ECS Transactions, 16 (10) 215-218 (2008)
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Silicon Nanomembranes Incorporating Mixed Crystal Orientations

Shelley A. Scott, Deborah M. Paskiewicz, Donald E. Savage, and Max G. Lagally

University of Wisconsin, Madison, Wisconsin 53706, USA

We present a method for fabricating hybrid-orientation surfaces composed of regions of single-crystal Si(001) and Si(110), with the potential for transfer to foreign surfaces, providing a material suitable for high-performance CMOS devices on a variety of host substrates.

Introduction

The desire for increased processor speed leads to a demand for high-carrier-mobility CMOS devices. The complementary nature of CMOS, with both n-type and p-type channels, means that the lowest-mobility channel will limit the device speed. In the conventional (001) orientation of Si, the hole mobility is dramatically less than the electron mobility (1), (2), and hence serves as a bottleneck in CMOS performance. To compensate for the lower hole mobility, it is customary to fabricate the p-type device regions 3-10x larger than the n-type regions, consuming an undesirably large quantity of device real estate. The current drive imbalance between n-type and p-type channels can be minimized, thus negating the need for disproportionately large p-type regions, by fabricating mixed regions of Si(110) (high hole mobility) and Si(001) (high electron mobility) on a single substrate; so-called hybrid-orientation technology (HOT) (1).

We fabricate a mixed-crystal-orientation material in flexible membrane form, using Si nanomembrane (SiNM) transfer and overgrowth, to produce a “quilt” of Si(001) and Si(110).

Experiment

The SiNM fabrication process begins with a SOI(110) substrate, which is composed of a thin template layer of Si(110) separated from a bulk Si(001) substrate by a buried oxide layer. The (110) template layer is patterned with an array of holes using standard photolithography and reactive ion etching (RIE), and removed from its handle substrate via selective removal of the buried oxide layer in 49% hydrofluoric acid (HF) (3), (4), (5). This procedure creates a temporarily free-standing Si(110)NM, which is then bonded at 500°C to a Si(001) substrate. Note that the holes define the regions where the Si(001) crystal planes are exposed through the membrane. We then deposit Si over the structure using chemical vapor deposition (CVD) with silane precursor gas, at a substrate temperature of 580°C. Growth of Si via CVD on Si(001) planes is known to proceed at a faster rate than on Si(110) (6), allowing planarization of the surface (i.e., hole filling), to produce a flat mesh of Si(001) and Si(110) regions. Figure 1 illustrates these processing steps. A variety of membrane thicknesses can be obtained by thinning the as-supplied SOI wafer by cycles of thermal oxidation and oxide stripping in buffered dilute HF. The HOT structure is characterized at various stages of processing with optical microscopy, tapping mode atomic force microscopy (AFM), and x-ray diffraction (XRD).

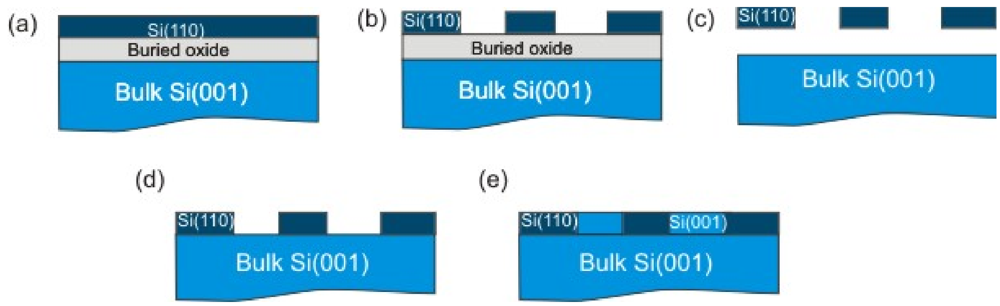

Figure 1. HOT fabrication via membrane transfer and overgrowth, illustrated in cross-section. (a) The original SOI(110) substrate; (b) after lithography and RIE; (c) after removal of the buried oxide in HF; (d) after bonding to a bulk Si(001) substrate; (e) after CVD growth of Si.

Results and Discussion

An AFM image taken from a 190nm thick released and bonded membrane is shown in the bottom right of Figure 3a, showing a recessed (001) region, which is exposed through the holes patterned in the (110) membrane, along with a schematic diagram of the cross-section in the upper right. After overgrowth, the recessed regions are filled in by the preferential growth on the (001) surface with CVD, as illustrated by a comparison of the AFM images in Figure 3a (before overgrowth) and Figure 3b (same membrane after overgrowth), revealing that the surface has become more planar. Using XRD to obtain the thickness of the membrane after overgrowth, and an AFM step height measurement across the boundary of the two orientations, we determine that the Si growth rate is ~10x faster on the (001) orientation than the (110) orientation at our growth temperature of 580°C. An illustration of the cross-sectional geometry of the structure after overgrowth is depicted in Figure 3b.

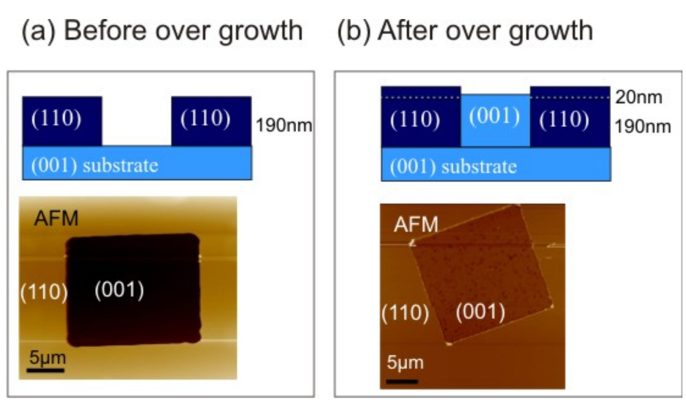

Figure 3. CVD overgrowth for planarization: (a) Cross-sectional schematic of a Si(110) membrane bonded to a Si(001) substrate (top), and an AFM scan of the surface (bottom); (b) the same structure after overgrowth with CVD, the schematic (top) shows the grown thicknesses of each orientation. Color contrast denotes height in the AFM images.

The order of magnitude faster growth rate on Si(001) compared to Si(110) was used to planarize membranes with a range of different thicknesses. Figure 4 shows an example of optical-microscope images of 86nm thick membranes before (a) and after (b) overgrowth. Figure 4a demonstrates that bonding of the Si(110) membrane to a Si(001) host results in a fairly smooth surface with an absence of obvious bubbles or trapped particulates, at least on the scale of several mm. Figure 4b provides evidence that the bonding is robust, as this membrane has survived both the pre-growth chemical clean (IMEC and RCA) and the actual growth process itself without damage.

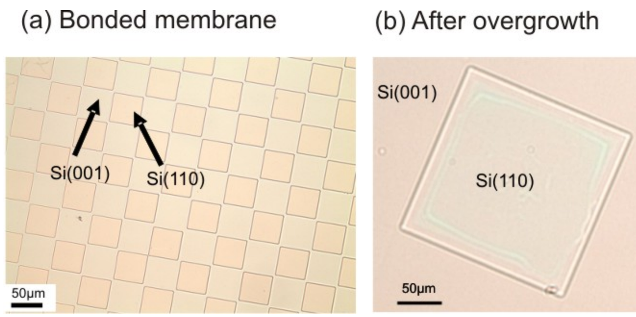

Figure 4. Optical-microscope images of 86nm Si(110) NMs bonded to a Si(001) host. (a) Si(110) membrane bonded to Si(001) host; (b) Si(110) membrane bonded to Si(001) host, after overgrowth with CVD. The crystal orientations are indicated on the images.

The degree of planarization was assessed by taking step height measurements across the boundaries of (001) and (110) regions with AFM, as depicted in Figure 5. The optical-microscope image on the left was taken from a 70nm Si(110)NM bonded to Si(110) and subsequently overgrown using the growth rate ratio for the two orientations that was determined from the AFM scans in Figure 3, along with XRD. Note that when the growth front is fairly planar, it becomes difficult to distinguish the different regions with the optical microscope. Figure 5b shows an AFM scan across the intersection of the two different orientations, and a step height measurement yields a planarization to within 0.5nm for a 70nm overgrown HOT structure. It is apparent from Figure 5 that a line of defects exist along the boundary region between the two interfaces, however this region would typically be removed during shallow trench isolation in device fabrication (7). This material is ideal for fabricating CMOS inverters, where the mobility can be optimized by fabricating n-type channels on (001) and p-type channels on (110).

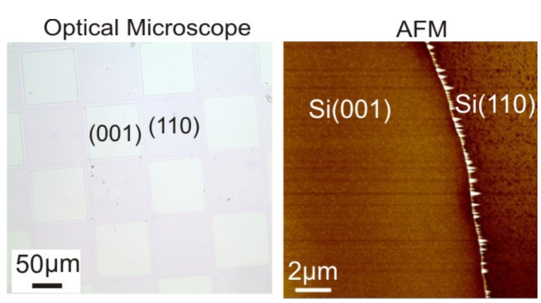

Figure 5. Images of 70nm Si(110) membranes after overgrowth.

HOT fabrication via this method of membrane transfer and overgrowth is simple and negates the need for a chemical-mechanical polishing step to remove the excess material, or use of masking. A very appealing aspect of this technique is the transferability of the membranes, which opens possibilities for various in-plane alignments during transfer in order to optimize also the relative in-plane channel directions along the two orientations. Moreover, as we are simply employing epitaxial growth, there is little concern for defect generation during the overgrowth, and the high temperatures required for techniques such as amorphization and templated recrystallization (8), are avoided here. XRD and AFM roughness measurements imply that the growth is of good quality, with an RMS roughness of 0.4nm on both the membrane and the overgrown (001) regions, comparable to the original host (001) substrate.

An obvious advantage of the SiNM transfer and overgrowth technique is the potential to obtain this material in flexible form, where the Si(110) membrane would be transferred and bonded to a SOI(001) substrate, rather than bulk Si(001), prior to overgrowth, allowing a subsequent release process to generate a free-standing flexible HOT material. It then becomes possible to transfer the entire planar HOT structure to foreign hosts, such as flexible plastics.

Conclusions

The selective growth of Si(001) compared to Si(110) in CVD growth has been used to planarize hybrid-orientation surfaces, formed by releasing and transferring Si(110)NMs. These features have the potential to be of use on a variety of different host surfaces because of the possibility of transfer.

Acknowledgments

Research supported by DOE, AFOSR, NZ-FRST, NDSEG, NSF, and Soitec.

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