Thin-Film Aluminum Microstructure as a Hot-Electron Microwave Radiation Detector

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We have found that the thin film aluminum structures shaped into a chain of micron sized islands connected by narrow isthmuses can modify their electrical and structural properties under microwave radiation. As a result, at the temperature of 4.2 K the film structures turn into a kind of lateral periodic structure N-S-N, where N is for normal islands, S is for superconducting isthmuses. Current-voltage characteristics of the samples, as well as changes of these characteristics under low power radiation, have been studied over the temperature range from 1.3 to 10 K. The sensitivity of a structure as a microwave detector runs $10^5$ V/W.

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Currently, scientists apply themselves to a search and development of highly sensitive detectors and mixers for UHF and IR diapasons. In particular, radioastronomy makes high demands of such devices. The up-to-date detectors are based on quantum principles. A penetrating quantum of electromagnetic radiation (photon) produces quasiparticles (current-carriers usually) in the material of a detector. As a result, electrical properties of the detector change. These changes are fixed by the next following blocks of a receiver. Effective transformation of photons to quasi-particles as well as a small or stable number of background particles are necessary to provide a high sensitivity of a detector. Such requirements determine the materials of the detector, namely, they are semiconductors which possess a few carriers or superconductors with a few normal excitations at $T < T_c$, whose number is guaranteed by low working temperatures of the detector. Contemporary detectors with a superconductor as a sensitive element are of two types of structures: superconductor-isolator-superconductor (SIS-detector or mixer) and superconducting submicron bridge between the sides of a normal metal (N-S-N - hot electron detector or mixer). Another important thing to improve the reliable work of the detector is to match the resistance of the structure with the impedance of the microwave system, to which the detector belongs. The desirable magnitudes of resistance should hit into the range from 10 to 100 Ω. To find a built-in detector of microwave radiation, which could be suitable for low temperature devices, we have studied the chain of metal film islands (each size was about 1 μm) connected by isthmuses 0.1 μm in width.

The main measurements were carried out on the aluminum structures. The aluminum film about 100 nm thick was deposited on the Si substrate masked by photoresist. To form the drawing on the aluminum film, the liftoff process was applied. As a result, the structure consisting of a chain of triangles (rhombuses) was formed. All the triangles (rhombuses) were bound by the top of one triangle to the basis of the next one (the top of the previous rhombus to the top of the next one). The side of a triangle was 1 μm, the width of a contact was about 0.1 - 0.2 μm. Fig. 1a presents the SEM image of the fully proceeded structure. The structure was surrounded with the electrical gold layout, which allowed CVC (current - voltage characteristic) to be measured. The main experimental results of the given paper were obtained for rhombuses. An understanding of CVC structures consisting of triangles. To be irradiated by the electromagnetic field (38 GHz) the sample was placed into the slit of the wave-guide centered against its wide wall along its axis. The narrow wall of the wave-guide was narrowed up to 0.5 mm in order to allow the sample to tie built into the continuous current measuring circuit after it was placed into

FIG. 1: SEM image of the sample: a) after the preparation process; b) after the first modification and measurement; c) after multiple modifications.
the microwave cell. The narrowing of the wave-guide aimed simultaneously to make a concentrator of the electric field. The output power of the applied oscillator reached 10 mW. To change the microwave field on the sample, a microwave attenuator was applied. The prepared inset based on a wave-guide was mounted in the helium cryostat. The setup allowed us to measure the CVC characteristics over the temperature range from 1.3 to 10 K under the electromagnetic irradiation of the different power. The preliminary measurements showed the linear behaviour of CVCs of the structures, the resistance ratio was $R_{300}/R_{4.2} \approx 20$. The resistance of each sample at 4.2 K was about 6 Ω. Then the sample was exposed to microwave irradiation at helium temperature (the input power at the wave-guide section containing the sample ran up to 10 mW). The variations of CVC began to manifest at the power of about 0.1-1 mW. Then the resistance of the structure decreased to 2 Ω at small bias voltages and at the same temperature of 4.2 K the samples demonstrated rather unexpected behaviour of CVCs, which was very similar to those of superconducting one-dimensional channels with the phase-slip centers (Fig. 2, curve 4.2 K). The linear CVC corresponding to the 2 Ω resistance was observed up to the current $I_{c1}$ (from 10 to 100 μA, for different samples). At the current $I_{c1}$ an abrupt voltage increase was observed, corresponding to an increase of the resistance of the structure. As current increased the current the CVC transformed to a broken line consisting of linear sections connected by the sections of a voltage sharp increasing. The slope of linear sections was divisible by 10 or 20 Ω for the structures consisting of triangles or rhombuses, respectively. Fig. 2 presents the CVC measured at different temperatures for one of the samples. At temperatures higher than 6 K, the samples demonstrate linear CVCs, which correspond to the resistance of about 100 Ω. It should be noted that about ten samples were measured, so the above mentioned resistance are to be taken for an order of magnitude. As the temperature decreases below 6 K, a non-linearity occurs at small voltage shifts, which corresponds to the abrupt decrease of the resistance in the case. The CVCs have the form of a broken line in the temperature range from 4.2 to 1.5 K, their resistance are 2 Ω for the currents lower than those at the first stage. The resistance disappears below 1.4 K at this stage, and the aluminum structure transforms into the superconducting state.

As a result of the study of more than ten samples, we concluded that, the behaviour of the samples corresponded, on the whole, to the properties of the periodic superconducting - normal chain. Some parts of the chain (islands) were in the normal state while the others (isthmuses) were superconducting. Such the unexpected behaviour (the critical temperature of the superconducting transition of aluminum runs 4.2 K) testifies to the change of properties resulting from our manipulations with the sample. The microwave irradiation can be in our opinion such a provocative factor. It should be noted that the modification described was obtained in all the samples under investigation. Fig. 1b presents the SEM image of the structure which possesses the above mentioned properties as exposed to microwave irradiation and measured in liquid helium. Some changes can be observed nearby narrow places as compared to Fig. 1a. They are due to the changes in structural properties of materials (CVC changes) as well as to the material transfer (vagueness nearby isthmuses). Fig. 1c represents the micrograph of the sample which was multiply exposed to the microwave irradiation. Drastic changes of the sample shape already took place. The rhombuses were transformed to "circles", which are connected by strips of the modified material. Noticeable migration of the material in the sample under the microwave irradiation is observed in an electron microscope. The structural changes also take place, which result in new electrical properties of the sample.

After the CVC of the sample became non-linear due to our manipulations, we studied its variation under the low power microwave irradiation. Fig. 3 presents CVC recording at 4.2 K. Damping decrement along the microwave path is indicated in decibel as a parameter for the curves. It is evident from Fig. 3 that microwave irradiation results in the total voltage increment of the structure (at the constant current) as well as in the shift of voltage increment steps towards lower currents. The inset in Fig. 3 demonstrates the dependence of the first CVC current step position (Fig. 3) on the microwave radiation power at the entrance to the wave-guide section. The position of the step is proportional to the microwave power. The value of slope $dV/dI$ can be estimated from this dependence. The product of this derivative by the step resistance $dV/dI$ is the sensitivity of our structure as a detector. According to our estimate, the value of the
sensitivity is $10^5$ V/W within the region of CVC steps.

Fig. 4 presents CVC of the aluminum sample (chain of rhombuses) which was exposed to, so to speak, the minimum dose of irradiation as follows: the current of 30 $\mu$A was conducted through the sample at 4.2 K. The microwave oscillator was turned on by a meander stated under the regime of modulation at the frequency of 1 kHz. The signal was transmitted from potential contacts of the sample to an oscillograph. The attenuator of the microwave track was gradually opened. At the particular moment (20 dB for the given measurement) the signal of the modulated microwave power appeared abruptly. After that the attenuator was closed and CVC measurements were fulfilled at the larger attenuation in the microwave track. As evidenced by Fig. 4, the characteristic features of the CVC of the sample are analogous to those presented in Fig. 3, except for the transition between ohmic parts realized by leaps from one state to another and vice versa. An instability manifests itself in both superconducting and resistive states of an isthmus. It is necessary for the existence of such an instability that the other state of the system should be more energetically profitable than the starting one, no matter what kind it is: resistive or superconducting. In this case the system of carriers will try to transform from one state to another. In the opposite case only hysteresis would simply be observed.

As a result of manipulations at helium temperature, our periodical aluminum structure gained new properties which are of interest from the practical and scientific viewpoint. CVC and the SEM image show that at 4.2 K the sample proved to be a sequential chain of triangles (rhombuses) of the normal metal connected by superconducting isthmuses. The initial section of CVC with the resistance of 2 $\Omega$ corresponds to the normal state for the general area of a triangle, except for a contact tip, while the isthmuses proved to be superconductors with the transition temperature up to 5.8 K. The critical current and critical temperature are not the same for each isthmus because of their different sizes. Consecutive abrupt voltage increments corresponding to the transition of each isthmus to the resistive state were observed as the resistance of all the structure increased by the value of the isthmus resistance. These speculations completely embrace the results of the experimental observations of the CVCs’ behaviour.

The resulting structure looks as an alternation of parts of relatively large normal metal sections bridged by superconducting isthmuses, which corresponds to a series of consecutive "hot electron detectors". The structure does not change until the temperature of the transition is reached and becomes superconducting below this temperature (about 1.3 K). Some advantages should be mentioned as compared to traditionally used "hot electron detectors". The structure consists of the single material being in two different solid states. Such the structure can facilitate the exit of hot electrons from superconducting parts as compared to the case of heteroboundaries in traditional detectors, whose ability can result in the improvement of frequency characteristics of the detector at the mode of the diffusion exit of carriers. The ohmic resistance of the structure and its elements hit into the suitable range to provide the matching with the microwave track or with an antenna. Unfortunately we have no the certified devices to measure the sensitiv-

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**FIG. 3:** Change of the current - voltage characteristic, effected by microwave irradiation of different powers. Attenuation in decibels is specified as a parameter for the curves: (a) 70 dB; (b) 60 dB; (c) 50 dB; (d) 45 dB; (e) 44 dB; (f) 43 dB; (g) 41 dB. The inset shows the dependence of CVC, first step position on the current curve, on the microwave power.

**FIG. 4:** Current - voltage characteristic of the sample effected by microwave irradiation. Attenuation in decibels is specified as a parameter.
ity at extremely low levels of the microwave power and to compare with the background.

The behaviour of the material at the liquid helium temperature under the action of the microwave irradiation proved to be the most enigmatic result among the above described. Such a scaling low-temperature migration of aluminum under ordinary conditions has not, probably, been observed before. Material science investigations are required in this case. First of all, the question arises: what is the microstructure of modified areas and what is a role (or a mechanism) of the microwave effect? The similar experiment carried out with the Bi samples did not show any changes in them under the microwave irradiation. The interest in Bi is due to the fact that the amorphous Bi modification is superconducting at the temperature below 5.5 K.

From the viewpoint of the scientific interest the above described samples are considered to be the lateral structure N-S-N in which parts of films of different materials do not overlap. The properties of isthmuses (the volume of the superconducting phase) can relatively smoothly change directly in the process of measurements at the helium temperature. In the light of stated above it is interesting to carry out more detailed measurements of CVC and their derivatives.

The experimental results obtained in the work have shown that the aluminum samples shaped into a chain of islands connected by narrow isthmuses modify their electric and structural properties under the microwave irradiation at the liquid helium temperature. As a result of the modification, they transform into the periodic lateral structure N-S-N at 4.2 K, where N is for normal islands, S is for superconducting isthmuses. The CVC of the samples as well as their changes under the low power microwave irradiation were studied at different temperatures in the range from 1.3 to 10 K. CVCs of modified chains proved to be broken lines with the sections of the abrupt voltage increment corresponding to the consecutive transition of the superconducting isthmuses to the normal metallic state. The sample sensitivity as a microwave detector is $10^5$ V/W in the region of the transition between linear sections of the CVC.

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