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Charge transformer to enhance noise performance of single-electron transistor amplifiers in high-capacitance applications

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A device, called a charge transformer, is proposed for noise matching single-electron transistor amplifiers to high-capacitance devices. The operation principle is demonstrated on a prototype charge transformer with four capacitors made using a GaAs/AlGaAs heterostructure with a two-dimensional electron gas. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1431393]

Following the discovery of Coulomb blockade phenomena arising from discreteness of charge and the advances in nanofabrication techniques, we have been able to make new kinds of devices that enable us to control and measure the motion of a single electron.[1,2] One of the most exciting examples of such a device is a single electron transistor (SET) which is an extremely precise solid-state electrometer.[3,4] SETs have already been used in metrological applications[5] as well as a tool for imaging localized individual charges in semiconductors.[6] Recent demonstration of single photon detection[7] and rf operation of SETs[8,9] make them exciting for new applications ranging from astronomy to quantum computer read-out circuitry. However, despite the many orders of magnitude better charge sensitivity of SETs with respect to commercial electrometers, in terms of noise, it is not advantageous to use SETs as an electrometer when the device under test has a large capacitance.

To illustrate the origin of this problem, let us consider the typical SET amplifier circuit shown in Fig. 1 (a). The device under test and the signal on the detector are represented by a capacitor C_D and a current source, respectively. The problem arises from the extremely small capacitance of the SET, which is constrained by the operation temperature. When the input capacitance of the SET, C_{SET}, is much smaller than C_D, only a small fraction of the input power, given by C_{SET}/C_D, can couple to the SET.[10] Since, for a typical SET, $C_{\mathrm{SET}}<1$ fF, the suppression factor becomes unacceptable when the macroscopic device has a capacitance in the pF or nF range. Therefore, SET amplifiers are not currently used for measuring real macroscopic devices. Other low-capacitance electrometers, such as a recently proposed quantum point contact electrometer, also suffer from a similar capacitance mismatch problem.[11] We believe, if we can address this capacitance mismatch problem, SETs may find many new ultralow-noise analog applications.

In principle, placing multiple SETs in parallel may solve the input capacitance mismatch problem. However, real SETs are subject to offset charges present near the active region of the device.[12] Thus, operation of multiple SETs in parallel would require an individual feedback circuit for each SET to compensate the effects of offset charges, which is not practical when a large number of SETs are needed. We propose an alternative solution to the input capacitance mismatch problem by using a matching device called a charge transformer. A similar problem, due to an inductance mismatch, exists in the operation of superconducting quantum interference devices. The problem is addressed, in general, using a flux transformer.[13] The charge transformer will be placed between the macroscopic device under test and the SET as shown in Fig. 1(b). The function of the charge transformer is similar to the dc/dc power converters that have long been used in various power applications to generate a voltage that is higher than the voltage of the available power supply. There are various dc/dc power converter circuits, most of which use a charge pump design based on voltage doublers.[14] Unlike transformers based on magnetic induction, such circuits use capacitors, switches, and diodes, and do not use any components that store magnetic energy. Note, however, that the design issues of a charge transformer for low-noise applications are very different from those for power applications. In this letter, we discuss a charge transformer circuit that is suited for low-noise applications. The

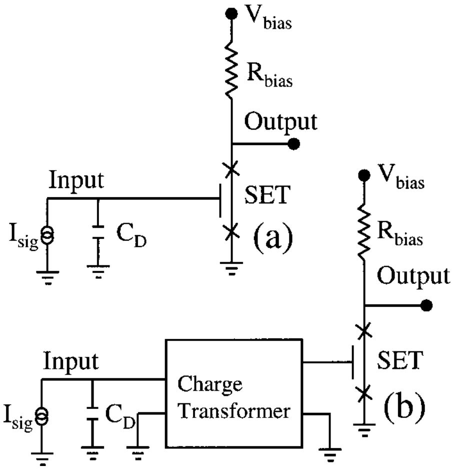

FIG. 1. Simplified circuit of SET amplifier without (a) and with (b) a charge transformer.

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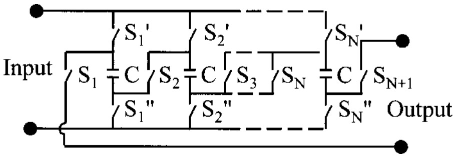

FIG. 2. Circuit diagram of a charge transformer which consists of N capacitors and $3N+1$ switches.

operation principle of such a charge transformer is tested on a prototype transformer fabricated using a GaAs/AlGaAs heterostructure with a two-dimensional electron gas (2DEG).

The goal of a charge transformer is to effectively couple a significant fraction of the input power to the SET. This can be achieved using N capacitors of value C, where $C = \sqrt{C_D C_{\mathrm{SET}}}$ and $N = \sqrt{C_D / C_{\mathrm{SET}}}$. If we connect these N capacitors in parallel with the device under test, because the equivalent capacitance of N-such capacitors in parallel is C_D, an effective coupling between the charge transformer and the device under test can be achieved. Now, if we disconnect these N capacitors and connect them in series with the SET, because the equivalent capacitance of N such capacitors in series is C_{SET}, we can effectively couple the total energy stored in these capacitors to the SET. This idea can be implemented using the circuit shown in Fig. 2. The circuit consists of N capacitors and $(3N+1)$ switches labeled S_i, S_i', and S_i'' that enable the capacitors to be connected in parallel (switches S_i' and S_i'' are closed and switches S_i are open) or series (switches S_i' and S_i'' are open and switches S_i are closed). In operation, the charge transformer must be switched back and forth between these two states at a speed faster than the signals that need to be measured. Furthermore, the switch capacitance and resistance must be low in order not to degrade the noise performance of the charge transformer. Noise analysis of a realistic charge transformer will be discussed in detail elsewhere.[15]

In steady state, when the loads are capacitive, the charge transformer can be characterized by a single internal parameter, the charge Q on each capacitor. The output and input voltages (V_{in} and V_{out}) as well as the charges on the equivalent capacitors seen by the external circuit from the input and output sides of the charge transformer (Q_{in} and Q_{out}) can be expressed in terms of Q ($V_{\mathrm{in}} = Q/C$, $V_{\mathrm{out}} = NQ/C$, $Q_{\mathrm{in}} = NQ$, and $Q_{\mathrm{out}} = Q$). Thus, the charge transformer would step up the input voltage by a factor of N, but since the charge at the output is reduced by the same factor, as with any other transformer, the charge transformer cannot provide any power gain.

A charge transformer with four capacitors and 13 switches has been fabricated using a GaAs/AlGaAs heterostructure grown by molecular-beam epitaxy. The heterostructure consists of a high quality 2DEG located 1000 Å below the top surface. The carrier density, $n = 3.8\times10^{11}\ \mathrm{cm}^{-2}$, and mobility, $\mu = 3.7\times10^{5}\ \mathrm{cm}^2/\mathrm{Vs}$, were determined using Hall measurements at 4.2 K. The picture of the charge transformer fabricated using standard photolithography techniques is shown in Fig. 3. To form each capacitor, we used two triangular regions of 2DEG defined by mesa etching. The capacitive coupling between these two regions of 2DEG is provided by a rectangular Ti/Au metal layer evaporated over the 2DEG. Based on the lithographical dimensions, the equivalent capacitance between these two triangular regions is estimated to be $C = 0.93$ pF. The capacitor circuit is formed using 3 μm wide wires defined by etching the 2DEG. Each wire can be switched on and off using a 3–4 μm wide top metallic gate. The switch capacitance is much smaller than C, thus is not expected to perturb the operation of the charge transformer. Extending out from the active region of the device, there are four 2DEG leads which are the input and output leads of the charge transformer and three metallic gate leads which control switches S_i, S_i', and S_i''. Note that a 2 μm thick polyimide layer was used to electrically isolate the gate lead for S_i from that of S_i''.

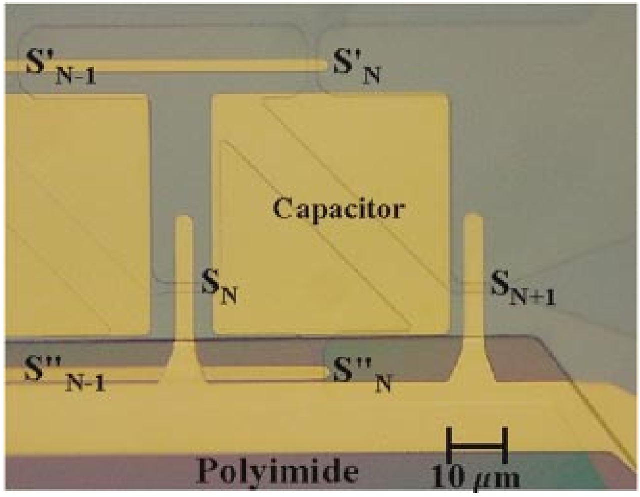

FIG. 3. (Color) Picture of a charge transformer fabricated on a GaAs/AlGaAs heterostructure.

The operation of the charge transformer has been tested at 77 K. The switches were controlled using a dual pulse generator. The pulses were shaped such that, during a pulse period of T, the capacitors were connected in parallel or in series for a duration of $T/4$ and each time in between these two connections, the capacitors were isolated from each other for a duration of $T/4$. A low-frequency sinusoidal signal, V_{in}, was applied to the input of the charge transformer and the output was connected to a voltage divider made out of two resistors. The first resistor connected to the output of the charge transformer is chosen to be large ($R = 1$, 10, or 100 MΩ) to imitate an electrometer and placed next to the charge transformer to minimize the stray capacitance seen by the charge transformer output. The output signal, V_{out}, was measured using a lock-in amplifier. Measured voltage ratio, $V_{\mathrm{out}}/V_{\mathrm{in}}$, is plotted as function of pulse period in Fig. 4. At low frequencies, the voltage ratio was found to be independent of signal frequency. If the measurements were performed using an ideal electrometer with an infinite input resistance, then the voltage ratio would be independent of pulse width; $V_{\mathrm{out}}/V_{\mathrm{in}} = N = 4$. The data clearly indicate that the deviation from the ideal operation is due to the resistance of the measuring circuit. The deviation is most pronounced at low R and when longer pulse periods are used. On the other hand when R is large, i.e., $R = 100\ \mathrm{M}\Omega$, the voltage ratio approaches 4 with the faster operation of the switches.

The deviation from ideal operation can be understood as a resistor/capacitor (RC) effect introduced by the measurement circuit. We have modeled this effect by considering a

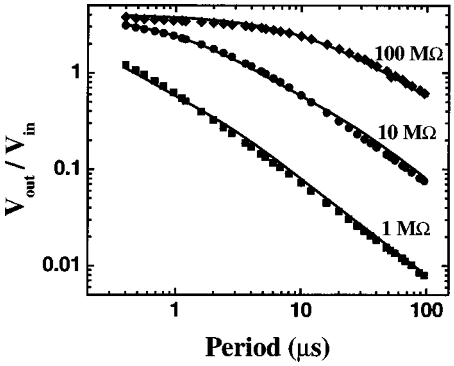

FIG. 4. The voltage ratio, V_{out}/V_{in}, versus pulse period for three different values of resistance seen by the out of the charge transformer. Solid lines are the best theoretical fit to the data obtained using $C=0.8$ pF and $C_M=0.16$ pF.

case where the input of the charge transformer was connected to a constant voltage source and the output was connected to a measuring circuit described by a resistor R and a capacitor C_M connected in parallel. In this model, C_M represents the stray capacitance of our measuring resistor. $V_{out}(t)$ was calculated following a simple circuit analysis. The high-frequency components of $V_{out}(t)$ that are commensurate with the pulse frequency are not relevant, since the signal frequencies of interest are much slower than the pulse frequency. In fact the voltage ratio that is relevant to the experiment is given by $\langle V_{out}\rangle/V_{in}$, where $\langle V_{out}\rangle$ is the time averaged value of $V_{out}(t)$. We find when the pulse widths are much smaller than the RC time constant of the measurement circuit that $\langle V_{out}\rangle/V_{in}\approx 4$. We fitted the data by taking capacitance values as an adjustable parameter. We assumed identical capacitance values in all three cases of R and obtained a good fit to the data, as shown in Fig. 4, with reasonable values of $C=0.8$ pF and $C_M=0.16$ pF.

In summary, we have presented a device, called a charge transformer, which can be used to enhance the noise performance of SET amplifiers when placed between the SET and a high capacitance device under test. This device is implemented using GaAs/AlGaAs heterostructures with a high quality 2DEG. The charge transformer can also be fabricated using other semiconductors, including using Si metal–oxide–semiconductor field-effect transistors, and can operate at high temperatures. We believe SET amplifiers, integrated with a charge transformer on the same chip, may find applications in various fields where low-noise electrometers are needed.

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