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Improved Angle Tolerance in 4H-SiC Trench Filling Epitaxy Using Chlorinated Chemistry

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Abstract. Trench filling epitaxy on 4H-SiC using trichlorosilane ($HSiCl_3$) and hydrogen chloride (HCl) has shown to improve the tolerance to trench angle misalignment relative to the $[11\bar{2}0]$ substrate direction in deeper trenches than previously reported. Extraction of growth rates from cross-sectional SEM shows that epilayer growth on the mesa corner facet is the most sensitive to trench misalignment, suggesting that HCl may mediate the facet growth rate within ±1.5° from $[11\bar{2}0]$ to maintain symmetric growth.

Introduction

Trench filling epitaxy (TFE) is a practicable approach to produce high-voltage, energy efficient superjunction power electronic devices from silicon carbide [1, 2]. For superjunction fabrication, TFE involves etching uniformly spaced trenches into an n-doped 4H-SiC substrate and homoepitaxially refilling the trenches with p-doped material to produce a lateral stack of p-n junctions with a charge-balanced depletion region. To achieve this balance, trenches must be filled without the formation of voids to ensure an even doping distribution [3]. However, typical TFE by chemical vapor deposition (CVD) from silane and propane under hydrogen dilution, leads to faster SiC deposition at mesa tops than inside the trenches, which causes trenches to seal before filling can be completed [4-6]. The direction of epilayer growth near the mesa top is also shown to be sensitive to slight misalignment of the trench angle to the $[11\bar{2}0]$ direction in 4H-SiC (Fig. 1), which also can lead to premature trench closure by inclination of the growth angle [7, 8].

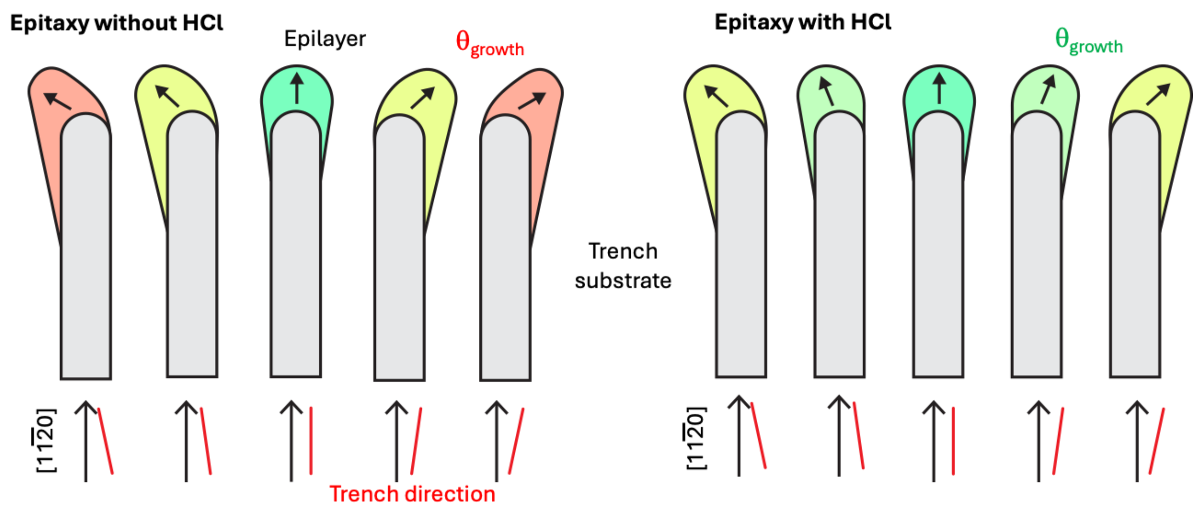

Fig. 1. Schematic diagram of inclined epilayer growth on mesas due to trench/ substrate misalignment with and without HCl during CVD.

Efforts to mediate the growth rate at the mesa top and improve trench filling rate and quality have focused on the use of halogenated agents, typically HCl or chlorinated precursors [9-12]. It is known that chloride compounds can improve the SiC growth rate on planar substrates, which is suggested to be caused by removal of condensed Si in the boundary layer and by the formation of surface-active intermediates, such as $SiCl_2$, SiH and SiCl [13-14]. In trench filling, HCl also has the benefit of acting as a spatially selective etchant, favoring etching near the mesa tops rather than inside the trenches, which can prevent trench-sealing overgrowth. Recently, it is also shown that HCl can improve the processing window for TFE by increasing the tolerance for trench angle misalignment to the substrate [15]. In this report, the relationship between misalignment angle, epilayer growth rate and the role of HCl are considered. Although improved misalignment tolerance improves trench filling, voids remain present in this work due to the influence of other factors affecting trench filling, such as trench aspect ratio, sidewall angle and tuning of the CVD conditions and chemistry. The relationship between void size and misalignment tolerance is not directly extracted and is therefore not discussed.

Experimental

Commercial n+ doped (0.02 Ω cm) 4H-SiC(0001) substrates off-cut by 4° in $[11\bar{2}0]$ were coated with a 500 nm layer of SiO_2 by low-pressure chemical vapor deposition (LP-CVD) at 500 °C *via* tetraethyl orthosilicate (TEOS). The trench pattern was then applied to the wafer by photolithography using AZ5214E photoresist and subsequent sputtering of a 900 nm thick Ni layer at ~0.7 Å s^{-1} from an Ar plasma at 140 W RF power with a 30 sccm Ar injection rate. After the photoresist and excess Ni was removed by solvent lift-off in acetone/ isopropanol, trenches were etched to 5 µm and 10 µm depth by ICP-RIE in an SF_6/ Ar plasma at respective RF and LF powers of 60 W and 1000 W. To prepare the trenches for epitaxy, the remaining Ni and oxide layers were removed by a full RCA clean.

Trench epitaxy was performed using an LPE ACiS-M8 reduced-pressure (RP)-CVD at 1550 °C and 100 mBar with the susceptor rotating at 60 rpm. Facets at mesa corners were introduced by ramping the temperature from 1100 °C to the growth temperature under 100 slm H_2 flow prior to growth. Source gases were used at fixed flow rates of 26 sccm (C_2H_4) and 70 sccm ($HSiCl_3$) with 100 slm H_2 dilution to grow a 6 µm epilayer at ~6.3 µm h^{-1}. Growth was completed both with and without HCl, which was added at a flow rate of 500 sccm. In all cases, doping markers were added for every 1 µm of growth by 30 s bursts of N_2. The samples are characterized by cross-sectional SEM recorded on the $(11\bar{2}0)$ plane by cleaving through the trench patterns along the $\langle\bar{1}100\rangle$ direction.

Results and Discussion

Trench Refill Misaligned to the $\langle 11\bar{2}0\rangle$ Direction. It is previously shown that using a chlorinated growth process in trench filling epitaxy can significantly improve the tolerance for trench misalignment to the 4H-SiC $\langle 11\bar{2}0\rangle$ direction [14]. This effect has been replicated here for trenches of both 5 µm and 10 µm depth (4 µm pitch), shown by a plot of trench misalignment angle (θ_{mis}) versus epilayer growth angle (θ_{growth}) in Fig. 2a. Using n+ doping markers recorded by cross-sectional SEM of refilled trenches, the angle at which adjacent growing surfaces fuse over time, denoted as θ_{growth}, shows how far the epilayer growth deviates from vertical as the trench direction is varied about $\langle 11\bar{2}0\rangle$ (Fig. 2c). Similar to previously reported data, using $HSiCl_3$ and HCl (500 sccm) in the growth process allows vertical epilayer growth (θ_{growth}≈0°) even when the trench angle is misaligned at ±1.5°, indicated by the green shaded section in Fig. 2a. A so far unreported trend emerges when the misalignment is >4° in magnitude, where θ_{growth} begins to straighten by 5-10° from a local maximum at θ_{mis}=±5°. This is visualized in Fig. 2c by arrows marked on cross-sectional SEM images of 10 µm deep filled trenches. Notably, misalignment at negative angles seems to cause a further deviated growth angle of approximately 5° relative to positive misalignment angles.

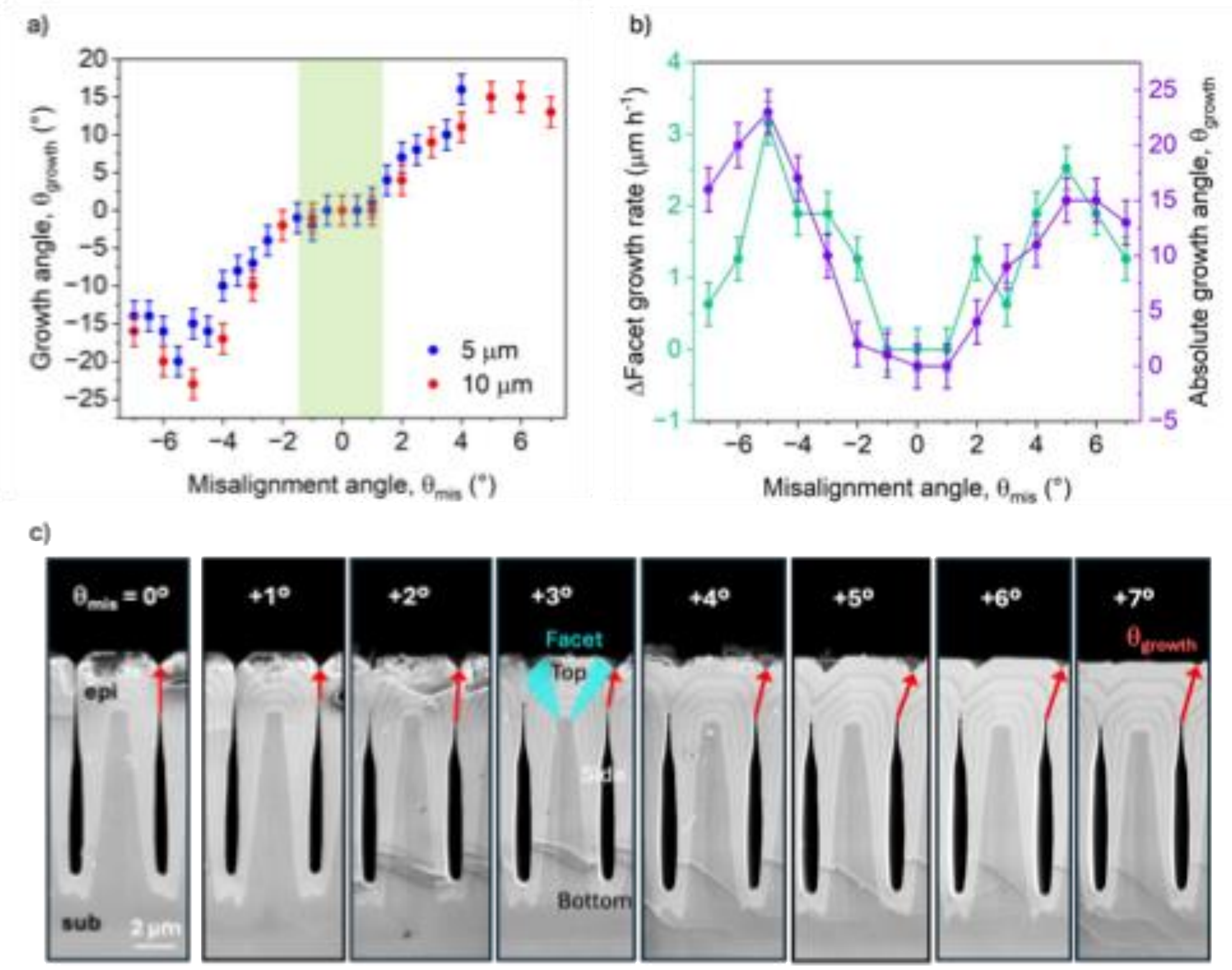

Fig. 2. a) Graph of trench misalignment angle versus epilayer growth angle for 5 µm and 10 µm deep trenches refilled under 500 sccm of HCl. **b)** Graph of difference in facet growth rate on each side of the trench (left axis) and the magnitude of the epilayer growth angle (right axis) versus trench misalignment angle. **c)** Cross-sectional SEM images recorded on the $(11\bar{2}0)$ plane of 10 µm deep trenches from 0° to 7° misalignment, showing inclined growth marked by the arrow direction.

Initial growth rates can be extracted by measuring the thickness of the epilayer at the first doping marker on each trench surface (top, bottom, sidewall and facet shown in Fig. 2c). For the 10 µm deep trenches, the growth rate on the mesa top and trench bottom are unaffected by θ_{mis}, remaining at ~5 µm h^{-1} and ~2.5 µm h^{-1}, respectively. However, the sidewall growth rate varies from ~2.5 µm h^{-1} to ~5.7 µm h^{-1} and can be asymmetric at each side of the trench, leading to a discrepancy of up to ~1.23 µm h^{-1} at θ_{mis}=-5°. Most significantly, the growth rate on the facet (top corner of the mesa) is dependent on θ_{mis}, varying from ~1.9 µm h^{-1} to ~5.7 µm h^{-1} with a difference between left and right facet growth of up to ~1.23 µm h^{-1} at θ_{mis}=-5°. The difference in facet growth rate for each misalignment angle is plotted in Fig 1b (left axis) with the magnitude of θ_{growth} (right axis) showing a clear correlation between asymmetric facet growth and deviated overall epilayer growth. Since HCl has been shown to etch the SiC epilayer near the mesa top and on the facet, it is possible that HCl improves trench misalignment tolerance through controlling growth at the facet by crystal plane dependent etching [8, 9]. As misalignment will expose difference facet and sidewall surfaces, their activity for both growth and etching will likely be asymmetric, accounting for non-vertical epilayer growth.

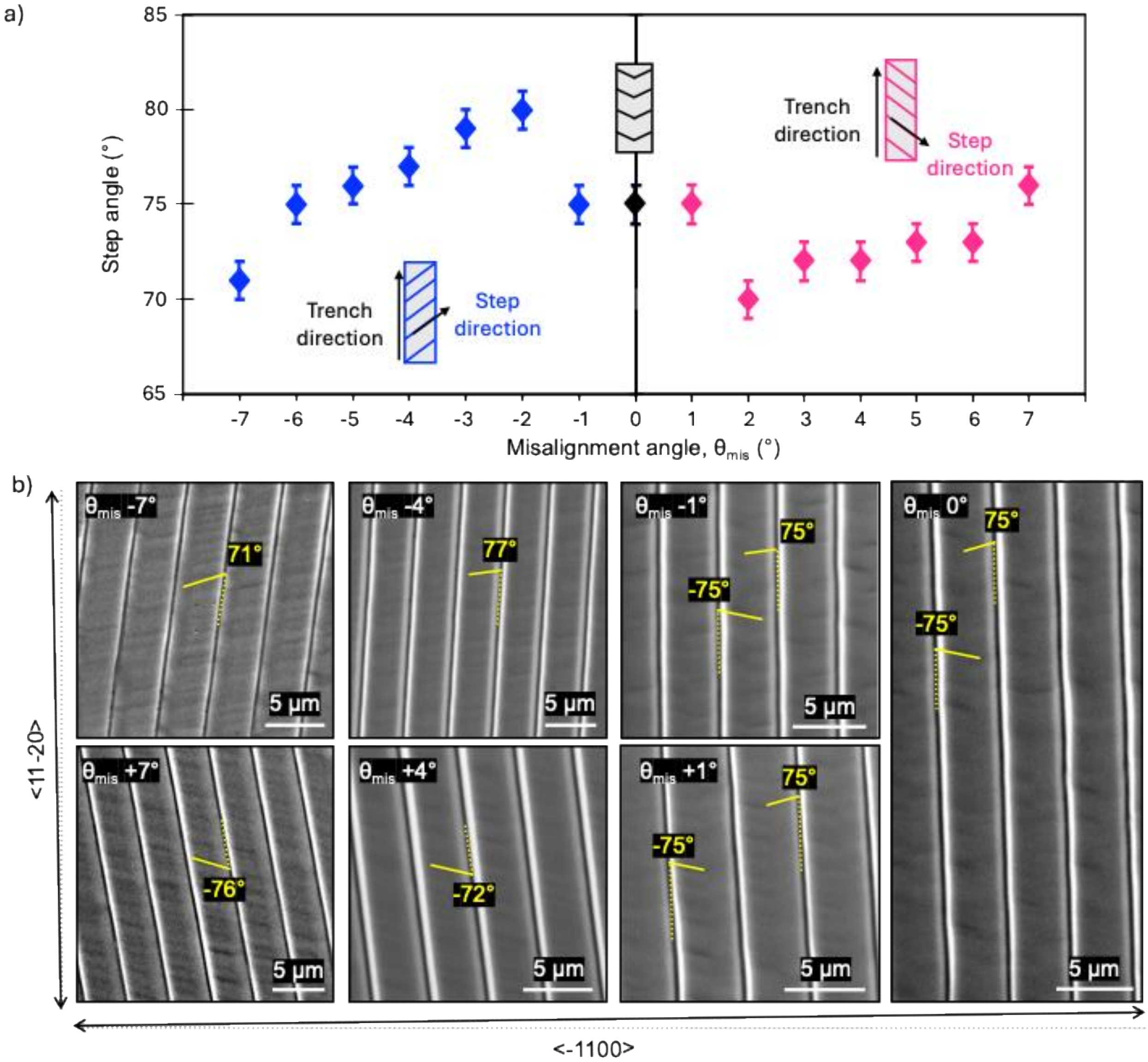

Fig. 3. a) Plot of step angle versus trench misalignment angle for 10 µm deep, 4 µm pitch trenches filled under 500 sccm HCl. Step angle refers to the surface step direction in the epilayer overgrowth relative to the trench direction. **b)** Top-down SEM images of the epilayer overgrowth for trenches filled under 500 sccm HCl, showing surface step angles.

Further evidence for HCl affecting growth on corner facets is observed by top-down SEM of the epilayer surface. Fig. 4 shows the epilayer surface of 10 µm deep trenches filled without HCl at varied misalignment angles. The direction of surface steps is observed, which shows a single step direction for each misalignment angle, that decreases from 75° from the trench direction at θ_{mis}=0° and 55° at θ_{mis}=6°. Notably, the step direction for trenches aligned to the $\langle 11\bar{2}0\rangle$ direction is 75°, rather than 90°, which are present in the substrate and would be expected to be inherited by the epilayer for step-flow growth on a planar 4H-SiC substrate. This may indicate that facet or sidewall growth can cause a twisting of the overall growth direction, since both facets and sidewalls will exhibit different surface structures based on the trench misalignment angle.

Comparing the epilayer step directions for trenches filled without HCl (Fig. 4) and with HCl (Fig. 3) shows a clear difference, especially at low (<±2°) misalignment angles. Surface steps at θ_{mis}<±2° show two symmetric directions at 75° and -75° from the trench direction, compared with the single step at 75° for trenches filled without HCl.

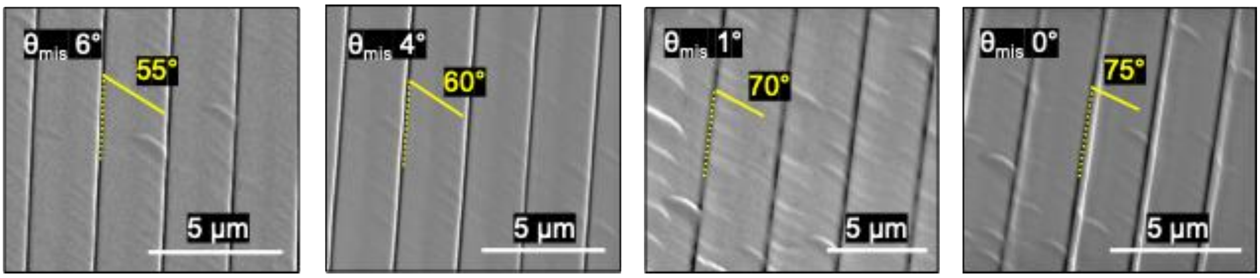

Fig. 4. Top-down SEM images of epilayer overgrowth on refilled 10 µm deep, 4 µm pitch trenches filled without HCl. Images are recorded with the stage tilted 40° away from the viewing angle. Annotations mark the surface step angle relative to the trench direction.

According a plot of step angle versus trench misalignment angle shown in Fig. 3a, which was extracted from top-down SEM images partly presented in Fig. 3b, the step angle abruptly increases from 75° to 80° at θ_{mis}=-2° and decreases to 70 at θ_{mis}=+2°. This 5° twist is followed by an approximately linear deviation in step angle from misalignment angles of ±2° to ±6°, with a larger deviation observed at ±7°. This trend reflects that of the growth angle extracted from cross-sectional SEM and, therefore, suggests that an appearance of two symmetric step directions indicates vertical growth. While the mechanism of this can only be conjectured from these empirical data, it can be suggested that the step angle may be controlled by the relative epilayer growth rates on the trench sidewall, facet and mesa top, causing a twist in step angle. The difference in step angles between trenches filled with and without HCl may, therefore, by rationalized by HCl acting as a mediator for the facet growth rate for trench directions <2° from $\langle 11\bar{2}0\rangle$, which may expose surface structures more susceptible to etching by HCl compared with those exposed at higher degrees of misalignment.

Summary

Using a chlorinated gas mixture in trench filling CVD on 4H-SiC can help to minimize epilayer growth inclination caused by misalignment of the trench direction to the $\langle 11\bar{2}0\rangle$ substrate direction. Using HCl in refill epitaxy has broadened the processing window for photolithography processing to allow a ±1.5° error in mask alignment, and this effect seems independent of the trench depth. Based on the relationship between mesa corner facet growth rate and trench misalignment angle, asymmetric facet growth accounts for epilayer deviation, indicating that HCl most likely controls growth on the facets and its activity depends on the stability of the exposed facet.

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