A Seven-Junction Cooper Pair Pump

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Abstract

We have measured current-voltage curves and individual charge transfer events in single-Cooper-pair pumps. We observe clear charge pumping in units of $2e$, but this behavior is accompanied by significant effects from unwanted quasiparticles.

Key words: superconductivity; tunneling; SET;

A single-electron tunneling (SET) pump consists of a chain of tunnel junctions with gate electrodes capacitively coupled to the islands between junctions. Electrons are pumped by pulsing the gates to allow tunneling at each junction in sequence, producing a current proportional to the repetition frequency, $I_p = ef$ [1]. Pumps with seven junctions have produced such a current with metrological accuracy [2], but only at f ~10^7 Hz, giving I_p ~1 pA. The maximum rate for tunneling of electrons is limited by the stochastic tunneling time, R_jC_j, where R_j and C_j are respectively the junction resistance and capacitance. One must wait ~$100R_jC_j$ to reduce missed tunneling errors to ~1 ppb. The current generated by existing SET pumps is sufficient for certain metrological applications such as a capacitance standard [3], but other applications such as the quantum metrology triangle [4] require ~1 nA or more.

One promising scheme for larger current is to operate a charge pump in the superconducting state. A single-Cooper-pair tunneling (SCPT) pump transfers charge via *coherent* Josephson tunneling processes that are not subject to the probabilistic tunneling time limit of the normal state. Past studies of three-junction SCPT pumps [5] did not show clear pumping behavior, but the ratio of the Josephson energy for a single junction to the charging energy for a single electron was small:

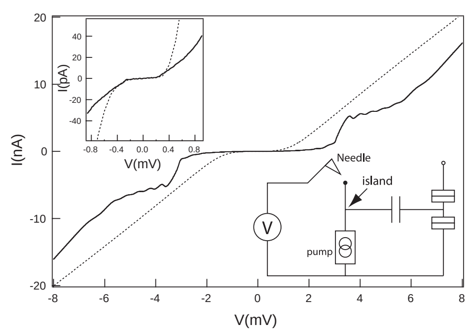

Fig. 1. Pump IV curves without pumping in normal (dashed) and superconducting (solid) states. Upper inset: Magnification near $V = 0$. Lower inset: Schematic of measurement circuit.

E_J/E_C ~0.03. We are investigating SCPT pumps with more junctions, larger E_J/E_C, and an integrated SET electrometer for detecting individual charges in order to understand the conditions necessary for controlled pumping of Cooper pairs.

Each pump consists of six μm-scale Al islands linked by Al_2O_3 tunnel barriers (junction areas ~100 nm×100 nm), patterned by e-beam lithography and deposited using two-angle evaporation with an intermediate *in situ* oxidation step. The lower inset of Fig. 1 shows a schematic of the measurement circuit. The arrays terminate in an island (120 μm×120 μm) capacitively coupled to a codeposited SET electrometer that measures the charge transferred through the

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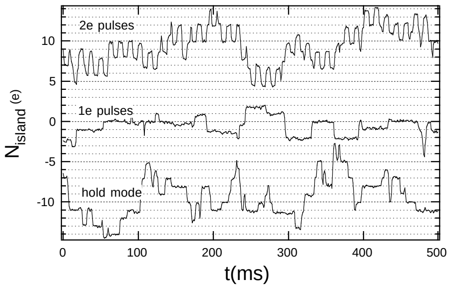

Fig. 2. Excess island charge *vs.* time for 3 different conditions (see text). Traces are offset for clarity.

pump [2,6]. A cryogenic needle switch contacts the island to allow current-voltage (IV) measurements. All measurements are performed at ~25 mK with cold microwave filtering on all lines. We focus here on one of four pumps that we have measured, all of which showed similar behavior.

We employed two methods to characterize our pumps: IV measurements and single-charge measurements. The latter uses the SET electrometer to monitor individual charges transferred through the pump and is able to detect much smaller levels of error or leakage than the IV measurement [2,6].

In the normal state, the IV curves with and without pumping show plateaus in the current near zero voltage bias (not shown). As expected, the pumping curves are offset by $I_p = \pm ef$ with well-defined plateaus ~200 μeV wide. Shuttle error measurements in the normal state showed an error per electron of ~10^{-5} and a leakage rate in the "hold mode" (*i.e.*, while not pumping) of ~0.1 Hz. From the IV curve at large V we find E_C ~143 μeV and R_j ~43 kΩ. The latter value implies $E_J \sim 15\mu$eV from the Ambegaokar-Baratoff relation; thus E_J/E_C ~0.1 for this pump.

In the superconducting state, the IV curve (Fig. 1) shows a broad plateau between $\pm 14\Delta/e$ ($\Delta \sim 210\mu$eV), above which conduction occurs via multiple Josephson quasiparticle processes [7] as indicated by current peaks spaced by $\sim 2\Delta/e$. Between $V \sim 200$ μeV and $14\Delta/e$ the current increases in steps also spaced by $\sim 2\Delta/e$, with the current doubling at each successive step (not visible in the figure). Below ~200 μeV there is a region of width $2E_C/e$ that is insulating within the limits of our instrumentation (Fig. 1 inset). We applied a magnetic field to decrease Δ and found that features attributed to Δ scaled as expected, and features attributed to E_C did not change. The IV curve while pumping in the superconducting state did not show clear, robust plateaus, but the shuttle error technique still allows us to investigate the behavior near $V = 0$.

Figure 2 shows the charge transferred through the pump in the superconducting state for three different conditions. The bottom curve ("hold mode") shows leakage with no pumping, which occurs through discrete jumps in the island charge at rates exceeding 100 Hz. The bandwidth of the SET electrometer (a few hundred Hz) limits our ability to count these events accurately, but a close examination of the traces suggests there are roughly equal numbers of $1e$ and $2e$ jumps. In the middle curve ("$1e$ pulses") we apply "shuttling" gate pulses with amplitudes $V_g = e/C_g$, where C_g is the gate capacitance. These pulses alternate between forward and reverse pumping sequences, each of which takes 350 ns, with a 12 ms wait time between each sequence. For an SET pump in the normal state this should simply shuttle an electron on and off the island every 12 ms. The resulting trace looks similar to the hold mode trace, except with a lower leakage rate, which we currently do not understand. What is apparent, however, is the lack of any pumping behavior at the 12 ms period. In contrast, when we double the gate amplitude in the top trace ("2e pulses") we *do* see clear shuttling of $2e$ every 12 ms, along with both $1e$ and $2e$ random events. This indicates that the SCPT is transferring individual Cooper pairs as desired, although in the presence of a large amount of other tunneling events.

The presence of many $1e$ events in both the hold and pumping modes, and the onset of conduction at $V \sim E_C/e$, indicate the presence of a significant number of quasiparticles in the superconducting state. This "quasiparticle poisoning" is a common problem with SCPT devices, but has been solved in some cases [8]. It is not surprising that $2e$ pumping is seen in the single-charge measurements but not in the IV measurements, since the former involved a long wait between each pumping sequence while the latter did not.

Our work shows that pumping of individual Cooper pairs is possible, and it highlights the necessity of the single-charge measurement technique for investigating the detailed operation of the SCPT pump. Further investigations are needed to understand fundamental issues such as quasiparticle poisoning and the optimal value of E_J/E_C for an SCPT pump.

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