Superconducting single-electron push–pull amplifier stage

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Two superconducting single-electron transistors were used to build a push–pull amplifier stage with a voltage gain of 5.2 that dissipates only 10 fW of power. This amplification stage would be most useful for measuring the voltage across a high-impedance sample at low temperature. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1433944]

A push–pull stage consisting of two transistors in series is a basic building block of analog electronics that is often used at the output of an amplifier.[1] Here, we report on a characteristics of a push–pull stage made with superconducting single-electron transistors (SET's). Like most single-electron circuits, this amplifier has a high charge sensitivity and a high input impedance. It exhibited a voltage gain of 5.2, and dissipated only 10 fW of power. A voltage amplifier of this sort would be most useful for measuring the voltage across a high impedance sample at low temperature. In this application, a high input impedance and low power dissipation are imperative. Here, the measured amplifier characteristics are presented and the possible improvements of this circuit are discussed.

Figure 1 shows a scanning electron microscope photograph of the push–pull stage and a schematic diagram of the circuit. The amplifier consists of two nominally identical single-electron transistors in series that share a common input electrode, V_{in}. In the fabrication process, first the aluminum input electrode was deposited on an oxidized silicon substrate. The top 8 nm of the input electrode was then oxidized to electrically isolate it from the rest of the circuit. The two aluminum islands of the transistors were subsequently deposited so that they overlap the input electrode, thus forming overlap capacitors where the islands overlap the input leads. The tunnel junctions that connect the islands to the aluminum source and drain electrodes were formed by shadow evaporation. Two planar tuning gates, V_{g1} and V_{g2}, that are used to tune the offset charges are also visible in Fig. 1. Further fabrication details are described in Ref. 2.

The push–pull stage was measured in a dilution refrigerator at temperatures between 25 and 500 mK. Measurements on the individual SET's revealed that the tunnel junctions were all identical with capacitances of $C_j = 155$ aF and resistances of 1.3 MΩ. The input capacitances were $C_{\mathrm{in}\,1} = 800$ aF and $C_{\mathrm{in}\,2} = 810$ aF, the tuning gate capacitances were 45 aF, and the stray capacitance of each island was estimated to be 190 aF. The total capacitance of each of the islands was $C_\Sigma = 1.35$ fF.

The output voltage, V_{out}, is a quasiperiodic function of the input voltage. This is because the Coulomb blockade in the upper transistor is modulated with a periodicity $e/C_{\mathrm{in}\,1}$ and the Coulomb blockade in the lower transistor is modulated with a periodicity $e/C_{\mathrm{in}\,2}$. Here, e is the charge of an electron. The precise form of this quasiperiodic function depends on the voltages applied to the two tuning gates, V_{g1} and V_{g2}. By adjusting the voltages on the tuning gates, it was possible to change the input–output transfer function so that the output was proportional to the input over a certain dynamic range. The voltage gain is a complicated function of the circuit parameters but the largest gain achievable is on the order of the gain of a single transistor, $g_{\max} = -C_{\mathrm{in}}/C_j$. Figure 2 shows the input–output characteristics of the push–pull stage when the tuning gates are set for the maximal gain. There is a nearly linear region where the output voltage is -5.2 times the input voltage. The maximum output swing is set by the threshold voltage of the transistors $e/C_\Sigma = 80\ \mu$V.

This amplifier stage can either be used as an electrometer to detect charge, or as a voltage amplifier. Used as an electrometer, superconducting SET's have higher charge sensitivities than normal SET's.[3] A charge sensitivity of $10^{-4} e/\sqrt{\mathrm{Hz}}$ at 10 Hz is typically achieved.[4] When using such an electrometer, it is essential that the parasitic input capacitance be very small. Any charge placed on the input of the electrometer will be divided between the parasitic input capacitance and the input capacitors of the electrometer. The larger the parasitic capacitance, the less charge is coupled to the electrometer. In practice, this means that the electrometer must be fabricated on the same chip as the sample that produces the charge that should be measured. This limits the use of the electrometer to cases where it is possible to fabricate the sample and the electrometer together on a chip.

When the push–pull stage is used as a voltage amplifier, it can be on a separate chip and thus can be employed in a wider variety of circumstances. One of the strengths of this circuit is that it draws virtually no current. This means that the voltage across high-resistance samples could be measured without there being a leakage current through the voltmeter. Another advantage is that it dissipates very little power, about 10 fW. This is important if the amplifier is to be used in a dilution refrigerator where very little power dissipation can be tolerated. The disadvantage that is paired with the low power dissipation is the relatively high output impedance (1 MΩ). The output impedance must be higher than the resistance quantum $h/e^2 \approx 25$ kΩ, otherwise the charging

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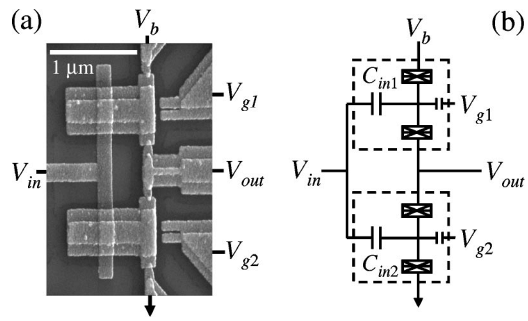

FIG. 1. (a) A scanning electron microscope photo of the sample and (b) a schematic diagram of the circuit. The dotted lines outline the two superconducting SET's in the circuit.

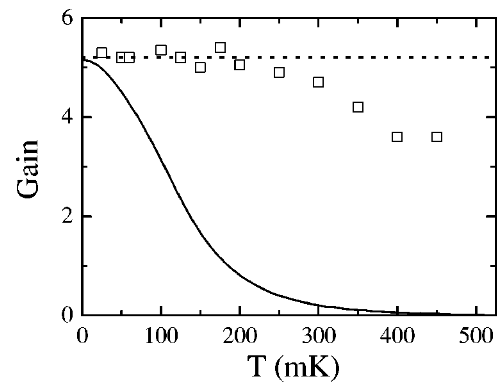

FIG. 3. The voltage gain as a function of temperature. The dashed line is a simulation in the superconducting state. The solid line is a simulation in the normal state.

effects are washed out by quantum fluctuations. The high output impedance results in a slow circuit response.

The voltage sensitivity is the charge sensitivity divided by the input capacitance. For a charge sensitivity of $10^{-4}e/\sqrt{\mathrm{Hz}}$ at 10 Hz and a capacitance of 800 aF, this results in a voltage sensitivity of $20\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 10 Hz. This sensitivity is comparable to high input impedance field effect transistor amplifiers and could be improved by increasing the input capacitance as is discussed next.

Figure 3 shows the gain as a function of temperature. The voltage gain of the amplifier remains constant at 5.2 until a temperature of 250 mK. The calculations for the voltage gain as a function of temperature in the normal state and in the superconducting state are also included in Fig. 3. The calculations were performed using the orthodox theory of single-electron tunneling.[5] The theory predicts that the zero-temperature gain should be maintained to much higher temperatures in the superconducting state than in the normal state. The calculations indicate that the gain in the superconducting state should not decrease until a temperature of approximately half the superconducting critical temperature is reached. This is because the abruptness of the onset of current at the threshold of the Coulomb blockade is determined by the superconducting gap and not by thermal fluctuations. The experiments in the superconducting state show that gain is maintained to higher temperatures than is expected for the normal state but lower than theory predicts for the superconducting state. The reason for this discrepancy is unclear.

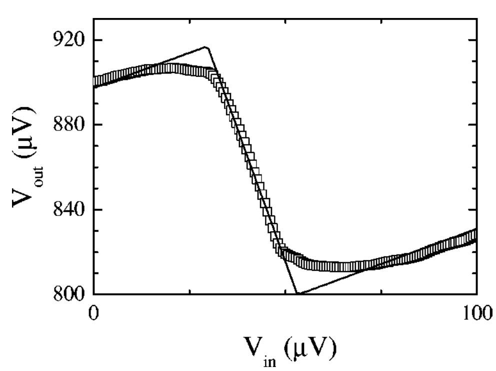

FIG. 2. The output voltage as a function of the input voltage. The squares are the measurement and the solid line is a simulation based on the orthodox theory.

Finally, we speculate on the ultimate performance of a single-electron push–pull amplifier. The way to generate higher gain and lower voltage noise is to increase the input capacitances. However, increasing the input capacitance decreases the charging energy and that reduces the operating temperature. The charging energy E_C must be much larger than the energy of thermal fluctuations for the amplifier to work, $E_C = e^2/C_\Sigma \gg k_B T$. Here, k_B is Boltzmann's constant and T is the absolute temperature. This means that the larger the gain and the lower the voltage noise of the amplifier, the lower the operating temperature must be. In practice, this restricts the use of this voltage amplifier to temperatures below 100 mK. The smallest junction capacitances that have been fabricated with shadow evaporation are on the order 1 af.[6] By combining these junctions with input capacitors of 1 fF, a voltage gain of 1000 could theoretically be achievable at low temperature. The lowest low frequency charge noise reported so far is $8\times10^{-6}\ e/\sqrt{\mathrm{Hz}}$ at 10 Hz.[4] This would correspond to a voltage noise of $1.3\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 10 Hz. Such an amplifier would be useful for measurements of the voltage across a high-impedance sample in a dilution refrigerator.

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