CHARACTERIZATION OF CRYSTALS FOR STEERING OF PROTONS THROUGH CHANNELLING IN HADRONIC ACCELERATORS*

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Abstract

Channeling of relativistic particles through a crystal may be useful for many applications in accelerators, and particularly for collimation in hadronic colliders. Efficiency proved to be dependent on the state of the crystal surface and hence on the method used for preparation. We investigated the morphology and structure of the surface of the samples that have been used in accelerators with high efficiency. We found that crystal fabrication by only mechanical methods (dicing, lapping, and others) leads to a superficial damaged layer, which is correlated to performance limitation in accelerators. A planar chemical etching was studied and applied in order to remove the superficial damaged layer. RBS channeling analysis with low-energy protons and $^4He^+$ highlighted better crystal perfection at surface, as a result of the etching. A protocol for preparation and characterization of crystal for channelling has been developed, which may be of interest for reliable operation with crystals in accelerators.

INTRODUCTION

Channeling of relativistic charged particles may 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]. 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 for channeling because of its high crystalline perfection, low cost and large knowledge on its usage. 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.

The crystals demonstrating the highest efficiency were built with a novel geometry, namely in the form of a mechanically bent strip; the secondary curvature due to anticlastic forces proved useful for steering the protons through channeling. [6] With these kinds of crystals, extraction efficiency up to 85% has been obtained at IHEP with 70 GeV/c protons on a regular basis since 2000.

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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. Preliminary studies [7-8] indicated that preparation of samples induces a "dead layer" at the surface, characterized by a great number of defects and crystalline disorder, which does not act as an active layer for channeling.

A new experiment based on application of bent crystals is actually planned for beam-halo cleaning in the H8 beam line at CERN SPS [9-10]. For the purpose, we refined the preparation methodology of crystal surface to obtain high degree of crystalline order and low surface roughness.

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. As an example we report in Figure 1 the image of the 70-GeV/c beam (at IHEP) deflected through mechanically treated and chemically polished crystal.

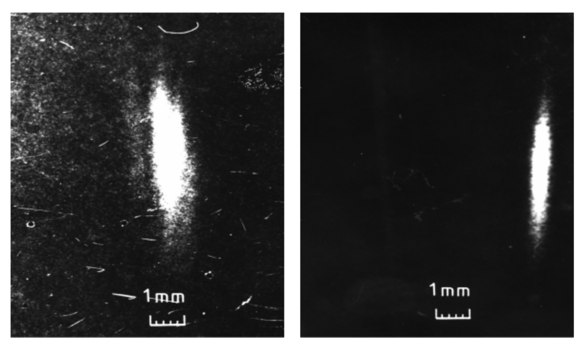

Figure 1: Image of the beam deflected through mechanically treated (left) and chemically polished crystals (right). The profile of the beam bent by a chemically polished crystal is more uniform and sharp (20 μrad vs 100 μrad at 70 GeV/c).

As shown in Figure 1, chemical etching results in very neat beam profile, without lateral broadening induced by mechanical polishing. Previous results attributed beam broadening under application of mechanically treated crystals to the presence of surface nearly-amorphous damaged layer, that can be efficiently removed by chemical etching. However, chemical etching resulted in strong enhancement of surface roughness of the crystal, which is undesirable effect for application at high energy accelerators.

CRYSTAL MORPHOLOGY

With respect to previous preparation methodology, we changed chemical etching procedure by reducing the etching time and slightly modifying the chemical composition of the etching bath. As for mechanical polishing, we applied new instrumentation (Logitech 1PM51), to investigate the possibility of obtaining very smooth surface without structural defects.

Figure 2 collects scanning electron microscopy (SEM) images of a sample just after cut (a), mechanically treated (b) and chemically polished (c) under old methodology. Mechanical polishing induces a neat smoothing of the surface, and eliminated the numerous small craters created by the saw during cut. Smooth zones (region A) and zones with densely distributed cracks (region B) typically coexist in chemically etched crystals. Craters after etching are more extended in lateral dimensions but reduced in number with respect to the as-cut sample.

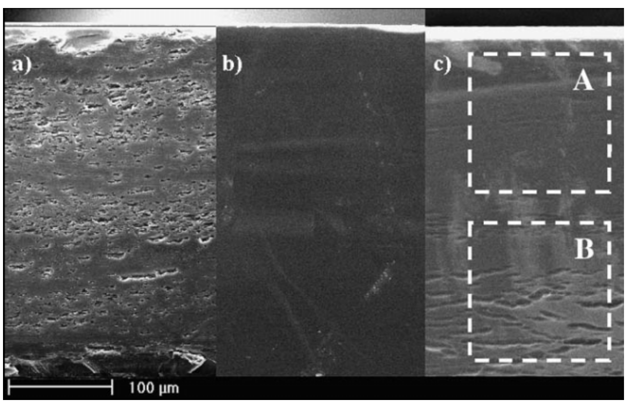

Figure 2 SEM images of sample cut by mechanical dicing saw: (a) as-diced; (b) after mechanical polishing; (c) after chemical etching.

Atomic force microscopy (AFM) was applied for quantitative analysis of surface roughness. AFM images over 10×10 μm^2 of surface of silicon crystals after chemical etching using the old and the new methods are collected in Figure 2 a) and b), respectively. In Figure 2 a) very deep craters are present, highly densely distributed all over sample surface. This effect was attributed [8] to selective etching process, that tends to remove the highly defected areas of the crystal, while maintaining unchanged the areas with lower density of crystalline defects. The presence of deep and spatially dense craters is highly reduced in terms of dimensions, depth and density by the new preparation. Quantitative results of AFM measurements are collected in Figure 3. We were able to significantly reduce surface roughening induced by anisotropic chemical etching with respect to previous methodology.

a)

b)

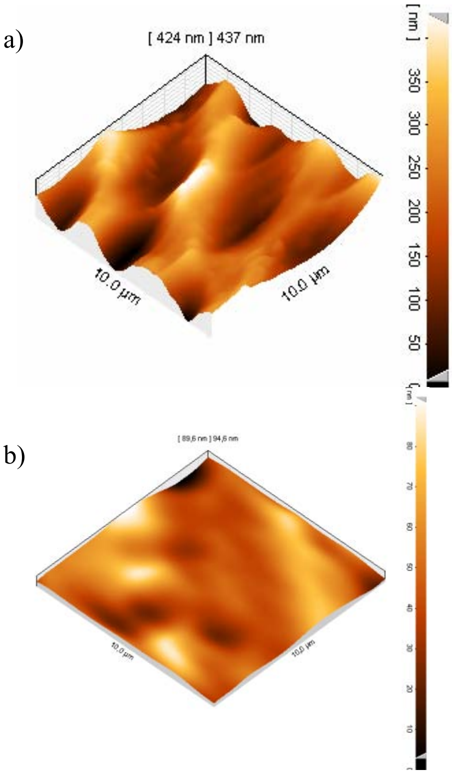

Figure 3: Atomic force microscopy images of silicon crystals after chemical etching under: a) the old methodology reported in Ref 7; b) the new methodology developed for the new experiment in the H8 CERN-SPS beam line.

Moreover, mechanical polishing with new procedure (AFM picture not reported) resulted in very smooth surface, with average roughness lower than 30 nm.

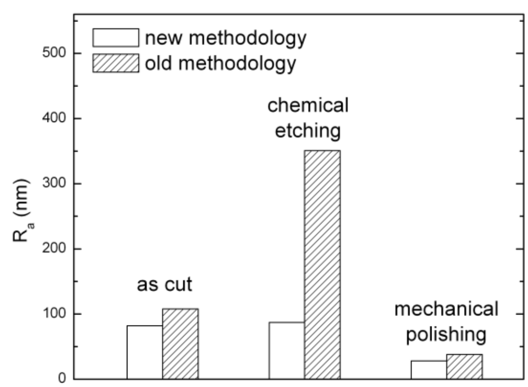

Figure 4: Quantitative analysis of AFM in terms of surface roughness of the crystal under different preparation methodologies; results from the old methodology (Ref. 7) are compared with results obtained with methodology applied for preparation of crystal for H8 beam line CERN-SPS experiment.

CRYSTAL STRUCTURE

Crystalline structure of the first microns of silicon crystal has been investigated using Rutherford backscattering in channeling condition (c-RBS). Measurements were performed at INFN/LNL Labs. 2.0 MeV $^4He^+$ and protons were applied as probe at backscattering angle θ=160°.

The different stopping power of $^4He^+$ and protons at the energies under study allowed in-depth analysis of about 1 μm and 10 μm, respectively. Enhanced stopping power of $^4He^+$ resulted in higher in-depth resolution with respect to protons, proportionally. c-RBS spectra of chemically etched crystal prepared under new methodology are displayed in Figure 4. The RBS spectrum in random orientation is reported as a comparison with respect to the yield of the perfectly aligned crystal.

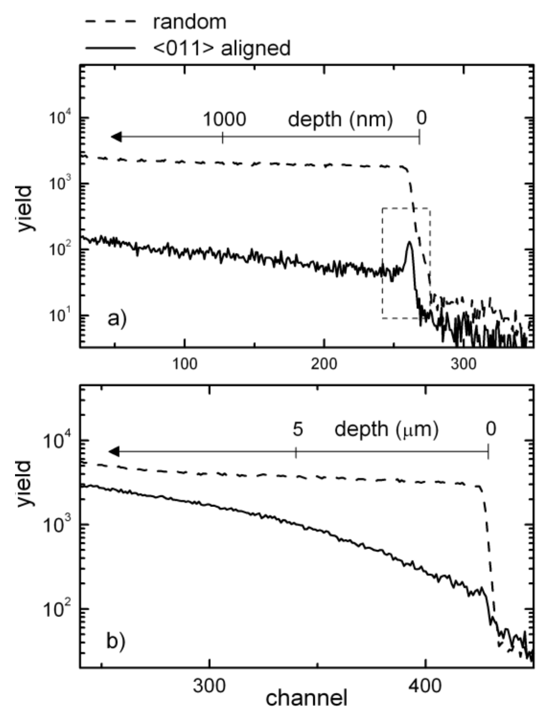

Figure 5: RBS channeling spectrum of sample after chemical etching, using 2.0 MeV $^4He^+$ (a) and protons (b). The spectrum in random orientation is recorded as a reference for scattering yield. Analysed region depends on beam energy loss: it is about 1.5 μm and 10 μm for $^4He^+$ and protons, respectively. Enhanced depth resolution of $^4He^+$ with respect to protons allows appreciating surface scattering peak (dashed rectangle in (a)), which is typical of crystalline structure with very low lattice defects.

Surface backscattering peak in the dashed rectangle for $^4He^+$ c-RBS spectrum is due to scattering event at the very beginning of crystal surface (i.e. the first atomic planes), where $^4He^+$ have not yet been channeled along crystalline planes. The peak cannot be clearly detected in case of protons probe due to limited depth resolution of protons. The presence of such peak in $^4He^+$ spectrum and the highly reduced scattering yield of aligned crystal for both $^4He^+$ and protons indicate very low concentration of crystal defects at least over the analyzed depth. Further investigation is in progress to obtain quantitative information on crystal defects distribution from c-RBS spectra.

CONCLUSIONS

Newest results on preparation methodology of crystals for channeling are rather encouraging form both morphological and structural standpoints. The crystals for forthcoming experiments in the H8 beam line at CERN-SPS have been built according to this new technique.

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