FABRICATION OF CRYSTALS FOR CHANNELING OF PARTICLES IN ACCELLERATORS

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Abstract

We propose a method to fabricate crystals through silicon micromachining techniques, i.e., anisotropic silicon etching. Characterization of the crystals highlight that the crystals are free of lattice damage induced by the preparation. Crystals were positively tested at the external line H8 of the SPS with 400 GeV protons for investigation on planar and axial channeling as well as on single and multiple volume reflection experiments by the H8-RD22 collaboration.

INTRODUCTION

Channeling consists of confinement between the atomic planes of charged particles traversing a crystal. If the crystal is bent, the particles can follow such bending. Deflection of high-energy positively charged particles by a bent crystal is a method, whose potential has been widely exploited, for beam steering in accelerator physics, e.g., for extraction [1], focusing [2], splitting [3], collimation [4], undulation [5]. We review the methods we developed at the *Sensors and Semiconductors Laboratory* in Ferrara about fabrication of crystals for channeling.

CRYSTAL FABRICATION

There is class of chemical reactions related to crystalline silicon whose erosion rate depends on the crystalline orientation. Thus, with proper choice of the components of the solution, anisotropic erosion would results in a high-precision cut of a silicon crystal (see Figure 1).

Si crystals have been prepared starting from a 4-inch (110) Si wafer with the wafer's flat oriented perpendicular to <111> direction. A 100-nm layer of Si_3N_4 was deposited onto all faces of the wafer through low-pressure chemical vapor deposition and patterned with standard photolithographic techniques [11] with the masking pattern aligned with the wafer's flat. The wafer was immersed in KOH solution (20% weight concentration) with the Si_3N_4 pattern as a masking layer [12], which resulted in erosion of uncovered regions of the wafer (see Figure 2)

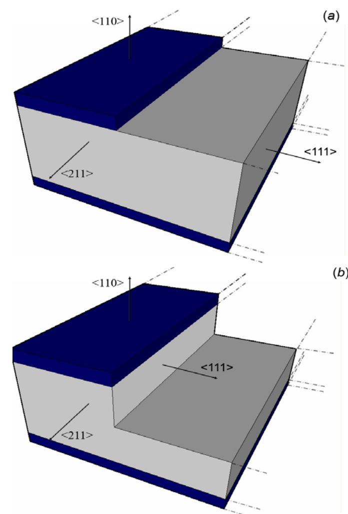

Figure 1: Schematic view of fabrication of a silicon crystal via anisotropic etching. (a) sample after patterning with Si_3N_4 (dark regions) and prior to chemical attack; (b) the unmasked areas undergo etching along the <110> direction while negligible erosion occurs along the <111> direction. Proper timing allows one to make controlled indentations or complete cut of the sample.

For the experimental parameters of the solution we chose, the etch rate of (111) planes is negligible with respect to that of the (110) planes, thereby chemical erosion proceeds as depicted in Figure 1b. The protecting layer of Si_3N_4 was finally removed from the lateral surfaces. It results in a crystal with regularly shaped equi-distant rectangular slots (see Figure 3). Then, the wafer can be cut to achieve either a batch of independent strips (Figure 4) or a rigid frame interconnecting a series of regularly positioned strips (Figure 4).

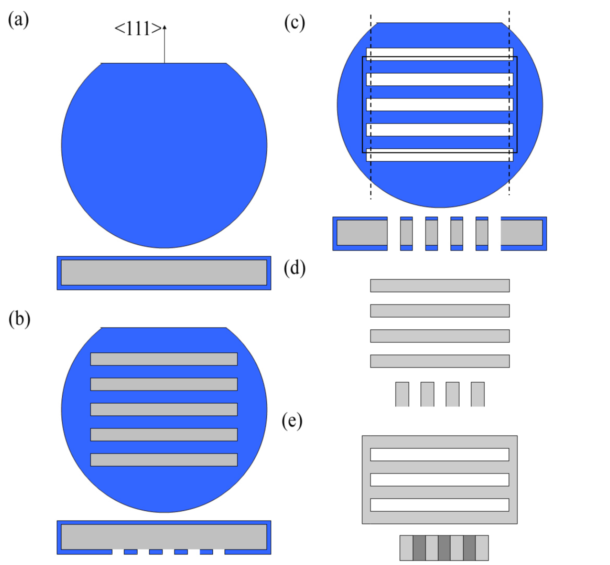

Figure 2: Fabrication of crystals for channeling (not to a scale) (a) deposition of a uniform 100-nm thick Si_3N_4 layer, (b) pattering of Si_3N_4, (c) anisotropic KOH etching and mechanical dicing along either the dashed line to release a series of independent strip-like crystals or the solid line to manufacture a multi-strip crystal with a frame, (d, e) final removal of the Si_3N_4 film. Masking by KOH-resistant Si_3N_4 thin film patterned onto the surfaces of the Si crystal allows fabrication of rather complex geometries.

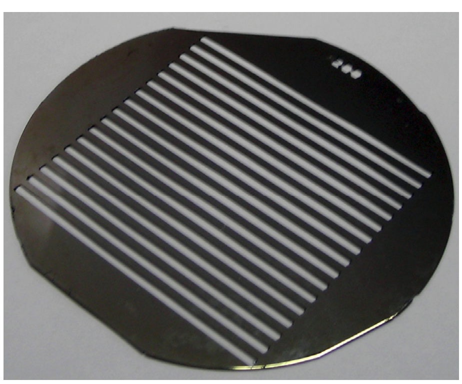

Figure 3: Si single crystal with equi-distant rectangular slots obtained by anisotropic etching.

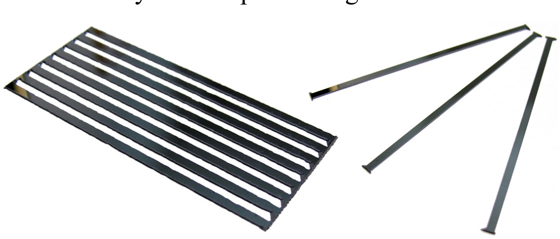

Figure 4: on the left, strips crystals connected by a common frame, on the right, single strips crystals.

Strip crystals were employed to study channeling and volume reflection effects in a single crystal, while multi-crystals are useful to study multi-channeling or multi-volume reflection effects. Both this type of crystals were positively tested at the external lines H8 and H4 of the SPS with 400 GeV protons and 150GeV π^- for investigation on axial channeling and on single and multiple volume reflection experiments by the H8-RD22 collaboration.

Morphological investigation of the roughness of the crystal surface was done by atomic-force microscopy (AFM). Analysis was carried out over one of the (110) surfaces of the samples, i.e., to the lateral surface of the crystal, which are the planes interacting first with halo-beam particles. Clear evidence of ultra-flat surface with a roughness down to the monolayer level was achieved over a relatively wide scan as reported in Tab. I and compared to the roughness of previously used methods [7,9] relying on isotropic methods.

Table 1: Comparison between standard roughness, R_a, obtained by different etchings. R_a was measured by AFM over 10x10 μm^2 large area.

Methodology	R_a (nm)
Isotropic etching (first generation)	135 (Ref. [7])
Isotropic etching (second generation)	23 (Ref. [9])
Anisotropic etching	<1

Standard roughness featured R_a=0.25 nm, i.e., it was decreased by nearly two orders of magnitude with respect to the fabrication via isotropic etching [7,10].

The crystal quality in proximity of cut surfaces was analyzed by High Resolution TEM (see Figure 5), which showed an ordered arrangement of the atomic columns, which was preserved up to the crystal surface. Similar observations over different area of the sample confirmed previous determination.

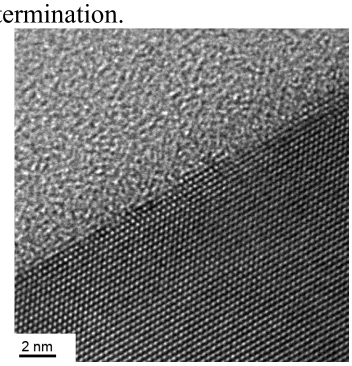

Figure 5: High-resolution TEM characterization of the entry face of the crystal. Analysis highlights ordered and atomically sharp termination of the crystal surface. The amorphous material above the crystal is the embedding epoxy used in the preparation of the cross-section sample.

Crystal bending is achieved by means of specificately designed crystal holders, see Figure 6. For beam deflection it is exploited anticlastic bending of the silicon strips: as consequence of bending imparted along the main size of the crystal, a secondary bending along the transversal size of the strip is achieved.

Figure 6: a multi-strip crystal mounted in a bending device.

CONCLUSIONS

We developed a technique of silicon macromaching, based on photolithography and wet chemical etching which allows the realization of silicon crystals free of any damage induced by the working process. Such crystals have been used by H8-RD22 collaboration to study planar and axial channeling of positive [9, and negative particles at H8 and H4 CERN beam lines. A crystal of length along the beam 2mm and bending angle 150 μrad was installed in the SPS circulating beam: operating in channeling mode, it will be used in a tentative of collimation of the circulating proton beam by the CERN experiment UA9.

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