

Broadband single-electron tunneling transistor

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A single-electron tunneling transistor has been directly coupled on-chip to a high electron mobility transistor. The high electron mobility transistor (HEMT) is used as an impedance matching circuit with a gain close to unity. The HEMT transformed the 1.4 M Ω output impedance of the single electron tunneling (SET) transistor by two orders of magnitude down to 5 k Ω , increasing its bandwidth to 50 kHz. This circuit makes it possible to observe the motion of individual electrons at high frequencies. The requirements for the bandwidth in high frequency applications is discussed.
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The single-electron tunneling (SET) transistor^{1,2} is a device capable of measuring charge with a charge sensitivity of $10^{-4}e/\sqrt{\text{Hz}}$ at 10 Hz. It is by far the most sensitive device available for measuring charge. Using a SET transistor, the transfer of single electrons to a small metal island has been observed.³ Although the intrinsic speed of a SET transistor is limited by its RC response time to 10–100 ps, it is impossible to make measurements at this speed in a typical measurement setup. The intrinsically large output impedance of the tunnel junctions ($R_T \gg R_K = 25.8 \text{ k}\Omega$) coupled with the inevitable capacitances of the filtering⁴ and the leads ($C_L \approx 100 \text{ pF/m}$), reduces the bandwidth of SET devices to a few hundred Hz. There are, however, applications where one would like to make very fast charge measurements. For instance, in SET devices the shot noise can be suppressed below the Schottky value due to electron correlations.^{5,6} To directly probe this intrinsic shot noise one needs to measure at high frequencies where the shot noise dominates over the $1/f$ noise.⁷ It is the shot noise which sets the ultimate sensitivity of the SET transistor.

Furthermore, Likharev⁸ proposed that a current could be measured simply counting the number of electrons that pass a certain point in a circuit. In order to be able to perform such an experiment, a wide-band SET transistor must be developed. In this letter, we describe the integration of a SET transistor with a high electron mobility transistor (HEMT). The HEMT transforms the high output impedance of the SET transistor and makes high frequency operation possible.

The observation of the shot noise requires that the $1/f$ noise spectral density,⁹ $S_{1/f} = \alpha \langle I \rangle^2 / f$, be much smaller than the shot noise spectral density, $S_{SN} = 2e \langle I \rangle$. The parameter α is system dependent and for a SET transistor with a $1/f$ charge noise magnitude of $10^{-4}e/\sqrt{\text{Hz}}$ at 10 Hz, $\alpha \approx 10^{-5}$. Therefore, to measure the shot noise of a SET transistor with a bias current of 100 pA would require a bandwidth of at least 100 kHz.

To measure a current by detecting the electrons that go by, it is important that only one electron passes the measur-

ing point at a time. This condition can be met in a series array of small tunnel junctions coupled to the SET transistor.^{10,11} Under certain conditions, the correlated motion of electrons in the array is possible, resulting in the generation of narrow-band SET oscillations with a frequency $fs = \langle I \rangle / e$, where $\langle I \rangle$ is the dc current flowing through the array. The correlations in the time domain can be studied by monitoring the charge motion at a certain point in the array with a SET transistor. The bandwidth of the SET transistor should be at least comparable to the SET oscillation frequency; a current of 1 pA through the array requires a bandwidth of at least 6.3 MHz.

In order to perform such high frequency charge measurements, the bandwidth of the SET transistor must be increased by placing an impedance matching circuit close to the SET transistor, which has a high input resistance and is able to drive high capacitance leads. A cryogenic high-electron mobility transistor¹² satisfies both requirements; at low temperatures it has a very high input resistance as well as a low output impedance. We have integrated an aluminum SET transistor on-chip next to a GaAs–AlGaAs HEMT. The voltage output of the current-biased SET transistor was directly connected to the gate of the HEMT.

The on-chip HEMT was optimized for megahertz operation in a dilution refrigerator.¹³ The design is a tradeoff between a large signal response, i.e., transconductance and low power dissipation ($\sim \mu\text{W}$). For a saturated source-drain current I_{DS} , the HEMT response is determined by its transconductance, $g_m = (\partial I_{DS} / \partial V_{GS})_{V_{DS}}$, and can be controlled by the ratio of the channel width W , and the active layer thickness d . Here V_{GS} is the gate-source voltage and V_{DS} is the drain-source voltage. Beside parasitics, its high frequency operation is determined by the transit time $1/\tau \approx g_m / C_G$, which is the time spent by the electrons under the gate capacitor C_G .

The HEMT structures were fabricated using a GaAs/Al_{0.3}Ga_{0.7}As heterostructure grown by molecular beam epitaxy. The two-dimensional electron gas (2DEG) had a sheet density of $n_s = 4 \times 10^{11} \text{ cm}^{-2}$ and a mobility of $\mu = 9 \times 10^5 \text{ cm}^2/\text{Vs}$ and was situated at a depth $d = 75 \text{ nm}$ below the surface. The source-drain channel was 60 μm long and

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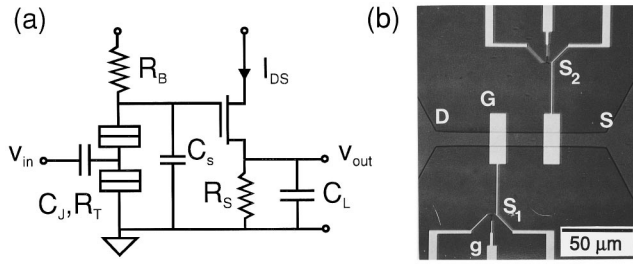


FIG. 1. (a) Schematic circuit of the integrated circuit. The circuit is comprised of a directly coupled SET transistor as a charge sensitive input stage. The tunnel junctions are indicated by the boxes. The voltage output of the SET transistor is directly coupled to the input gate of the HEMT which buffers the output signal of the SET transistor. (b) Photomicrograph of the device. Two SET transistors S_1 and S_2 are coupled to a horizontal 2DEG channel, connecting the source (S) to the drain (D) of the HEMT. Note that the SET transistor is much smaller than the dimensions of the HEMT. A small signal to the gate of the SET transistor (g) is transferred to the gate of the HEMT (G).

10 μm wide and was defined by electron-beam lithography and a mesa etch. The Ohmic contacts to the 2DEG were made by thermal diffusion of Ni-AuGe.

The SET transistor was fabricated directly next to the 2DEG channel using accurate alignment. The SET transistor consisted of a small metallic island weakly coupled to the leads by two ultrasmall tunnel junctions, as shown in Fig. 1(a). The tunneling of electrons through the junction was strongly affected by the Coulomb blockade, which inhibits tunneling below a certain threshold voltage. The threshold voltage was controlled by an input gate, which was capacitively coupled to the island. The Al-A AlO_x -Al junctions were fabricated using a two-angle shadow evaporation technique.¹⁴ The gate of the HEMT was directly coupled to the output voltage of the SET transistor as shown in Fig. 1(b). The SET transistor was situated 40 μm away from the 2DEG channel. Beside the integrated circuits, the chip also contained single HEMTs and SET transistors for detailed device characterization.

The dc performance of a single HEMT is shown in Fig. 2. The measurements were performed in a dilution refrigerator with a base temperature of 10 mK. The HEMT was biased using low noise mercury cells. The gate was defined by

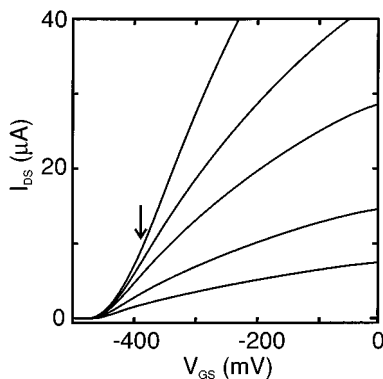


FIG. 2. Gate-source characteristics taken at base temperature of 10 mK and a magnetic field of 0.2 T for different values of the drain-source voltage: $V_{DS} = 20, 40, 60, 80, \text{ and } 100 \text{ mV}$. The arrow indicates the working point of the HEMT, at a gate-source voltage of -390 mV . At this point the transconductance is $g_m = 0.2 \text{ mS}$.

the channel width $W = 10 \text{ } \mu\text{m}$, the gate length $L = 10 \text{ } \mu\text{m}$, and had a nominal area of $100 \text{ } \mu\text{m}^2$. The gate length was larger than the elastic scattering length of the electrons so the transport along the channel was diffusive. Typical source-drain characteristics are shown in Fig. 2. At source-drain voltages larger than 100 mV, the source-drain current saturates. The channel pinches off smoothly, at a gate threshold of -450 mV . The experimentally measured gate capacitance of 0.13 pF agrees well with the value of 0.15 pF, estimated for the geometrical capacitance.

To measure the characteristics of the SET transistor, a magnetic field of 0.2 T was applied to keep the aluminum in the normal state. The circuit parameters of the current biased SET transistor were obtained by fitting the experimentally measured output voltage vs gate voltage characteristics $V_0 - V_g$, to the theoretical calculated curves using the orthodox theory.¹⁵ The SET transistor had junction capacitances of $C_1 = 0.24 \text{ fF}$, $C_2 = 0.29 \text{ fF}$; tunnel resistances of $R_1 = 720 \text{ k}\Omega$, $R_2 = 700 \text{ k}\Omega$; and a gate capacitance of $C_g = 80 \text{ aF}$. Consequently, the gain of the SET transistor was less than unity $K_V = (\partial V_0 / \partial V_g)_{I_b} = C_g / C_2 \approx 0.3$ and the total output impedance was 1.4 M Ω . The maximum output voltage swing of the SET transistor is set by the threshold voltage $V_T = e / C_\Sigma \approx 0.25 \text{ mV}$, where $C_\Sigma = C_1 + C_2 + C_g$ is the total island capacitance.

The SET transistor and the HEMT were put in their optimal working points by setting the dc bias voltages of each device. The current bias of the SET transistor was realized by putting a 20 M Ω metal film resistor R_B , in series with the device and was about 25 pA. The resistor was placed in the cold, off-chip, as close as possible to the device to reduce stray capacitances. The HEMT was used in a source-follower configuration with a gain close to unity. The channel was biased at a source-drain voltage $V_{DS} = 100 \text{ mV}$, just in its saturation region. Then the gate-source voltage was set to $V_{GS} = -390 \text{ mV}$ by means of a cold 46 k Ω source resistor R_S . At this point, the drain current was 8.5 μA and the transconductance was 0.2 mS. The settings were such that the total power dissipation in the HEMT was 0.8 μW and did not seriously affect the SET transistor characteristics. The total output impedance and the gain of the circuit were then calculated using simulation, yielding an output impedance of $Z_{out} \approx 1/g_m = 5 \text{ k}\Omega$ and a gain of $G_H = 0.74$. The experimentally measured gain of the HEMT in the source-follower configuration was $G_H = 0.72$ and thus in good agreement with the simulations.

The frequency response of the circuit was then determined by applying a small ac signal $v_{in} = e / 2C_g \approx 1.5 \text{ mV p-p}$ to the gate of the SET transistor. The response of v_{out} at the output of the HEMT was measured using a low noise differential amplifier. Figure 3(a) schematically shows the response of the circuit. For frequencies up to 50 kHz, the gain of the total circuit, $G_{tot} = v_{out} / v_{in} \approx 0.21$, is shown in Fig. 3(b). This agrees well with what one would expect from the gain parameters of the individual circuits, $G_{tot} \approx K_V G_H$. The signal-to-noise ratio at 50 kHz was $\sim 10 \text{ dB}$, and decreased rapidly above the corner frequency due to the stray capacitance of the 2 cm long lead from the SET transistor to the bias resistor $C_s \approx 2.5 \text{ pF}$. In order to reduce this capaci-

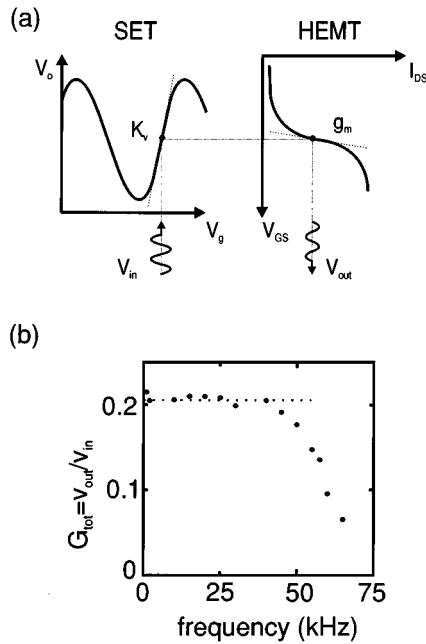


FIG. 3. (a) Schematic of the device operation. The SET transistor and the HEMT are set in their optimal working points, denoted by the black dots in their transfer characteristics. A small ac voltage signal is transferred via the voltage transfer coefficient K_v , and the transconductance g_m , to the output of the HEMT. The experimental response of the circuit is shown in (b). The gain of the circuit is 0.21. At a corner frequency of 50 kHz the response decreases rapidly due to stray capacitances.

tance a low capacitance thin-film resistor¹⁶ of about 1–10 k $\Omega/\square$ must be fabricated on-chip *close* to the circuit. The development of high Ohmic resistors for SET devices is in progress and can be implemented in our multilayer fabrication approach.¹⁷ Alternatively, one could use an array of small junctions close to the SET transistor as a (nonlinear) bias resistor.¹⁸

In conclusion, we have transformed the impedance of a SET transistor by two orders of magnitude down to 5 k Ω , increasing its bandwidth to 50 kHz. It is the first demonstration of the direct integration and operation of a metallic SET

device with a semiconductor HEMT. Optimization of the design suggests operation in the megahertz range will be possible.

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