Optimizing the epitaxial growth of niobium nitride for superconducting electronic applications

Electronic systems based on silicon have achieved performance levels that enable the development of artificial intelligence, machine learning, and quantum computing, opening new opportunities in automation, robotics, and the creation of intelligent systems. However, the potential for further development of silicon-based electronics is limited due to challenges associated with efficient heat dissipation from the circuits, leading to overheating and restricting further miniaturization. An alternative to silicon may be devices based on superconducting materials. Unlike ordinary materials, electrons moving in a superconductor do not interact with the crystal lattice, thus preventing lattice vibrations, which are typically associated with energy loss in the form of heat. The use of superconducting elements in electronic circuits allows for the minimization of energy losses and more efficient heat management. However, the quantum processes underlying the operation of superconducting devices are highly sensitive to disturbances, significantly affecting their performance. They require extremely low temperatures around 4.2K (-269°C) and high-quality materials free from structural defects.

A starting point for creating electronic components could be Josephson junctions, which consist of two layers of superconductor separated by a thin layer of ordinary (non-superconducting) material only a few atomic layers thick. One of the main limitations in the development of Josephson junctions is the structural quality resulting from the materials currently used and the techniques employed in their fabrication, which affects their performance and stability. A promising material is niobium nitride (NbN), which becomes superconducting at 17K and exhibits high chemical stability, ensuring that devices based on this material do not degrade quickly during operation. Additionally, the crystal structure of niobium nitride is similar to that of other nitrides, such as gallium nitride (GaN) and aluminum nitride (AlN), which are widely used in LED diodes and lasers, enabling their integration with other semiconductor technologies.

This project aims to investigate the possibility of obtaining high-quality niobium nitride (NbN) layers free from structural defects and Josephson junction structures based on NbN through molecular beam epitaxy (MBE). This technique allows for the fabrication of materials with atomic-layer precision and provides precise control over the chemical composition and thickness of the layers while avoiding the incorporation of contaminant atoms into the structure. The first task will be to investigate how the choice of substrate (the material on which the epitaxial layers are grown) and MBE growth parameters affect the quality of niobium nitride. Currently, NbN layers with high transition temperatures to the superconducting state contain structural twin boundaries, which arise from the formation of NbN grains with slightly different orientations. When such grains meet, a boundary is formed where the atomic arrangement deviates from the ideal. This phenomenon leads to the creation of a rough NbN surface, which presents a significant challenge when attempting to grow Josephson junctions with a barrier just a few atomic layers thick. The use of alternative substrates and optimization of the growth conditions may help eliminate these defects from the niobium nitride layers.

To assess the quality of the layers, transmission electron microscopy (TEM) will be used, allowing for imaging of the atomic structure of the materials. This will also help to describe and better understand the mechanisms of NbN growth and defect formation. Another important task in the project will be the growth of a thin (~1 nm), continuous barrier layer on the surface of the NbN layer, followed by the epitaxial growth of an additional NbN layer, which will allow the formation of Josephson junctions. This requires developing a procedure for transitioning from NbN growth conditions to barrier growth conditions that will not degrade the NbN surface. It will also be necessary to investigate which growth conditions should be selected to achieve ideal boundaries between these layers.

The results obtained within this project should allow for the proposal of new material solutions for electronics based on Josephson junctions. Furthermore, a better understanding of the mechanisms of NbN epitaxy using MBE will open new possibilities for manufacturing Josephson junctions with modified structures, enabling the improvement of their parameters.