Investigating growth mechanisms in ultrathin amorphous Mo_xSi_{1-x} films with atomic force microscopy

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Introduction

Amorphous superconducting MoSi thin films are promising materials for applications in superconducting nanoelectronics, including single-photon detectors, quantum circuits, and cryogenic amplifiers [1]. Their electrical and superconducting properties are strongly governed by growth conditions, structural homogeneity, and level of disorder [2].

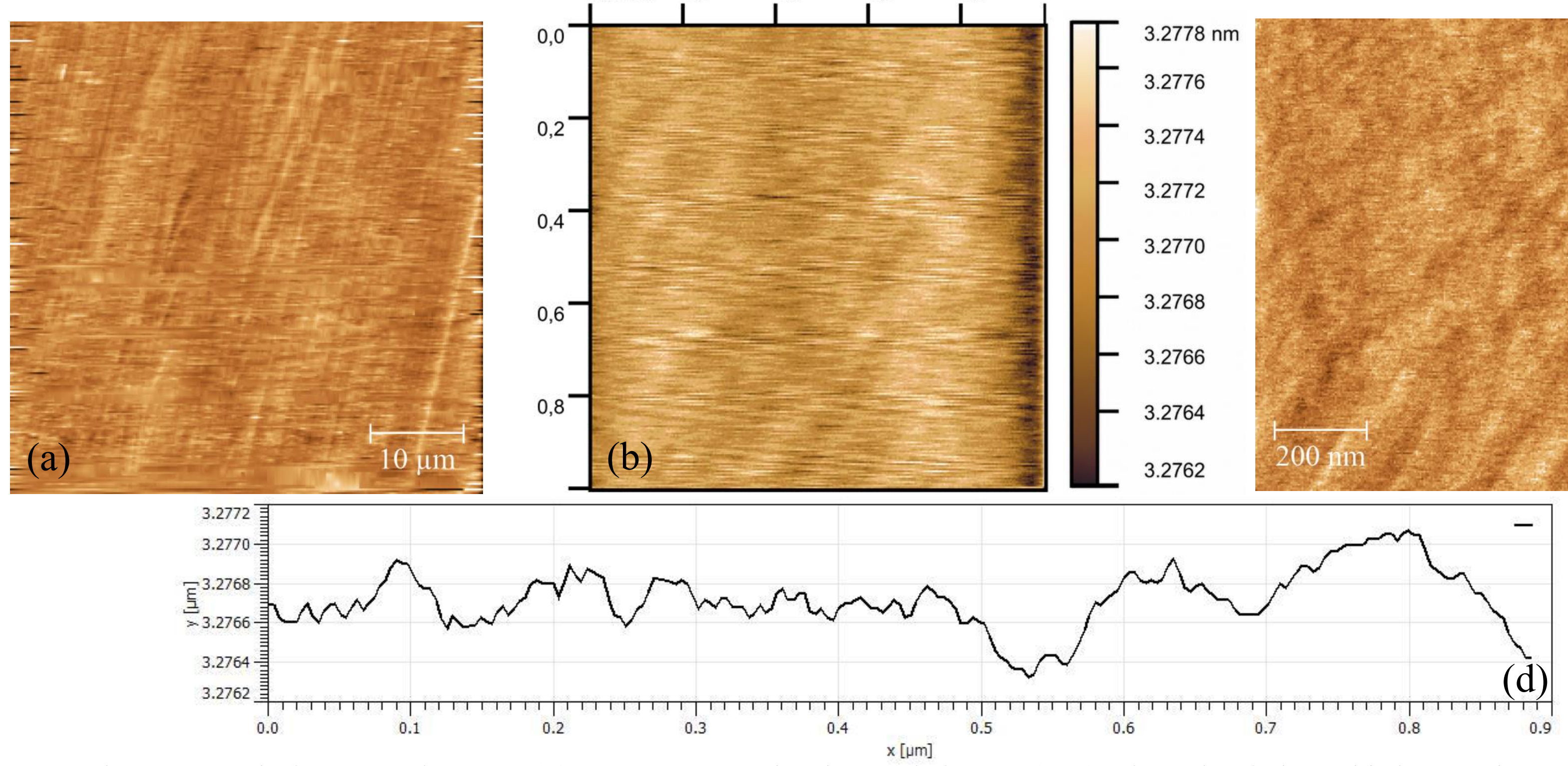
Structural features arising during film growth, including nanoscale inhomogeneities, local crystallization, and disorder-related defects, can significantly affect the superconducting properties of Mo_xSi_{1-x} thin films. In particular, the emergence of polycrystalline phases and increased structural disorder may lead to a suppression of the critical temperature and enhanced inhomogeneity of the superconducting state. In amorphous MoSi systems, disorder-induced localization effects additionally influence charge transport and contribute to variations in normal sheet resistance and superconducting transition width [3]. The obtained results provide a basis for optimizing the fabrication of MoSi thin films with tailored properties for next-generation superconducting devices.

Methods

Vacuum deposition technology based on DC-magnetron sputtering from two separate sources in argon atmosphere enables the fabrication of amorphous thin and ultrathin films (down to 4 nm) with various superconducting properties and stoichiometric compositions. The influence of discharge power, stoichiometry, and substrate material, on film roughness, thickness, surface parameters was analyzed using atomic force microscopy.

Atomic force microscopy (AFM) is an effective tool for studying the growth of ultrathin amorphous Mo_xSi_{1-x} films, as it enables high-resolution analysis of surface morphology, roughness, thickness, and nanoscale structural inhomogeneities that are difficult to detect by other methods in amorphous systems. Its ability to characterize local surface features without requiring crystalline order makes AFM particularly valuable for assessing how deposition conditions influence film growth and the structural factors that affect superconducting properties.

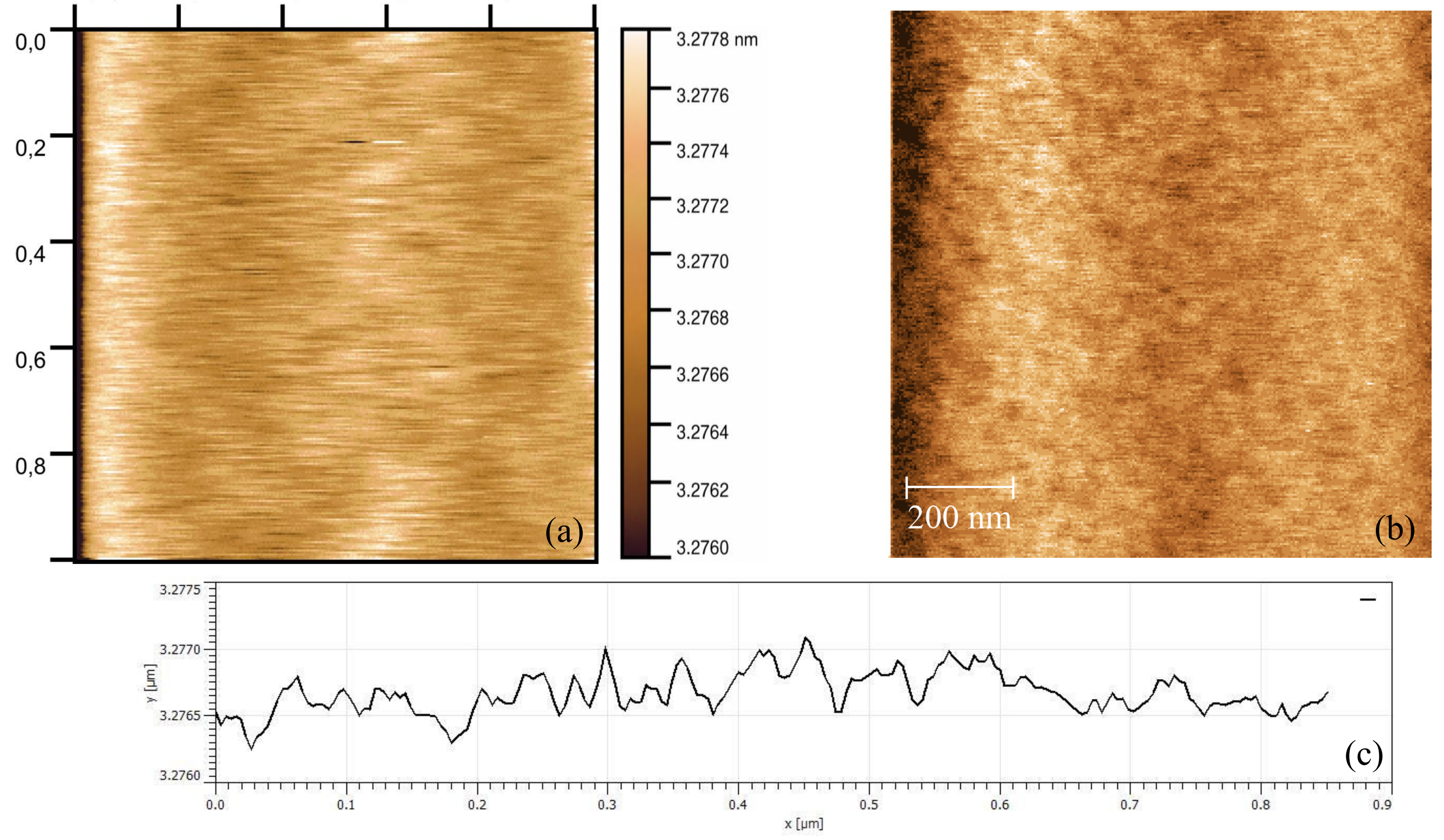
Substrate and ultrathin MoSi film analysis



The upper-left AFM image (a) represents the lateral force (LF) signal of the Si/SiO₂ substrate surface, which was used for the series of MoSi 50/50 samples. The LF image reveals local friction contrast and nanoscale surface inhomogeneities, which are probably related to the substrate polishing process. The average surface roughness of the substrate is R_a = 0.67 nm, indicating a smooth surface suitable for the growth of ultrathin MoSi films. The low substrate roughness was additionally confirmed by specular X-ray reflectometry measurements, which yielded a roughness value of approximately 0.4 nm.

The other AFM images and the scan profile correspond to the 0.9 nm MoSi thin film with Mo/Si 50/50 composition deposited on the Si/SiO₂ substrate. The height 1x1 µm image (b), LF image (c), and scan profile (d) show only minor surface fluctuations, without pronounced defects or abrupt height variations. The root mean square roughness of the 0.9 nm MoSi film is 0.28 nm, confirming the formation of a continuous, smooth, and uniform ultrathin film. No pronounced crystalline grains or phase-separated surface features are observed in the AFM images, which is consistent with the amorphous structure of the film.

Surface morphology of MoSi thin film

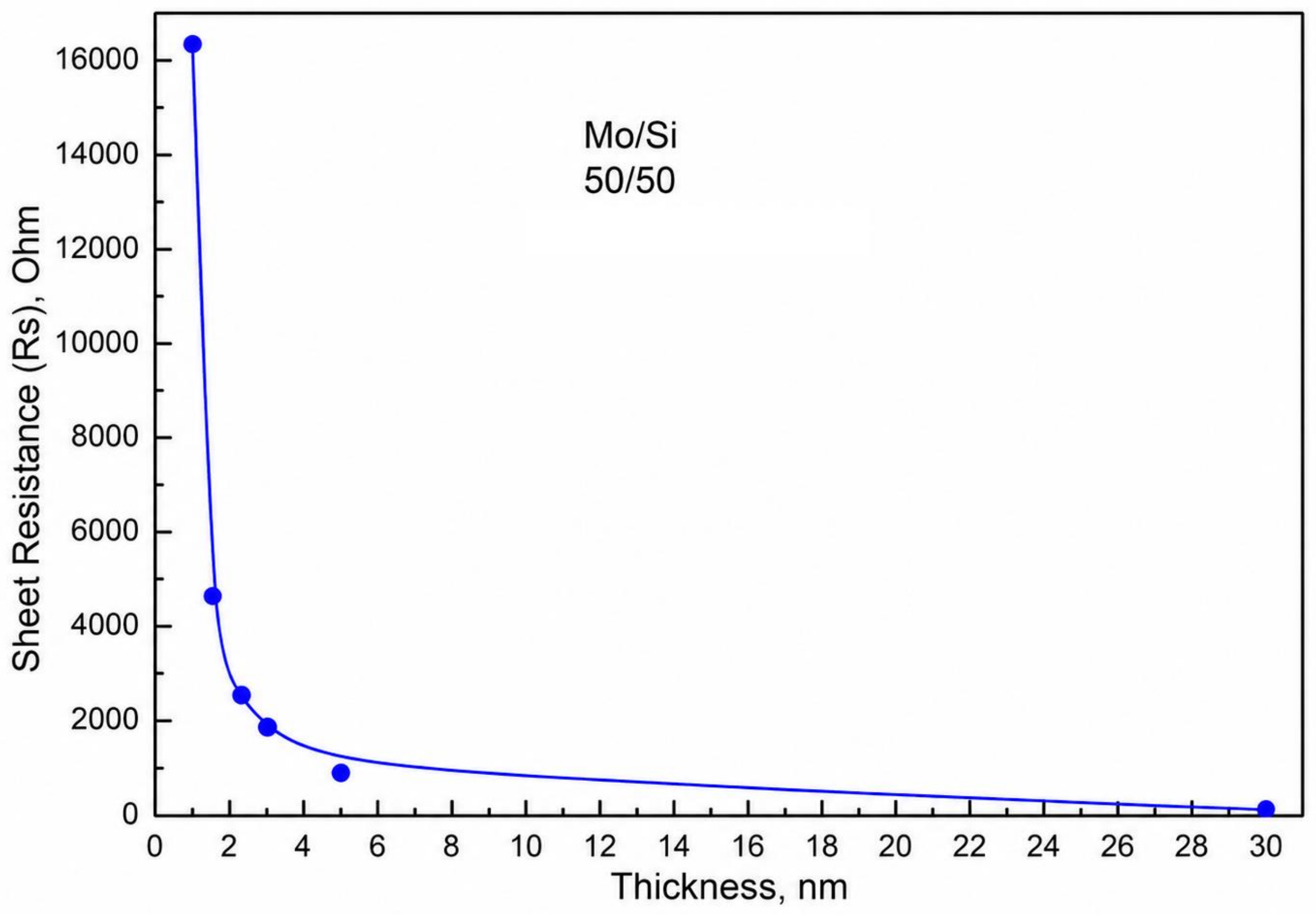


AFM images and scan profile of the 2.5 nm MoSi thin film with Mo/Si 50/50 composition are shown in panels (a–c). The height image in panel (a) shows a smooth and homogeneous MoSi surface over an approximately 1 × 1 µm scanned area, without large defects or sharp height variations. The low roughness value of Ra = 0.47 nm confirms the formation of a smooth continuous film.

Panel (b) presents the lateral force (LF) image, which reveals local friction contrast and subtle surface inhomogeneities that are less visible in the height image. These features may be related to local variations in friction, adhesion, or growth morphology of the MoSi layer.

Panel (c) shows the height profile along a selected scan line. Only minor height fluctuations are observed, confirming the uniform, continuous, and morphologically smooth surface of the 2.5 nm MoSi 50/50 thin film.

Thickness-dependent sheet resistance control in MoSi thin films



The graph shows the sheet resistance dependence on the thickness of MoSi thin films with Mo/Si 50/50 composition. A sharp decrease in resistance is observed for ultrathin films, while thicker films demonstrate significantly lower sheet resistance, indicating improved film continuity and conductivity with increasing thickness. This behavior is typical for ultrathin conductive films, where the electrical properties are strongly affected by film thickness, morphology, and the degree of structural continuity.

The obtained results show that film thickness is one of the key parameters controlling the sheet resistance of MoSi layers. By adjusting the deposition conditions, such as sputtering power, deposition time, and growth rate, it is possible to control the final film thickness and, therefore, achieve the desired sheet resistance values. This makes MoSi thin films suitable for applications where precise control of electrical parameters is required.

Conclusion

- Amorphous MoSi thin films with Mo/Si 50/50 composition were successfully obtained by DC-magnetron sputtering.
- The increased silicon content suppresses crystallization and supports the formation of an amorphous MoSi structure.
- AFM analysis confirms uniform film growth: the surface is continuous, homogeneous, and free from pronounced defects.
- The height images and scan profile show only minor surface fluctuations, indicating stable and uniform deposition over the scanned area.
- The low roughness value of Ra = 0.47 nm demonstrates improved surface smoothness and high morphological quality of the MoSi films.
- Controlled deposition conditions make it possible to tune the surface morphology and electrical properties of MoSi thin films.

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Acknowledgement

This work is supported by the National Research Foundation of Ukraine, project No.22.07/0044 and by the IEEE program "Magnetism for Ukraine 2025-2026", project number 9918.