0.13 µm BiCMOS Embedded On-Chip High-Voltage Charge Pump with Stacked BEOL Capacitors for RF-MEMS Applications

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Abstract. In this paper we demonstrate an on-chip high-voltage charge pump integrated in a 3 µm SiGe:C BiCMOS technology. The charge pump is intended to be used for the actuation of BiCMOS embedded RF-MEMS devices like witches and varactors. A new type of charge pump is introduced using stacked BEOL capacitors as charge/discharge capacitors to overcome the output voltage limitations of charge pumps with standard MIM capacitors. The electrical characterization of both MIM and stacked BEOL capacitor charge pumps show that BEOL capacitors are useful to improve the maximum charge pump output voltage due to extremely reduced leakage currents. By this BiCMOS embedded charge pumps with high output voltages of >60 V can be generated directly on the chip.

Index Terms: RF-MEMS, monolithic integration, BiCMOS, high-voltage charge pump.

1. Introduction

Latest developments in SiGe BiCMOS technologies have shown a tremendous advantage compared to RF-CMOS providing Heterojunction Bipolar Transistors (HBTs) with f_t/f_{max} of 300/500 GHz targeting f_{max} values of 700 GHz [1 – 2]. Beside the high performance HBTs, the existence of a standard CMOS together with advanced technology features like embedded RF-MEMS and Si photonics are key enabling technologies to realize high performance multifunctional mm-wave systems [3].

In recent years a fully embedded RF-MEMS technology module has been developed using the high performance 0.13 µm BiCMOS technologies SG13S/G2. Thanks to these developments monolithic integrated low loss RF-MEMS devices like switches [4] and varactors [5] can be realized directly on the chip. For the actuation of these MEMS devices the electrostatic actuation principle is the preferred solution due to the simple implementation scheme into standard CMOS technologies. Most of the RF-MEMS devices using electrostatic actuation require high voltages from 40 – 100 V [6 – 7] although low actuation voltage RF-MEMS switches with only 5 V have been demonstrated with the main drawback of large area consumption [8]. Recently we demonstrate two different RF-MEMS devices, a 140 GHz capacitive-type switch [4] and a MEMS varactors [5] with high pull-in voltages of 60–70V in a 0.13 µm BiCMOS embedded RF-MEMS platform.

In the past several on-chip high-voltage charge pumps for MEMS applications have been demonstrated. In [9] a BiCMOS embedded high-voltage charge pump with > 40V output voltages has been demonstrated in a 0.25 µm BiCMOS technology. In [7] and [10] charge pumps with ~50 V output voltage have been realized using a 0.18 µm HV CMOS or 0.6 µm CMOS process respectively. Obviously all these reported charge pump circuits are not suitable due to the limited output voltage if actuation voltages of more than 60 V are required. Beside the consideration of process and design optimization to realize high voltage transistors only minor attention has been given to the influence of charge pump charge/discharge capacitors. Usually only the breakdown voltage has been taken into account as the main criteria for the capacitors. If capacitor breakdown voltages are too low a simple series connection of capacitors can be used to limit the voltage drop for each capacitor. Indeed not only the breakdown voltage has to be considered because capacitor leakage currents can introduce a significant low output resistance limiting the harge pump output voltage. Therefore alternative capacitor types with high breakdown voltages and lowest leakage currents are strongly required to achieve charge pumps with > 60V output voltage for BiCMOS embedded high actuation voltage RF-MEMS applications.

In this paper we demonstrate a high-voltage charge pump integrated in a 0.13 µm SiGe:C BiCMOS technology. A new type of charge/discharge capacitors using stacked BEOL capacitors with lowest leakage current is introduced to overcome the output voltage limitations of charge pumps with standard MIM capacitors.

The electrical characterization of both MIM and stacked BEOL capacitor charge pumps show that stacked BEOL capacitors are very useful to improve the maximum charge pump output voltage for more than 25V due to extremely reduced leakage currents. By this BiCMOS embedded charge pumps with high output voltages of 70V together with high performance RF-MEMS devices become feasible.

2. High-Voltage Generation

A. High-Voltage Generation Circuit

The capacitive charge pump is based on the circuit topology introduced by Pelliconi [11] to provide charge pumps with low power consumption and high efficiency. The main building blocks of a single charge transfer block and the cascaded CP stages are shown in Fig. 1 and a detailed explanation of the circuit operation is provided in [11].

The charge pump is implemented in IHPs 0.13 µm BiCMOS technology SG13G2 including high voltage MOS-transistors and 7 metal layers. Two 24 stage charge pumps were realized to investigate influence of capacitor type. A circuit topology with charging and discharging capability was used to achieve fast operation without requirement of discharge resistors [9].

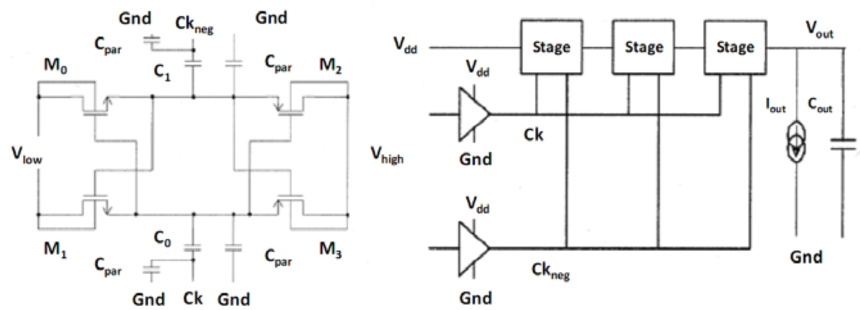

Fig. 1. Main charge pump building blocks: Single charge transfer block (left) and cascaded charge transfer blocks to increase the output voltage [11].

The maximum output voltage is mainly defined by the supply voltage, the capacitors C_0 and C_1 (together with the parasitic capacitances) and the output resistance and output capacitance limiting the maximum achievable output voltage. For the operation of RF-MEMS devices an ideal open-circuit is present thus high output resistances in the GΩ-range are present. But the capacitors itself can introduce a significant low output resistance due to high leakage currents. To analyze the effect of leakage currents on the maximum achievable output voltage charge pumps with standard MIM and stacked BEOL capacitors are fabricated and analyzed.

B. MIM vs. Stacked Metal Capacitors

The two different types of charge/discharge capacitors are analyzed in terms of available capacitance *per area*, leakage current and breakdown voltage. Suitable charge pump capacitors can be realized using either the BEOL MIM capacitors between the Metal-5 (M5) and the TopMetal-1 (TM1) metallization layer with a thin Si_3N_4 dielectric layer or a stacked BEOL capacitor using the parasitic capacitances between the metallization layers with SiO_2 as dielectric layer. In Fig. 2 the cross sections of both capacitor types are shown. MIM capacitors with Si_3N_4 layer as dielectric (ε_r =7) provide a capacitance *per area* of ~1.5 fF/µm². In comparison the stacked BEOL capacitors provide only ~0.3 fF/µm² due to the large SiO_2 thickness ranging from 550–2000 nm in between the different metal layers (ε_r = 4.1) increasing the area to achieve a certain capacitance. Especially for the stacked BEOL capacitors, additional area is required for the interconnection of the metal layers reducing the effective capacitance *per area*.

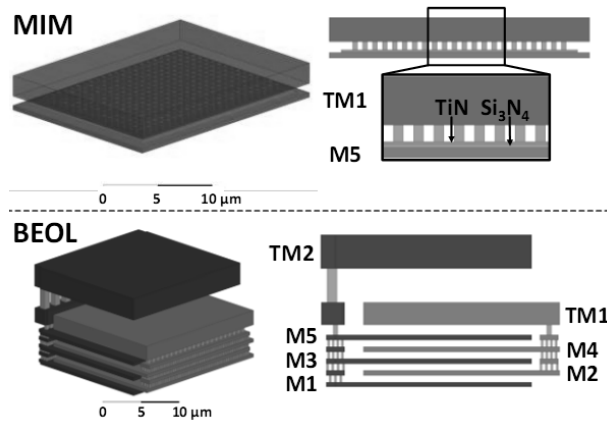

Fig. 2. 3D and cross section view of both MIM capacitor and stacked BEOL capacitor.

Beside the capacitance *per area* the leakage current and the maximum breakdown voltage need to be considered. The leakage current behavior and the breakdown voltage characteristics are analyzed using I-V measurements for fabricated MIM and stacked BEOL capacitor test structures similar to the ones shown in Fig. 3. The voltage is swept between 0–200 V with a current compliance of ~10 µA. I-V measurement results are shown in Fig. 3 for three different chips on a 200 mm wafer.

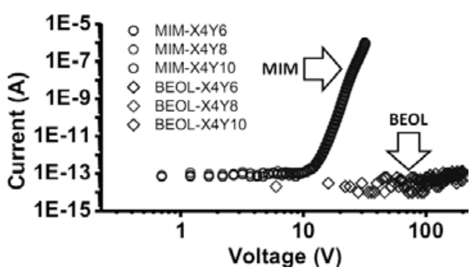

Fig. 3. I-V measurement results for MIM and stacked BEOL capacitor showing a significant difference of the leakage currents.

Obviously there is a significant difference between the MIM capacitor and the stacked BEOL capacitor leakage current. In case of the MIM capacitor, a significant increase of the leakage current can be observed starting from 12 V and reach > 1 µA already at 30V. In comparison the leakage current of the stacked BEOL capacitor is almost constant even up to 200 V with values of < 100 fA.

Based on the I-V characteristics a charge/discharge capacitor lumped element model can be extracted including a parallel capacitor and resistor. Figure 4 shows the equivalent parallel resistance R_{leak} *vs.* the applied voltage. Obviously the resistance R_{leak} is strongly decreasing for the MIM capacitor to values in the MΩ-range. In comparison the R_{leak} is almost constant with values in the TΩ-range for the stacked BEOL capacitor.

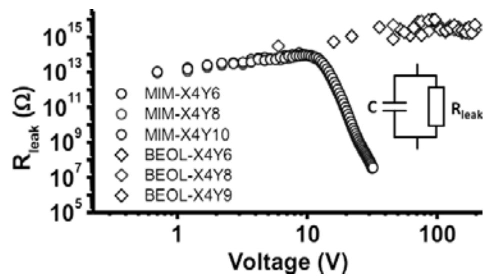

Fig. 4. Leakage current resistor R_{leak} *vs*. applied voltage for MIM and stacked BEOL capacitor extracted from I-V measurements.

Indeed no dielectric breakdown has been observed for the specific MIM and the stacked BEOL capacitors but in case of the MIM capacitor this is related to the current compliance mode limiting the applied voltage. For specific BiCMOS process test structures a MIM breakdown occurs at ~30 V. If charge pumps with more than 60 V output voltages are targeted one MIM capacitor is not suitable to handle these high voltages thus a series connection of at least two MIM capacitors is mandatory.

3. Charge Pump Characterization

For the comparison two types of charge pumps have been fabricated. Microphotographs of the fabricated charge pumps are shown in Fig. 5. The charge pump consumes only ~ 0.2 mm² including the charge transfer blocks, the ring oscillator (RO) and the probe pads.

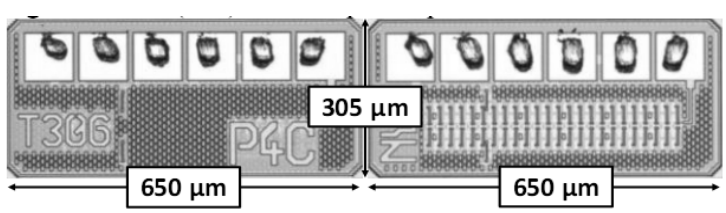

Fig. 5. Microphotograph of the MIM (left) and stacked BEOL capacitor (right) charge pump with dimensions of 650×305 µm².

The input *vs*. output voltage is shown in Fig. 6 for three different chips on the wafer. A fixed ring oscillator control voltage of 3.3 V is chosen. The input voltage is swept from 0–5 V in 200 mV steps. The output voltage is measured using a high measurement input resistance of >10 GΩ. A significant difference between MIM and stacked BEOL capacitor output voltage can be observed. While the MIM capacitor charge pump output voltage saturates already at 40 V with an input voltage of 3.5 V the stacked metal capacitor charge pump can generate output voltages of up to 70 V for a 5 V input voltage.

Beside the output voltage the charge pump current consumption is also measured. In Fig. 7 the overall current consumption of the charge pump including the charge transfer blocks and the RO is shown for different output voltages. Up to 40 V the current consumption of 4 mA is similar for both types of charge pumps. Comparing the achieved output voltage *vs*. the current consumption above 40 V a significant difference between MIM capacitor and stacked metal capacitor charge pump can be observed and an increase of current do not lead to an increased output voltage for the MIM capacitor charge pumps.

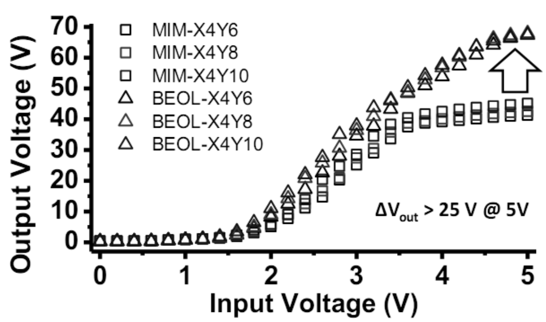

Fig. 6. Output voltage *vs*. input voltage for the MIM and stacked BEOL capacitor charge pumps.

Finally a wafer-level output voltage analysis is done for a fixed input voltage of 5V to compare the uniformity of the charge pump performance on a 200 mm wafer. The wafer-level output voltage is shown in Fig. 8. A significant variation of the maximum output voltage is observed for the charge pumps using MIM capacitors. The reason is the non-uniformity of the Si_3N_4 dielectric layer deposition which can influence the thickness and the leakage current, respectively. For low operation voltages up to 5 V this effect is negligible but for high voltage applications this cannot be ignored. In comparison the output voltage uniformity of the stacked BEOL capacitors is significantly improved with small variations of only 1–2 V. The right side of the wafer has to be excluded due to the position of the charge pumps directly at the right edge of the test chip.

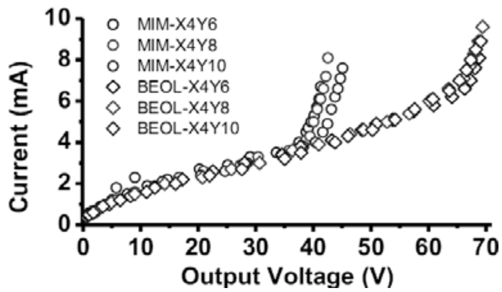

Fig. 7. Current consumption vs. output voltage for the MIM and the stacked BEOL capacitor charge pumps.

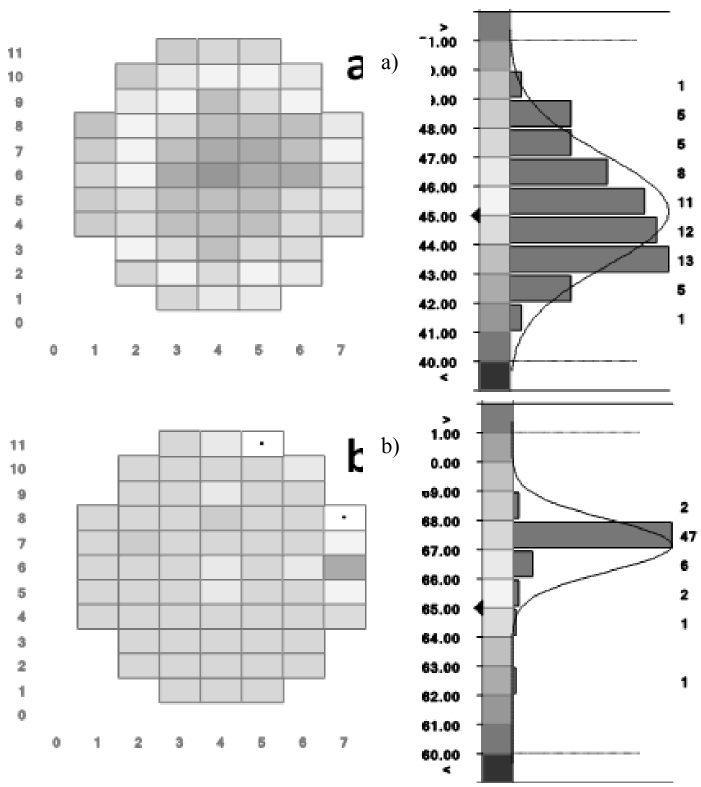

Fig. 8. Wafer-level output voltage for a fixed 5V input voltage for charge pump with a) MIM capacitor and b) stacked BEOL capacitor.

Finally the use of stacked BEOL capacitors for high-voltage charge pumps enables the realization of higher output voltages with an improved uniformity which is an important aspect if sensitive RF-MEMS varactors require very accurate control of the actuation voltages.

4. Charge Pump Reliability Test

Reliability tests are applied to evaluate the long-term reliability of both types of charge pumps. The charge pumps are continuously actuated and the output voltage is measured at every 10 minutes (Fig. 9).

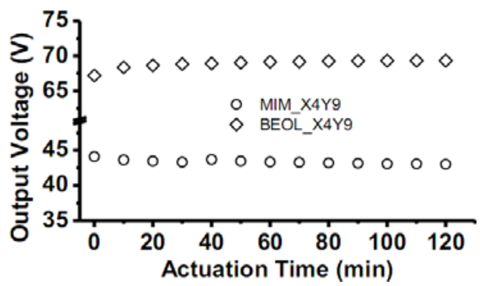

Fig. 9. Measured leakage current *vs*. applied voltage.

No remarkable output voltage variation can be observed. A slight output voltage decrease for the MIM capacitor and a slight increase for the stacked metal capacitor charge pump are observed which can be explained by the charge depletion in the MIM capacitor due to the high leakage current and the charge accumulation in the stacked BEOL capacitors due to the extremely low leakage currents.

5. Conclusion

In this paper we demonstrate a high-voltage charge pump with 70 V output voltage integrated in a 0.13 µm BiCMOS technology. A new type of charge/discharge capacitors using stacked BEOL capacitors with lowest leakage current are introduced to overcome the output voltage limitations of charge pumps with standard MIM capacitors. Stacked BEOL capacitors provide a lower capacitance per area, but due to the negligible leakage current and high breakdown voltages, smaller capacitors can be realized saving area and costs. For the considered technology platform charge pumps with stacked BEOL capacitors are useful to improve the maximum charge pump output voltage of more than 25 V compared to MIM capacitor charge pumps due to extremely reduced leakage currents with very good wafer-level uniformity and reliability.

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