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Superior Imaging Quality of Scanning Helium-Ion Microscopy: a Look at Beam-Sample Interactions

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Scanning Helium-Ion Microscopy (SHIM) offers high-resolution imaging at the sub-nanometer scale. SHIM is characterized by the high brightness of its ion source, its high secondary electron yield as well as the deep penetration of He^+ ions. However, studies thus far have not placed sufficient emphasis on the reasons for such behavior or on the energy-dependence of SHIM resolution. In this presentation, we will provide new understandings on these questions by investigating the characteristics of the beam-sample interaction involved in SHIM, and compare it with those of Scanning Electron Microscopy (SEM) and Scanning Gallium Ion Microscopy (SGIM).

The collisions between ions and sample atoms can be statistically treated as two independent types of events: electronic collisions and nuclear collisions [1]. In an electronic collision, the ion is said to scatter inelastically from the atom, exciting a secondary electron (SE) in the sample atom and losing energy in the process, but maintaining its original direction since its mass is much larger than the electron mass. In a nuclear collision, the ion scatters elastically without exciting any electrons. Here we define the interaction radius R as the radius inside of which secondary electrons escape the solid, centered at the position of the incident beam.

The qualitative behavior of a helium ion beam in a solid is simulated in Figure 1, which was obtained using the *SRIM* software developed by J. Ziegler. The cross-sections of SEM and SGIM beams are also shown for comparison. As the He^+ beam initially enters the sample with high energy, it experiences mainly electronic collisions, generating multiple secondary electrons along the way while maintaining its direction quasi-perfectly without scattering: we call this the 'electronic loss phase'. Only much deeper in the solid do the He^+ ions enter a 'nuclear loss phase', in which they experience predominantly nuclear collisions and scatter at increasingly large angles within the solid. In comparison, for SGIM there is no electronic loss phase because the beam broadens immediately upon entering the solid. And for SEM at 30 keV in Fig. 1c, the electrons penetrate and scatter far more easily than either helium or gallium ions, so the interaction radius of SEM is also much larger than for SHIM.

This behavior is explained by a theoretical description of stopping power given by Bethe-Bloch and LSS theory [3]. We find that the imaging quality of SHIM can be optimized significantly by increasing the incident beam energy: R is reduced by roughly 40-50 % if the energy is doubled from 30 keV to 60 keV, as shown in Figure 2. This is consistent with the decrease in the stopping power ratio S_n/S_e as E increases. In contrast, the opposite trend holds for electrons and gallium ions in most solids [4].

It is becoming increasingly clear that SHIM technology represents a substantial advance in the field of high-resolution microscopy, and offers many promises for scientists in a variety of applications. The analysis in this presentation explains the high spatial resolution of SHIM in comparison with existing techniques. We speculate that application of SHIM to transmission microscopes through a very thin sample would be especially advantageous given the deeply-penetrating properties of helium ions at high energy[5].

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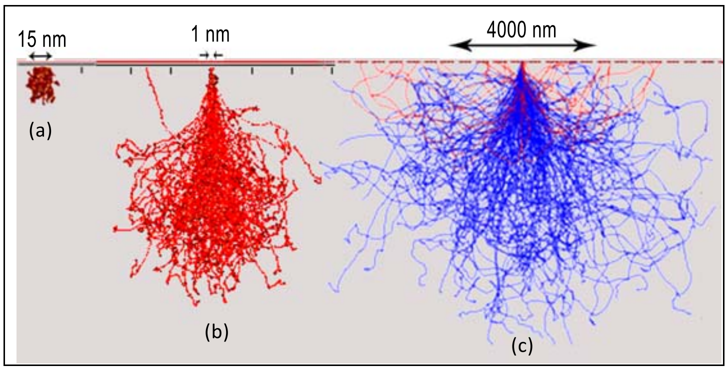

FIG. 1. Comparison of interaction volumes for SHIM (b), SGIM (a) and SEM (c) in a Si sample. The interaction volume of SHIM is sharply peaked at the incoming point, allowing for a significantly smaller interaction radius than SGIM or SEM. In all three cases, the beam enters at the top of the figure and is simulated with zero-width and 30 keV. (The SEM result is not to scale because of its significantly larger interaction volume)

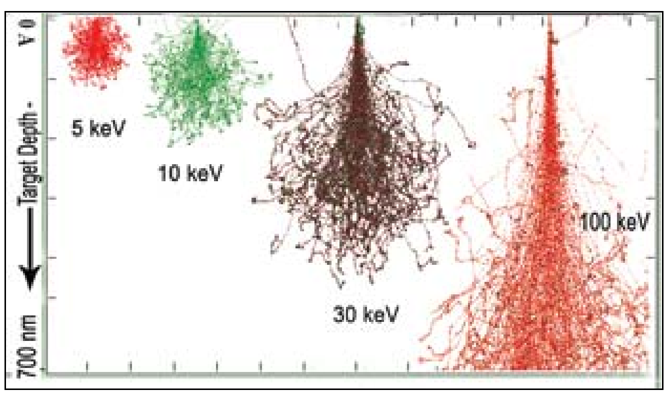

FIG. 2. Interaction volume of SHIM in Si for E=5 keV, 10 keV, 30 keV and 100 keV. As *E* is increased, the penetration depth increases but the interaction radius R becomes smaller.

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