quality of SiC wafers is fundamentally determined by the characteristics of the precursor materials, particularly the SiC powders used as the foundational raw material [4]. High-purity SiC powders with consistent particle sizes and controlled crystalline phases are essential for producing wafers with the desired electrical conductivity, thermal stability, and mechanical integrity [9,10]. Any impurities or deviations in the powder properties can lead to defects in the SiC lattice structure, compromising the performance and reliability of the final semiconductor devices [9]. Therefore, the development of high-quality SiC powders is a cornerstone of advancing SiC wafer manufacturing and ensuring the long-term success of power semiconductor technologies.

The rapid increase in silicon sludge generated is a significant trend accompanying in from silicon solar cell manufacturing [11,12]. This by-product, rich in silicon content, presents a valuable opportunity for recovery and utilization across various industries, including semiconductors, where high-purity silicon is essential for wafer fabrication and device manufacturing. Additionally, silicon sludge can be processed into fine powders, which serve as a sustainable source of silicon for the production of silicon carbide (SiC) powders—a critical material in power electronics and semiconductor devices. By integrating these by-products into the silicon supply chain, industries can reduce reliance on virgin raw materials, enhance process efficiency, and contribute to environmental sustainability. Cutting is achieved by abrasive slurry, which consists of suspension silicon carbide particles. During the process of wafer cutting almost 50% of silicon is lost in the sludge [13]. Several attempts were made to recycle the silicon sludge retrieved from the wire saw machines. However, there are no high successful results reported so far.

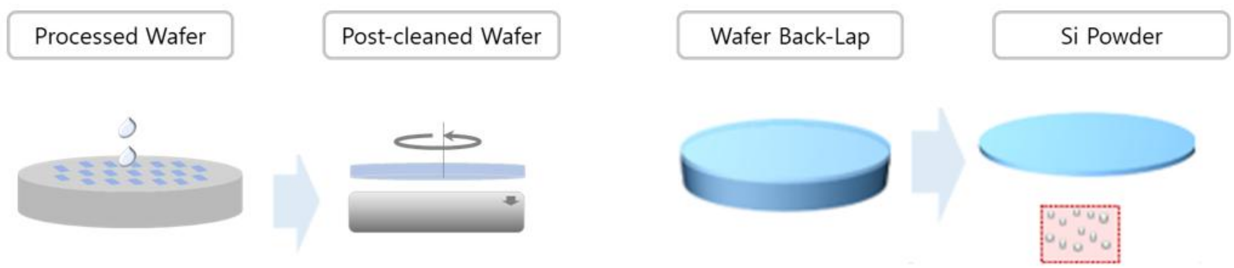
In the semiconductor industry, silicon is extracted from used wafers and back-grind wastewater, offering a reliable and sustainable source for SiC synthesis. These advancements in material recovery and processing not only optimize resource utilization but also align with the growing demand for high-performance materials in applications such as power electronics, electric vehicles (EVs), and renewable energy systems. By leveraging silicon sludge and other by-products, industries can achieve a more circular and efficient supply chain, supporting both economic and environmental objectives.

To address the challenges of obtaining high-quality SiC powders while ensuring a stable supply chain, this study explored the potential of utilizing semiconductor process by-products as sustainable raw materials for SiC wafer fabrication. Silicon by-products such as used Si wafers and back-grind wastewater, are readily available in semiconductor manufacturing facilities and offer a promising source of high-purity Si. These by-products can be processed into silicon powders, which can then be synthesized into SiC powders for SiC wafer production. By capitalizing on these readily available materials, manufacturers can reduce reliance on virgin raw materials, minimize waste generation, and enhance the environmental sustainability of SiC production processes. In detail, this research investigated the preparation and characterization of SiC powders derived from two distinct Si sources: used Si wafers and back-grind wastewater. Used Si wafers, which are inherently high-purity and large-particle materials, were crushed to produce fine Si powders, while back-grind wastewater, a by-product of wafer back-grinding, was processed to extract Si through solvent evaporation and milling. The resulting Si powders were then synthesized into SiC powders under carefully controlled conditions, with the aim of evaluating their suitability for SiC wafer manufacturing.

This study underscores the critical importance of optimizing precursor materials and supply chain management in the advancement of SiC wafer fabrication and power semiconductor technology. By leveraging semiconductor process by-products as sustainable raw materials, manufacturers can significantly enhance the efficiency, cost-effectiveness, and environmental sustainability of SiC production processes.

2. Experimental

In order to recycle these generated silicon in semiconductors and other industries, it is important to find a best methods for the solidified powder form Si solution. Two powders prepared from different methods is various, as shown in Fig.1. Si powder was prepared by crushing from the used Si wafer, as shown in Fig. 1(a). On the other hand, as for the method of recycling silicon wastewater, as shown in Fig. 1.(b), typical method of making solid silicon from various silicon byproducts is a method of solidifying a Si solution by forming a solid phase using a filter press with a silicon solution as shown in Figure 2. Specifically, a method of forming a silicon cake by extracting deionized water



(a) (b)

Fig. 1. (a) Cleaned wafer and back-grinding process and in semiconductor processes.

Fig. 2. Methods of Si powders prepared from the Si solution.

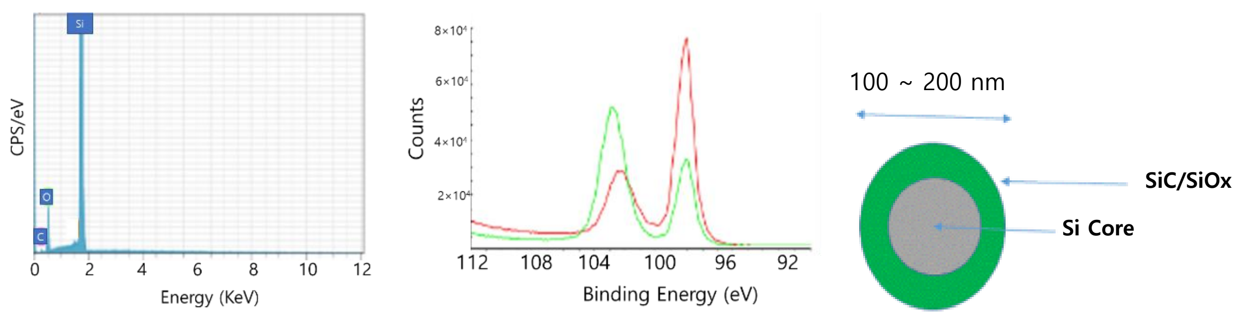
from a silicon solution is typical, and silicon cake can be dried to finally produce silicon powder. This study focuses on the synthesis and evaluation of silicon carbide (SiC) powders derived from two distinct silicon (Si) sources (used Si wafers and back-grind wastewater) for SiC wafer. Two different SiC powders were prepared by reaction of both Si powders with pure graphite (purity > 6N) at over 2100°C. Key objectives include analyzing the purity, particle size, and crystalline phases of the resultant SiC powders, as well as exploring their applications in semiconductor SiC devices manufacturing. Advanced analytical techniques, including energy dispersive X-ray spectroscopy (EDX), X-ray photoelectron spectroscopy (XPS), and scanning electron microscopy (SEM), were employed to investigate the composition and structural properties of the Si and SiC materials.

3. Results & Discussion

3.1 Characterization of Si Powders and Optimization of SiC Powder Synthesis for Semiconductor Applications

Si powders derived from back-grind wastewater yielded larger particle sizes (around 1 µm), which SiC powders are less suitable for advanced SiC wafer applications. The primary constituents of silicon (Si) powders derived from back-grind wastewater were confirmed through energy-dispersive X-ray spectroscopy (EDX) to be Si, O, and C, as illustrated in Figure 3(a). X-ray photoelectron spectroscopy (XPS) further revealed the presence of SiOx phases, indicative of an amorphous structure, as shown in Figure 3(b). These findings suggest that the surface of the Si powders interacted with ambient oxygen forming SiOx layers that significantly influenced their reactivity and applicability, as depicted in Figure 3(c).

In contrast, Si powders were successfully synthesized from used Si wafers with small oxidation



(a) (b) (c)

Fig. 3. Chemical composition results of Si powders: (a) EDX results, (b) and XPS results. And then, a schematic diagram of Si powders coated oxidized and carbonized Si as shown in (c).

Table I. Characteristics of Si Powders Prepared Using Various Methods.

Source	Method	Si	
		Size(μ m)	Oxidation(%)
Used Wafer	Crushing	90.1	0.04
	Polish+Crush	88.3	0.1
Back-grinded Waste	Evaporation	1.7	16
	Evaporation+Mill	0.75	3.88

under 0.1%, characterized by particle sizes around 100 μm, as shown in Table I. These attributes make them highly suitable for SiC wafer fabrication, aligning with the stringent requirements of power semiconductor manufacturing.

The quality of SiC powders, which are critical raw materials for SiC wafer manufacturing in power semiconductors, is determined by several key factors, including metal impurities and physical properties. High-quality Si powders are essential for achieving the purity and structural integrity required for SiC wafers. As such, the quality of Si powders and their supply chain management (SCM) are paramount for the success of SiC power semiconductor manufacturing. Obtaining Si powders from semiconductor processes, particularly through Si wafer back-grinding, is a promising approach to ensure the quality and consistency of SiC powders.

To evaluate the feasibility of Si powder synthesis from Si by-products, this study prepared Si powders using Si generated within a semiconductor company. In order to compare the quality of the synthesized Si powder, Si prepared for each raw material was analyzed, as shown in Table I. The results demonstrated that the Si powders prepared from used Si wafer exhibited superior quality, exceeding the performance of conventional raw materials. The size of Si powder over 80 um prepared from the used Si wafer, as shown in Table I with under 0.1 % oxidation. These powders were further assessed at a SiC powder mass production facility, and their suitability for SiC wafer fabrication was confirmed. From used Si wafers, high-purity Si powders were successfully synthesized.

This research highlights the potential of leveraging silicon by-products from semiconductor processes as sustainable raw materials for SiC powder synthesis. By securing high-quality SiC powders from used Si wafers, manufacturers can improve the efficiency and scalability of SiC wafer production, ultimately enhancing the performance of power semiconductor devices.

3.2. High-Purity α-Phase SiC Powders and Their Role in SiC Wafer Fabrication and Semiconductor Device Enhancement

The intrinsic properties of SiC powders are pivotal in determining their suitability for SiC wafer fabrication and the subsequent performance of semiconductor devices. High-purity α-phase SiC powders, specifically those derived from crushed Si wafers, exhibit a remarkable combination of characteristics that make them exceptionally well-suited for SiC wafer production, as shown in Fig.4. These powders possess particle sizes exceeding 500 μm, which not only enhance the structural integrity of the wafers but also facilitate efficient processing during manufacturing in Table II. Furthermore, their purity levels exceeding 99.9999% ensure minimal impurity incorporation, which is critical for achieving high-quality SiC wafers with superior electrical and thermal properties, as

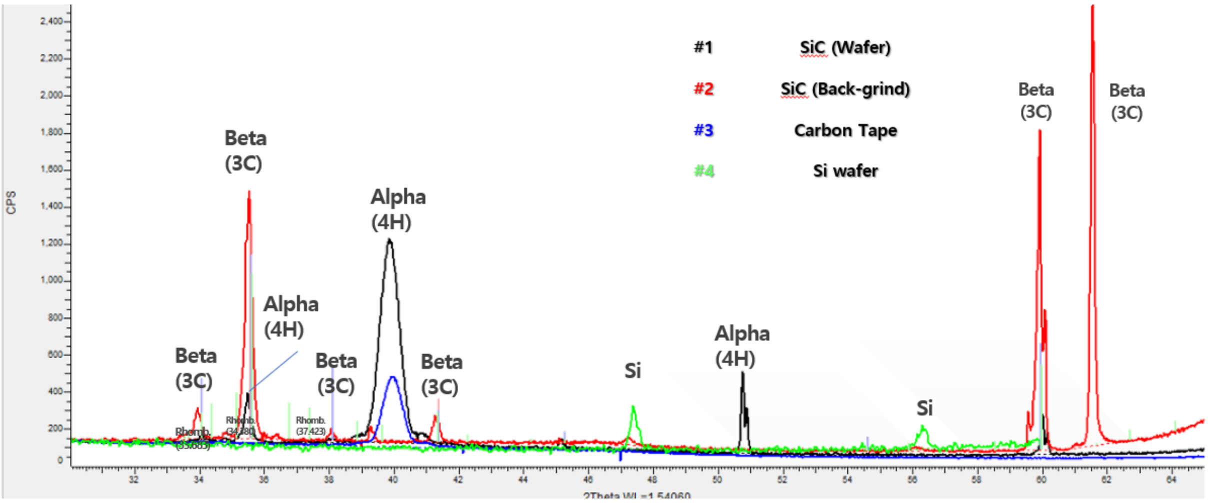


Fig. 4. XRD of two Size distribution of two different SiC powders prepared from different methods of filtered powder from back-grinding Si and crushed powders from process wafer in semiconductor industries.

shown in Table II. These attributes align seamlessly with current manufacturing workflows, enabling manufacturers to integrate SiC powders into existing production processes without significant modifications. This compatibility ensures a smooth transition to scalable SiC-based power device production, which is essential to meet the growing demands of the electric vehicle (EV) and renewable energy sectors. The large particle sizes of the α-phase SiC powders also contribute to reducing processing times and material waste, further enhancing the economic viability of SiC wafer fabrication.

Conversely, Si powder obtained from backgrind wastewater showed oxidation ratio (16%) of 1.7 μm in size, causing the problem of producing β-phase SiC, which is essential for SiC wafer applications, as shown in Fig. 4. The study highlights the critical role of SiC powder quality in determining the performance of SiC-based devices. Si powders from back-grind wastewater, though viable for certain applications, were found to be less effective for SiC wafer production. Si powders derived from back-grind wastewater present notable challenges for SiC wafer applications. These powders typically exhibit smaller particle sizes (~1.7 μm), which can lead to increased aggregation and poor sinterability, resulting in lower-quality wafers. Additionally, their higher oxidation ratios (16%) introduce oxygen impurities that can adversely affect the electrical properties of the final SiC devices. These characteristics render them less suitable for high-performance SiC wafer fabrication, though they may still find utility in applications where material cost and processing efficiency are prioritized over ultimate device performance.

In the realm of SiC wafer fabrication, high-purity α-phase SiC powders derived from polished Si wafers stand out as a highly promising material for SiC wafer production [9,10]. These powders, with their exceptional purity levels exceeding 99.9999% and particle sizes exceeding 500 μm, offer distinct advantages that align with modern manufacturing requirements for SiC-based power devices. Their superior quality ensures compatibility with existing production workflows, enabling manufacturers to seamlessly integrate advanced materials into current processes without the need for significant modifications. This characteristic is particularly valuable in the context of scalability, as it allows for the efficient and cost-effective production of high-performance SiC wafers, which are increasingly in demand for applications in electric vehicles (EVs), renewable energy systems, and other power electronics sectors. The use of α-phase SiC powders derived from polished Si wafers also enhances the intrinsic properties of the resulting SiC wafers, such as electrical conductivity, thermal stability, and mechanical strength. These improvements directly contribute to the performance of power semiconductor devices manufactured using these wafers, such as Schottky diodes, MOSFETs, and IGBTs. By leveraging the high purity and large particle sizes of these powders

Table II. Characteristics of SiC Powders.

Source	Method	SiC		
		Size(μm)	Purity	Crystal Phase
Used Wafer	Crushing	515	2N6	α-SiC
	Polishing + Crushing	490	>6N	α-SiC
Back-grinded Waste	Solidification	2.5	3.5N	β-SiC
	Solidification + Milling	3.1	4.5N	β-SiC

manufacturers can achieve wafers with minimal impurities, which is critical for maintaining the integrity of the lattice structure and ensuring optimal device characteristics. Furthermore, the scalability of SiC-based power devices is significantly enhanced, as these wafers can be processed using established manufacturing techniques, thereby reducing the time and cost associated with process development and implementation.

Si powders derived from back-grind wastewater, despite their potential as sustainable raw materials, fall short of meeting the stringent requirements for SiC wafer fabrication. These powders typically exhibit smaller particle sizes (~1.7 μm) and higher oxidation ratios (16%), which lead to challenges in achieving the desired purity and structural integrity for high-performance SiC wafers. The increased particle aggregation and poor sinterability associated with these powders result in wafers that are less suitable for applications requiring exceptional electrical and thermal properties.

However, these Si powders still offer viable alternatives for applications where material cost and processing scalability are prioritized over ultimate device performance. For instance, they can be utilized in lower-cost SiC devices or as part of hybrid manufacturing processes that combine different SiC powder sources to optimize material utilization and cost-effectiveness. Therefore, high-purity α-phase SiC powders derived from polished Si wafers represent a transformative solution for SiC wafer fabrication, offering superior quality, compatibility with existing workflows, and scalability for SiC-based power devices. These materials not only enhance the performance of the final devices but also align with the sustainability goals of the semiconductor industry by leveraging by-products from existing fabrication processes. While Si powders from back-grind wastewater may have limitations for high-performance SiC wafer applications, they provide valuable alternatives for specific use cases, demonstrating the diverse potential of Si-based materials in advancing semiconductor technology.

As you know, general Si wafer were doped with n-type or p-type dopant I used this doped wafer for preparation of SiC powder. The doping depth is very shallow and very low concentration, compared to that bulk wafer thickness and Si bulk atomic concentration. I did not any action for removing this doping amount for pure SiC powders. I checked the main doping amount. I do not observe remarkable impurities depending on doping amount in Table II.

3.3. Properties of SiC Powders and Their Impact on SiC Wafer Fabrication and Device Performance

The intrinsic properties of SiC powders are pivotal in determining their suitability for SiC wafer fabrication and the subsequent performance of semiconductor devices. High-purity α-phase SiC powders, specifically those derived from crushed Si wafers, exhibit a remarkable combination of characteristics that make them exceptionally well-suited for SiC wafer production. These powders possess particle sizes exceeding 500 μm, which not only enhance the structural integrity of the wafers but also facilitate efficient processing during manufacturing.

Conversely, Si powders derived from back-grind wastewater present notable challenges for SiC wafer applications. These powders typically exhibit smaller particle sizes (~1.7 μm), which can lead to increased aggregation and poor sinterability, resulting in lower-quality wafers. Additionally, their higher oxidation ratios (16%) introduce oxygen impurities that can adversely affect the electrical properties of the final SiC devices. These characteristics render them less suitable for high-performance SiC wafer fabrication, though they may still find utility in applications where material cost and processing efficiency are prioritized over ultimate device performance.

4. Conclusion

Silicon carbide (SiC) has emerged as a pivotal material in modern power electronics due to its exceptional electrical and thermal properties, making it essential for high-performance semiconductor devices. However, the production of SiC wafers relies heavily on the quality and purity of precursor materials, which directly impact the performance of the final products. This study explores the synthesis and characterization of SiC powders derived from two distinct silicon (Si) sources: used Si wafers and back-grind wastewater. These by-products, readily available in semiconductor manufacturing, were selected as potential raw materials for SiC wafer fabrication. The research focuses on optimizing the production process to maximize the quality of SiC powders. High-purity α-phase SiC powders were successfully synthesized from used Si wafers, exhibiting exceptional purity (>99.9999%) and large particle sizes (>500 μm), making them highly suitable for SiC wafer manufacturing. Conversely, Si powders obtained from back-grind wastewater, while similar in size of 1.7 μm, showed higher oxidation ratios (16%) and were less effective in producing α-phase SiC, which is essential for SiC wafer applications. The study highlights the critical role of SiC powder quality in determining the performance of SiC-based devices. High-purity α-phase SiC powders derived from used Si wafers demonstrated outstanding compatibility with existing manufacturing workflows, supporting the scalability of SiC-based power electronics. By controlling the characteristics of SiC powders from Si raw materials to SiC devices, this study contributes to advancing Si-based material technology and enhancing the performance of power semiconductor devices. The findings provide valuable insights for optimizing SiC wafer fabrication processes, ensuring a stable supply chain, and meeting the growing demand for high-performance SiC materials in power electronics.

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