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Microwave Detection Properties of Asymmetrically Narrowed $YBa_2Cu_3O_{7-x}$ Structures

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Results of our research demonstrate possibilities of detection of microwaves radiation by means of asymmetrically narrowed $YBa_2Cu_3O_{7-x}$ oxygen-rich ($x \leq 0.2$) and oxygen-decomposed ($x > 0.5$) in the necked region at temperatures higher than the critical temperature of the superconductor T_c at which superconductor exhibits properties of a heavily-doped semiconductor. Both types of structures, mounted into a 10 GHz waveguide, generate sub-linearly increasing amplitude of detected voltage with increase of incident power of pulsed 10-GHz-frequency microwave radiation. The voltage sensitivity $S_{x \leq 0.2} \geq 1.3$ mV/W of oxygen-rich and $S_{x > 0.5} \geq 9$ mV/W of oxygen-decomposed structure were measured at room temperature. Asymmetrical shape of nonlinear current-voltage dependences depend on oxygen content x in the necked region and temperature of the tested structure. Our results show that the asymmetrically narrowed structure with a necked region down to 10 μm made of partially deoxygenated $YBa_2Cu_3O_{7-x}$ superconductor can be used as a nonsuperconducting, nonlinear on-chip element (detector of MW power) in the $YBa_2Cu_3O_{7-x}$ chip operating at temperatures below critical temperature T_c of the chip superconductor.

Keywords: high-T_c-superconductor, microwaves detection, oxygen stoichiometry, critical temperature of superconductor.

1. INTRODUCTION

Analysis of high-T_c superconductors (HTS) indicate that they have comparatively short coherence length of order of the size of unit cell and that, due to strong electron-phonon coupling, exhibit properties of heavily-doped semiconductor at temperatures above critical temperature of the superconductor T_c. The electric and magnetic properties of the cooper oxide based HTS materials, like those of $ReBa_2Cu_3O_{7-x}$ (Re = rare earth chemical elements), are sensitive to oxygen numeric concentration x [1]. It was experimentally demonstrated that the critical temperature T_c as well as critical current density J_c and the first critical magnetic field H_{c1} of the oxygen decomposed $YBa_2Cu_3O_{7-x}$ superconductor at temperatures $T < T_c$ decreases with decrease of the oxygen content x in it [2].

Superconductors reveal themselves as ultrafast (~ 1.5 ps [3]) and ultrasensitive detectors of photons not only in visible but also in IR range [4] because of material's quantum nature, low electric noise, cryogenic operation environment, and extremely narrow superconducting energy gap 2Δ (2Δ ~ 32 meV, for $YBa_2Cu_3O_{7-x}$ [5]) which is more than two orders of magnitude narrower than in semiconductors. The intergrain weak-links, screw dislocations and other two- and three-dimensional defects in the superconductor exhibit comparatively lower T_c, J_c and H_{c1} if compare with defect-free volume of the material. Therefore, they strongly influence the absorption of microwaves (MW) power by HTS. Structural defects also determine the temperature dependence of the MW power dissipation [6] taking place in superconductors due to different relaxation of excess energy of thermally excited charge carriers in the material at various temperatures [7].

As it was also shown experimentally [8] and theoretically [9] the absorption of MW power by the monocrystalline superconductor can be associated with energy dissipation in resistively shunted conductive *S*-*N*-*S* junctions at temperatures $T < T_c$ (here *S* and *N* stands for superconducting and nonsuperconducting or normal state material, respectively), emphasizing the significant role of flux motion [10] and pinning in the mixed state of the type-II superconductors. Flux motion can be controlled by means of introducing into the superconductor the asymmetric magnetic pinning centres [11], which play role of reversible rectifier of the vortex flow in the superconductor. Moreover, the external magnetic field and input current strength can tune both the polarity and magnitude of the rectified vortex flow [11].

Our work is devoted to investigation of the asymmetrically-necked superconducting $YBa_2Cu_3O_{7-x}$ structures, which exhibit nonlinear asymmetric current-voltage dependences at temperatures above T_c. Strong coupling between electrons and phonons in our tested superconductor impedes investigation of hot carrier phenomena that takes place in semiconductors as well. Investigations of hot electron electromotive force arising in asymmetrically-necked structures of heavily-doped *n*-GaAs thin film mesas with neck shaped down to submicron dimensions revealed the dependence of voltage sensitivity of the structure on the size of the neck [12]. Therefore electric properties of normal sate $YBa_2Cu_3O_{7-x}$

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structures at temperatures ranging above T_c are explained by means of free carrier nonuniform heating phenomena [13]. However, at temperatures $T < T_c$, when $YBa_2Cu_3O_{7-x}$ material obtains the superconducting state, electric properties of this structure is predetermined by a dissipative motion of Abrikosov magnetic vortices [6] which are oriented perpendicularly to the biasing current direction.

2. SAMPLES AND EXPERIMENTAL SETUP

0.3-µm-thick $YBa_2Cu_3O_{7-x}$ films were manufactured using metalo-organic-chemical-vapour deposition (MOCVD) method onto monocrystalline $LaAlO_3$ substrates. X-ray diffraction results show that the epitaxial $YBa_2Cu_3O_{7-x}$ films were of orthorhombic crystalline structure with *c*-axis oriented perpendicularly to the substrate's plane. High quality superconducting films were characterised by the zero-resistivity temperature $T_{c0} = 91$ K, the material's superconducting transition width $\Delta T_c = 0.4$ K, and its critical current density J_c (78 K) ~ 1.7 MA/cm^2 at 78 K ambient temperature. Electrodes for measurements of electric properties were produced by means of ~ 0.1-µm-thick silver film thermal evaporation onto surface of the superconducting film at room temperature. After silver deposition, the $YBa_2Cu_3O_{7-x}$ film was additionally annealed at 375 ºC for 1.5 h to obtain four low resistivity electric probes.

The testing structures were made of $YBa_2Cu_3O_{7-x}$ films by means of photolithography and chemical etching. The typical asymmetric shape of the structure narrowed down to 10 µm ÷ 30 µm in the neck is shown in Fig. 1.

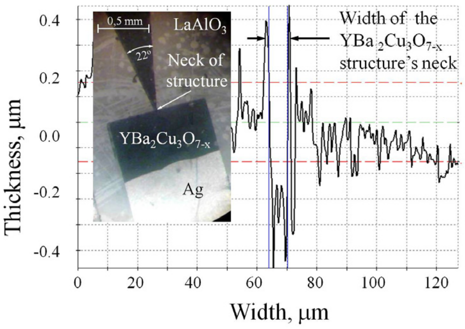

Fig. 1. Asymmetrically-necked 0.3-µm-thick $YBa_2Cu_3O_{7-x}$ structure manufactured by means of photolithography and chemical etching. The thickness and the width of the structures' neck has been measured by a profilometer

To reduce the current induced heating of the superconducting device, mounted into a 50-Ω-impedance high-frequency transmission line, the *I*-*V* dependences in temperatures range of 78 K < *T* < 300 K have been measured by means of 10-µs-long current rectangular-pulses from pulsed-current source operating at 20 Hz repetition rate.

Assuming resistivity dc-measurement results, we select two groups of samples. The asymmetrically-shaped $YBa_2Cu_3O_{7-x}$ devices of the first group were characterized by a metallic-like resistivity vs. temperature dependence in range of temperatures $T > T_c$ with the onset of the superconducting state in the device at critical temperature $T_c \sim 84$ K ÷ 85 K which is characteristic temperature for $YBa_2Cu_3O_{7-x}$ thin films with oxygen depletion level of $x \leq 0.2$ [1]. For the second group we attribute superconducting devices which did not demonstrate the superconducting transition at temperatures $T \geq 78$ K. The resistivity of those devices with temperature decrease at temperatures $T > T_c$ corresponded to the oxygen depletion level of $x > 0.5$ [1]. We suppose that the higher level of oxygen depletion occurred due to selective chemical etching of the superconducting film with structural defects (e. g. grain boundaries, screw dislocations etc.) what resulted in a decrease of oxygen content in the device's neck.

For the MWs detection measurements, the asymmetrically shaped $YBa_2Cu_3O_{7-x}$ structure has been mounted into 10 GHz waveguide (Fig. 2).

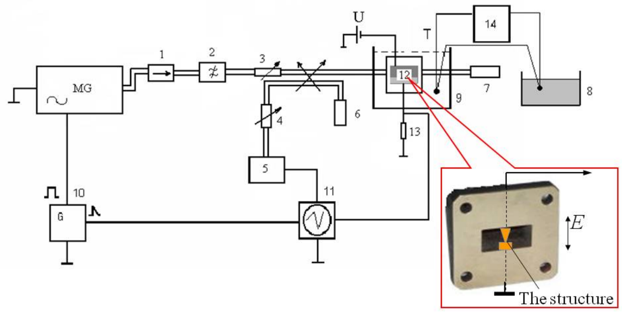

Fig. 2. The experimental setup for measurements of MW detection: 1 – isolator; 2 – filter of the 2nd harmonic; 3 and 4 – attenuators; 5 – MW power meter; 6 and 7 – matched loads; 8 – vessel with melting ice; 9 – vessel with liquid nitrogen; 10 – pulse generator; 11 – digital oscilloscope, 12 – waveguide head with a $YBa_2Cu_3O_{7-x}$ structure; 13 – load resistor; 14 – digital multimeter; T – thermocouple. *Inset*: demonstrates orientation of electric *E* component as well as position of the testing structure in the waveguide

The tested superconducting structure has been fixed at centre of waveguide, perpendicularly to its wider walls in a place of strongest MW electric field and oriented as it is shown in inset of Fig. 2. The MW absorption measurements were performed at room temperature and at temperature of liquid nitrogen. The electric field component of MW signal with adjustable electric power up to 400 W, pulse duration of 10 µs, and repetition rate of pulses 100 Hz was used. The amplitude of a detected signal by the superconducting structure has been measured by means of oscilloscope with the measurement error less than 5 %.

According to our rough estimations, the superconducting $YBa_2Cu_3O_{7-x}$ structure, located in the centre of 10-GHz-waveguide, absorbs less than 5 % part from full incident MW power [14] assuming structure's resistivity at certain temperature.

3. RESULTS AND DISCUSSION

A linear volt-watt (*V*-*W*) dependence which has been measured at room temperature for the $YBa_2Cu_3O_{7-x}$ (i. e. heavily doped/degenerate semiconductor) structure selected from the first group (i. e. $x \leq 0.2$) is shown in Fig. 3. The dependence has been measured at biasing dc-voltage of $U_b = 2$ V, connected along the testing structure in the forward and reverse directions as it is shown in Fig. 3. In addition to electric field of MWs, dc-biasing amplifies an asymmetrical distribution of electric field which affects asymmetrical distribution of electric charge density in the structure [13 – 14].

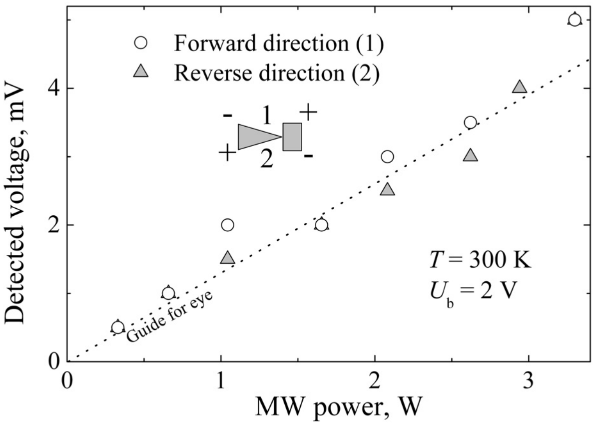

Fig. 3. The detected voltage vs. incident MW radiation power dependence at room temperature of a 0.3-μm-thick $YBa_2Cu_3O_{7-x}$ ($x < 0.2$) detector which is dc-biased at $U_b = 2$ V in forward (1) and reverse (2) directions

According to our rough estimations, 2 V bias voltage in a 10-μm-wide and 0.3-μm-thick neck of our $YBa_2Cu_3O_{7-x}$ detector creates ~12 mA direct current (current density of ~0.4 MA/cm^2) at both forward and reverse directions. At these conditions, the sensitivity of the detector is $S_{x<0.2} \geq 1.3$ mV/W. However, the value of sensitivity could be an order of magnitude higher than that one estimated from our experimental results if the detectors resistance (in this experimental case the resistance of our detector at room temperature was of 41 Ω) would match with impedance of the waveguide [14].

At larger incident MW power, the *V-W* dependence of the asymmetrically narrowed $YBa_2Cu_3O_{7-x}$ structure can change from linear into sub-linear (not shown here), following law of $U_d = 0.083 \times P(\mathrm{W})^{0.64}$ μV/W, here U_d is the detected voltage by the structure in μV and P(W) is the incident power of MW in watts. A declination from linear law of volt-watt dependence we explain by Joules heating of the tested structure. Experimentally noticeable heating takes place at incident MW power greater than 200 W.

A room temperature dependence of detected signal's amplitude vs. dc-biasing voltage of the $YBa_2Cu_3O_{7-x}$ ($x \leq 0.2$) detector illuminated with 3.3 W MW power (Fig. 4) demonstrates effect of biasing voltage onto detector's sensitivity.

The amplitude of detected voltage for both forward and reverse direction of the bias voltage increases up 7.4 mV at $U_b = 3.9$ V and then drastically drops down to value 2.5 mV at $U_b = 4$ V. The non-monotonous rise of the detected voltage in the vicinity of the $U_b = 1.8 \text{ V} \div 2$ V can be explained by improved matching of the bias-increased resistance of our detector with the waveguide's impedance. The fast drop in detected voltage at $U_b = 4$ V is associated with irreversible changes taking place in the neck region of $YBa_2Cu_3O_{7-x}$ detector and related with Joules heating of the structure biased at current density (according to our estimations) of ~0.8 MA/cm^2.

Low temperature measurements of the $YBa_2Cu_3O_{7-x}$ ($x \leq 0.2$) detectors at temperature $T = 80 \text{ K} < T_c$ showed that the amplitude of the detected voltage stays below 1 mV (i. e. sensitivity threshold of our measurement setup) in whole range of tested dc-biasing voltages.

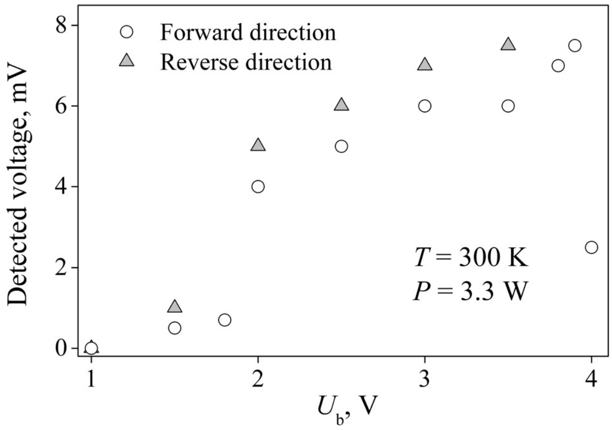

Fig. 4. The room temperature dependence of detected voltage vs. voltage of dc-biasing of a 0.3-μm-thick $YBa_2Cu_3O_{7-x}$ ($x < 0.2$) detector in forward (1) and reverse (2) directions at constant MW radiation power of 3.3 W

The typical sub-linear dependences of the detected voltage (*e.m.f.*) vs. incident MW power, measured at two different temperatures for the second group of tested samples. i. e. $YBa_2Cu_3O_{7-x}$ detectors, with oxygen depletion level $x > 0.5$, are shown in Fig. 5.

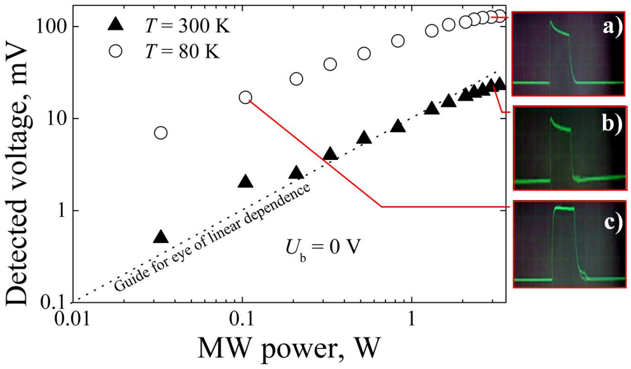

Fig. 5. The detected voltage (*e.m.f.*) vs. incident MW power dependence of a 0.3-μm-thick $YBa_2Cu_3O_{7-x}$ ($x > 0.5$) detector at temperatures $T = 300$ K and 80 K and $U_b = 0$ V. Oscillogrames a), b), c) (on the right) show 10 μs long pulse shape of MW power. Awry shape of rectangular-pulse at higher MW power (see a) and b)) confirms an onset of Joules heating effect in the detector

The amplitude of detected voltage by the tested structure increases with increase of incident MW power. The detector's sensitivity is $S_{x>0.5} \geq 9$ mV/W, calculated as a detected voltage in mV divided by incident MW power in W. The same as it was noticed for the first group of detectors, the second group also exhibits a resistance mismatch with impedance of the waveguide. This is the reason why a real sensitivity of the second group of detectors can be of order of magnitude larger than that one of estimated for perfect matching.

A sub-linear character of dependences in Fig. 5 is caused by onset of Joules heating effect in the detector.

This is confirmed by pulse-traces of 10-μs-long MW pulse. Awry shape of rectangular-pulse at power greater than 1 W (see Fig. 5, a and b) confirms a presence of Joules heating in the detector.

The Joules heating assisted change in material's electric resistivity can affect shape of sublinear *V-W* dependences. To verify resistivity change with increase of bias current and to estimate a potential of MW detection by asymmetrically narrowed $YBa_2Cu_3O_{7-x}$ structures the nonlinear current-voltage (*I-V*) dependences of both groups of detectors were measured at 300 K and 80 K temperatures.

At temperature $T = 80$ K the nonlinear *I-V* dependences of the tested devices were found to be symmetric for both bias current polarities of oxygen-rich and oxygen-deficient detectors. A decrease of amplitude of detected voltage with temperature decrease was already partially confirmed by low temperature MW measurement results.

The nonlinear *I-V* dependence of the second-type asymmetrically narrowed $YBa_2Cu_3O_{7-x}$ structure at temperature $T = 125$ K is show in Fig. 6. The positive and negative branches of *I-V* dependence are plotted in the single quadrant (++) of Cartesian system, reversing sign of negative I and U values, to see how big is the parameter $\Delta I = I_1 - I_2$ for the same bias-voltage U applied in the forward and reverse directions of our detector. Here I_1 and I_2 are current strengths at $U = \text{const}$ for forward and reverse biasing polarities, respectively.

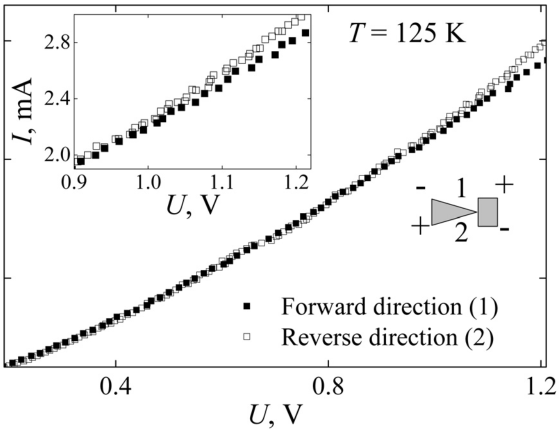

Fig. 6. The asymmetric current-voltage (*I-V*) dependence of asymmetrically-narrowed $YBa_2Cu_3O_{7-x}$ ($x > 0.5$) structure at $T = 125\ \text{K} > T_c$. Polarity of the rectangular-shape pulse of electric current and corresponding *I-V* dependence are denoted by symbols 1 (for the forward) and 2 (for the reverse) bias polarities

The differential-electric-resistance (see Fig. 6) of our device decreased from 516 Ω at $U = 0.2$ V down to 325 Ω and 330 Ω at $U = 1.1$ V, for current flow in forward and reverse directions, respectively. This property can be explained by means of high electric field assisted tunnelling of charge carriers through oxygen decomposed, insulating barriers (e.g. grain boundaries, screwed dislocations etc.) located in the structure's neck. Voltage $U = 1.1$ V in a 10-μm-long neck can create an electric field of $E \geq 100$ kV/m affecting the charge's mobility in this region. Decrease of the resistance can be also caused by current-induced Joule's heating of the detector. We suppose that inputs from both phenomena might affect the differential electric resistance of our asymmetrically narrowed structures.

The parameter ΔI, determining asymmetry of the *I-V* characteristic for the forward and reverse directions of bias current vs. bias voltage typical dependence is shown in Fig. 7. The parameter ΔI depends on current induced gradient of charge density in the detector's neck (the current density appears to be of $J \geq 50\ \text{kA/cm}^2$ at $U = 1.1$ V), what results in an asymmetric distribution of the electric field and rise of the thermoelectric phenomenon of hot carriers [13].

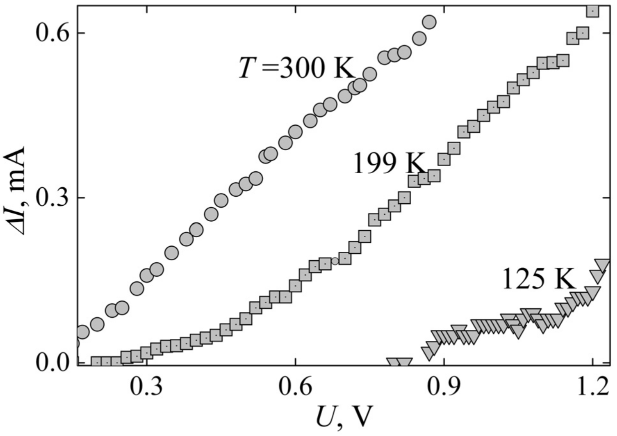

Fig. 7. The parameter ΔI vs. bias voltage dependences calculated for the same device presented in Fig. 6 at temperatures in range of $T > T_c$. In all cases $\Delta I = I_1 - I_2$ was positive

For lower x (i.e. oxygen-rich $YBa_2Cu_3O_{7-x}$ material) and for lower temperatures, the parameter ΔI decreases. Similar phenomenon has been already observed in asymmetrically-necked *n*-GaAs [12], *n*-Si materials [15] and explained by means of the electric field nonhomogenous distribution, affecting drift mobility of electric charge in the material. In our case, taking experimental values from Fig. 7, a ratio $\Delta I^{0.9\ \text{V}}(T) = (\Delta I_1 - \Delta I_2)/(T_1 - T_2) = 3.4 \times 10^{-6}$ A/K can be calculated for a fixed bias voltage of $U = 0.9$ V. It let us to conclude that magnitude of parameter ΔI, which partially determines sensitivity of the MW detector, increases with increase of temperature and biasing current of asymmetrically-necked $YBa_2Cu_3O_{7-x}$ structures operating in regime of hot carriers thermo *e.m.f.*

It is worth also adding that our tested asymmetrically narrowed structure with a necked region made of $YBa_2Cu_3O_{7-x}$ partially deoxygenated material (a controllable oxygen depletion in $YBa_2Cu_3O_{7-x}$ thin films by means of focussed laser beam was recently demonstrated in [16]) can be used as a nonsuperconducting, nonlinear on-chip element (i.e. rectifier, MW power detector etc.) in the $YBa_2Cu_3O_{7-x}$ superconducting chip, which operates at temperatures below critical temperature T_c of the chip superconductor.

4. CONCLUSIONS

1. We demonstrate potential of detection of 10 GHz frequency microwave radiation by means of an asymmetrically narrowed $YBa_2Cu_3O_{7-x}$ structures

optimally doped by oxygen (i. e. $x < 0.2$) in the necked region and structures with a reduced oxygen content (i. e. $x > 0.5$) in it at temperatures higher than the critical temperature of the superconductor T_c at which superconductor exhibits properties of a heavily-doped semiconductor. Due to Joules heating both structure types generate a sub linearly increasing amplitude of detected signal vs. power of an incident microwave radiation.

2. The voltage sensitivity $S_{x<0.2} \geq 1.3$ mV/W of oxygen-rich and $S_{x>0.5} \geq 9$ mV/W of oxygen-deficient structure measured at room temperature depend on oxygen content x in the necked region of the $YBa_2Cu_3O_{7-x}$ detector and its temperature.

3. The asymmetrically narrowed structure with a necked region made of partially deoxygenated $YBa_2Cu_3O_{7-x}$ material can be used as a nonsuperconducting, nonlinear on-chip element (i. e. diode or detector of MW power) in the $YBa_2Cu_3O_{7-x}$ superconducting chip operating at temperatures below critical temperature of the chip's material.

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