LOW POWER HIGH PERFORMANCE VOLTAGE RECTIFIER FOR AUTONOMOUS MICROSYSTEMS

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Abstract: This paper reports on a highly efficient CMOS integrated full wave rectifier optimized for energy harvesting power generators. The rectifier is realized with two stages which can be fully integrated in a standard CMOS process without special process options. Using only the first stage in combination with a PMOS transistor connected as diode achieves an efficiency of approximately 50 %. Using an additional optimized low power active diode (AD) as second stage the efficiency rises up to 95 % and only a voltage drop of some 10 mV occurs. The input voltage amplitude range is between 1.8 V and 3 V and the overall power consumption of the rectifier is 1 µW @ 2 V input.

Key Words: CMOS rectifier, active diode, AC / DC converter

1. INTRODUCTION

Many power generators convert mechanical vibration energy into electrical energy [1,2]. Thus, the output is an alternating voltage which must be rectified before it can be used as power supply for electric circuits. The frequency of this input voltage is normally low, ranging from some 10 to some 100 Hz. Depending on the used generator the maximum values of the input amplitude diverse. Especially electro-magnetic micro generators deliver only small output voltages. If this alternating voltage is rectified with a discrete *pn*-diode a voltage drop of about 0.6 V occurs. Even Schottky diodes have voltage drops of about 0.3 V. Thus, the already small voltage of the generator is further reduced in the rectifier. Another disadvantage is the discrete realization. For small embedded autonomous microsystems (see Fig. 1) a full integrated solution should be preferred to reduce system volume and packaging effort.

Common CMOS integrated rectifiers have also a comparable voltage drop to discrete solutions. Due to this, the efficiency is in the low percentage range. If a diode or MOSFET based half way rectifier is used the efficiency of the rectifier is about 25 % because only every second half wave is used and a voltage drop occurs over the MOSFET. A full wave rectifier uses both half waves, but also has twice the voltage drop.

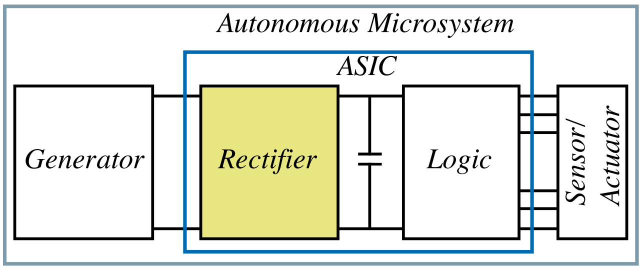

Fig. 1: Schematic of an autonomous micro-system with CMOS integrated rectifier.

The rectifier proposed in this paper uses a novel topology to convert the negative half waves into positive ones and an additional diode to avoid back flow of the current. If this diode is replaced with an active diode, nearly no voltage drop could be observed and very high power efficiencies are achieved.

2. CONVENTIONAL RECTIFIERS

Several conventional CMOS integrated rectifiers can be found in literature, e.g. [3]. Opposite to their discrete counterparts simple *pn* junctions are normally not used in the rectifiers. *pn* junctions are often not specified in forward direction in CMOS processes and they are not suited for higher frequencies, because of the large depletion region [4]. However, CMOS transistors connected as diodes are used instead. Transistors are well documented and suitable for high frequencies. The voltage drop over such a transistor diode is about the threshold voltage V_T of the used transistor. Attention must be given connecting the bulk contact of the transistor. A PMOS transistor is realized in an *n*-well and must always be connected to the highest potential to avoid leakage and latch-up effects. Due to this, a dynamic bulk regulation, consisting of two transistors, must be added. Fig. 2 shows a simple PMOS diode which work as a half wave rectifier with additional bulk regulation transistors.

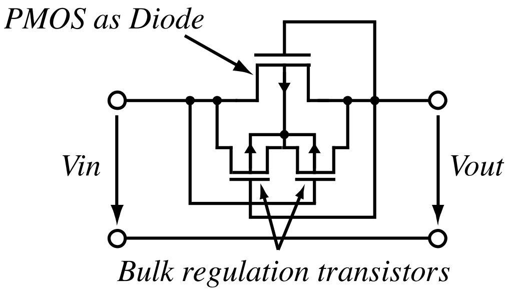

Fig. 2: Circuit diagram of a PMOS transistor connected as diode and the bulk regulation transistors.

3. PROPOSED RECTIFIER

The main goals of this novel rectifier are the reduction of the voltage drop over the MOSFETs and achievement of a high efficiency. This rectifier can be separated into two stages: (i) the negative voltage converter and (ii) the diode part (see Fig. 3).

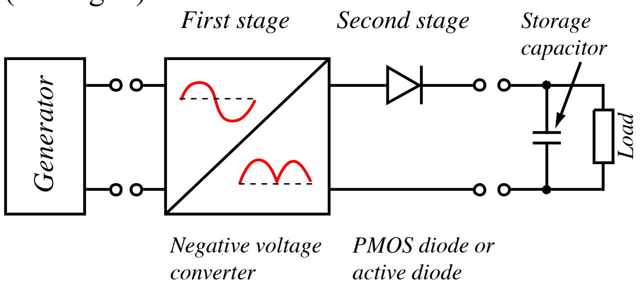

Fig. 3: Proposed two stage rectifier with first stage (negative voltage converter) and second stage (diode part).

3.1 First stage: Negative voltage converter

The first stage of the proposed rectifier circuit is used to convert the negative half waves of the input sinusoidal wave into positive ones. This conversion is done with only four standard CMOS transistors (Fig. 4). The left side is realized with PMOS transistors and always delivers the highest potential at *Vin* to node *A*. The right side consists of NMOS transistors and the low voltage potential is at point *B*. No additional dynamic bulk regulation transistors are necessary, because this is inherently given in this circuit. Thus, the bulk of the PMOS transistors can be directly connected to point *A* and the NMOS to point *B*. A high voltage potential at point *1* leads to the conducting stage of *MP1* and *MN2*. Thus current can flow from *1* over *MP1* to the output and then back to *2* over *MN2*. In the opposite voltage case *MP2* and *MN1* are conductive.

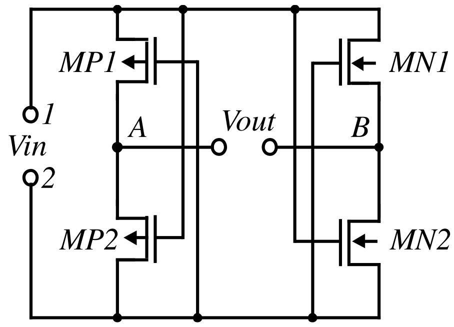

Fig. 4: Circuit diagram of the first stage (negative voltage converter).

The W/L ratio of the transistors depends on the expected current flow and on the CMOS process parameters. In our case a ratio of 400/2 µm is used.

In this implementation 3.3 V transistors are used. Care must be taken not to exceed the gate-oxide breakdown voltage or the maximum allowed source-drain voltage. This circuit has also been successfully simulated using 5 V and high voltage (20 V) transistors, which can withstand voltage peaks even from piezo-electric harvesters.

The minimum operating voltage of this circuit is determined by the threshold voltage of the used transistors. No threshold voltage drop V_T is seen between the input and the output of the first stage. The ability to convert nearly the entire voltage applied at the input to the output is the main advantage of this circuit. But it can not be used as a rectifier, because the current direction is not controlled. Thus, a capacitor can not be charged.

3.2 Second stage: Diode part

The main function of the second stage is to control the current direction. This could be in the simplest case a conventional MOSFET connected as diode as shown in Fig. 2. Using this, a full wave rectifier with only one voltage drop V_T results.

In order to achieve very high output voltages and high efficiencies the diode should be replaced by another element, the active diode (AD). This active diode works nearly as an ideal diode, with current flowing in only one direction and nearly no voltage drop. The main difference to an ideal diode is the current consumption of the device. A complex realization of an active diode is presented in [5]. The active diode presented in this paper is simpler and based on a fast and low power comparator circuit. Details about the comparator can be found in [6]. Fig. 5 shows a schematic of the active diode. *MP* is the switch which is controlled by the comparator. If the voltage at the *anode* is higher compared to the *cathode* the output of the comparator is 0 V and *MP* is turned on. If the *cathode* potential is higher the output is high and *MP* is nonconducting. The supply voltage of the comparator is taken from the storage capacitor. Using a PMOS transistor as switch no additional start-up circuit is necessary for this active diode.

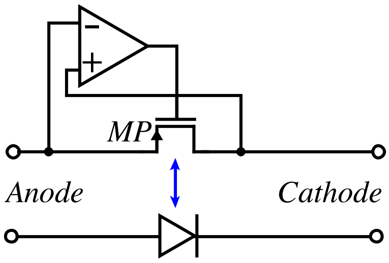

Fig. 5: Circuit diagram of the proposed active diode (AD) with comparator and switch MP.

However, the active diode can work on its one as an efficient one wave rectifier. Combining both stages a full wave rectifier with the same power consumption can be realized.

4. PERFORMANCE

The main aspects of rectifiers are the maximum output voltage which can be reached for a given input voltage and the efficiency, which is simply the quotient of the output and the input energy over one period (see equ. 1).

$$Eff = \frac{\int u_{out} i_{out} dt}{\int u_{in} i_{in} dt} \qquad (1)$$

The circuits have been simulated with Cadence using a 0.35 µm HV CMOS process from *austriamicrosystems*. The voltage and efficiency values strongly depend on the used frequency, storage capacitor and ohmic load. For these simulations the frequency is 100 Hz, a capacitance of 5 µF and a load of 20 kΩ are used. The power consumption of the comparator is also important for the overall efficiency of the rectifier. The power consumption is 1 µW @ 2 V input and the comparator works up to a frequency of 10 kHz.

4.1 Output voltage and efficiency

The maximum achievable output voltage is very important especially for energy harvesting applications. Fig. 6 shows the input and the output wave form of different rectifiers. The efficiency over the input amplitude is shown in Fig. 7.

A simple PMOS transistor connected as a diode shows a large voltage drop and only every second half wave is used. In combination with the first stage every half wave is used. If the PMOS diode is replaced with the active diode a strong increase of the output voltage can be observed. The voltage drop is only some 10 mV.

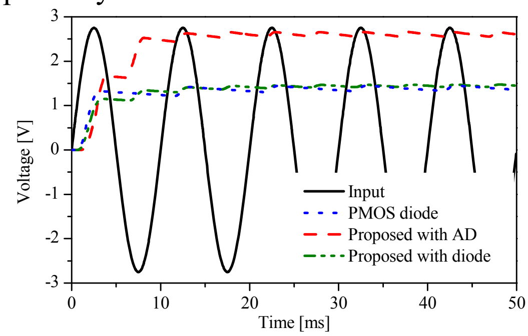

Fig. 6: Input and output wave forms of different rectifiers.

The calculated efficiency versus the input amplitude for these rectifiers is plotted in Fig. 7. The efficiency increases with increasing input amplitude, because the voltage drop over the PMOS diode is nearly constant. Thus, the output voltage increases. Using the proposed first stage the efficiency is nearly doubled, because every half wave is now rectified. This stage in combination with the active diode shows an efficiency of about 90 %. The maximum efficiency is around 2.5 V input amplitude. At lower voltages the comparator has less current and thus, is slower which reduces the efficiency. At high input voltages the comparator is very fast, but consumes more energy. As the current is taken from the storage capacitor the overall efficiency is reduced.

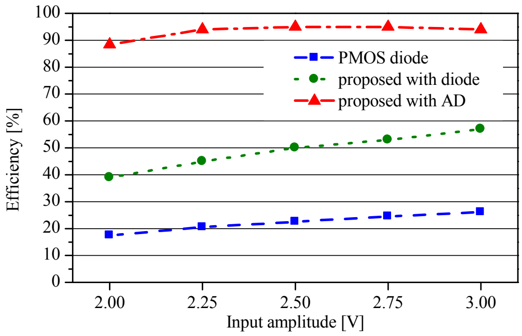

Fig. 7: Efficiency of different rectifiers versus the input amplitude.

5. MEASUREMENTS

The rectifiers are fabricated in a 0.35 µm CMOS process from *austriamicrosystems* [7]. Fig. 8 shows the layout of the proposed rectifier with first stage, switch and the comparator. On the right side is a micrograph of the CMOS chip.

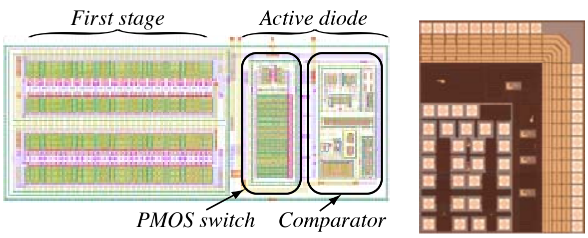

Fig. 8: Layout of the proposed rectifier (250 x 100 µm²) and micrograph of the CMOS chip.

Fig. 9 shows the measured input and output wave form of the active diode. The input amplitude is 2 V. The detail view on the right side shows a negligible voltage difference between the input and the output. Also a small voltage drop of the input voltage can be observed when the comparator turns on the switch to load up the storage capacitor.

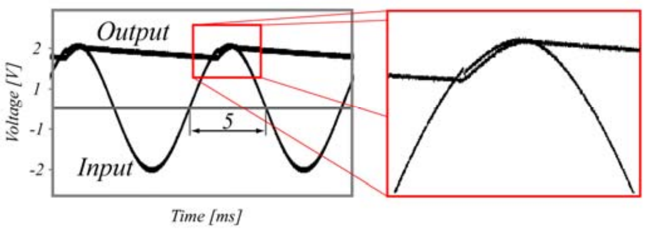

Fig. 9: Measured input and output wave form of the active diode.

6. CONCLUSION

A novel rectifier concept consisting of a voltage converter and an active diode was presented. No additional bulk regulation transistors are needed and nearly the entire input voltage appears at the output. In combination with a MOSFET diode the efficiency is about 50 %. In combination with an active diode efficiencies over 90 % can be reached. The maximum output voltage is only a few 10 mV below the input voltage.

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