Abstract

The epitaxial growth conditions and superconducting properties of nanostructured devices made of rhenium (superconducting below T=1.7 K) on sapphire were explored. Epitaxial growth of rhenium thin films onto a single crystal α-Al_2O_3 substrate was realised using molecular beam epitaxy. The pressure in the MBE chamber was in the range of 10^{-10} Torr. The cleanness of the substrate was verified using XPS, and the growth of rhenium was monitored using RHEED. The orientations of the two crystals were $(0001)Al_2O_3//(0001)Re$ and $<2\bar{1}\bar{1}0>Al_2O_3//<01\bar{1}0>Re$, which was confirmed using X-ray diffraction. The in-plane misfit between the lattices is -0.43% at room temperature, which allows us to estimate the critical thickness of rhenium to be between 10 nm and 15 nm.

For deposition, rhenium was heated using an electron beam. A deposition rate of 0.1 Å/s was maintained. The temperature of the evaporating rhenium is estimated to reach approximately 3000°C. Substrates were heated during growth using either a Joule-heated W filament located behind the sample, or electron bombardment. Generally deposition temperatures of 800°C and 900°C gave reproducible results.

The effect of deposition temperature was studied on samples that had the same thickness but were deposited at different temperatures. Three thickness groups were selected: 25 nm, 50 nm and 100 nm. Every sample was dominated by the (0001) epitaxial orientation. Orientations $(11\bar{2}0)$, $(10\bar{1}0)$, $(10\bar{1}1)$ were present, but their intensities were small and decreased with increasing deposition temperature. Extensive AFM imaging was used to observe the morphology of the films. The 25 nm thick films were decorated with grains. The diameter of the grains ($\sim$ 50 nm) did not vary significantly on these samples, however, they became more uniform with increasing deposition temperature, and the surface became smoother. On the 50 nm and 100 nm thick films spirals and holes can be observed. The diameter of the spirals on the 50 nm thick film increased from 100 nm to 500 nm when the temperature of the deposition was increased from 800°C to 900°C. On the 100 nm thick sample the diameter of the spirals also increased with higher deposition temperature, but the increase was not as significant. XRD rocking curves measured on all samples narrowed with increasing deposition temperatures, indicating reduced mosaicity among the (0001) crystallites. High-resolution θ-2θ scans evidenced disorder in the 50 nm thick film, corresponding to strain values in the range of 0.01. Deposition temperature of 1000°C lead to the dewetting of a 50 nm thick sample, and islands with atomically flat surfaces were formed.

The frequently observed spirals are most likely the result of screw dislocations. The origin of the holes that accompany the spirals is a dewetting process that starts when the thickness of the film reaches approximately 10 nm. We quantified the temperature evolution of the film during growth, taking into account emission, reflection and transmission between all surfaces. This thermal model confirmed that the temperature of the film increases as the rhenium film grows. The dewetting was studied using Mullins' theory of thermal grooving. A surface diffusion coefficient of 4×10^{-12} cm^2/s was obtained, which is consistent with the observed dimensions of the surface topography.

Wires with widths ranging from 100 nm to 3 μm and superconducting quantum interference devices were fabricated from the rhenium films. Transport measurements were conducted using a helium-3 refrigerator. It was found that the lithography process does not affect the superconducting properties of the rhenium. Critical temperatures between 1.43 K and 1.96 K were measured. We could correlate the superconducting transition temperature with the topography and the crystallinity of the films. The mean free path of electrons and the superconducting coherence length were obtained. For two of the films, both the mean free path and the effective coherence length were over 100 nm. These two films were in the clean limit, but the fabricated wires were in the dirty limit.

On one film, SQUIDs of 1 μm diameter with 50 nm and 20 nm wide nanobridges acting as Josephson junctions were fabricated. The SQUIDs were cooled down using a dilution refrigerator. Critical current oscillations were measured. The flux noise values obtained were as low as 2.6×10^{-5} $\Phi_0/\mathrm{Hz}^{1/2}$.