IN-SITU DEPTH PROFILE OF SOLAR WIND HELIUM FROM GENESIS DIAMOND-LIKE CARBON.

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Introduction: NASA's Genesis mission collected samples of solar wind (SW) that can be analyzed with high precision in laboratories with the ultimate goal of determining the composition of the sun and the solar nebula from which it was formed [1]. It is thus important to characterize SW conditions during the collection periods. The SW conditions and compositions have been measured by in-situ spacecraft using the Genesis Ion Monitor (GIM) and the Solar-Wind Ion Composition Spectrometer (SWICS) on the Advanced Composition Explorer (ACE)[2]. Solar wind has also been implanted into Genesis collector materials, chosen to support laboratory analysis [3]. Therefore, physical conditions for the ion implantation of solar wind elements into Genesis collectors are well defined.

A Monte Carlo program, the Transport of Ions in Matter (TRIM), is useful to analyze ion implantation profiles [4]. However, TRIM simulation may overestimate the projected range of ions for low-energy ion implantation less than several keV [5]. Therefore, implantation profiles for low-energy solar wind elements, e.g., H and He, should be carefully evaluated experimentally, using laboratory ion implantation. In this context, depth-profiles from analyses of Genesis collectors document the physics of ion-solid interactions of solar wind: they are initial experiments needed to reveal ancient solar activities recorded by natural samples (from moon, asteroids, etc.).

Helium is the second most abundant element in the solar wind (~4% in atomic) and a minor element in the terrestrial atmosphere (~5 ppm in atomic). So, we can expect that (1) abundant He is implanted in Genesis collectors, and (2) the He implantation profiles observed do not show terrestrial contamination. In fact, the implanted SW He was measured from collectors by conventional mass spectrometry [6, 7]. However, the SW implant profiles are not known because it is difficult to apply conventional methods (e.g., secondary ion mass spectrometry) because of extremely low ionization yields of He [8, 9].

In this study, we used a novel technique – sputtered neutral mass spectrometry (SNMS) using strong-field ionization [10] – to measure He profiles in Genesis collectors, thus revealing the nano-scale depth distribution of SW He. Our instrument can quantify ^{4}He present at 10s ppma analyzing a few-micron sized area of a solid surface. Here we report the first results for a depth profile of SW ^{4}He from a Genesis collector, a diamond-like carbon film on a silicon (DOS) wafer.

Experimental Methods: DOS 60939, a diamond-like-carbon film deposited on a silicon wafer substrate, from the Genesis B/C arrays was used in this study. The B/C arrays collected bulk SW and so were exposed continuously during the science collection period of Genesis (852.83 days) [2, 3].

A SNMS instrument called LIMAS was used [10]. A pulsed primary beam of ^{69}Ga with 30 keV and 30 nA was focused on a sample surface of 800 nm in diameter. The pulse period was set to 200 ns. Sputtered neutrals were ionized by a focused (50 μm in diameter) fs-laser beam under a strong-field ionization condition. The laser pulse was 40 fs with 3.5 mJ and 1 kHz repetition. We accumulated post-ionized ions for 10 000 primary beam pulses at one spot. The primary beam was rastered on the sample with a square pattern of 15 × 15 spots with a step of 500 nm interval. The raster covered an area of 8 × 13 μm^{2} on the surface because the incident angle of the primary beam, formed by the optical axis of the primary beam on the surface and the normal to the surface at the point of incidence, was set to 55° (Fig. 1).

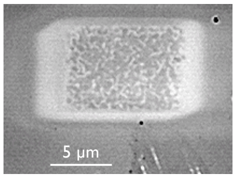

Fig. 1. Sputtering crater on Genesis DOS sample.

Positive ions were introduced into a multi-turn time-of-flight mass spectrometer by an acceleration voltage of -4 kV with 1 kHz repetition synchronized with the primary ion pulses. Only ions generated from the center (2.5 × 4 μm^{2}, 5 × 5 spots) of the sputtered craters were used to determine depth profiles in order to avoid crater edge effects. A flight path length for the mass spectrometer was set to 68 m for ^{4}He^{+}. We measured ^{4}He^{+}, ^{12}C^{3+}, ^{12}C^{2+} and ^{12}C^{+}.

Results and Discussion: Two peaks at m/z = 4 are observed from DOS 60939, corresponding to ^{4}He^{+} and ^{12}C^{3+} (Fig. 2). The mass resolution is calculated to be M/ΔM = 8600 (at 10% valley) with peak width of 5 ns (FWHM). The ^{4}He peak has no interferences under these conditions. A depth profile from DOS 60939 is shown in Fig. 3. Intensities of carbon ions appear constant during the entire analysis indicating stable sputtering rate and stable post ionization. The ^{4}He profiles strongly suggest an ion implant, but the background (~3 × 10^{-4} counts) is high. The background corresponds to a blank of ^{4}He from (1) photo-ionization of residual ^{4}He gas in the vacuum chamber and (2) ^{4}He adsorbed on the sample surface from the residual gas and then sputtered from the surface during measurements. Note that the vacuum in the sample chamber was maintained under ultra-high vacuum (3 × 10^{-8} Pa).

The ^{4}He depth distribution, after background subtraction is shown in Fig. 4. An ion-implanted DOS reference was prepared in the laboratory and used for calibration from intensity to concentration. The distribution has a peak at ~20 nm and the peak concentration is about 2.2 × 10^{20} cm^{-3}. The distribution decreases with depth following an approximately Gaussian. A similar decrease is also observed from the maximum towards the surface before the distribution becomes flat at depths < ~15 nm.

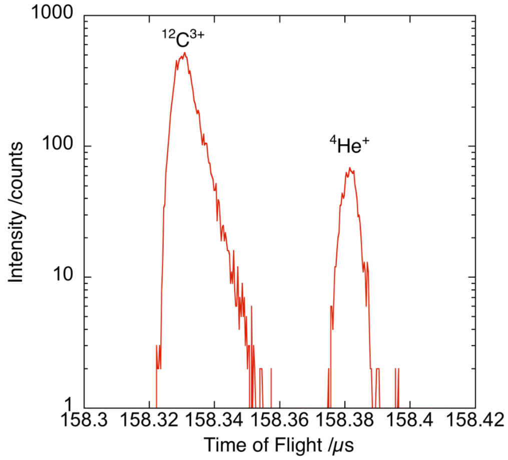

Fig. 2. Mass spectrum at m/z = 4 from Genesis DOS sample.

We simulated the implant profile of Genesis SW ^{4}He by TRIM using data based on the solar wind energy distributions from ACE/SWICS [2]. The simulated distribution reproduces the projection range, the deep portion of the profile, and the absolute concentration at a given depth. This congruence between simulation and observation stops at a depth of ~15 nm. Atom-mixing layers by sputtering of 30 keV ion beam would be 10-20 nm. Indeed, the depth resolution in this study is estimated to about 10-20 nm, consistent with the depth where the data deviates from the model. This demonstrates that the SW energy distribution can be quantitatively derived from implantation distribution of the SW. Therefore, the SW energy distribution can, ideally, be calculated by their depth profiling, and the profiles can be useful for understanding ancient solar activities experienced by natural samples, as well as space weathering evolution of solar system objects.

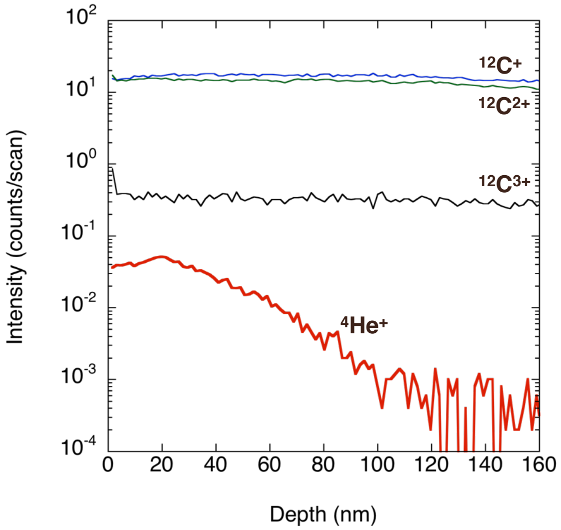

Fig. 3. Depth profile from Genesis DOS sample.

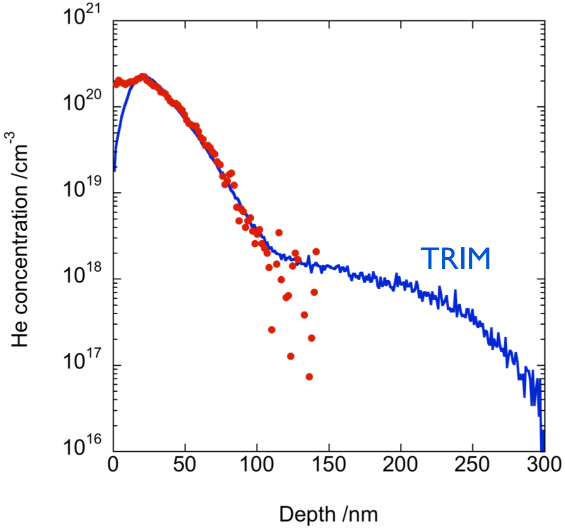

Fig. 4. Depth distribution of solar wind ^{4}He from Genesis DOS sample (circle) with TRIM simulation (line).

References: [1] Burnett, D. S. and Genesis Science Team (2011) *PNAS* 108, 19147-19151. [2] Reisenfeld D. B. et al. (2013) *Space Sci. Rev.* 175, 125-164. [3] Jurewicz A. J. Z. et al. (2003) *Space Sci. Rev.* 105, 535-560. [4] Ziegler J. F. et al. (2013) http://www.srim.org. [5] Nakajima K. et al. (2001) *JJAP* 40, 2119-2122. [6] Heber V. S. et al. (2009) *GCA* 73, 7414–7432. [7] Heber V. S. et al. (2012) *APJ* 759, 121. [8] Warhaut M. et al. (1979) *LPSC Proceedings* 2, 1531-1546. [9] Gnaser H. and Oechsner H. (1991) *Sur. Inter. Anal.* 17, 646–649. [10] Ebata S. et al. (2012) *Sur. Inter. Anal.* 44, 635-640.