Ru epitaxy on differently oriented sapphire substrates for advanced interconnect applications

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Ruthenium is emerging as a promising alternative to Cu for advanced interconnects in future semiconductor technology. The traditional use of Cu in interconnects has faced significant challenges as device dimensions continue to shrink. These challenges include increased resistivity at smaller line widths due to surface and grain boundary scattering, and degraded electromigration performance, which collectively impact the reliability and performance of Cu-based metallization [1,2].

Ru offers several advantages over Cu, leading to lower line resistances. Ru can provide similar or lower resistivity at reduced dimensions, due to its shorter mean free path compared to Cu. Moreover, Ru's ability to maintain reliability without the need for diffusion barriers and adhesion liners allows for a larger metallization volume, further reducing line resistance [1,2].

Recent studies have shown that epitaxial single-crystal Ru films can exhibit low resistivity, close to the bulk resistivity, even at thin film thicknesses [3,4]. The measured resistivities indicate that single-crystal Ru can outperform polycrystalline films considerably, leading to increased interest in such films for future interconnect technologies. Moreover, Ru is an anisotropic conductor with low resistivity along the hexagonal [0001] axis. Aligning interconnect lines along this axis could lead to a significant further reduction in line resistance. Therefore, epitaxial growth is essential to harness these benefits and improve the performance of Ru interconnects in advanced semiconductor technologies.

Here, we study the epitaxy of Ru by physical vapor deposition on sapphire substrates with c-, a-, r, and m-plane orientations at a deposition temperature of 400°C. Epitaxy on c-plane sapphire leads to hexagon-on-hexagon orientation (Figs. 1 and 2) and ultralow resistivities, close to the Ru bulk resistivity perpendicular to the [0001] axis (7.4 μΩcm) or films thicker than about 30 nm (Fig. 3). X-ray diffraction indicates high crystal quality with a (002) rocking curve half width of 0.48°, consistent with a low Rutherford ion channeling yield of 5% (Fig. 4). The resistivity scaling is consistent with an *ab initio* model including surface scattering only (Fig. 3) [5], confirming that the impact of grain boundary scattering is minimized in epitaxial films.

By contrast, deposition on a-, r-, and m-plane sapphire leads to multiple epitaxial orientations, without clear signs for polycrystalline or minority phases. Ru on a-plane sapphire shows mainly (0001) our of plane orientation with some polycrystalline minority phase present (not shown). Epitaxy on m-plane sapphire leads to a both (0001) and (11-20) out of plane orientations (Fig. 5). Note that both orientations are epitaxial, as revealed by pole figures (not shown). By contrast, epitaxy on r-plane sapphire leads to a tilted twin structure with a {01-11} twinning plane, as revealed by TEM (Fig. 6). Surface faceting is also observed in this case. Due to the multiorientation microstructure and the resulting domain boundaries, the resistivities of epitaxial Ru on a-, m-, and r-plane sapphire is however higher than that of Ru on c-plane sapphire, reaching around 9 to 10 μΩcm for films above 30 nm. Future work is thus needed to understand the epitaxy on such substrates to enable Ru with the low-resistivity [0001] axis in-plane.

We finally comment on the prospects of integrating epitaxial Ru films in advanced interconnects of future CMOS technology nodes.

References:

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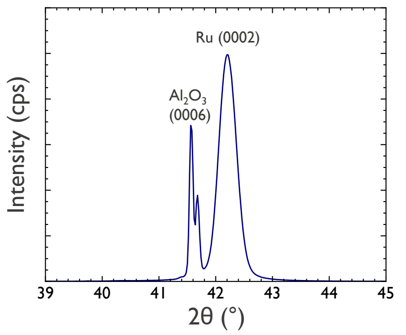

Figure 1: 2θ-ω XRD pattern of a 50 nm thick Ru film deposited on c-plane sapphire

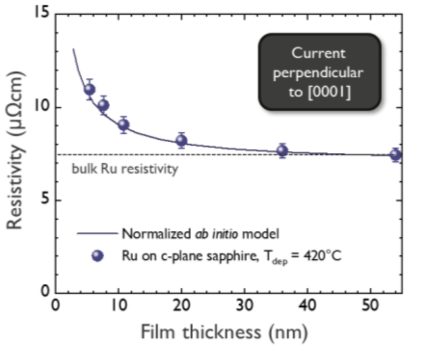

Figure 3: Resistivity vs. thickness of epitaxial Ru on c-plane sapphire.

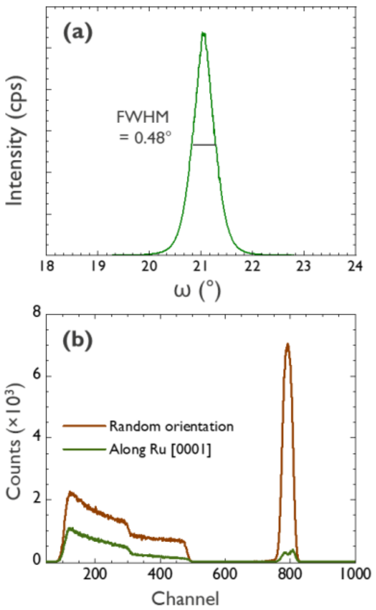

Figure 4: (a) XRD rocking curve and (b) Rutherford ion channeling of a 50 nm thick Ru film deposited on c-plane sapphire.

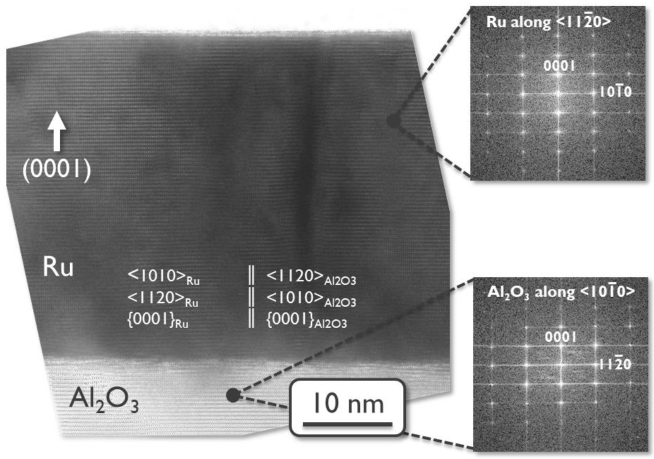

Figure 2: TEM image and corresponding Fourier transforms of a Ru film deposited on c-plane sapphire.

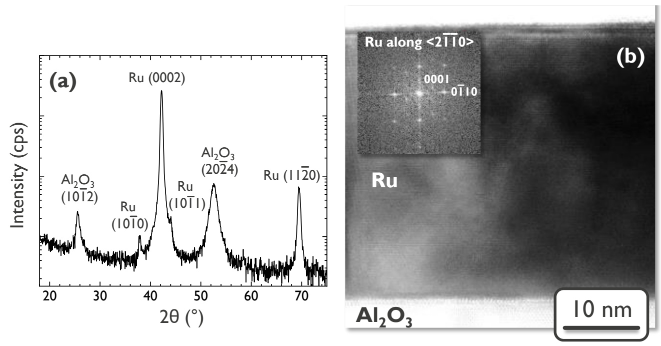

Figure 5: (a) 2θ-ω XRD pattern as well as (b) TEM image and corresponding Fourier transforms of a Ru film deposited on m-plane sapphire.

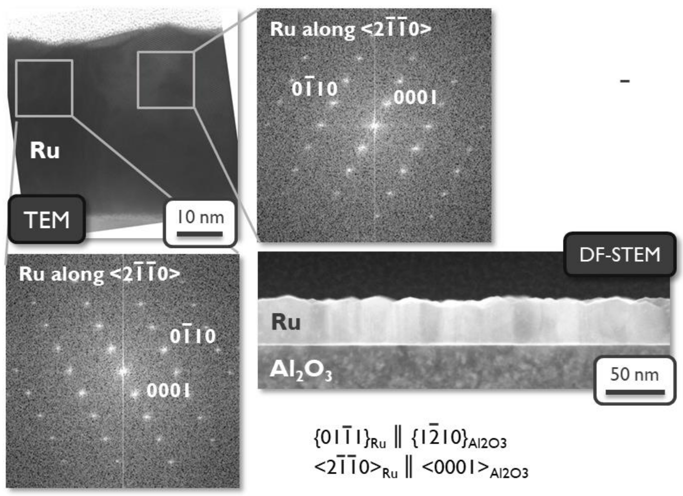

Figure 6: TEM images and corresponding Fourier transforms of a Ru film deposited on r-plane sapphire.