

Surface removal of copper thin film under the ultrathin water environment for nanoscale process

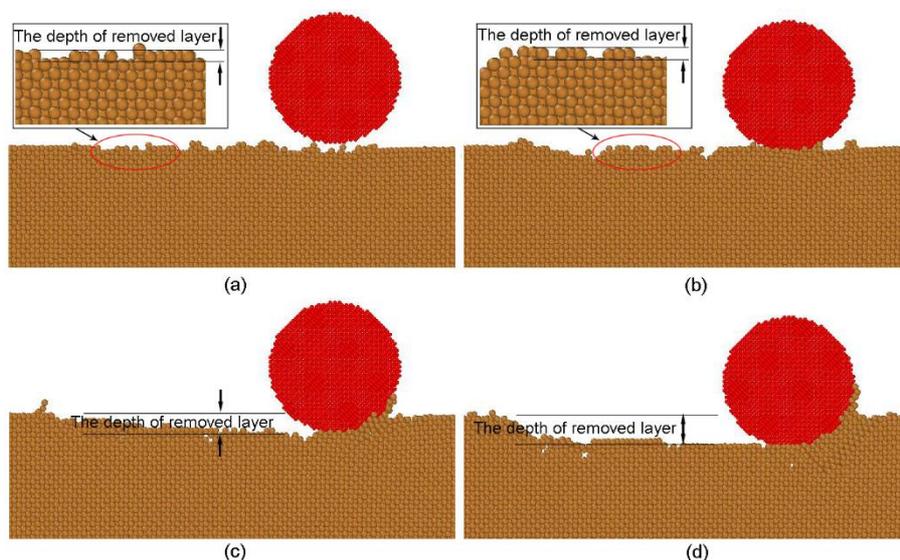


Figure S1 Snapshots of worn morphology of the slice (with 0.5 nm thickness) of xz plane under various scratching depth (h): (a) -0.2 nm, (b) 0.1 nm, (c) 0.5 nm, and (d) 1.0 nm, at a scratching distance of 9 nm, for the nanoscratching with water film of 1.0 nm thickness.

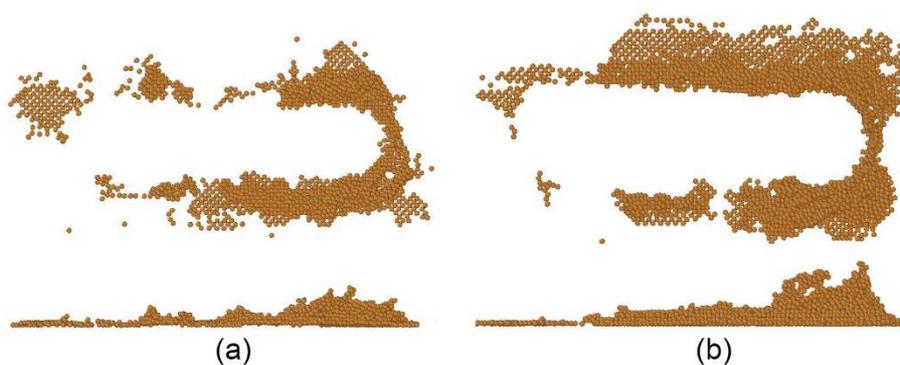


Figure S2 Snapshots of ridge morphology for nanoscratching with water film thickness of 1.0 nm at scratching depth of (a) 0.5 nm and (b) 1.0 nm.

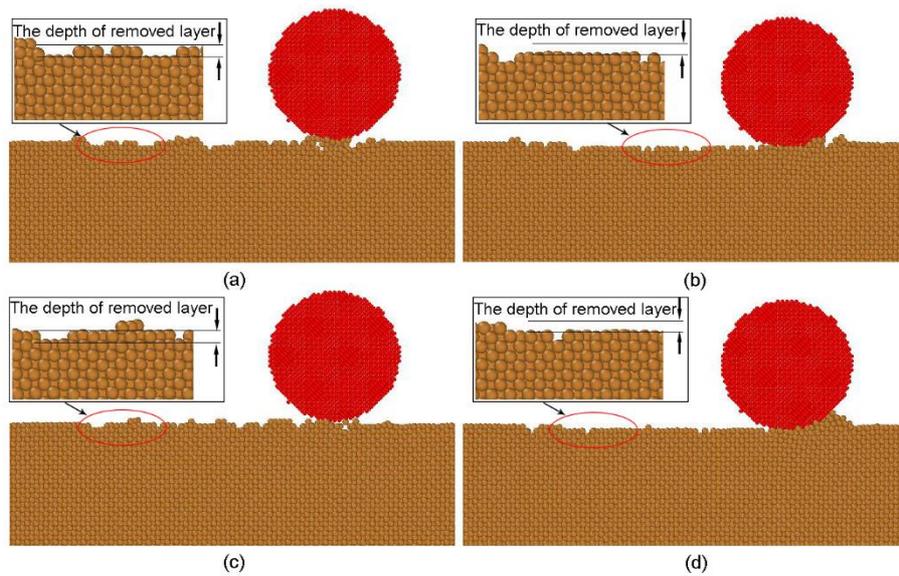


Figure S3 Snapshots of worn morphology of the cross-sectional views of xz plane with omission of water film, under various water film thickness (H) and scratching depth (h), $H=0.3$ nm: (a) $h=-0.2$ nm, (b) $h=0.1$ nm; $H=0.5$ nm: (c) $h=-0.2$ nm, (d) $h=0.1$ nm.

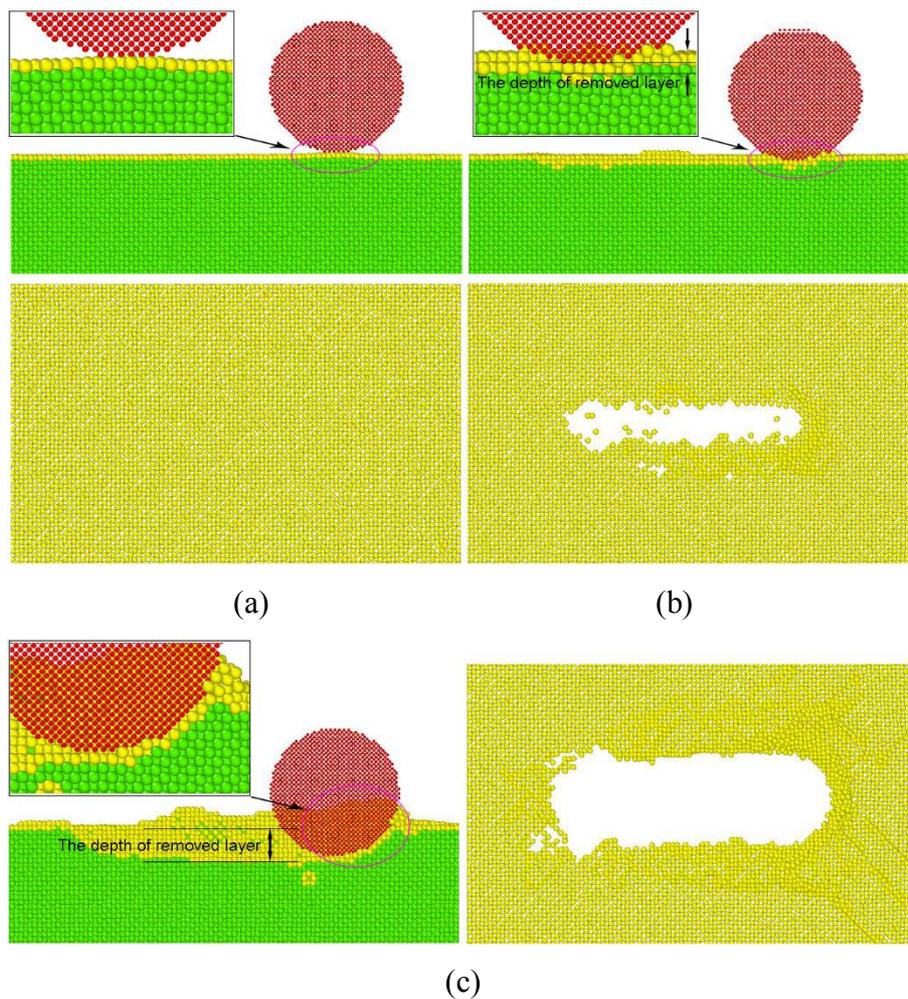


Figure S4 Snapshots of worn morphology of the cross-sectional views of xz plane and

the plane views of xy plane under various scratching depth (h): (a) -0.2 nm, (b) 0.1 nm, and (c) 1.0 nm, at a scratching distance of 9 nm, for the dry nanoscratching process.

Yellow and green represent the initial surface Cu atoms and other Cu atoms, red represents the abrasive particle.

For the dry nanoscratching, Fig S4(a) and S4(b) show that the monoatomic layer removal occurred at scratching depth of 0.1 nm, whereas the Cu surface still maintained its perfect lattice structure at scratching depth of -0.2 nm.

With the scratching depth increasing to 1.0 nm in Fig. S4(c), the abrasive particle contacted with Cu atoms and resulted in large removed zone, and almost all of the surface Cu atoms contacting with particle were removed during scratching process. As the particle moved forward, a large number of deformed atoms accumulated to form clusters or chips ahead of the particle, and meanwhile, the remarkable ridges along both the left and right sides of particle were produced. After the particle passed by, a groove was formed.