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Further improved technique for channeled stopping power measurements

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ABSTRACT

A few years ago, an ingenious method was proposed to quickly and accurately measure the difference between random and aligned stopping powers without the need for free-standing mono-crystalline thin films; the main idea was to increase the energy of the incident ion beam so that the channel numbers for a characteristic feature in the backscattering spectrum in random and aligned direction coincide, thus compensating for the difference in stopping power endured by the outgoing ions (Greco et al. 2007) [7]. A small drawback of this method is that the total length of the path that the ion travels through the thin film is slightly different in random and aligned geometries. We have improved this method by changing the measurement geometry such that the aligned and random ions travel the exact same distance through the thin film. Representative results for 0.5–3 MeV He ions channeled in <011> Si are presented and show that earlier measurements appear to overestimate slightly the reduction in stopping power for channeled ions.

1. Introduction

Stopping powers need to be known accurately for the conversion of energy loss to depth when thin films are profiled by ion scattering spectrometry methods such as Rutherford Backscattering Spectrometry (RBS) and Elastic Recoil Detection (ERD, or FRES for Forward REcoil Scattering). Precise measurements [1–3] of absolute stopping powers in a thin film require comparison of the energy loss experienced by transmitted energetic ions with the areal density as determined by some other method (weighing or quartz crystal monitor). For practical applications, often the target being analyzed is a single crystal, and ions may be channeled which is known to reduce the stopping power [4–6]. For channeled stopping powers, it is not necessary to measure the stopping power absolutely; instead it suffices to compare the stopping power for channeled and “random” ions in the same film. A few years ago, an ingenious technique was developed to allow accurate comparison of channeled and random stopping powers without the need for free-standing thin films [7].

The drawback of comparing random and channeled stopping powers in a backscattering geometry is that only the incoming ions are channeled, and on their way out (after the backscattering event) suffer an energy loss which depends on their energy and therefore is not identical for the two situations. The technique proposed earlier [7] counters that problem by adjusting the beam energy so that the signals of a buried layer as measured in both random and aligned geometries coincide. The difference in beam energy then exactly makes up the difference in stopping power experienced by the incoming ions. However, in order to change from aligned to random geometry, a 4° tilt is used in two directions around the surface normal. As a result, the path length of the outgoing ions, for a detector angle of 167°, may vary by up to 4%. While small, this may amount to a sizable fraction of the difference between random and channeled stopping powers. Here, we propose a slightly modified technique which avoids the systematic error due to path length difference altogether, while maintaining the other aspects (adjusting beam energy, no free standing film required) of the earlier technique.

2. Improved measurement technique

The modified geometry is illustrated in Fig. 1 and consists simply of measuring along a channel direction other than the one closest to the surface normal. In this figure, the Silicon-On-Insulator thin film of mono-crystalline Si (depicted as an array of circles) on an amorphous SiO_2 layer (shown as a rectangle containing randomly positioned spheres) is supported by a regular Si wafer (not depicted). The arrow coming from the right represents the incoming ion beam which are scattered through $\pi-\varphi$ degrees if

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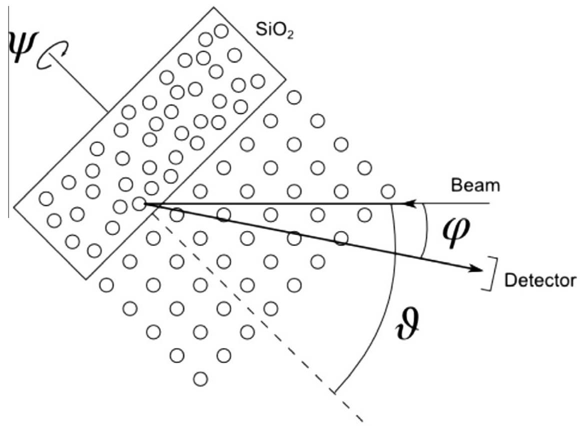

Fig. 1. Measurement geometry. Circles: Si atoms (not to scale) in c-Si overlayer. Rectangle: amorphous SiO_2 layer. Arrows: incident ion beam and scattered ions on their way to the detector. Dashed line: surface normal; the sample can be spun around the normal as indicated by the angle ψ. Dotted lines: off-normal channel direction (e.g., <0 1 1> axes when the surface normal is along <0 0 1>). The incident beam, surface normal and outgoing ions are all in the horizontal plane.

they exit along the arrow pointing to the detector. The angle θ between the surface normal (dashed line) and incident beam is chosen so that channeling can occur if the sample spin angle ψ is such that one of the channeled directions (illustrated as dashed lines) coincides with the incident beam.

In this geometry, the path length of incoming and outgoing ions, for a scattering event at any depth, is independent of the sample spin angle ψ. Care has to be taken that the channel axes do not accidentally coincide with the outgoing ion direction. Measurements in this geometry require a three-axis goniometer which allows the angle ψ to be spun without affecting the angle θ between incident beam and surface normal.

When the accelerator energy is increased in order to match the energy of the outgoing ions that have scattered from the marker (in our case the interface between the SiO_2 and the Si overlayer) in random geometry with those in aligned geometry, we found that the uncertainty on the absolute value of the beam energy as measured by the generating volt meter used to determine the accelerator voltage was significant. We therefore determined the energy difference between the incident ions in random and aligned geometries from the difference in position of the Si surface signal of the random spectrum measured at either energy. This required three spectra: random and aligned at a fixed energy, and random at the increased energy.

3. Experimental results

The improved technique was used to measure the stopping power difference for He ions channeled along <0 1 1> crystal axes in Si at several incident energies between 1 and 3 MeV. Two sets of beam slits, 235 cm apart, defined the ion beam resulting in a beam divergence of <1 mrad (entrance slits nearly closed) to >3 mrad (entrance slits wide open). A silicon-on-insulator (SOI) sample consisting of 135 nm monocrystalline Si on top of 180 nm SiO_2 on top of a Si wafer was measured. Both the substrate and the Si overlayer were <0 0 1> oriented. The detector was positioned at a 170° backscattering angle. The solid angle of detection was 6.6 mSr. After having aligned one of the <0 1 1> axes with the ion beam and having measured the channeled spectrum, the random spectrum was measured. For an initial series of measurements, the random spectrum was measured by changing the spin angle ψ by 7° whereas for a second series of measurements, the spin angle was

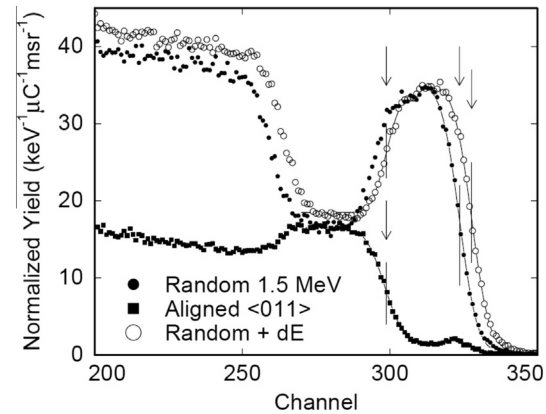

Fig. 2. Random and aligned backscattering spectra of 1.5 MeV He ions incident on a SOI sample. Solid squares: channeled. Solid circles: random spectrum at the same energy. Open circles: random geometry after the energy was increased to match the position of the Si/SiO_2 interface.

continuously varied (“rotating random”). Both series gave results identical within the statistical measurement error. The random spectrum was measured, first at the same energy as the aligned spectrum and then at a beam energy manually adjusted so that the measured position of the SiO_2-Si interface matched that in the aligned spectrum. An example of one such measurement is shown in Fig. 2. In this figure, solid square symbols indicate the counts registered in the channeled direction with 1.5 MeV incident He ions and solid circles indicate the random spectrum at the same energy. The open circles depict the spectrum in random geometry after the energy was increased to match the position of the Si/SiO_2 interface. The arrows and thin vertical lines near channel 300 indicate the half-height position of that interface whereas the arrows near channel 330 show the positions of the half-height of the Si surface channels of the two random spectra. Fig. 3 shows an example of how the difference in energy is obtained. The surface and interface channels are plotted on the x- and y-axis respectively for two channeled spectra and for several random spectra for which the beam energy was gradually increased. A line is fitted through the points for the random data and the energy difference in terms of channels is then given by the difference in surface channel numbers between this line and the value for a channeled spectrum. The uncertainty in the energy of surface peaks and

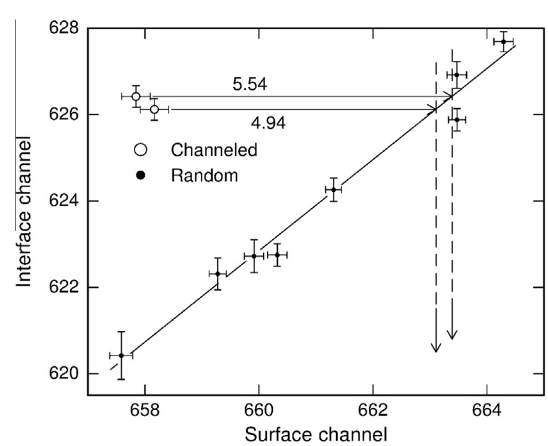

Fig. 3. Interface channel number as a function of surface channel number for two different channeled spectra taken at 2000 keV and random spectra taken at several energies. The solid line is a linear fit through the random spectra points. The energy difference used to calculate the difference in stopping powers is given by the distance between this line and a channeled spectrum point.

Table 1
Measured stopping power difference between random and aligned ions backscattered off the interface between SiO_2 and the monocrystalline Si overlayer, for several incident beam energies.

Incident energy (random; MeV)	0.417	0.518	0.620	0.722	0.905	1.250	2.038	2.541	3.046
Stopping power (eVcm^2/10^{15} at)	63.1	60.4	57.0	55.1	50.9	42.7	24.6	21.7	19.9
Standard deviation (eVcm^2/10^{15} at)	1.9	1.8	1.8	1.7	2.8	1.7	1.1	2.4	3.8
Channeled S_e as % of random S_e	94	89	87	84	72	72	55	54	55

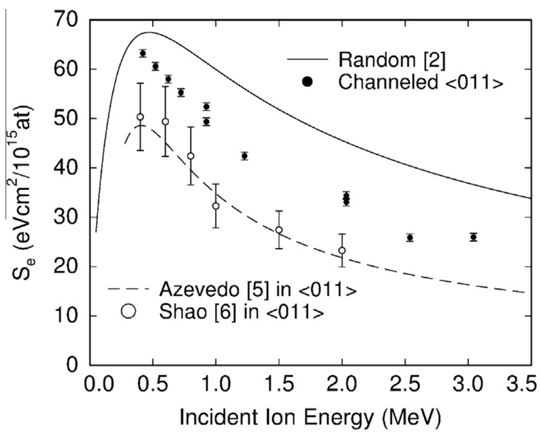

Fig. 4. Stopping power for He in Si, our measurements (solid circles) along <0 1 1> compared to random values (solid curve) and several earlier measurements (open circles and dashed line).

interface position leads to an apparent error of only 0.4–1.2 keV in the difference in stopping between the two samples. However when the measurements were repeated a number of times the standard deviation in these subsequent measurements exceeded those apparent errors. The results are summarized in Table 1 and shown in Fig. 4.

Fig. 4 shows our measurements, together with the random stopping power for He in Si from the literature as well as some earlier results from the literature. Several measurements at each energy were made and the uncertainty in each point is the standard deviation of those measurements, taking into account the uncertainty in each measurement based on the error in the position of the features in each spectrum used to calculate the stopping power differences. Most of the measurements overlayed nicely. We plotted two points for 0.722 MeV and 2.038 MeV where we found disagreeing values. From the position of the points, below the solid curve for random stopping power but above the dashed curve and open circles indicating earlier measurements, it is clear that earlier measurements tended to overestimate somewhat the reduction in stopping power for channeled ions, especially at beam energies below 2 MeV. Since the path of the channeled ions is substantially shorter in our work compared to earlier work (191 nm vs 420 nm), it is unlikely that the reduction is less because of dechanneling when the ions penetrate deeper into the crystal. A direct comparison with earlier measurements using the method developed by Greco et al. cannot be made since they measured along < 1 0 0 > whereas our measurements are along <0 1 1>. One possible reason for a difference in stopping power reduction as measured by different laboratories could be a difference in ion beam divergence. The ion beam normally is defined by two small apertures, separated by a distance of several meters. By varying one of the apertures, one can vary the beam divergence. We have repeated a series of measurements at two different beam divergences (<1 mrad and >5 mrad) and indeed found a small difference, less than 2%. In the light of such a small difference, it seems unlikely that the discrepancy between the measurements reported in the literature and our new results is due to a difference in beam divergence. Recent measurements of the random and channeled stopping powers for He in GaN found an even smaller reduction of only 30% in the energy range 1.7–3.7 MeV [8]. Similarly, a reduction of only (31 ± 5)% of the random stopping power was found at 3.3 MeV using transmission measurements but using much thicker crystals (3.6 μm) [9]. Several calculations of the channeled stopping power of He in <0 1 1> Si have been reported, however the results either over- or underestimate the actual stopping powers, depending on the energy of the incident ions and the interatomic potential as well as calculation method used in the simulations [10].

4. Conclusion

In conclusion, we have improved a recently developed method to measure stopping powers in channeling directions and applied this method to the case of He ion channeled in <0 1 1> Si. These initial measurements show that the reduction in stopping power is slightly less than previously thought and that the uncertainty is indeed reduced.

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