**Introduction**

In the past decades, experiments performed in linear helium-containing plasma devices indicate that a fiber form nanostructure, so-called “fuzz”, is generated on tungsten surface under certain conditions: the surface temperature is from 1000 to 2000K and the incident ion energy is higher than 30 eV. The diameter of each tendril is roughly 10-50 nm and up to micron in length. The nanorods structure dramatically change the tungsten morphology which leads to the decrease of optical reflectivity and thermal conductivity by several orders of magnitudes. It also can cause the enhancement of tritium retention and tungsten release. In addition, the unipolar arc on the tungsten fuzz surface is easily ignited in response to the pulse irradiation.

**SURO-fuzz Model**

Fig. 1. The schematic view of 3D KMC simulation. The light blue, dark blue and black cells represent vacuum, tungsten and helium bubble, respectively. (a) Penetration and reflection of helium particles at the tungsten surface and migration and agglomeration in the tungsten substrate. (b) Bubble growth and resulting surface lifted. (c) He atoms escape from the simulation and W fraction migration after helium bubble rupture

The size of the simulation box is 251.3*251.3*251.3nm. The height of the tungsten material, which locate at the bottom of the simulation box, is 175nm for enough space of helium atoms migration. The simulation box is divided into 50*50*50 cells with the periodic boundary conditions in x- and y-directions. In z-direction, the free surface is set for the fuzz layer growth at the top of substrate and the bottom is the absorbed boundary.

**Simulation Results**

Fig. 2. The cross section view of tungsten surface evolution as a function of helium fluences from $8.14 \times 10^{17}$m$^{-2}$ to $3.42 \times 10^{18}$m$^{-2}$.

At the initial stage in figure 2 (a), the tungsten surface does not modified by helium implantation. The helium atoms are seemed as seeds of bubble formation. This is the period of incubation. As the helium fluence increases, bubbles and blisters form near the surface. The surface starts to be protruded by the growth of the helium bubbles. Finally, the rupture of the helium bubbles leads to a dramatical change of the morphology of tungsten surface.

**Fig. 3.** Two adjacent cross section of tungsten surface morphology. The dash lines between (a) and (b) show the connection of both fibers and defects in y-direction. (c) Top view of two connected fiber in (a) and (b).

The dashed lines between figure 3 (a) and (b) show the connection of fibers and defects in y-direction. Especially, the top view of fiber (I) and (II) is amplified in figure 3 (c). These two fibers are connected in both x- and y-directions. In conclusion, the growth of tungsten fuzz in the SURO-FUZZ simulation is in 3D scale.

**Fig. 4.** Fuzz layer thickness as a function of square root of time, at the substrate temperature of 1120 K.

It can be seen that, the growth rate of fuzz layer thickness follows square root of time dependence, which in an agreement with the experimental observations. The duration of time step in our simulation is only influenced by diffusion coefficient. Thus, the diffusion coefficient can be a dominance factor in the process of fuzz growth.

**Fig. 4.** The retention ratio of particles on fuzzy surface when that on smooth surface equals 1/3.

Two kinds of retention mechanism are used:

\[ P = 1 - \frac{1}{1 + f} \]

\[ f \text{ is reflection probability,} \]
\[ N \text{ is the reflection times,} \]
\[ f \text{ is a factor to adjust the reflection probability} \]

When \( f = 2 \), the reflection rate on fuzzy surface is 51.1% lower in comparison with smooth surface, which consist with the experimental result:

<table>
<thead>
<tr>
<th>$f=1$</th>
<th>$f=2$</th>
<th>$f=3$</th>
<th>$f=4$</th>
<th>$f=5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45.2%</td>
<td>51.1%</td>
<td>55.0%</td>
<td>58.0%</td>
<td>60.0%</td>
</tr>
</tbody>
</table>

The formula for reflection probability only suitable when \( f \) is smaller than 4. The probability which depends on the incident ion energy and angular distribution is needed to be found.

**Summary**

In this study, the surface evolution of tungsten fuzzy nanostructure on tungsten surface under the helium bombardment is investigated by a 3D kinetic Monte Carlo code called SURO-FUZZ. The SURO-FUZZ simulations are in the micron- and second-scale, which approaches to the experimental observation. The evolution of tungsten surface morphology against the helium fluence can well reproduce the formation process of tungsten nanostructure. Further, the thickness of fuzz layer shows a dependence on the exposure time, which also was observed in the experiment.

**Fiber form nanostructure of tungsten surface morphology, called “fuzz”, which degrades the performance of tungsten material, has been observed on both linear tokamak and stellarator. A three-dimensional (3D) kinetic Monte Carlo (KMC) code, SURO-FUZZ has been developed to investigate the formation of fuzzy nanostructure in micro- and second-scales. The time evolution of fuzz morphology under Helium bombardment is studied by SURO-FUZZ. The growth rate of tungsten fuzz shows a good agreement with the experimental results.**