Study of the Nb-Nb oxide-Pb film structures with a scanning tunneling microscope

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The surface of niobium films, which were used previously to produce niobium-based film structures, niobium-niobium oxide-lead, is studied with a scanning tunneling microscope. The results are in good agreement with the observable properties of these structures which contain Josephson and tunnel junctions.

The nonlinear properties of superconducting film structures Nb-Nb oxide-Pb, including the tunnel and Josephson characteristics of these films, as well as the feasibility of using them as nonlinear elements in the IR region of the spectrum have recently been studied extensively.[1–3] Depending on the method of fabrication, these structures had different current-voltage characteristics: some were typically tunnel structures, others were characteristic of superconducting microbridges or point contacts. It was assumed in Refs. 1 and 2 that the Nb-based structures are tunnel junctions with microbridges which penetrate the oxide layer. The existence of microbridges is confirmed by the following circumstances. First, such junctions have inordinately high Josephson critical currents ($\gtrsim 10$ mA). Secondly, measurements in a magnetic field carried out by Vedeneev *et al.*[2] showed that a superconducting critical current which flows through a junction is a sum of two currents: one current, which oscillates in a magnetic field, is a purely tunnel current and the other current, which decreases slowly with increasing magnetic field, flows through a microbridge.

We felt it worthwhile to study the surface of a niobium film in order to understand how microbridges are formed. We used for this purpose a tunneling scanning microscope built at the Institute of Physics Problems.[4] Surface profiles of niobium films about 0.8-μm thick, deposited on sapphire and ruby substrates, were obtained. The film surface was not worked in any way before taking the measurements. The measurements were carried out at pressures 0.01–0.1 torr. The scanning range of the microscope was $\sim 10\times 10\ \mu\text{m}^2$. Profiles of sections with dimensions from 40×40 to 15000×15000 Å^2 were recorded in various parts of this range. To quantitatively estimate the quality of the surface, we determined the optimum plane by the method of least squares and calculated the mean square deviation of the surface from this plane. The results are presented in Table I.

Figure 1a shows one of the profiles and Fig. 1b shows the recording of the potential relief of the section which corresponds to Fig. 1a and which characterizes the local work function φ (the potential barrier) of the normal electrons from the film surface. The recording was made by modulating the spacing between the scanning point and the film. The oxide film, which manifests itself as noise on the surface, is characterized by lower values of φ. Since the mean value of φ is rather high (~ 2 eV), and since the

TABLE I

Section, Å^2	Deviation, Å	
	20° C	850° C
800 x 800	8.8	18.5
800 x 800	7.8	–
1500 x 1500	7.5	–
3000 x 3000	11.3	23
3000 x 3000	–	44
11000 x 11000	15.9	–

inhomogeneities amount to no more than 20% of this value, a change cannot distort appreciably the surface profiles which we obtained (these profiles are in fact the recording of the direct tunnel current). In Fig. 1 we see that the film has protrusions: crystallites 40–50 Å high, with higher values of φ. The low noise level on the surface of the protrusion implies that the oxide film is thin or possibly nonexistent. Crystallites of this sort, which are formed when Nb is deposited on a hot substrate with a temperature of 850 °C, apparently can function as microbridges in the oxide layer.

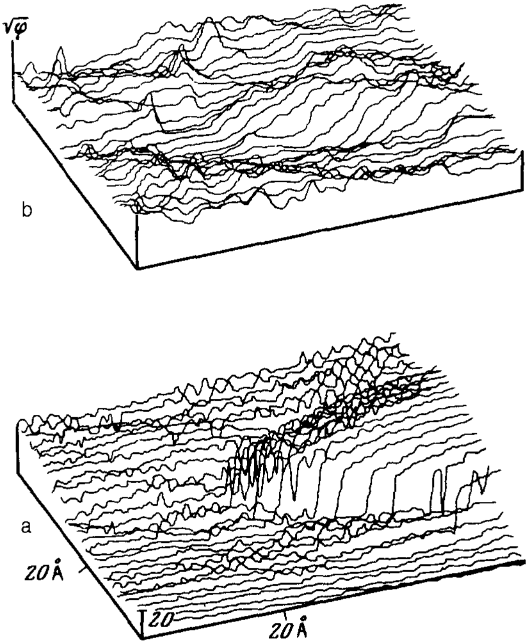

FIG. 1. (a) Surface profile of an oxidized Nb film in a region with dimensions ~50×50 Å; (b) potential relief $\varphi^{1/2}$ in the same region of the surface.

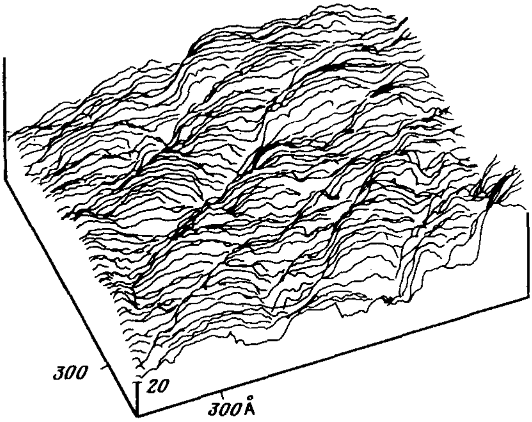

FIG. 2. Surface profile of an Nb film deposited without heating of the substrate; traces of the substrate polishing are clearly visible.

Since the spacing between the tunneling scanning microscope needle and the surface of the metallic film (in the experiments which we are describing) is about 10 Å, the thickness of the oxide layer at the surface should be no greater than 10 Å. We can estimate from this result the mean value of the dielectric constant ϵ of the niobium-based tunnel junctions. Since, according to the data of Ref. 1, the ratio ϵ/d (d is the thickness of the dielectric layer of the junction) varies in the range $(0.13–0.64)\times 10^8$ cm^{-1}, the mean value of ϵ is on the order of a few units.

The profiles of niobium films which were deposited without heating the substrate did not reveal the presence of the crystallites mentioned above. It is unlikely that microbridges can form in tunnel junctions based on such films, which apparently have an amorphous structure.

A smaller-scale recording of the surface profiles of films revealed smooth surface irregularities due to the substrate profile. Figure 2 clearly shows traces of mechanical polishing of the substrate, seen as a series of parallel grooves, situated approximately 300 Å from each other.

We thus conclude that the experimentally observed surface structure of niobium films deposited on a hot substrate does in fact form the base for tunnel junctions with a large number of microbridges that penetrate the oxide layer. The number of bridges can be estimated on the basis of the following considerations. The average density of the critical current J_c in Nb-Nb oxide-Pb structures is, according to the data of Ref. 1, in the range 1 to 10^2 A/cm^2. The critical current density j_c for a single niobium bridge is on the order of magnitude 10^5 A/cm^2. Knowing the approximate size of the tunnel junction ($\mathcal{S}\sim 10^{-4}$ cm^2; Ref. 1) and ignoring the critical tunnel current compared with the current transmitted through the bridges, we estimate the area of all bridges of the junction to be

$$S=\frac{J_c}{j_c}\,\mathcal{S}\approx 10^{-9}-10^{-7}\,\mathrm{cm}^2.$$

Working from the size of the crystallites found experimentally, whose area is on the order of 10^{-13} cm^2, we estimate the total number of microbridges in the tunnel junction to be

$$N \sim \frac{s}{10^{-13}} \sim 10^4 - 10^6.$$

A junction has, on the average, one bridge for an area 10^3 Å × 10^3 Å or fewer, which is fully consistent with the observable surface relief (Fig. 1), especially if we take into account that not all microcrystalline protrusions on the surface can form microbridges.

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