Enhanced quantized current driven by surface acoustic waves

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We present the experimental realization of different approaches to increase the amount of quantized current which is driven by surface acoustic waves through split gate structures in a two dimensional electron gas. Samples with driving frequencies of up to 4.7 GHz have been fabricated without a deterioration of the precision of the current steps, and a parallelization of two channels with correspondingly doubled current values have been achieved. We discuss theoretical and technological limitations of these approaches for metrological applications as well as for quantum logics.

Within the last decade, circuits with single-electron-transistors (SET) have been successfully fabricated for high frequencies up to the 100 MHz range for electrometers \[1\]. In application of SETs as electron-pumps e.g. for current standards, however, the maximum operation frequency \( f \) is always limited to several 10 MHz. Only then the necessary tunneling events occur with a sufficient probability and a high precision of current is provided. The resulting small output currents in the order of 1 pA for a single device are both, difficult to measure with a high absolute precision and ineligible to drive other devices (e.g. quantum dot lasers \[2,3\] or resistance standards \[4\]). A single device also needs at least 2 gate contacts \([5]\) and influences of local unstable background changes need to be compensated \([6]\), thus a parallelization of SET based devices to increase the current output implies a delicate operation and to our knowledge has not been realized yet.

In contrast to that, quantized acousto-electric currents driven by surface acoustic waves (SAW) through a split-gate confined potential within a 2DEG are by far larger due to the higher possible operation frequencies of about 2.7 GHz realized up to now \([7]\). In this letter we show how such quantized currents can be increased even further using higher operation frequencies up to 4.7 GHz as well as by using parallelization of split-gate structures.

Our samples were fabricated similarly to earlier works by Shilton et al. \([8]\). The inter-digital-transducers (IDTs) for the highest frequencies were scaled down to a periodicity of 500 nm using a careful compensation of proximity effects for the electron-beam exposure. The AlAs/GaAs heterostructures have carrier mobilities of 300,000 to 650,000 cm\(^2\)/Vs and concentrations of 2.6 to 4.2 × 10\(^{11}\) cm\(^{-2}\). This results in mean free paths above 3 \(\mu\)m that are much larger than all fabricated channel lengths. These channels have been defined by metallic Schottky-gates as well as by wet etched trenches within the 2DEG \([9]\).

There are several constraints for the operation frequency of SAW current standards: the lower frequency limit is given by the minimum SAW-induced confinement potential. Its increased width leads to a lower energetical separation of the single electron levels such that the quantization of the number of electrons per cycle is washed out \([10]\). In addition to that half of the SAW-wavelength must always be smaller than the channel length to achieve quantized currents \([11]\). In fig.1a) the acousto-electric current versus split-gate voltage \(V_G\) is shown for an SAW frequency of about 1 GHz. The first flat plateau with quantized current \(I = e \times f\) develops at split-gate voltages around \(V_g\) slightly below the pinch-off voltage. A further decrease in operation frequency such that the SAW-driven electrons can be detected with a comparable slow SET-electrometer appears accomplishable. Samples with higher energetic level spacing and also larger channel lengths are needed, whereas the latter requires high mobility heterostructures to avoid backscattering inside of the channels.

FIG. 1. Measured acousto-electric current versus voltage applied to the rectangular shaped Schottky-split-gates at a temperature of 1.4 K. The horizontal dashed lines indicate the values \(n \times e \times f\). a) Sample driven with \(f=0.9756\) GHz and split-gate dimensions of 800 nm× 2600 nm. b) At \(f=4.6835\) GHz a much higher rf-power \(P\) is needed. The dimensions of the split-gate are 700 nm × 700 nm.
FIG. 2. The measured quantized acousto-electric current was measured for 5 different frequencies. It depends linearly on the driving frequency up to 4.7 GHz without an increase of deviations from the quantized value.

The high frequency limit is first of all set by technological problems. The piezoelectric effect itself works up to the Debye-frequency (far into the THz range), but the conversion of rf-signals into a sufficiently large induced SAW potential within a GaAs based 2DEG requires large area IDTs, which are difficult to fabricate for high frequencies. Our IDTs consist of 70 finger pairs with a length of 80 µm and nominal widths and separations down to 125 nm. The resulting current plateaus for the corresponding frequency of 4.7 GHz can be seen in fig.1b. The flatness of the plateau

$$\min \{dI_{SD}/dV_G\} = dI_{SD}/dV_G(V_G = V_q) \approx 0 \quad (1)$$

and the deviation of the absolute value at this gate-voltage from the theoretical value

$$I(V_G = V_q) - nef \approx 0 \quad (2)$$

are not significantly worse compared to our devices with lower operation frequencies. According to Flensberg et al. [12] due to nonadiabaticity effects the precision of the quantized currents should be reduced if

$$f \tau \ll 1 \quad (3)$$

with an estimated characteristic back-tunneling time $\tau \approx 10$ ps. Even at this high frequencies, where the condition (3) is not strictly fulfilled ($f \tau = 1/20$ for $f=5$ GHz) this kind of deviations appears to be not dominant [13]. An overview over measured current plateau values of samples with different operation frequencies is depicted in fig.2. Within the accuracy of our measurements no significant deviation from the linear frequency dependence of the quantized current values could be observed.

In addition to samples with enhanced IDTs we also have fabricated samples in which two split-gate structures work in parallel. The inner geometry of such samples can be seen in the SEM-picture in fig.3. A shallow etching technique has been used to remove the doped GaAs layer locally in order to deplete the 2DEG and thus isolate the channels from the two side-gate areas. The distance $X = 5 \mu$m between the two channels has been chosen large enough such that the Coulomb energy between two passing electrons

$$E_C = \int_X^\infty \frac{1}{4\pi\epsilon_0\epsilon_r} \frac{e^2}{r^2} dr = 0.02 \text{ meV} \quad (4)$$

is negligible compared with other energy scales in the device. Therefore Coulomb-drag effects [17] were not utilized to modify the device’s properties. Also interference effects are assumed to play a crucial role only, if the length of a loop through the two channels is significantly shorter.

FIG. 3. The double SAW-split-gate device is patterned with etched trenches of 600 nm width and 90 nm depth. The geometrical length and width of each of the channels ($\#1$, $\#2$) is $2 \mu$m and 960 nm, respectively. The width of the channel can be changed with voltage applied to the side-gates.

An overview over measured current plateau values of samples with different operation frequencies is depicted in fig.2. Within the accuracy of our measurements no significant deviation from the linear frequency dependence of the quantized current values could be observed.

FIG. 4. Acousto-electric current measured for each of the channels ($\#1$, $\#2$) versus gate voltage applied to the respective nearby gate (lower voltage scale). The calculated sum of currents through the two single channels (dashed line) and the measured parallel current ($\#1$ and $\#2$) exhibits a first current plateau at $2e \times f$, whereas the voltage applied to the second side-gate is shown in the upper scale. The applied rf-frequency and -power is $\approx 0.976$ GHz and 13 dBm, respectively.
First, the measurement parameters for each channel $i$ were independently optimized, namely $V_{q,i}$, the frequency and $rf$-power, while the other channel was completely pinched off. In a second step both channels were opened slightly by applying voltages $V_{q,1}$ and $V_{q,2}$ to allow parallel transport of electrons within each cycle, while the influence of the respective more distant side-gates was also taken into account. In fig. 3, the measured quantized current for the two individual channels, their algebraic sum and the measured parallel current is depicted for the above sample. The precision of the doubled quantized current is not reduced compared to the single channel value, which indicates the applicability and benefit of this parallelization for metrology [13].

Recently, a parallel connection of SAW-driven electrons has also been proposed for quantum computation [10]. One major benefit of this concept over other proposals lies in the high repetition rate of individual qubit operations leading to a reduction of errors. As shown in fig. 4, the first step towards a realization of this concept, namely the parallelization of SAW-driven electrons, is possible if the gate-voltages are chosen properly. Higher operation frequencies, as shown in the previous section, might be advantageous for this application as well.

Other approaches to increase the amount of quantized current were not successful yet: the use of a different piezoelectric substrate than GaAs with a higher sound velocity $v_S$ could easily provide a higher frequency ($f = v_S/\lambda$) and a higher amplitude for a given periodicity $\lambda$ of the IDTs. Also the application of a higher harmonic $(n \times f)$ to split-finger IDTs seems promising, but needs high power levels that are not easy to provide. Until now, also pumping of more than one electron per cycle $(n \times e)$ [13] could not be realized with sufficient accuracy. We also could not confirm [19] the theoretical assumption, that the energetic level spacing (caused by Coulomb blockade) is constant and therefore the width of all current plateaus, too [12]. In contrast, we sometimes observe only one or two plateaus.

In conclusion, different approaches for the enhancement of the quantized current value in SAW-driven structures have been experimentally studied and realized. It was shown that using higher frequencies of up to 4.7 GHz as well as a parallel connection of split-gates the device could be significantly improved. Using the presented techniques, other related effects like SAW-quantum computing, SAW-pumped lasers and SAW-current-driven resistance standards get closer to realization.

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