Existence of Shapiro Steps in the Dissipative Regime in Superconducting Weak Links

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We present measurements of microwave-induced Shapiro steps in a superconducting nanobridge weak link in the dissipative branch of a hysteretic current-voltage characteristic. We demonstrate that Shapiro steps can be used to infer a reduced critical current and associated effective local temperature. Our observation of Shapiro steps in the dissipative branch shows that a finite Josephson coupling exists in the dissipative state and thus can be used to put an upper limit on the effective temperature and on the size of the region that can be heated above the critical temperature. This work provides evidence that Josephson behaviour can still exist in thermally-hysteretic weak link devices and will allow extension of the temperature ranges that nanobridge based single flux quantum circuits, nanoSQUIDs and Josephson voltage standards can be used.

A superconducting weak link (WL) can be realised by creating a narrow constriction between two bulk superconducting electrodes. If the constriction dimensions are made sufficiently small (comparable to $3.5\xi$, where $\xi$ is the Ginzburg-Landau coherence length) then the weak links are expected to exhibit characteristic Josephson behaviour \cite{1}. In this situation nanobridge constrictions can be used instead of traditional Josephson tunnel junctions based on oxide barriers, or superconductor-normal-superconductor (SNS) junctions. The majority of work in the area has focussed on development and optimization of micron-sized superconducting quantum interference devices (nanoSQUIDs), which are implemented using two WLs \cite{2}. NanoSQUIDs can be used for many applications including single magnetic nanoparticle detection \cite{3}, scanning SQUID microscopy for imaging of nanoscale phenomena \cite{4, 5}, and nanoelectromechanical system (NEMS) readout \cite{6, 7}. Aside from magnetometer-based applications, WL Josephson junctions could be used in place of traditional junctions for single flux quantum (SFQ) circuits \cite{2}, and Josephson voltage standards used in the metrology community \cite{8, 9}. Weak links also have utility as Josephson elements in qubits and parametric amplifiers \cite{10, 11} as well as for single quasiparticle trapping and counting \cite{12}.

In general, hysteresis is observed in the current-voltage characteristics (IVC) of WLs. Unlike conventional tunnel junctions, where the hysteresis can be explained by the junction capacitance in the resistively and capacitively shunted junction (RCSJ) model \cite{13}, the origin of hysteresis in WL junctions is attributed to heating, and subsequent thermal runaway of the junction \cite{14}. This situation was first described by Skocpol, Beasley, and Tinkham (SBT) \cite{15} who stated that as the bias current $I_{dc}$ applied to the WL is increased above the critical current $I_c$, a ‘hotspot’ region in the WL forms, in which the local temperature exceeds the critical temperature $T_c$. When $I_{dc}$ is then reduced the hotspot is maintained by Joule heating and remains in the dissipative state. The WL is only able to return to the superconducting state when $I_{dc}$ is reduced to below the retrapping current $I_r$, where $I_r < I_c$.

In recent years further refinements have been made to the SBT model by inclusion of a temperature dependent thermal conductivity at temperatures below $T_c$ \cite{20, 21}, and extension of the model to millikelvin temperatures \cite{22}. In addition, a significant amount of recent work has been carried out to understand and reduce the hysteresis in the IVC \cite{23, 24}.

Weak link thermal models \cite{18, 20, 22} indicate that with a sufficiently large bias current the temperature in regions of the electrodes can be higher than $T_c$, in some cases extending several micrometers into the banks. Indeed, Kumar et al. present a device-state diagram for WL-based nanoSQUIDs showing that at $T < T_H$ (where $T_H$ is the crossover temperature between the hysteretic and non-hysteretic regimes) and $I_{dc} > I_c$, the WLs and the micron-scale leads are in the resistive state \cite{23}. Preliminary nanoSQUID measurements in the hysteretic regime showed no magnetic flux dependence of the retrapping current \cite{21, 22}. However, Biswas et al. have recently demonstrated that thermally-optimized nanoSQUIDs do exhibit magnetic flux dependence of the retrapping current \cite{26}, indicating that the Josephson coupling does not completely vanish in the dissipative state. The Josephson effect can also be demonstrated through the observation of microwave-induced Shapiro steps \cite{27}. We have previously observed Shapiro steps in WLs operated in the non-hysteretic regime \cite{28} and they have also been found in long nanowires when driven into the ‘phase slip center’ regime \cite{29, 30}.

In this Letter we demonstrate Josephson behaviour in hysteretic nanobridge WL junctions by observation of Shapiro steps, and combine the experimental data with our model to estimate the average local temperature of the WL. To do this we measure the IVC of the WL at a temperature $T < T_H$ whilst applying a radio-frequency (rf) current. Notably, we observe Shapiro steps on the dissipative branch of the hysteretic IVC previously thought to be in the fully normal state where it was assumed that the nanobridge and parts of the bank have $T > T_c$. 

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The WLs reported in this Letter are fabricated by electron-beam lithography (EBL) and dry etching. A niobium film of thickness 150 nm is sputtered onto a silicon substrate on top of which a 30 nm thick aluminium film is defined by EBL and thermally deposited by lift-off. An array of 10 nanobridges is defined to a width of 40 nm and an electrode-electrode separation of 100 nm. The niobium is then dry etched into the silicon substrate using a CHF$_3$/SF$_6$ plasma. The aluminium hard mask is left on.

Electrical measurements of the WLs are carried out in a 4He dip Dewar. The temperature is varied between 4-9 K by varying the position of the probe in the cold helium gas column. The IVCs are measured in a four-terminal configuration using an optically isolated measurement unit optimised for high-precision electrical metrology [31] designed at the National Physical Laboratory (NPL). To investigate the effects of rf irradiation on the WL the device is biased with an rf current. A bias resistor. The voltage across an individual WL is measured using the NPL analog-to-digital converter (ADC). To investigate the influence of rf irradiation an rf current is applied to the entire array using an rf synthesizer and on-chip 50 Ω resistor.

Typical IVCs measured without rf irradiation are shown in Figure 2 taken at different temperatures. The behaviour is qualitatively similar to that observed by de Cecco et al. in SNS Josephson junctions [32]. The existence of Shapiro steps in the hysteretic IVC (at $V_{rf} < 1.17$ V) on both the up and down sweeps indicates that the WL is not in a fully dissipative state but instead provides evidence of a finite Josephson supercurrent existing in the dissipative state.

In order to investigate the evolution of the IVC under microwave irradiation we measure many IVCs whilst increasing the rf current. Figure 3(a) shows a differential resistance ($dV/dI_{dc}$) map obtained by numerically differentiating the measured IVC. The differential resistance map shows the evolution of the IVC as a function of the applied rf current where the dark regions of the colour map indicate regions where there is a plateau in the IVC. These plateaus can be seen in the IVC traces and form at the expected voltages $V = n(hf/2e)$, where $f = 20$ GHz is the frequency of the rf current. Figure 3(b) shows three traces from the differential resistance map. The trace at $V_{rf} = 0.63$ V shows Shapiro steps on the down (current swept from negative $I_{dc}$ to zero) sweep of the dissipative branch of the hysteretic IVC. The trace at $V_{rf} = 1.03$ V shows that Shapiro steps appear on both the up (current swept from zero to positive $I_{dc}$) and the down sweeps of the IVC. When sufficiently large rf currents are applied, as shown by the trace taken at $V_{rf} = 1.28$ V, the hysteresis in the IVC disappears and the WL behaves as a non-hysteretic junction whilst still exhibiting Shapiro steps. This behaviour is qualitatively similar to that observed by de Cecco et al. in SNS Josephson junctions [32]. The existence of Shapiro steps in the hysteretic IVC (at $V_{rf} < 1.17$ V) on both the up and down sweeps indicates that the WL is not in a fully dissipative state but instead provides evidence of a finite Josephson supercurrent existing in the dissipative state.

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FIG. 1. Scanning electron micrographs of a niobium WL array and measurement schematic. To measure a single WL IVC a bias current is driven through the entire array via the NPL digital-to-analog converter (DAC) voltage source and a bias resistor. The voltage across an individual WL is measured using the NPL analog-to-digital converter (ADC). To investigate the influence of rf irradiation an rf current is applied to the entire array using an rf synthesizer and on-chip 50 Ω resistor.

FIG. 2. (a) IVC of a weak link nanobridge measured at a bath temperature of 6.51 K exhibiting thermal hysteresis. (b) IVC of weak link nanobridge at a bath temperature of 7.48 K showing no hysteresis. (c) Critical current and retrapping current measured at different bath temperatures. Hysteresis occurs at $T < T_H$. For this sample $T_H \approx 7.35$ K.
In a WL operated in the dissipative regime, the temperature is not constant, but is expected to be highest in the vicinity of the hysteretic state. This is because the dissipative regime is characterized by an increase in temperature due to Joule heating. The effective local temperature is determined by finding the relationship between the applied rf voltage from the synthesizer and the rf current that reaches the device. The scaling between the applied rf voltage and the rf current is given by the equation:

$$\frac{h}{2e} \phi + I_c \sin(\phi) = I_{dc} + I_{rf} \sin(2\pi f t).$$

(1)

We use the trace with $I_{rf} = 0$ in order to determine a value for the normal-state resistance $R_n$ which we keep constant for all other IVCs. The fit to the $I_{rf} = 0$ IVC is shown in Figure 3(a), with fitting parameters of $I_c^* = 690 \mu A$ and $R_n = 0.55 \Omega$. To analyse IVCs with finite $I_{rf}$, it is necessary to provide a scaling between the applied rf voltage from the synthesizer and the rf current that reaches the device. The scaling is determined by finding the relationship between $I_{rf}$ in the RSJ model and the onset of the first Shapiro step. The step onset predicted from the model is then compared to that observed in the measurements and used to determine a scaling between $V_{rf}$ and $I_{rf}$ (1 V corresponds to $318 \mu A$; see Supplementary Note 1). Figures 3(b-e) show RSJ model fits to measured IVC at different $I_{dc}$ values using $I_c^*$ as the only fitting parameter. As $I_{rf}$ is increased the additional dissipated power leads to an increase in $I_c^*$ and corresponding reduction of $I_c^*$.

The best fit values of $I_c^*$ found at each $I_{rf}$ are shown in Figure 3(a). As $I_{rf}$ is increased, the value of $I_c^*$ reduces as discussed above. The vertical dashed line in the figure denotes the crossover from hysteretic to non-hysteretic junction behaviour. After this point the steps in the IVC have less contrast and fitting is done using the numerically differentiated data. Only one point in this region is fitted to demonstrate that there is no large discontinuity beyond the crossover line. An estimate of the effective local temperature of the WL is made using the $I_c(T)$ data from Figure 2(c) and the results are shown in Figure 3(b). Note that our fitting procedure gives an estimate of $I_c^*$, and thus the WL effective local temperature for values of $I_{dc}$ in the vicinity of the hysteretic state. The reduced critical current associated with this temperature is thus described as $I_c^* = I_c(T^*)$. The dissipative region of the IVC is now at this lower critical current. To determine this reduced $I_c^*$ we fit the dissipative region of the measured IVC by numerically solving the first-order differential equation describing the RSJ model with an applied rf current [32],

$$\frac{h}{2e} \phi + I_c \sin(\phi) = I_{dc} + I_{rf} \sin(2\pi f t).$$

(1)
the bridge, and then to decrease within the banks until it reaches $T_{\text{bath}}$ (see Figure 5(c)). The estimated $T^*$ therefore is an effective averaged temperature of the system, since it corresponds to the equivalent bath temperature of a WL with critical current $I_c^*$ at $I_{rf} = 0$ (see Figure 2(c)). Note that while we find that $T^*$ is always well below $T_c$, it is possible that the local temperature in the center of the bridge may be higher and can even exceed $T_c$. Figure 5(c) shows three possible temperature distributions, the SS’S case where the temperature in the bridge is below $T_c$, the SNS case where only the bridge (and possibly small regions of the banks) is above $T_c$, and the SNS case where the bridge and large regions of the banks are above $T_c$. The existence of Shapiro steps in our nanobridges rules out the latter case as the length $L$ of the region above $T_c$ must be below $3.5\xi$. For $L(T > T_c) > 3.5\xi$ no Shapiro steps are expected to be observed.

In conclusion we present experimental evidence of a finite Josephson supercurrent existing in the dissipative state of WL Josephson junctions demonstrated by the existence of Shapiro steps on the retrapping branch of the device IVC. We demonstrate that as the WL transitions to the dissipative state, Joule heating occurs and the elevated temperature results in a reduced critical current $I_c^*$. We use the RSJ model in combination with $I_c^*$ to describe the evolution of the Shapiro steps over the full range of our hysteretic data, and to infer an associated effective local temperature of the WL which we find to be below $T_c$ for all the data. While it is still possible that locally the temperature exceeds $T_c$, the spatial extension of this region must be small.

Importantly, the existence of a Josephson supercurrent also demonstrates that WLs may be operated as Josephson junctions even in the dissipative state. This has relevance to the operation of hysteretic WL-based nanoSQUIDs, as well as demonstrating that rf irradiation can be used as a probe of Josephson behaviour in the dissipative regime of single WLs. It is also critical to the understanding of WLs for use in applications such as SFQ circuits and Josephson voltage standards where response to high-frequency (GHz) pulses are important. The Shapiro steps can be used as a tool with which to investigate WL behaviour as well as informing the optimisation of WL junctions and SQUIDs. Different geometries, materials, and thermal shunts can be investigated.

FIG. 4. IVC traces shown at different $V_{rf}$ amplitudes. ‘Up’ sweep shown in red, ‘Down’ sweep shown in black, and RSJ model shown in green. (a) IVC at $I_{rf} = 0$ used to find $I_c^*$ and $R_n$. The ‘up’ sweep shows that as the initial state critical current $I_c^*$ is reached the junction transitions to a lower critical current $I_c^*$. During the ‘down’ sweep the junction remains on this path until the Joule heating is no longer sufficient to stop the junction re-entering the fully superconducting regime. The RSJ model is used to determine $I_c^*$ and $R_n$. $R_n$ is kept constant for the remainder of the analysis. (b) IVC with applied rf of $V_{rf} = 1\,\text{V}$ ($I_{rf} = 318\,\mu\text{A}$). Our model uses $I_c^*$ as the only fitting parameter to reproduce the Shapiro step position and total number of steps for the full range of applied $I_{rf}$ in the hysteretic region of the colourmap shown in Figure 3. Measured IVC and RSJ model fits at (c) $V_{rf} = 0.25\,\text{V}$ ($I_{rf} = 79.5\,\mu\text{A}$), (d) $V_{rf} = 0.5\,\text{V}$ ($I_{rf} = 159\,\mu\text{A}$), and (e) $V_{rf} = 0.75\,\text{V}$ ($I_{rf} = 238.5\,\mu\text{A}$).

FIG. 5. (a) Best fit of $I_c^*$ at different $I_{rf}$. As $I_{rf}$ is increased, $I_c^*$ reduces. (b) Temperature inferred from value of $I_c^*$ and the $I_c(T)$ shown in Figure 2(c). Dashed vertical line in both graphs refers to the $I_{rf}$ value beyond which the IVC are non-hysteretic (i.e., $V > 1.17\,\text{V}$ in Figure 3). The fits to the RSJ model beyond this line (shown in red) are harder to achieve due to reduced step contrast. (c) Illustration of nanobridge and three possible temperature distributions. The effective local temperature $T^*$ can have a region that is above $T_c$, the existence of Shapiro steps limits the size of this region to be less than $3.5\xi$, which suggests that we do not have a large portion of the banks at a temperature greater than $T_c$. 

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using this rf irradiation technique.

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