Встановлені технологічні особливості процесу виготовлення швидкодійного високотемпературного надпровідного мікрополоскового захисного пристрою, який здатен за пікосекундний проміжок часу (час переключення або швидкодійність) обмежити потужність що проходить скрізь нього з антенно-фідерного тракту до безпечного рівня для чутливих напівпровідникових елементів приймача (запобігання струменевого руйнування p-n переходу). Дослідження дозволяють визначити особливості та умови використання сучасних технологічних методів щодо створення надпровідного мікрополоскового захисного пристрою з урахуванням впливу матеріалу підкладки, надпровідника, контактів та методу їх з'єднання на перемикаючі властивості надпровідних плівок захисного пристрою. До перемикаючих властивостей надпровідних плівок відноситься швидкість фазового переходу з надпровідного в непроводящее стан. Для визначення ступеню впливу матеріалу на перемикаючі властивості пропонується використати: параметр кристалічної решітки, коефіцієнт теплового розширення матеріалів, ступінь взаємодії молекулярних структур контактуючих поверхонь, ймовірність виникнення локальних дефектів на поверхні (зон непровідності). У роботі окреслені основні умови способи нанесення плівки, нанесення визначеної надпровідної плівки (YBCO) на обрану підкладку, які слід виконувати для створення працездатного захисного пристрою.. Результати роботи дозволяють оцінити ступінь впливу матеріалів контактів, методу нанесення на мікроструктуру (як плівку на підкладку, так і контактів на плівку) на перемикаючи властивості захисного над провідникового захисного пристрою. Такі результати можуть бути використані при синтезі високотемпературних надпровідних швидкодіючих пристроїв захисту елементів приймачів від токового руйнування p-n переходів

Ключові слова: високотемпературна надпровіднв плівка, магнетронного напилення, лазерне напилення, матеріал підкладки, контакти на надпровідники

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ANALYSIS OF THE TECHNOLOGY TO MANUFACTURE A HIGH-TEMPERATURE MICROSTRIP SUPERCONDUCTIVE DEVICE FOR THE ELECTROMAGNETIC PROTECTION OF RECEIVERS

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1. Introduction

The YBCO compound with critical temperature above 93 K, higher than temperature of liquid nitrogen (77 K), was synthesized in 1987. Since transition of such materials to superconducting state occurs at temperatures substantially higher than those of classical superconductors, they are called high-temperature superconductors (HTSC). Cheapness and simplicity of cooling the new superconductive materials with liquid nitrogen compared with liquid helium predetermined development of the lines of applied studies aimed at the use of superconductivity in technology, medicine, biology, etc. [1–3].

The high-frequency properties of HTSC have begun to be studied with the aim of improving Q-factor of resonators, filters, antennas [1, 4–6]. However, researchers and engineers were facing technological problems in introduction of HTSC structures ranging from creation of defect-free samples to construction and maintenance of a reliable nitrogen cooling system [7–9]. Such problems slowed down the process of introduction of HTSC structures, particularly into SHF systems. However, specialists have managed to overcome the difficulties with the advent of modern technologies of thin epitaxial films [9, 11]. With advance of the superconductor technology, new HTSC materials were discovered (Bi–Sr–Ca–Cu–O, T=115 K, Tl–Ba–Ca–Cu–O, T=125 K [3, 12, 13]) and methods of precise deposition of thin HTSC films were developed. These methods allow producers, firstly, to reduce size of HTSC devices and improve the Q-factor due to reduction of radiation losses, and secondly, reduce operating frequencies of the HTSC devices and extend the frequency tuning range [4]. Therefore, thin HTSC films are currently used in various SHF devices (film single-contact and two-contact superconducting quantum interference devices (SQUID), flow transformers; bolometers; filters, etc.) [1, 6–8].

Analysis of recent literature [1, 6–8] shows that the HTSC properties are rather poorly studied in this microwave range. At the same time, it became necessary to study both the HTSC properties and the materials used in this frequency range. Consequently, each HTSC device requires an individual approach, both to the choice of manufacturing technology and composition and the choice of materials with a compatible crystal lattice structure which is determined by specific destination of devices as well as peculiarities of their operating conditions.

Therefore, it is relevant to analyze modern technologies and conditions of fabrication of HTSC films, substrates, contacts, and the features of their design integration with the aim of creation of a microstrip protective superconducting devices for electromagnetic protection of semiconductor elements of receivers.

2. Literature review and problem statement

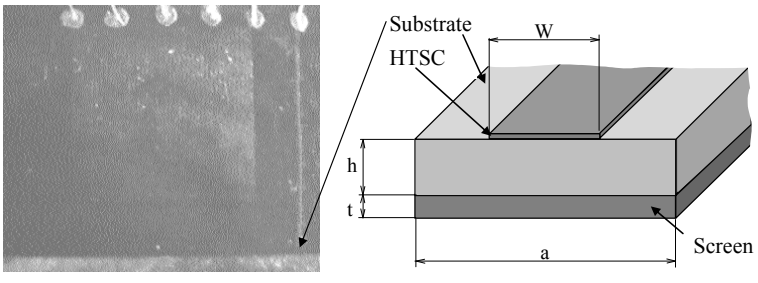
It is proposed in [1] to use a microstrip structure (Fig. 1) which limits to a safe level exposure to powerful electromagnetic effect (PEME) on the radio electronic elements of the receiver.

Absence of such protection inevitably causes disruption in operation of electronic radio equipment as a result of voltage and current induced in external and internal circuits. Such currents can bring about local release of large amounts of heat in a rather short period of time on some radio elements of the receiving device, and, as a consequence, their erosion (electrochemical) destruction [6].

Present-day studies in the theory of high-temperature superconductivity and a high level of nanotechnologies have allowed engineers to introduce the HTSC devices into microwave equipment [1, 2] (protective devices for radio communication systems, antennas, coils for medical tomographs, etc.) [3–5]. However, in connection with the specific features of the HTS protection of SHF receivers [1, 4, 16] against electromagnetic damage, objective technological difficulties arise in the choice of:

– necessary electromagnetically resistant HTSC materials and substrates compatible by their *crystal lattice structure and thermal expansion coefficient* (dielectrics are chosen depending on where and how the superconducting protection is established);

– material and method of burning low-resistance contacts into the surface of the film of the superconducting microstrip protection device (the contact transient resistance should be minimized).



a *b*

Fig. 1. High-temperature superconducting film microstrip device protecting the SHF receiver against electromagnetic damage: appearance (*a*); structure (*b*)

Studies of each design of superconducting protection require an individual approach. It is necessary to conduct separate analysis in order to select technological approaches (choice of materials for HTSC films, substrates, low-resistance contacts and the packaging method) for creating a superconducting microstrip film protective device [1] taking into account conditions of its operation in SHF devices [16–18]. Therefore, it is advisable to make a comparative analysis of the technologies used in selection of materials for the film, substrate, contacts and the procedure for assembling them in order to design the microstrip device for superconducting protection of receivers proposed in the study [1].

3. The aim and objectives of the study

This study objective is to elaborate recommendations on the use of modern methods, materials, technologies, synthesis devices to create the proposed version of a high-temperature microstrip superconducting electromagnetic high-speed (less than picoseconds) device to protect receiver elements against destruction of their p-n structures.

To achieve the objective, it is necessary to solve the following tasks:

– conduct a comparative analysis of methods for deposition of HTSC films on a substrate taking into account requirements to resistance of the protective sample to current loads (more than a megamper per square centimeter);

– determine criteria of choosing a substrate for the corresponding HTSC structure taking into account agreement of their coefficient of thermal expansion at the temperature of liquid nitrogen;

– form a list of possible technologies for making contacts to a protective device made in the form of a high-temperature superconducting film.

4. Materials and methods for creating a HTSC based prototype of a protective device

Modern technologies will be considered and technological features of construction of the HTS microstrip device for protecting elements of the receiving device against electromagnetic damage will be formulated in this study.

The principle of operation of the HTS protective device is based on the use of the phase transition of its high-temperature superconducting film from the superconducting (S) to the non-superconducting (N) (or resistive) state. The response rate (of phase transition) of such a device is less than one picosecond within the frequency band of modern measuring devices which include oscilloscopes, spectrum analyzers, etc. This response rate of the device embedded in an antenna-feeder system is high enough to limit power of a coming strong signal to a level safe for sensitive semiconducting (including digital) elements of the SHF receiver. However, conditions of use of the device and the features of operation of SHF devices predetermine requirements to accuracy of film deposition [14], choice of substrate [15] and design of a cooling system. Also, it is necessary to choose the right method of applying contacts to the surface, for example, various features for imbedding into antennas or the waveguide transmission line [1, 6, 10].

Thus, it is necessary to study modern methods for synthesizing superconducting films, choosing a substrate, and applying contacts which will make it possible to choose the technology for manufacturing a specific protective filter-limiter for a microwave device [1] based on the HTSC microstrip design.

4. 1. Basic methods for synthesis of HTSC films

4. 1. 1. The method of laser spraying

Laser deposition of HTSC films can be carried out using various spraying methods [11–17]. Choice of the method depends, for example, on composition of the spraying targets. It should be noted that composition of the obtained HTSC films must be constant [1] to create a fast-acting microstrip protective device. Even the high cost of equipment is paid off with its efficiency and ease of the process control. A generalized diagram of the experimental equipment used for laser spraying of HTSC materials is shown in Fig. 1 [11].

The laser beam is focused on the target surface inside the vacuum chamber at an angle to it. Deposition of the sprayed material on the heated substrate can take place both in vacuum and in atmosphere of a definite composition. For spraying of HTSC materials, it is necessary to use excimer lasers ArF (η=193 nm) [12, 13, 17], KrF (η=248 nm) [18–20], XeCl (η=308 nm) [21], lasers on yttrium-aluminum garnet with neodymium NdYAl (η=1064.532 nm) [22, 23]. It is also possible to use infrared CO_2 lasers (10 μm) both for spraying targets and surface modification [24]. The nature of laser ablation, that is, composition of the sprayed substance by elements, spatial and temporal distribution of the ablating torch, presence of clusters or microdroplets depend on the interaction of the focused laser beam with the surface of the solid body.

This process is quite complicated and essentially depends both on parameters of the laser beam (wavelength, energy and power, radiation quality, i.e. divergence, beam shape and mode structure) and the nature of the sprayed surface (composition, morphology).

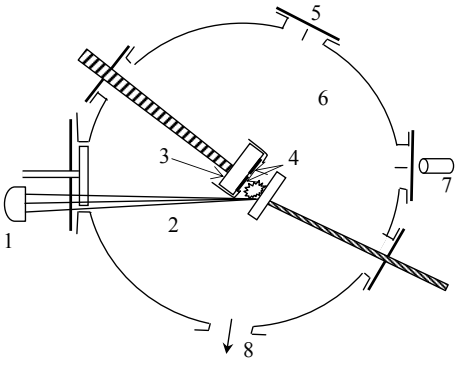


Fig. 2. Diagram of the equipment used for laser spraying of the HTSC material: lens 1; laser beam 2; heater 3; substrate 4; gas 5; rotating target 6; pyrometer 7; evacuation 8

The use of high-power lasers with a short (10–100 ns) pulse duration allows one to completely evaporate the substance from the volume of the crater formed under the action of focused radiation. Such evaporation (congruent ablation [11]) ensures escape of the target substance in integral of the same composition as the target. An increase in duration of the pulses and consequently the time of interaction of the radiation with the surface result in heating of the target volume larger than the crater. The process of thermal diffusion starts at the interface and composition of the evaporated substance differs from that of the target. When transition is made to continuous lasers, evaporation has the same character as with an electron beam. A similar process can take place during sequential irradiation of the same target site. To avoid this undesirable process, the target is continuously moved so that there is a fresh surface area under the laser beam every time. Cation composition of the film depends on distribution of the sprayed material in composition and spatial and temporal distribution of the ablation torch. A number of studies have shown that spatial distribution of the torch takes place according to this law: $\cos^n\theta$ where n=1,2; θ is the angle counted from the normal to the surface. But when counting by mass as a whole, cosine distribution proceeds quite well and characteristics of scatter of individual components can vary significantly. Graphs of scatter of individual components plotted during evaporation of a YBaCuO stoichiometric target by irradiation of Nd: YAG laser are presented in [23]. It was shown that the Y, Ba and Cu scatter indicatrices do not coincide. The mismatch of scatter direction of individual components of the target necessitates determination of the substrate position at which deviation of the film composition from that of the target is minimal. To level up composition and achieve film uniformity, substrate is often placed in a rotating holder.

Disadvantage of the laser spraying method consists in presence of microdroplets in the laser torch. Cluster particles containing tens and hundreds of molecules contribute to maintaining of stoichiometric composition and do not violate morphology of the film surface but microdroplets deposited on the surface make it rough, cause various disturbances and worsen overall quality of the film. However, fall of microdroplets on the film surface can be significantly reduced by using various screens. It is proposed in the study [24] to use the method of fast rotation of sputtered targets in which centrifugal separation of the main torch and microdroplets is achieved.

Heat treatment of films obtained by laser spraying differs fundamentally little from heat treatment in other methods of film deposition. Post-oxidation and annealing of films after their application are used. Plasma sources of oxygen activation are used for post-oxidation of films in the process of spraying as well as in other methods. As was noted, both oxygen ions and atoms have a positive effect on the film growth process during plasma activation of oxygen. Authors of study [25] in which YBaCuO films were obtained at a temperature of silicon substrate as low as 400 °C suggested that molecular ions of oxygen play the main role. However, the results of the study have shown that a stream of atomic oxygen has a significant effect on film growth as well. The results of this study were confirmed by studies [14, 26] in which dissociation of N_2O by ArG laser irradiation was used to obtain atomic oxygen. It proves the opinion that it is atomic oxygen that ensures obtaining of superconducting films at a substrate temperature of about 600 °C.

The process of laser ablation and heat treatment conditions were studied in [15, 16, 23]. However, no general recommendations for producing films by laser spraying were given. It is because spraying conditions differ greatly both in the laser structure (energy and power density, wavelength, focal spot size) and other characteristics (pressure in the chamber, substrate temperature, distance from the target). With technological advance, the process of producing films by the laser method is becoming more and more widespread since all abovementioned parameters easily vary and enable quick establishment of optimum conditions at which high-quality films are obtained. To design protective devices using the laser method, monocrystalline films with high critical characteristics were created (currents of transition of a high-temperature film into a mixed and non-conducting state). The advantage of using lasers is that laser radiation can be simultaneously used for other purposes. Rapid high-temperature laser annealing [17], substrate irradiation during spraying by the same laser radiation [16] which is used for spraying the target were used. Lasers for deposition of films with patterns were used [25–27].

4. 1. 2. The method of magnetron spraying

Magnetron spraying systems (MSS) are, in essence, diode-type systems in which interaction of electric and magnetic fields in combination with the shape of the target surface being sprayed creates such configuration of magnetic traps for electrons at which the electron drift currents close themselves (Fig. 3, 4).

As a result, three maxima coincide in the MSS [15, 16, 28]:

– the functions of distribution of electrons by energy;

– the number of ionization acts which create one electron per unit path of its directed motion;

– the number of electrons liberated from the target by one ion.

Abnormal glow discharge realized in the MSS takes place in crossing electric and magnetic fields.

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An anomalous glow discharge in the MSS takes place in crossed electric and magnetic fields. The electrons emitted in the target under the action of ion bombardment are captured by the magnetic field and complete complex cycloidal motion along closed trajectories near the target surface. As a result of multiple collisions of electrons with atoms of the working gas (usually A1), the degree of ionization increases sharply and the ion current density grows (approximately 100 times compared with the diode spraying systems (SS) without a magnetic field) which results in a substantial (50-100 times) increase in the rate of spraying of the target material.

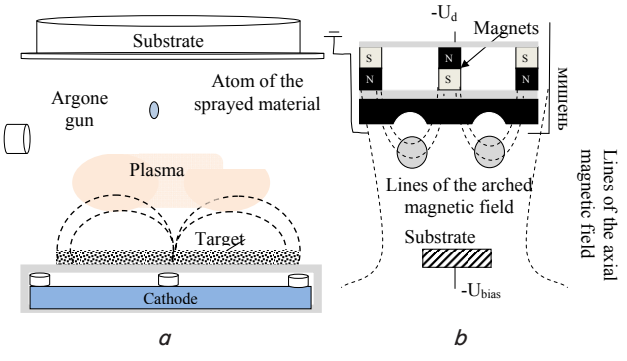

Fig. 3. The principle of operation of the magnetron spraying system (MSS): the method of magnetron spraying (*a*); the diagram of unbalanced MSS (*b*)

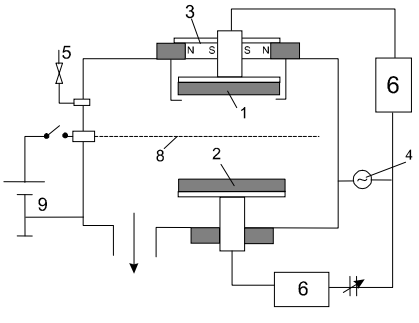

Fig. 4. A variant of structural arrangement of the MSS: lens 1; laser beam 2; heater 3; substrate 4; gas 5; rotating target 6; pyrometer 7; evacuation 8

The superconductor can be sprayed using non-balanced magnetrons (NM) (Fig. 3, *b*). The magnetron is called non-balanced because along with the main arch magnetic field formed above the target surface, there is an additional axial magnetic field leaving the target for the substrate. When a negative potential, –Ud, is applied to the magnetron target, an anomalous glow discharge is ignited above its surface. Electrons of the discharge plasma in their cycloidal motion along the force lines of the arch magnetic field ionize the working gas, argon (Ar). Ar^+ ions accelerate in the near-cathode electric field of the target and bombard its surface. The process of target spraying results in that metal atoms are released from its surface. They correspond to the target material (e. g. Ti, Al, Cr, etc.) and have average energy from 10 to 20 eV. Also, additional secondary electrons are released. Metal atoms move to the substrate surface on which they are deposited layer-by-layer and, thus, coating is formed. However, this method requires costly equipment although film quality is higher than that of the standard magnetron spraying.

In addition to implementation of the low-temperature process organically fitting the super large scale circuit (SLSC) manufacture technology featuring submicron dimensions of the elements, the main MSS advantages de-

termining the possibility of their wide industrial use are as follows:

– higher energy efficiency of the process compared with the SS of diode and triode types and hence a higher film deposition rate. This is explained by the fact that due to the presence of a magnetic field, the high efficiency of the plasma formation process is combined in the MSS with a high spraying coefficient at ion energy of 400–500 eV, characteristic of the MSS;

– obtaining of required stoichiometry in simultaneous spraying of several targets by controlling the power supplied to each of the targets;

– the ability to control the spraying area as a result of using several independent magnetic systems;

– the possibility of changing the structure and properties of the films due to simultaneous spraying of several targets with different pressures speeds and composition of the gaseous medium (percentage ratio of Ar and O_2), the bias potential on the substrate and other methods;

– low porosity and high adhesion of films even at small thicknesses;

– lower (compared to the conventional diode SS) radiation and thermal effects on the treated structures and the possibility of their further reduction with thermal ensulation of the deposition process;

– inversion of the process enabling the use of MSS for pretreatment (etching) of the substrate and deposition of a wide range of materials;

– versatility of the process enabling deposition of virtually any material on the film substrate in a single vacuum cycle and compatibility of the process with other operations of the technological cycle of IC manufacture.

The possibility of formation in a wide range by varying parameters of the deposition process provides application of high-quality films with required properties. Being a source of the surface type and providing an opportunity of choosing configuration of the spraying zones and target shapes, the MSS provides a high deposit thickness uniformity on both plane and relief surfaces. Since the substrate is not the MSS electrode, it is possible to exert controlled influence on conditions of film formation and impart it desired electrophysical properties.

For this purpose, plates are subjected to controlled heating by a stream of charged particles with applying a bias potential (constant, adjustable or high-quality) both to the substrate holder and the MSS anode. Providing operation in a wide pressure range, the MSS makes it possible to use this parameter as a parameter controlling a number of film properties: adhesion, structure, thermal and mechanical stresses, uniformity

One of the important problems in deposition of films is ensuring maximum uniformity of the film coating thickness (in order to exclude nonuniformity of the phase transition of the HTSS film from superconducting to nonconducting state). This problem can be solved in various ways:

– choice of the shape and size of the target and location of the spray zone on it;

– simultaneous spraying of several targets;

– choice of optimal location of the substrate relative to the target;

– moving the substrate relative to the target during film deposition;

– choice of an optimal value of the working pressure.

The magnitude of working pressure has a significant impact not only on uniformity but also on the film deposition rate. When spraying a film by standard MSS, working pressure usually lies in the range of 0.1–1.0 Pa. Therefore, most of the atomized atoms undergo repeated collisions with the working gas (gas mixture) atoms on their way from the target to the substrate. As a result of these collisions, both the energy state of the particles and the trajectory of their motion change [29, 30].

Table 1

Atomic mass values of certain metals and gases

Metal or gas	Atomic mass
Aluminum	27
Calcium	40
Titanium	48
Copper	63
Strontium	88
Yttrium	89
Niobium	93
Barium	137
Tantalum	181
Tungsten	194
Thallium	204
Lead	207
Bismuth	209
Neon	20
Argon	40
Krypton	84
Xenon	131

Sputtered high-energy atoms having a large atomic mass (for example, Bi, Tl and Pb with $Am>200$) can move until their energy becomes close to thermal energy (the moment of thermolysis). In this case, the average length of their directed run is $La=L\cdot a$ (where L is the length of free run of the sputtered atom in the gas; a is the number of its collisions before the moment of thermolysis). For particles with a large atomic mass and insignificant scatter angle during collision, the distance can be taken as the length of a straight run. If the distance from the spraying point to the condensation point is $r<L_0$, then almost all sputtered particles will reach the condensation surface. If $r>L_0$, then some of the sputtered atoms will diffuse back into the target as a result of collisions. Particles having a small atomic mass (for example, Ca with $Am=40$) return to the target, mainly due to backscattering from a distance $r<L_0$.

As can be seen from Table 1, the components that make up the sputtered target of HTSC material (for example, Ca and Bi) differ greatly in their atomic mass.

In this connection, an experimental study of the effect of working gas (Ne, Ar, Xe) pressure and the target-to-substrate distance on the deposition rate and backscattering of Cu and A1 differing greatly in their values of Am is of considerable interest. It was found that with an increase in pressure (from 0.7 to 4 Pa) and a target-to-substrate distance (from 50 to 145 mm), the rate of film deposition decreased for the substrate and increased for the target. However, reverse deposition on the target occurred almost at a 2.5 times faster rate than for Cu (which in the first approximation corresponds to the ratio of atomic masses of Cu and A1). In the studied ranges of the process parameter variation, the rate of film deposition on the substrate decreased by 15–48 because of reverse deposition of sput-

tered particles on the target and the walls of the working chamber. It was found that with an increase in the power applied to the target, reverse deposition of sputtered atoms on it decreases. This can be explained by a local decrease in the working gas density in the cathode region because of its heating resulting in a decreased number of collisions of the working gas atoms with the atoms of the sprayed material and their reverse deposition on the target decreases. The studies carried out in [31] have shown that with a decrease in the operating pressure from 4 to 0.7 Pa, both the flux of neutralized ions reflected from the target and the film deposition rate increased, the latter much faster. In this case, in the total stream of atoms deposited on the substrate, the fraction of reflected particles during spraying increases from 2 to 4 for Cu in Ar, from 12 to 20 for Ti in Ar, and from 27 to 50 for Ta and W in Ne (that is, on average, 2 times). Also, the number of reflected particles increases significantly with an increase in ratio of the atomic masses of the material being sprayed and the working gas used. Since the atomic masses of Tl, Pb, Bi are more than 5 times greater than the value of this parameter for Ar, when spraying these materials, there will be a large flow of reflected high-energy particles that will bombard the substrate and the HTSC film growing on it, which can affect grain size, morphology and degree of contamination of the film as well as the magnitude of mechanical stresses. As shown in [32, 33], with the use of a planar MSS structure, energy of the sprayed particles lies in the range of 10–100 eV and grows as the atomic mass of the sprayed material increases. This energy sharply decreases and the deposition rate significantly increases simultaneously with an increase in atomic mass of the working gas (for example, when Ar is replaced with Xe). Relatively high energies of sputtered particles (about 100 eV) occur at an average value of the spraying factor, the ratios of atomic masses of the target material and the working gas (for example, combination of Ta–Ar, W–Ar) are large. In this case, heating of substrates is determined by neutralized ions rebouncing from the target. When using reactive spraying in a mixture of the working gas with oxygen, energy of the formed oxides reaches 500–1,200 eV [33]. The main substrate heating sources in the process of deposition of films using MSS include the energy delivered by sputtered atoms, released by the heat of condensation and, finally, delivered by neutralized ions [32]. As for heating through plasma radiation, it is insignificant and the effect of high-energy electrons can be eliminated, e. g. by applying a positive bias to the MSS anode or using grounded screens.

In addition to pressure, the target-to-substrate distance has a decisive influence on properties of HTSC films deposited by using MSS. It was found in [33] that when this distance in a planar HF MSS was 35 mm, transition of the film to the superconducting state began at 92 K and ended completely at 86 K. Increase of this distance to 35 mm caused a sharp 'blurring' of transition which ended at 29 K.

In addition, deposition rate of HTSC films and their composition substantially depend on the angle of inclination of the substrate relative to the target.

During the last decade, there has been an intensive development and improvement of the MSS, one of the structure versions of which is presented in Fig. 4.

A characteristic feature of magnetron deposition of HTSC films at low pressures is the intense back spraying of a growing film as a result of its bombardment with negative high-energy oxygen ions. To eliminate this phenomenon, an MSS design was used in [31] in which dimensions of the target and its annular spraying zone significantly exceeded dimensions of the substrate. The latter was placed directly above the center of the target and a screen was installed between the target and the substrate. The screen had an opening corresponding to the substrate dimensions. Naturally, the bulk of the sputtered target material was deposited on the screen, so rate of deposition on the substrate did not exceed 2 nm/min. However, the HTSC films had a distinct crystal structure and high parameters (Tc=88 K) which was explained by the authors as a result of high reactivity of oxygen and the high kinetic energy of the deposited atoms of the target material. In some designs of MSS, instead of a screen, a grid is placed between the target and the substrate to which a negative bias (–70 V) is applied. However, as indicated in [31–33], the bias applied to the grid eliminates bombardment of a growing film by negative oxygen ions and accelerates positive Ar, Y and Ba ions which, in this case, bombard the film and change its structural and electrophysical properties (which changes switching properties of the film). With simultaneous reactive spraying of three independent targets on YO_3, CuO, and BaO_2 with the help of HF MSS, bombardment of the growing film by negative oxygen ions can be eliminated if all three targets are located in the same plane around the ring and the substrate is placed above them in such a way that its projection onto the plane of this ring is located at its center [31]. Comparison of the magnetron and laser methods for synthesis of HTSC films shows a significant advantage of the latter.

4. 2. The choice of substrate of the HTSC film

To choose substrate material for a HTSC protective device (PD), it is necessary to identify four main factors that influence parameters of the HTSC film [15, 35].

1. Chemical reactions in the boundary (interferential) region between the HTSC film and the substrate. The products of these reactions resulting from contamination of HTSC films with new phases can cause loss of superconducting properties of the film and the release of copper from the HTSC film into silicon significantly change its electrophysical properties. Such heterogeneity reduces speed of the HTSC protective device which is unacceptable.

2. Mechanical stresses between the film and the substrate. These stresses can reach a significant value because of difference in thermal expansion coefficients (TEC) of the HTSC film and the substrate. For example, TEC of YBaCuO films, depending on oxygen content and the change of phase transitions during thermal cycling, is in the range of $(8.5–15)\cdot10^{-6}\cdot1/K$ while TEC of the most frequently used substrates is $5\cdot10^{-6}$ 1/K for Al_2O_3; $7\cdot10^{-6}$ 1/K for stabilized Y_2O_3; $9.4\cdot10^{-6}$ 1/K for $SrTiO_3$; $13\cdot10^{-6}$ 1/K for MgO.

3. Orientation of crystallites. The best parameters for the HTSC protective device films are obtained at a high epitaxial orientation of crystallites or in monocrystalline films. For example, lattice parameters of LaAlO (0.379 nm) are consistent with an accuracy of 1 % with the corresponding parameter for YBaCuO which gives grounds to expect high densities of critical currents in this case.

4. The value of dielectric constant and dielectric loss of the substrate material. For example, the substrates prepared of $SrTiO_3$ and used for HF devices are not suitable for protective devices because they have a very high dielectric constant (ε=100, 1000 and 18000 at τ=300.77 and 4.2 K,

respectively [35]) and have significant dielectric losses in SHF devices ($tg\delta=5\cdot10^{-6}$ and $9\cdot10^{-6}$, respectively). Significantly less losses in SHF devices are observed for substrates prepared of lanthanum aluminate $LaAlO_3$ (ε: 15 at f=1 kHz and 26 at f=0.1–1 THz, $tg\delta=6\cdot10^{-4}$ (300 K) and $5\cdot10^{-6}$ (4 K)) [35].

Choice of a substrate material for a protective device is not an easy task. On the one hand, it is desirable to have substrates with a certain crystalline structure which enables epitaxial growth of HTSC films and, on the other hand, it is necessary to apply films on widely used materials (silicon, silicon oxide, gallium arsenide, etc.).

To obtain epitaxial HTSC films, monocrystals can be used. Their unit cell parameters are close to the corresponding parameters of the HTSC films or they differ by about two times. In the first case, the crystallographic directions of HTSC films <110> will lie along the directions of the <110> type of the substrate and the mismatch can be taken with respect to the value "a"/Y_2 of the substrate (these values of mismatch are given in Table 2 [30]).

Table 2

Crystal structure and lattice constant for substrate materials

Substrate material	Crystal structure	Lattice constant	Mismatch with YBaCuO, %
$NdGaO_3$	Orthorhombic	0.38	0.42
$LaAlO_3$	Hexagonal	0.378	1.2
$LaGaO_3$	Orthorhombic	0.390	2.1
$SrTiO_3$	Cubic	0.390	2.2
ZrO_2	Cubic	0.507	6
MgO	Cubic	0.402	9

Both monocrystalline and polycrystalline substrates with thermal expansion coefficient corresponding to HTSC are required for superconducting electronics and SHF devices.

In the second case, the cracks and pores formed as a result of difference in the lattice parameters, TEC of the substrate material and the HTSC seem to be closed, "healed" due to the chaotic distribution of crystallites forming the polycrystalline film [3, 6].

These cases are especially important when constructing protective devices since the heterogeneities arising during synthesis will spontaneously trigger the switching process of the superconductor into the nonconducting state (uncontrolled protection triggering) leading to a failure of protection or signal reception process.

Therefore, for the chosen compound Y-Ba-Cu-O which has lattice parameters (Fig. 5): a=0.38; b=0.39 and c=1.17 nm, one of the most suitable materials for protective device construction is strontium titanite, SrTiO (a_0=0.39 nm) for which mismatch with the "a" parameter is 2 %, and 2 % between "c" in YBaCuO and "c" in $SrTiO_3$.

This circumstance explains the widespread use of $SrTiO_3$ substrates for obtaining high-quality YBaCuO films [35, 36]. The $YBa_2Cu_3O_7$ films on the $SrTiO_3$ substrate have a very close correspondence of the structure obtained resulting in high ordering of crystals in films. The crystal "c" axis is usually perpendicular to the substrate plane ensuring high jc values (up to $5\cdot10^6$ A/cm^2) and small ΔT (1 K) [6, 8].

The considerable cost and very high dielectric constant significantly limit the use of $SrTiO_3$, especially in SHF protection devices. Besides, it should be borne in mind that strontium is released from $SrTiO_3$ during high-temperature annealing. It replaces barium in $YBa_2Cu_3O_7$ and reduces the value of Δt_{pd} (the response time of the protective device based on the microstrip structure with a $YBa_2Cu_3O_7$ film).

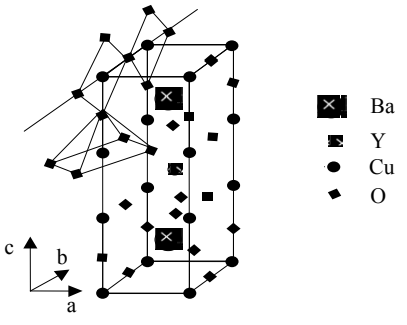

Fig. 5. Crystal structure of YBaCuO

Thermal expansion coefficient in substrates is usually lower than in films of the $YBa_2Cu_3O_7$ type (Table 3) [16] which inevitably causes thermomechanical stresses in films during their high-temperature annealing.

Thus, to create an HTSC protective limiter in an experimental sample, it is necessary to use a $LaAlO_3$ substrate on which $YBa_2Cu_3O_7$ film is sprayed by the magnetron method and contacts are burned in.

Table 3

The value of thermal expansion coefficient of materials of some types of HTSC films and substrates

Material	Average TEC value, grade, in the range	
	30–500 °C	500–900 °C
YBaCuO	1.44×10^{-5}	1.69×10^{-5}
LaSrCuO	1.44×10^{-5}	1.38×10^{-5}
$SrTiO_3$	1.02×10^{-5}	1.11×10^{-5}
Zr stabilized withY_2O_3	1.1×10^{-5}	1.03×10^{-5}
MgO	1.24×10^{-5}	1.3×10^{-5}
sapphire	0.68×10^{-5}	0.75×10^{-5}
aluminum	0.62×10^{-5}	0.7×10^{-5}
silica	$<10^{-6}$	$<10^{-6}$
silicon	2.6×10^{-6}	$>10^{-6}$
gallium-arsenide	6.6×10^{-6}	$>10^{-6}$

Note: TEC – thermal expansion coefficient

However, it is necessary to analyze whether pressing of contacts into the superconducting film will not violate properties of the protective device and from what material it should be made.

4. 3. Features of the manufacture of contacts for a protective device made in the form of high-temperature superconducting microstrip line

Choice of a specific material for making contacts of the device and the method of their manufacture depends on the intended purpose and conditions of the device operation. In this study, technology of contact choice and the method for applying them to a high-temperature superconducting film being a power limiter or a protective element for reducing level of power passing through the antenna to the receiver was studied.

To apply stable low resistance contacts [29] to the surface of a high-temperature film which will be used as the basis for the current limiter, the following conditions must be met:

– the contact should have low transient resistance at a high critical current density of the superconductor (up to 5106 A/cm^2);

– exclude, if possible, formation of oxides on contacts, that is formation of a dielectric layer on the HTSC-metal interface;

– the contact material must not enter into chemical reactions with the material of the HTSC film (otherwise, destruction of superconducting properties of the film may take place).

It is worth to bear in mind that when depositing HTSC films on a substrate, a thin dielectric layer is formed in the subsurface layer as a result of violation of the HTSC stoichiometry or crystalline structure. This layer should be removed before applying contacts to the surface of HTSC metal (usually Ag and Au). In practice, ion cleaning in in plasma of inert gases (argon more often) is used but thickness of the non-superconductive subsurface layer is reduced and cleaning does not remove gases completely since structural changes occur to a depth of up to 4 nm (breakage of Cu–O bonds and oxygen diffusion). Cleaning in oxygen plasma causes smaller changes but the whole film is sensitive to the cleaning conditions (process time, angle of ion fall on the surface). Cleaning by removal of the surface layer of the HTSC film material is also accompanied by destruction of superconducting properties of the surface. Therefore, surface of the HTSC film is a very unstable formation, so it is necessary to protect it with films of other materials immediately after deposition. Unfortunately, a very limited number of materials can be used for this purpose.

Most of the metals come into chemical reactions with the HTSC film material causing destruction of superconducting properties of the near-surface HTSC layers and oxidation in materials contacting with it. There is only a limited list of materials: Ag, Au, Pt, Ir, Ru, Rh, Pd, Os, Hg whose oxides have lower binding energy than in Cu–O. Oxide film is not formed only when Ag and Au are deposited on the YBaCuO surface, in all other cases, oxide films with thickness from 4 nm for Cu and up to 14 nm for Al are formed. The process of material oxidation is accompanied by destruction of superconductivity and formation of a 2–5 nm thick semiconductor surface layer.

5. Discussion of the results obtained in the study of the technology of manufacturing a superconducting device for electromagnetic protection of receivers

Advantages of the study:

– establishment of the technology for creating a microstrip superconducting protective device using even the same equipment that is used in application of metal superconducting films;

– determination of the substrate type (Si, MgO, $SrTiO_3$, $LaGaO_3$) having properties enabling deposition of HTSC films on them and creation on their basis an HTSC protective device that will operate (switch) at currents above the critical level (106 A/cm^2). However, before deposition of any superconductor on the substrate, it is necessary to check its compatibility with the material of the chosen HTSC protective device with respect to the crystal lattice parameters;

– establishing the technology enabling application of ohmic contacts (Ag, Au) to the high-temperature film surface. Such contacts shall not violate superconductivity of the protective device in operation (current below critical value) and transient (superconductor → not conductor) conditions or reduce speed (1 picoseconds) of current triggering of the electromagnetic protection.

However, there are disadvantages as well:

1. The superconducting and structural parameters of the films are strongly dependent on the oxygen deficiency in the $YBa_2Cu_30_{7+x}$ lattice. The phase with critical temperature *T*c~90 K and the crystal lattice parameter "c" within 1.168 to 1.170 exist only for $x<0.2$. In the case when $x>0.4$, superconductivity in YBCO is absent and the crystal lattice parameter $c>1.178$ nm. Under optimized spraying conditions and subsequent cooling, most of the films turned out to be quite well saturated with oxygen already when removed from the spraying unit. Therefore, any incorrect mode of film application may lead to oxygen saturation of the film with a loss of superconducting properties and inability to use it for synthesis of the protective device. At the same time, this is possible not only during film deposition but also during application of contacts. That is, even if all conditions were met, 30 to 40 of 100 samples produced by the magnetron method had defects. A conclusion can be drawn that a decrease in oxygen concentration not only leads to a decrease in density of carriers of electric current but most importantly, to an increase in surface resistance and, accordingly, to a decrease in critical temperature, Tc. Also, possible replacement of oxygen by fluorine is of interest. However, fluorine has lower valence than oxygen and therefore does not fall into oxygen vacancies but occupies a position between the lattice points violating stability of the superconducting phase. Nevertheless, attempts to saturate the HTSC with fluorine continue to occur and a slight increase in Tc can be expected in some cases.

2. When applying HTSC films on a substrate, a thin dielectric layer is formed in the subsurface layer as a result of violation of the HTSC stoichiometry or crystalline structure. This effect brings about a parasitic capacitance and a decrease in the protective device triggering time. Therefore, it is necessary to take measures to remove this layer before applying contacts of metal (usually Ag and Au) on the GTSC surface. In practice, ion cleaning in the plasma of inert gases (argon more frequently) is used but thickness of the superconducting surface layer decreases and cleaning does not destroy gases completely as structural changes occur to a depth of 4 nm (break of the Cu–O bond takes place). Cleaning in oxygen plasma causes smaller changes but films are rather sensitive to the cleaning conditions (processing time, angle of ion falling on the surface). Cleaning by removal of the surface layer of the HTSC film material is also accompanied by destruction of superconducting properties of the surface. Therefore, surface of the HTSC film is a very unstable formation, so it is necessary to protect it with films of other materials immediately upon deposition.

3. What was not made in the study:

– analysis of the amplitude and frequency response of the proposed superconducting protection device;

– studies of possible degradation of the superconductor during its long-term operation in the SHF range.

4. The studies mentioned but did not explain that the superconducting film can be restored after current destruction.

However, the above disadvantages and technological problems do not limit the possibility of incorporation of high-temperature superconducting films into SHF devices. For example, superconducting microstrip antennas are being developed in the USA, Germany, Japan for space stations of

cellular communication (5G, 6G technologies) and the high-speed electromagnetic sensitivity of HTSC films is already taken into account.

The study reveals technological features of manufacturing the superconducting protective device given in [1, 6]. However, improved technologies make it possible to create multilayer HTSC systems that will not only limit powerful signals to a safe level but also solve complex problems of SHF signal processing.

6. Conclusions

1. The laser synthesis method is the most convenient for manufacture of HTSC films: it is sufficiently reliable, ensures a high deposition rate (up to 50 nm/min), however, the magnetron method is more suitable for manufacture of thin films embedded in low-current protective systems as it ensures necessary quality level in less than 1-micron thick films.

2. The studies have shown that $LaAlO_3$ substrates significantly exceed all other substrates (Si, MgO, $SrTiO_3$, $LaGaO_3$) in critical characteristics (*Tc*, *jc*), the degree of interaction of the protective device film with substrate, consistency of lattice constants, TEC and the level of losses in the SHF range. For example, the lattice constant of $LaAlO_3$ (0.379 nm) is consistent (with accuracy of 1 %) with the corresponding parameter of $YBa_2Cu_3O_7$ compared with accuracy of up to 10 % for a $SrTiO_3$ substrate. Dielectric constant of a substrate made of $LaAlO_3$ does not exceed 17 at 53 GHz and at 77 K and frequency of 10 GHz, the coefficient of dielectric loss is 10^{-4}. Such high properties of $LaAlO_3$ enable its use in creation of a HTSC-SHF film protective device. $LaGaO_3$, can also be used, however, it has an orthorhombic structure which often leads to formation of twinned crystals.

The best parameters of HTSC films are obtained at a high epitaxial orientation of crystallites in monocrystalline films. For example, lattice parameters of LaAlO (0.379 nm) are consistent (with an accuracy to 1 %) with the corresponding parameter for YBaCuO which makes it possible to expect obtaining of high densities of critical currents.

3. Of all currently known methods of making ohmic contacts, two are the most suitable. In the first of them, before deposition of Ag or Au, surface of the HTSC film is cleaned from the nonsuperconducting phase by ion spraying. In the second method, YBaCuO films are grown in presence of oxygen and annealed at T=850 °C and a high rate of temperature build-up while Au is deposited at T=20 °C, immediately after cooling the YBaCuO film without vacuum disturbance. The minimum resistance achieved at HTSC-film-normal metal interface is 10^{-10} Ω·cm^2 which makes it possible to recommend their use to ensure a smooth current flow from the HTSC film of the protective device through the contacts to the wired communication lines.

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