Metallic Thin Films for MEMS/NEMS Applications

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Metallic thin films have been considered as potential structural materials for some MEMS/NEMS device applications where their significantly higher electrical conductivity and ductility relative to silicon, oxide or nitride systems are extremely advantageous. Unfortunately polycrystalline metallic films exhibit low strength and hardness, high surface roughness, and significant residual stress making them unusable for these applications. In this presentation we report on synthesis and characterization of amorphous and amorphous-nanocrystalline metallic alloys that overcome these barriers. These alloys are also fairly chemically simple, making them compatible with the usual NEMS/MEMS fabrication routes such as chemical etching and release.

Figure 1 shows a series of cross sectional TEM bright-field micrographs of the Al samples containing 0, 8, 32 and 50at%Mo. All four images are taken at an identical magnification. Figure 1A shows the standard columnar microstructure of pure Al films. The majority of the grains nucleates at the substrate and grow all the way to the surface. The average surface grain diameter, as obtained by AFM, was about 380 nm. Figure 1B shows that the growth mode of $Al_{92}Mo_8$ films is distinctly different from that of pure Al. Although the initial nucleation density at the Si interface is extremely high, most grains do not grow all the way to the surface and are subsumed by either faster-growing or re-nucleated grains. The average surface grain size of 162 nm is less than half of that in the pure Al films. The increase of grain diameters with film thickness is described by the van der Drift model [1]. Figure 1C shows a cross section of the $Al_{68}Mo_{32}$ film. The film surface is remarkably smooth, characteristic of sputtered amorphous films [2]. The Mo phase, demonstrated to be present in the diffraction pattern, is not visible under bright field conditions. Further investigation revealed that the $Al_{68}Mo_{32}$ microstructure consisted of nanocrystalline Mo islands densely and randomly dispersed in an amorphous Al-rich matrix. Figure 1D shows a cross section of the $Al_{50}Mo_{50}$ sample. Here the microstructure is again crystalline, similar to that of the 8at% sample, showing a high nucleation density at the substrate interface and significant roughness at the film surface. Careful analysis provided no evidence for the crystalline intermetallic equilibrium phases or non-equilibrium amorphous phases. The microstructure of the $Al_{68}Mo_{32}$ film was strikingly different from that of the other alloy compositions. To elucidate the morphology of the Al-Mo compositions with extremely fine structure we have performed high resolution transmission electron microscopy (HRTEM). Figure 2(A) and (B) shows HRTEM micrographs of the $Al_{84}Mo_{16}$ and $Al_{68}Mo_{32}$ films in cross-section, respectively. The structure of $Al_{84}Mo_{16}$ film is composed of nanoscale FCC crystallites embedded in a continuous amorphous matrix, while the structure of the $Al_{68}Mo_{32}$ film is essentially completely amorphous with a small fraction of ordered BCC domains.

A systematic investigation of microstructure and properties as a function of Mo content resulted in an optimum film composition of $Al_{68}Mo_{32}$ with a unique microstructure comprised of a dense distribution of nm-scale Mo crystallites dispersed in an amorphous Al-rich matrix. These films were found to exhibit unusually high nanoindentation hardness (Figure 3A) and a very significant reduction in roughness (Figure 3B) compared to pure Al,

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while maintaining resistivity in the metallic range. A single-anchored cantilever 5 µm long, 800 nm wide and 20 nm thick showed a resonance frequency of 608 kHz (Figure 3C), yielding a Young's modulus of 112 GPa, in good agreement with a reduced modulus of 138 GPa measured by nanoindentation. We have fabricated fully released NEMS cantilevers (Figure 3D) of various geometries from these films. At 4.3 and 20.0 nm thickness, these are the thinnest released metal cantilevers reported in the literature to date [3].

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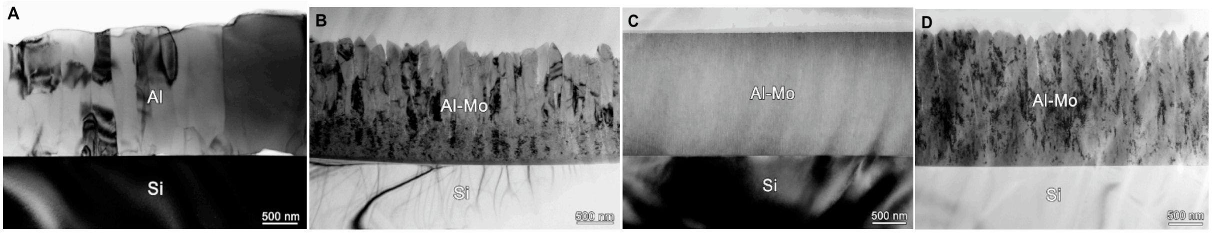

Figure 1. Cross-sectional bright-field TEM micrographs of (A) pure Al, (B) $Al_{92}Mo_8$, (C) $Al_{68}Mo_{32}$ and (D) $Al_{45}Mo_{55}$ thin films.

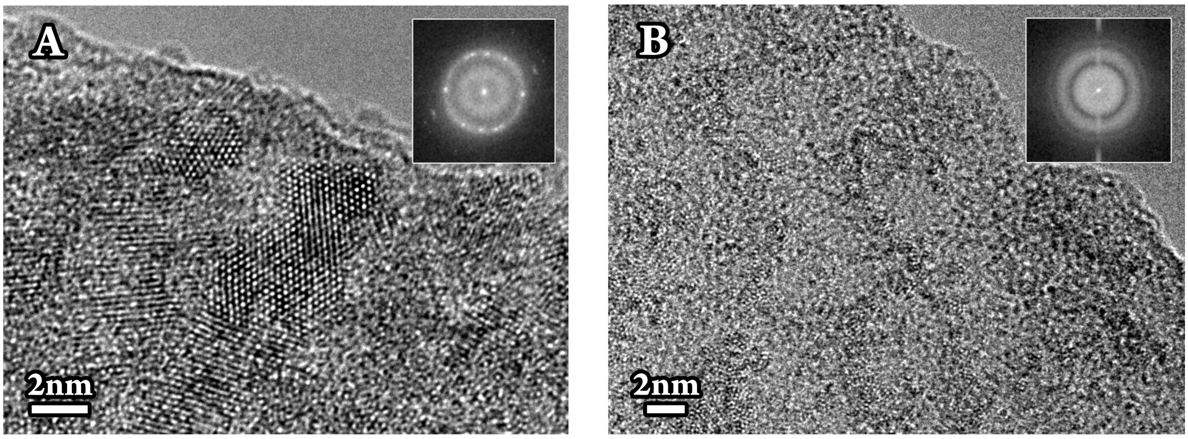

Figure 2. HRTEM micrographs of (A) $Al_{84}Mo_{16}$ and (B) $Al_{68}Mo_{32}$ thin films in cross section. FFTs inset into images.

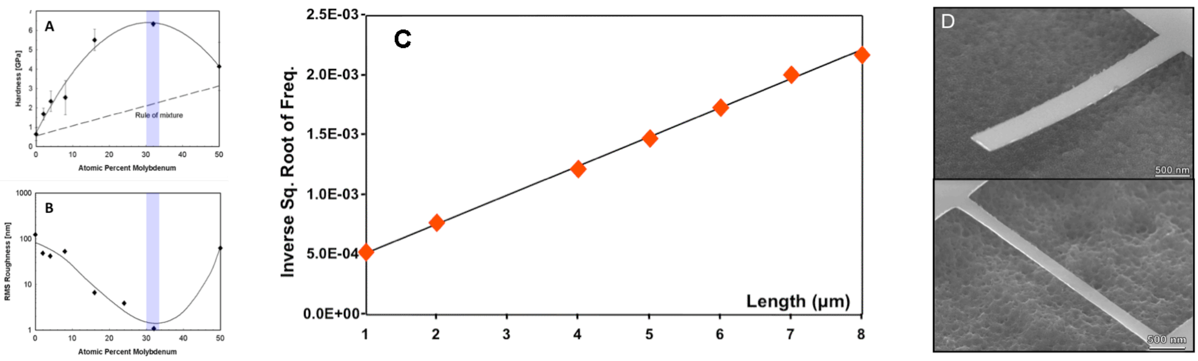

Figure 3. Hardness (A) and surface roughness (B) as a function of Mo content; (C)Inverse square root of frequency as a function of a cantilever length; (D) Single and double clamped devices.

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