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Epitaxial Growth and Characterization of 4H-SiC Layer on C-Face and Si-Face Substrates

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Abstract. 4H-SiC is a wide-bandgap semiconductor that has become essential for power electronics due to its large bandgap, high critical electric field, and excellent thermal stability. Within the {0001} basal orientation, the two polar surfaces – Si-face and C-face – exhibit distinct behaviours during chemical vapor deposition (CVD) homoepitaxy, with direct implications for device performance and manufacturing. In this work, *n*-type epitaxial layers were deposited on 150 mm, 4° off-axis Si-face and C-face substrates under identical conditions in a single-wafer hot-wall LP-CVD reactor (T > 1600 °C, P = 3.0 kPa, C/Si = 1.05, silane/propane/ethylene precursors, N_2 doping, HCl additive). Characterization analysis revealed pronounced polarity-dependent differences. AFM analysis showed that C-face epilayers exhibited smoother surfaces and reduced step bunching compared with Si-face layers. Optical and photoluminescence inspections show polarity-dependent defect propagation, with the C-face displaying reduced replication of extended defects under the explored conditions. However, nitrogen incorporation on the C-face orientation was more than 25× higher than Si-face orientation and displayed poor uniformity, highlighting the limited effectiveness of site-competition epitaxy on this orientation. In contrast, the Si-face provides tighter control of doping concentration and lateral uniformity, albeit with higher step bunching and rougher surfaces. These findings emphasize a fundamental trade-off in 4H-SiC homoepitaxy: the C-face offers morphological and structural advantages, while the Si-face ensures superior doping control and process stability. A deeper understanding of these polarity-dependent mechanisms is essential to optimize epitaxial growth strategies and to enable the design of high-performance SiC power devices.

Introduction

Silicon carbide (SiC), and notably the 4H polytype, has emerged in the power semiconductor market due to its excellent physical properties, such as wide bandgap and high electrical breakdown field, which make it ideal for high-power, high-frequency and high-temperature applications. Among the different crystallographic orientations of 4H-SiC, the {0001} plane has two distinct polar faces: the Si-face (silicon termination) and the C-face (carbon termination). Although the Si-face is currently the most widely used in industrial production and research, the C-face exhibits structural and chemical features making it of growing interest, especially regarding the epitaxial growth and performance of MOS (metal-oxide-semiconductor) structures [1, 2].

From an epitaxial growth perspective, the two polarities show markedly different behaviours. The Si-face has been extensively studied and optimized, largely because it offers a relatively wide process window for step-flow homoepitaxy under chemical vapor deposition (CVD), particularly when off-axis substrates are used to suppress polytype inclusions [3–5]. The introduction of chlorinated chemistries (e.g., HCl, dichlorosilane, methyltrichlorosilane) has further stabilized

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growth on the Si-face, enabling high growth rates (up to ~100 μm/h) while suppressing silicon droplet formation and 3C-SiC inclusions. The C-face, on the other hand, is characterized by a higher chemical reactivity and faster etching in hydrogen ambient, which can result in smoother step structures and lower surface roughness compared to the Si-face under optimized conditions. These characteristics are also linked to differences in step bunching behaviour, terrace stability, and surface free energy.

Defect formation is another crucial factor distinguishing the two polarities. On Si-face substrates, triangular defects and inclusions of 3C-SiC are typical, although several strategies involving growth rate optimization, C/Si ratio control, and Cl-based chemistry have been developed to mitigate them. In contrast, the C-face has been reported to promote lower replication of basal plane dislocations (BPDs) and a higher probability of their conversion into threading edge dislocations (TEDs), which is beneficial for device reliability, particularly in bipolar devices where BPDs are known to degrade performance. However, the C-face remains more susceptible to 3C inclusions when growth parameters are not tightly controlled, and its epitaxial layers may suffer from non-uniformities at very high growth rates [5, 6].

Doping incorporation is strongly polarity-dependent. As well known, nitrogen incorporation is more efficient on the C-face, leading to higher and less controllable background doping levels compared to the Si-face under identical conditions. This behaviour has been linked to differences in surface kinetics and adsorption mechanisms, with simulations suggesting that the Si-face exhibits a stronger dependence on the C/Si ratio and growth temperature, whereas the C-face is governed by more complex surface-chemistry interactions. Aluminium incorporation (*p*-type doping) is also influenced by polarity, with distinct activation energies and incorporation pathways reported on the two surfaces. These differences make doping control on the C-face more challenging, despite its potential advantages in structural quality [7, 8].

Finally, the SiO_2/SiC interface quality is another critical parameter. The Si-face generally provides more stable and lower-defect-density MOS interfaces, while the C-face, although exhibiting a significantly faster oxidation rate (approximately an order of magnitude higher), typically shows higher interface trap densities and degraded channel mobility [7, 9]. Nevertheless, the unique chemical and structural features of the C-face suggest that, with improved understanding of epitaxial mechanisms and interface engineering, it could open new opportunities for enhancing MOS performance, particularly in applications where high mobility is essential.

Experiment Set-Up

In order to obtain a systematic and direct comparison of the effects of crystallographic polarity on the homoepitaxial growth of 4H-SiC, with particular attention to their relevance in the fabrication of power electronic devices, *n*-type epitaxial layers were grown on 150 mm substrates, cut at 4° off-axis, with opposite polar terminations (Si-face and C-face). Both surfaces of the {0001} basal plane, although being of great technological interest, are known to exhibit substantial differences in terms of surface energy, chemical reactivity, and dopant incorporation mechanisms. Understanding these differences under controlled and comparable experimental conditions is therefore crucial to defining the advantages and limitations of each orientation in epitaxy for industrial applications. To ensure that the observed variations could be attributed solely to the substrate polarity, all other process parameters – growth temperature, reactor pressure, precursor flows, C/Si ratio, and dopant flow – were kept constant in all depositions.

Growth

Growth was carried out in a single-wafer hot-wall LP-CVD reactor at temperature above 1600 °C, a total pressure of 3.0 kPa, and a fixed C/Si ratio of 1.05. Silane (SiH_4), propane (C_3H_8), and

ethylene (C_2H_4) were employed as silicon and carbon precursors, with nitrogen (N_2) introduced as the dopant to achieve *n*-type conductivity and hydrogen (H_2) as carrier gas. Hydrogen chloride (HCl) was added to suppress silicon droplet formation on the growing surface.

The target epilayer specifications, consistent with requirements for medium- and high-voltage devices, included a thickness of approximately 9.5 µm and a doping concentration of $\sim 6 \times 10^{16}$ cm^{-3}.

A total of six epitaxial runs were performed – three on Si-face and three on C-face substrates – allowing a controlled assessment of growth morphology, defectivity, and dopant incorporation as a function of crystallographic polarity.

Characterization

The thickness and doping concentration distribution in the epitaxial layers, expressed as [maximum value – minimum value]/mean [%], was assessed using Fourier Transform Infrared (FT-IR) spectrometry and Mercury-Probe Capacitance Voltage (Hg-CV), respectively.

The defectivity characterization was conducted using Candela and Altair tools, both from KLA. The Candela tool uses highly sensitive optical technology able to simultaneously measure scattering intensity at various angles of incidence, topographic variations, surface reflectivity and phase shift, and photoluminescence for the detection and classification of crystallographic defects as stacking faults. A simultaneous Bright-field and Dark-field optical path to capture a variety of defects in the sub-micron to 5-micron range is used in the Altair optical microscope. The surface roughness was tested by Atomic Force Microscopy (AFM).

AFM analysis highlights substantial morphological differences between the two polarities. On the Si-face, epitaxial growth exhibits a pronounced tendency toward step bunching, which results in a significant increase in surface roughness compared to that measured on the C-face. Moreover, surface roughness on the Si-face is not uniform across the wafer diameter: greater roughness is observed towards the edges, caused by thermal gradients and precursor flow distribution within the reactor (**Fig. 1**). Conversely, growth on the C-face produces more regular surfaces, characterized by lower roughness and the absence of macroscopic step bunching. This difference is attributable to the higher chemical reactivity of the carbon termination, which promotes more isotropic growth. However, this enhanced reactivity is coupled with greater susceptibility to the formation of point defects, limiting the ability to achieve electrically uniform and well-controlled epilayers.

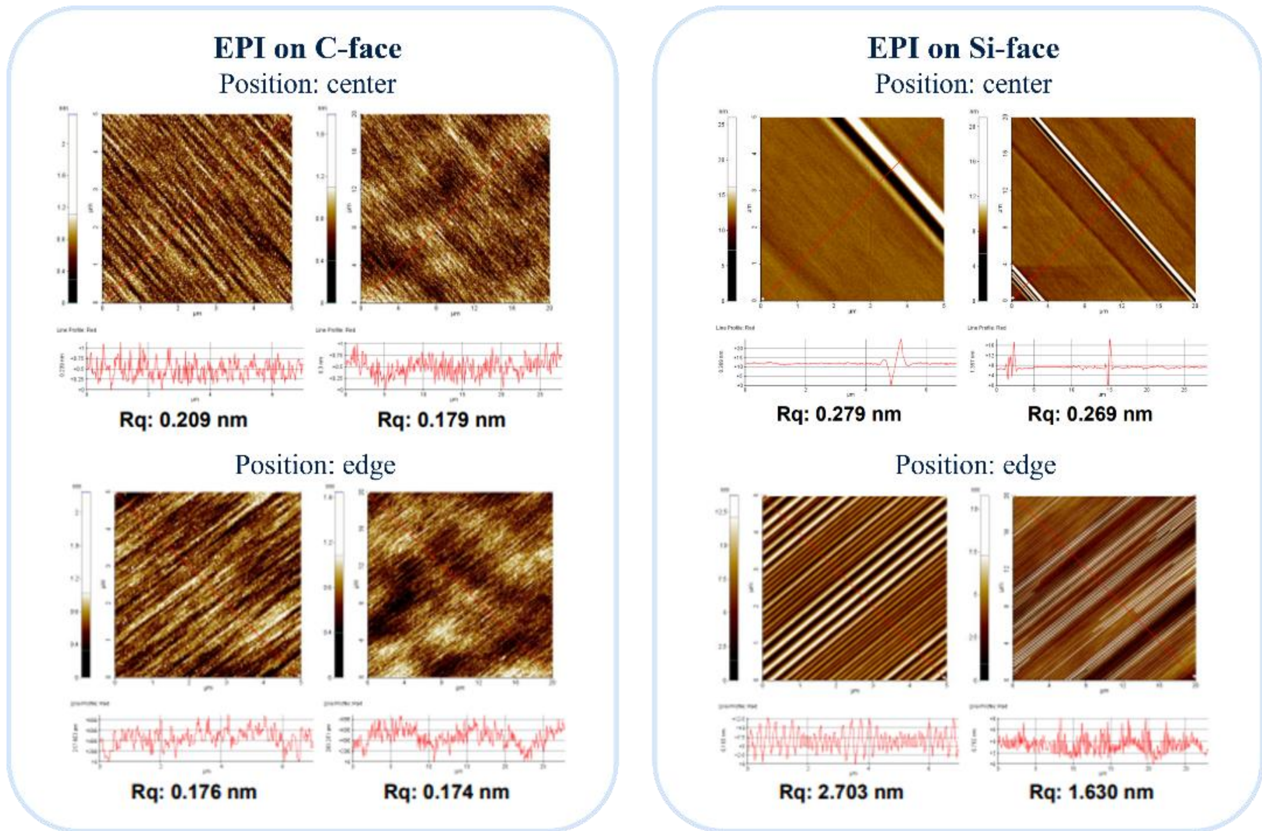

Fig. 1. AFM images of 4H-SiC epitaxial layers grown at same growth conditions on 4° off-axis C-face and Si-face substrates in two different wafer position (center and edge). Scan size is 5x5 e 20x20 μm^2, respectively, for the samples.

Defectivity inspections further confirmed the crystallographic polarities dependence of epitaxial quality. Samples grown on C-face substrates exhibit higher density of triangular defects than their counterparts deposited on Si-face substrates. These triangular features, associated with stacking faults and local lattice instabilities, originate from the enhanced chemical reactivity and the less controlled growth dynamics typical of carbon termination. The higher incidence of these defects on the C-face represents a significant limitation in terms of application, as it can compromise the electrical stability of the epilayers, inducing preferential leakage paths, and reducing the reliability of power devices manufactured on this orientation.

In addition to morphological and defectivity differences, doping incorporation strongly depends on polarity. Despite identical epitaxial growth conditions − including precursor fluxes, dopant flow, and C/Si ratio − the nitrogen concentration in layers grown on the C-face was found to be more than 25 times higher than in those grown on the Si-face, significantly exceeding the target value. This discrepancy is linked to the distinct surface structure and higher reactivity of the C-face, which make nitrogen incorporation far less controllable. On the Si-face, the site competition mechanism between carbon and nitrogen allows the C/Si ratio to effectively modulate dopant incorporation, leading to more reproducible and uniform doping profiles. In contrast, nitrogen on the C-face incorporates more readily and non-selectively, irrespective of the C/Si ratio. As a result, the doping distribution on the C-face shows greater dispersion and irregularity, whereas the Si-face displays a flatter and more controlled profile (**Fig. 2**). By comparison, the thickness distribution appears unaffected by polarity, showing no measurable difference between C-face and Si-face growth.

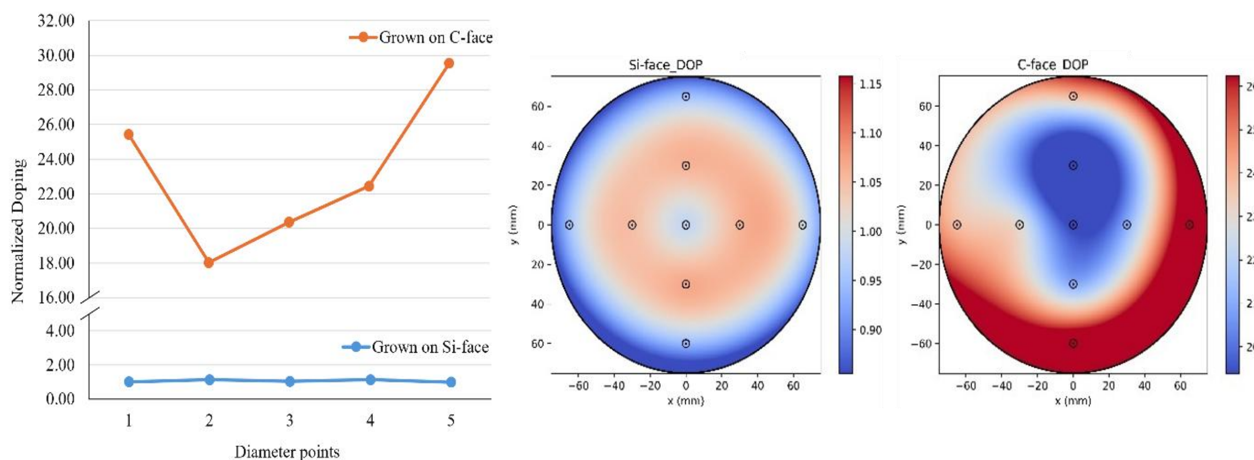

Fig. 2. The left graph depicts the doping distribution, normalized against the target value (~6× 10^{16} cm^{-3}), along the wafer diameter grown on the C-face (in orange) and Si-face (in blue) 4H-SiC, respectively. Doping distribution maps for growth on the Si and C-face are displayed on the right.

Summary/Conclusion

The comparative study of 4H-SiC homoepitaxy on Si- and C-face substrates demonstrates a clear polarity-dependent trade-off. The C-face enables smoother surfaces and reduced step bunching, suggesting potential advantages for structural quality and defects mitigation. However, it suffers from excessive and poorly controllable nitrogen incorporation, resulting in poor doping uniformity. The Si-face, while yielding rougher surfaces, offers superior doping control through site-competition mechanisms, making it more suitable for device-oriented epitaxy where doping precision is critical. These results emphasize the need for polarity-specific growth strategies and provide insights into optimizing epitaxial processes for next-generation SiC power devices.

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