Shot Noise in the Current of a Surface Acoustic-Wave-Driven Single-Electron Pump

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We have measured the noise at ≈ 1.6 MHz in the current produced by a single-electron pump that uses an ≈2.7 GHz surface acoustic wave (SAW). The current can be varied by altering the voltage applied to surface gates. Over the range of gate voltage where the current is close to the quantized value corresponding to one electron being transported per cycle of the SAW, the noise in the current is dominated by shot noise, whereas away from this range the noise mostly arises from switching the charge states of electron traps in the material. By combining measurements of the shot noise and the current, we determined how the error rates—the probabilities of transporting zero or two electrons in a cycle—vary with gate voltage when the current is close to the quantized value. The results obtained suggest that these two probabilities are controlled by closely linked mechanisms.

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Devices capable of delivering n electrons in each cycle of a controlling signal, thereby producing an accurately quantized current $I = nef$ where e is the electronic charge and f the frequency of the signal, would find important applications in electrical metrology. Single-electron pumps [1] and turnstiles [2] have therefore attracted considerable attention, but only surface-acoustic-wave (SAW)-driven single-electron pumps [3,4] operate at a frequency that is high enough ($f_{SAW} \sim 3$ GHz) for the current to be sufficient for a current standard. There are also proposals to use SAW-driven pumps in quantum cryptography [5] and quantum computation [6]. However, the accuracy of the SAW pumps must be improved substantially if they are to be used for these applications. Achieving this improvement will require a more detailed understanding of the operation of the devices. In the work presented here, we address this by measuring the shot noise in the current produced by a SAW-driven single-electron pump, which enables us to determine the probabilities p_n of transporting n electrons in a cycle.

The operation of the single-electron pump is illustrated in Fig. 1. A negative voltage is applied to a split gate on the (100) surface of a $GaAs/Al_{0.33}Ga_{0.67}As$ heterostructure, forming a narrow depleted channel between two regions of two-dimensional electron gas (2DEG), and a SAW is launched towards this channel along a [110] direction from an interdigitated transducer situated 2 mm away. A wave of electrostatic potential accompanies the SAW because the substrate is piezoelectric (the deformation potential is negligible), so that, for a sufficiently high SAW amplitude, a potential well moves through the channel in each cycle of the SAW. Electrons can be captured from the source 2DEG into this potential well and transported through the channel to the drain 2DEG [Fig. 1(b)]. Further details can be found in Refs. [3–5,7,8].

In ideal operation, the number of electrons n transported in a cycle would be fixed by the Coulomb interaction between the electrons and the minimum size reached by the potential well as it moves towards the center of the channel. Varying this minimum size by sweeping the gate voltage would result in a steplike variation of the current, with the nth plateau occurring at a quantized value $I = nef_{SAW}$. In real devices, errors in the electron transport cause the plateaus to be sloping and not at the ideal quantized values. No complete understanding of the error mechanisms exists because the dynamics of the electrons within the device presents a difficult time-dependent many-body problem. However, particular aspects of the electron transport have been studied using simplified models: tunneling of electrons in the ground state of the well back to the source 2DEG [9]; nonadiabatic effects caused by a rapidly decreasing coupling between the well and the source 2DEG [10]; and excitation caused by electrons rapidly leaving the well in a classical model [7]. These works do not accurately reproduce all the features of the experiments and, in particular, tend to predict a degree of

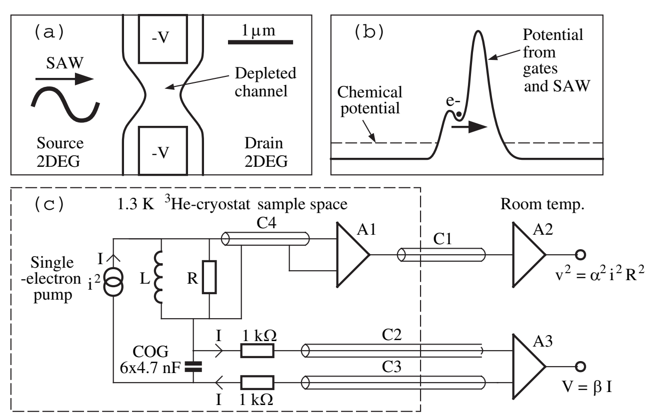

FIG. 1. (a) Schematic diagram of the active region of a SAW-based single-electron pump. (b) Illustration of the mode of operation of the device. (c) Circuit used to perform the measurements. The device is represented as a current source producing dc current I and current noise power i^2. Further details are given in the main text.

current quantization that is much better than that observed. To inspire and verify a more accurate model of the devices, new information from experiments would be highly beneficial. Measurements of the shot noise in the current, which have proven to be very useful in studying the processes occurring in low-dimensional systems [11,12], could provide this information.

Shot noise in the current arises when error mechanisms cause random fluctuations in the number of electrons transported in different cycles of the SAW. If all cycles transport $n-1$, n, or $n+1$ electrons, with corresponding probabilities p_{n-1}, p_n, and p_{n+1}, then the power spectral density (PSD) of the shot noise is [8,13]

$$i^2_{\rm shot} = 2[p_{n-1} + p_{n+1} - (p_{n-1} - p_{n+1})^2]e^2 f_{\rm SAW} \quad (1)$$

and is independent of frequency for frequencies well below the SAW frequency [13]. Combining shot-noise measurements with measurements of the mean current

$$I = (n + p_{n+1} - p_{n-1})ef_{\rm SAW} \quad (2)$$

therefore enables p_{n-1}, p_{n+1}, and $p_n = 1 - p_{n-1} - p_{n+1}$ to be extracted, fully characterizing the operation of the device. Note that when $p_{n-1}, p_{n+1} \ll 1$, Eq. (1) becomes $i^2_{\rm shot} \approx 2(p_{n-1} + p_{n+1})e^2 f_{\rm SAW}$, which has a simple interpretation: cycles that transport $n-1$ or $n+1$ electrons appear as negative or positive pulses of current, respectively, on top of a constant background current, resulting in shot noise proportional to $p_{n-1} + p_{n+1}$. The shot noise is therefore expected to be minimized on the current plateaus, with values that reflect the probability of an error occurring in the electron transport, and maximized between the plateaus.

In previous work [8] the noise of the SAW pump was measured at ~1 kHz. The PSD of the noise between the quantized plateaus in the current was found to exceed the theoretical value for the shot noise by nearly 3 orders of magnitude, and was interpreted [8] as being caused by switching the charge states of single-electron traps close to the 1D channel. The large switching noise made it impossible to extract the shot-noise contribution in that work, but the results showed that the switching noise decreases with frequency and suggested that a measurement frequency above ~1 MHz would result in the shot noise dominating over the switching noise. In the present work we have measured the noise at a frequency of ≈1.65 MHz using the circuit shown in Fig. 1(c). In this circuit, the SAW pump drives a current through the resonant circuit formed by superconducting inductor $L \approx 290\ \mu$H and various capacitances: the capacitance of cable C4, the capacitance at the input of the amplifier A1, and the self-capacitance of the inductor. Using a resonant circuit enables a large impedance to be achieved, $R \sim 300$ kΩ, that would otherwise be shorted at ~1 MHz by parasitic capacitances. The capacitance of the cable C1 to room temperature would short the voltage developed across the resonant circuit at ~1 MHz, so a cryogenic amplifier A1 must be used. Complete details of the design and operation of the cryogenic amplifier are given elsewhere [14].

The voltage across the resonant circuit is amplified by a factor $\alpha \approx 40$ by $A1$ and $A2$ and is then sampled using a GaGe CS1602-10 16-bit analogue-to-digital converter. To determine the noise in the current produced by the device, typically several seconds of data are sampled. The fast-Fourier transform of these data is then calculated and averaged over a 10 kHz wide range centered on the resonant frequency (≈1.65 MHz). The resulting value is then scaled, using the measured gain of the amplifier and a factor that takes into account the shape of the resonance peak, so that the input-referred PSD of the current noise at the resonant frequency is produced. The background noise, comprising the Johnson noise of the resonant circuit and the current noise of the amplifier (≈15 fA Hz$^{-1/2}$ at 1.65 MHz), is then subtracted. The value of the background noise is determined by applying sufficient negative voltage to the split gate that the single-electron pump produces no current.

All measurements were taken at ≈ 1.3 K. The 2DEG carrier density and mobility are ≈ 1.64×10^{11} cm^{-2} and ≈1.04×10^6 cm^2 V^{-1} s^{-1}, respectively. The device is nominally identical to that used in [8] with a 2DEG situated 90 nm beneath the surface and a split gate that has a gap that is 0.7 μm long (in the direction of SAW propagation) and 1.2 μm wide. The dc current produced by the device is measured using a Stanford Research Systems SR570 current preamplifier [$A3$ in Fig. 1(c)].

Figure 2 shows how the current produced by the device and the noise in the current at ≈1.65 MHz vary with gate

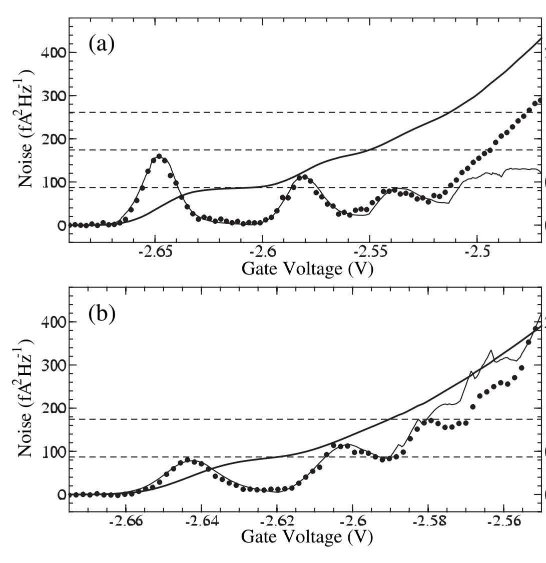

FIG. 2. Variations with gate voltage of the current noise near 1.65 MHz (dots represent values obtained from ≈5 s of sampled data, left-hand axis), current (bold line, right-hand axis), and $i^2_{\rm switch} + i^2_{\rm minshot}$ (line, left-hand axis) for (a) cooldown A and (b) cooldown B. The dashed lines indicate $I = {\rm nef}_{\rm SAW}$.

voltage for two cooldowns "A" and "B" of the device that were separated by warming to room temperature. Plateaus in current are seen that are sloping because errors are occurring in the transport. Values for the microwave frequency and power were used throughout this work that optimized the quantization of the first current plateau, 2.71683 GHz and 11.5 dBm for cooldown A, and 2.71708 GHz and 11.75 dBm for cooldown B.

The graphs in Fig. 2 show that the noise is suppressed on the current plateaus and reaches values of $\sim$100 fA^2 Hz^{-1} between the plateaus. To interpret these results, we note that if the nth and $(n+1)$th plateaus are clearly visible, then between these plateaus but not close to them it is reasonable to expect that only the probabilities p_n and p_{n+1} are finite. The shot noise will then have its minimum possible value for a particular value of current: the presence of cycles that transport fewer than n or more than $n+1$ electrons would obviously increase the shot noise. From Eq. (1), the "minimum" shot noise is therefore given by

$$i^2_{\text{minshot}} = 2(p_{n+1} - p^2_{n+1})e^2 f_{\text{SAW}}, \tag{3}$$

with $p_{n+1} = (I/ef_{\text{SAW}}) - n$. The maximum value of i^2_{minshot} is 35 fA^2 Hz^{-1} (when $p_{n+1} = 0.5$), but Fig. 2 shows that the noise below the clearly visible first plateau reaches a value a few times larger than this.

Characteristics of the extra noise are shown elsewhere [15] to be consistent with it being caused by switching the charge states of single-electron traps in the heterostructure.

Previous work [8] has shown that the effect of a change in the charge state of a trap close to the depleted channel of the device is to effectively change the gate voltage by an amount ΔV_g that is roughly constant over the range of gate voltage that separates two current plateaus. If the charge state of this trap switches between two states, then noise will be produced with PSD proportional to the square of the change in current ΔI between the states. The switching will also result in the measured current being an average of the currents produced in the different states, weighted by the time spent in the different states. Provided ΔV_g is small enough for the measured "averaged" characteristic to be close to the nonaveraged "underlying" characteristics, and also small compared to the scale over which the gradient changes, then ΔI will be proportional to the gradient dI/dV_g of the measured characteristic and the PSD of the switching-type noise can be written

$$i^2_{\text{switch}}(f) = \sigma(f)\left(\frac{dI}{dV_g}\right)^2. \tag{4}$$

For a real device the value of σ at the measurement frequency is likely to vary with gate voltage because the energies of the single-electron traps will be gate-voltage dependent. For the purpose of estimating the contribution from switching noise on the first plateau, we make the approximation that σ(1.65 MHz) varies linearly with gate voltage. The variation of σ(1.65 MHz) can be determined from the noise measured at the values of gate voltage when the current is $0.5ef_{\text{SAW}}$ and $1.5ef_{\text{SAW}}$ by assuming that the shot noise has the value $i^2_{\text{minshot}} = 35$ fA^2 Hz^{-1} at those points. Between those two points, σ(1.65 MHz) varies by approximately -20% and $+80\%$ for cooldowns A and B, respectively.

The variation with gate voltage of $i^2_{\text{switch}} + i^2_{\text{minshot}}$, which should give the measured noise away from the plateaus, is shown in Fig. 2. It can be seen that for currents from zero to $\sim 2ef_{\text{SAW}}$, the accepted approximation for the switching noise leads to an excellent agreement with the experimental data. Although the shot noise is expected to be larger than i^2_{minshot} when on the plateaus, it is not clearly seen in the figure because of the scale and the measurement sensitivity.

Figure 3 shows the current, measured noise, and i^2_{switch} calculated as above, across the center of the first current plateau for both cooldowns. Each data point for the noise corresponds to data taken over a total of $\approx$35 s ($\approx$15 s) for cooldown $A(B)$. From Fig. 3, it can be seen that the estimated contribution from switching-type noise on the flattest part of the current plateau is $<$10% of the measured noise for cooldown A, and $\sim$30% for cooldown B. The noise measured on the plateau is therefore mostly shot noise.

By subtracting the estimated switching noise from the measured noise to obtain the shot-noise contribution, and using the measured value of the mean current I, the probabilities p_0 and p_2 can be estimated from Eqs. (1) and (2). Figure 4 shows how these probabilities vary across the plateau. From Fig. 4, it can be seen that the probabilities p_0 and p_2 are both finite on the flattest part of the plateau

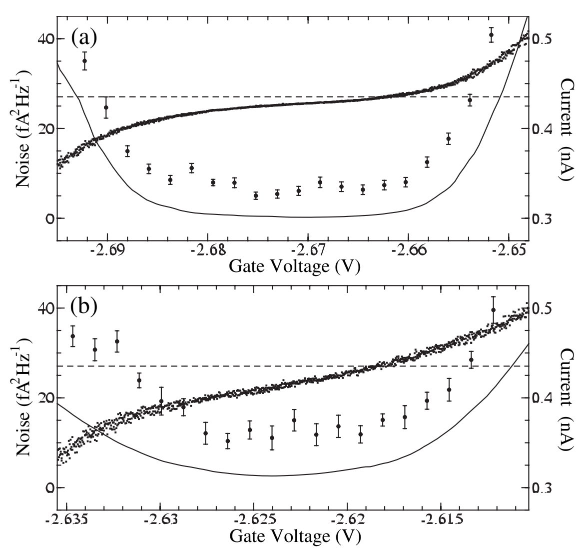

FIG. 3. Variations with gate voltage of the current noise near 1.65 MHz (large dots with error bars, left axis), current (curve composed of small dots, right axis), and i^2_{switch} (line, left axis). (a),(b) Cooldowns A and B, respectively. The dashed lines indicate $I = ef_{\text{SAW}}$.

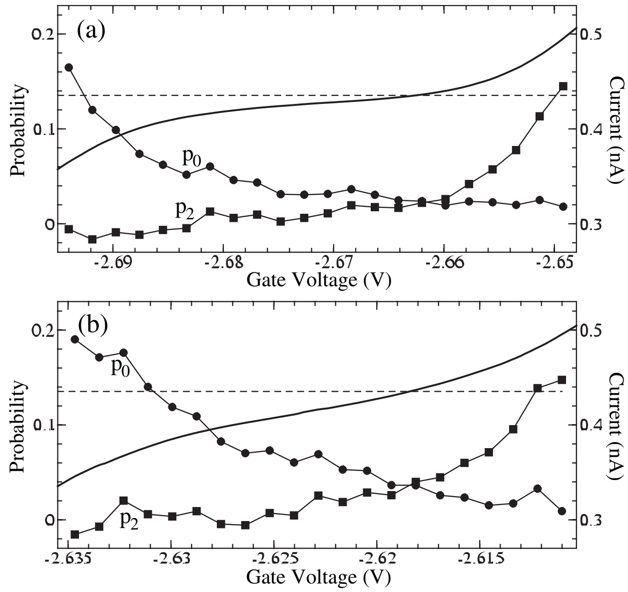

FIG. 4. Variations with gate voltage of the probabilities p_0 (circles, left axis) and p_2 (squares, left axis), and the current (line, right axis). (a),(b) Cooldowns A and B, respectively. The dashed lines indicate $I = ef_{\mathrm{SAW}}$.

and also at the point where the current is equal to the ideal quantized value. Further, over the flattest region of the plateau, p_0 decreases as the current increases at roughly the same rate as p_2 increases. For cooldown $A(B)$, where the center of the flattest part of the plateau is $\approx 2\%(5\%)$ below ef_{SAW}, we find $p_0 + p_2 \approx 4\%(9\%)$ over the flattest part. The data for the two cooldowns therefore demonstrate that the observed degree of quantization is approximately proportional to the sum of the error probabilities $p_0 + p_2$ over the flattest part of the plateau. This observation illustrates the direct link between the accuracy of quantization and the shot noise in the current.

In conclusion, we have measured for the first time the shot noise in the current produced by a SAW single-electron pump. Using these measurements we calculated the probabilities p_0 and p_2 of zero and two electrons being transported in a cycle and found that $p_0 + p_2$ is approximately constant across the center of the plateau. The observation that p_0 varies with gate voltage at minus the rate that p_2 varies suggests that the processes that lead to missing electrons and extra electrons are fundamentally linked. This is not an obvious feature of the traditional model of the devices [4,7,9], which suggest no such a link. Our results should help to identify the correct details of the processes that lead to errors in the single-electron transport and therefore aid the development of an adequate theoretical model.

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