Wave-form sampling using a driven electron ratchet in a two-dimensional electron system

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We utilize a time-periodic ratchetlike potential modulation imposed onto a two-dimensional electron system inside a $GaAs/Al_xGa_{1-x}As$ heterostructure to evoke a net pumped direct current. The modulation is induced by two sets of interdigitated gates, interlacing off center, which can be independently addressed. When the transducers are driven by two identical but phase-shifted periodic signals, a lateral pumped direct current $I(\varphi)$ results, which strongly depends on both, the phase shift φ and the wave form $V(t)$ of the imposed gate voltages. We find that for different periodic signals, the phase dependence $I(\varphi)$ closely resembles $V(t)$. A simple linear model of pumping in two-dimensional electron systems is presented, which reproduces well our experimental findings. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2001740]

Most studies on electronic transport in nanostructures are based on transport experiments, where a current is driven through the system by biasing at least one contact using an external electrical potential. Up to now, only few experiments were reported, where the current is generated by a temporal and spatial periodic potential modulation in an externally unbiased system, as proposed in Ref. 1. These systems closely resemble ratchets and molecular motors,[2] which attracted much attention in recent years, due to their extraordinary high efficiency to transform heat into directed motion. Experimental realizations of these so-called electron pumps range from arrays of $Al/Al_2O_3/Al$ tunneling junctions,[3,4] open and closed artificial semiconductor quantum dot structures,[5,6] electrons captured in the potential landscape of moving surface acoustic waves,[7] to semiconductor devices such as charge-coupled devices (CCD), nowadays routinely used for digital photographic imaging. While most experiments utilizing parametric pumping are carried out in the Coulomb blockade (CB) regime,[3–5] only few experiments so far are performed in the open regime.[6,8] Coulomb blockade systems already serve as metrological standards for both the electrical current[3,5] and the capacitance,[4] reaching relative errors of 10^{-11} (Ref. 3) and 10^{-6} (Ref. 4), respectively.

In this letter we present electronic transport experiments in a laterally confined strip of a two-dimensional electron system (2DES). By imposing a spatial and temporal periodic potential perturbation,[8] using interdigitated gates, similar to a CCD, a dynamic ratchetlike potential landscape is created that drives a net lateral pumped direct current.

The sample presented here is fabricated from a molecular beam epitaxy grown $GaAs/Al_xGa_{1-x}As$ heterostructure, containing a 2DES 54.8 nm below the surface. The electron density n and mobility μ at 4.2 K are 4.13×10^{15} m^{-2} and 94.5 m^2/V s, respectively. Samples from other heterostructures (not presented here) yield similar results. A Hall bar-shaped mesa is fabricated using optical lithography, etching, contact metallization, and annealing. On top, two sets of interdigitated gate transducers (IGTs) are defined by electron beam lithography and subsequent metallization. Each set consists of 75 gate stripes, (each 250-nm wide) interlacing off center by two thirds of the lattice period of 1 μm. A schematic top view of the sample is shown in Fig. 1(a). Measurements are performed inside a ^{3}He cryostat at a base temperature of 300 mK.[9] The pumped source-drain direct current is measured using a transimpedance converter, whose output signal is filtered by an eight-pole 48 dB per octave low-pass Bessel filter, set to a corner frequency of 10 Hz. The same wave form—with a well-defined phase difference φ—is applied to the two sets of gates, using two frequency-locked arbitrary wave-form generators. The signals applied to gates 1 and 2 can be expressed as $V_1(t)=-V_0/2+V_0W(2\pi ft)$ and $V_2(t)=-V_0/2+V_0W(2\pi ft-\varphi)$, respectively, where $W(t,\varphi)$ represents one of the normalized[10] wave forms—sine, rectangle, or triangle—f the frequency, t the

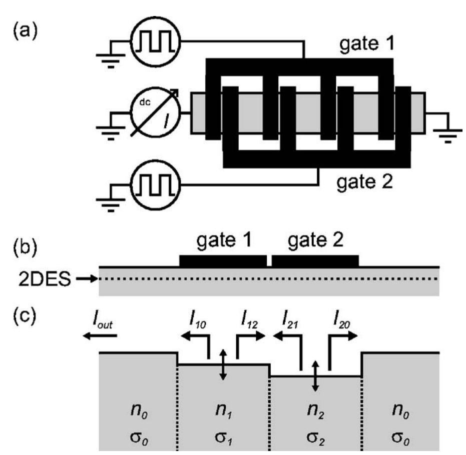

FIG. 1. (a) Schematic top view of the sample. Two sets of metallic interdigitated gates (black) are evaporated on top of a mesa stripe (gray). By applying time-periodic signals to the gates, a source-drain current is induced. (b) A cross-sectional view of the sample. (c) A schematic of the pumping mechanism.

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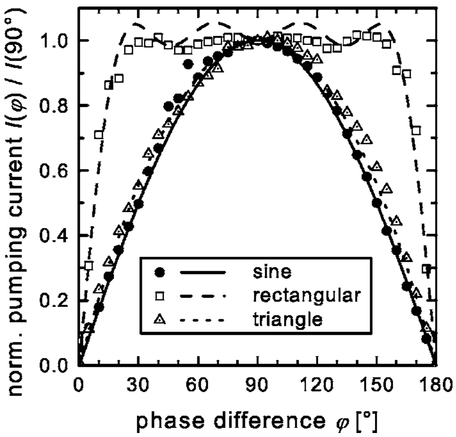

FIG. 2. Experimental phase dependence of the normalized pumped direct current $I(\varphi)/I(90°)$ for different wave forms (symbols) at a frequency of 90 kHz and a peak-to-peak value of the excitation voltage of 0.35 V. The lines represent the results of the simulation.

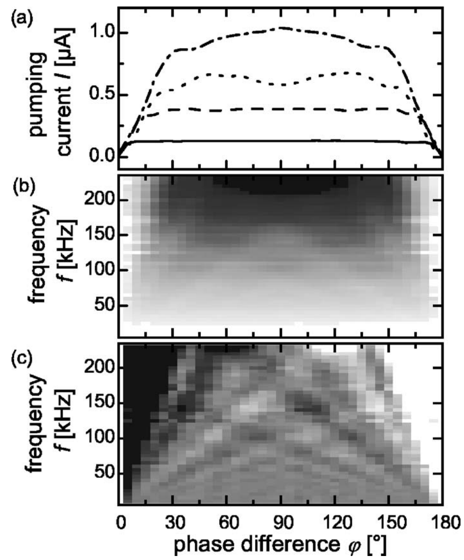

FIG. 3. Rectangular wave-form signals for a peak-to-peak value of the excitation voltage of 0.35 V at different frequencies. (a) $I(\varphi)$ traces (solid line: 30 kHz; dashed line: 90 kHz; dotted line: 150 kHz; and dashed-dotted line: 210 kHz), (b) gray scale plot of I and (c) gray scale plot of the $\partial I/\partial\varphi$. Darker gray tones indicate (b) higher currents and (c) higher derivatives $\partial I/\partial\varphi$, respectively.

time, and V_0 the amplitude. In order to eliminate parasitic currents, which, i.e., result from thermal voltages or the rectification of capacitive currents inside the nonideal AuGe contacts, we measure the output current $I_{\text{out}}(\varphi)$ in the interval $[0°; 360°]$ and define the pumped current $I(\varphi)=0.5[I_{\text{out}}(\varphi) - I_{\text{out}}(360°-\varphi)]$ for $\varphi \in [0°;180°]$.

Figure 2 shows experimental, normalized $I(\varphi)/I(90°)$ traces for different wave forms at a frequency of 90 kHz and a peak-to-peak value of the amplitude V_0=0.35 V. The symbols represent the experimental results. The fact that the pumped current as a function of the phase difference, especially for the sine and rectangular signals, closely resembles the wave form of the pumping signal is somewhat surprising and will be analyzed in more detail below. Since the phase can be changed arbitrarily slowly, this observation may open possibilities for novel wave sampling devices, even for very high frequencies.

For a deeper understanding of whether our experimental results are coincidental for the present device or are a general feature of driven ratchets in 2DESs, we develop a simple hydromechanical model of electron pumping in the artificial superlattice. It is based on a single unit cell (one period of the superlattice), as shown in Figs. 1(b) and 1(c). In the present experiment, we use temporal periods that are much longer than all relevant relaxation times of the electron system. For a treatment of the high frequency limit, see Ref. 11. The unit cell is divided in three regions, as can be seen in Fig. 1(c). Due to capacitive coupling between the gate electrodes and the 2DES, we assume a linear relationship between the applied gate voltage V_i and the electron density n_i inside the respective region i. If we restrict the discussion to small gate voltages only ($V_D < V_i < 0$, where V_D=−0.45 V is the voltage at which the 2DES is fully depleted), we can assume the conductivity σ_i to be only depending on n_i, via $\sigma_i = n_i \mu e$, neglecting small changes of the mobility μ. By changing V_1 the electrons have to move from (to) neighboring regions 0 and 2 into (out of) region 1. The ratio $I_{10}/I_{12} = \sigma_0/\sigma_2 = n_0/n_2$ of electrons moving from (to) area 0 and 2, respectively, is determined by Kirchhoff's laws. Using this result, one can derive, e.g., the current from region 1 into region 2

$$I_{12} = \frac{\sigma_2}{\sigma_0+\sigma_2}\frac{\partial(en_1)}{\partial t} = e\frac{n_2}{n_0+n_2}\frac{\partial n_1}{\partial t}. \quad (1)$$

This results in an output current I_{out} of the unit cell of

$$I_{\text{out}} = I_{10} + I_{21},$$

$$= e\left[\frac{n_0}{n_0+n_2}\frac{\partial n_1}{\partial t} + \frac{n_1}{n_1+n_0}\frac{\partial n_2}{\partial t}\right]. \quad (2)$$

By inserting Fourier series expansions of the respective time-dependent electron-densities $n_i(t)$ (as defined by the wave forms applied to the IGTs), one can evaluate the pumped direct current I of the device, by integrating the output current I_{out} over one temporal period of the input wave form. For the sine wave form, the result is plotted in Fig. 2 as a solid line that reproduces the experimental findings very well.

In order to model more complex wave forms, we have to consider that in any real sample, a finite resistance R and capacitance C between the gate electrode and the 2DES is present, resulting in a finite RC cutoff frequency f_{cutoff} which suppresses the higher Fourier components of the modulation signal. To account for this experimentally determined cutoff frequency of ≈300 kHz, we have weighted the Fourier components by a three-term-Blackman-Harris $\nu_{\text{BH}}(f)$ distribution.[12] If we assume $\nu_{\text{BH}}(f_{\text{cutoff}}) = e^{-1}$, we only have to include the first seven Fourier components into our calculation. The results are plotted as dashed and dotted lines into Fig. 2, for the rectangular and triangular wave forms, respectively. They match remarkably closely the experimental data, although effects such as the gate voltage dependent mobilities μ_i are neglected.

For the rectangular wave form the pumped current is plotted for different frequencies in Fig. 3(a). It can be clearly seen, that the pumped current increases linearly with the frequency of the gate signal.[8] For low frequencies, i.e., 10 kHz, the resulting output wave form nearly perfectly resembles the imposed rectangular wave form. Additional oscillations in the signal can be observed, especially for higher frequencies. They are a direct consequence of the *RC* constant of the system, which results in higher harmonics being more efficiently attenuated at higher operating frequencies. With increasing f the traces become more and more "softened." Ultimately for $f > f_{\mathrm{cutoff}}$ (not shown here) the current is determined only by the first harmonic, resulting in a nearly sinusoidal output current. To illustrate that the oscillations in the pumping efficiency indeed originate from the effective filtering of the high-frequency contributions, a gray scale plot of $I(\varphi, f)$ is presented in Fig. 3(b). In order to emphasize the fine structure, the derivative $\partial I / \partial \varphi$ is numerically calculated and plotted against φ and f in Fig. 3(c). Apart from the flanks (dark area on the left-hand side and bright area on the right-hand side of the figure) the oscillatory features extend diagonally from the lower corners of the plot, corresponding to the harmonic components of the rectangular wave form, as predicted by the model.

This damping of the higher harmonics also explains why the triangular wave form is not reproduced very well. For the triangular wave form the unattenuated Fourier coefficients scale such as $(2n-1)^{-2}$, while for the rectangle they scale like $(2n-1)^{-1}$, with $n=1,2,3,\ldots$. So the higher Fourier coefficients of the triangular wave form are, *per se*, much weaker than the respective coefficients for the rectangular wave form, resulting in an $I(\varphi)$ characteristic, which is mainly dominated by lower harmonics, in particular the first one.

We have presented a method to sample an arbitrary periodic wave form by using interdigitated gates on top of a 2DES. The high-frequency operating limit is intrinsically determined by the *RC* constant of the system, as this leads to the attenuation of higher harmonics. The results were explained within a simple hydromechanical model of electron pumping. The described system may serve as the foundation for future signal sampling devices in solid state electronics. Following our proof of principle, better device parameters will lead to a higher cutoff frequency, eventually allowing a very high frequency operation of the device.

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