YBCO Step Edge Josephson Junction: Fabrication, Characterization, Modeling and Applications

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by

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Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy to the

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Dedicated
to
my family

CERTIFICATE

This is to certify that the thesis entitled "**YBCO Step Edge Josephson Junction: Fabrication, Characterization, Modeling And Applications**" being submitted by Sandeep Kumar to the Department of Physics, Indian Institute of Technology Delhi is worthy of consideration for the award of the degree of Doctor of Philosophy and is a record of the original Bonafide research work carried out by him under my guidance and supervision. He has fulfilled all the criteria for the submission of the thesis, which in my opinion has reached the necessary standard.

The results contained in this thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma.

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Sandeep Kumar

ABSTRACT

High temperature superconductors-based Josephson junctions have brought a new revolution in the field of superconducting electronics as they can be operated at temperatures that are achievable with single-stage cryocoolers or liquid nitrogen, which is very economical as compared to liquid helium or helium-based multistage cryocoolers. $YBa_2Cu_3O_{7-x}$ (YBCO) is the most suitable high temperature superconductor because of its high critical temperature (92 K) and ease of preparation. There are various ways through which Josephson junctions based on high temperature superconductors are fabricated; among them, step edge junctions are preferred because of their ease of fabrication and flexibility of placing them anywhere on the substrate, which makes it feasible to make high density array of Josephson junctions. However, the I_cR_n product (also called the characteristic voltage) of the step edge junctions is low, and techniques are required to improve their I_cR_n product.

In the present work, the step edge Josephson junctions are fabricated on MgO (100) substrates using the standard photolithography and ion beam etching techniques, while the superconducting film is deposited using the pulsed laser deposition (PLD) technique. In order to tune the properties of step edge Josephson junctions, the effect of step angle and the width of the microbridge is studied. The step angle is varied by varying the direction of the ion beam falling relative to the substrate, which is done by placing the substrate at different orientations with respect to the ion beam. The step angle is varied from 10° to 35° and the microbridge width and length are kept as 10 μm and 100 μm respectively. It is found that as the step angle increases, the critical current (I_c) of the junction drops while its normal state resistance (R_n) rises. The overall I_cR_n product is found to be increasing with an increase in the step angle at all temperatures from 68 K to 77 K. For the 35° step angle junction, the I_cR_n value is obtained to be 0.34 mV at 77 K. For lower step angle junctions, the superconductor grain to grain coupling exhibits more superconductor-normal-superconductor (SNS) type behavior, but as the step

angle increases, the superconductor-insulator-superconductor (SIS) type behavior becomes apparent. For studying the effect of microbridge width on the transport properties, the microbridge width is varied from 20 μm to 2 μm while keeping the step angle fixed as ~ 19° and the microbridge length as 100 μm. A decrease in the critical current (I_c) and an increase in the normal state resistance (R_n) of the step edge junctions are observed with a decrease in the width of the microbridge, while the I_cR_n product increases with a reduction in the microbridge width. The critical current density value is found to be maximum for the 2 μm wide junction. The behavior of all the junctions is superconductor-normal metal-superconductor (SNS) type. The I_cR_n product for the junction with a 2 μm wide microbridge is obtained as 0.4 mV at 77 K. When the step angle is taken to be ~ 35° and the microbridge width to be 2 μm the I_cR_n product of the step edge Josephson junction is found to be ~ 0.52 mV.

In order to understand the exact nature of the step edge Josephson junction, the I-V characteristics of the step edge Josephson junctions are simulated using the resistively capacitively shunted junction (RCSJ) model and compared with experimental results of step edge junction with step angle of ~ 35°, and microbridge width of 2 μm. When the I-V curves are simulated using the RCSJ model considering a single junction forming at the step edge, the simulated data does not fit with experimental data. However, when the I-V curves are simulated using the RCSJ model considering two Josephson junctions connected in series, the simulated data fits well with the experimental data. Comparison of the simulated curves with the experimental curves at different temperatures indicates that the noise factor increases with increasing temperature.

Another possible method to enhance the I_cR_n product of the junction is to induce oxygen vacancies in the junction area, which is achieved here by irradiating the junction area with Argon (Ar) ions for various time intervals varying from 1 min to 6 min. The junction has a step angle of ~ 35°, and a microbridge width of 2 μm. It is found that with the increase in the

exposure time of Ar ion irradiation, the value of I_c decreases, and the R_n value increases. The value of $I_c \sim 70$ μA and R_n value of ~ 9.4 Ω have been observed at 77 K after irradiating for 4 min so that the I_cR_n product of the junction is achieved to be ~ 0.66 mV at 77 K.

Finally, a DC Superconducting Quantum Interference Devie (SQUID) is fabricated on STO (100) substrate using step edge Josephson junctions. SQUID has two parallel step edge Josephson junctions with a microbridge width of 2 μm and length of 50 μm and a loop area of 20×50 μm^2. The electrical transport properties, such as R-T and I-V, and voltage-flux characteristics are studied. Furthermore, it is observed that with the increasing number of thermal cycles, the critical temperature of the device decreases, and the wettability of the device increases. In order to increase the stability of the device, passivation of the device is done using the S1813 photoresist layer. It is found that the passivated device becomes water repellent, its contact angle is 108° and does not deteriorate with long time exposure to moisture. The transport properties of the passivated device are found to remain unaffected as compared to the bare device, which makes the passivation technique effective for the operation of YBCO based devices using liquid nitrogen cryostats. The voltage-flux characteristics of the passivated SQUID are observed for a magnetic field of amplitude 6×10^{-7} T. The period of one modulation corresponds to a magnetic field of 1.2×10^{-7} T. The sensitivity of the SQUID is ~ 10^{-10} $THz^{-1/2}$.

सार

उच्च तापमान अतिचालकों पर आधारित जोसेफसन जंक्शन ने अतिचालक इलेक्ट्रॉनिक्स के क्षेत्र में एक नई क्रांति ला दी है, क्योंकि इन्हें ऐसे तापमानों पर संचालित किया जा सकता है जो एकल-चरण क्रायोकूलर या तरल नाइट्रोजन द्वारा प्राप्त किए जा सकते हैं, जो तरल हीलियम या हीलियम-आधारित बहुस्तरीय क्रायोकूलर की तुलना में अधिक किफायती होता है। उच्च क्रांतिक तापमान (92 K) और बनाने की प्रक्रिया में आसानी के कारण, $YBa_2Cu_3O_{7-x}$ (YBCO) सबसे उपयुक्त उच्च तापमान अतिचालक है। उच्च तापमान अतिचालकों पर आधारित जोसेफसन जंक्शन बनाने के कई तरीके हैं, जिनमें स्टेप एज जंक्शन को प्राथमिकता दी जाती है, क्योंकि इसे बनाना आसान होता है और इसे सबस्ट्रेट पर कहीं भी स्थापित किया जा सकता है। इससे जोसेफसन जंक्शनों का उच्च घनत्व वाला सरणी बनाना संभव हो जाता है। हालांकि, स्टेप एज जंक्शनों का IcRn गुणनफल (जिसे विशेष विभव वोल्टेज भी कहा जाता है) कम होता है और इसे बढ़ाने के लिए उपयुक्त तकनीकों की आवश्यकता होती है।

इस शोधकार्य में, MgO (100) सबस्ट्रेट पर स्टेप एज जोसेफसन जंक्शन का निर्माण किया गया है, जिसमें मानक फोटोलिथोग्राफी और आयन बीम नक़्क़ाशी तकनीकों का उपयोग किया गया है, जबकि अतिचालक फिल्म को स्पंदित लेजर निक्षेपण (PLD) तकनीक द्वारा बनाया गया है। स्टेप एज जोसेफसन जंक्शनों के गुणों को समायोजित करने के लिए स्टेप कोण और माइक्रोब्रिज की चौड़ाई के प्रभावों का अध्ययन किया गया है। स्टेप कोण को नियंत्रित करने के लिए आयन बीम के गिरने की दिशा को बदला गया, जिसे सबस्ट्रेट की विभिन्न दिशाओं में उन्मुख करके प्राप्त किया गया। स्टेप कोण को 10° से 35° तक बदला गया, जबकि माइक्रोब्रिज की चौड़ाई और लंबाई को क्रमशः 10 μm और 100 μm रखा गया। यह पाया गया कि स्टेप कोण बढ़ने के साथ, जंक्शन की क्रांतिक धारा (I_c) घटती है जबकि इसका सामान्य अवस्था प्रतिरोध (R_n) बढ़ता है। सभी तापमानों, (68 K से 77 K) पर I_cR_n गुणनफल में वृद्धि देखी गई। 35° स्टेप कोण वाले जंक्शन के लिए I_cR_n का मान 77 K पर 0.34 mV प्राप्त हुआ। कम स्टेप कोण वाले जंक्शनों में, अतिचालक से अतिचालक कण- युग्मन, अधिक अतिचालक- सामान्य-

अतिचालक (SNS) प्रकार का व्यवहार प्रदर्शित करता है, जबकि उच्च स्टेप कोण पर यह, अतिचालक-कुचालक-अतिचालक (SIS) व्यवहार प्रदर्शित करने लगता है। माइक्रोब्रिज की चौड़ाई का विद्युत परिवहन गुणों पर प्रभावों का अध्ययन करने के लिए, इसकी चौड़ाई को 20 μm से 2 μm तक बदला गया, जबकि स्टेप कोण ~19° और माइक्रोब्रिज की लंबाई 100 μm रखी गई। यह पाया गया कि माइक्रोब्रिज की चौड़ाई कम करने से क्रांतिक धारा (I_c) घटती है और सामान्य अवस्था प्रतिरोध (R_n) बढ़ता है, जबकि I_cR_n गुणनफल बढ़ता है। 2 μm चौड़ाई वाले जंक्शन के लिए क्रांतिक धारा घनत्व का मान अधिकतम प्राप्त हुआ। सभी जंक्शन अतिचालक- सामान्य चालक- अतिचालक (SNS) प्रकार के पाए गए। 2 μm माइक्रोब्रिज वाले जंक्शन के लिए IcRn गुणनफल 77 K पर 0.4 mV प्राप्त हुआ। जब स्टेप कोण ~35° और माइक्रोब्रिज चौड़ाई 2 μm ली गई, तो IcRn गुणनफल ~0.52 mV प्राप्त हुआ।

स्टेप एज जोसेफसन जंक्शन की सटीक प्रकृति को समझने के लिए, इसके I-V गुणों का प्रतिरोधी-धारिता संकुल जंक्शन (RCSJ) मॉडल का उपयोग करके अनुकरण किया गया और इसे 35° स्टेप कोण और, 2 μm माइक्रोब्रिज चौड़ाई वाले जंक्शन के प्रयोगात्मक परिणामों से तुलना की गई। जब RCSJ मॉडल में केवल एक जंक्शन माना गया, तो अनुकरित डेटा प्रयोगात्मक डेटा से मेल नहीं खाया। लेकिन जब मॉडल में दो जोसेफसन जंक्शन श्रृंखला में जुड़े माने गए, तो अनुकरित डेटा और प्रयोगात्मक डेटा अच्छी तरह मेल खाए। विभिन्न तापमानों पर अनुकरित और प्रयोगात्मक I-V वक्रों की तुलना से पता चलता है, कि रव कारक, तापमान बढ़ने के साथ बढ़ता है।

जंक्शन के I_cR_n गुणनफल को और बढ़ाने के लिए एक अन्य संभावित विधि जंक्शन क्षेत्र में ऑक्सीजन रिक्तियों को बढ़ाना है, जो कि इस शोध में, 1 मिनट से 6 मिनट तक के विभिन्न समय अंतरालों के लिए जंक्शन क्षेत्र को आर्गन (Ar) आयनों के साथ विकिरणित करके प्राप्त किया गया है। 4 मिनट तक विकिरण के बाद, 77 K पर, Ic ~70 μA और Rn ~9.4 Ω प्राप्त हुआ, जिससे I_cR_n गुणनफल ~0.66 mV तक बढ़ गया।

अंततः, एक एकदिश धारा अतिचालक क्वांटम इंटरफेरेंस यंत्र (SQUID) को STO (100) सबस्ट्रेट पर स्टेप एज जोसेफसन जंक्शनों का उपयोग करके बनाया गया। इस SQUID में दो समानांतर स्टेप एज जोसेफसन जंक्शन हैं, जिनकी माइक्रोब्रिज चौड़ाई 2 μm, लंबाई 50 μm और लूप क्षेत्र 20 × 50 μm^2 है। इसके विद्युत परिवहन गुणधर्मों, जैसे R-T, I-V, और वोल्टेज-फ्लक्स विशेषताओं का अध्ययन किया गया। इसके अलावा, कई तापीय चक्रों के साथ, यंत्र के क्रांतिक तापमान में गिरावट देखी गई और इसकी अस्थिरता में वृद्धि हुई। यंत्र की स्थिरता बढ़ाने के लिए, इसे S1813 प्रकाश- प्रतिरोध परत से निष्क्रिय किया गया। पाया गया कि निष्क्रियित यंत्र जल प्रतिरोधी बन गया, जिसका संपर्क कोण 108° था और यह नमी के लंबे समय तक संपर्क में रहने पर भी खराब नहीं हुआ। निष्क्रिय करने के बाद भी यंत्र के परिवहन गुणधर्मों में कोई बदलाव नहीं देखा गया, जिससे संकेत मिलता है कि YBCO आधारित यंत्रों को तरल नाइट्रोजन निम्नतापस्थायी में संचालित करने के लिए यह निष्क्रिय करने की तकनीक प्रभावी है। निष्क्रियित SQUID के वोल्टेज-फ्लक्स गुणधर्मों का अध्ययन 6 × 10^{-7} T चुंबकीय क्षेत्र पर किया गया। एक मॉडुलन अवधि 1.2 × 10^{-7} T चुंबकीय क्षेत्र के अनुरूप थी। इस SQUID की संवेदनशीलता ~ 10^{-10} $THz^{-1/2}$ प्राप्त हुई।

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$\mathbf{H}$	Applied Magnetic Field
$\mathbf{I_{bias}}$	Bias Current
$\mathbf{k_B}$	Boltzmann's constant
$\mathbf{C}$	Capacitance
$\boldsymbol{\xi}$	Coherence Length
$\mathbf{H_c}$	Critical Magnetic Field
$\mathbf{T_c}$	Critical Temperature
$\mathbf{I}$	Current
$\mathbf{e}$	Electronic Charge
$\mathbf{f}$	Frequency
$\boldsymbol{\lambda_j}$	Josephson Penetration Depth
$\mathbf{H_{c1}}$	Lower Critical Magnetic Field
$\boldsymbol{\lambda_L}$	London Penetration Depth
$\boldsymbol{\Phi}$	Magnetic Flux
$\boldsymbol{\Phi_0}$	Magnetic Flux Quantum
$\mathbf{M}$	Magnetization
$\mathbf{R_n}$	Normal State Resistance
$\mathbf{h}$	Plank's Constant
$\boldsymbol{\lambda}$	Penetration Depth
$\boldsymbol{\mu_0}$	Permeability of Free Space
$\boldsymbol{\hbar}$	Reduced Plank's Constant
$\mathbf{R}$	Resistance

β_c	Stewart-McCumber Parameter
Δ	Superconducting Energy Gap
δ	Superconducting Phase
I_s	Supercurrent
T	Temperature
D	Thermal Noise Intensity
H_{c2}	Upper Critical Magnetic Field
V	Voltage
w	Width of Microbridge