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Improved Mesa Designs for the Growth of Thin 4H-SiC Homoepitaxial Cantilevers

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Abstract. The lateral expansion of thin homoepitaxial cantilevers from mesas has been used to produce areas of on-axis 4H-SiC completely free of dislocations. Cantilever expansion is influenced by the geometric shape and crystallographic orientation of the pregrowth mesa. In order to form larger areas of defect free silicon carbide (SiC), progressive coalescence must occur when adjoining cantilevers merge. The progressive coalescence is largely dictated by the shape and orientation of the pregrowth mesa. We report on refinements to the pregrowth mesa geometry and orientation that allows rapid initiation of cantilever growth and promotes progressive coalescence of merging cantilevers. These modifications to the pregrowth mesa geometry permit larger areas of defect free 4H-SiC to be realized.

Introduction

Commercial suppliers of SiC substrates have made great progress in reducing micropipe density. However, commercially available substrates are still known to have a high density of crystalline defects on the order of 10^4 dislocations per cm^2. It has been shown that these dislocations adversely affect the high power performance of some SiC devices. In particular, the high density of crystalline dislocations in the substrate have prevented SiC power electronics from reaching their full theoretical potential. There exists a need to produce and evaluate 4H-SiC devices that are completely free of crystalline dislocation defects.

NASA Glenn Research Center has previously reported the homoepitaxial growth of thin cantilevers from the tops of mesas arrayed across on-axis 4H-SiC substrates that are completely free of dislocations [1]. However, the size of the cantilevers is dictated by additional factors besides increased growth time. As the cantilevers expand laterally they have a natural tendency to evolve into stable $\{1\bar{1}00\}$ crystal facets. Once a stable $\{1\bar{1}00\}$ facet is obtained, no further lateral expansion occurs in the direction of that facet in the absence of a concave interior corner [1, 2]. The coalescence of cantilevers from adjoining mesa arms can be used to increase the area of the cantilever. However, progressive (i.e., perfect) coalescence must be achieved to ensure that the resulting cantilever remains free of dislocations.

This paper reports on refinements to the pregrowth mesa geometry and orientation beneficial to dislocation free cantilever enlargement. These refinements increase the probability that progressive coalescence will occur as adjoining cantilevers merge to produce a single larger area of 4H-SiC that is completely free of dislocations.

Experimental

Commercially available 4H-SiC, on-axis, silicon face substrates are patterned with arrays of pregrowth mesa shapes and prepared for growth by a process more fully described in [3]. The samples were subjected to an in-situ two minute, H_2 etch at ~1640 °C, followed by step flow growth conditions in a modified commercially available horizontal flow cold wall chemical vapor

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deposition system. Two growth runs were performed under similar conditions of SiH_4 = 7.3 sccm, C_3H_8 = 3 sccm, H_2 = 8400 sccm, pressure = 200 mbar and a temperature of ~1640 °C for 180 minutes. The growth rate varies as a function of position over the quarter wafer substrate. Note that step free cantilever growth has no vertical growth rate; however, these conditions correspond to 8° off-axis sample growth rates of 2-4 µm / hour [1].

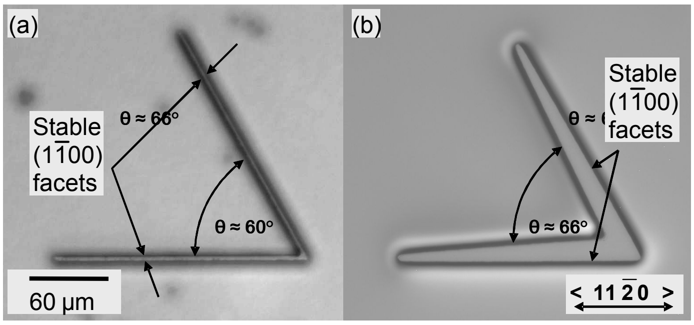

Fig. 1. a) Pregrowth mesa with interior and exterior sidewalls aligned to stable $\{1\bar{1}00\}$ facets. b) Pregrowth mesa with tapered interior sidewalls ensuring a slight misalignment away from stable $\{1\bar{1}00\}$ facets.

Following the growth runs the samples were inspected and photographed using an optical microscope fitted with Nomarski differential interference contrast (NDIC) optics. Atomic force microscopy (AFM) in tapping mode was used to verify the step-free surface morphology of some of the as grown cantilevers. Molten KOH etching for five minutes at 500 °C, was used for defect decoration within the cantilevered region.

After KOH etching, each of the mesas were optically inspected and graded into one of three different categories: fully developed webbed cantilevers without etch pits, fully developed webbed cantilevers with etch pits in the cantilever coalescence region, fully developed webbed cantilevers with 3C-SiC nucleation. Mesas within ~3mm of the edge of the substrate, partially developed cantilevers, mesas with screw a dislocation or those that had been compromised by poor photolithography were excluded from the survey. KOH etch pits that formed over the original pregrowth mesa support structure were not counted as being an etch pit in the cantilevered region, these etch pits have previously been observed and attributed to threading edge dislocations [2]. Etch pits were not observed in cantilevered regions where coalescence did not occur.

Discussion and Results

When a pregrowth mesa shape has side walls that are aligned to a prismatic $\{1\bar{1}00\}$ plane, this stable facet face does not expand laterally. Figure 1a & 1b shows two similar mesas with the same crystallographic orientation. The arms of the "V" shape have outer sidewalls aligned to equivalent stable $\{1\bar{1}00\}$ planes. The mesa in Fig 1a also has the interior sidewalls of the "V" shape aligned to equivalent stable $\{1\bar{1}00\}$ planes. The mesa in Fig 1b has interior sidewalls slightly misaligned from stable $\{1\bar{1}00\}$ facet faces by ~3°, leaving an interior angle of ~ 66°. Figures 2a & 2b show typical results after 180 minutes of exposure to step flow growth. Since the interior sidewalls of the mesa, illustrated in Fig. 1a, already form a stable $\{1\bar{1}00\}$ facet, only the inner concave corner acts as a favorable bonding site that is the driving mechanism for the extension of cantilevers. In the mesa illustrated in Fig. 2b, the entire interior of the "V" shape is in an unstable plane, further promoting cantilever enlargement along the whole length of the tapered interior arms of the

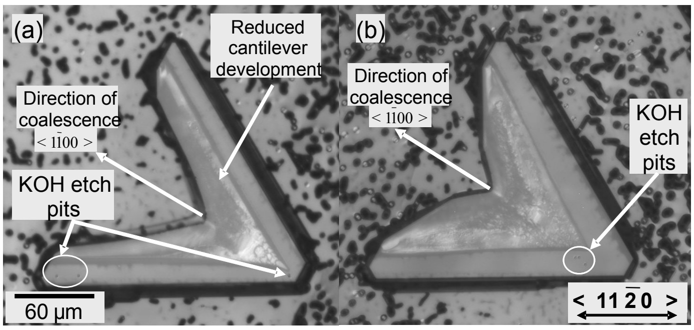

Fig. 2. a) Post growth results for typical mesa cantilever development is restricted to the interior corner of the "V". b) Post growth mesa with tapered interior sidewalls where cantilever development occurs along the entire interior region of the "V" and progressive coalescence enable perfect merging of the adjoining cantilevers.

"V". At the same time, the interior concave corner is also expanding enabling the cantilevers from each arm of the "V" to progressively coalesce at one point and move outward along the $<1\bar{1}00>$ direction as shown in Fig 2. This progressive coalescence helps to insure that perfect coalescence (i.e., no dislocations) of the cantilevers occur. Notice in Fig. 2, that after 180 minutes of growth neither of these mesas exhibit any cantilever development along the exterior sidewalls of the "V" shape, as these are aligned to stable $\{1\bar{1}00\}$ facet faces and there is no nucleation point, such as an interior concave corner [1].

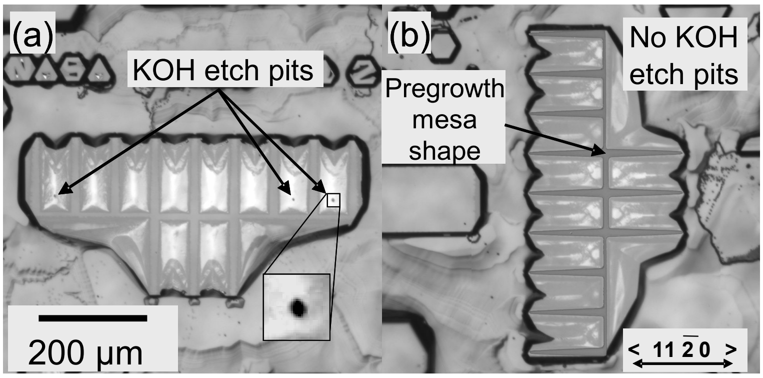

Fig. 3. a) Post growth mesa with longer arms aligned parallel to the $<1\bar{1}00>$ direction. KOH etch pits have formed in some of the "U" shaped cantilever coalescence regions. b) Composite image showing shape of pregrowth mesa and Post growth mesa with longer arms aligned parallel to the $<11\bar{2}0>$ direction. No etch pits have formed in the cantileved region.

Two identical nonsymmetrical pregrowth mesa shapes with multiple "U" shaped interior regions were also exposed to the growth conditions stated earlier. The mesas differ only in crystallographic orientation. Both mesas have tapered arms for a slight (~3°) misalignment from major facet faces. Figure 3 shows post growth, post KOH results for the two orientations of the mesa that attained fully webbed cantilevers. Figure 4 is a close up view of a portion of a partially webbed mesa with the orientation depicted in Fig 3a. Continued lateral expansion of the cantilevers, in the fast $<11\bar{2}0>$ growth direction can lead to multiple points of coalescence, as seen in Fig. 4. The stable $\{1\bar{1}00\}$ facets that form as the cantilever develops, as shown in the top portion of Fig. 4, does not incorporate adatoms that impinge upon the surface of the cantilever. Instead, adatoms migrate toward the energetically favorable corner of the cantilever, where the adatoms are readily incorporated into the cantilever. This action forms a small area of cantilever where the growth rate is slightly faster than the rest of the expanding cantilever. Thus, as the two adjoining cantilevers come close to one another, multiple coalescence points can form, as seen in Fig. 4. When nonprogressive coalescence (i.e., multiple points of coalescence) occurs, there is an increased probability of dislocations or 3C-SiC being formed. Nonprogressive coalescence is similar to growing cantilevered webbed regions on closed shaped mesas. Previously published data shows that when an enclosed area is webbed over, the burgers vector of the enclosed region is conserved [4]. The burgers vector of any threading dislocation that may reside within the interior region of the nonprogressively merged cantilever is conserved, resulting in the formation of dislocations at the coalescence of cantilevered regions.

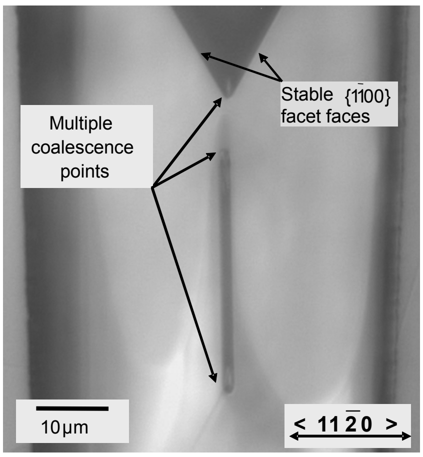

Fig. 4. Close up view of a partially webbed ,"U" shaped region with tapered arms aligned to the $<1\bar{1}00>$ direction has undergone nonprogressive coalescence resulting in the formation of multiple coalescence points.

Figure 5 is a close up view of a portion of a partially webbed mesa with the orientation depicted in Fig 3b, as the cantilevers develop along the entire length of the tapered arms of the mesa, cantilever merging occurs in a progressive manner.

Due to the taper present in the pregrowth mesa structure along with the interior corner moving in the $< 1\bar{1}00 >$ direction, this biases the cantilever merging process to take place in the interior corner and progressively coalesce outward. Progressive coalescence of the cantilevers enables the "U" shaped interior region to fully web over, creating a single larger area of dislocation free 4H-SiC. Although, the time to attain a fully webbed cantilevered region takes longer with a mesa orientation of Fig. 3b, the probability of perfect progressive coalescence of the cantilevers is increased, as shown in Fig. 6. For the graph of Fig. 6, a total of 162 fully webbed mesas were examined by optical microscopy and cataloged; the results are graphed in normalized percent.

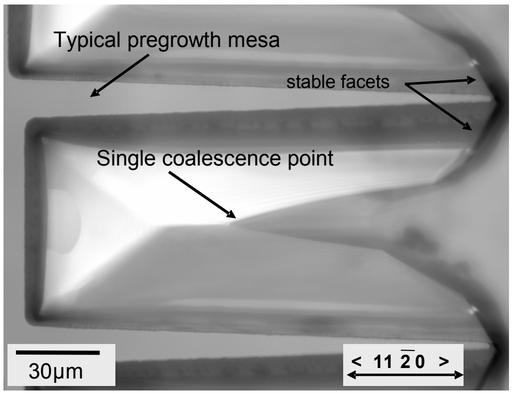

Fig. 5, Close up view of a partially webbed "U shaped reagion with tapered arms aligned to the $< 11\bar{2}0 >$ direction, showing progressive coalescence.

Summary

We have demonstrated that rapid cantilever development can be promoted through the use of mesas with geometric shapes with interior sides that are slightly misaligned (~3) from stable $\{1\bar{1}00\}$ crystal facet faces. Conversely, cantilever development can be inhibited by aligning mesa sides parallel to stable $\{1\bar{1}00\}$ facets.

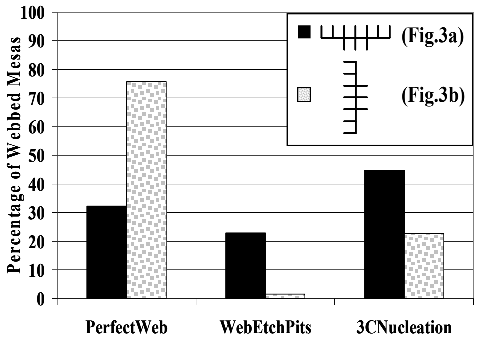

Fig. 6, This graph shows cantilevers that coalesce on mesas with an orientation of Fig. 3a are more likely to have defective cantilevered regions than mesas with an orientation of Fig. 3b.

Acknowledgments

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