Effect of stress on the evolution of mask-edge defects in ion-implanted silicon*

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In an effort to extend the scaling of advanced complementary metal-oxide semiconductor devices, strain has been incorporated to enhance carrier mobility. In this study, the effect of strain on the solid-phase epitaxial regrowth process of patterned wafers was explored. Implants of $1 \times 10^{15}/\mathrm{cm}^2$ Si^+ with an energy of 40 keV were introduced into these patterned regions forming a continuous amorphous layer. After implantation, the oxide and nitride masks were removed and the wafers stressed uniaxially between 0 and 250 MPa. The wafers were subsequently annealed under stress to crystallize the amorphous layer, which was monitored using transmission electron microscopy. It was found that without stress, defects formed at the mask edge where the vertical and lateral epitaxial regrowth fronts meet. These defects were threading dislocations which form at the amorphous-crystalline interface and propagate to the surface. Tensile stress levels of as little as 50 MPa were found to begin to suppress the formation of mask-edge defects by altering the shape of the corner of the regrowing amorphous layer at the mask edge. Tensile stress appears to retard the lateral recrystallization velocity, creating the obtuse corner geometry necessary to prevent the occurrence of a pinch point at the corner and thereby suppressing defect formation. The evidence suggests that the half-loop threading dislocation nucleates at the corner. The role of varying the stress on the formation of mask-edge defects will be discussed. © *2006 American Vacuum Society.* [DOI: 10.1116/1.2162566]

I. INTRODUCTION

The solid-phase epitaxial regrowth (SPER) of an amorphous layer in silicon and germanium has been a subject of interest for years. SPER involves the process of recrystallizing an implantation-induced amorphous layer by annealing the layer at temperatures above 500 °C. During the anneal, the underlying single-crystal Si acts as a seed for crystallization of the amorphous layer. In unpatterned wafers, the regrowth is unidirectional toward the surface. In patterned silicon, the regrowth can occur in multiple directions, both parallel and perpendicular to the surface. Defects have been known to form along mask edges of various shapes upon annealing.[1] In these studies the stress applied by deposited thin films was found to suppress mask-edge defect formation. The formation of these mask-edge defects has been attributed to the meeting of the lateral and vertical epitaxial fronts.[2] This type of defect has been shown to cause leakage currents, and as a result, it degrades device performance.[3,4]

The effect of strain on many factors in the study of semiconductors has been very important throughout the years in an effort to help continue the scaling of complementary metal-oxide semiconductor (CMOS) devices. The effect of stress and strain on the growth of epitaxial fronts has been the subject of various studies by Barvosa-Carter and Aziz.[5–7] They have demonstrated that stress can have a measurable effect on the solid-phase regrowth velocity.

The purpose of this study is to study the effect of varying levels of stress on the epitaxial regrowth rates in order to understand the role thin films play in suppression of the mask-edge defect formation. Efforts were made to begin to understand and artificially simulate the stress induced by the nitride pads via the use of a three-point bending apparatus. The effects of the magnitude and orientation of stress on the lateral SPER front were observed and analyzed.

II. EXPERIMENTAL CONDITIONS

In order to study the effects of strain on both lateral and vertical amorphous silicon epitaxies, 200 mm silicon wafers with 80 Å of thermally grown silicon dioxide capped by 1540 Å of deposited silicon nitride were used. Following photolithography a selective etch process was used to remove nitride and oxide regions, exposing the underlying silicon. The patterned material was then subjected to a 40 keV Si^+ implant to a dose of 1×10^{15} at./cm^2, creating amorphous silicon pockets in the exposed silicon regions. The oxide and nitride regions acted as an effective implant mask. The wafer was then cleaved into multiple sample sets. Samples that were to have stresses applied were made 10 cm in length and 1 cm in width so that the appropriate bending forces could be applied by a quartz three-point bending apparatus. Some material was left with the oxide-nitride implant mask intact while the majority of the material had the mask removed, thus eliminating any stresses induced by the mask. To remove the mask, the material was soaked in 49% hydrofluoric acid for 30 min. Thermal anneals were performed on the sample matrix. The anneal temperature varied from 550 to 750 °C for times between 5 and 60 min. Lower temperatures were used to observe the condition of the amorphous-crystalline growth front in cross-sectional trans-

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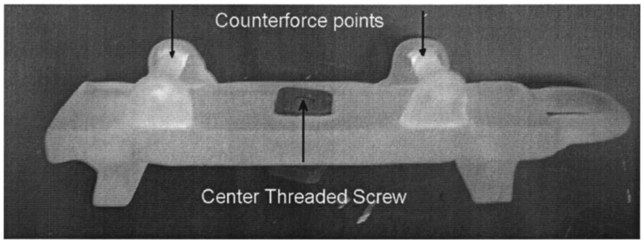

FIG. 1. Quartz apparatus used to create three-point bending in silicon samples. The counterforce points pin the silicon from the top and the screw applies an upward force resulting in a gradient radius of curvature in the silicon.

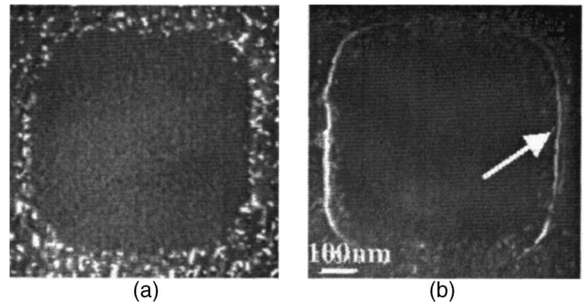

FIG. 2. PTEM showing the effect of removing the oxide-nitride implant mask on the formation of an edge defect after a 750 °C, 10 min anneal. The sample in (a) still has the mask present, while the sample in (b) has had the mask removed. The white arrow indicates the location of the edge defect (Ref. 1).

mission electron microscopy (XTEM), while higher temperatures were used to observe the presence of line defects created when the vertical and horizontal epitaxy fronts meet in plan-view transmission electron microscopy (PTEM).

In order to apply uniaxial stress to the material during annealing, a quartz apparatus was designed and fabricated. Each strip was then placed into a three-point bend, as shown in Fig. 1, and stressed. The strip is centered in the holder with each end held in place by quartz rods that would act as counterforce points. Then, a centrally located graphite screw was turned, gradually bending the silicon sample and creating a stress gradient along the length of the sample. At the screw, stresses were the highest and reduced along the length of the sample toward the two counterforce points. For a compressive stress the sample surface was placed towards the screw, and for a tensile stress it was placed in the holder facing away from the screw. The local radius of curvature was measured by incrementally measuring the deflection of a laser off of the bent silicon sample at various points along its surface, thus mapping out the entire bend contour of the material. This stress was then calculated by using the local radius of curvature and the following equation:

$$\sigma = \frac{Ec}{r},$$

where E is the elastic modulus of silicon in the $\langle 110 \rangle$ direction (generally accepted as 85 GPa), c is the half thickness of the wafer, and r is the measured local radius of curvature. It should be pointed out that the strain applied by the bending apparatus has not been observed to change upon heating from room temperature to 300 °C and thus is believed to be very close to the strain at the annealing temperature. The same is not true of thin films for which the strain and thus the stress will depend on the thermal-expansion coefficient differences as the temperature increases.

III. RESULTS AND DISCUSSION

It was observed following a 750 °C, 5 min anneal that material having an original oxide-nitride implant mask in place did not show the formation of edge defects, as shown in Fig. 2(a). Moreover, the removal of this mask prior to annealing did result in the formation of an edge defect, Fig. 2(b), indicating that the stresses applied by the mask were

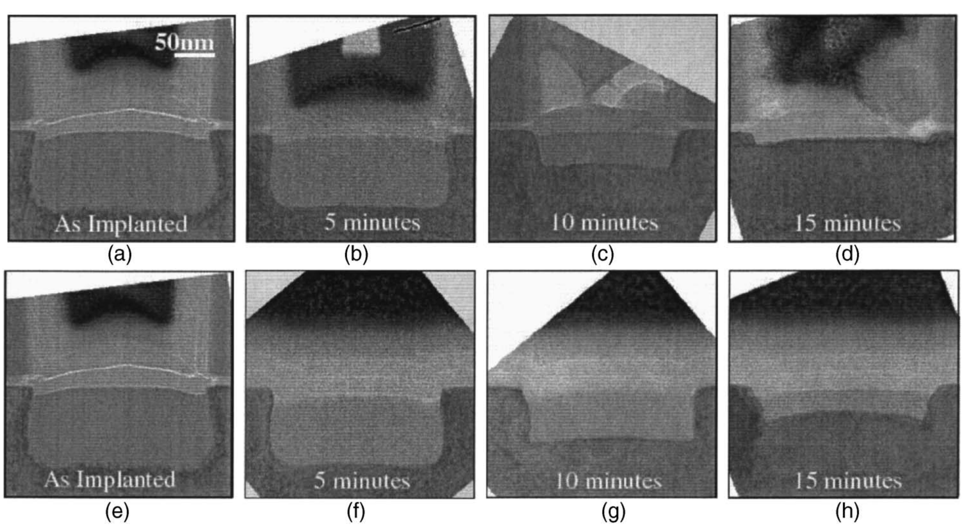

FIG. 3. XTEM partial recrystallization series at 550 °C. Images (a) and (e) are as implanted with the mask present. Images (b), (c), and (d) are material annealed with the mask present, and (f), (g), and (h) are material annealed after etching off the oxide-nitride mask. It is important to note the presence of the film and its associated tensile stress increases the corner velocity, thus preventing the apparent pinch point formation observed in the lower images without stress.

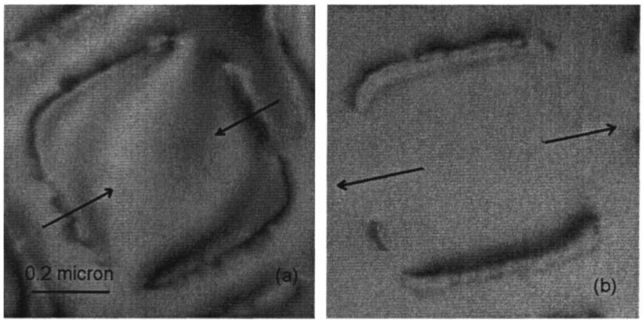

FIG. 4. Bright-field PTEM images showing the presence of the edge defect for a sample in 100 MPa of (a) compression and (b) tension while annealed at 750 °C for 5 min. The arrows indicate the direction of the stress in both images. It is observed that the edge defect has been suppressed for the sample in tension but only in the direction of the applied stress, while the material in compression shows a defect that extends around most of the perimeter. Note that the plan-view image was taken off axis along the **g**040.

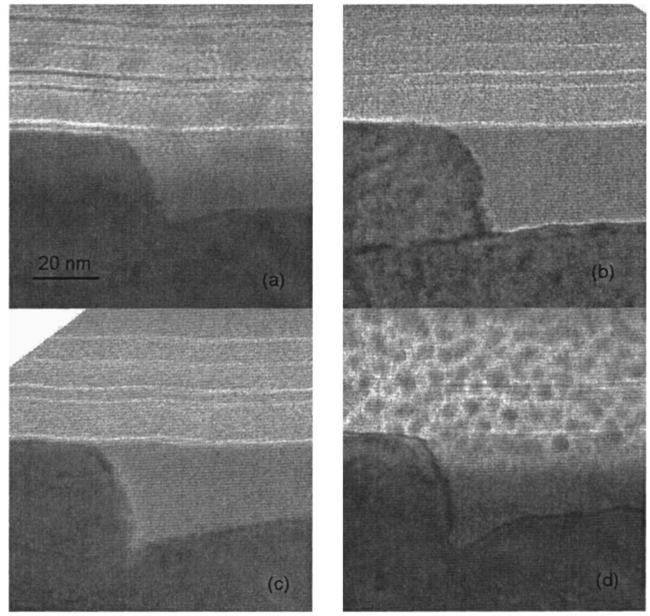

FIG. 5. XTEM of material to which (a) 50 MPa tension, (b) 100 MPa tension, (c) 50 MPa compression, and (d) 100 MPa compression have been applied while annealing at 550 °C for 13 min. It is observed that compression results in an acute angle at the corner of the amorphous-crystalline interface, while tension results in an obtuse angle.

such that was an effect on the silicon epitaxy. As seen in Figs. 3(a)–3(d), the stresses from the mask accelerated the vertical epitaxial regrowth, preventing the formation of a pinch point and suppressing defect formation. In order to determine how this defect was being formed a series of XTEMs was taken of material annealed at 550 °C for 5, 10, and 15 min to observe the amorphous-crystalline epitaxy front, Figs. 3(a)–3(h). The vertical epitaxial rate of the front is slower in the material that has had the mask removed, thereby indicating an increase in the vertical epitaxy velocity when the film is present. Further investigation found that when the vertical front epitaxy rate was increased sufficiently to produce an obtuse angle at the corners, "pinching" would not occur, and an edge defect would not form. Thus, with the mask removed there could exist a tensile stress at which the epitaxial regrowth velocity could be increased such that the defect would again be suppressed. One of the goals of this project is to find the magnitude of this stress.

Figure 4 shows the PTEM result of annealing material at 750 °C for 5 min while applying an external 100 MPa uniaxial stress, compression (a) and tension (b), using the three-point bend apparatus on material that has had the oxide-nitride film removed. It is observed that while the edge defects occur in the material stressed by tension they only exist in the direction parallel to the stress, and that in the direction perpendicular to the stress the defects are either greatly reduced or nonexistent. This implies that compressive stress of 100 MPa do not prevent mask-edge defect formation but that tensile stress as small as 100 MPa is sufficient to suppress defect formation presumably by altering the amorphous layer regrowth velocities. This is verified in Fig. 5. By examining the geometry of the amorphous pockets in the cross section of material annealed at 550 °C for 13 min, it is clear that samples in compression have an acute corner angle (formation of a pinch point), whereas samples in tension have a more obtuse angle. The defects are not observed to glide toward the surface after formation. Anneal at temperatures up to 900 °C resulted in no decrease in the half-loop dislocation density.[1] What is not seen is the expected increase in the vertical epitaxy rate observed in the thin-film case. This may imply that differences in the stress distribution between the thin film and the bending apparatus may affect the vertical regrowth velocity.

Our method of bending the silicon samples has recently been achieved, allowing dramatically higher stresses to be reached. A small strip of silicon is placed between the screw and the sample, dispersing the force of the screw across a larger area and making the apparatus closer to a four-point bend than a three-point bend. Wafer stresses of approximately 250 MPa could be reached. A maximum stress of 250 MPa in compression and 175 MPa in tension were possible (higher stresses consistently broke the samples). It is likely that during its processing, the etch was not stopped at the perfect time, causing surface cracks in the wafer. These indentations act as stress razors, and cause the strips to fracture at a lower level of stress. In bending, brittle materials are

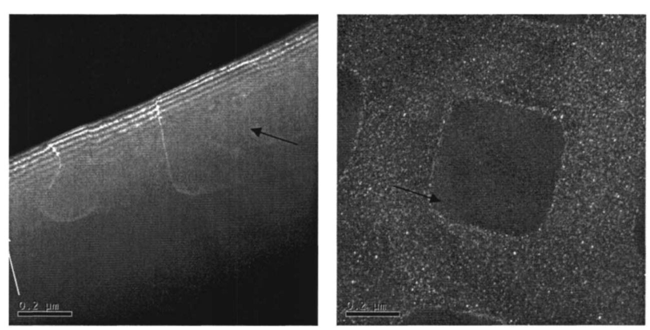

FIG. 6. PTEM after 550 °C, 1 h annealing at (a) 250 MPa compression or (b) 175 MPa tension. Note that there is no defect suppression for the compression case but a complete defect suppression in the tensile case.

very notch sensitive; a small notch can cause propagation of the crack through the material at a low stress.

Ten strips were bent in tension with nearly all of them breaking before a stress of 175 MPa; the average stress at fracture was about 140 MPa. One sample was annealed in tension at a stress of 175 MPa. Tests were performed to determine whether or not this higher stress level affected defect formation. Figure 6 shows the PTEM results of annealing at 550 °C for 60 min at these higher stress levels. For the compression case defect formation continues to be observed but for the tension sample complete suppression of defect formation is observed.

IV. CONCLUSIONS

It has been found that by applying a uniaxial tensile stress to silicon containing implantation-induced amorphous silicon pockets, defects normally observed to form during solid-phase epitaxy can be suppressed. It is shown that the applied stress directly the relative velocities of the vertical and lateral components of the amorphous-crystalline interface at the pinch point. Tension leads to elongation of the amorphous crystalline interface shape at the corner whereas compression enhances the formation of a pinch point. Pinch point formation favors defect formation. A similar suppression effect is observed when surrounding oxide-nitride masks are present during annealing which also place the silicon in a state of tension. It should be pointed out that the stress applied by the bending apparatus has not been observed to change upon heating from room temperature to 300 °C and thus is believed to be very close to the strain at the annealing temperature. The same is not true of thin films for which the strain and thus the stress will depend on the thermal-expansion coefficient differences as the temperature increases.

Further studies are needed to further the understanding of the effects of the nitride pads and uniaxial loading on SPER. By applying a wide range of stresses to various samples, it should be possible to estimate the stress which the nitride pads exert upon the surface of the silicon, thus providing a calibration between FLOOPS models of stress and actual measured data.

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