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***Abstract* — Our experiments show that linearity can be achieved if transistors are designed to operate in the one-dimensional ballistic transport regime in the quantum capacitance limit. We report third order intercept points (IIP3) of around -13dBm at maximum transconductance under these particular transport and device operation conditions, meeting the requirements for state-of-the–art mobile communication systems. The advantage of our approach becomes most apparent when normalizing the IIP3 values with power at maximum transconductance. Although, our results do not yet show an improvement over devices operating in the velocity saturation regime due to the presence of scattering, they provide compelling evidence for the potential of our approach. Our findings make our approach an excellent candidate for low power applications in the early stages of RF receivers when linearity is critical.**

***Index Terms* — Ballistic Transport, Linearity, Nanowire Transistor, 1-D Transport, Quantum Capacitance, RF CMOS, Transconductance.**

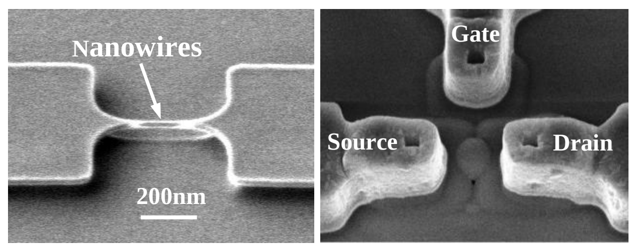
I. INTRODUCTION

Linearity is one of the most important requirements in all RF communication systems. Good linearity ensures minimum contributions of higher order harmonics and inter-modulation terms and results in less distortion at the output of RF front-end stages [1]. Traditional ways to achieve linearity involve complex circuit design methods [2], and/or requires operation of the device in the velocity saturation regime [3] which implies high supply voltages and large power consumption – a scenario that is not ideal for portable and low power applications.

In MOSFETs, transconductance, and output conductance are major sources of nonlinearity. The focus of this work is on the transconductance linearity due to its dominant role for today's RF systems and circuits when considering the frequencies in question [4]. Linearity is directly proportional to transconductance and is inversely proportional to the second derivative of the transconductance [1] which indicates that devices with constant transconductance versus gate voltage curves, and small variations over a specific voltage range, are more linear. In this paper, we take advantage of the fact that in 1-D, ballistic devices operating in the quantum capacitance limit ($C_Q<C_{OX}$ as explained in section III) [5],[6], the density of states, and the velocity have inverse energy dependences, and all the gate voltage drops in the channel rather than across the gate oxide resulting in a linear increase in current with channel potential and a constant transconductance over a specific voltage range [5].

In addition, the unique scaling potential of low-dimensional systems such as nanowires (NWs) in terms of body thickness, channel length, and oxide thickness makes NW devices an outstanding choice for applications that require a high degree of linearity [6].

In this work, fully CMOS compatible silicon nanowire (SiNW) gate-all-around (GAA) n-MOS transistors (see Fig. 1) [7] are characterized in terms of linearity.



(a) (b)

Fig. 1. Tilted top view SEM images of (a) released 200nm nanowire and (b) GAA SiNWT. Nanowires have triangular cross-section with a diameter of ~6nm. A gate dielectric of 4nm thermally grown silicon dioxide wraps the entire wire. Channel and source/drain doping levels are $10^{15}cm^{-3}$ and $10^{20}cm^{-3}$ respectively.

II. LINEARITY

When using the conventional definition of the third order intercept point, IIP3 (1), as a standard figure of merit for linearity

$$IIP3 = \frac{2g_{m1}}{3g_{m3}R_S} = \frac{4\left(\frac{\partial I_D}{\partial V_{gs}}\right)}{R_S\left(\frac{\partial^3 I_D}{\partial {V_{gs}}^3}\right)} \quad (1)$$

we can compare the linearity of the same nanowire device

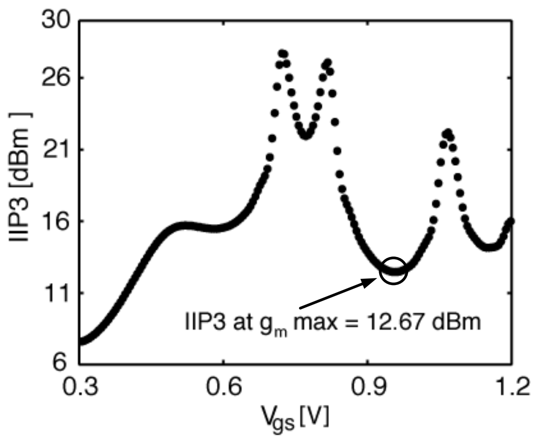


Fig. 2. IIP3 for a device biased in the velocity saturation regime.

in terms of both the conventional operation in the velocity saturation regime and our proposed operation in the 1-D, ballistic transport regime in the quantum capacitance limit. Fig. 2 shows the IIP3 for the device operating in the velocity saturation regime. Peaks are mathematical anomalies and are not relevant for the following discussion. An IIP3-value of 12.67dBm is extracted at the maximum transconductance indicative of a highly linear device operating at this bias point.

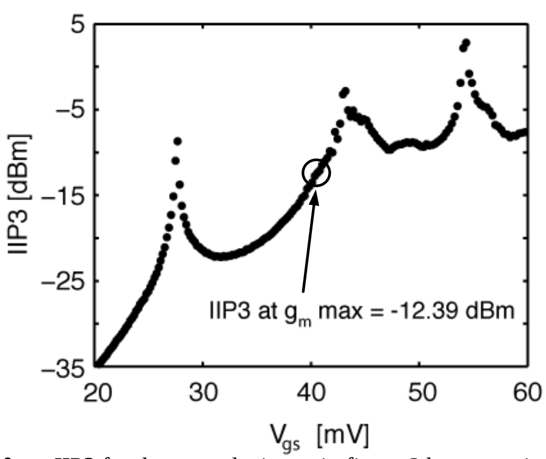


Fig. 3. IIP3 for the same device as in figure 2 but operating in the 1-D quasi-ballistic quantum capacitance limit.

Fig. 3 shows the extracted IIP3 data when operating the same device in the 1-D ballistic regime in the quantum capacitance limit for comparison. For the maximum transconductance point, an IIP3-value of -12.39dBm is found. Note that this value is considered sufficient [8] to meet the standards for many mobile communication systems currently in use. While in itself an impressive finding, the key observation in this article is that the above high degree of linearity is obtained at an extremely small DC power. The required supply power voltage for operation in the 1-D ballistic transport regime in the quantum capacitance limit is ~200mV which is five times smaller than the required supply voltage for operation in the conventional velocity saturation regime. When normalizing both of the above IIP3 values with the DC power at maximum transconductance, Fig. 2 and Fig. 3 yield ~34dB and ~27dB respectively. The lower number for the 1-D ballistic device in the quantum capacitance limit is a result of the quasi-ballistic nature of the 200nm long channel, which yields a different velocity versus energy dependence than a fully ballistic transistor. *Operating the nanowire transistor in the ideal 1-D ballistic transport regime in the quantum capacitance limit is expected to result in an IIP3-value normalized to the DC power which is higher than what is obtained in the conventional case at maximum transconductance***.**

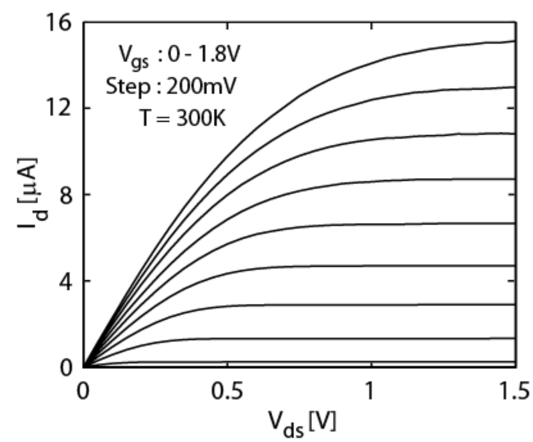


Fig. 4. Output characteristic of a device with a channel length of 200nm at room-temperature.

III. Transconductance Results

In the following we will discuss the details of our analysis and experimental observations, for the conventional velocity saturation regime of operation and 1-D ballistic transport in the quantum capacitance limit.

In order to ensure device operation in the velocity saturation regime an electric field of approximately one volt per micrometer is needed in the channel. For a device with a channel length of 200nm, a V_{ds} of more than 200mV is thus required to reach the velocity saturation regime (see Fig. 4). We have performed transconductance calculations at V_{ds} of one volt which is the typical supply voltage for current RF circuits ensuring operation in the velocity saturation regime. Fig. 5 shows the measured transconductance as a function of gate voltage for this bias point which results in the IIP3-values of Fig. 2. The “boxed” area denotes the V_{gs}-range over which the device operates in current saturation. Next, we want to extract the

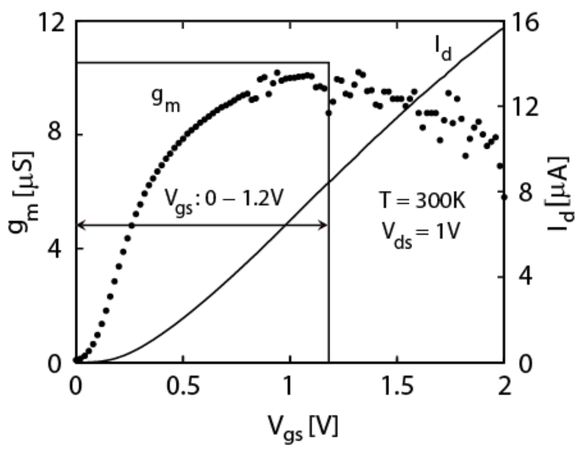


Fig. 5. Transconductance as obtained when operating in the velocity saturation regime.

transconductance for the same device if operation is in the 1-D ballistic quantum capacitance limit. The idea behind this set of condition is as follows:

In MOSFETs, the total capacitance (C_{tot}) is the series combination of the oxide capacitance (C_{OX}) and the capacitance associated with the semiconducting channel which is called the quantum capacitance (C_Q). C_Q is proportional to the density of states (DOS) of the channel material (see Fig. 8). When the oxide capacitance is much greater than the quantum capacitance, C_{tot} is approximately equal to C_Q and the device operates in the so-called quantum capacitance limit. Under these conditions the applied gate voltage translates into a one-to-one movement of the conduction and valence subbands. Using this finding, ignoring scattering and assuming that only ONE 1-D band contributes to the current flow, it has been shown that [5]:

$$I_D = \frac{2q^2}{h}\left(V_{GS} - V_{th}\right) \tag{2}$$

In other words, a constant transconductance of $2q^2/h$ (77.46μS) is expected if a device operates under the above conditions. (q is the charge of an electron and h is the Plank's constant.) With the above arguments in mind, we have analyzed the transconductance at a V_{ds} of 200mV to avoid velocity saturation. Note, that this voltage is five times less than the supply voltage of a conventional RF circuit. Since for our devices, the ideal 1-D quantum capacitance limit had not been reached experimentally, we have implemented a device simulator which translates the experimentally obtained transfer characteristics into the expected response of a 1-D NWFET in the quantum capacitance limit. Furthermore, we have developed an approach that allows comparing our experimental transfer characteristics with simulations to identify the number of 1-D modes contributing to current flow as discussed in greater detail below. Employing both, the knowledge about the gate voltage range over which only one degenerate 1-D mode contributes as well as the translation between gate voltage and band movement based on the capacitances involved, we have extracted the related transconductance shown in Fig. 6. Note that the underlying dataset had been obtained at 77K to ensure 1-D ballistic transport conditions (see sections below). The important finding of Fig. 6 is that a rather constant transconductance value is indeed observed over a certain gate voltage range which results in the IIP3-value displayed in Fig. 3.

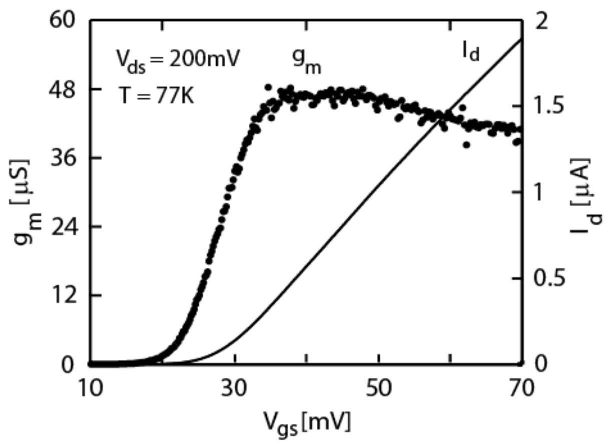


Fig. 6 A rather constant transconductance is obtained through operation in the 1-D ballistic transport regime in the quantum capacitance limit.

IV. QUASI BALLISTIC TRANSPORT

For silicon devices, diffusive transport is known to dominate the electrical characteristics even at channel lengths as small as 50nm. In order to operate as close as possible to the desired ballistic transport conditions, we have i) chosen devices with a channel length of 200nm, the shortest available gate length in our study and ii) measured the transfer characteristics at a temperature of 77K to reduce phonon related scattering effects in the channel.

V. 1-D TRANSPORT IN THE QUANTUM CAPACITANCE LIMIT

When cooling our samples down to 4K, features that clearly indicate 1-D transport conditions become apparent (see Fig. 7). A step-like change in current through the device as a function of gate voltage is indicative of a transition between 1-D subbands [9]. In our case, a second subband starts contributing at a gate voltage of around 1.6V. The same measurement reveals a threshold voltage of about 0.9V for this device. Comparing the simulated

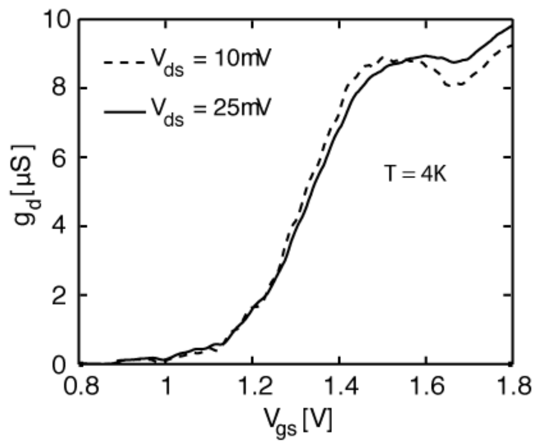


Fig. 7. 1-D effects are clearly apparent in the conductance characteristics for two different drain voltages.

allows gathering initial insights into the relation between mode spectrum [10] with the experimental data from Fig.7 gate voltage and band position. We find that a gate voltage range of around 500mV corresponds to a band movement of about 85meV. This observation is confirmed further by calculating the response of the conduction and valence band of our silicon nanowire devices as a function of gate voltage from the known gate capacitance and calculated quantum capacitance contributions.

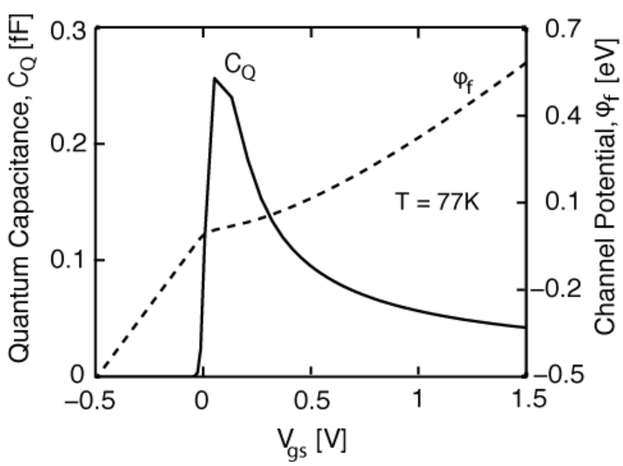


Fig. 8. Left and right axes show the simulated quantum capacitance and the band movement for a single one-dimensional subband respectively.

Fig. 8 shows simulation results for T=77K. Next, we use this information to extract data sets as the one displayed in Fig. 6 by measuring the transfer characteristics at 77K. Note that at this temperature k_BT is smaller than the 1-D mode spacing ensuring one-dimensional transport conditions but sufficiently large to suppress interference related effects that become dominant at even lower temperatures.

VI. Conclusion

Through a combined experimental/simulation approach, we have shown that a constant transconductance resulting in high RF linearity can be achieved through 1-D ballistic transport in the quantum capacitance limit. While for this transport regime the achieved IIP3-value is lower than for the velocity saturation regime, initial findings show that potential improvement can be obtained when normalizing the IIP3-values to the power consumption at maximum transconductance. In other words, at a given linearity level the power consumption can be reduced by operating in the 1-D ballistic transport regime in the quantum capacitance limit. This new approach can enable applications such as networks with many portable receivers which are on listening mode and rely on batteries with limited capacity.

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