TEM CHARACTERIZATION OF SOLAR WIND EFFECTS ON GENESIS MISSION SILICON COLLECTORS.

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Introduction: The Genesis Discovery Mission passively allowed solar wind (SW) to implant into substrates during exposure times up to ~853 days from 2001 to 2004. The spacecraft then returned the SW to Earth for analysis. Substrates included semiconductor wafers (silicon, sapphire, and germanium), as well as a number of thin films supported by either silicon or sapphire wafers [1]. During flight, subsets of the SW collectors were exposed to one of 4 SW regimes: bulk solar wind, coronal hole solar wind (CH, high speed), interstream solar wind (IS, low speed) or coronal mass ejections (CMEs) [2]. Each SW regime had a different composition and range of ion speeds and, during their collection, uniquely changed their host SW collector. This study focuses on bulk vs IS SW effects on CZ silicon.

Why study changes to the matrix of the SW collectors? SW capture changed the surface chemistry and near-surface structure of the Genesis collectors, in ways (and extent) that depend on the matrix. Therefore, depending upon the collector material analyzed, the SW damage may affect the ability to clean the collectors, and may even be a factor in the SW analysis.

Because of the crash landing in UTTR, and even because of spacecraft outgassing, Genesis collector fragments require cleaning before SW analysis. Experience has shown that cleaning procedures optimized on flight-spare materials may not work for the returned collectors. For example, Humayun et al (2011) [3] developed a cleaning technique for silicon-on-sapphire collectors, a thin, ultra-clean silicon film produced by chemical vapor deposition onto a commercial sapphire substrate. Flight spare wafers were successfully cleaned with only a few nanometers of the surface dissolving in the cleaning solution, but when actual flight wafers were cleaned the entire Si layer immediately dissolved.

Physical damage to the silicon single-crystal substrate incurred during SW collection may allow a diffusive redistribution of SW atoms within the crystal structure [4] known as “radiation-induced segregation”. This redistribution has been observed in silicon collectors but not others (e.g., diamond-like carbon films on silicon [5]). The redistribution of SW in the collector is not necessarily gain or loss; however, it suggests spatially variable diffusion coefficients, and there is the *potential* for damage from exposure to space to affect the retention of some elements in some collectors and, perhaps, even from one SW regime to another (see [6] for possible issues for SW Na in Si).

Note that not all of these changes to the matrix create difficulties for the researcher. Paramasivan G. J. *et al.* (2018) [7] investigates using the implanted SW H to monitor the cleaning of the collector surface of silicon.

Results:

This work, an extension of our previous work, [8], uses TEM to directly observe changes in lattice structure within the zone of solar wind collection.

Fig. 1 shows a HRTEM section of CZ silicon implanted with low speed (IS) solar wind. In comparison to Fig. 2 bulk SW sample, the low speed SW sample is missing the deeper bulk lattice strain but still has an

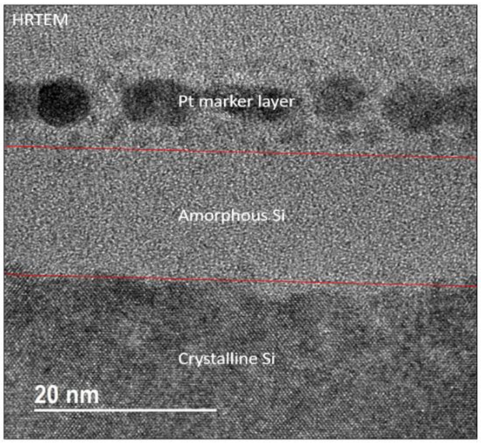

Fig. 1 20662 SI-CZ Low-speed SW, showing amorphous layer and no bulk lattice strain.

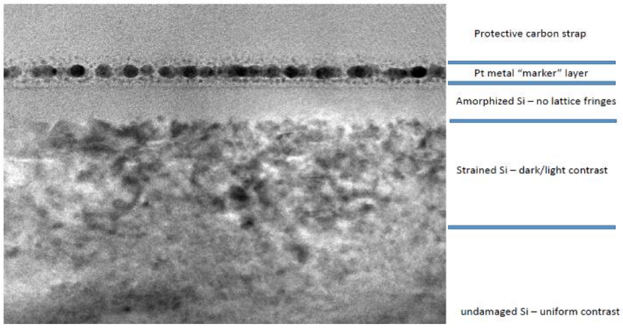

Fig. 2. 61202 Si-CZ bulk SW, showing amorphous layer and strained lattice.

a-Si layer that is approximately the same thickness as the bulk SW sample. Fig. 3 shows the H and He implant profiles for the low-speed and bulk SW which in part explains the lack of deeper bulk defects in the low speed SW sample.

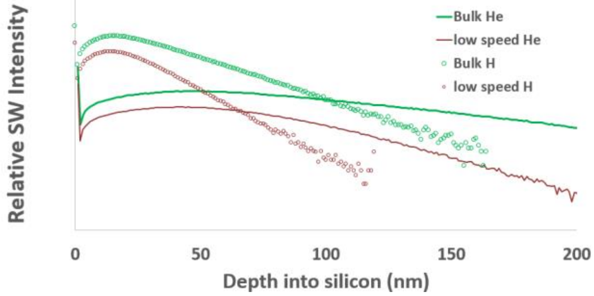

Fig. 3. H and He implant profiles into silicon calculated using the SRIM program [9] and SW distributions from spacecraft data. Relative intensities from [10] and [2].

Discussion: The low speed SW H and He in Fig. 3. has lower total ions, but these are packed more closely to the surface, consistent with the lack of deeper bulk defects observed in the low speed SW TEM sample. SW He ions also contribute to the deeper bulk SW lattice strain effects and they are significantly higher in concentration at depth than the low speed SW He ions. SW ions heavier than He are also present and may damage the lattice, but these ions exist in trace amounts.

Fig. 4 shows that the SW ion distribution is a good proxy for the damage made during implantation of SW. From a diffusion point of view, there is significant damage at depth, making diffusion into the collector faster and allowing for dissipation of the excess energy in the crystal caused by the implant. For the low-speed SW sample, the deep crystal is relatively pristine, and it would be more difficult for the SW H to diffuse to the depths of the collector. Accordingly, even though there is more damage at the peak position of the bulk SW sample, there are also more places for the H to dissipate quickly than there are for the low-speed SW sample.

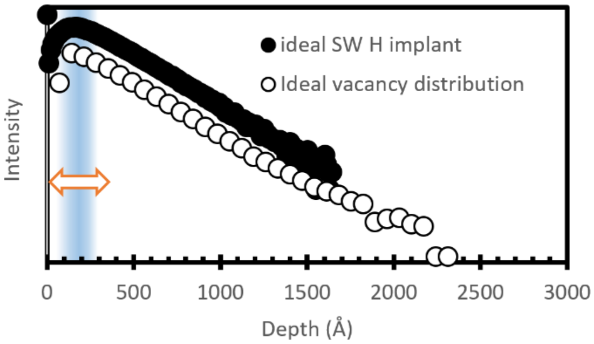

Fig. 4. Shapes (intensities not to scale) of bulk solar wind and the vacancies that would form as calculated by SRIM. SRIM assumes an undamaged matrix for each incoming ion and no movement with time. While good for diamond-like carbon collectors [x,y] because the movement of the SW is negligible after collection, the SRIM model is not completely accurate for all the Genesis SW collectors. Markers in legend. Blue graded region marks peak damage. Double arrow marks center of peak H damage and directions of movement for vacancies to attain a lower energy state.

This observation allows us to make some estimates for what we will see in future TEM samples using the SRIM curves for the high-speed and CME SW (not shown). It will be interesting to see if these future TEM sections have an amorphous silicon layer or simply damage to the lattice. Although the SW H peak is deeper in Si, the fluence is less and the He is not as deep as it is for the bulk SW. The CME SW contains proportionally more He than the other regimes (e.g. ratio of He/H of 0.0478 in CME vs. 0.0391 in bulk [2]) and is higher in energy. So, we expect to see damage at a depth similar to the bulk SW in the TEM sample, but may not see an amorphous silicon layer at the surface, since the low-speed SW component was minimized in the CME sample.

Conclusions: The solar wind affects the matrix of the silicon collectors; moreover that effect is different among the SW regimes. The physical and chemical changes need to be documented and characterized in order for Genesis researchers to get the best SW analyses most efficiently from their allocated samples. These TEM sections are a first step to that goal.

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