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Experimental investigation of hybrid single-electron turnstiles with high charging energy

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We present an experimental study of hybrid turnstiles with high charging energies in comparison to the superconducting gap. The device is modeled with the sequential tunneling approximation. The backtunneling effect is shown to limit the amplitude of the gate drive and thereby the maximum pumped current of the turnstile. We compare results obtained with sine and square wave drive and show how a fast rise time can suppress errors due to leakage current. Quantized current plateaus up to 160 pA are demonstrated. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3127229]

Development of a quantum current standard based on the discreteness of the electron charge has been one of the major goals of metrology for more than twenty years.[1] The desired standard would generate the current $I=nef$ by transferring n electrons (e) per cycle at frequency f. The most precise device of this kind was based on seven tunnel junctions in series.[2] It reached the relative accuracy of 10^{-8}, but the maximum current was only on a picoampere level. However, closing the quantum metrological triangle,[3] which is one of the prime needs for the quantum current standard, requires about 100 pA or more. The quest for standards with higher currents has involved several candidates, based, e.g., on superconducting devices,[4] surface acoustic waves,[5] and semiconducting quantum dots.[6] However, none of them has reached metrological accuracy. In this letter, we study the benefits of increased charging energy for the turnstile based on a hybrid single-electron transistor (SET), see Fig. 1(a), proposed and demonstrated in Ref. 7. It was first realized as a NISIN (N =normal-metal, I=insulator, and S=superconductor) structure, but the SINIS version reported in Ref. 8 promises higher accuracy.[9]

The operation of the turnstile is based on the superconducting gap Δ, which expands the stability domains of the charge states, see Figs. 1(b) and 1(c). A small bias voltage V_b can be applied since the current is ideally zero when $|V_b| < 2\Delta/e$. The bias yields a preferred direction of tunneling, when the gate voltage $V_g(t)$ is alternated between the charge states. The gate voltage is convenient to express in normalized units as $V_g(t)C_g/e \equiv n_g(t) \equiv n_{g0}+A_g w(t)$, where C_g, n_{g0}, and A_g are the gate capacitance, dc offset, and drive amplitude, correspondingly. The gate waveform, e.g., sine or square, is expressed with $w(t)$. By extending the gate sweep over several charge states, current plateaus with $n>1$ can be obtained. However, the first plateau is optimal for metrology.

The errors of the turnstile were analyzed theoretically in Ref. 9 in which, e.g., the tradeoff between the pumping speed and the error rate was considered. Experimentally, the most critical error source appears to be the subgap leakage, i.e., residual conductance in the superconducting gap.[7,8,10] Often the leakage shows up as a constant slope at low bias. Then it can be described as the ratio $\eta_n = R_N/R_n$ between the normal-state resistance and the leakage resistance at plateau n. The index $n=0$ refers to the dc zero-bias leakage. Higher-order tunneling events due to Andreev reflection or Cooper-pair-electron cotunneling are known to be leakage processes that affect the operation of the turnstile.[9] Possible other mechanisms include Cooper-pair breaking,[11] nonequilibrium quasiparticles and nonidealities of the tunnel barrier. In Ref. 9 it was shown that the higher-order processes are suppressed by the Coulomb blockade. Specifically, Andreev re-

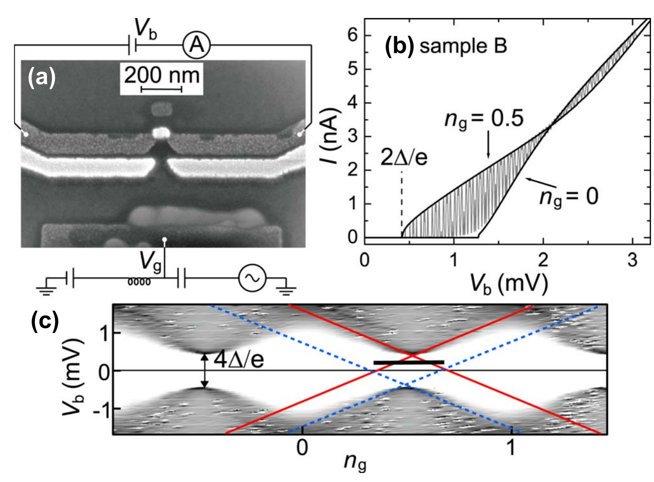

FIG. 1. (Color online) (a) Scanning electron micrograph of a typical turnstile, and a sketch of its measurement circuitry. The bright areas are AuPd (normal metal), and the darker parts are Al (superconductor). (b) Measured (gray) and simulated (black) dc IV curves of sample B. The dc gate voltage was swept during the measurement and hence the envelopes correspond to the simulated IV curves with $n_g=0$, 0.5. (c) Measured dynamic conductance dI/dV_b of sample A as a function of V_b and n_g. The white areas are stability regions of charge states, where the conductance is negligible. They are limited by the thresholds for tunneling in the direction preferred by positive bias (solid lines) and negative bias (dashed lines). The pumping gate signal, when applied, alternates along the thick black line.

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TABLE I. The parameters of the samples A, B, and C.

	R_N (kΩ)	E_c/k_B (K)	Δ (μeV)	E_c/Δ	η_0 ($\times 10^{-5}$)
A	1540	10	250	3.4	8
B	315	7	210	2.9	4.7
C	64	8.5	220	3.3	7

flection vanishes in the regime $n_g = 1/2 \pm A_{g,\mathrm{Ar}}$, where $A_{g,\mathrm{Ar}} = 1/2 - \Delta/4E_c$ is the threshold amplitude for Andreev reflection at the first plateau. The charging energy $E_c = e^2/2C_\Sigma$ depends on the total capacitance of the island C_Σ. Note that here and in the amplitude threshold discussion below we assume the bias voltage $eV_b = \Delta$, which minimizes the thermal errors.[7] Together with the threshold for the wanted forward tunneling process, $A_{g,\mathrm{ft}} = \Delta/4E_c$, $A_{g,\mathrm{Ar}}$ yields the requirement $E_c > \Delta$. In this case, the turnstile could be operated at error rates below 10^{-8}, which is the prime motivation for studying turnstiles with high charging energy. This theoretical result was supported by the experiment of Ref. 8, where the leakage η_0 was below 10^{-5}. Yet, typically, the leakage of SINIS structures has been of $\eta_0 \sim 10^{-4}$.

The first hybrid turnstiles were fabricated with standard two-layer electron beam lithography process, and the charging energy was of the order of $E_c/k_B \approx \Delta/k_B \approx 2.5$ K.[7,8] To increase E_c, we used the trilayer germanium process.[12] The samples were metalized in an electron-gun evaporator.

In this letter, we present data from three samples, A, B, and C, all with relatively high charging energy, but with substantial differences in R_N. All measurements were performed at temperature of about 0.1 K. The sample parameters are summarized in Table I. All samples show leakage that is too strong to be explained by the higher-order processes, and that is strongest in the gate-open state, unlike expected for Andreev reflection.[9] In addition, the leakage parameter η_0 does not seem to depend on R_N. Albeit counterproductive in general, the observable leakage helps us here to demonstrate how the leakage at the plateau η_1 can be suppressed from η_0 by using square-wave drive.

The parameters of the samples were estimated by fitting their dc *IV* curves to simulations based on the sequential tunneling model including the cooling effect of the SINIS structure.[13] The measured and the simulated *IV* curves of sample B are presented in Fig. 1(b).

The large resistance variation makes this set of samples ideal for studying the speed of the turnstile. A high pumping frequency can cause two kinds of errors: missed tunneling and backtunneling, i.e., tunneling in the direction against the bias. When the gate signal is extended over the backtunneling thresholds, the dashed lines in Fig. 1(c), tunneling in the forward direction is still preferred, but backtunneling can be statistically significant. With sinusoidal drive and at low frequencies, however, tunneling occurs typically before the backtunneling threshold is exceeded. Note that backtunneling prevents precise pumping of charge in the case of the normal metal SET.[9]

The backtunneling effect can be seen as backbending of the current plateaus in Fig. 2(a). The effect is most pronounced at low V_b and high A_g. The experimental backtunneling slopes are reproduced precisely by our simulations based on the sequential tunneling model with the sample parameters estimated from independent dc measurements.

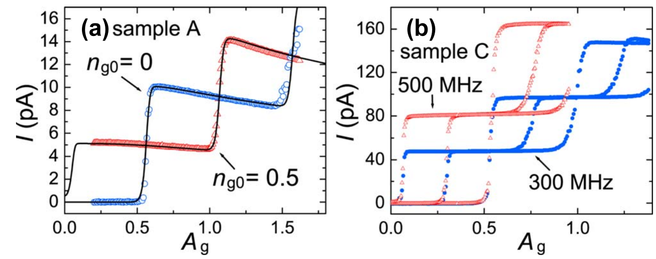

FIG. 2. (Color online) (a) The current of sample A vs gate amplitude with 32 MHz sine wave and at $eV_b = 0.8\Delta$. The lines show the corresponding simulated currents. (b) The measured plateaus of sample C with 300 and 500 MHz sinusoidal drives and at $n_{g0} = 0$, 0.25, and 0.5. The bias voltage was $eV_b = 1.36\Delta$.

Such an excellent agreement between the experimental data and simulations was also observed for the other two samples.

In Fig. 2(b), we demonstrate with the low-Ohmic sample C a plateau at 160 pA, which is an order of magnitude higher than in Refs. 7 and 8. The experiments cannot be reproduced by our constant-temperature simulations, since there is already significant heating at the highest plateaus. More ideal behavior is expected at the same current level at the first plateau. However, we were limited by the maximum frequency of our rf generator, which is 500 MHz.

In Figs. 3(a) and 3(b) we show the effect of backtunneling on the pumped current of sample B at the first plateau $n_{g0} = 0.5$ and $eV_b = \Delta$, with both sine and square wave drive. In all cases, there is a flat region between the thresholds for forward tunneling ($A_{g,\mathrm{ft}}$) and backtunneling ($A_{g,\mathrm{bt}} = 3\Delta/4E_c$), shown by the dashed vertical lines. Above $A_{g,\mathrm{bt}}$, backtunneling deteriorates the pumping accuracy. Since the rise time of the square wave was constant, about 3 ns, the backtunneling rate did not depend on frequency. At 120 MHz, sine and square waves are almost identical due to the finite rise time of the square wave.

High gate amplitude increases the rate of forward tunneling and thus decreases the effect of missed tunneling. How close to $A_{g,\mathrm{bt}}$ the gate amplitude can be set depends on

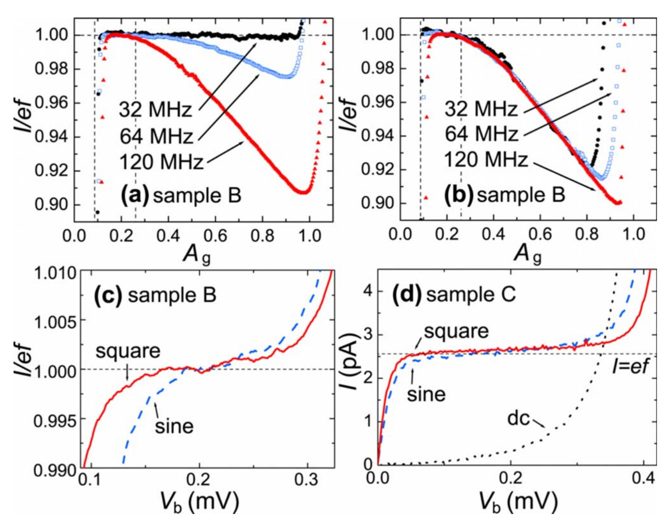

FIG. 3. (Color online) The first plateau of sample B at sine wave (a) and square wave (b). The frequencies are 120, 64, and 32 MHz. $A_{g,\mathrm{ft}}$ and $A_{g,\mathrm{bt}}$ are marked with the dashed vertical lines. (c) The first plateau of sample B as a function of bias voltage at 64 MHz at sine wave and square wave. (d) The plateaus of sample C at 16 MHz sine and square cases. For comparison, we show also the subgap dc *IV* curve with gate open.

temperature. In general, the maximum amplitude is inversely proportional to E_c. In the experiments below, we used the amplitude half way between the thresholds $A_{g,\text{mean}}=\Delta/2E_c$, which is, e.g., about 0.17 for sample B. The pumping regime is thus drastically different from that of the first turnstiles with $E_c \approx \Delta$ and $A_{g,\text{mean}} \approx 0.5$.

At zero temperature, the rate of single-electron tunneling process with electrostatic energy change E_p is $\Gamma_p = \sqrt{E_p^2-\Delta^2}/R_{N,i}e^2$, where $R_{N,i}$ is the resistance of the junction i. The tunneling rates depend on Δ, and since E_p is roughly proportional to $1/C_\Sigma$, they depend also on the $R_{N,i}C_\Sigma$ time constant. However, if the gate amplitude is limited by the backtunneling effect, the forward tunneling rate at the extreme gate value can be expressed as $\Gamma_p=\gamma_a\Delta/R_{N,i}e^2$. The tunneling rate is thus independent of the capacitance. The prefactor γ_a depends on the exact form of the amplitude limit, e.g., $\gamma_a=\sqrt{5}/2$ for $A_{g,\text{mean}}$ and $\gamma_a=\sqrt{3}$ for $A_{g,\text{bt}}$. In Ref. 9, the estimate for the maximum amplitude of the turnstile was based on $A_{g,\text{Ar}}$, which increases as a function of E_c. Above $E_c=2\Delta$, however, backtunneling sets a more restrictive limit. Hence the maximum current saturates to somewhat above 10 pA estimated for $E_c=3\Delta$ with the superconducting gap of aluminum and error rate of 10^{-8}.

There are two obvious strategies to increase the maximum current. Parallelization of turnstiles is an attractive option because of the simplicity of the operation of a single device. Another possibility is to find an alternative superconductor and to fabricate a device with both high Δ and high E_c.

An additional benefit of high charging energy is that it suppresses the leakage when the gate is not open. In Figs. 3(c) and 3(d) we demonstrate, as suggested in Ref. 9, how a square wave signal can be used to pass the gate-open state quickly and hence to decrease the slope of the plateau as a function of bias voltage. In Fig. 3(c), the plateau of sample B is clearly improved by using the square wave.

The effect of the square wave is more pronounced in the case of a fast sample and a low frequency. Then the influence of leakage is high in relative terms, and the rise times of the sine and square waves of our generator are significantly different. This can be seen in Fig. 3(d) with sample C and frequency 16 MHz. The slopes with sine and square waves are $\eta_1=9.8\times10^{-5}$ and $\eta_1=3.8\times10^{-5}$, correspondingly. Also, both the sine and the square wave plateaus extend to higher bias voltage than the dc plateau.

The results of Fig. 3 are traceable to the national low-current standard of MIKES,[14] which was used to calibrate the Keithley 6430 current meter. It was then used to calibrate the DL Instruments 1211 current amplifier. The turnstile could not be measured with the Keithley current meter directly because of its relatively high input noise. The gain of the DL Instruments 1211 amplifier was stable within a few parts in 10^{-4} for several months. For each measurement, we determined the input bias of the amplifier by comparing different polarities. The uncertainty of our measurements was about 10^{-3}. In the case of sample B at 64 MHz, also the turnstile reached the accuracy of about 10^{-3}.

To conclude, we have studied the operation of SINIS turnstiles with high charging energy. The backtunneling effect was shown to limit the drive amplitude and thus the maximum current of the turnstile at the highest charging energies. Under certain circumstances, a square wave drive decreases the influence of subgap leakage. We note, however, that a square wave tends to heat the island, whereas a sine signal can also cool it.[15] Hence, the optimum signal may be of some intermediate form.

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