Robust single-parameter quantized charge pumping

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This paper investigates a scheme for quantized charge pumping based on single-parameter modulation. The device was realized in an AlGaAs–GaAs gated nanowire. We find a remarkable robustness of the quantized regime against variations in the driving signal, which increases with applied rf power. This feature, together with its simple configuration, makes this device a potential module for a scalable source of quantized current.
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Single-electron pumps and turnstiles transporting a well defined number n of charges per cycle[1] have attracted much interest, in particular, for their potential application in integrated single-electron circuits[2] and in metrology, providing a direct link between time and current units.[3] Different approaches have been investigated, such as arrays of gated metallic tunnel junctions[4–7] or semiconducting channels along which the potential can be modulated continuously.[8–13] One of the main issues for applicability in metrology is to achieve a high current output simultaneously with accurate charge transfer. Usually, increasing the current level by raising the frequency leads to loss in accuracy, such that parallelization has been considered[14] as an alternative to faster driving. The stringent requirements on phase and amplitude matching of the driving signals typical for many systems, requiring cross-capacitance compensation for each gate pair and channel, only allow a few approaches to be considered for a scalable current source, such as those where only a single voltage parameter needs to be modulated (e.g., see Refs. 7, 12, and 13). Here, we investigate the single-parameter scheme demonstrated in Refs. 12 and 15. We find a remarkable robustness in the driving signal which should allow the application of the pump as a building block in a scalable source of quantized current.

The device was realized in an AlGaAs/GaAs heterostructure. A 700 nm wide wire connected to the two-dimensional electron gas was created by etching the doped AlGaAs layer. The device was contacted using an annealed layer of AuGeNi. This channel is crossed by three Ti–Au finger gates of 250 nm separation, as shown in Fig. 1(a). A quantum dot (QD) with a discrete quasibound state between the two upper gates is formed by applying sufficiently large negative dc voltages V_1 and V_2 to gates 1 and 2, respectively. The lowest gate was grounded and not used. An additional sinusoidal signal of power $P^{\rm rf}$ is coupled to gate 1. If the oscillation amplitude is high enough, the energy ε_0 of the quasibound state ψ drops below the chemical potential μ of the leads during the first half-cycle of the periodic signal and can be loaded with an electron from the left reservoir [see Fig. 1(b)]. During the second half-cycle, ε_0 is raised sufficiently fast above μ to avoid backtunneling and the electron can be unloaded to the right. In this way, a current is driven through the sample without an applied bias and the device acts as a quantized charge pump. For details on this pumping mechanism, we refer to Ref. 12.

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The pumped current through the unbiased device as a function of gate voltages V_1 and V_2 is shown in Fig. 2. Measurements were performed at temperature $T=300$ mK. Sinusoidal signals of rf powers $P^{\rm rf}=-29$, -26, and -24 dBm and frequency $f=500$ MHz were applied to gate 1. Plateaus of different qualities can be seen around the values of $I=nef=n$ 80 pA for $n=1,2,3,4$, where on average n electrons of charge e per cycle are transported. To describe the behavior qualitatively, we assume that for the voltage range applied to gate 2, a high enough tunnel barrier for electrons in the drain is induced so that no electrons will be loaded from the drain. This assumption is justified since the considered voltage range lies well beyond the pinch-off voltage $V_2^{\rm po}=-100$ mV. The steplike variation in I along V_2 can be explained by considering that the voltage at gate 2 determines the number n_l of electrons loaded *from the source* in each cycle since it controls the dot potential during the loading phase (see also Fig. 1). In addition, it can prevent some of the captured electrons from being unloaded to the drain during the emission phase. The resulting current is determined by $I=n_u ef$, where $n_u \leq n_l$ is the number of unloaded electrons *to the drain*. The case where $n_u < n_l$ occurs when V_1 is made more positive so that the rf modulation added to V_1 is not sufficient to cause

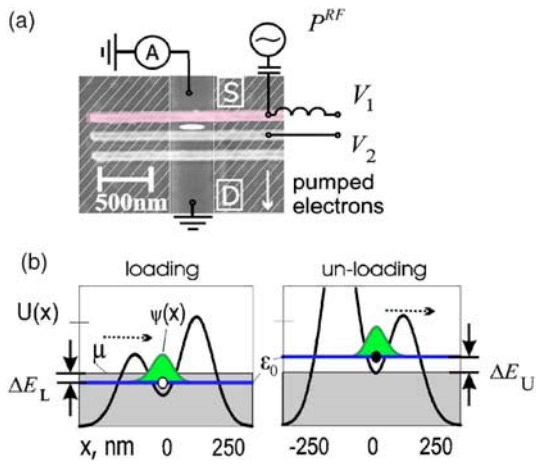

FIG. 1. (Color online) Scanning electron microscopy picture of the device shown in (a). Gate voltages are indicated, showing gate 1 colored in red as being modulated. The source (S) and drain (D) reservoirs are indicated. The hatched regions are depleted of the two-dimensional electron gas, defining a wire of about 700 nm in width. A quasibound state is formed between gates 1 and 2, as indicated by the white ellipse. The lowest gate is not in use. (b) Schematic of the potential along the channel during loading (left) and unloading (right) of the quasibound state $\psi(x)$.

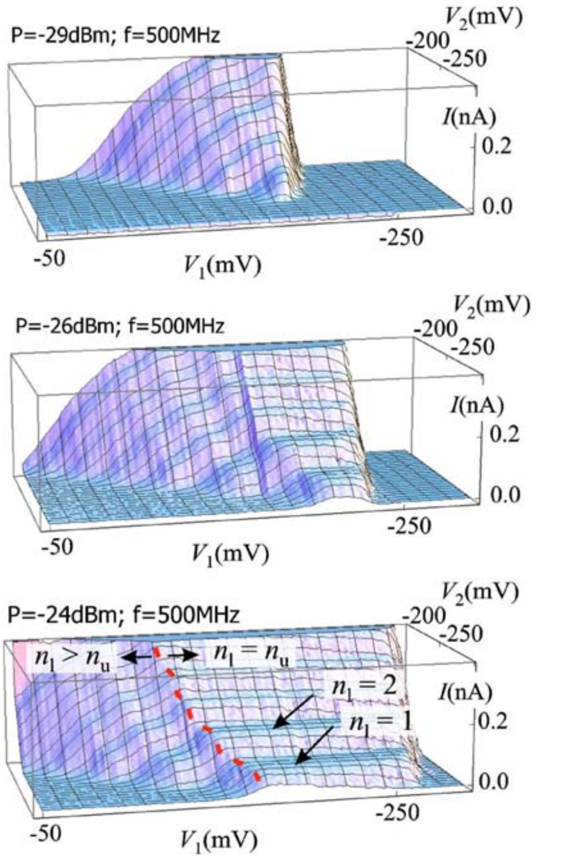

FIG. 2. (Color online) Pumped current through the unbiased device as a function of V_1 and V_2. The rf power of the driving signal at $f=500$ MHz was varied between the three cases shown.

emission of all electrons over the barrier at gate 2. This explains the less pronounced steps along V_1 toward more positive values, with plateau lengths related to the charging energy E_C of the isolated dot: As soon as one electron is emitted to the drain the energy of the isolated dot is lowered by E_C and might not be sufficient anymore to emit the remaining electrons over the right barrier. Tuning V_1 to more negative values will eventually lead to complete unloading of all loaded electrons to the drain, i.e., $n_u=n_l$. Comparing the different plateau lengths for sufficiently large power, e.g., $P^{\rm rf}=-24$ dBm, we conclude that for the pronounced and more extended plateau along V_1, one finds the case of $n_u=n_l$. The length of this plateau is a measure of the robustness of the quantized regime in the voltage applied to gate 1.

To investigate the robustness further, the plateau along V_1 at $n_u=1$ is plotted in more detail in Fig. 3(a) for rf powers $P=-28$, -27, -26, -25, -24, and -23 dBm. The voltage on gate 2 was set to $V_2=-230$ mV. The width of the plateau increases with applied rf power. To describe the rf-power dependence, we restrict our model for simplicity to a single quasibound state. The energy of this state is modulated by the signal on gate 1 as $\varepsilon_0(t)=E_0+\alpha[V_1+V^{\rm rf}\cos(2\pi f t)]$, where $\alpha<0$ describes the conversion from voltage to energy scale, and E_0 is the energetic offset, including a dependence on V_2. Quantized pumping then requires complete loading of one electron exclusively from source and complete unloading exclusively to drain. In order for such a sequence to be possible, the dot has to be isolated during the phase when ε_0 crosses μ. In terms of tunneling rates to source, R_S, and drain, R_D, we require R_S and $R_D \ll f$ for $\mu-\Delta E_L<\varepsilon_0<\mu+\Delta E_U$. Here, ΔE_U is the amount of energy the quasibound state has to gain above μ in order to unload electrons to the drain. Similarly, ΔE_L is the energy of the quasibound state below μ before loading sets in (see Fig. 1). This means that no electrons can be captured for $\alpha V_1>(\mu-\Delta E_L)-(E_0+\alpha V^{\rm rf})$. Also, no electron can be emitted for $\alpha V_1<(\mu+\Delta E_U)-(E_0-\alpha V^{\rm rf})$. The length of the plateau can therefore be written as $\Delta V_P=(\Delta E_U+\Delta E_L)/\alpha+2V^{\rm rf}$. The modulation amplitude is related to the power given in dBm via $V^{\rm rf}=10^{P^{\rm rf}/20}V_0$, where V_0 corresponds to the amplitude at $P^{\rm rf}=1$ mW. The linear dependence of ΔV_P on $V^{\rm rf}$ is confirmed experimentally and shown in Fig. 3(b). The line corresponds to $V_0=2714$ mV and $(\Delta E_U+\Delta E_L)/\alpha=-238$ mV.

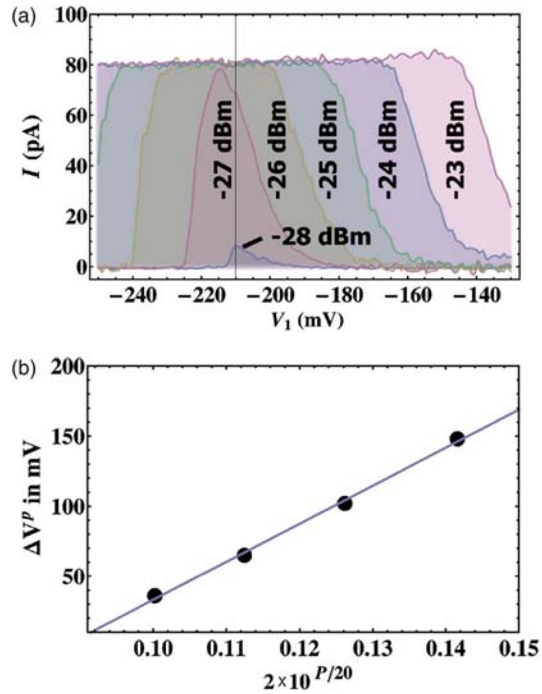

FIG. 3. (Color online) (a) Pumped current as a function of V_1 for $V_2=-230$ mV different rf powers. (b) Width of the plateau plotted for rf powers $P=-26$, -25, -24, and -23 dBm, scaled to be proportional to the rf amplitude.

For future applications as a single-electron source, it might also be important to determine the range of ε_0 over which the QD is isolated. From bias spectroscopy, a value for $\alpha=-0.28$meV/mV has been obtained for the QD in the open regime. Assuming the same value in the isolated regime, we conclude that the QD is nonadiabatically blockaded over an energy range $\Delta E_U+\Delta E_L$ of more than 50 meV around μ.

The accuracy of this concept demonstration device has been determined in the regime of $n_u=n_l=1$. Here, the contribution of the plateau quality along V_1 to the overall uncertainty can be neglected compared to the one of the much shorter plateau along V_2 in the high-power regime. The measured current for $P=-24$ dBm at the flattest part of the plateau at $V_1=-200$ mV of $I=80.0\pm0.5$ pA corresponds to the theoretical value of ef to better than 1%. Systematic deviations from ef are expected from incomplete loading ($n_l<1$) (Ref. 12) and an unwanted surplus of electrons in the QD. The latter deviation occurs roughly with a probability of about e^{-E_C/k_BT}, where E_C is the charging energy of the dot. However, with $E_C\approx1$ meV (determined in the open regime) and $T=300$ mK, this mechanism is negligible compared to the error arising from incomplete loading. Incomplete loading is determined by the barrier shape and can be reduced by tuning the gate and channel width as well as wafer characteristics. Estimates in Ref. 12 have shown that for a suitable choice of barrier shapes, an accuracy of 1 in 10^8 could, in principle, be achieved.

From the investigation above, we conclude that the device can be conveniently implemented into a larger network where many channels are driven by the same gate. Even if the voltage signal arriving at each channel has experienced different attenuations, synchronous operation is possible in the robust high-power regime. The robustness in the driving signal and its simple configuration together with the potentially high speed of tunable barrier schemes, make nonadiabatic single-parameter pumps promising candidates for an accurately quantized, large-current source as needed for fundamental experiments in metrology and quantum electronics.

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