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Exploring the behavior of superconductors and Josephson junctions: temperature and current effects by RCSJ model

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Abstract

The behavior of superconductors and Josephson junctions with respect to temperature and current is discussed in this article. The damping nature of superconductors decreases with increase of temperature which increases the conductivity of superconductors and the current across the junction is dependent on superconducting properties of materials. The Cooper pairs that move through a superconductor without resistance across the Josephson junction determines the current through it and its dynamic properties can be affected by the vibrational energy of the atoms in the junction, leading to the creation of phonons which can interact with the Cooper pairs and reduces the current. The behavior of Cooper pairs across the junctions which describes the collective properties and temperature of superconductor can be investigated using RCSJ model. Finally, the entropy of Cooper pair can affect the temperature dependence of Josephson current, with an increase in entropy leading to a decrease in current. Through studying these properties and their interactions can help in the development of better superconducting materials for use in various applications.

Keywords
Damping nature, temperature, superconductors, Josephson junctions, Cooper pairs, RCSJ model.

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1 Introduction

Superconductivity is a fascinating area of study in solid state physics that arises from the formation of Cooper pairs, which are subatomic particles consisting of two 1/2 spin electrons. Heike Kamerlingh-Onnes, a Dutch physicist, discovered superconductivity in 1911 when studying the electrical resistance of different metals at liquid helium temperatures [1]. According to Kamerlingh-Onnes, the electrical resistance of various metals decreases around 0.08 Ω at 4 K to less than 3×10^{-6} Ω at about 3 K over a temperature range of 0.010 K.

The discovery of the Meissner effect, which occurred in 1933, led to a breakthrough in Superconducting theories, aiding the development of London equations. In 1962, British researcher Brian David Josephson made a prediction that depicts the passage of a supercurrent across a tunnel barrier and explains the quantum mechanics tunnelling of Cooper pairs under a weak link. Josephson junctions (JJ) technology has advanced since the 1960s, with early junctions made of soft materials like lead. Research on dynamical phenomena followed, such as chaotic behavior, quantum dynamics, and solitons. With the development of niobium–based technology in the 1980s and the discovery of high-temperature cuprate superconductors in 1986, JJs have become useful for building ultrafast digital circuits, large-scale integrated circuits, and ultra-sensitive sensors. They are used in medicine to measure tiny currents in the heart and brain. JJ are investigated for high-temperature superconductors and metallic low-temperature superconductors, demonstrating that they can behave as just one superconductor when two superconductors are brought closer together. The Josephson effect has significant theoretical and practical implications and has been a subject of significant research. Josephson was awarded the Nobel Prize in Physics in 1973 [2].

JJs are an important tool for superconducting electronics, including magnetometers, circuits, and quantum information. The recent studies in the dynamics of Josephson junctions have focused on investing the vortices in long Josephson junctions (LJJs) and fascinating the new field of quantum ratchets as highly coherent microwave radiation sources, radiation detectors, and the design of fluxon qubits [3]. A Simple Physical Model for JJs, Resistively-Capacitively-Shunted-Junction (RCSJ) model consists of three different channels, Figure 1 [4].

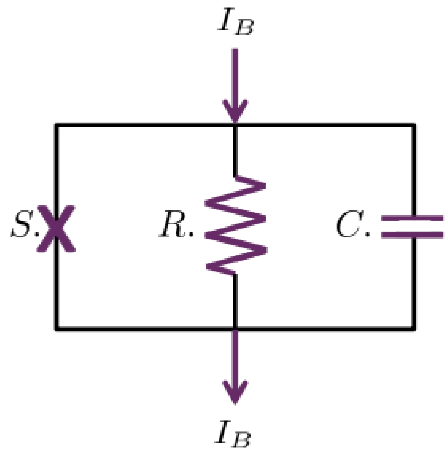

Figure 1: Simple RCSJ model.

The super current across the junction is defines as $I_s = I_c \sin\phi$ and $V = \frac{h}{4\pi e}\frac{d\phi}{dt}$, where I_c is critical current, ϕ is phase difference, V is voltage across jucntion and R is resisntance. Using an ohmic resistance in the circuit is a common way to treat quasiparticle current. In superconducting quantum interferometry applications, a parallel resistance much smaller than the junction's quasiparticle resistance is often used. This parallel resistance determines the resistance in the RCSJ model, according to Kirchhoff's law. The second Josephson equation can be used to eliminate ϕ or V, and the junction current can be written using the second law of JJ [4] for RCSJ model as

$$I = \frac{hC}{4\pi e}\frac{d^2\phi}{dt^2} + \frac{h}{4\pi eR}\frac{d\phi}{dt} + I_c \sin\phi \tag{1}$$

where R represents the normal–state resistance and C indicates the junction capacitance. It is possible to translate the equation into dimensionless form by $t \to t\sqrt{\frac{2eI_C}{\hbar C}}$ [5]

$$\frac{d^2\phi}{dt^2} + \frac{1}{Q}\frac{d\phi}{dt} + \sin(\phi) = \frac{I}{I_c} = i \tag{2}$$

where $Q = \sqrt{\frac{2eI_C R^2 C}{\hbar}}$ is called the quality factor. Researchers studied a Pb/Ag superconductor/normal metal heterostructure and found a spatially constant superconducting gap, despite differences in the individual layers' Fermi surfaces, lattice constants, and electronic densities of states. The projected spatially variable pair potential that has a discontinuity across the interface contrasts with this. The results suggest the transmission of electrons across the interface is high enough for a new band structure to emerge. More theoretical work is needed to develop predictive power for the proximity effect from realistic microscopic models [6]. The physics of solitons in Josephson junctions is a vital research field, with applications in nonlinear physics, superconductivity, and high-frequency devices. Solitons are called "fluxons" and are important due to the magnetic flux quantum ($\phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15}$ wb) they represent. Fluxons in conventional Josephson junctions are studied, including mutual coupling and interaction with the environment. An annular Josephson junction is used as an example. Fluxon dynamics in stacked junctions are also studied, including discovery of Cherenkov radiation phenomenon [7].

A cross-sectional perspective of the junction across the plane perpendicular with the exterior magnetic field (H) shows that a fluxon within a Josephson junction transports a magnetic flux that is equal to the corresponding flux quantum (ϕ_0). The junction consists of an insulator layer between two superconducting electrodes that are formed as thin films on a dielectric substrate. Circulating supercurrents act as a screen for the external magnetic field, which penetrate the bulk superconductor up to the London penetration depth (λ_L). The screening effect is weakened in the Josephson barrier region, where the magnetic field penetration distance is larger called Josephson penetration depth (λ_J). For long Josephson junction, where the Josephson barrier extends significantly beyond λ_J, the screening present tangle at the intersection edge becomes unstable in the substrate's surface plane as the magnetic field increases. This results in the formation of a Josephson vortex, which is also known as a fluxon due to the flux quantization property of superconductors [8].

Fluxons in long Josephson junctions exhibit soliton physics and can reach Swihart velocity when accelerated by a bias current. By substituting thin films of high dynamic inductance superconductor for the bulk superconductive electrodes in Josephson junctions, researchers were able to slow down relativistic fluxons. The reduced Swihart velocity and increased characteristic impedance make these junctions useful for superconducting electronics [9]. This system produces coherent terahertz electromagnetic radiation with unclear mechanism. When the current-voltage characteristic shifts from its upper to inner branches, strong radiation is produced. Parametric resonance can be achieved in the zero field step area of stacked long Josephson junctions, leading to the coexistence of fluxons with longitudinal plasma waves as collective excitations. This stack of coupled JJs serves as a laboratory for studying collective excitations in superconducting nanostructures. Modeling and simulating the phase dynamics of LJJ is a current challenge [10].

In order to comprehend the resistive transition on high-T_c superconductors and the impacts of higher harmonics, the study investigates a model of resistively along with capacitively shunted conventional Josephson junction arrays characterised by a nonsinusoidal current-phase relationship. When a cosine term is added, the global resistance is modulated, causing the weak links to transition between mixed superconductive-normal states. Josephson junction arrangements are currently being investigated for modelling processes in unstructured superconducting films and as possible superconductor quantum bits. The resistively and capacitively shunted Josephson Junction model is commonly used to describe the resistive transition in granular superconductors [11].

Microelectronics, consisting of small electrical components such as transistors, are used to control various electronic devices such as washing machines and computers. Shrinking components allows for more devices to be fabricated on a small chip and results in faster operation. As components continue to shrink, they will eventually reach a size where they need to follow the laws of quantum physics. This leads to the development of new quantum nano-electronic components. Research has been done to investigate the possibility of making devices based on the tunneling of single electrons, but it is still far from being implemented in everyday electronics. The development of quantum nano-electronic components is necessary for continued progress in microelectronics.

2 Materials and method

2.1 Current and temperature relation in RCSJ model

The probability of tunneling across a barrier affects the flow rate of particles, with a higher transmission coefficient resulting in an increase in the maximum supercurrent. In the normal state, resistance increases with decreasing transmission coefficient. Assuming paired and unpaired electrons tunnel in the same way, the product of maximum supercurrent and resistance can become independent of the barrier transmission coefficient. This relationship was first derived by Ambegaokar and Baratoff for tunnel junctions as [12]

$$I_c = \frac{\pi}{2eR_c}\,\Delta_0(T)\,\tanh\left(\frac{\Delta_0(T)}{2T}\right) \tag{3}$$

where I_c is critical current, Δ_0 is the superconductor's energy gap, and e is the elementary charge. As in this study, we use the RCSJ model to describe the total current in the Josephson junction. The Ambegaokar–Baratoff relation Equation 2.1 is used to determine the critical current I_c in terms of the superconducting energy gap and temperature. This is important because the RCSJ model requires I_C as an input parameter. By substituting this temperature-dependent I_C into the RCSJ Equation (3), we obtain a more realistic expression Equation (4) that includes supercurrent, resistive, and capacitive contributions, allowing accurate analysis of current behavior under practical conditions.

$$I = \left[\frac{\pi}{2R_c e}\,\Delta_0(T)\tanh\left(\frac{\Delta_0(T)}{2k_BT}\right)\right]\sin\phi + \frac{\hbar C}{2e}\frac{d^2\phi}{dt^2} + \frac{\hbar}{2eR}\frac{d\phi}{dt} \tag{4}$$

Also [13]

$$\Delta_0(T) = 1.763\,k_BT_c\,\tanh\left(2.2\sqrt{\frac{T_c}{T}-1}\right), \quad T \le T_c \tag{5}$$

In order to showcase the flexibility of our model, we have adjusted its parameters to suit two different SIS junction structures: Nb/AlN/Nb and $Nb/Al_2O_3/Nb$. These junctions have a critical temperature of 9.3 K and R_c=R_n=8 Ω [13]. However, the IcRN product of the junctions is notably lower than what would be predicted by the Ambegaokar-Baratoff formula, indicating that there is likely a significant pair-breaking mechanism occurring at the interfaces [14]. On solving and expending Equation (4), one can obtain

$$I = \left[\frac{\pi}{2R_Ne}\Delta_0(T)\tanh\left(\frac{\Delta_0(T)}{2k_BT}\right)\right]\sin\phi + \frac{V(t)}{R_N} + \frac{dq}{dt} \tag{6}$$

The RCSJ model also describes another variation of Equation (2), which is frequently used to represent Josephson junctions as

$$i = \sin\phi + \dot{\phi} + \beta_c\ddot{\phi} \tag{7}$$

The dimensionless Stewart-McCumber parameter is the only material-dependent parameter in this equation. Moreover, β_c can be expressed as

$$\beta_c = \frac{\pi^2 RC}{\Phi_0 e}\left[\Delta_0(T)\tanh\left(\frac{\Delta_0(T)}{2k_BT}\right)\right] \tag{8}$$

The parameter β_c controls how a Josephson junction behaves. If β_c is greater than 1, the junction is underdamped. If it is less than 1, the junction is overdamped. The current density ($j_z(x)$) across the junction can be described using the RCSJ model [15] as

$$j_z(x) = j_c\sin\phi + \frac{\Phi_0}{2\pi\rho t_b}\dot{\phi} + \frac{\varepsilon\varepsilon_0\Phi_0}{2\pi t_b}\ddot{\phi} \tag{9}$$

Here t_b is thickness of barriers and ρ is the resistivity.

2.2 Single Josephson junction (SJJ)

There is an additional set of variables for the SJJ that are defined as

$$\begin{cases} K = n_1 + n_2 \\ k = \frac{1}{2}(n_2 - n_1) \end{cases} \qquad \begin{cases} \Delta = \frac{1}{2}(\phi_1 + \phi_2) \\ \delta = (\phi_2 - \phi_1) \end{cases} \tag{10}$$

The formula utilises k to represent the difference between Cooper pairs that exist between electrodes and K to represent the total amount of Cooper pairs. The phase difference across the Josephson junction (δ) and the average phase Δ are conjugate variables to n and N. The Hamiltonian ($H(\vec{n})$ for the circuit is described in detail using the following expression [16]

$$H(\vec{n},\vec{\phi}) = \frac{(2e)^2}{2}\,\vec{n}^TC^{-1}\vec{n} + U(\vec{\phi}) \tag{11}$$

where $\vec{n}^T = [n_1, n_2]$, $U(\vec{\phi}) = -E_J\cos(\phi_2 - \phi_1)$, and $C = \begin{bmatrix} C+C_0 & -C \\ -C & C+C_0 \end{bmatrix}$ is Capacitance matrix.

The Hamiltonian from Equation (11) also can be written in more general with K zero as

$$H(k,\delta) = 4E_{C\sum}k^2 - E_J\cos\delta \tag{12}$$

where $E_{C\sum} = \frac{e^2}{2C+C_0}$ is an effective charging energy of JJ including the stray capacitance C_0.

2.3 Two Josephson junctions (TJJ)

Also, TJJ is useful to introduce the junction variables, defined as

$$\begin{cases} K = n_1 + n_2 + n_3 \\ k_1 = +\frac{K}{3} - n_1 \\ k_2 = -\frac{K}{3} - n_3 \end{cases} \qquad \begin{cases} \Delta = \frac{1}{3}(\phi_1 + \phi_2 + \phi_3) \\ \delta_1 = \phi_2 - \phi_1 \\ \delta_2 = \phi_3 - \phi_2 \end{cases} \tag{13}$$

The Hamiltonian for lower impedance is obtained [16] as

$$H = 4E_C(k_- + k_g')^2 - E_J(\delta_+)\cos(\delta_- + \gamma(\delta_+)) \tag{14}$$

where $k_- = n_2$, the conjugate variable to k_2 is $\delta_- = \phi_2$ (if $\phi_1 = -\phi_3$) which represents the phase. Moreover, $E_J(\delta_+)$ is defined as

$$E_J(\delta_+) = \sqrt{E_{J1}^2 + E_{J2}^2 + 2E_{J1}E_{J2}\cos\delta_+} \tag{15}$$

$$\gamma(\delta_+) = \arctan\left[\frac{E_{J1} - E_{J2}}{E_{J1} + E_{J2}} \tan\frac{\delta_+}{2}\right] \tag{16}$$

Here, $E_C = \frac{e^2}{2E_{C\sum}}$, $k'_g = \frac{Q'_g}{2e} = \frac{(C_1-C_2)V/2+C_gV_g}{2e}$.

In more genral, Hamiltonian of Equation (14) can be simplified as

$$H(k_-, k_g, \delta_-) = 4E_C(k_- + k_g)^2 - E_J\cos(\delta_+/2)\cos\delta_- \tag{17}$$

2.4 Thermodynamic properties of cooper's pair across junction

To study the thermodynamic properties of cooper pairs across JJ is study on the basis of partition function defined as

$$Z = \mathrm{Tr}\left[\exp(-\beta H)\right] \tag{18}$$

where H is the Hamiltonian of the system, and $Tr(A)$, stands for the trace of the quantum-mechanical operator A [17].

2.4.1 Thermodynamic properties of cooper's pairs present in single JJ of RCSJ Model

Moreover,

$$Z_{SJJ} = \mathrm{Tr}\left[\exp\left\{\beta\left(E_J\cos\delta - 4E_{C\sum}k^2\right)\right\}\right] \tag{19}$$

The mean vibrational energy across the Josephson junction is obtained as [18]

$$U_{SJJ}(\beta) = \frac{\partial}{\partial\beta}\ln Z_{SJJ}$$

$$= \frac{\exp\left\{\beta\left(E_J\cos\delta - 4E_{C\sum}k^2\right)\right\}}{\mathrm{Tr}\left[\exp\left\{\beta\left(E_J\cos\delta - 4E_{C\sum}k^2\right)\right\}\right]} \tag{20}$$

The vibrational mean free energy ($F_{SJJ}(\beta)$) across junction is obtained as

$$F_{SJJ}(\beta) = -\frac{1}{\beta}\ln Z_{SJJ}$$

$$= -\frac{1}{\beta}\ln\left[\mathrm{Tr}\left[\exp\left\{\beta\left(E_J\cos\delta - 4E_{C\sum}k^2\right)\right\}\right]\right] \tag{21}$$

The vibrational specific heat capacity (C_{SJJ}) is given as [18]

$$C_{SJJ} = k_B\beta^2\frac{\partial^2}{\partial\beta^2}\ln Z_{SJJ}$$

$$= k_B\beta^2\left[\frac{\mathrm{Tr}\left[(-E_J\cos\delta + 4E_{C\Sigma}k^2)^2 e^{\beta E_J\cos\delta - 4\beta E_{C\Sigma}k^2}\right]}{\mathrm{Tr}\left[e^{\beta E_J\cos\delta - 4\beta E_{C\Sigma}k^2}\right]} - \left(\frac{\mathrm{Tr}\left[(-E_J\cos\delta + 4E_{C\Sigma}k^2) e^{\beta E_J\cos\delta - 4\beta E_{C\Sigma}k^2}\right]}{\mathrm{Tr}\left[e^{\beta E_J\cos\delta - 4\beta E_{C\Sigma}k^2}\right]}\right)^2\right] \tag{22}$$

The vibrational entropy ($S(\beta)$) is obtained as

$$S(\beta) = k\ln Z(\beta) - k\beta\frac{\partial}{\partial\beta}\ln Z(\beta)$$

$$= k\left[\ln\mathrm{Tr}\left(e^{\beta E_J\cos\delta - 4\beta E_{C\Sigma}k^2}\right) + \beta\frac{\mathrm{Tr}\left[(-E_J\cos\delta + 4E_{C\Sigma}k^2)e^{\beta E_J\cos\delta - 4\beta E_{C\Sigma}k^2}\right]}{\mathrm{Tr}\left(e^{\beta E_J\cos\delta - 4\beta E_{C\Sigma}k^2}\right)}\right] \tag{23}$$

Similar to single JJ of RCSJ model the thermodynamic properties of cooper's pairs can also be calculated using Equation (17) for Hamiltonian.

2.5 Computational details

The numerical simulation was carried out using resistance of $R = 8\,\Omega$, capacitance of $C = 7\times10^{-15}$ F, magnetic flux quantum of $\Phi_0 = 2.07\times10^{-15}$ Wb, Boltzmann constant of $k_B = 1.380649\times10^{-23}$ J/K, electron charge of $e = 1.6\times10^{-19}$ C, and critical temperature of $T_c = 9.3$ K, with an applied voltage of $V = 5\times10^{-3}$ V. The temperature was varied from 0.1 to 9.8 K with a step size of 0.1 K to avoid singularities at T=0.

2.6 Error and limitation

The present model may involve both computational and physical limitations. Computationally, numerical instability can arise at very low temperatures (near T→0). Physically, the model assumes identical tunneling behavior for paired and unpaired electrons and neglects interface effects such as strong pair-breaking mechanisms, inelastic scattering, and material inhomogeneity. Additionally, the Ambegaokar–Baratoff relation is ideally valid for perfect tunnel junctions, while real SIS junctions (Nb/AlN/Nb and Nb/ Al_2 O_3/Nb) may deviate due to non-ideal barrier properties, making the results approximate rather than exact.

3 Results and discussion

3.1 Nature of damping parameters

Damping parameters with temperature is shown in Figure 2 is based on the data of AlN. The nature of damping parameters with temperature sure decreases with increasing temperature because at low temperature the dissipation energy is lower while at high temperature dissipation energy high. In superconductors, damping parameters refer to the way in which the material resists the flow of electrical current.

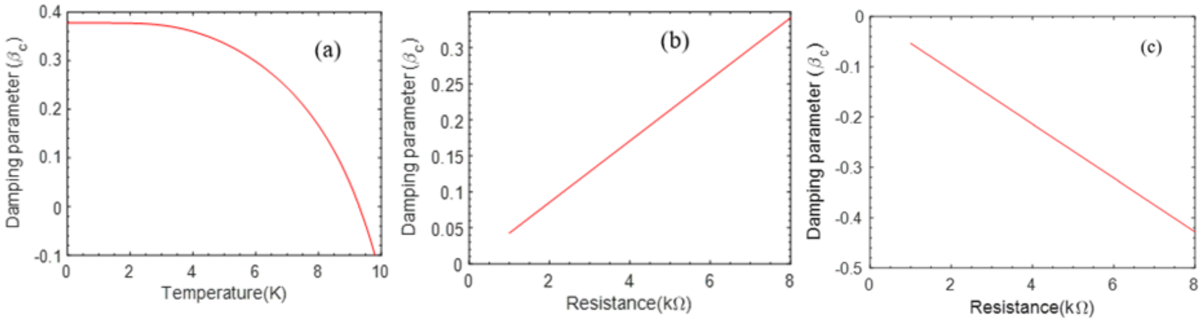

Figure 2: Damping Parameters with (a) temperature, (b) below critical temperature and (c) above critical temperature.

When damping parameters decrease with temperature, it means that the superconductor becomes more conductive as the temperature increases. This behavior is observed in some types of superconductors, known as conventional or low-temperature superconductors, Figure 2(a). Cooper pairs, which are made up of electrons within a superconductor at low temperatures, are able to flow through the information without being dispersed by flaws or impurities. As the temperature increases, thermal energy starts to break up these pairs, leading to an increase in scattering and resistance. However, in some materials, the damping parameters decrease with temperature, allowing the Cooper pairs to continue to move through the material with low resistance. It appears that the damping behavior of the superconductor increases with resistance when the temperature is below the critical temperature as shown in Figure 2(b). This is because at low temperatures, the superconductor is more susceptible to the effects of impurities and defects, which can increase the resistance and lead to increased damping. It is seems that the damping behavior of the superconductor decreases with resistance when the temperature is above the critical temperature as shown in Figure 2(c). This is because at high temperatures, the superconductor is in its normal state, and the resistance is already finite. Increasing the resistance further could potentially lead to a decrease in damping behavior.

3.2 Variation of current with temperature

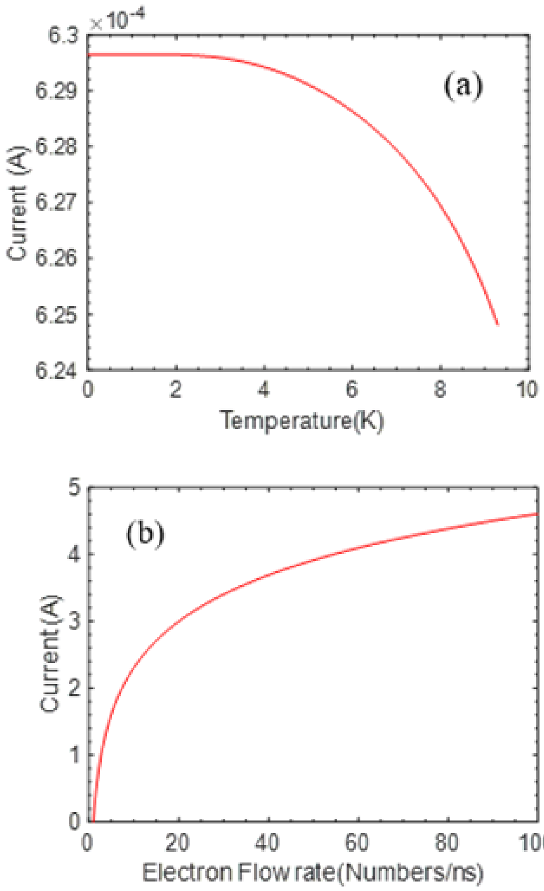

Figure 3: Mohr circle and stability curve under stress.

The temperature increases towards Tc (9.3K), the superconducting properties of the materials start to break down, and resistance starts to appear. This can result in a decrease in the current across the junction, as the superconducting properties that were allowing current to flow without resistance are no longer present. Aminov et al. in 1991 found that the current-voltage characteristics of high-temperature superconducting junctions varied significantly with temperature, with a sharp decrease in current observed as the critical temperature [19]. Furthermore, the behaviour of superconducting junctions in relation to temperature is complicated and contingent on the particular materials and circumstances. However, in general, an increase in temperature can lead to a breakdown of the superconducting properties of the materials, resulting in a decrease in the current across the junction The nature of current with temperature and electron flow rate in shown in Figure 3.

Current can flow across the junction between the two superconducting materials because Cooper pairs of electrons pass through the superconducting materials without encountering any resistance. An increase in the number the Cooper pairs causes an increase in the current flowing across the junction because the current under the junction has become directly related to the total number of tunnelling Cooper pairs across the barrier.

3.3 Thermodynamic properties of cooper pairs across SJJ and TJJ

The behavior of tunneling Cooper pairs across the junction can be affected by the vibrational energy of the atoms in the junction of superconductors. The difference in phase between both superconductors may dephase as a result. For higher value of vibrational energy, the phase coherence can be disrupted which causes the reduction of flow of Cooper pairs and hence the current at the junction. In addition, the vibrational energy also creates the phonons which interact and scatters the Cooper pairs at the junction and results a reduction in current. Thus, the impact of vibrational energy on Cooper pair in Josephson junction is significant and can affect the junction properties [20].

In superconductors, cooper pairs are described by the microscopic wave function which describes its collective behavior. This depends upon the barrier height and the length of junctions. Therefore, the behaviour of Cooper pairs throughout the junction is unrelated to the mean energy free idea. In superconductors, specific heat is very low that is temperature can change rapidly. In Josephson junction, the temperature of superconductor can affect its behavior. For example, at low temperature Josephson current is mostly determined by the phase difference while at high temperature the current becomes more sensitive to the temperature due to increased entropy of cooper pairs [21].

The behaviour of a Josephson junction, a kind of junction that exists between two superconductors, can be influenced by the entropy about conventional Cooper pairs present in a superconductor. Specifically, the entropy can affect the temperature dependence of the Josephson current flowing through the junction. At very low temperatures, the entropy of the Cooper pairs in the superconductors is very low, and the Josephson current is proportional to the two superconductors' phase difference. However, as the temperature is increased, the entropy of the Cooper pairs increases, and the Josephson current becomes more sensitive to temperature. This is because at higher temperatures, there are more thermal excitations of the Cooper pairs, which can cause them to break apart and tunnel through the barrier between the two superconductors at different rates. As a result, the Josephson current becomes less coherent, and the temperature dependence of the current becomes stronger. Additionally, at temperatures around the superconductors' critical temperature, the entropy of the Cooper pairs can lead to the breakdown of superconductivity, which can cause the Josephson junction to stop behaving like a superconductor.

4 Conclusion

The study concludes, the junction property of superconductors is complex and depends on various factors as flow of Cooper pairs, temperature, damping parameters, current, electron flow rate and thermodynamic properties of Cooper pairs. The damping parameter decreases with an increase in temperature that is conductivity of superconductor increases. Damping parameter increase with resistance below critical temperature (T_c) and decrease above T_c. The flow of cooper pairs determines the flow of current across the junction. The thermodynamic properties of cooper pairs affect the behavior of junction, particularly due to the vibrational energy of atoms at the junction. The concept of mean free energy is not relevant to the behavior of Cooper pairs across a Josephson junction or in superconductors in general. The entropy of Cooper pairs in a superconductor can also affect the behavior of a Josephson junction, particularly at low temperatures, where the Josephson current is mostly determined by the phase difference between the superconductors.

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References

[1] Van Delft D, Kes P. The discovery of superconductivity. Physics Today. 2010;63(9):38-43.

[2] Braginski AI. Consequences of Brian Josephson's theoretical discovery. Journal of Superconductivity and Novel Magnetism. 2021;34(6):1-4.

[3] Ali A, Susanto H, Wattis JA. Breathing modes of long Josephson junctions with phase-shifts. SIAM Journal on Applied Mathematics. 2011;71(1):242-69.

[4] Sinha A, Ghosh A. Statistics of synchronization times in Kuramoto oscillators. Europhysics Letters. 2023;141(5):53001.

[5] Kalantre SS, Yu F, Wei MT, Watanabe K, Taniguchi T, Hernandez-Rivera M, et al. Anomalous phase dynamics of driven graphene Josephson junctions. Physical Review Research. 2020;2:023093.

[6] Nam H, Zhang C, Lee W, Zhu S, Gao HJ, Niu Q, et al. Behavior of superconductivity in a Pb/Ag heterostructure. Physical Review B. 2019;100:094512.

[7] Goldobin E, Wallraff A, Ustinov AV. Cherenkov radiation from fluxon in a stack of coupled long Josephson junctions. Journal of Low Temperature Physics. 2000;119:589-614.

[8] Ustinov AV. Long Josephson junctions and stacks. In: AIP Conference Proceedings. vol. 427; 1998. p. 2-6.

[9] Wildermuth M, Powalla L, Voss JN, Schön Y, Schneider A, Fistul MV, et al. Fluxons in high-impedance long Josephson junctions. Applied Physics Letters. 2022;120(11).

[10] Rahmonov IR, Yu M, Plecenik A, Zemlyanay EV, Bashashin MV. Numerical study of a system of long Josephson junctions with inductive and capacitive couplings. EPJ Web of Conferences. 2016;108:02038.

[11] Ponta L, Carbone A, Gilli M, Mazzetti P. Resistively and capacitively shunted Josephson junctions model for unconventional superconductors. In: Proceedings of the 24th Canadian Conference on Electrical and Computer Engineering (CCECE). IEEE; 2011. .

[12] Gabovich AM, Moiseev DP, Shpigel AS, Voitenko AI. Josephson tunneling critical current between superconductors with charge- or spin-density waves. Physica Status Solidi B. 1990;161(1):293-302.

[13] Alam S, Jahangir MA, Aziz A. A compact model for superconductor-insulator-superconductor (SIS) Josephson junctions. IEEE Electron Device Letters. 2020;41(8):1208-11.

[14] Uchihashi T. Two-dimensional superconductors with atomic-scale thickness. Superconductor Science and Technology. 2017;30(1):013002.

[15] Kleiner R, Buckel W. Superconductivity: An Introduction. 3rd ed. Wiley-VCH Verlag GmbH & Co. KGaA; 2016.

[16] Watanabe M, Haviland DB. Quantum effects in small-capacitance single Josephson junctions. Physical Review B. 2003;67(9):094505.

[17] Chester GV. The quantum-mechanical partition function. Physical Review. 1954;93(3):606-11.

[18] Ramantswana M, Rampho GJ, Edet CO, Ikot AN, Okorie US, Qadir KW, et al. Determination of thermodynamic properties of CrH, NiC and CuLi diatomic molecules with Hulthen-type plus Yukawa potential. Physics Open. 2023;14:100135.

[19] Aminov BA, Ponomarev YG, Sudakova MV. Temperature dependence of parameters of Josephson junctions based on high-Tc superconductors. Physica C: Superconductivity. 1991;185–189:2531-2.

[20] Scharf B, Braggio A, Strambini E, Giazotto F, Hankiewicz EM. Thermodynamics in topological Josephson junctions. Physical Review Research. 2021;3:033062.

[21] Vischi F, Carrega M, Braggio A, Virtanen P, Giazotto F. Thermodynamics of a phase-driven proximity Josephson junction. Entropy. 2019;21:1005.