

Single-parameter quantized charge pumping in high magnetic fields

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We study single-parameter quantized charge pumping via a semiconductor quantum dot in high magnetic fields. The quantum dot is defined between two top gates in an AlGaAs/GaAs heterostructure. Application of an oscillating voltage to one of the gates leads to pumped current plateaus in the gate characteristic, corresponding to controlled transfer of integer multiples of electrons per cycle. In a perpendicular-to-plane magnetic field the plateaus become more pronounced indicating an improved current quantization. Current quantization is sustained up to magnetic fields where full spin polarization of the device can be expected. © 2009 American Institute of Physics. [DOI: 10.1063/1.3063128]

Generating well defined currents by manipulating single charges has attracted considerable interest in the past two decades from both fundamental and applied points of view.¹ A particular potential of application lies in the field of metrology to provide a link between time and current units.² Different approaches have been studied, such as arrays of tunnel-connected metallic islands controlled by a number of phase shifted ac signals³⁻⁶ or semiconducting channels along which the potential can be modulated continuously.⁷⁻¹¹ The pumping mechanism demonstrated in Ref. 10 allows gigahertz pumping comparable to surface-acoustic-wave pumps⁸ while promising a higher degree of control. It employs three electrodes, of which two are modulated at a fixed phase shift and with different amplitudes. In Ref. 11 it was shown that for such a device, a single modulated voltage signal is sufficient for pumping, and a numerical investigation indicated the importance of the tunnel barrier shape for improving the accuracy. A possible way to manipulate these tunnel couplings might be the application of a magnetic field, owing to its influence on the wave function and the corresponding rearrangement of electrons between quantum states (see, for instance, Ref. 12). Therefore the operation of such a single-parameter charge pump has been realized in the presented work when a perpendicular-to-plane magnetic field was applied.

Two devices similar to the one in Ref. 11 have been investigated, which were both realized in an AlGaAs/GaAs heterostructure with carrier concentration of $2.1 \times 10^{15} \text{ m}^{-2}$ and mobility of $97 \text{ m}^2/\text{Vs}$ in the dark. A 700 nm wide wire connected to two-dimensional electron gases was created by wet etching the doped AlGaAs layer. This channel is crossed by two 100 nm wide Ti–Au finger gates of 250 nm separation. A schematic is shown in the inset of Fig. 1(a). A quantum dot (QD) with discrete quasibound states between the gates can be created by applying sufficiently large negative voltages V_1 and V_2 to gate 1 and gate 2, respectively. An additional radio frequency (rf) signal is coupled to gate 1. The resulting voltages are therefore $V_1 = V_1^{\text{dc}} + V_1^{\text{ac}} \cos(2\pi ft)$ and $V_2 = V_2^{\text{dc}}$ at gate 1 and gate 2, respectively. If the oscillation

amplitude is high enough, then the bound state drops below the Fermi level during the first half-cycle of the periodic signal and can be loaded with electrons from source. During the second half-cycle the bound state is raised sufficiently fast to avoid backtunneling and electrons can be unloaded to the drain. The resulting current changes in steps of ef as the voltage parameters are varied, where e is the electron charge and f is the pumping frequency. For a detailed discussion we refer to Ref. 11.

The measured characteristic for device 1 is shown in Fig. 1. The measurements were performed at a base temperature of $T=40 \text{ mK}$. The pumping frequency was chosen to be $f=50 \text{ MHz}$ at a rf power of $P^{\text{rf}}=-16 \text{ dBm}$. As shown in Fig. 1(a) the pumped current increases in steps of ef as V_2 is made more positive. The red and blue curves compare the dependence of the pumped dc current on V_2 without and with perpendicular magnetic field of $B=3 \text{ T}$ applied, respectively. With the applied field the step edges shift and become steeper. The evolution of the step edges can be seen in more detail in Fig. 1(b), showing the derivative dI/dV_2^{dc} in arbitrary units as a function of V_2 and B . Below 0.3 T the step edges first shift toward more positive voltages. Then for fields between 0.3 and 3 T a linear shift toward more negative voltages is found. The shift toward more negative voltage may

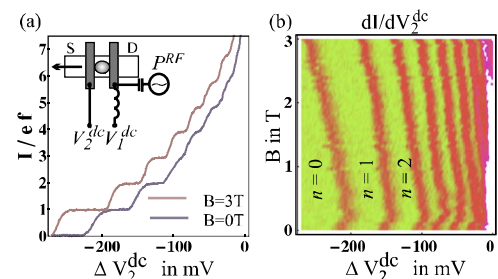


FIG. 1. (Color online) (a) Pumped current I normalized by ef vs the variation in the dc voltage applied to gate 2, ΔV_2^{dc} . The inset shows a schematic of the device, with the dashed arrow indicating the direction of the pumped electrons. S and D indicate source and drain contacts. (b) dI/dV_2^{dc} in arbitrary units as a function of applied B -field and ΔV_2^{dc} . The number of electrons n pumped per cycle is specified in the figure. The measurements were performed in device 1 at $f=50 \text{ MHz}$, base temperature of $T=40 \text{ mK}$, and power of $P^{\text{rf}}=-16 \text{ dBm}$.

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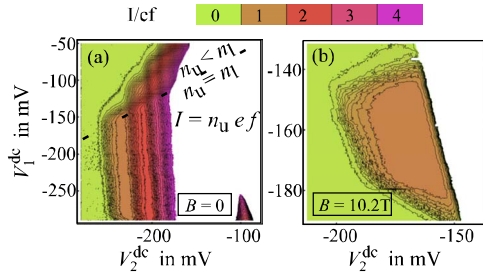


FIG. 2. (Color online) Pumped current at $f=500$ MHz through device 2 as a function of V_1^{dc} and V_2^{dc} . In (a) no magnetic field was applied. The dotted line indicates the transition above which the emission of electrons to the drain n_u is not complete and smaller than the number of loaded electrons n_l . In (b) the pumped current is shown when a perpendicular-to-plane field of $B=10.2$ T was applied.

be linked to the increase in confinement of the charges, assuming the current drop at the step edge is caused by back-tunneling of electrons loaded during the first half-cycle.

For intermediate fields above 3 T the plateau structure of the pumped current evolves in a more complex way, which will be subject to future investigations. Now we focus on the behavior in high magnetic field. An example for quantized pumping in the high field regime is shown in Fig. 2 for a second device. Here, the dependence of the pumped current on the two gate voltage parameters V_1^{dc} and V_2^{dc} is shown for (a) $B=0$ and (b) $B=10.2$ T, respectively. Note that in this device pumping occurs at a different set of voltage parameters due to different effective dimensions of the QD, leads, tunneling barriers, and according changes in the electronic properties. Device 2 was operated at a higher pumping frequency of $f=500$ MHz and higher base temperature of $T=300$ mK. The rf power was set to $P^{\text{rf}}=-23$ dBm. In Fig. 2(a) up to four plateaus corresponding to quantized currents of $I=n_e f$ ($n=1,2,3,4$) are observed. The tilted dashed line indicates the border above which the number of electrons n_l loaded during the first half-cycle is larger than the number of electrons n_u , which has sufficiently high energy to be unloaded to the drain reservoir¹³ during the second half-cycle. Any electrons remaining in the dot will be deposited back to the source. The condition $n_u=n_l$ typically leads to a higher accuracy and robustness.¹³

Figure 2(b) shows the gate voltage dependence of the pumped current at $B=10.2$ T. Only one plateau corresponding to $I=ef$ is observed and multielectron plateaus are completely suppressed. At the same time the single-electron plateau is extended along V_2^{dc} . This is shown more clearly in Fig. 3 for a particular voltage V_1^{dc} . Part (a) shows the plateau region without magnetic field. The plateaus in zero field are not as well pronounced as in device 1. However, the quantization improves significantly when a magnetic field is applied, as shown in part (b). In the latter case, as V_2^{dc} is tuned to more positive values, the current drops sharply and becomes negative, whereas without magnetic field the current continues to increase, showing further plateaus near multiples of ef . The sharp current drop as V_2^{dc} becomes more and more positive might be due to increasing tunneling coupling to the drain reservoir such that a large amount of charges enters and leaves the dot through drain. The resulting ac current might be rectified, for instance, by nonlinearities of the amplifier, eliminating the quantization plateau and leading to the measured negative dc current. Note that this sharp

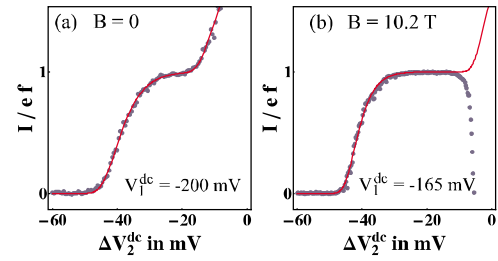


FIG. 3. (Color online) Pumped current I normalized by ef at $f=500$ MHz through device 2 vs the variation in the dc voltage applied to gate 2, ΔV_2^{dc} , at fixed V_1^{dc} . In (a) no field was applied, while (b) shows the characteristic for $B=10.2$ T. The gate characteristic was fitted using Eq. (3) together with the following parameters: for zero field (a), $V_a=-40.4$ mV, $V_b=4.6$ mV, $\Delta_2=6.4$ while for the measurements at $B=10.2$, (b) the values $V_a=-42.32$ mV, $V_b=3.31$ mV, and $\Delta_2=12$ were used.

transition to large and unquantized current also occurs at zero field but at more positive values of V_2^{dc} .

We now evaluate the plateau shape in more detail. For quantization steps dominated by backtunneling, the occupation probability $P(t)$ of the dot switches from 1 at most positive V_1 to some well-defined P_0 as the charge state is energetically lifted up from the Fermi sea. Denoting by t_0 the starting moment of backtunneling and observing¹¹ that its rate depends exponentially both on V_1 (via entrance barrier height) and V_2 (via level position), we can describe the time evolution of $P(t)$ as [see Eq. (2) of Ref. 11]

$$\dot{P}(t) = -\Gamma_L(t)P(t) \quad \text{with } P(t_0) = 1, \quad (1)$$

$$\Gamma_L(t) \equiv \Gamma_0[V_1(t_0)]\exp[-\alpha V_2^{\text{dc}} - \beta t], \quad (2)$$

where $\alpha > 0$ and $\beta \propto -dV_1/dt \propto fV_1^{\text{ac}} > 0$ are constants and Γ_0 is the starting rate for backtunneling. Equation (1) holds for a limited fraction of the period when V_2^{dc} is negative enough to make the exit barrier blocked. Estimating P_0 from the limit $t \rightarrow \infty$ of the solution to Eq. (1) gives $P_0 = \exp[-(\Gamma_0/\beta)\exp(-\alpha V_2^{\text{dc}})]$.

A phenomenological generalization of this theory to the case of several steps is to choose individual starting rates $\Gamma_0 \propto \exp \Delta_i$ for each of the backtunneling transitions $i \rightarrow i-1$ ($i=1,2,\dots,n$) and sum up the corresponding values of the transferred charge per period eP_0 . A fitting formula corresponding to this procedure is

$$I/ef = \sum_{i=1}^n \exp \left[-\exp \left(-\frac{V_2^{\text{dc}} - V_a}{V_b} + \Delta_i \right) \right], \quad (3)$$

where V_a , V_b , and Δ_i will be used to fit the data points. The data in Fig. 3 are modeled by including the first two plateaus, i.e., $n=2$. Parameters V_a and V_b are chosen so that always $\Delta_1=0$. In this way, Δ_2 determines the flatness of the first plateau independently of position and scale of the plateau structure along the voltage axis. The parameters for modeling the data are given in Fig. 3. In particular, $\Delta_2(B=0)=6.4$ for pumping in zero field, while $\Delta_2(B=10.2 \text{ T})=12$ and is significantly increased when the field was applied. $\Delta_2(B=10.2 \text{ T})$ was chosen under the assumption that the second plateau would start just outside the region where pumping can be achieved. Operating the pump exactly in the middle of the ef plateau, this model predicts a deviation from the exact value of $1 - \exp[-\exp(-\Delta_2/2)]$ so that B -field op-

eration has reduced the error by an order of magnitude from 4% to 0.3%.

Note that for the investigated devices, full spin polarization of source and drain (with filling factor of 1) occurs at an applied field of 8.9 T. Therefore at the higher applied field of 10.2 T only spin polarized electrons are loaded from the source. As the spin flip times of the electron on the QD should be significantly longer than the average hold time during pumping,¹⁴ fully spin polarized quantized charge pumping through the device can be expected. Furthermore the spin state of source and drain at the given field could be independently tuned via the carrier density by additional top gates on each side of the QD. Such a device might thus serve as a clocked source of spin polarized single electrons for spin electronics and quantum information processing.

From the investigation above we conclude that the accuracy in single-parameter pumping can be improved by the application of a high perpendicular-to-plane magnetic field.¹⁵ The phenomenon of quantized pumping can be sustained in high fields in contrast to the conceptually related charge pumps using surface acoustic waves,¹⁶ allowing spin polarized quantized charge pumping. So far we have tested and observed quantized pumping in such devices up to fields of 16 T. The magnetic field as an additional control parameter makes single-parameter pumps in AlGaAs/GaAs heterostructures, promising candidates for an accurately quantized, large-current source as needed for fundamental experiments in metrology and quantum electronics.

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