MORPHOLOGICAL AND STRUCTURAL STUDIES OF CRYSTALS FOR CHANNELING OF RELATIVISTIC PARTICLES

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Abstract

Channeling of relativistic particles through a crystal may be useful for many applications in accelerators. It has been experimented that significant role is played by the method used to clean the crystal surfaces that the particles beam encounters first. It was experimentally observed that chemical cleaning of the surfaces via etching leads to better performance than conventional mechanically treated samples do. We investigated the physical reasons for such a behaviour through characterization of the surfaces of the crystal. We observed that mechanical dicing causes a superficial layer rich in dislocations and lattice imperfections, extending tens of microns into the crystal, which is removed via etching. Such a disordered layer is the first portion of the crystal experienced by the incoming particles and results in a mosaicity degree that exceeds the critical angle of relativistic particles for channeling, i.e., it acts like an amorphous layer.

INTRODUCTION

Channeling of relativistic charged particles would be a powerful method in accelerator physics [1-3] because it may be an alternative for construction of the components presently used in accelerators such as dipoles, collimators and focusing elements [4]. For this reason, the use of bent crystals for beam extraction in circular accelerators has been intensively investigated in several laboratories during last decade. The advantages of the method of channeling are low cost, compactness and minimal disturbance to the beam in the environment of the accelerator.

Silicon is an excellent candidate to fabricate crystals for channeling because of its high crystalline perfection, low cost and established knowledge of its handling. Since pioneering experiments [5], a continuous improvement in performance has been carried out, arising to new schemes for the crystals and also to technological development.

Building Si crystals with the right dimensions for each specific application does demand dicing, lapping, and other operations that alter the original quality of the lattice. Preparation of samples induces a "dead layer" at surface, characterized by a great number of defects and crystalline disorder, which does not act as an active layer for channeling. It has been demonstrated that significant improvement in the features of the samples for channeling can be achieved once a specific etching treatment is imparted to the crystal surface [6].

In this work we report on a systematic analysis of the crystalline perfection of the surface of Si crystals applied in channeling experiments, depending on the preparation methodology.

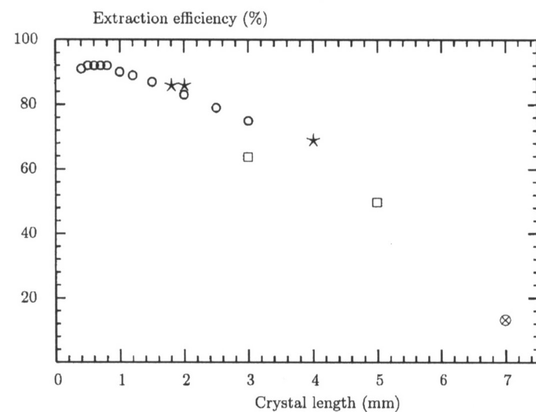

Figure 1: Extraction efficiency for 70-GeV protons. Recent results [6] (*, strips, 1.8, 2.0, and 4 mm long), results of 1999-2000; (□, "O-shaped" crystals 3 and 5 mm), and of 1997 (⊗, strip 7 mm). Also shown (o) is the Monte Carlo prediction for a perfect crystal with 0.9 mrad bending.

CHANNELING EFFICIENCY

In the frame of the CERN-INTAS collaboration 2000-132, we recently achieved a substantial progress with Si crystal-assisted beam deflection at the 70-GeV

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accelerator at IHEP. Extraction efficiency of the order of 85% was repeatedly obtained for an impinging intensity as high as 10^{12} protons [6].

Key reason of this successful operation was the use of very short crystals for extraction. Crystal length was selected close to the optimal value foreseen by the physics of proton channeling. Fig. 1 shows theoretical predictions of extraction efficiency as a function of the crystal length, for an impinging proton beam of 70-GeV, as compared to experimentally recorded levels with crystals of different size and design.

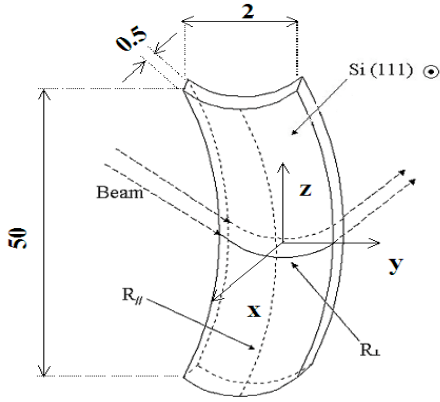

Figure 2: Scheme of the bent crystal plate. Dimensions are expressed in mm, y is the direction tangent to the incident beam on the middle of the crystal, x is oriented along the thickness (crystalline direction (111) of silicon) and z is oriented along the height. The crystals were manufactured at the Semiconductors and Sensors Laboratory of the University of Ferrara as narrow strips, about 2-mm thick in the direction of the beam.

A recent design to produce a short crystals is the use of the anisotropic properties of a crystal lattice. From the theory of elasticity it is known that bending a crystal plate in the longitudinal direction causes "anticlastic bending" or twists to appear in the orthogonal direction. For Si (111)-oriented, the crystal plate takes the shape of a saddle as sketched in Fig. 2.

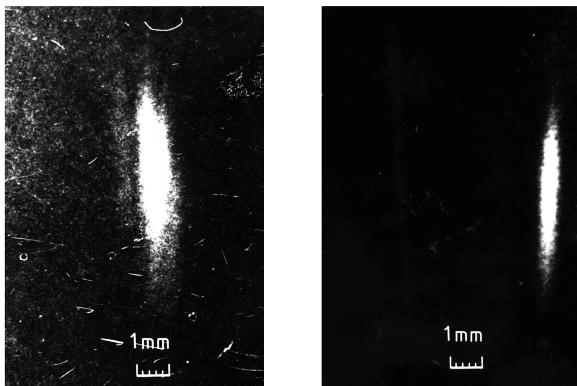

Figure 3: Image of the beam deflected through mechanically treated (left) and chemically polished crystals (right). The profile of the beam bent by a chemically polished crystal is more uniform and sharp (20 mrad vs 100 mrad at 70 GeV).

A comparative study [7] about the performance of mechanically polished samples vs. chemically etched specimens was carried out at IHEP. Protons, 70-GeV in energy, were extracted from the main stream through both types of crystals. Fig. 3 shows the results of the tests for the chemically polished deflectors vs. those for the unpolished samples. The crystals with chemically polished faces have shown the best perform for beam extraction. The profile of the beam bent by a chemically etched crystal turned out to be more uniform and sharp. Its width was ascribed to the crystal thickness once beam divergence within the critical angle of channeling (20 μrad at that energy) was taken into account. On the other hand, the beam bent by the mechanically polished crystal exhibited irregularities, corresponding to an angular spread of the order of 100 μrad.

MORPHOLOGICAL CHARACTERIZATION

As a general rule for microelectronics, when the dimensions of silicon devices scale down, wafers with minimal impurities are needed, thus great care must be taken for cleaning procedures. Bearing this scheme in mind, we borrowed from microelectronics a cleaning methodology to manufacture the samples for channelling.

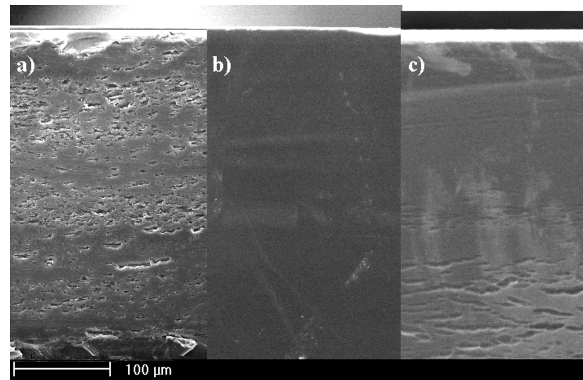

Figure 4: (a) A sample cut to form $0.497 \times 20 \times 5$ mm^3 (thickness, length, height respectively) by means of a mechanical dicing saw with a 30000 rpm angular velocity and 0.150 mm thickness of diamond blade. The linear velocity was 2 mm/sec. (b) A mechanically treated sample and (c) a chemically polished sample.

The first step is removal of organic and metallic impurities that are present on the wafer surface. The process of dicing a wafer by a diamond-blade saw to reach the wanted dimensions induces a superficial layer rich in scratches, dislocation, line defects and anomalies. In order to remove the defects, two types of surface cleaning are carried out: mechanical polishing and chemical etching. For mechanical polishing, the sample is fixed on a special slide, which is put onto a rotating plate covered with different abrasive cloths. The chemical method consists of a planar etching [7], which allows the removal of planes of silicon one by one. Fig. 4 consists of electron-microscopy photos of some samples: just after the cut (a), mechanically

treated (b) and chemically polished (c). Fig. 4(a) shows a sample cut by the dicing saw at 30000 rpm angular velocity by a 150-µm-thick diamond blade. The linear velocity was 2 mm/s. Fig. 4(b) illustrates a mechanical-polished sample after a sequence of four abrasive cloths with decreasing roughness. Fig. 4(c) is a chemically polished sample through 30 min chemical-etching. Chemical etching allows slow erosion for precise manufacturing of the samples to an extent that is not otherwise possible.

Atomic force microscopy (AFM) was carried out first to measure the standard roughness, R_a, of the surfaces induced by dicing at top speed. An area of 40×40 µm^2 was chosen for collection of images (Fig. 5) prior to (*a*) and after (*b*) chemical etching. Fig. 5(*a*) shows the levels of roughness as a function of the state of the surface.

Mechanical polishing highly reduces the roughness by a factor of five with respect to the unpolished surface. Rather surprisingly, 20 min of chemical etching enhances the roughness even if compared to the as-cut sample. However, for longer etching times (up to 40 min), R_a tends to decrease (see Fig. 6(*b*)).

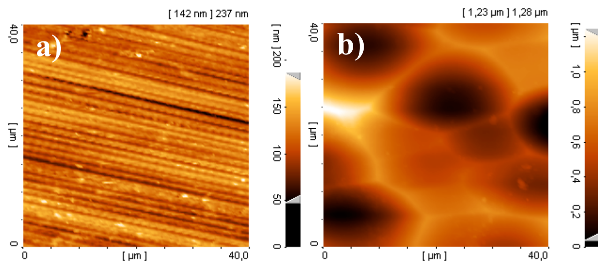

Figure 5:AFM images of the surface of an as-diced Si crystal (a) and after 40 min chemical etching (b).

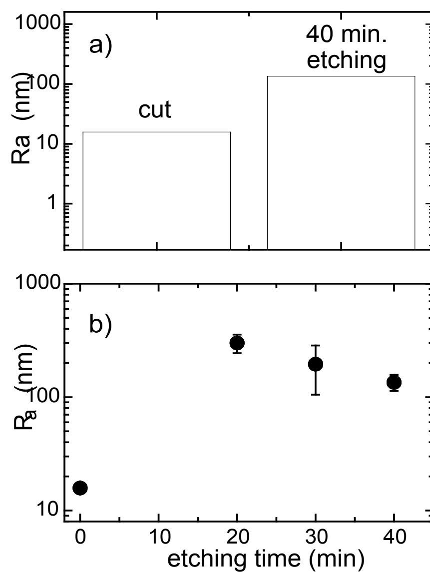

Figure 6: (a) Standard roughness (R_a) of the sample as-diced and after chemical etching; (b) R_a for chemically etched samples as a function of the etching time.

Thus, the evolution of the surface under etching can be rationalized as follows: the part of the crystal damaged by the dice has greater chemical reactivity due to lattice imperfections, therefore it reacts first. Then, corrosion to non-damaged part of the crystal starts being effective at lower rate, resulting in a flat surface at longer times.

STRUCTURAL CHARACTERIZATION

Among the techniques for structural study of surfaces, Rutherford backscattering channeling of alpha/protons at low energy provides a very precise method and, ultimately, is the same physical phenomenon as that of the target for which the crystals are being designed.

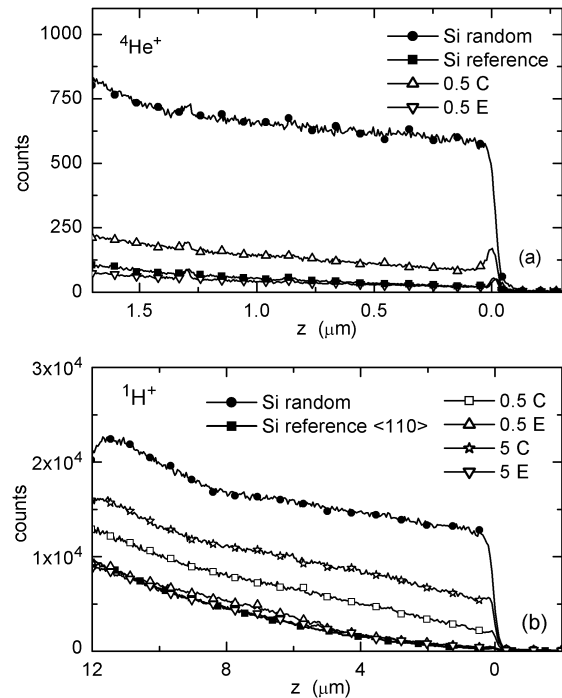

Figure 7: RBS-channeling spectra recorded using alpha particles (*a*) and protons (*b*). Reference spectra from a “perfect” crystal in random and best channeling orientation are reported. For both α particles and protons the yield of the samples after chemical etching (E) is the same as that of the reference crystal under channeling regime. The as-cut sample diced at higher speed (5 C), instead, exhibits higher yield with respect to the sample cut at 0.5 mm/min (0.5 C).

In Fig. 7(*a*), RBS-channeling spectra obtained from 2.0-MeV $^4He^+$ beam on sample cut at 0.5 mm/min are reported after normalization to the collected charge. Two reference spectra of a random and aligned Si crystal are also reported. Under such experimental conditions, we estimated an in-depth analyzed region of about 1.5 µm. Three main observations can be drawn. First: a surface Si peak is recorded in all the spectra due to surface scattering; the peaks for the reference crystal and for sample E (chemical etching) are similar, while samples C (as-cut) and M (mechanically polished, not reported) exhibit a longer tail towards the bulk of the crystal. This evidence highlights the presence of a

surface disordered structure for samples M and C, which is not detected for sample E. Moreover, the extension of the unchanneled region for sample M is broader than for sample C. Second: irrespective of the surface peak, the RBS signal from the inner part of the sample exhibits a very regular shape, indicating a homogeneous in-depth distribution of defects, which are responsible for dechanneling events as far as the analyzed depth is concerned. Third: the normalized height of spectra pertaining to samples M and C is the same at any depth but the surface region, and is systematically five times higher than the height for sample E. This evidence clearly shows that, despite the enhanced roughness induced by 30 min of chemical etching, the etched crystal exhibits highly improved crystalline order with respect to both C and M samples.

A complete analysis on the entire series of samples was carried out using a 2.0 MeV proton beam, which is more penetrating and allows investigation of a deeper region (up to 14 μm) with respect to α particles (see Fig. 7(*b*)). The as-diced crystal cut at 5 mm/min exhibits a higher yield for backscattered protons, under channeling conditions, with respect to the as-diced crystal cut at 0.5 mm/min (Fig. 7(b)), i.e., the samples cut at higher speed highlighted larger crystalline disorder. Mechanically polished samples show an intermediate yield with respect to sample C and E, though they exhibited little reproducibility. Concerning chemical etching, backscattering yield of all samples was the same irrespective of the dicing speed and perfectly overlaps with the spectrum of a reference single-crystal. This is a clear proof of the effectiveness of chemical etching for removal of the superficial damaged layer, at least within the penetration range of the technique.

CONCLUSIONS

Considerable progress in crystal channeling research has been obtained over the years. Extraction efficiency of the order of 85% was repeatedly obtained for an impinging intensity as high as 10^{12} protons. Channeling in crystals proved to be positively affected by superficial etching treatments. Chemically polished samples exhibit a more ordered crystalline structure, indicating the removal of the amorphized layer, which was formed when the crystal was diced.

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