Highly Bent (110) Ge Crystals for Efficient Steering of Ultrarelativistic Beams

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INTRODUCTION

In a recent experiment De Salvador and co-workers [1,2] studied three different coherent interaction phenomena between a (111) Ge short strip crystal (1.85 mm long) and an ultra-relativistic proton beam: efficiencies of 72.5% and 95.3% for channeling and VR, respectively, were obtained. The planar channeling efficiency for a nonparallel beam was higher than what reported for a similar Si sample and higher than previous experiments on Ge at similar energies.

Though the experimental results presented in the previous paper are very promising and the ensemble of several key factors such as bending device strategy, careful choice of strip size and, most important, optimal crystal quality of the manufactured strip proved to be greatly beneficial for the final performances of the Ge crystal, nevertheless those results are not complete.

In this work, an experimental investigation of channeling and VR phenomena with highly bent, thin (110) Ge strips is presented. In principle, (110) Ge lends itself better than (111) one to channeling, owing to the stronger coherent field generated by lattice atoms and to higher critical angle for incoming particles, as a result of longer inter-planar distance.

EXPERIMENTAL

Ge (110) strips can in principle be obtained by (110) wafers with the same procedures described in ref. [3,4]. On the other hand this particular orientation of Ge wafers is not of large interest for microelectronic applications and therefore much less available on the market.

In order to circumvent this problem, some strips of (110) Ge were produced starting from a <100> Ge wafer (purchased by UMICORE) according to the procedure described in ref. [4].

The ultrarelativistic channelling experiments were performed at the H8 extracted beam line of the SPS accelerator at CERN. A 400 GeV proton beam was used.

RESULTS AND DISCUSSION

Two Ge strips with two different curvature radii of the (110) planes were measured: R_a = 8.2 and 2.3 m. The strips were aligned in order to exploit (110) planar channeling.

Fig. 1 presents the horizontal deflection angle in the case of the crystal with a 2.3 m radius (dashed line) and with a 8.2 m one (continuous line) for particles impinging on the crystal in a spatial range of ± 0.2 mm in the horizontal direction and ± 0.5 mm in the vertical one, with a divergence range of ± 2 μrad in the horizontal direction.

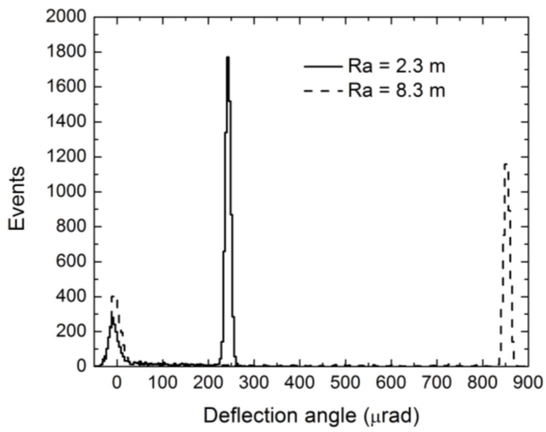

Fig. 1. Deflection angle for the Ge (110) planar channeling condition.

The obtained efficiency and critical angle values for planar channeling cannot be easily compared with pristine previous experimental measurements with Ge crystals given the differences in the experimental setups. For instance, a maximum efficiency of 60% was reported for Ge (110) with a three-point bent 50 mm long crystals for 450 GeV protons with an incoming divergence of 3 μrad. The efficiency measured by Biino et al. [5] was quickly decreasing at increasing curvature radius: at the values used in our experiment (R_a=8.2 m and 2.3 m) the efficiency was about 52% and 13% respectively for the 2 radii. The results herewith reported improve this value: the maximum efficiency is higher than 74% at R_a=8.2 m and decreases to 56% at R_a=2.3 m. This significant efficiency improvement has been most likely obtained thanks to the short crystal bending strategy that we demonstrated to be applicable to Ge crystals. In fact, the shorter crystal reduces the effects of multiple scattering and the homogeneous curvature reduces dechanneling. Moreover our samples present a very low dislocation density reducing the dechanneling sources to those of an ideal crystal.

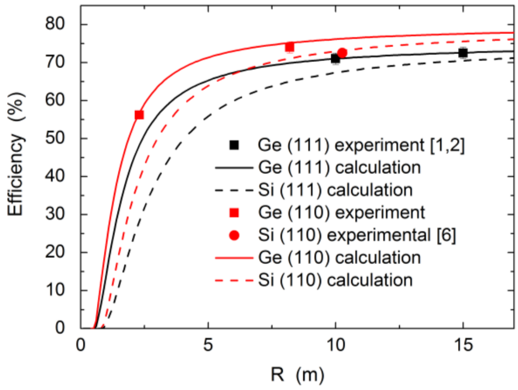

Fig. 2. Planar channeling efficiency versus curvature radius for Ge and Si crystal strips as compared to simulated values. Si datum is from ref. [6], Ge (111) are from reference [1,2] and Ge (110) are from the present work. Simulations are obtained by semi-analytical calculation.

In fig. 2 we report the efficiency results obtained as a function of the curvature radius. The data are compared with existing recent literature data for Ge and Si samples and with the efficiency obtained by semi-analytical calculation, on the basis of Moliere effective potential for (110) planes of Ge with the specific curvature radius. The method will be better described in a forthcoming paper.

A very good agreement between the calculated and evaluated curves is obtained for all the data. This allows to conclude that the calculated curves are accurate extrapolations of the experimental trends at all the curvatures. Moreover, no parameter is introduced in the calculation to correct the data for possible defects neither in Si or in Ge, therefore we can conclude that both Si and Ge performs at the "ideal crystal" limit. The difference between the two kinds of crystals are only due to the difference in the potential shape.

As expected, the deeper well in the Ge crystal allows for the retention of a higher efficiency also at higher curvature (low radius) with respect to Si.

The volume reflection condition was obtained by rotating the goniometric sample holder of a fraction of the bending angle in such a way that the beam becomes tangent to the (110) strip planes in the bulk of the crystal. In this condition data were acquired for both curvatures. The deflection angle is shown in fig. 3 for both curvature radii.

As can be noted, most of the particles are deflected to a negative angle in the opposite direction of the channeling one as typically reported for the VR phenomenon. A small fraction of particles is deflected at positive angles thanks to the volume capture phenomenon: some of the particles, after losing a fraction of their energy by multiple scattering, can be captured by the channel and can continue their path in a curved trajectory. Those particles which complete their trajectories in the bent channel cause the peak at large angles visible for both the curvature radii. Some of the captured particles may undergo dechanneling because of their large oscillating amplitude in the channel; those particles fill the tail that joins the main volume reflection peak to the small volume capture peak in the plot. In order to quantitatively estimate the VR phenomenon, we have fitted the main peaks with gaussian curves, determining the average deflection angles θ_{VR} of (17.3 ± 0.3) μrad and (11.4 ± 0.2) μrad for the larger and smaller curvature radii, respectively. The θ_{VR} values are consistent with theories expressing the present understanding of the VR phenomenon. We also estimated the VR efficiency according to assessed procedures. The obtained values are (96.6 ± 0.9) % and (99.5 ± 0.8) % for the larger and smaller curvature radii, respectively. The very low probability of volume capture at high curvature radius accounts for the exceptionally high efficiency value herein observed.

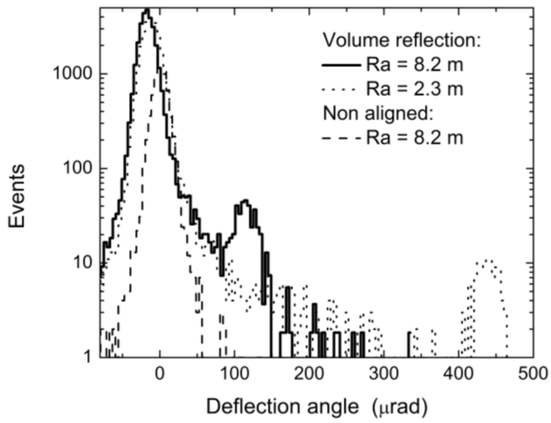

Fig. 3. Horizontal deflection angle in the volume reflection condition. The thick line is relative to R_a=8.2 m, the dotted one to R_a = 2.3 m. Nonaligned beam deflection in the 8.2 m case is reported for comparison (dashed line).

ACKNOWLEDGMENTS

This work was funded by INFN, V^{th} Commission (experiment COHERENT) and by the Ministry of Research and University (PRIN Project 2009).

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