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SOLID STATE

Synthesis of Thin Niobium Films on Silicon and Study of Their Superconducting Properties in the Dimensional Crossover Region

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Abstract—Niobium films with a thickness of 4–100 nm are synthesized on a silicon substrate under ultrahigh vacuum conditions. Measurements of the electrical resistance show a high superconducting transition temperature T_c in the range of 4.7–9.1 K and record-breaking small transition widths ΔT_c in the range of 260–11 m. The dependences of T_c and ΔT_c on the magnetic field are investigated, and the superconducting coherence lengths and mean free paths of conduction electrons for different thicknesses of the synthesized films are determined. A significant influence of the magnetic field on ΔT_c is found, which reveals the transition from three- to two-dimensional superconductivity at thicknesses below 10 nm. The dependences of T_c and ΔT_c on the thickness of the films and the magnitude of the magnetic field are discussed within the framework of existing theories of superconductivity in thin films of superconducting metals.

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INTRODUCTION

Niobium is widely used as a superconductor due to its high (~9.2 K) superconducting (SC) transition temperature. However, niobium is a metal-getter that reacts extremely actively, first of all, with oxygen; therefore, obtaining pure niobium in the form of a thin film for applications in SC electronics [1, 2] is not an easy task. In the applied technological sense, it is practically impossible to obtain a niobium film, in which the mean free path of conduction electrons l exceeds the Bardeen–Cooper–Schrieffer (BCS) coherence length for niobium $l > \xi_{BCS} = 38$ nm [3]. Such niobium is called “clean” in the terminology of the physics of superconductors [4]. In practice, the inverse relation $l \ll \xi_{BCS}$ is always fulfilled; such niobium is called “dirty” [4]. In this case, the role of the SC coherence length is played by the value $\xi_s = 0.54\sqrt{l\xi_{BCS}} \ll \xi_{BCS}$. Niobium belongs to a group of the type-II superconductors, into which the magnetic field penetrates in the form of Abrikosov vortices [4].

1. EXPERIMENTAL TECHNIQUE

The technique of synthesis of thin-film structures is constantly being improved, and today it is possible to create ultrahigh vacuum conditions in which the deposited niobium film absorbs the minimum possible amount of impurities from the residual atmosphere of the vacuum chamber with the achievement of the maximum temperature of the SC transition T_c for thicknesses d in the range of 10–30 nm with very narrow resistive transitions to the SC state [5–12]. In this work, we present the results of the preparation of thin niobium films in the thickness range of 4–100 nm, as well as the study of the parameters of their transitions to the SC state.

The synthesis of niobium films was carried out by magnetron sputtering on single-crystal (100)-oriented silicon substrates with an epi-ready surface treatment quality (Crystal GmbH, Germany). The substrates were cleaned in a multi-beam ultrasonic bath in acetone (high purity) and isopropyl alcohol (high purity), then they were annealed at 800°C for 5 min in an ultrahigh vacuum chamber (SPECS, Germany) with a residual vacuum of ~2×10^{-8} Pa. After annealing, the sample was moved through an ultrahigh vacuum line to a magnetron sputtering chamber (BESTEC, Germany) with a residual gas pressure after niobium presputtering below 5×10^{-8} Pa, in which an intermediate layer of high-resistivity silicon with the thickness of 10 nm was first deposited on the substrate at room temperature (target of 99.999% purity from Girmet, Russia). High-purity argon (>99.9999%) at a pressure of 6×10^{-1} Pa was used as a plasma-forming gas. An