OPPORTUNITY OF DEVELOPMENT OF NIOBIUM COATED COPPER CAVITY

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Abstract

Non quadratic losses in the cavities of the NbCu type are explained by fluxons penetrating into the roughness of the working layer surface when the magnetic RF-field amplitude exceeds the first critical field B_{c1}. From this explanation it follows that it is possible to reduce these losses considerably by decreasing the roughness of the copper cavity surface. The given results of measuring B_{c1} two-layer NbN/Nb and three-layer NbN/Nb/NbN have been obtained with a planar magnetron. They have shown that B_{c1} of these films is higher than of the Nb films. A possibility of using the improved axial magnetron is discussed in the paper. This magnetron is very close to the planar magnetron in its productivity of the sputtering process.

1 INTRODUCTION

Working with NbCu cavities having Nb films sputtered by the magnetron method, the authors found non quadratic losses leading to substantial decrease of Q-value at $E_a > 1 \div 2\,/$ [1]. The beginning of Q-value decrease correlates with the exceeding of the magnetic RF-field amplitude B_a of the first critical field B_{c1} of the film [2]. The problem of non quadratic losses was discussed at the 8th Workshop RF Superconductivity [2, 3, 4, 5], but the methods of decreasing these losses were not found out.

2 EXPLANATION OF NON QUADRATIC LOSSES

It is supposed that the Nb film surface is rough (hillock-like) [1, Fig. 3(b)] and there are big hillocks with a height of $h_b \gg \xi$ (ξ is the coherence length) and transverse size $d_b \simeq \lambda$ (λ is the depth of penetrating magnetic field). According to [1, 2], $B_{c1} \simeq 10\,\mathrm{mT}$, the second critical field $B_{c2} \simeq 3\,\mathrm{T}$, thermodynamic critical field $B_{ct} \simeq 100\,\mathrm{mT}$, $\lambda \simeq 230\,\mathrm{nm}$, $\xi \simeq 10\,\mathrm{nm}$, $\kappa = \lambda/\xi \simeq 23$. Below the calculated estimations have been made at these parameters.

At $B_e > B_{c1}$ ($B_e = B_a \sin\omega t$, ω is a circle frequency of the RF field) the magnetic field penetrates into the body of the big hillocks as fluxons. Similarly as it penetrates into the plate perpendicular to the field. The minimal height of the hillock h_m, where one fluxon can penetrate, is defined by the ratio $h_m = \varphi_0/4\lambda B_a \simeq (\pi\kappa/\ln\kappa)(\xi/\bar{B}_a)$ (φ_0 is the quant of the magnetic flow, $\bar{B}_a = B_a/B_{c1}$). It is supposed that $h_b > \xi\pi\kappa/\ln\kappa$. It may be considered that the penetration time τ_f of fluxons is much less than the period T of the RF field [2]. The number of fluxons is proportional to the area of the perpendicular field hillock transverse cross-section, and their total length is proportional to the volume of the hillock.

Every fluxon is influenced by two forces: the bernulli pressure difference F_r, which may be interpreted as the action of the force from the side where fluxons are pictured in the surface of the hillock, and the Lorentz force from the side of the screening RF field current F_{rf}. It is known that the total action of these forces at the distances from the surface less than λ, leads to the appearance of the Bean — Livingston barrier. Here the penetrated fluxons are treated by the force $F_l = F_r - F_{rf}$ directed to the surface (at $B_a \ll B_{ct}$ — $F_r \gg F_{rf}$).

From the condition when the pinning force F_p for a single fluxon is less than F_l, in the approximation *of the flat boundary of the hillock* it follows

$$\frac{x}{\xi} < \left(\frac{p}{4} + \frac{\ln\kappa}{\kappa}\frac{B_e}{B_{c1}}\right)^{-1} \simeq 8\left(2p + \frac{B_e}{B_{c1}}\right)^{-1}, \qquad (1)$$

where $p \leq 1$ is a co-ordinate parameter of the pinning force, x is the distance of fluxon from the surface of the hillock ($x \ll \lambda$). The condition (1) divides the hillock into two regions: vertex the upper part where the fluxons can be considered totally free, and the pre-foot part,where a part of fluxons can be captured by the centers of pinning. The captured fluxons will annihilate with those which penetrated into the opposite half-wave of the field with the energy yield per the unit of length $\Delta W_a = \varphi_0 B_{c1}/2\mu_0 \ln\kappa$, that corresponds to the model of remagnetizing proposed in [1]. Under the influence of force F_l the free fluxons are moving to the surface [6] and when reach it, they disappear. Here from the unit of the fluxon length, the energy $\Delta W_l \simeq 2\Delta W_a\, \ln(x_i/\xi)$ dissipates (x_i is the initial fluxon coordinate). New fluxons are produced in the region of the borderline determined in (1) with the interval of τ_f. The time of fluxon moving to the surface is $\tau_i \simeq (\mu_0 \ln\kappa B_{c2}/\rho_n B_{c1}) x_i^2 \simeq 1,5\cdot 10^{-12}(x_i/\xi)^2$ which is much less than the periods of the RF field (ρ_n is resistance of Nb in the normal state). The sum energy produced per the period of the $\tau_i + \tau_f$ regularity of fluxons, exceeds ΔW_a very much. In the hillock with several penetrated fluxons, the free fluxons are moving under the influence of the interaction forces F_i, they try to create a balanced vortex cell.

The motion of fluxon under the influence of interaction forces F_i as well as under the Lorentz forces F_l, and the annihilation process of the captured fluxons are leading to additional energy yield which practically does not depend on B_a. The dependence of additional losses on B_a is determined only by the dependence on B_a number of fluxons penetrating into the hillocks on the unit of the cavity surface and lengths of these fluxons. The number of fluxons in big hillocks grows proportionally to B_a. The number of hillocks, which fluxons penetrate into, grows with B_a increasing and is determined by the distribution of hillocks on their height.

If to suppose that the total length of fluxons on the unit of the cavity surface $L_f{=}m(\bar{B}_a)^2\,(h_b/d_b^2)\varepsilon{\cdot}f$ ($m{<}1$ is defined by the geometry of the hillocks, ε is the fraction of the area of the big hillocks basis from the area of the cavity surface, f reflects non quadratic dependence L_f on $(\bar{B}_a{-}1)$), the discussed surface losses can explain the non quadratic losses leading to the decrease of Q-value and are presented by the sum of 3 terms. The power of losses: P_l defined by the action of forces F_l does not depend on ν; P_i defined by forces F_i is proportional to ν^2; P_a defined by the annihilation process linearly depends on ν [1]. It is supposed that dependences P_l, P_i and P_a on $(\bar{B}_a{-}1)$ are different. Then the surface resistance defined by non quadratic losses R_{sn} is written as

$$R_{sn}(\bar{B}_a,\nu){=}\frac{m\,\delta\,g\,\varepsilon}{(\ln\kappa)^2}\,\rho_n\,\frac{h_b}{d_b^2}\,f\left(1{+}\frac{\nu}{\nu_a}{+}\frac{\nu^2}{\nu_i^2}\right) \qquad (2)$$

($\delta{=}\tau_i/(\tau_i{+}\tau_f){<}1$, $g{\simeq}0,1$ is a mean value of $\ln(\frac{x_i}{\xi})(\frac{\xi}{x_i})^2$, $\nu_a(\bar{B}_a{-}1)$ and $\nu_i(\bar{B}_a{-}1)$ are the frequencies at which $P_l{=}P_a{=}P_i$). From (2) it follows that the B_{c1} increasing as well as h_b decreasing, shifts the beginning point of non quadratic losses and reduces them. At $h_b{\leq}\xi$ fluxons won't produce and non quadratic losses defined by the roughness of the film surface will disappear.

The frequency dependence in (2) is in a good agreement at $\nu_a{\simeq}\nu_i{=}0,5\,\mathrm{GHz}$ with experimental frequency dependence $R_{sn}^{'}{=}\frac{\partial R_{sn}}{\partial B_a}$ from [1, Fig. 2] (obtained at $(\bar{B}_a{-}1){\leq}1$), supposing h to be equal in all the cavities (similar technology of preparing the copper surface of the cavities) (Fig. 1).

Quantitatively (2) is in agreement with $R_{sn}^{'}$ at $\delta{\cdot}\varepsilon{\simeq}10^{-5}$. It means that at the beginning the non quadratic losses are determined only by the losses in separate and seldom located hillocks.

It is known that in the region of quadratic losses the surface resistance R has a frequency dependence $R(\nu){=}R_{s0}(1{+}\nu^2/\nu_0^2)$, where R_{s0} is the residual surface resistance, ν_0 is the frequency at which R_{s0} is compared with R_s quadratically dependent of ν. From the comparison of experimental values of Q_0 at $\nu_1{=}0,352$ and $\nu_2{=}1,5$ [1, Fig. 1, Fig. 6] reduced to one temperature, it follows that $\nu_0{\simeq}3\,\mathrm{GHz}$, i.e. in these cavities Q_0 is mainly determined by R_{s0}.

Experimental dependences $Q(\bar{B}_a)$ [1, Fig. 1, Fig. 6] at $(\bar{B}_a{-}1){>}1$ are well described by formula

$$\frac{R_{sn}(\bar{B}_a,\nu)}{R(\nu)}{=}\frac{Q_0}{Q}{-}1{=}\exp\left[q(\nu,R_{s0})(\bar{B}_a{-}1)\right]{-}1 \qquad (3)$$

($q(\nu,R_{s0})$ is determined by dependence $\nu(\bar{B}_a{-}1)$ and proportional to R_{s0}^{-1}). The dependence (3) on R_{s0} and

[1]In our work [2] it is silently supposed that due to the roughness of the film surface, the Bean — Livingstone barrier is absent. The detailed analysis has shown that the proposed model of penetrating toroidal fluxons is false. If only two fluxons of this type are produced in every period in the cavity, they yield the power of $P_f{\simeq}5\cdot10^{-2}\bar{B}_a\mathrm{W}$ moving under the influence of the current screening the RF field. This model can explain a sharp fall of Q-value at $B_a{>}B_{ct}$ in the cavities of the bulk Nb [7].

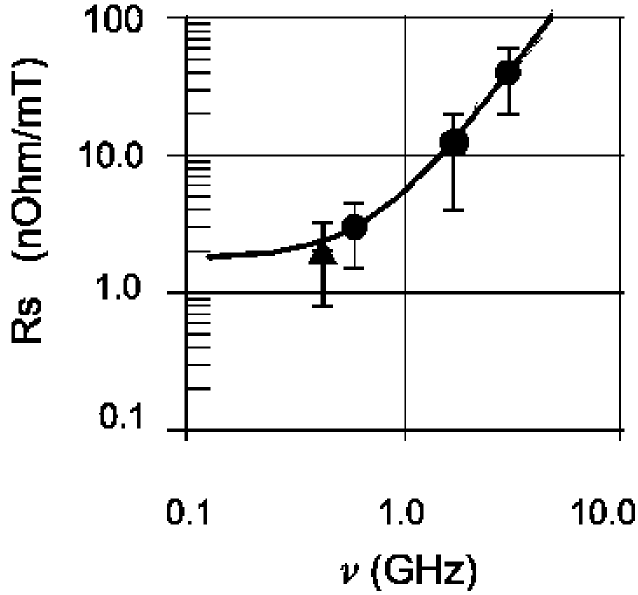

Figure 1: Dependence $R_{sn}^{'}$ NbCu cavities on frequency ν. Dependence (2) is normalized on the data at $\nu{=}0,5\,\mathrm{GHz}$, $\nu{=}1,5\,\mathrm{GHz}$ and $\nu{=}2,79\,\mathrm{GHz}$ — •.

$\bar{B}_a$ is in a good agreement with [4, Fig.6]. From the comparison of dependencies (3) at $\nu{=}0,352\,\mathrm{GHz}$ and $\nu{=}1,5\,\mathrm{GHz}$ we obtain $\nu_i{\simeq}1\,\mathrm{GHz}$ at $(\bar{B}_a{-}1){>}1$ (at $(\bar{B}_a{-}1){\leq}1$ $\nu_i{\simeq}0,5\,\mathrm{GHz}$). It is seen that ν_i grows with increasing $(\bar{B}_a{-}1)$ that reflects relative reducing of the contribution of fluxon interaction forces as well as of annihilation process into non quadratic losses. Dependence (3) on B_a reflects non quadratic dependence of the density of the total fluxon length $f(\bar{B}_a{-}1)$.

Thus, the picture of non quadratic losses, defined by the roughness of the Nb film, is in a good agreement with well known experimental results.

3 MAGNETIC CHARACTERISTICS OF THE NIOBIUM NITRIDE — NIOBIUM FILMS

Expecting production of screening and protecting NbN layers in the NbCu cavities, we have studied superconducting properties of two-layer NbN/Nb and three-layer NbN/Nb/NbN films sputtered by the planar magnetron at the room temperature of the substrate (silicon). The results of experimental research are given in the table below. All the films were obtained at the pressure of working gas of 2.2 Pa. B_{c1} measured at the temperature of 4.2 K.

	Nb	NbN	NbN/Nb	NbN/Nb/NbN
d,nm	300	300	300/200	300/200/50
$\mathbf{B_{c1}}$,mT	**7**	**6**	**20**	**23**
T_c,K	9,9	14,2	12,8	12,8
I_{mag},A	5	4,2	4,2/5	4,4/5/4,4

As it follows from the table, B_{c1} **is approximately by 3 times higher in the 2 and 3-layer films in comparison with the Nb film sputtered at the same regime of the magnetron**. The reasons of the found B_{c1} increasing are not clear yet. Probably, it happens because of interference of the NbN and Nb phonon spectra. It is not clear either how this effect depends on the ratio of the NbN and Nb thickness. Having in mind that this effect can improve the NbCu cavity properties, it is worth studying this further by means of both planar and axial magnetrons.

4 INCREASING THE CAPABILITY OF AXIAL MAGNETRON

From the comparison of the properties of Nb films sputtered with axial [1] and planar [8] magnetrons, the latter provides the better film properties. It can be explained by the capability of the used axial magnetron which is not very good [1]. To rise the capability of the axial magnetron, we offer a magnetron with the improved magnetic system [9] which is close to the capability of the sputtering process of the planar magnetron. This magnetron will allow to create the 3-layer NbN/Nb/NbN working films in the unified technological cycle at the room temperature of the cavities. These films will have a higher B_{c1} because of the higher capability of the sputtering process and in the result of the found effect of B_{c1} increasing in the 2 and 3-layer films. Besides, it is possible to expect the R_{s0} reduction at a higher rate of sputtering and, consequently, the growth of Q_0.

5 DISCUSSION

The improved axial magnetron provides a higher rate of sputtering, which should result in increasing B_{c1} and, thus, in shifting the borderline of non quadratic losses and decreasing their growth. Production of NbN/Nb and NbN/Nb/NbN structures of the working layer, as it is shown in section 3, allows us to increase B_{c1} approximately by 3 times. The roughness h of the Nb film sputtered by the magnetron method has own roughness h_{Nb} and also reflects the roughness of the copper substrate h_{Cu}. Naturally, it is possible to suppose that h_{Nb} is less than Nb grains in these films and $h_{Nb} \ll h_{Cu}$ (see [1, Fig. 4, Fig. 3(a)]), i.e. $h \simeq h_{Cu}$. Then, as it follows from (2), that non quadratic losses can decrease sufficiently by polishing of the copper surfaces till the roughness of the order of 10nm, when the fluxons do not penetrate into the hillocks. The parts of the toroidal fluxons can produce in case of the smooth working layer in the region where $B_a \exp(-x/\lambda) \sin \omega t > B_{c1}$. The picture of motion of these fluxons is analogous to the described one in section 2 at $B_a < B_{ct}$. The non quadratic losses may be expected to be small up to $B_a \simeq B_{ct}$ if the working layer is smooth.

6 CONCLUSION

To reduce non quadratic losses in NbCu cavities it is proposed to:

— smooth down the roughness of the copper substrate,

— use the improved axial magnetron providing a higher sputtering rate for Nb films,

— create two-layer (NbN/Nb) and three-layer (NbN/Nb/NbN) working films in the unified technological cycle.

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