

Design of 900 Mhz AC to DC Converter Using Native Cmos Device of TSMC 0.18 Micron Technology for RF Energy Harvest Application

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Abstract RF signal carries very low amount of energy and can be easily dissipated as heat loss. Threshold voltage and leakage current that are inherent in MOS transistors significantly affect the performance of an RF AC to DC converter. A device with bulk connected to its drain improves the threshold voltage and leakage current. This work designs the half-wave and full-wave AC to DC converters with devices' bulk connected to source and devices' bulk connected to drain. The designs used the native devices in TSMC 0.18 micron CMOS technology, and were simulated using transient analysis in different process corners and operating temperatures. In simulations, the RF signal was represented by a sinusoidal input of 900 MHz frequency and of 390 mV amplitude. The sizes of transistors and the number of stages, of each converter, that resulted to highest power efficiency were determined via circuit simulations. The optimal design was a four-stage half-wave AC to DC converter with devices' bulk connected to drain, which produced a DC output of 2.7 V with 37.42 % efficiency at 100 kilo ohm load.

Keywords RF Energy Harvest, AC to DC Converter, Native MOSFET, Bulk-drain Connection

1. Introduction

Today's technology allows electronic devices to be operated at low input voltages. These low power devices can be used in many applications such as temperature sensors, pressure sensors, biomedical sensors and RFID systems. The battery can be used as a source for these low power devices; however, battery has finite life and need to be changed periodically. Harvesting environmental energy can extend the battery life and minimize cycle of disposing and replacing of battery. The RF signals carry a small amount of energy which can be stored in a battery to operate low power devices by means of RF energy harvesting device.

The input RF signal that will undergo RF to DC

conversion must have minimal loss and must be greater than the magnitude of the input signal. Schottky diodes are commonly exploited component in a RF to DC converter circuit [1]; however, production cost may increase because of the non-standard CMOS process [2]. An alternative solution for this problem is to use diode connected CMOS. The problem arises in using diode connected CMOS transistor is the threshold voltage of the transistor itself. The works of Mandal et al. [3] to Shokrani et al. [8] proposes several threshold cancellation techniques to minimize the effect of the turn on voltage of the CMOS device. In 2012, works of Lin et al. [7] exploited the use of native CMOS device in lowering the threshold voltage of the transistor. However, the drawback of using a low threshold voltage device is the increase in leakage current. This current should be minimized because it decreases the overall output voltage and efficiency of the circuit. A simpler leakage current prevention technique is used by Shokrani et al. [8] in which was done by connecting the bulk to the drain of MOS transistor.

This study aims to design an AC to DC converter for 900 MHz RF energy harvester circuit using Native CMOS device with proper connection of bulk. The second section presents a characterization of the threshold voltage and leakage current of native MOSFET devices in TSMC 0.18 um CMOS process. The third section is the design of an AC to DC converter base on multi stage half-wave rectifier using native CMOS device with bulk connected to source and bulk connected to drain. The fourth section of this paper is the design of AC to DC converter base on multistage full-wave rectifier with bulk connected to source and bulk connected to drain. It also includes the summary and the final design base on the gathered data.

2. Characterization of Threshold Voltage and Leakage Current of 0.18 Micron Native Nmos Devices

The transistors that were utilized in this work were characterized to determine the actual threshold voltage and the leakage current. The threshold voltage was determined through linear extrapolation technique [9]. The linear extrapolation method was done by measuring the drain current as a function of gate voltage.

The characterization procedure done in this work included the comparison of the threshold voltage and leakage current for the bulk connected to drain and bulk connected to source. According to Shokrani & et al. [8], the threshold voltage is minimized by connecting the bulk to the drain. The threshold voltage when the bulk of a MOS transistor was connected to drain at TT process corner and 25 °C varies from 54 mV to 74 mV while for bulk connected to source it varies from 56 mV to 76 mV as shown in Fig. 1.

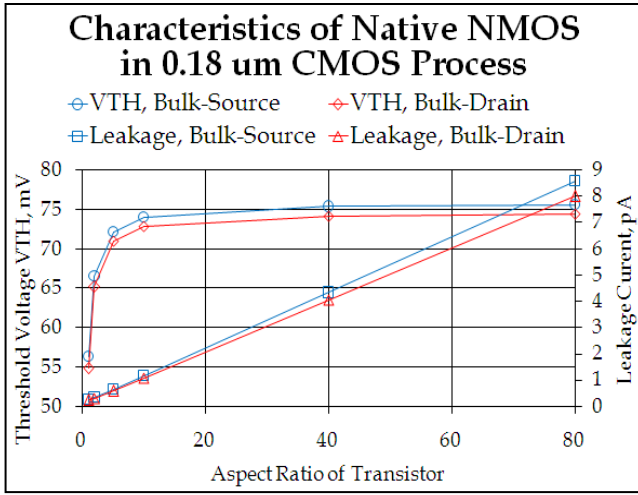


Figure 1. Threshold voltage and leakage comparison of native NMOS with bulk connected to source and bulk connected to drain at 20°C across TT process corner.

The lowering of threshold voltage was due to the reason that when a positive voltage is applied to the MOS transistor, the source to bulk voltage becomes negative as described in Equation 3 [8]. The works of Shokrani et al. [8] in 2012 also stated that the leakage current will be decreased when the bulk of the transistor is connected to the drain. This effect was graphically shown in Fig. 1 and can be described by Equation 2. During reverse bias region, the source to bulk voltage became positive resulting to an increase in threshold voltage V_{TH} .

$$V_{th} = V_{th0} + k_1(\sqrt{\varphi_s + V_{SB}} - \sqrt{\varphi_s}) + k_2 V_{SB} \quad (1)$$

$$I_{Reverse} = I_{Leakage} = I_{SO} \left(\frac{W}{L}\right) \left(1 - e^{-\frac{V_D}{V_T}}\right) (1 + \lambda_{sub} V_D) \quad (2)$$

3. Design of Ac-Dc Converter Using Multi-Stage Half-Wave Rectifier

The design of AC to DC converter based on multi-stage half-wave rectifier implemented the principle of voltage doubler. Moreover the design utilized the native CMOS device which is available in TSMC 0.18 um CMOS process and two bulk connections; bulk connected to source and bulk connected to drain. The source voltage for a 900 MHz frequency is set to 390 mV [10]. The design procedure is shown in Fig. 2 and the efficiency is computed by dividing the dc output power (P_{DC}) to the ac input power (P_{ac}) as shown in Equation 3.

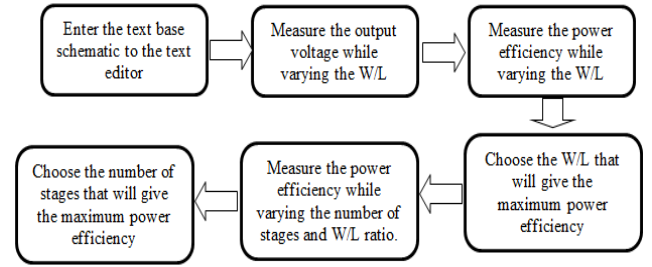


Figure 2. Design procedure for half-wave and full-wave AC-DC converter.

$$\eta = \frac{P_{DC}}{P_{ac}} \quad (3)$$

A simple RLC resonant circuit shown in Fig. 3 is connected at the input of the multi stage half wave rectifier design to improve the available voltage at the input of the rectifier and provide higher power transfer. This resonant circuit is tuned using Equation 4 and 5.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

$$\frac{V_{out}}{V_{in}} = \frac{1}{R} \sqrt{\frac{L}{C}} \quad (5)$$

To determine the maximum number of stages and optimum size of transistors to be used, the power efficiency is measured while adding stages and varying the width to length (W/L) ratio of the transistor. The length of the transistor is fixed at 0.5 um and the number of stages is varied from 1 to 10 stages. The circuit for n-stage AC to DC converter based on half-wave rectifier with bulk connected to source is shown in Fig. 4. The same procedure is followed in the design of n-stage AC to DC converter based on half-wave rectifier with bulk connected to drain.

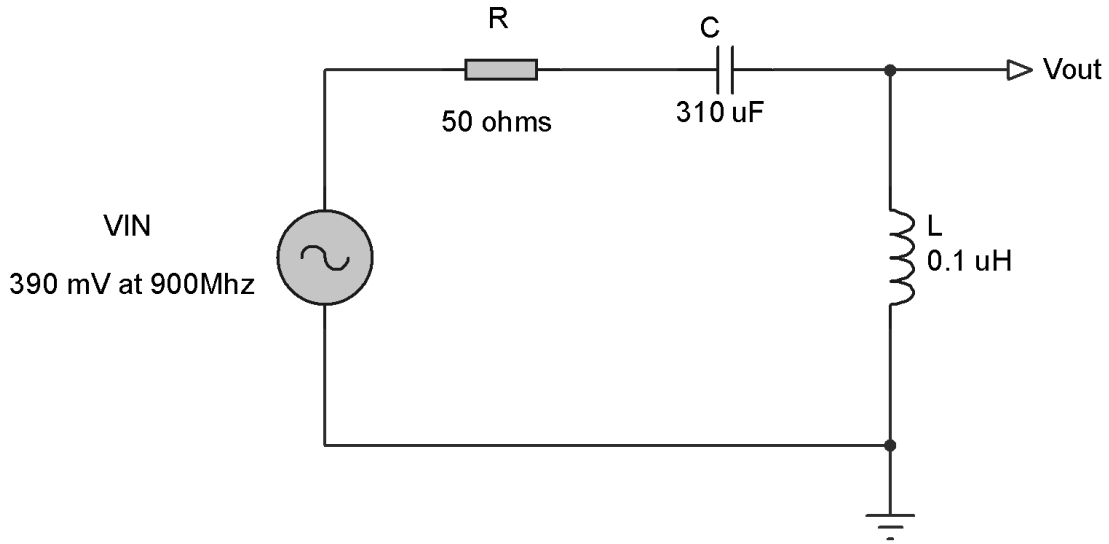


Figure 3. Impedance matching network.

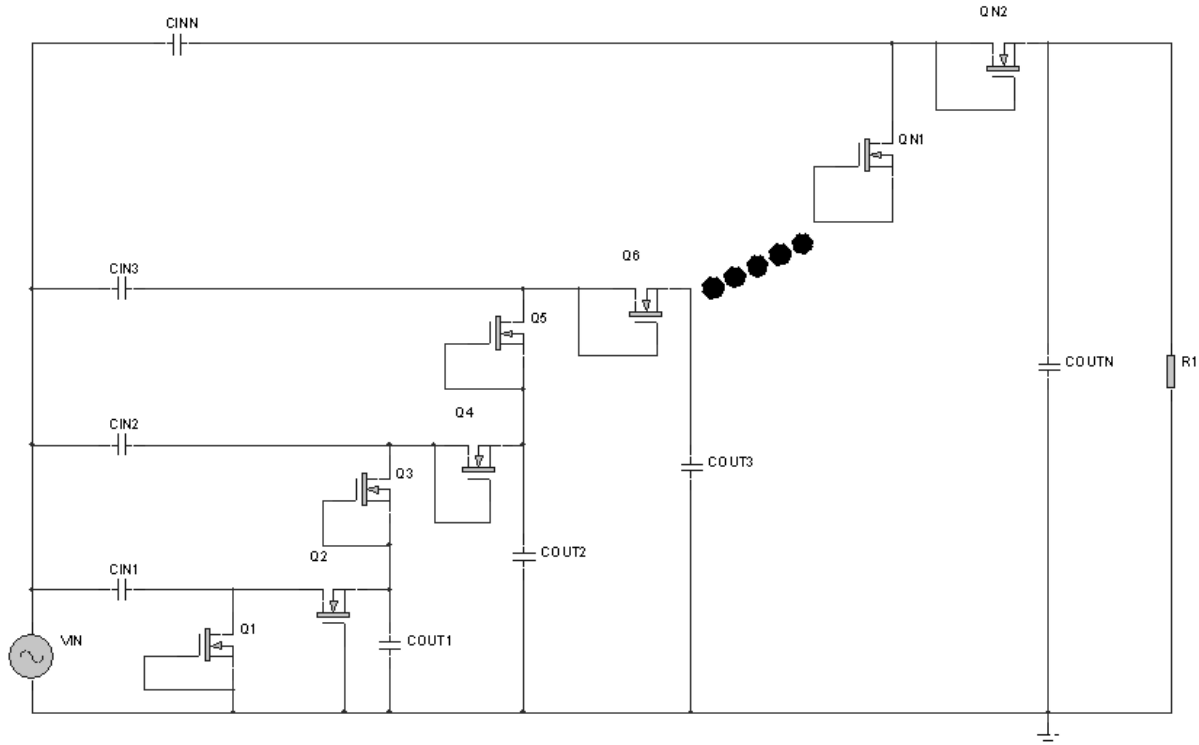


Figure 4. N-stage AC to DC converter based on multi-stage half-wave rectifier with bulk connected to source

As the stages were added to the design, the efficiency improves due to an increase in the DC output voltage but it reaches a maximum point and begun to decrease as shown in Table I. The transistors' efficiency peaks at 4 to 5 stages. Increasing the number of stages would result to an increase in the number of components, hence the power loss due to leakage current and super threshold region would also increase in proportion to the number of stages as describe in Equations 8, 9, and 10 [12]. P_{sub1} and P_{sub2} are the power due to subthreshold region, P_{sup} is the power due to superthreshold region and P_{leak} is the power loss due to

leakage current. In this case, a five stage with $W/L = 40$ was chosen in the design of half-wave multi-stage multiplier with bulk connected to source because it gives the maximum overall efficiency of 31.47 %, output voltage of 1.59 V, and output current of 0.57 uA at load of 100 kΩ.

$$\eta = \frac{P_{ON}}{P_{ON} + P_{LossN}} \tag{6}$$

$$P_{Loss} = P_{sub1} + P_{sup} + P_{sub2} + P_{leak} \tag{7}$$

$$P_{LossN} = N \times P_{Loss} \quad (8)$$

Table 1. Power efficiency and DC output voltage with varying stages, W/L = 40, Half-wave, bulk connected to source

Number of Stage	Power efficiency (%)	DC output Voltage (V)
1	1.14	0.4937
2	6.47	1.0308
3	17.84	1.5140
4	31.43	1.7621
5	31.47	1.5913
6	26.03	1.3838
7	21.10	1.2179
8	16.37	1.0803
9	13.30	0.9645
10	10.36	0.8657

Table 2 shows the result for the n-stage half-wave rectifier with bulk connected to drain. The optimum size in this case was a four stage circuit with W/L=20. It gives a maximum overall efficiency of 37.42% with output voltage of 2.7V and output current of 27.01 uA at load R1 = 100 kΩ.

Table 2. Power efficiency and DC output voltage with varying Stages, W/L=20, Half-Wave, Bulk connected to Drain

Number of Stage	Power efficiency (%)	DC output Voltage(V)
1	13.35	3.3312
2	28.88	3.6289
3	35.27	3.1282
4	37.42	2.10013
5	34.32	2.2678
6	30.78	1.9574
7	27.50	1.7258
8	23.88	1.5323
9	19.82	1.3604
10	17.44	1.2430

4. Design of Ac-Dc Converter Using Multi-Stage Full-Wave Rectifier

The design of the AC to DC converter based on multi-stage full-wave rectifier was based on the design of the half-wave AC to DC converter. An additional NMOS diode

connected MOS transistor circuit was used to allow conduction on the other half cycle.

Referring to Table 3, the efficiency increases as the second and third stage were added but started to drop when fourth and fifth stages were also added. The drop in efficiency was expected because of the power loss exhibited by the added transistors. The W/L ratio that gives the maximum efficiency is W/L=30 at 22.89 % efficient. It also gives an output voltage of 1.98 V and output current of 19.81 uA for load of 100 kΩ.

Table 4 shows the result for full-wave design with bulk connected to drain. The schematic is similar with Fig. 5 but the bulk connection was transferred to the drain. The W/L ratio that gave the highest efficiency and good amount of voltage was a three stage circuit with W/L=30 at 24.29 % efficient. It has an output voltage of 2.03 V and output current of 20.31 uA for load 100 kΩ.

Table 3. Power efficiency and DC output voltage with varying the number of stages, W/L = 30, Full-wave, bulk connected to source

Number of Stage	Power efficiency (%)	DC output Voltage (V)
1	19.47	0.8543
2	22.14	1.4645
3	22.89	1.9813
4	22.27	2.4157
5	21.42	2.7942

Table 4. Power efficiency and DC output voltage with varying the number of stages, W/L = 30, full-wave, bulk connected to drain

Number of Stage	Power efficiency (%)	DC output Voltage (V)
1	21.46	0.8716
2	23.74	1.4986
3	24.29	2.0307
4	23.48	2.4782
5	22.50	2.8684

5. Summary of Results

As a summary, Table 5 presents a performance comparison between half-wave and full-wave designs with bulk connected to source and bulk connected to drain. Based on the result of the study, a four stage half-wave rectifier with bulk connected to drain was implemented as the final design. The final schematic diagram of the design is shown in Fig. 5 and the complete specification is shown in Table 6.

Table 5. Summary of the results for both half – wave and full – wave AC to DC converter

Parameter	Half –Wave		Full –Wave	
	Bulk connected to source	Bulk connected to drain	Bulk connected to source	Bulk connected to drain
Number of Stages	4	4	2	2
DC Output Voltage	1.59 V	2.70 V	1.98 V	2.03 V
DC Output Current	0.57 uA	27.01 uA	1981 uA	20.31 uA
Output Power	25.57 uW	73.74 uW	39.35 uW	41.33 uW
Efficiency	31.47%	37.42%	22.89%	24.29%

Table 6. 4-Stage Half-Wave Rectifier as AC-DC Converter

Parameter	Half –Wave
	Bulk connected to drain
Number of Stages	4
Width	10 um
Length	0.5 um
DC Output Voltage	2.100 V
DC Output Current	27.01 uA
Output Power	73.74 uW
Input Voltage	390 mV
Efficiency	37.42%

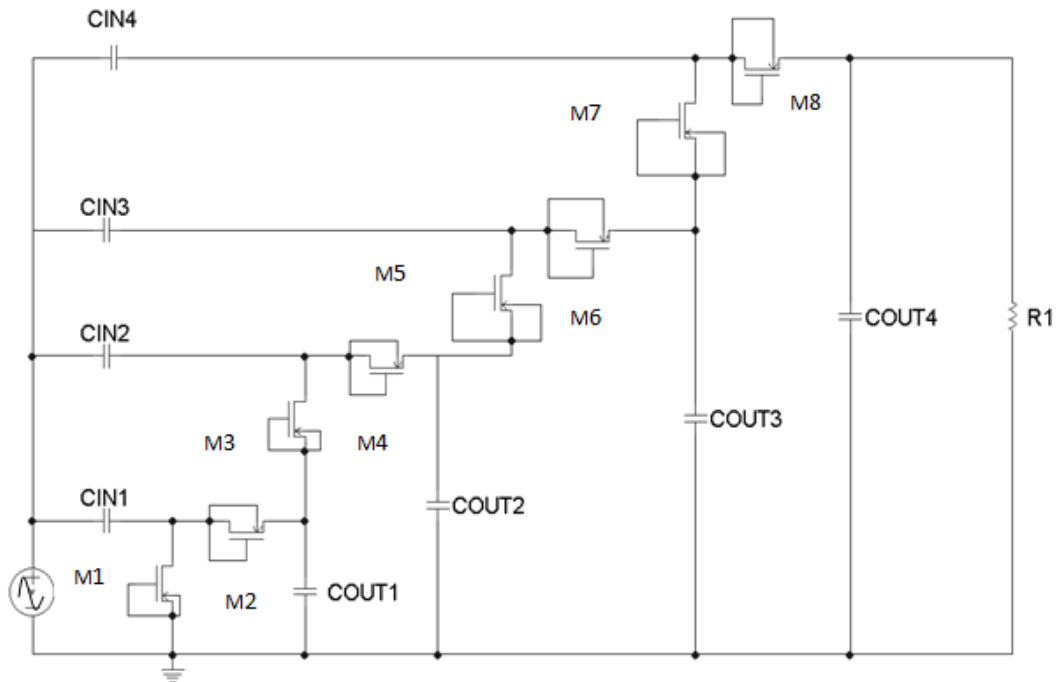


Figure 5. 4-stage half-wave AC-DC converter with bulk connected to drain

It can be seen in Fig. 6 that the sinusoidal input with frequency of 900 MHz and 390 mV peak produced DC output of 2.7 V. Moreover, the output has increased from 694 mV to 2.7 V, with average increment of 610mV per stage.

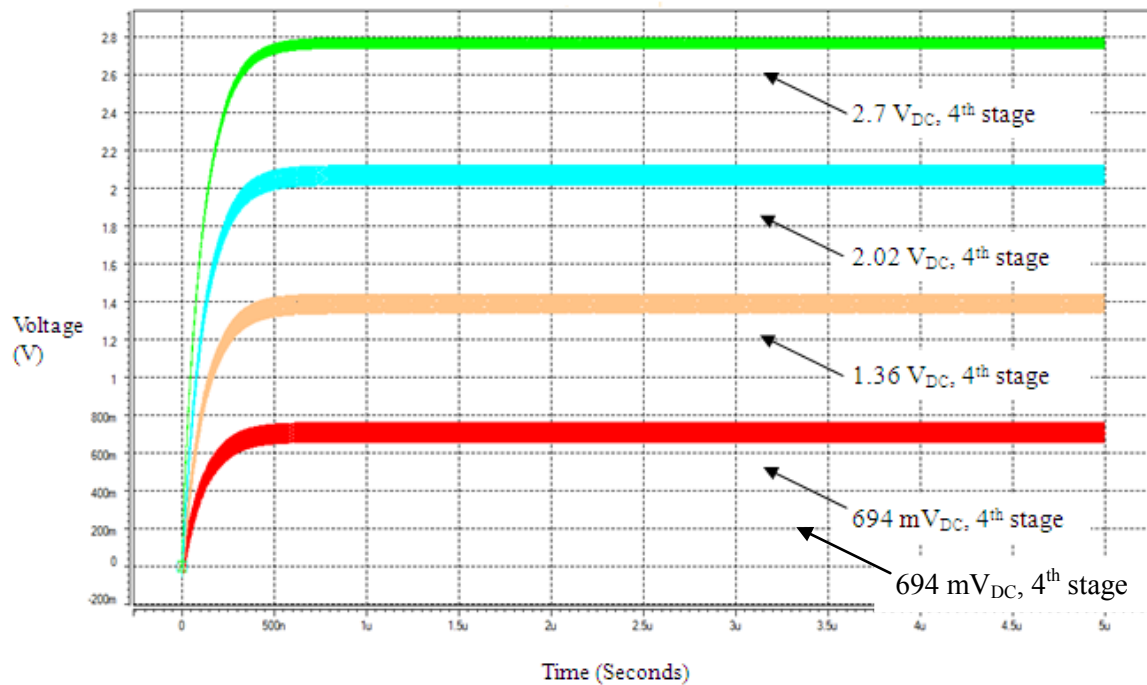


Figure 6. Output voltage across each stage of 4-stage half-wave AC-DC converter with bulk connected to drain

6. Conclusions

This work designed 900 MHz AC to DC converters using native devices in TSMC 0.18 micron CMOS technology. Native NMOS with bulk connected to drain yielded lower threshold voltages and lower leakage currents, as compared to native NMOS with bulk connected to source. At room temperature, typical process, and device size of 10, native NMOS with bulk-drain connection had 72.9 mV threshold and 1.08 pA leakage, while native NMOS with bulk-source connection had 74 mV threshold and 1.18 pA leakage. Four designs were implemented in this study, namely: (Design 1) multi-stage half-wave rectifier with bulk-source connected native devices, (Design 2) multi-stage half-wave rectifier with bulk-drain connected native devices, (Design 3) multi-stage full-wave rectifier with bulk-source connected native devices, and (Design 4) multi-stage full-wave rectifier with bulk-drain connected native devices. Input RF signal was simulated using 900 MHz and 390 mV sinusoidal voltages. Optimum number of stages in each design was determined, and simulations showed that highest efficiency was achieved in 4 stages for half-wave rectifiers and 2 stages for full-wave rectifiers. Among the four designs, the 4-stage half-wave rectifier with bulk-drain connection yielded the highest output of 2.7 V with highest efficiency of 37.42% at 100 k Ω .

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