

# Surface Roughness Limit for Super-Machined Mirrors Measured with Scanning Probe Microscopy

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Atomic surface roughness<sup>1</sup> is known as the roughness limit of a surface in the field of precision engineering, which is a target for ultra-precision machining or optical film fabrication. For example, atomic layer epitaxy (ALE) for various single crystals has been extensively studied<sup>2-4</sup> and applied to the fabrication of X-ray multilayer structures<sup>5</sup> in order to realize atomic interfacial roughness (the roughness limit) as well as high reflectance. Surface roughness is an important parameter in assessing the quality of high performance X-ray imaging optics, as a measure of topographic relief. Scanning probe microscope techniques have been desirable to perform experiments on surface roughness measurements, which had shown to correlate with the roughness affecting the X-ray reflectance and X-ray scattering.<sup>6</sup> Further, these methods offer the possibility of direct real-space determination of the atomic structure in three dimensions.

Fig. 1 shows the inter-atomic interaction for AFM, where  $\lambda$  is inter-atomic and inter-ionic spacing and  $r$  is the radius of the surface atom or ion. Based on the geometric model of atomic topography, we calculated a series of atomic surface roughness for pure metal crystals, shown in Fig. 2. The three-dimensional rms atomic surface roughnesses for pure metal crystals are between 0.28 Å and 0.68 Å. Table 1 shows the calculated surface roughness limits of the materials often used in X-ray multilayer fabrication.

The present work focuses on not only in above theoretical calculation but also in experimental measurements with scanning probe microscopy. We experimentally measured a muscovite at the atomic scale with the scanning probe microscope techniques as shown in Fig. 3. The nearly hexagonal array of light spots in the image corresponds to holes in the center of hexagonal rings of K<sup>+</sup> ions in the muscovite cleavage planes. The light spot rings are separated by approximately  $\sim 5.2$  Å that is characteristic of cleaved muscovite in which the K<sup>+</sup> ions are left on lower hexagonal sheet. The three-dimensional root-mean-square (rms) roughness  $\sigma$  and

arithmetical mean deviation roughness  $R_a$  are 0.25 Å and 0.20 Å, respectively, while the theoretical  $R_a$  is 0.35 Å and  $R_a$  is 0.28 Å.

Furthermore, we also measured the mirror surfaces generated by polishing, grinding and diamond turning techniques. The scaling surface roughness was measured on selected super-machined mirrors with scanning probe microscopy, shown in Fig. 4. The AFM maps of precision ground BK-7 glass and diamond turned nickel are shown in Figs. 5 and 6, respectively. From Figs. 3, 5 and 6, we can understand well the gap between the atomic level surface and the current super-machined mirror surfaces.

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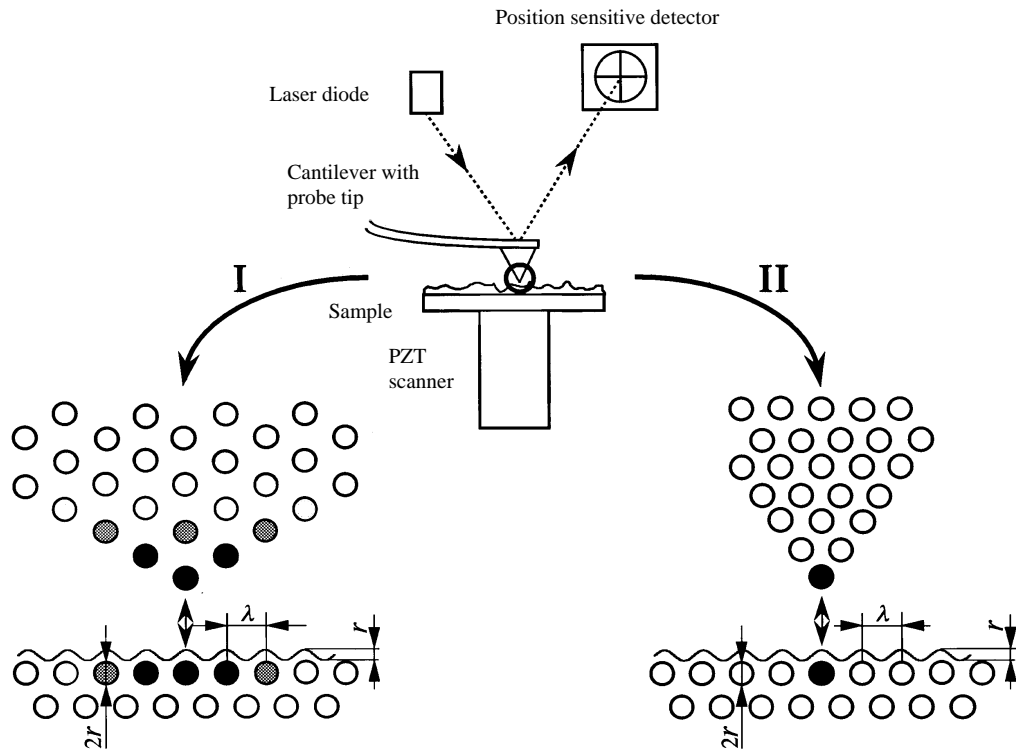


Fig. 1 Schematic illustration of inter-atomic interaction for AFM.

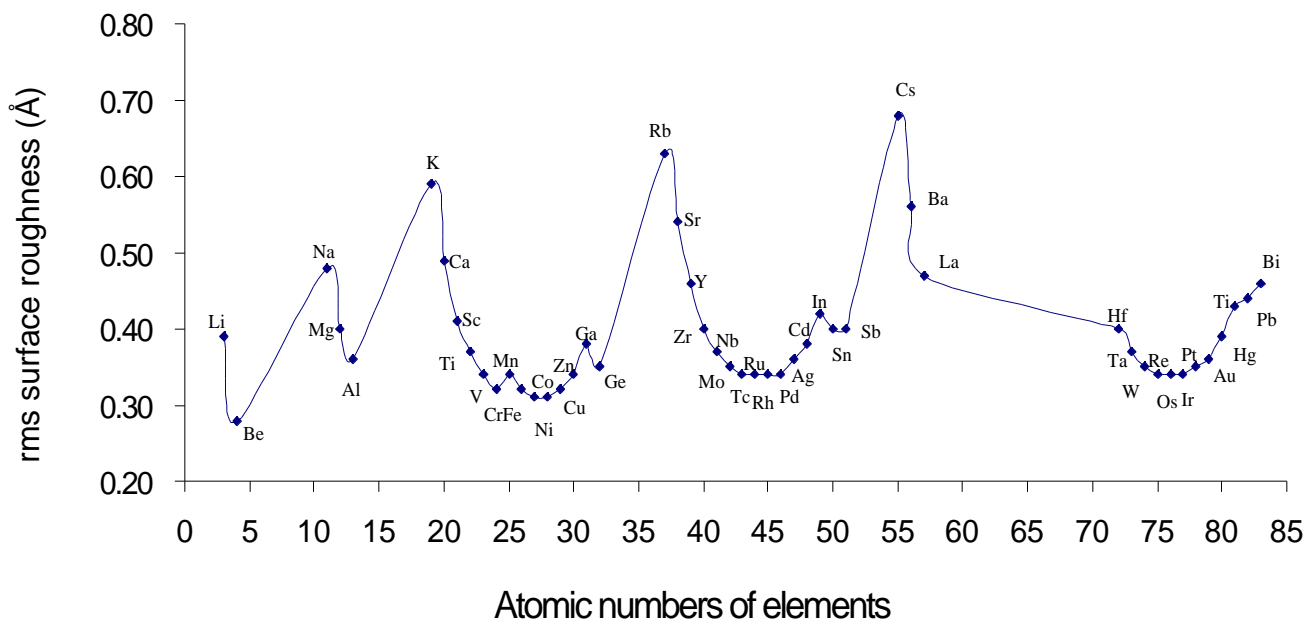


Fig. 2 Three-dimensional rms atomic surface roughness for pure metal crystals.

Table 1 Three-dimensional rms atomic surface roughness (in Å) for materials commonly used in X-ray multilayer fabrication.

Be (4) <sup>a</sup>	Fe (26)	Co (27)	Ni (28)	Mo (42)	Ru (44)	Rh (45)	Pd (46)	W (74)	Re (75)	Pt (78)	Au (79)
0.28	0.32	0.31	0.31	0.35	0.34	0.34	0.34	0.35	0.34	0.35	0.36
Be <sup>2+</sup>	B <sup>3+</sup>	C <sup>4+</sup>	Si <sup>4+</sup>	Fe <sup>2+</sup>	Co <sup>2+</sup>	Ni <sup>2+</sup>	Mo <sup>4+</sup>	Pd <sup>2+</sup>	W <sup>6+</sup>	Re <sup>4+</sup>	
0.04 (3) <sup>b</sup>	0.03 (4)	0.02 (3)	0.07 (4)	0.16 (4)	0.19 (6)	0.14 (4)	0.16 (6)	0.16 (4)	0.11 (4)	0.16 (6)	
0.07 (4)	0.07 (6)	0.04 (4)	0.10 (6)	0.20 (6)	0.23 (8)	0.17 (6)		0.22 (6)	0.13 (5)		
0.11 (6)		0.04 (6)		0.23 (8)					0.15 (6)		
				Fe <sup>3+</sup>			Mo <sup>6+</sup>		Re <sup>7+</sup>		
				0.16 (6)			0.10 (4)		0.10 (4)		
				0.20 (8)			0.15 (6)		0.13 (6)		

<sup>a</sup> Numbers in parentheses are the atomic numbers of elements.

<sup>b</sup> Numbers in parentheses are coordination numbers of ions.

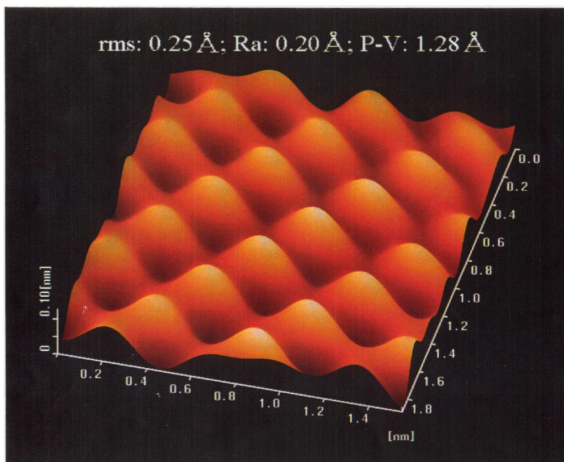


Fig. 3 AFM image of muscovite.

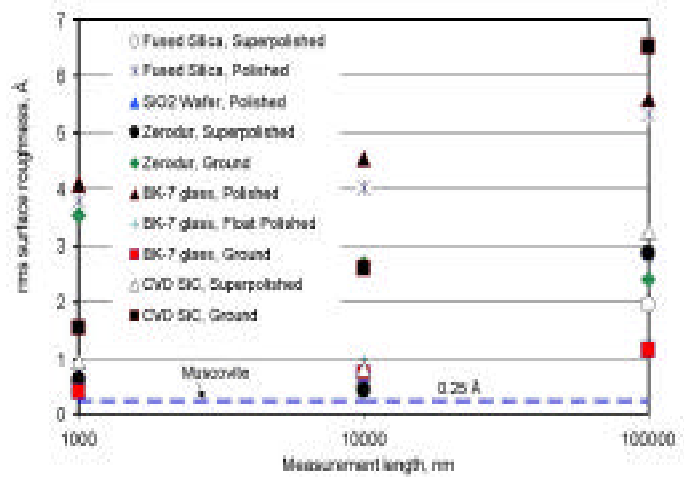


Fig. 4 Roughness of super-machined surfaces.

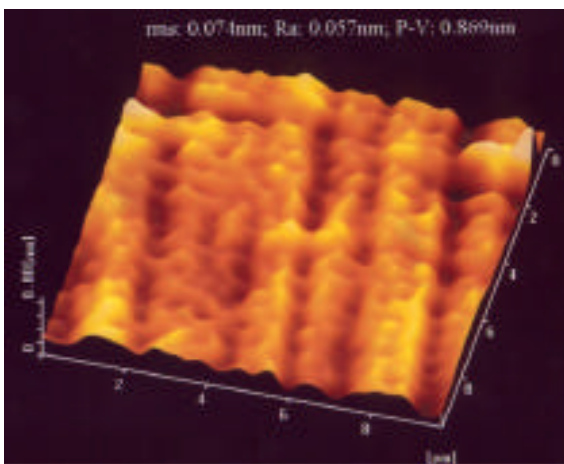


Fig. 5 AFM image of ground BK7 glass.

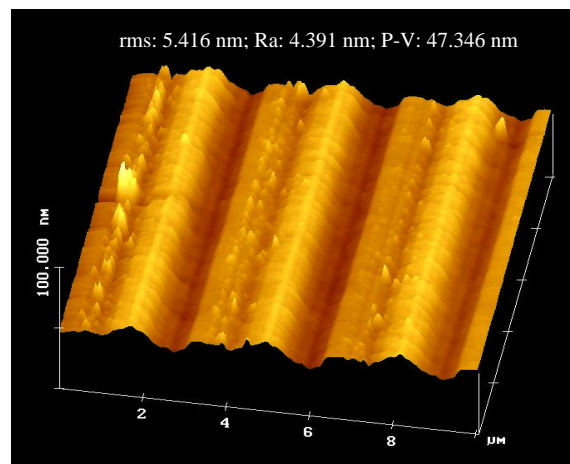


Fig. 6 AFM image of diamond-turned nickel.