A SET QUANTIZER CIRCUIT AIMING AT DIGITAL COMMUNICATION SYSTEM

Santanu Mahapatra[†], Adrian Mihai Ionescu, Kaustav Banerjee[*] and Michel Declercq
Electronics Laboratory(LEG), Swiss Federal Institute of Technology Lausanne (EPFL), CH-1014, Switzerland
[*]Centre for Integrated System, Stanford University, USA
[†]Email: santanu.mahapatra@epfl.ch

ABSTRACT

A SET based quantizer circuit has been developed in this work for the purpose of digital communication system. This proposed circuit, which consists of only two SET devices, offers ultra low power dissipation, small quantization noise error and zero granular noise error. The proposed circuit does not require any external sampling signal for sampling the baseband signal. The sampling rate can be controlled by just varying the device capacitor.

INTRODUCTION

Single electron transistors (SET) have recently attracted special attention due to their very low power consumption and ultra small size (of the order of few nano meters) [1]. However, even though some clear functionality has been reported at the device level and a few *niche* applications have been demonstrated [1, 2], there is still a strong need to identify and develop mainstream circuit applications for SETs. It is worth noting that the operation of the SET devices is based on the *Coulomb Blockade* phenomenon [1, 2], which is quite unique compared to the principle of operation of MOS transistors. This work exploits the particular Coulomb Blockade property of SET devices in order to develop a quantizer circuit for the purpose of digital communication.

OBJECTIVES

A simple digital communication transmitter system is presented in Fig. 1. In this system, the baseband signal (band limited to 3.3 kHz in case of audio signal) is sampled and quantized (at Nyquist rate) using a sample-and-hold circuit and then fed to an A/D converter for encoding [3]. A simple sample-and-hold circuit often fails to follow a signal accurately as it produces a considerable amount of quantization error. To suppress this quantization error a lot of methods have been proposed (e.g., delta modulation, adaptive delta modulation, compander, etc.) [3]. However, all such methods suffer from : (i) a lot of hardware overhead and computation (for instance, the adaptive delta modulation requires a processor in order to compute the step height) and (ii) granular noise problems [3]. The quantization circuit reported in this work consists of only two SET devices (resulting in a minimal circuit complexity) and one load capacitance (C_L), which is able to quantize any type of signal with a very low quantization noise error and with zero granular noise error. The circuit validation has been carried out using: (i) the standard, largely accepted, SIMON simulator [2] for single electron devices and (ii) parameters of the SET devices that correspond to reported fabricated and measured devices [4-6]. It is also demonstrated that this circuit does not require any external sampling signal for the quantization of the baseband signal, the sampling rate of the baseband signal can be controlled by varying the value of the capacitance of the SET devices.

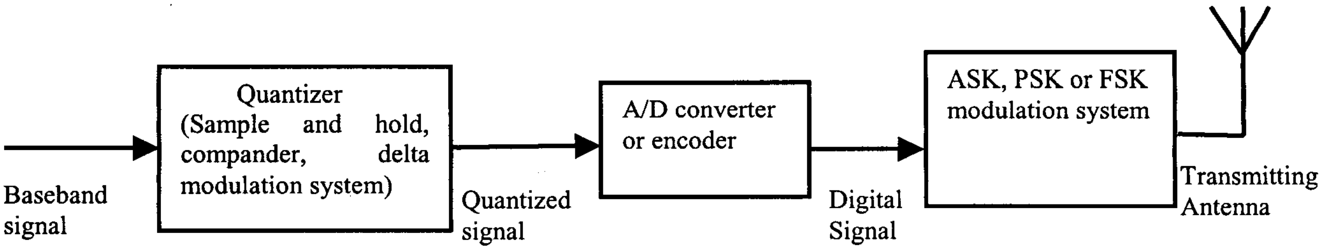

Fig. 1. Block diagram of a simple digital communication transmitter system

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CIRCUIT DESCRIPTION

The schematic of the proposed SET-based quantization circuit is shown in Fig. 2. The performance of this circuit is verified with arbitrary input signals as shown in Fig. 3, with realistic values [4-6] of the tunnel and gate capacitance (C_T and C_G respectively) of the SET device, $C_T = C_G = 2$ aF and a value of the tunnel resistance (R_T) of 100 KΩ.

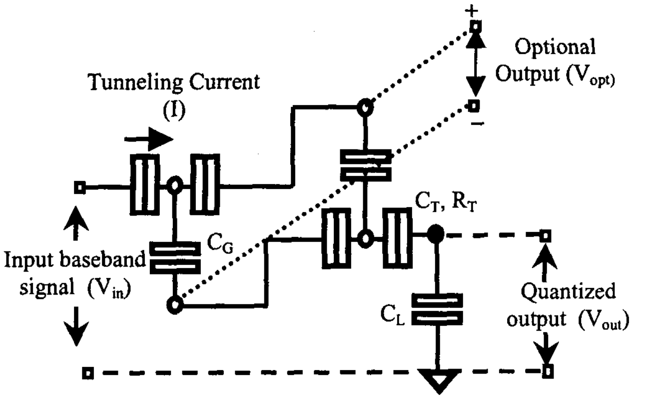

Fig. 2. Circuit diagram of the proposed SET-based quantizer: C_G and C_T are the gate and tunnel capacitance, R_T is the tunnel resistance and C_L is the load capacitance ($C_L >> C_G$, C_T). The solid circle represents interconnect and all the hollow circles represent islands.

In Fig. 3 the input waveform is plotted along with the quantized output of the circuit and it is demonstrated that the quantized output follows the input signal quite accurately. Two interesting observations can be made from the simulations reported in Fig. 3. First, it is worth noting that the heights of the quantized steps are all equal to e/C_L (where e is the electronic charge). This is due to fact that a step jump at the output occurs when a single-electron tunnels through the circuit and an elementary charge is trapped at the load capacitor. Therefore this behaviour cannot be mirrored by any CMOS equivalent circuit. Secondly, the widths of these quantized steps are varying which is contrary to conventional MOS based quantizer. Note also that in this figure the input signal is divided into 6 regions corresponding to the different signal slopes. It is very important to highlight that the width of the quantized steps is constant for each region characterized by a constant slope and hence the quantized output of this circuit is frequency modulated. Another exclusive characteristic of this circuit is that it does not encourage any granular noise in region 5 (flat signal). Therefore, the proposed SET circuit can be uniquely used to quantize any type baseband signal and the output of this circuit (i.e., the quantized signal) is frequency modulated. It follows that present sample-and-hold-compander-delta-modulation-system could be replaced by this proposed very tiny (comparable with the size of a SET inverter [7]) SET circuit. The power dissipation of the proposed circuit is eventually dynamic, i.e., the proposed circuit draws current from the input voltage source only when the output changes from one step to another (i.e., when the electron tunnelling happens) as shown in Fig. 3. It follows that the circuit has an ultra-low power dissipation compared to any other conventional solutions. However one specific overhead of the proposed SET circuit is related to the specific encoding of the quantized output into digital format. In the proposed circuit, the information of the baseband signal is captured by the step-width of the quantized signal and not by its step-height.

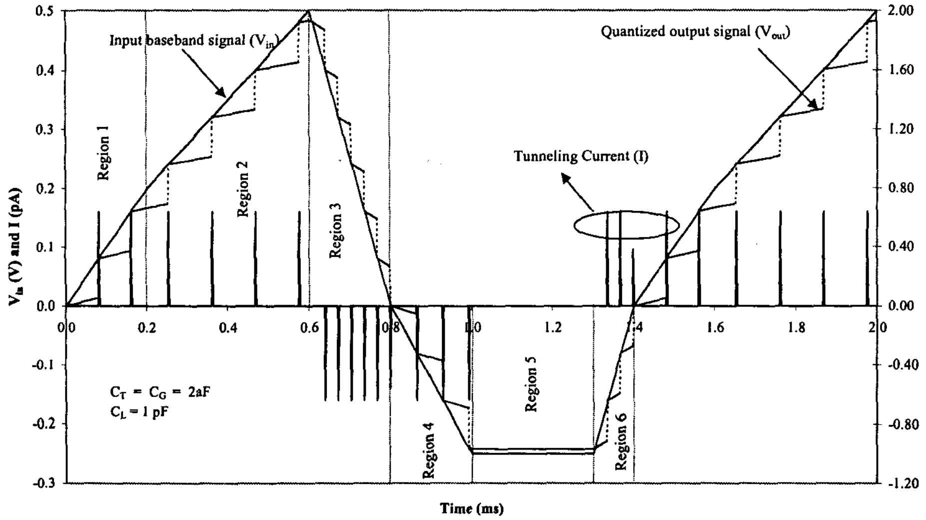

Fig. 3. Evaluation of the performance of the proposed circuit with an arbitrary input signal, using SIMON single electron simulator [2]. In the same figure the tunnelling current is also plotted as a function of time.

RESULTS AND DISCUSSION

As seen in Fig.3, in Region 1, when the system is in Coulomb blockade (no electron tunnelling occurs), the output increases with input as: $V_{out} = V_{in}\, C_{eq}/(C_L+C_{eq})$, where C_L is load capacitance, C_{eq} is the equivalent capacitance of the quantizer (excluding the C_L). Since $C_L >> C_{eq}$, V_{out} remains almost constant when the system is in Coulomb blockade. When V_{in} is sufficiently large to overcome the Coulomb-blockade voltage, one electron tunnels through the circuit and get trapped at the load capacitance, and consequently V_{out} increased by a factor of $e/(C_L+C_{eq})$, which results a step jump. However, after one electron tunnelling the system again enters into Coulomb blockade state and V_{out} becomes almost constant with V_{in} until a second electron tunnels and results another step jump.

In our investigation, particular attention has been paid to the control of the sampling-rate of the input signal by varying the value of the capacitance of the tunnel junction and the gate. In Fig. 4 the effect of different values of tunnel and gate capacitance on the sampling rate is demonstrated for a 2.5 KHz (principle frequency) signal. The figure shows that the sampling rate increases with increasing value of the capacitance. This is due to the fact that the Coulomb Blockade voltage is proportional to $(e/2C_\Sigma)$, where C_Σ is the total capacitance associated to the island. Hence, as the value of island capacitance increases, a smaller value of the voltage is needed for the electron to tunnel through the device and hence, for higher value of the capacitance, the sampling rate increases. In this connection it can also be observed that as the device capacitance goes down, the ability of the proposed quantizer to handle higher amplitudes increases.

Although in this work the performance of this circuit is demonstrated only for audio frequency signal (i.e., signal frequency less than 3.3 KHz), it clearly appears that the system exhibits similar performance even in very high frequency range (above MHz range), which is very useful for other communication applications. This is due to the fact that the principle of this circuit is solely based on the Coulomb Blockade phenomenon, which is transparent to the frequency of the baseband signal. Only the value of the capacitance of the SET devices (i.e., the dimension of the island) has to be tuned for proper operation. Finally it should be mentioned that the proposed circuit, using $C_T = C_G = 2$aF, can accurately quantize the input signal up to a temperature of 2K. The working temperature of the quantizer can be increased by properly scaling down the device capacitance (C_T and C_G) values.

There is another optional output port exists in this proposed circuit as shown in Fig. 2. The output (V_{opt}) taken from this optional port is plotted along with the input baseband signal in Fig. 5. The advantage of this optional port is that the quantized output is in the same order of the input baseband signal. However there are two disadvantages of this optional output port. First, this optional output port is floating, i.e., there is no ground reference. Secondly, is that V_{opt} is taken across two islands (which are not interconnects). Therefore if V_{opt} is fed to any system, the input capacitance of that system should be much less than the island capacitance in order to avoid the capacitative overloading. However this problem may be solved by using an advanced "wireless interconnects" [8] techniques.

In conventional quantizer the information of baseband signal is stored in the step height. Therefore due to the presence of noise, if the step height gets altered then the quantized waveform could carry invalid information. However, in the SET proposed circuit, the baseband signal information is stored in step width (contrary to the conventional system), and hence the SET quantizer system expected to be more immune to noise.

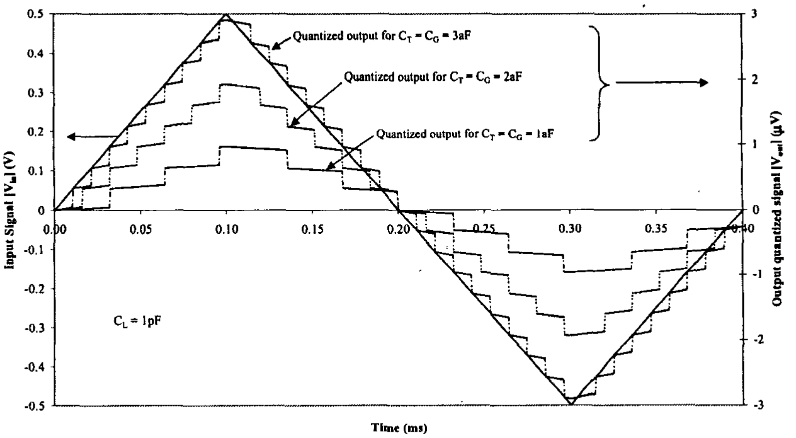

Fig.4. The effect of device capacitance on the sampling rate for three values of device capacitance (1aF, 2aF and 3aF). The solid line represents the input baseband signal, where all the broken line represent the quantized output of the proposed circuit.

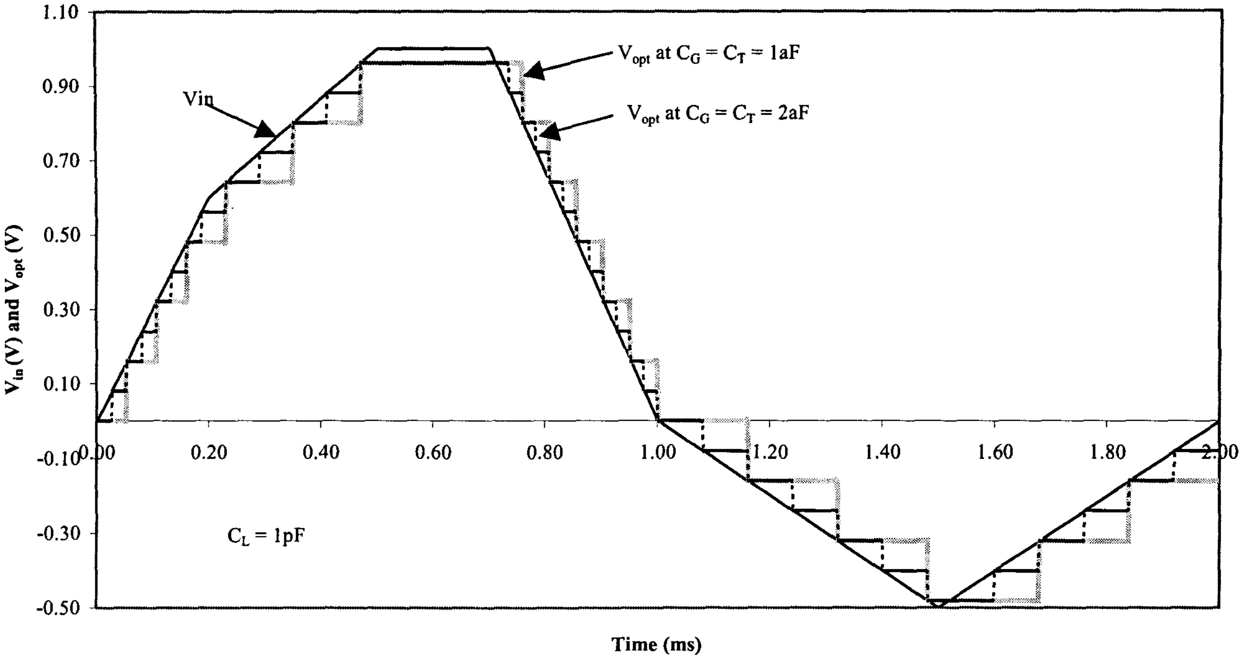

Fig. 5. Evaluation of the performance of the optional port (V_{opt}) of the proposed circuit with an arbitrary input signal and for two values of device capacitance (1aF and 2aF).

CONCLUSION

A novel circuit based on SET devices for the quantization of baseband signal has been proposed and validated. The functionality of the proposed circuit has been verified using the SIMON simulator and reported parameters for fabricated and measured SET devices. The circuit exhibits excellent performance in quantizing various types of baseband signals in the audio frequency range. It has also been demonstrated that the sampling rate can be controlled without using any external sampling signal by simply varying the value of the device capacitance. Finally, it is worth noting that the proposed minimal quantizer-circuit architecture (using two SETs), demonstrates unique advantages in terms of: (i) quantizing performance over any frequency range, (ii) ultra-low power dissipation, and (iii) reduced area consumption. It therefore appears a strong candidate for future digital communication applications.

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