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Comparison of the Properties of Mono-like, Monocrystalline, and Multicrystalline Silicon for Photovoltaic Applications.

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ABSTRACT

Quasi-mono silicon (Mono-like) (ML-Si) offers improved crystal quality over multicrystalline silicon (mc-Si) while maintaining lower production costs. Manufactured via directional solidification with seeded growth, ML-Si achieves a crystallographic structure comparable to Czochralski-grown monocrystalline silicon (Cz-Si). This study compares the physical and chemical properties of ML-Si, Cz-Si, and mc-Si using scanning electron microscopy (SEM), X-ray diffraction (XRD) and EDX analysis performed with SEM analysis. Results show that ML-Si closely matches Cz-Si in surface morphology and crystal orientation. The EDX spectra indicate that Silicon is the dominant element. After alkaline texturing, the reflectivity of ML-Si is approximately 5% higher (absolute) than that of Cz-Si across the 300–1200 nm range, but significantly lower than that of mc-Si. This reduced reflectivity compared to mc-Si, combined with its lower dislocation density and fewer grain boundaries lead to improved structural uniformity and superior optical performance. Consequently, ML-Si combines the economic benefits of high performance of Cz-Si and the cost advantages of mc-Si production, making it as promising material for high-efficiency, low-cost photovoltaic applications.

1 Introduction

Crystalline silicon wafers, including single-crystalline silicon grown by the Czochralski method (Cz-Si) and multicrystalline silicon (mc-Si), continue to dominate the global photovoltaic (PV) industry owing to their well-established processing technologies, material stability, and favourable electronic properties [1–3]. Crystalline silicon technologies account for the overwhelming majority of global PV production, reflecting decades of technological optimisation and industrial maturity [2]. Cz-Si wafers are characterised by excellent crystallographic uniformity, low defect densities, and

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superior minority carrier lifetimes, enabling high power conversion efficiencies in advanced solar cell architectures [3–4]. However, the Czochralski crystal growth process remains relatively energy-intensive and costly, particularly due to ingot shaping and wafer slicing losses [5].

In contrast, mc-Si is typically fabricated by directional solidification (DS), a casting method that allows reduced manufacturing costs and higher throughput [6]. Despite its economic advantages, mc-Si inherently contains grain boundaries, dislocations, and impurity accumulations, which can act as recombination centres and negatively affect device performance [7, 8]. Significant research efforts have therefore focused on improving the crystal quality of cast silicon materials and mitigating structural defects [6–9].

To bridge the performance–cost gap between Cz-Si and mc-Si, quasi-monocrystalline silicon, commonly referred to as mono-like silicon (ML-Si), has emerged as a promising alternative substrate material. ML-Si is produced using seeded directional solidification, where monocrystalline Cz-Si seeds are placed at the base of the crucible to promote preferential crystal growth, typically along the $\langle 100 \rangle$ orientation [9–11]. This approach enables the fabrication of square wafers compatible with industrial production lines while significantly reducing the formation of high-angle grain boundaries compared with conventional mc-Si.

Structurally, ML-Si exhibits characteristics intermediate between mc-Si and fully monocrystalline silicon. It demonstrates reduced dislocation density, improved crystallographic orientation, and enhanced structural uniformity [11–13]. Several studies have reported that mono-like silicon can achieve minority carrier lifetimes and electronic properties approaching those of Cz-Si, while maintaining the economic advantages of cast silicon processing [12–15]. Furthermore, investigations into the behaviour of ML-Si under various chemical treatments have highlighted its favourable surface morphology and structural stability compared with conventional mc-Si [16].

Recent progress in crystal growth optimisation, defect engineering, and impurity segregation control has further improved the material quality achievable through directional solidification techniques [2, 6, 14]. Consequently, ML-Si is increasingly recognised as a technologically viable compromise that combines the electronic performance of Cz-Si with the reduced production costs of mc-Si [17].

In the present study, a comparative investigation of ML-Si, Cz-Si, and mc-Si wafers is conducted using scanning electron microscopy (SEM), X-ray diffraction (XRD), and energy-dispersive X-ray spectroscopy (EDX). The objective is to evaluate structural quality, crystallographic orientation, chemical purity and optical behaviour after alkaline texturing in order to assess the suitability of ML-Si for high-efficiency photovoltaic applications.

2 Materials and methods

2.1 The chemical texturing

This experiment is carried out on silicon Cz-si, ML-Si and mc-Si substrate pieces of size (2.5cm×2.5cm).

In our work we used basic texturisation (NaOH) such as: The NaOH solution which consists on: NaOH, IPA. This solution is heated to 80° C for 55 minutes. The next step is the characterization of these samples:

- a) A physico-chemical characterisation
- b) A morphological characterisation space.

3 Characterization of crystalline silicon

3.1 Morphological characterization:

Scanning electron microscopy (SEM) analysis of three types of silicon (Cz-Si, ML-Si, and mc-Si) at magnifications of 30 μm and 100 μm reveals distinct differences in surface morphology as a function of crystalline structure. All samples exhibit surface roughness; however, Cz-Si and ML-Si demonstrate highly comparable textures.

The mc-Si substrate (Fig. 1(a)) displays a heterogeneous surface, characterized by grains of variable shapes and orientations. This irregularity originates from the multicrystalline nature of the material, whereby grains with differing crystallographic orientations are etched at different rates, potentially affecting optical absorption and surface recombination.

By contrast, ML-Si and Cz-Si (Fig. 1(b) and 1(c)) present a predominantly uniform pyramidal texture, typical of $\langle 100 \rangle$ oriented silicon. The pyramids are well-defined and sharp, resulting from anisotropic etching along the $\{111\}$ planes. Regions of high pyramid density, covering approximately 80–90 % of the surface, promote efficient light trapping and reduce reflectance, whereas areas of lower density may marginally increase recombination losses.

Overall, the uniform pyramidal morphology of single-crystalline wafers is expected to facilitate consistently high photovoltaic performance, while the heterogeneous surface of mc-Si may impose limitations on optical uniformity and device efficiency. In conclusion, wafer crystallography and quality govern post-texturing morphology. Single-crystalline substrates promote uniform, well-defined pyramid formation, optimising light trapping and photovoltaic performance, whereas multicrystalline wafers exhibit more variable texturing and potentially less consistent device behaviour.

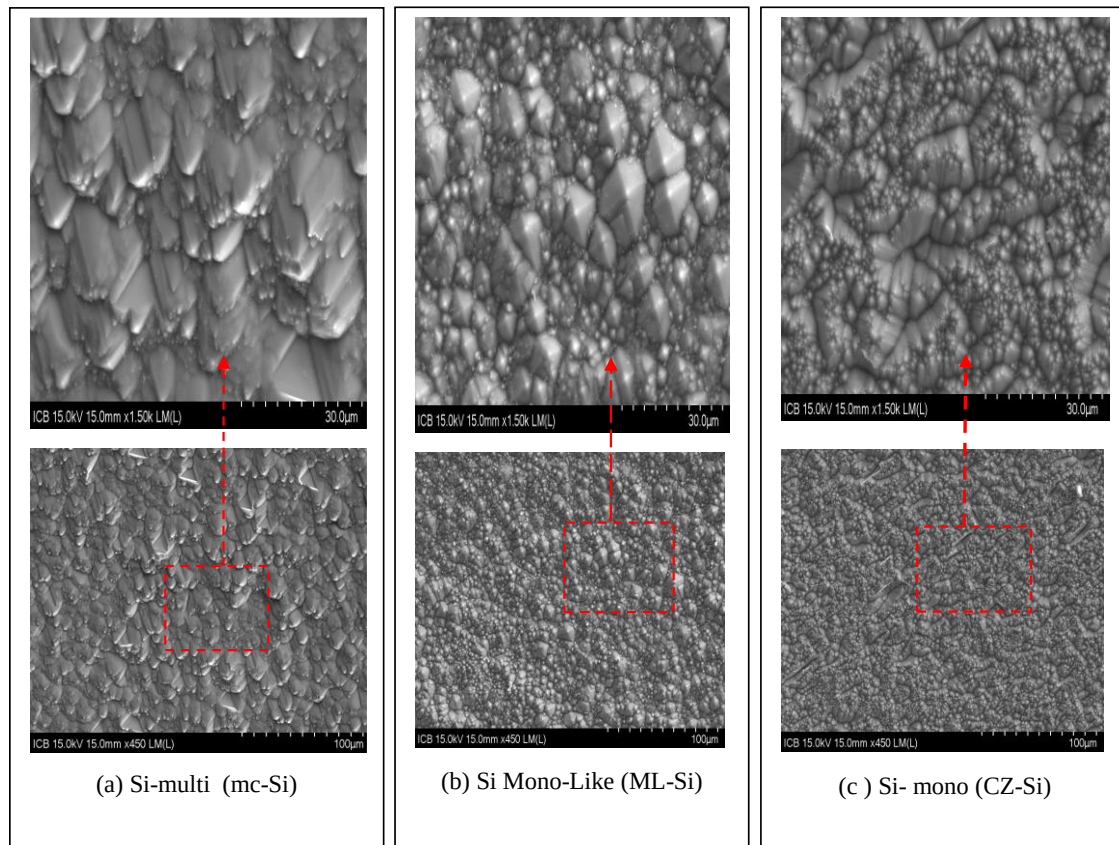


Fig. 1 – SEM images with NaOH added to silicon (Mono, Multi and Mono-Like) at 100 and 30 μm resolution.

3.2 Structural characterization: XRD measurements:

The crystallographic orientation of silicon wafers plays a crucial role in determining their optical behaviour and overall photovoltaic performance. Figure 2 presents the X-ray diffraction (XRD) spectra of the three silicon samples.

Both ML-Si and Cz-Si show a strong (100) preferential orientation, indicated by the diffraction peak at 69.17° corresponding to the (400) plane. This dominant orientation allows uniform anisotropic etching and the formation of well-defined pyramidal structures during alkaline texturing. As a result, light reflection is minimised, absorption is maximised, and photogenerated charge carriers are collected more efficiently. Our measurements confirm that, after alkaline texturing, the reflectivity of ML-Si is approximately 5% higher than that of Cz-Si across the 300–1200 nm range, but significantly lower than that of mc-Si, as shown in Figure 4.

In contrast, mc-Si displays multiple diffraction peaks at 28.42° and 47.30° , corresponding to the (111) and (220) planes, which reflect its random grain orientation (Fig. 2). This leads to uneven surface etching, higher reflectivity, and more surface recombination, all of which reduce the efficiency of photovoltaic devices. The experimental results below clearly show that these random grain orientations are directly linked to poorer light trapping and lower device performance.

Overall, the ML Si wafers demonstrate a remarkable balance between cost and performance. The seeded growth process encourages large grains with a preferential (100) orientation, combining the economic advantages of multicrystalline silicon with the high structural and optical quality of monocrystalline silicon. By linking crystallographic orientation to surface morphology, optical reflectivity, and charge carrier collection, our results highlight how precise structural control can directly enhance the efficiency of next-generation photovoltaic devices.

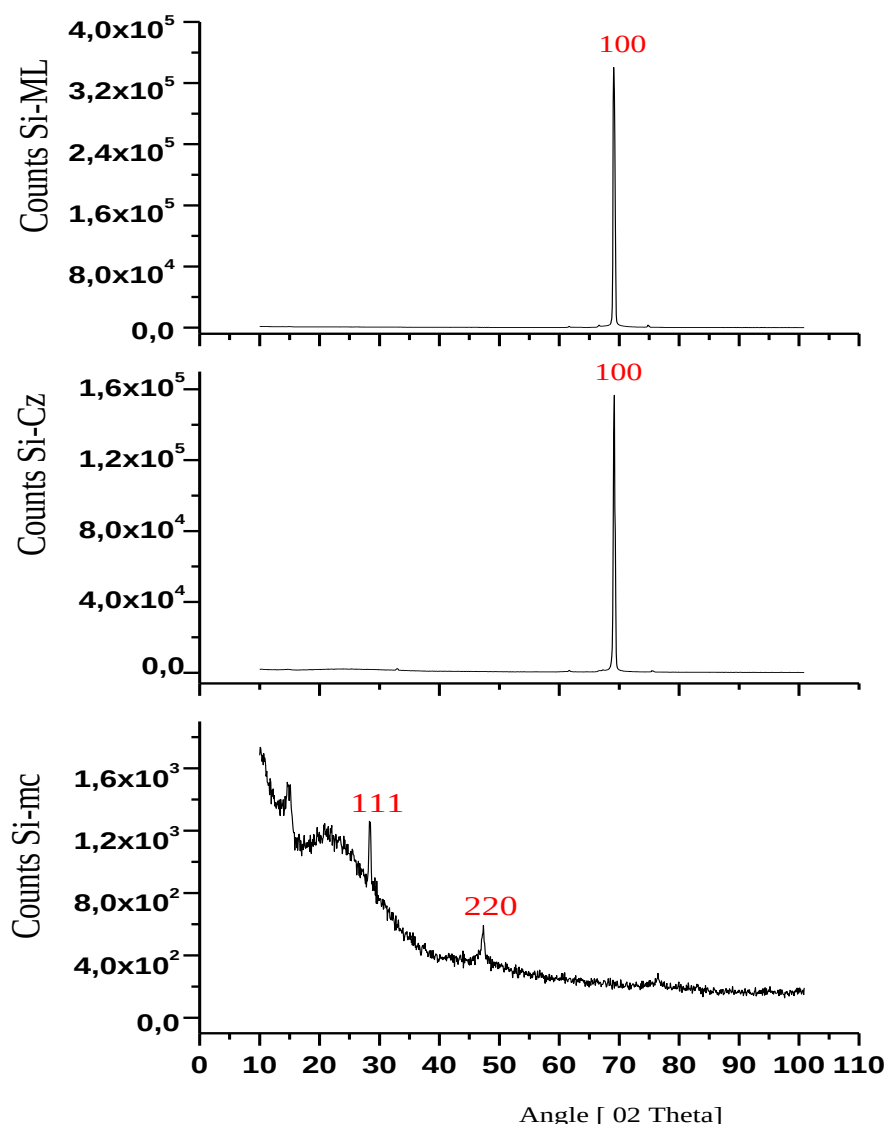


Fig. 2 – XRD Spectra for mono, multi and mono-like silicon.

3.3 chemical characterization: EDX analysis performed at the SEM

All EDX spectra (Fig.3) are characterized by a dominant silicon (Si) peak, accompanied by comparatively minor contributions from oxygen (O), carbon (C), and aluminium (Al). The relatively weak oxygen signal indicates that silicon is the principal constituent of the samples, while the detected oxygen is most plausibly attributed to the formation of a thin native silicon oxide (SiO_2) layer on the surface upon exposure to ambient conditions.

The presence of aluminium suggests trace metallic impurities, potentially introduced during synthesis or processing. The carbon signal is likely associated with surface contamination, which may arise from the crucible material, residual organic species, or handling during sample preparation and measurement. Overall, the EDX results confirm the predominance of silicon, with only minor secondary elements detected at low concentrations.

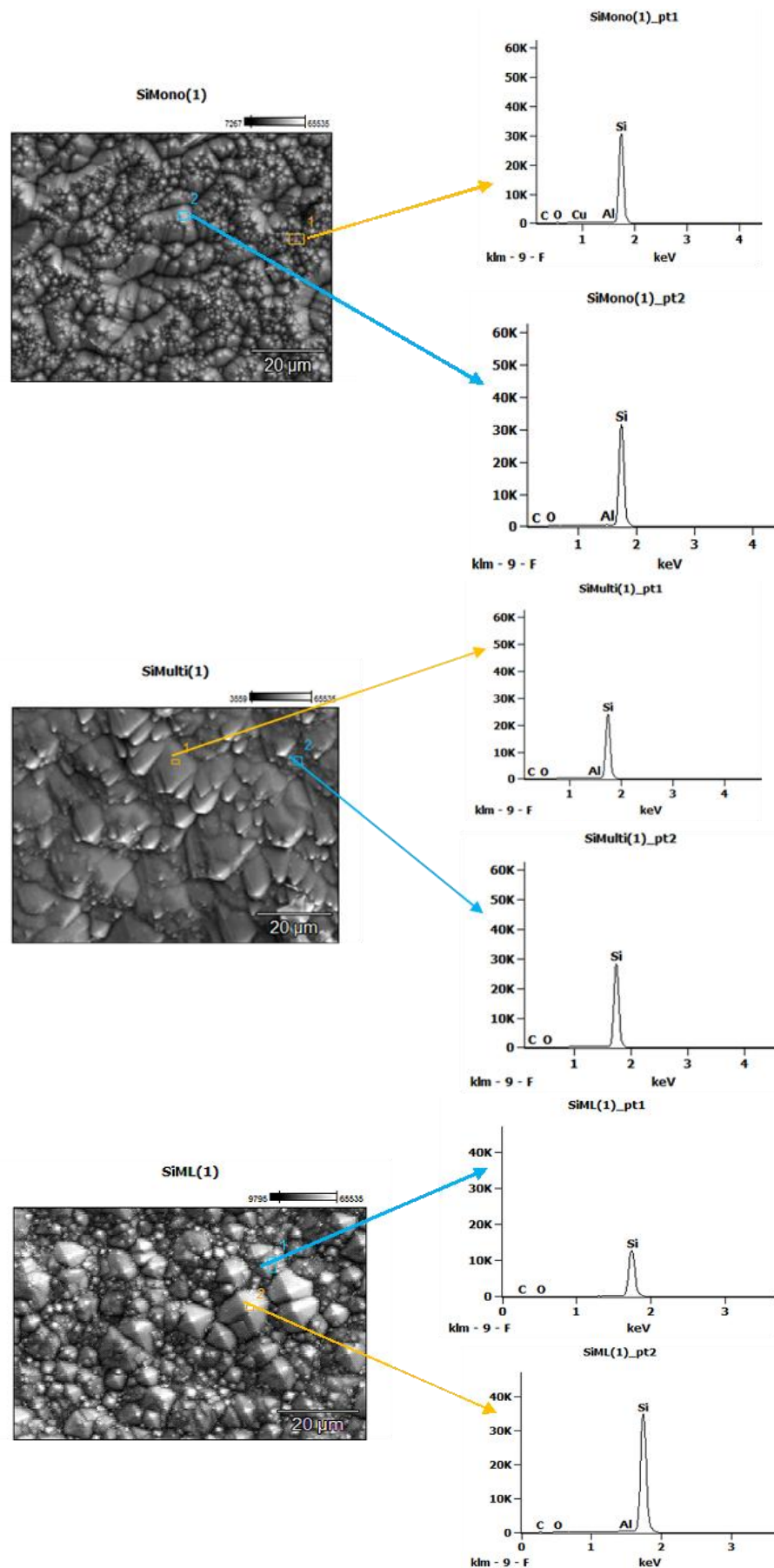


Fig. 3– EDX analysis by SEM: SEM micrographs of the analysed areas and their respective spectra.

3.4 Reflectance reduction by alkaline texture etching

The post-texturisation chemical treatment with NaOH reduces reflectivity for all three materials by forming random pyramidal structures, indicating enhanced light trapping at the textured surface and improved optical absorption.

As shown in Fig. 4, spectral reflectance measurements over the 300–1200 nm range reveal that textured ML-Si exhibits an average reflectivity ~5% higher than textured Cz-Si, but substantially lower than textured mc-Si.

This indicates that, despite the treatment, ML-Si still reflects slightly more incident light. The difference is likely associated with the quasi-monocrystalline structure of ML-Si, which provides better surface uniformity than mc-Si while remaining slightly less perfect than fully monocrystalline Cz-Si. The 5% difference relative to Cz-Si is mainly attributed to minor variations in pyramid size distribution and residual microstructural defects.

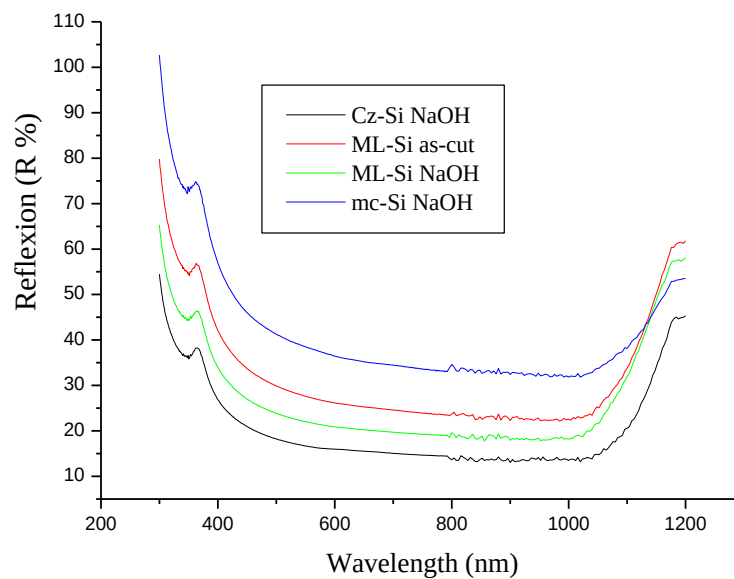


Fig. 4 – Reflectivity curve of mono, multi and mono-like crystalline silicon substrates after texturing in the NaOH solution as a function of wavelengths.

4 Conclusion

This comparative study demonstrates the significant potential of quasi-monocrystalline silicon (ML-Si) as a cost-effective alternative substrate for high-efficiency photovoltaic applications. ML-Si, produced via directional solidification with seeded growth, combines the economic advantages of mc-Si with a crystalline quality approaching that of Cz-Si.

Structural characterisation by SEM and XRD confirms the high degree of (100) orientation uniformity of ML-Si and structural homogeneity comparable to Cz-Si, while EDX analysis confirms its high chemical purity. After NaOH texturing, ML-Si displays optical reflection losses around 5% greater than Cz-Si, but significantly smaller than those of mc-Si, reflecting its improved light-trapping capability due to reduced dislocation clusters and limited high-angle grain boundaries.

Overall, ML-Si presents a compelling compromise between performance and cost, positioning it as a promising intermediate material for next-generation silicon photovoltaic cells. Future work on device-level electrical performance, long-term stability, and large-scale manufacturability will be critical to fully validate its industrial applicability.

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