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Charge pumping in driven electron ratchets

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Abstract

A sample structure that uses off-center, interdigitated gates to induce a DC current in a two-dimensional electron gas, driven by two phase shifted AC voltages, applied to the finger gates is discussed. We find that the current as a function of the phase shift resembles the waveform of the driving voltage. This can be explained using a transport model, based on local currents, which are given by Ohm's and Kirchhoff's laws. Despite its simplicity, the model is able to explain nearly all experimental observations, including the dependence of the pumping current on phase shift, waveform, frequency, and amplitude.

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1. Introduction

It is now well established that electrical charge in semiconductor structures can be *pumped* by cyclically driving appropriately placed electrodes. Applications range from now ubiquitous charge-coupled devices (CCD) [1] to current standards based on single electron charging [2]. Furthermore, such pumping mechanisms are of great fundamental interest [3], because the time-dependent, symmetry-broken potential that is present in these devices, can be regarded as a model system for Brownian motors, ratchets, and related systems [4].

We have recently demonstrated [5,6] that it is possible to realize tunable electronic ratchets by placing interdigitated gates, which are interlaced off-center, on top of a high-mobility transistor structure, containing a two-dimensional electron gas (2DEG) [7]. By driving these ratchets by two phase-shifted AC voltages, it is possible to induce a net DC current. Despite the apparent complexity of this rectification process, it can be described by a simple, near-equilibrium transport model, which is able to reproduce many of the features observed in the experiment [6]. Here, we will briefly introduce the setup and the results of such pumping experiments. We will then discuss in more detail the model, and how its results compare to the observed pumping current for a number of different experimental parameters.

2. Experimental details

The samples are fabricated from a $GaAs/Al_xGa_{1-x}As$ heterostructure, containing a shallow, high-mobility, 2DEG, located 55 nm below the surface. The electron density n and mobility μ at liquid He temperatures are $4.13\times10^{15}\,m^{-2}$ and $94.5\,m^2/Vs$, respectively. Using standard lithography and processing techniques, a Hall-bar-shaped mesa of 60 µm width is fabricated. Of the total length of the mesa, 75 µm are covered by the interdigitated gates, consisting of 2×75 finger gates of widths $w=250\,nm$. They are designed to be interlaced such that three regions can be distinguished: Regions 1 and 2 under the corresponding finger gates and the ungated region 0. A sketch of the sample geometry is given in Fig. 1.

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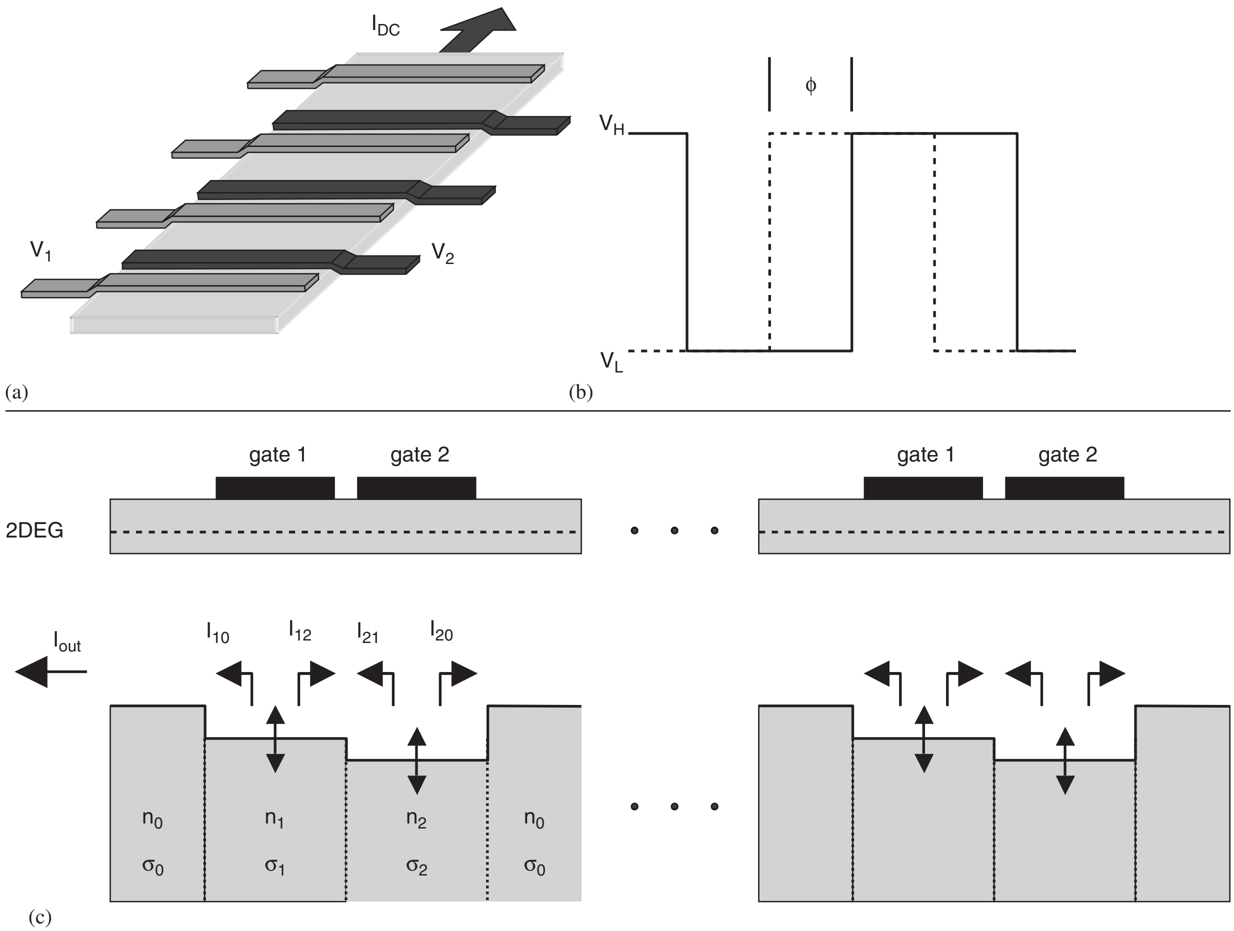

Fig. 1. (a) Schematic view of the sample, with the etched channel and the pair of off-center, interdigitated gates. (b) Definition of V_H, V_L, and ϕ for the rectangular driving voltage (see text). (c) Schematic section through the heterostructure, containing the 2DEG, and the gate fingers (top). For clarity, only two pairs of the periodic arrangement are shown. The bottom part of the figure shows a sketch of the local carrier densities in the sample, when both gates are differently (and negatively) biased. Note the three-step arrangement, resembling a symmetry-breaking saw-tooth potential. Also indicated are the different locally induced currents.

The interdigitated gates can be driven by AC signals of different amplitudes, frequencies, and waveforms. Furthermore, the phase difference between the signals applied to both gates, ϕ, can be adjusted arbitrarily. The direct part I_{DC} of the output current is determined using a transimpedance converter, and an eight-pole 48 dB/oct low-pass Bessel filter, set to a corner frequency of 10 Hz. All measurements are taken at low temperatures (≈ 0.3 K), however, since no ballistic or phase-coherent effects are taken into account, we do not consider such a low temperature to be crucial here. For further details on the pumping and measuring techniques, see also Ref. [6].

3. Results and discussion

Fig. 2 shows the measured pumping current I_{DC} as a function of the phase difference, ϕ at 35 kHz for sine and square waveforms. Note that in both cases, the phase dependence of the pumping current closely resembles the time dependence of the driving voltage. In other words, by slowly shifting the phase ϕ, the high-frequency AC signal can be sampled. Even though it had been observed before [3,5] that for a sinusoidal driving voltage, $I_{DC}(\phi)$ is roughly sinusoidal, it is somewhat surprising that the same similarity also holds for other waveforms.

For a better understanding of the pumping mechanism, we have recently developed a simple model based on time-dependent local conductivity and charge distribution [6]. Using this model, we were able to numerically calculate $I_{DC}(\phi)$ for different waveforms and found good qualitative agreement between model calculations and experimental results. In the following, this model will be discussed in more detail and an analytical result will be derived, which allows for a direct, quantitative comparison.

Fig. 1(c) shows a schematic section through the device. Also shown are the different local carrier densities n_0, n_1, and n_2 that are present in the ungated parts of the sample and under gates 1 and 2, respectively. Let us first restrict ourselves to just one pair of gate fingers and the adjacent ungated areas (left side of the figure). When the carrier density under one of the gates, gate 1 for example, changes as the result of the time-dependent gate voltage, the corresponding charge will be displaced to the adjacent regions 0 and 2. In general, the carrier densities n_0 and n_2

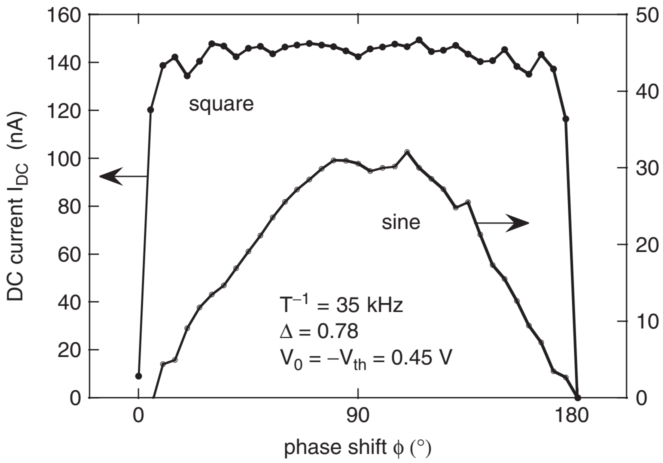

Fig. 2. DC pumping current as a function of the phase difference ϕ for square and sine waveforms. Note how the $I_{DC}(\phi)$ dependence resembles the shape of the applied, high-frequency voltage.

will be different, and thus also the corresponding conductivities σ_0 and σ_2. The resulting local currents I_{10} and I_{12} are given by Kirchhoff's law:

$$\frac{I_{12}}{I_{10}} = \frac{\sigma_2}{\sigma_0} \Rightarrow I_{10} = \frac{\sigma_0}{\sigma_0 + \sigma_2}(I_{10} + I_{12}). \tag{1}$$

Replacing $I_{10} + I_{12}$ with the change of the charge under gate 1, $eLw\,\mathrm{d}n_1/\mathrm{d}t$, and solving for I_{21} in an analogous fashion, we find the total output current $I_{out} = I_{10} + I_{21}$ of a single unit cell:

$$I_{out} = eLw\left(\frac{\sigma_0}{\sigma_0 + \sigma_2}\frac{\mathrm{d}n_1}{\mathrm{d}t} + \frac{\sigma_1}{\sigma_1 + \sigma_0}\frac{\mathrm{d}n_2}{\mathrm{d}t}\right). \tag{2}$$

Here, $L = 60\,\mu\mathrm{m}$, $w = 250\,\mathrm{nm}$, and e are the length and width of a single gate finger and the electron charge, respectively. Assuming that the conductivity is proportional to the carrier density (mobility $\mu \approx$ const.), which in turn is proportional to the applied gate voltage V, we find

$$I_{out} = C\left(\frac{V_0}{V_0 + V_2}\frac{\mathrm{d}V_1}{\mathrm{d}t} + \frac{V_1}{V_1 + V_0}\frac{\mathrm{d}V_2}{\mathrm{d}t}\right). \tag{3}$$

Note that all voltages are given with respect to the threshold voltage V_{th} to ensure $n \propto V$, so that for the ungated regions $V_0 = -V_{th}$. Also, we have rewritten the contribution from the change in charge $\mathrm{d}Q$ under the gate $eLw\,\mathrm{d}n = \mathrm{d}Q = C\,\mathrm{d}V$, with the capacity C of a single gate finger.

It is interesting to note that even though only standard, *linear* transport properties [8] have been used to derive the above relations, Eq. (3) already gives all essential ingredients for converting the AC driving voltages into a DC pumping current. The fact that the local currents I_{ij} are dependent on the voltages of both gates provides for the product terms that are necessary for rectification.

The applicability of the above model can be tested by numerically integrating Eq. (3) to obtain the DC contribution to I_{out} and comparing the normalized data to the experimental results. We find very good agreement for sinusoidal, rectangular and triangular waveforms [6], which gives us confidence that the above assumptions are justified. An important question, however, remains, concerning the absolute value of the pumping current I_{DC}. If all right- and left-going currents in Fig. 1(c) are taken to be independent of each other, the total current should be the sum of all individual current contributions and thus proportional to the number of gate finger pairs (75 in the present case). If, on the other hand, the sample is viewed as a CCD-type, "bucket-brigade" device, the current should just be given by the pumping efficiency of each single cell, independent of the number of cells connected in series. Since both predictions differ by almost two orders of magnitude, the experiment should easily be able to clarify this point.

To calculate the DC component of the output current, I_{out} is integrated over the period T of the driving voltage.

$$I_{DC} = \frac{C}{T}\int_0^T \frac{V_0}{V_0 + V_2}\frac{\mathrm{d}V_1}{\mathrm{d}t} + \frac{V_1}{V_1 + V_0}\frac{\mathrm{d}V_2}{\mathrm{d}t}\,\mathrm{d}t. \tag{4}$$

For a rectangular waveform, only one of the two gate voltages changes at a time, whereas the other remains constant (see Fig. 1(b)). Therefore, the integral can readily be evaluated, and after some straightforward calculation the pumping current is found to be

$$I_{DC,rect} = \frac{C}{T}\frac{2V_0(V_H - V_L)^2}{(V_0 + V_L)(V_0 + V_H)}. \tag{5}$$

Here, V_L and V_H are the "low" and "high" values of the rectangular driving voltage, respectively (see Fig. 1(b)). In the present experiment, the gates were driven from zero to negative voltages, i.e. $V_H = V_0$ and $V_L = V_0(1 - \Delta)$, which further simplifies the expression for I_{DC}:

$$I_{DC} = \frac{C}{T}\,V_0\,\frac{\Delta^2}{2 - \Delta}. \tag{6}$$

Using the geometric parameters of our sample and the experimental conditions of Fig. 2, $V_0 = 0.45\,\mathrm{V}$, $\Delta = 0.78$, and $T^{-1} = 35\,\mathrm{kHz}$, we find from Eq. (6) that a single pair of gate fingers induces a current of 0.17 nA. This is in strong disagreement (almost three orders of magnitude) with the experimental pumping current of $I_{exp} \approx 140\,\mathrm{nA}$ and clearly shows that in the present pumping scheme, the individual cells can be cascaded to increase the overall output current. Surprisingly, the experimental current is even larger than the sum of the contributions from all unit cells. At present, we do not have an explanation for this finding. Possible reasons may be (1) a slight lateral depletion under the gate, which increases the active gate area, (2) the fact that the mobility decreases with decreasing carrier density, which effectively increases Δ in Eq. (6), (3) pumping of charge outside the two-dimensional electron gas, e.g. in the doping layer, (4) nonlinearities in the measuring setup. None of these effects, however, can alone explain the large discrepancy, which thus remains a puzzle to be solved.

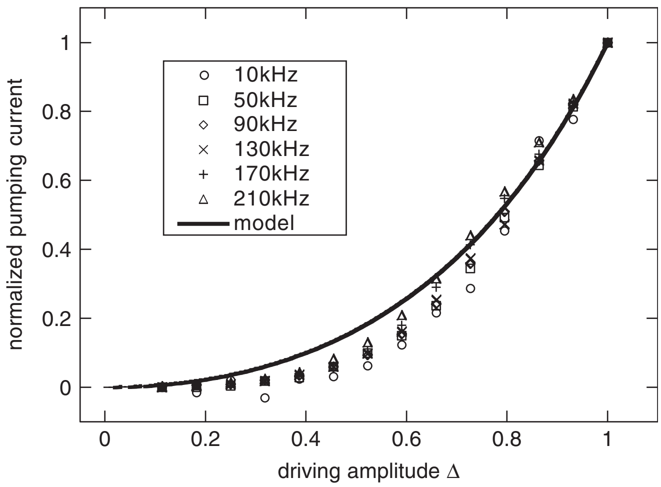

Fig. 3. Normalized pumping current as a function of the driving amplitude for different frequencies. All data fall on a single curve, which is closely approximated by the dependence predicted by our model (solid line).

To further test our model, we investigate the dependence of the pumping current on the driving amplitude Δ (see Eq. (6)). In Fig. 3 the pumping current, normalized to the maximum pumping current $I(\Delta = 1)$ is plotted for different frequencies. It can be seen that all data collapse on a single, frequency-independent function. It can also be seen that this function is in good agreement with the prediction of the result from Eq. (6), which further supports the validity of our model.

4. Summary

In summary, we have fabricated an interdigitated gate array, which can be used to pump a lateral current in a 2DEG by applying phase shifted AC voltages to the finger electrodes. We find that the current as a function of the phase shift closely resembles the waveform of the driving voltages. A simple, near equilibrium transport model is discussed, which can explain this as well as other experimental observations, including the dependence on frequency and driving amplitude. A large discrepancy, however, is found between the measured and simulated absolute currents, which presently is not well understood.

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