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The Methodology for Determining the Status of Normal Domains in Superconducting thin Film From Input Signal

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ABSTRACT

The results of the study of the state of the normal domains in the superconducting thin filmfrom the input signal, which characterizes the state of S-N phase transition of the thin film, are presented.

The ratios for determining phase state and S-N phase transition duration in case of strong impulse action are obtained.

It is shown that the length of the phase transition depends on the structural parameters of the thin film, amplitude and frequency characteristics of the input signal.

The results of numerical calculations of the dependence of the length of the S-N phase transition on the amplitude of the voltage of the input signal are given.The duration of the S-N phase transition has been shown to decrease as the amplitude of the input signal increases.

The duration of the mixed state at relatively small amplitude pulses is shown to depend on the amplitude and frequency characteristics of the input signal, as well as on the structural parameters of the superconducting thin film.

Key words: inputsignal, superconducting film, protection device, S-N phase transition, duration of the phase transition.

1. INTRODUCTION

Nowadays, along with the intensive development of telecommunications, communications, navigation systems, information retrieval systems, there is a significant growth of powerful generating devices and systems based on them [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].The analysis of the functioning of powerful generating systems showed the necessity to solve the problems of ensuring the protection of radio-electronic means (REM), which are the basis of telecommunication and communication facilities, navigation systems and information extraction systems. The results of REM protection studies using plasma technologies are presented in the works [11, 12, 13, 14, 15].

1.1 Problem analysis

The principle of operation of the protective device based on the HTS is related to the possibility of carrying out a reversible S-N phase transition therein.This physical phenomenon is feasible when the current flowing through the protective device exceeds the values of the firstI_{c1} and second I_{c2}critical currents characteristic of the given device.In [1] it is noted that the length of S-N phase transition in thin HTS films under the action of kilovoltage input signals does not exceed 10^{-11}…10^{-12}s. For massive superconductors, in caseof similar inputs, the S-N phase transition time does not exceed 10^{-9} s. Suchwide variation in data is cause by the lack of theoretical bases of S-N phase transition, which determine any mechanism of breakup of superconductivity, as well as the effect on the duration of phase transition as the design dimensions of the HTS, and amplitude frequency characteristics of the input action, which makes it impossible to formulate the basic principles for the construction of the protective device on the basis of HTS with the maximum possible response time.The mechanisms leading to the normal (resistive) state of the superconducting film are: the origin of the Abrikosov vortices on the edges of the film and their movement across the film until they disappear in the center; generation and movement of Josephson vortices along the boundaries of blocks and doubles; heat propagation of normal domain boundaries formed on the Abrikosov or Josephson vortices; destruction of superconductivity by electronic heating; processes of current destruction S of the state starting at the edges of the film and subsequent movement of the normal conductivity area from the edges of the film to the center thereof.In addition, one of the factors leading to the breakdown of the superconductivity of the HTS is the appearance of normal domains under the influence of the input signals.

The object is to develop a method for determining the state of normal domains in superconducting thin film from the input signal.

2. MAIN MATERIAL

2.1 Thestudy of normal domains in superconducting thin film from the input signal

As the amount of current flowing through the superconducting film, the normal conductivity zones spread at the edges, hence the volume of the superconducting charge carrierV_S region will decrease, causing a reduction in the overall density of superconducting charge carriers in the thin HTS film N_S .The change ofV_S and $n_S^{\text{ПЛ}}$ describes the state of the S-N phase transition of the thin film.When the current reaches the $I_{c2}$the values$V_S$and $n_S^{\text{ПЛ}}$ are equal to zero, and the entire film enters normal condition.The phase state indicator can then be defined as:

$$K_S(t) = n^{\text{ПЛ}}{}_S(t)V_S(t)\,. \tag{1}$$

Taking into consideration that the reduction of the superconducting region is determined by the breakdown of superconductivity at the edges of the film in the region λ_N, the expression for $V_S(t)$ will be expressed as follows:

$$V_S(t) = V_o - 2V_N(t)\,. \tag{2}$$

The increase in the volume of the normal area $V_N(t)$ is characterized by the change in the width thereof:

$$V_N(t) = \lambda_N(t)hl\,, \tag{3}$$

where $\lambda_N(t)$ is the width of N-area, which is defined as:

$$\lambda_N(t) = \frac{2\lambda_1^2}{hI_{c1}}i(t)\,, \tag{4}$$

whereλ_1 istheinputsignalpenetrationdepth of the film;
$i(t)$ iscurrent magnitude;
h is the film thickness.

Then the expression (2) can be rewritten as:

$$V_S(t) = l\left(Wh - 4\lambda_1^2\frac{i(t)}{I_{c1}}\right), \tag{5}$$

Wis the film width.

Taking (5) into account the expression for the phase state of the thin film is as follows:

$$K_S(t) = N_S l^2 (Wh - 4\lambda_1^2\frac{i(t)}{I_{c1}})^2\,. \tag{6}$$

Thus, the mixed state (S-N phase transition) is determined by the change in the volume of the superconducting area caused by the build-up of current through the thin film, from I_{c1}up to I_{c2}.

Related to the density of superconducting charge carriers is the current density, which can be written as:

$$j_S = -i\frac{1}{\omega\mu_0\lambda_N(t)^2}\dot{E}_m,$$

or

$$j_S = -i\frac{n_S^{\text{ПЛ}}(t)e^2}{\omega m_S}\dot{E}_m, \tag{7}$$

where ω is the input signal frequence;
e is the electron charge;

$\dot{E}_m$ is the electric field intensity.

Let us similarly write an expression for current density defined by normal charge carriers:

$$j_N = \frac{e^2 n_N^{\text{ПЛ}} t_N}{m_N}\dot{E}_m, \tag{8}$$

wheret_N,m_N, are themean free time and the effective mass of normal charge carriers, respectively.

A change in $n_S^{\text{ПЛ}}$ during a S-N phase transition results in a nonlinear change in the active resistance of the superconducting film from zero to R_N, characterizing the active resistance of the film in the normal state

The analysis of the results of the experimental studies showed that the variation of the active resistance of superconducting thin film at S-N phase transition is determined by the following expression:

$$R_{S\text{-}N}(t)=\frac{\rho_{S-N}(t)l}{S}, \tag{9}$$

where S is the cross-section area of superconducting thin film;
$\rho_{S-N}(t)$-electrical resistivity of the film at the point of S-N phase transition, which can be defined as:

$$\rho_{S-N}(t) = \rho_N\frac{i(t)}{I_{c2}}, \tag{10}$$

where ρ_N- electrical resistivity ofthe superconducting filminnormalstate.

Current reaching I_{c2} means complete normalization of thin film ($R_{S\text{-}N}=R_N$). Itis evident that the normal state of K_S is equal to zero.

Thus, the phase states of the thin film in case of strong impulse action can be written as:

$$\begin{cases} K_S = N_S h^2 l^2 (W - 2\lambda_l)^2, & 0 \le t < t_{c1}; \\ K_S(t) = N_S l^2 \left(Wh - 4\lambda_l^2 \dfrac{i(t)}{I_{c1}} \right)^2, & t_{c1} \le t < t_{c2}; \\ K_S = 0, & t_{c2} \le t < t_{и}, \end{cases} \qquad (11)$$

wheret$_{c1}$, t$_{c2}$ are the timevaluesforpoints when current reaches I$_{c1}$and I$_{c2}$ respectively;
t$_{и}$is the pulse duration time.

Based on the expression (11), let us determine the duration of the S-N phase transition:

$$t_{S-N} = t_{c2} - t_{c1}. \qquad (12)$$

We select the form of the impulse action according to the expression:

$$u_1(t) = U_m (e^{-a_1 t} - e^{-a_2 t}), \qquad (13)$$

where a$_1$ = 0,7/t$_{и}$, a$_2$= 3,25/t$_{ф}$ arethe frequency characteristics of the pulse,which are related to the impulse front timet$_{и}$ and to the impulse front timet$_{ф}$.

Then, taking into consideration (9), (11) and (13), the current flowing through the superconducting film can be presented as follows:

$$\begin{cases} i(t) = \dfrac{U_m}{R_{н}} \left(e^{-a_1 t} - e^{-a_2 t} \right), & 0 \le t < t_{c1}; \\ i(t) = \sqrt{\dfrac{U_m}{A} \left(e^{-a_1 t} - e^{-a_2 t} \right)}, & t_{c1} \le t < t_{c2}; \\ i(t) = \dfrac{U_m}{R_N} \left(e^{-a_1 t} - e^{-a_2 t} \right), & t_{c2} \le t < t_{Ц}, \end{cases} \qquad (14)$$

whereR$_{н}$, R$_N$are the load resistances (50 Ohm) and thin film resistance in normal state respectively;

$$A = \frac{\rho_n l}{S I_{c2}}.$$

Thevaluest$_{c1}$ andt$_{c2}$can be defined based on the expression (14) from the equations:

$$i(t_{c1}) = I_{c1} = \frac{U_m}{R^{,}} (e^{-a_1 t_{c1}} - e^{-a_2 t_{c1}}), \qquad (15)$$

$$i(t_{c2}) = I_{c2} = \sqrt{\frac{U_m}{A} (e^{-a_1 t_{c2}} - e^{-a_2 t_{c2}})}. \qquad (16)$$

The expression (16) on a time interval can be approximated by a considerably simple analytic function

$$u_1(t) = U_m (a_2 - a_1) t. \qquad (17)$$

Then the expression (12) for the S-N phase transition duration will have the form of:

$$t_{S-N} = \frac{I_{-2}^2 A - I_{c1} R^{,}}{U_m (a_2 - a_1)}. \qquad (18)$$

The expression (18) indicates that the duration of the phase transition depends on the design values of the thin film, the amplitude and the frequency characteristics of the input signal.

The dependence of the durationof S-N phase transition on input signal voltage amplitude for the data represented in Table 1 is shown in Figure 1.

Table 1: Theparametersofthe superconducting film and the input signal

Name	**Value**
The cross-section area of superconducting filmS, m^2	$4 \cdot 10^{-12}$
Resistivity constant of HTS (YBa$_2$Cu$_3$O$_7$) in N-stateN$_n$, Ohm·m	$16{,}4 \cdot 10^{-7}$
HTS density (YBa$_2$Cu$_3$O$_7$), kg/m^3	$6{,}3 \cdot 10^3$
Width of superconducting film W, m	$40 \cdot 10^{-6}$
Thickness of the superconducting filmh, m	$0{,}1 \cdot 10^{-6}$
Length of superconducting film l, m	0,25
REM pulse duration time t$_{и}$, s	$200 \cdot 10^{-12}$
REM acceleration time t$_{ф}$, s	$5 \cdot 10^{-12}$
Superconducting electronsannihilationtime,tc	$0{,}1 \cdot 10^{-12}$
Critical current first I$_{c1}$, A	$0{,}25 \cdot 10^{-2}$
Critical current second I$_{c2}$, A	10^{-2}
Penetrationdepth$_l$, m	$0{,}5 \cdot 10^{-6}$

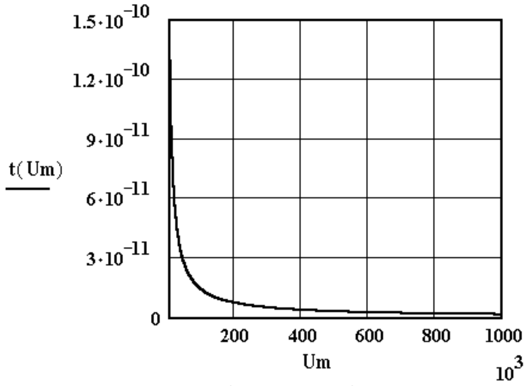

Figure1:ThedependenceofthedurationofS-Nphase transition onthevoltage amplitude ofinputsignal

An analysis of the relation represented in Figure 1 showed that the duration of the S-N phase transition decreases as the amplitude of the input signal increases. This is due to the fact that the rate of increase of the normal areas depends on the rate of increase of the input signal, which is determined by its amplitude.

The expression (18) is applicable to calculate the duration of the mixed state if the input signal amplitude is sufficiently large (more than 800 V for the calculated

REM values represented in Table 1).In such case, the time of the end of the phase transition is much shorter than the duration of the acceleration, which justifies the assumption (17).Меньшие амплитуды входного воздействия, вызывают разрушение сверхпроводимости за время соизмеримое с длительностью фронта $t_ф$входного воздействия.The smaller amplitudes of the input signal cause the superconductivity to break down in time commensurate with the acceleration time$t_ф$of the input signal.

In order to determine the length of phase transition in this case, let us introduce the restrictions on the duration of phase transition:

$$\begin{gathered} t_{c1} << t_ф ; t_{-2} \le t_ф ; \\ t_{c2} << t_и . \end{gathered} \tag{19}$$

Inthiscase, based on (19),thevaluest_{c1} andt_{c2} can be defines as follows:

$$\begin{gathered} t_{c1} = \frac{I_{-1}R'}{U_m(a_2 - a_1)} ; \\ t_{c2} = \frac{1}{a_2}\ln\left(\frac{I_{c2}^2 A}{U_m}\right). \end{gathered} \tag{20}$$

The duration of the S-N phase transition according to (12) will be:

$$t_{S-N}(t) = \frac{1}{a_2}\ln\left(\frac{I_{c2}^2 A}{U_m}\right) - \frac{I_{c1}R'}{U_m(a_2 - a_1)} . \tag{21}$$

Thus, the lifecycle of the mixed state at pulses with relatively low amplitude depends on the amplitude and frequency characteristics of the input signal as well as on the design values of the superconducting thin film.However, real REM, as demonstrated above, has sufficiently higher amplitudes (up to hundreds of kilovolts) that allows the expression (17) to be used to calculate the phase transition period.

3. CONCLUSION

The performed studies of HTS phase states have shown that superconducting thin films can be used to create protective devices with fast response time. Moreover, they can be used to create passive elements of integral ultra-high-frequency electronics such as restrictors and switches, as well as current switches.

The surface resistanceof thin film in the superconducting, mixed and normal phases is one of the main parameters characterizing the operation of such devices with low loss in passband.

The transition from the superconducting to the normal state creates the possibility to control the amplitude frequency characteristic of HTS-based devices.

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