FABRICATION OF SILICON STRIP CRYSTALS FOR UA9 EXPERIMENT

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On behalf of UA9 collaboration

Abstract

Bent silicon crystals have been recently installed in the SPS ring in the frame of the UA9 experiment, which is attempting the collimation of the SPS circulating beam by means of bent silicon crystals. We discuss their fabrication technique based on non-conventional use of established techniques of anisotropic etching of silicon in micro-machining. Morphological and structural analyses were carried out through electron and scanning-probe microscopy to show that the crystal exhibited flat surfaces with atomically sharp termination. Prior to installation in the SPS ring, crystals were tested by the UA9 collaboration on H8 SPS extracted beam with 400GeV protons in channeling and volume reflection experiments. The crystal holder is designed to bend the crystal and to compensate for torsional effects.

INTRODUCTION

Halo collimation is part of a particle accelerator, and is essential for the operation at high luminosity of LHC and any other particle accelerator operating at high intensity.
Following the positive results of beam extraction and collimation in Tevatron [1-3], SPS [4], IHEP [5,6] and an intense campaign on H8 SPS extracted beam [7-12], the UA9 experiment aims to collimate the halo of the CERN SPS circulating beam using bent silicon crystals [13]. Differently from a massive collimator which spreads the halo, a bend crystal coherently deflects all the particles to the same direction allowing collecting them on a massive absorber. UA9 is installed in the two-dipole empty cells of the straight section 5 of the SPS, across the cavern hosting UA1. UA9 alternate the use of four single crystals (two "quasi mosaic" and two "strip" crystals).

STRIP 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).

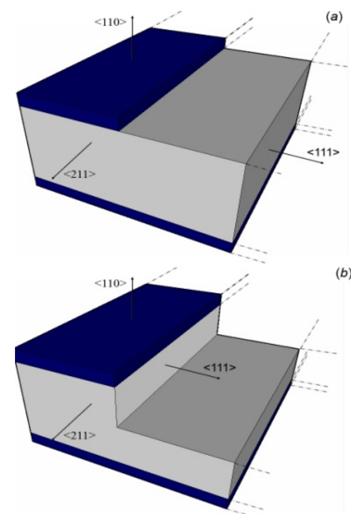

Figure 1: Schematic view of fabrication of a silicon crystal via anisotropic etching. (a) sample after patterning with Si_3N_4 (dark regions) and prior to chemical attack; (b) the unmasked areas undergo etching along the <110> direction while negligible erosion occurs along the <111> direction. Proper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

Silicon strip 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 vapour deposition and patterned with standard photolithographic techniques [14] with the masking pattern aligned with the wafer's flat. The wafer was immersed in a potassium hydroxide solution (20% weight concentration, 80 °C) with the Si_3N_4 pattern as a masking layer [15], which resulted in erosion of uncovered regions of the wafer (see Figure 2).

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 equidistant rectangular slots (see Figure 3). Individual silicon strips can be released by mechanical dicing the frame joining them.

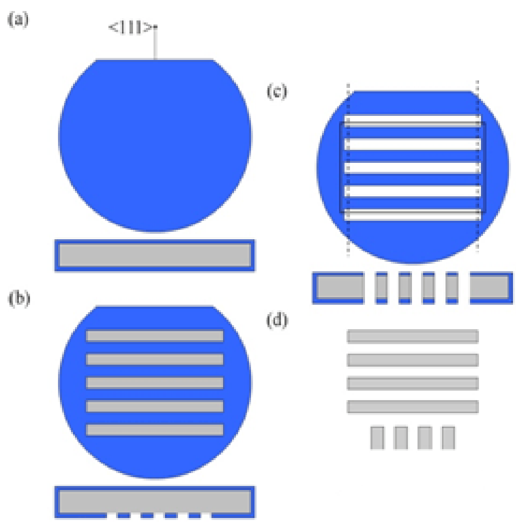

Figure 2: Fabrication of crystals for channeling (not to a scale) (a) deposition of a uniform 100-nm thick Si_3N_4 layer, (b) pattering of Si_3N_4, (c) anisotropic KOH etching and mechanical dicing along either the dashed line to release a series of independent strip-like crystals or the solid line to manufacture a multi-strip crystal with a frame, (d) final removal of the Si_3N_4 film.

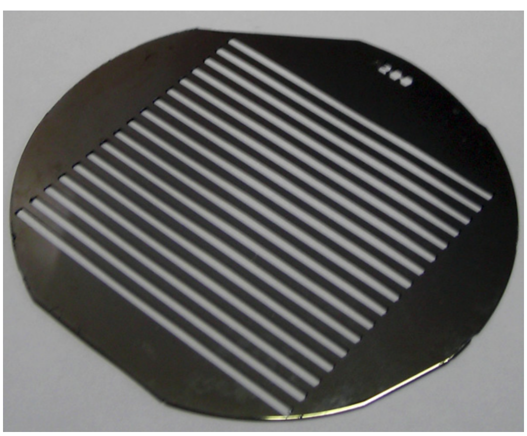

Figure 3: Si single crystal with equidistant rectangular slots obtained by anisotropic etching.

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

CRYSTALS CARACHTERIZATION

The UA9 collaboration selected two strip crystals for installation in the SPS circulating beam. Both the crystals have a thickness along the beam of 2 mm and their bending relies on anticlastic deformations [16, 17]. In two different periods, crystals have been characterized on CERN-H8 line with 400 GeV and subsequently installed in the SPS ring.

The crystal installed as first have been used to perform a study of volume reflection features behavior as function of the bending radius [9], axial channeling [10] and to measure nuclear dechanneling length [18].

Crystal deformational state has been characterized by optical white light interferometry (see Figure 5).

Such technique allows obtaining a 3D-map of the crystal surface with sub-nm resolution.

Crystal bending angle have been adjusted to 150 μrad.

A second crystal, installed a few months later, has been characterized by means of x-ray diffraction, which highlighted that the crystal off-axis is only -200 μrad and on H8 line during a dedicated run which allowed to adjust the bending angle to 176 μrad. A preliminary analysis showed a channeling efficiency larger than 80%.

A significant improvement to the crystal holder realized between the installations of the two crystals allows removal of torsion in a strip-like crystal. Such improvement, joint with the tracking capabilities of the detectors allowed providing a feedback system capable to finely adjust the crystal torsion to less than 1 μrad/mm.

In Fig. 5a is represented the particle deflection angle as a function of the vertical position along the crystal before torsion compensation. Region 1 corresponds to channeled particles, 2 to undeflected particles and 3 to volume reflected particles. Fig. 5b shows beam deflection as a function of the vertical position after torsion compensation. After torsion compensation each portion of the crystal intercepted by the beam is acting in the same way. A linear fit of the deflection angles allows to measure torsion, which is decreased from 34 to 1 μrad/mm.

Figure 6 shows the working principle of the mechanism used for torsion compensation (the crystal is drawn as a blue strip and its holder is sketch as grey). As already discussed torsion is obtained measuring the deflection angle of channeled particles as function of the crystal vertical position (34μrad/mm in the considered case). A laser beam impinges perpendicularly to the crystal surface at the crystal center (red dot in Figure 7(a-b)). The crystal height is 40mm, so due to torsion the crystal cross section in the central region is rotated of 20mm*34=680μrad with respect to the clamped regions. The goniometer supporting the crystal is rotated of 680μrad (Figure 7(c)) and a screw (drawn as an arrow) is mounted in the crystal holder and screw in until the reflected laser beam coincides with the incoming one, i.e. until the crystal surface is rotated back of 680μrad (Figure 7(d).

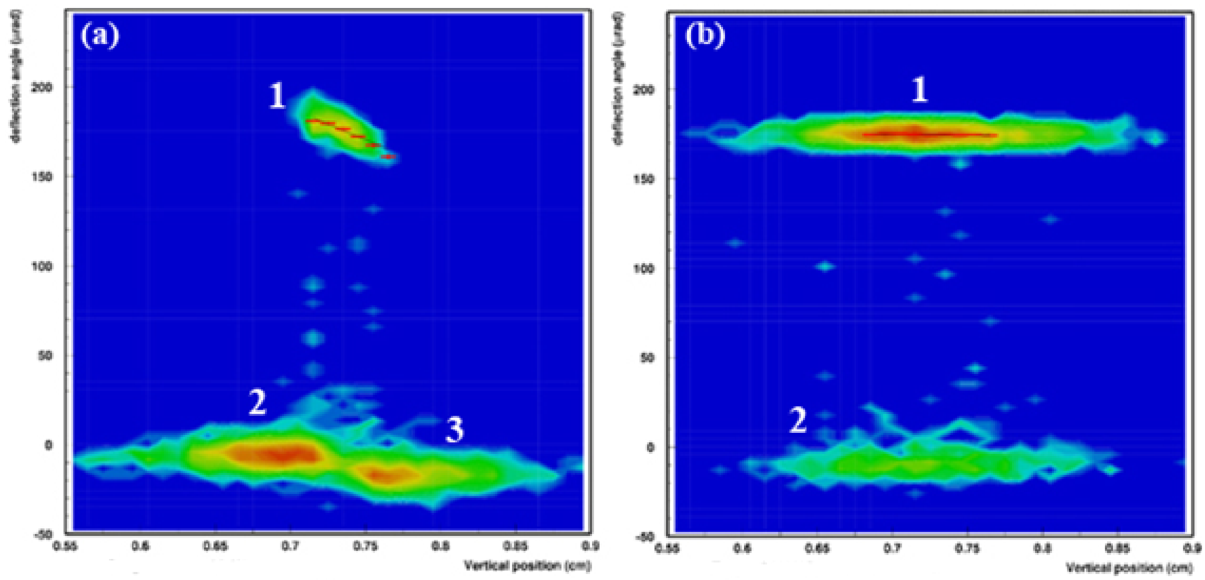

Figure 5: Particles deflection angle as function of vertical position along the crystal.(a) before torsion correction (b) after torsion correction. In both (a) and (b), region 1 represents the deflected beam and 2 the undeflected beam. In (a), region 3 corresponds to volume reflected particles. Due to crystal torsion different regions of the crystal are oriented in different way along the vertical direction, so a region of the crystal is aligned in such a way to excite VR instead of channeling. After torsion compensation this spot is no more present. A linear fit of the deflection maximum of deflection angles give the torsion in µrad/mm.

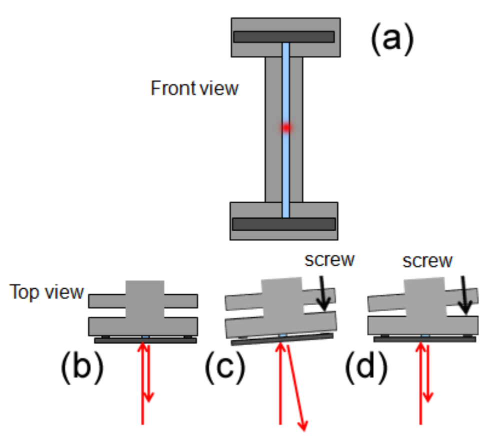

Figure 6: (a) sketch frontal view of a strip crystal mounted on its holder. (b-c-d) screw acting on the holder is used to compensate torsion; an optical setup acts as a feedback of the crystal alignment. See text for more details.

CONCLUSIONS

Silicon crystals in the shape of "strips", suited for studies of coherent interactions between crystals and charged particle beams, have been fabricated through silicon anisotropic etch techniques. Intensive characterizations of such crystals highlighted their high crystalline quality and allowed obtaining of high deflection efficiency. Among the various tested crystals, two of them have been selected by the UA9 collaboration for installation in the SPS ring and are currently used in an experiment which is attempting the collimation of the SPS circulating beam by means of bent silicon crystals.

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