Random telegraphic voltage noise due to thermal bi-stability in a superconducting weak link

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Random Telegraphic Voltage Noise due to Thermal Bi-stability in a Superconducting Weak Link

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Abstract. We investigated the random telegraphic voltage noise signal in the hysteretic bi-stable state of a superconducting weak link device. Fluctuation induced random switching between zero voltage state and non-zero-voltage state gives rise to a random telegraphic voltage signal in time domain. This telegraphic noise is used to find the mean lifetime of each of the two states. The mean life time in the zero voltage state is found to decrease with increasing bias current while that of resistive state increases and thus the two cross at certain bias current. We qualitatively discuss this observed switching behavior as arising from the bi-stable nature.

Keywords: Random telegraphic signal, Superconducting weak link, Phase slip
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INTRODUCTION

Superconducting weak link, acting like Josephson junction (JJ), between two bulk superconductors (SC) shows hysteresis in current voltage characteristics at low temperatures [1]. When the bias current is ramped up from zero, the device switches to resistive state at a critical current (I_c) but during current ramp down, it comes back to zero voltage state at a different bias current, called re-trapping current (I_r). At low temperatures, $I_r < I_c$, and thus one observes hysteretic (or bi-stable) current-voltage characteristics (IVCs) [1]. The hysteresis disappears above a crossover temperature (T_h), where I_r becomes higher than I_c. The origin of this bi-stable regime in WL is thermal Joule heating [2, 3, 4].

The SC state is described by a complex order parameter ($\psi = |\psi| e^{i\phi}$), with magnitude $|\psi|$ and phase 'ϕ'. Above I_c, the phase difference between the two bulk SC across the WL evolves with time, according to ac-Josephson relation [5], resulting into a voltage and thus resistive heating. Fluctuation driven phase-slip process (i.e. a phase jump by 2π across WL) gives rise to the energy (*hI/2e*) which is of the order of the Josephson energy E_J [5]. Depending on thermal heat balance in the device, phase slip event below I_c can cause thermal runaway in the hysteretic regime [6]. In conventional JJ, phase slip induced switching from SC state to resistive state has been studied earlier [7]. In non-hysteretic regime a finite voltage arises due to such stochastic phase slips happening at certain rate with each phase slip giving rise to a voltage pulse. Such phase-slips can occur due to thermal, quantum or external noise related fluctuations. Stochastic phase-slips in SC nano-wires have been well studied [6, 8]. Understanding of the fluctuation effects in the WL devices is important both from physics and technological perspective. The WLs are directly used in making micron size superconducting interference devices (μ-SQUIDs) that have been used to probe magnetism at nano-scale [9, 10]. For instance, μ-SQUID can be an ideal probe to study the magnetization reversal induced by quantum and thermal fluctuations in nano-scale magnetic memory bits, which may help to further reduce their size [11].

It is essential to understand the physics of thermal instability as arising from phase fluctuations in μ-SQUIDs and giving rise to bi-stable behavior for further improving their performance [1]. Here, we report a preliminary study on telegraphic voltage signal arising from random switching in the bi-stable regime of a shunted SC WL near T_h. Similar telegraphic signal has been seen in other systems [12,

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13]. We discuss our results qualitatively as arising from a free-energy capturing the bi-stability.

EXPERIMENTAL DETAILS

The device discussed here was made using electron beam lithography as discussed elsewhere [14]. Electrical transport measurements were performed using a closed cycle He-refrigerator down to 1.3K. A specially designed sample holder containing copper powder filter was used to minimize high frequency noise. A homemade ground-isolated current-source was used to reduce effect of external noise. The noise figure of the current-source as characterized is found to be 0.4nA/Hz$^{1/2}$. The data were recorded using a data acquisition card (capable of 100kS/s sampling rate) and a LabView program. The temperature was stabilized within 2mK during data acquisition.

RESULTS AND ANALYSIS

Figure-1 shows the variation of I_c and I_r with bath temperature as found from the IVCs at various temperatures. The IVCs are hysteretic below $T_h = 6.5$K as I_c is greater than I_r, see Fig. 1 inset.

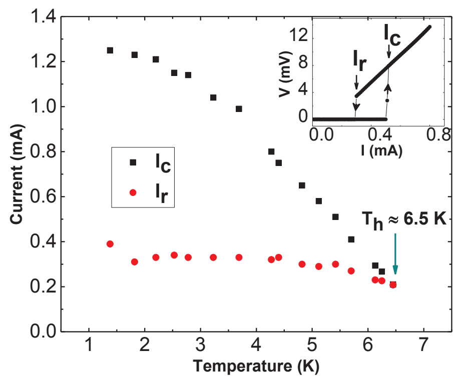

FIGURE 1. Variation of I_c and I_r with bath temperature. The inset shows a hysteretic IVC at T = 5.42K.

When the temperature is just below T_h we observe a random telegraphic signal (RTS) in voltage for current between I_r to I_c. The difference between I_r to I_c becomes extremely small close to T_h and thus RTS is seen in a very narrow current range. Fig. 2 shows this RTS in voltage at T = 6.45K and at 0.208 mA bias current. The RTS arises because of the random switching between the two states of the device, namely, the SC state (i.e. zero-voltage) and resistive state. Beyond this current range [I_r , I_c] the switching disappears and the system remains in one of the two stable states.

Given the bi-stable nature of the device below T_h we expect that the free-energy barrier between the two states reduces as T_h is approached. Thus just below T_h the WL can transit from one stable state to the other by overcoming the free-energy barrier with the help of fluctuations. At a given bias current the RTS arises due to certain transition rates from the two states determined by the barrier heights and the attempt rates. We denote $1/\tau_L$ as the transition rate from zero voltage state and $1/\tau_H$ as that from the resistive state. Since the random switching between these two states is stochastic in nature, we expect an exponential distribution [15] for the time (i.e. Δt_L and Δt_H) spent in each state as depicted in Fig. 2.

Fig. 3 shows the distribution (or histogram) of Δt_L and Δt_H for different bias-current values at 6.45K. To get the distribution of Δt_L and Δt_H we extracted the time intervals between two consecutive switching events in voltage signal using LabView program rather than acquiring long time-series data. For reliable statistical analysis we monitored more than 1000 switching events. The exponential fitting shows that the mean-life-times, τ_L and τ_H, vary with the bias current value. Figure 4 shows the variation of τ_L and τ_H as a function of the bias current. We clearly see that τ_L is large and τ_H is small at small bias current. With increasing current τ_L decreases and τ_H increases and the two cross near 0.208 mA bias current.

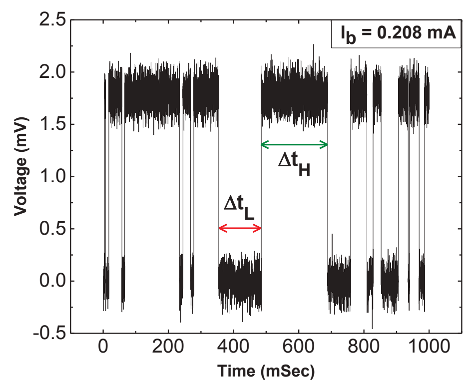

FIGURE 2. A typical telegraphic voltage signal in time domain at bias current, I_b = 0.208 mA and temperature T = 6.45K.

DISCUSSION

This type of bi-stability is captured nicely in our time dependent thermal model [16] together with the susceptibility of the two states to noise with the help of a fictitious potential 'U(p)'. Although this potential was only used to describe the temperature dynamics and it is not the actual free-energy of the WL device to really describe the bi-stability and the observed RTS. However, in the absence of a detailed model for free-energy, we propose a qualitative understanding using the free energy behavior capturing bi-stability.

Based on our result, we believe that the free energy has the form with two minima separated by a maximum, as shown in fig 5. The transition from one minimum to the other depends on the attempt rate and the barrier height. The attempt rate from SC state minimum is the Josephson time scale (τ_j) while that from resistive minimum is the thermal time scale (τ_{th}). Since $\tau_{th} >> \tau_j$, the transition rate from both minima will be equal (near 0.208 mA bias current) for the free energy at which the barrier height from SC minimum is little higher, rather than equal. Thus the life times vary and they cross as depicted in figure 4.

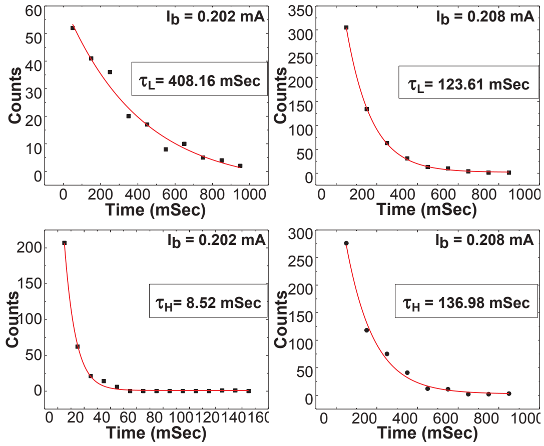

FIGURE 3. Distribution count of life times at two different bias currents. Top and bottom rows represent distributions for SC and resistive states respectively. The continuous red lines are exponential fit given by, $f=f_0\,exp(-t/\tau_{H,L})$.

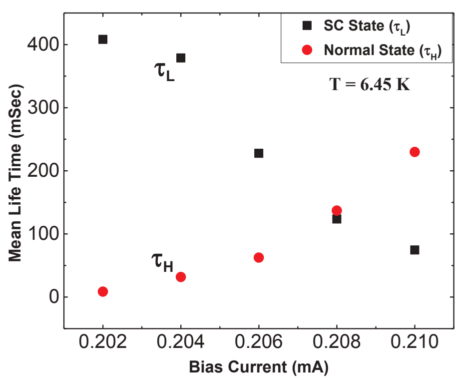

FIGURE 4. Mean life time ($\tau_{H,L}$) variation with bias current.

CONCLUSION

The random telegraphic signal in the bi-stable regime near cross over temperature was studied. As expected from the qualitative understanding, it is found from RTS data that the mean lifetime of the system in the zero voltage SC state decreases as the bias current increases towards I_c. Although we qualitatively discussed the observed telegraphic noise behavior, it requires further work to get the complete quantitative picture. The RTS signal may provide information about the phase slip mechanism.

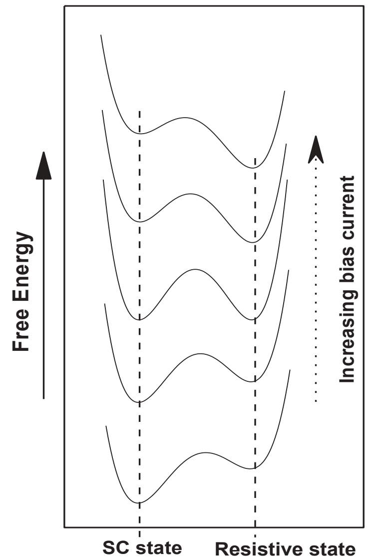

FIGURE 5. Free energy for telegraphic voltage signal.

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