Control of the Electromagnetic Environment for Single Josephson Junctions Using Arrays of dc SQUIDs

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Abstract—We have measured the current-voltage characteristics of small-capacitance single Josephson junctions at low temperatures \((T \leq 0.04 \text{ K})\), where the strength of the coupling between the single junction and the electromagnetic environment was controlled with one-dimensional arrays of dc SQUIDs. We have clearly observed Coulomb blockade of Cooper-pair tunneling when the zero-bias resistance of the SQUID arrays is much higher than \(h/e^2 \approx 26 \text{ k} \Omega\).

I. INTRODUCTION

The small-capacitance superconducting tunnel junction is a novel macroscopic quantum system [1],[2], which is of interest in the context of devices such as a quantum bit (qubit) for quantum computing. A major obstacle to the realization of a qubit is decoherence resulting from coupling to the electromagnetic environment. This environmental effect on nano-scale junctions can be studied by measuring the current-voltage (IV) characteristics of single junctions, because the IV curve of a single junction is sensitive to the "environment" composed of the measurement leads connected to the junction.

We have used one-dimensional arrays of dc SQUIDs for the leads to bias single junctions. The advantage of this SQUID configuration is that the effective impedance of the SQUID-array leads and the single junction in Figs. 1 and 2, respectively, in several magnetic fields. We indicate the magnetic field \(B\) as the frustration \(f \equiv BA/\Phi_0\), where \(A\) is the effective area of the SQUID loop and \(\Phi_0 = h/2e = 2 \times 10^{-15} \text{ Wb}\) is the superconducting flux quantum. Although our SQUID array is a nonlinear environment (Fig. 1), we may characterize it by the zero-bias resistance \(r_s\). From a to c, \(r_s = 0.61 \text{ M} \Omega, 3.2 \text{ M} \Omega, \text{ and } 43 \text{ M} \Omega\), respectively. In the single junction (Fig. 2), Coulomb blockade, or increase of differential resistance around \(V = 0\), is visible when \(r_s\) is much higher than \(h/e^2 \approx 26 \text{ k} \Omega\), which is consistent with the theory of single junctions connected to a linear environment [4]. In addition to Coulomb blockade, a region of negative resistance is clearly seen for \(f \geq 0.48\). This is evidence of coherent single-Cooper-pair tunneling in the single Josephson junction.

In Fig. 3, we compare the values of the local voltage maximum in the low-current part of the IV curve, or blockade voltage \(V_b\) with the theoretical prediction for the current-biased single Josephson junctions. Here, we include the data from [5] for the samples with the same nominal junction area \((0.1 \mu \text{m} \times 0.1 \mu \text{m})\) as in this work. Following [2], we calculated \(V_b\) numerically as a function of \(E_j/E_c\) for several values of \(k_BT/EC\). Here, \(E_j\) is the Josephson energy, \(E_c \equiv e^2/2C\) is the charging energy, and \(C\) is the junction capacitance. We used \(E_j = h\Delta/8eR_n\), where \(\Delta\) is the superconducting energy gap and \(R_n\) is the normal-state resistance (measured at \(T = 2 - 4 \text{ K}\)), and for \(E_c\) we estimated \(C\) from the junction area. When \(0.14 \text{ pF}/\mu\text{m}^2\) is assumed, the experimental data agree with the calculation.

II. EXPERIMENT

We fabricated \(\text{Al/Al}_2\text{O}_3/\text{Al}\) tunnel junctions on a SiO\(_2\) substrate using electron-beam lithography and a double-angle-evaporation technique. Each side of the single junction \((0.1 \mu \text{m} \times 0.1 \mu \text{m})\) are connected to two SQUID-array leads. The area of each junction is \(0.3 \mu \text{m} \times 0.1 \mu \text{m}\) and the effective area of the SQUID loop is \(0.7 \mu \text{m} \times 0.2 \mu \text{m}\) enabling four-point measurements of the single junction. Details of the sample preparation and characterization, and of the measurement setup are described elsewhere [3].

III. RESULTS AND DISCUSSION

For one sample, we show the IV curves at \(T = 0.02 \text{ K}\) of the SQUID-array leads and the single junction in Figs. 1 and 2, respectively, in several magnetic fields. We indicate the magnetic field \(B\) as the frustration \(f \equiv BA/\Phi_0\), where \(A\) is the effective area of the SQUID loop and \(\Phi_0 = h/2e = 2 \times 10^{-15} \text{ Wb}\) is the superconducting flux quantum. Although our SQUID array is a nonlinear environment (Fig. 1), we may characterize it by the zero-bias resistance \(r_s\). From a to c, \(r_s = 0.61 \text{ M} \Omega, 3.2 \text{ M} \Omega, \text{ and } 43 \text{ M} \Omega\), respectively. In the single junction (Fig. 2), Coulomb blockade, or increase of differential resistance around \(V = 0\), is visible when \(r_s\) is much higher than \(h/e^2 \approx 26 \text{ k} \Omega\), which is consistent with the theory of single junctions connected to a linear environment [4]. In addition to Coulomb blockade, a region of negative resistance is clearly seen for \(f \geq 0.48\). This is evidence of coherent single-Cooper-pair tunneling in the single Josephson junction.

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IV. CONCLUSION

We have demonstrated how a SQUID array, used as a tunable electromagnetic environment, can induce the Coulomb blockade of Cooper-pair tunneling in a single small capacitance Josephson junction.
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