Comparative study of RF energy harvesting rectifiers and proposal of output voltage universal curves for design guideline

Toru Nakura\textsuperscript{1}, Hiroaki Matsui\textsuperscript{2}, and Kunihiro Asada\textsuperscript{1}

\textsuperscript{1} VLSI Design and Education Center (VDEC), The University of Tokyo, 2–11–16 Yayoi, Bunkyo-ku, Tokyo 113–0032, Japan
\textsuperscript{2} Dept. of Electronic Engineering, The University of Tokyo, 7–3–1 Hongo, Bunkyo-ku, Tokyo 113–8654, Japan
a) nakura@vdec.u-tokyo.ac.jp

Abstract: This paper studies rectifier circuits for RF energy harvesting based on Dickson charge pump. The best configuration of rectifiers is found that the body terminals of FETs are connected to their drains. Its performance is particularly superior when the load resistance is relatively higher. We also studied some derivative circuits, where the gate terminals are connected not to the own drains but the drains of the second neighbor FETs. In addition to this, we propose a new design guideline for determining the optimal rectifier parameters based on the output voltage universal curve. It helps us to find the optimum rectifier design parameters depending on the specification of the application targets.

Keywords: energy harvesting, rectifier, universal curve

Classification: Integrated circuits

References

1 Introduction

Energy harvesting is the idea to collect weak energies of the surrounding environment, such as vibration, heat, light, radio waves, and so on, and to use those as a power source. This concept can be applied to realize the battery-less sensors. When using sensors to make wireless sensor networks (WSNs), life time of batteries is a serious problem because it is troublesome and expensive to replace a lot of sensor batteries. Moreover, if WSNs are installed in human bodies to monitor their health conditions or installed in high places to monitor the strength of a bridge, for example, replacing batteries can be dangerous or impossible. By using battery-less sensors with energy harvesting, we can save energy and reduce the cost for preservation of sensors so that the system life cycle can be extended [1].

We focused on RF energy harvesting using radio waves among energy sources since radio waves are ubiquitous here and there and easy to gather recently. Fig. 1 shows a rough mechanism of a wireless sensor using RF energy harvesting [2, 3], where radio waves received by an antenna are converted into a form that electrical circuits can use as a power. The system is composed of a rectifier and a DC-DC converter. A rectifier is a key component to convert AC radio waves into a DC voltage, and here we especially focus on the one for a startup circuit that needs high output voltage rather than high power efficiency. This paper compares several types of rectifiers for optimization of the rectifier circuit parameters in terms of high output voltage under the same induced antenna voltage. Furthermore, this paper proposes a new design guideline for the optimization.

2 Dickson charge pump and its derivative circuits

In order to convert AC power received by an antenna into DC power, a rectifier of Dickson charge pump [4] shown in Fig. 2 is often used. It is composed of diode connected transistors, coupling capacitors, a load capacitor, and two opposite phase

Fig. 1. Structure of the wireless sensor using RF energy harvesting that converts AC radio waves into a DC voltage source.

Fig. 2. Schematic of a Dickson charge pump that is composed of multi-stage diode connected MOS FETs and capacitors.
AC input powers. Here, one of the input powers is usually grounded. Circuit behavior of Dickson charge pump is: at first, diode-connected transistors whose drain and gate terminals are connected to input1 indirectly through coupling capacitors C become ON when input1 is higher than input2. Then, the charge of the coupling capacitors connected to input1 flows to the capacitors connected to input2 through the ON transistors, and the electric potential of the input2 capacitors is increased. Next, when input2 becomes higher than input1, the voltage of input2 and the voltage generated in the capacitors are added and increased. Repeating this charge and discharge process, the output voltage is increased more and more as the circuit node approaches to the final output voltage. Finally, the load capacitance $C_L$ stores the power as the output voltage that can be used as a DC power source.

There are two major problems of reducing the maximum output voltage of rectifiers: forward voltage drop and reverse current. When current flows through the diode-connected transistors, the source voltage experiences the threshold voltage ($V_{th}$) drop to the drain voltage. It is more obvious when $V_{th}$ is high. On the other hand when $V_{th}$ is too low, reverse current flows through the diode connected transistors. As the lower threshold voltage, the more reverse current tends to flow.

As just mentioned, there is a deep relation with the performance of the rectifier and the threshold voltage of the transistors. Seen in Fig. 3, in order to obtain the maximum output voltage from the rectifier, it is necessary to appropriately adjust the threshold voltage, not too low as well as not too high [5]. However, no external power supply can be used in RF energy harvesting, and thus it is difficult to control the threshold voltage and keeping it in an appropriate condition.

In order to overcome these problems, a rectifier based on Dickson charge pump which utilizes the body bias effect was developed [6]. The diode connected transistors are body-isolated using deep Nwell and their body terminals are connected to their drain terminals as shown in Fig. 4(c). The other parts are the same as the conventional Dickson charge pump as in Fig. 4(a). As a result of this connection, body bias effect makes threshold voltage lower in forward direction, and makes it higher in reverse direction. Moreover, this dynamic threshold voltage control needs little energy.

In order to verify the effectiveness of this body-drain connected rectifier, we compared three types of rectifiers, whose body connection are described in Fig. 4,
by HSPICE transient simulations with the default accuracy setting. Note that we run the SPICE simulations only on schematics, and the results do not take the Nwell related parasitic capacitance into account.

3 Simulation method and results

3.1 Simulation model and optimum configuration detection

Being viewed from the output side, equivalent circuit of Dickson charge pump at steady state is simply represented by the series connection of the internal resistance $R_{PMP}$ and voltage source $V_{PMP}$, and it is connected to the load resistance $R_L$. In order to realize the maximum efficiency, we can increase $V_{PMP}$ as much as possible and equalizing $R_{PMP}$ to $R_L$ for impedance matching.

Design parameters of the charge pump include the number of transistors (stages) $n$, the ratio of the transistor gate length $L$ and the gate width $W$. When the number of stages becomes larger, output voltage is more increased and $V_{PMP}$ becomes higher. However, with too many transistors, $R_{PMP}$ becomes too large and the pump performance deteriorates. The same is true for $W/L$. If $W/L$ becomes larger, on-resistance of the transistors become smaller and appropriate impedance matching becomes difficult.

In order to determine the optimum $n$ and $W/L$, we run lots of simulations. The simulation conditions are shown in Fig. 5. Input AC amplitude, $C$, $C_L$ and $L$ are fixed. In addition to this, the antenna resistance $R_A$ is inserted between the input power source and the coupling capacitors. Their values are as follows: AC peak amplitude is 50 mV, AC frequency is 539 MHz (frequency of Japanese television broadcast), $C$ is 500 fF, $C_L$ is 10 pF, $R_L$ is described later, $L$ is 60 nm which is the minimum size of our transistor process and $R_A$ is 50 Ω. $W$ and $n$ are swept under this condition, and we plot the final output voltage in each case. The values of $W$ are swept to 0.5 µm, 2.5 µm, 5 µm, 7.5 µm, ..., 42.5 µm, 45 µm. The values of $n$ are swept to 8, 12, 16, ..., 48. Table I shows the device parameters of the transistors used in this simulation.

![Fig. 4. Three types of body connection on rectifiers. Body terminals of type(c) is connected to their drain terminals, so the body bias improves both the forward current increase and the reverse current reduction [6].](image)

![Fig. 5. Simulation conditions. Input AC voltage and so on are fixed and the gate width and the number of the transistors are swept.](image)
One of the examples of the simulation results when $R_L = 400$ kΩ is shown in Fig. 6. It shows that the output voltage changes depending on $W$ and $n$. The output voltage is highest when $W$ is $32.5$ µm and $n$ is 40, so we recorded the condition with its maximum output voltage. The power efficiency of this point is not the highest and this condition does not suit to provide energy to the main circuits. However, high output voltage is more important than the high efficiency when using this rectifier as a start-up circuit. So we compare rectifiers from the viewpoint of the maximum output voltage, not of the maximum power efficiency.

We repeated this process sweeping $R_L$ to be 40, 50, ..., 90, 100, 200, ..., 900, 1000, 2000, 3000, and 4000 [kΩ], and recorded the maximum output voltage at each $R_L$. Note that in practical RF energy harvesting, an impedance matching circuit is connected between the input AC source and the rectifier in order to make the antenna impedance as the same as the input impedance of the rectifier so as to maximize the power efficiency. This input impedance adjusting role is substituted by changing $W$ and $n$.

### 3.2 Simulation results

With the method described above, we designed three types of rectifier whose body connections are different as shown in Fig. 4. Comparison results of those are shown in Fig. 7. Solid lines are the maximum output voltage of each $R_L$ when $W$ and $n$ are optimally tuned. The dotted lines are area of the optimally designed charge pump, sum of the MOS-caps and transistors area (note this does not include wiring area and deep Nwell area). When $R_L$ is small, there is no much difference in the maximum output voltage. On the other hand, when $R_L$ is large or when the output voltage is large, type(c) puts out better results than the other methods.

<table>
<thead>
<tr>
<th>Table I. Transistor parameters of 65 nm FD SOI CMOS</th>
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<tbody>
<tr>
<td><strong>SiO₂ thickness</strong></td>
</tr>
<tr>
<td>$V_{th}$ (no back bias)</td>
</tr>
<tr>
<td>$V_{DD}$</td>
</tr>
</tbody>
</table>

![Fig. 6.](image) Simulation results of the output voltage depending on the number of stages and the gate width. The maximum output voltage is obtained when $W = 32.5$ µm and $n = 40$. 
In order to realize better rectifier performance, threshold compensation method is combined with the body connection which utilizes the back bias effect. By connecting the gate terminal with drain terminals of second neighbor transistors, a higher voltage with the same phase of the original voltage is applied to the gate terminal and apparent threshold voltage becomes lower [7]. In the original paper, back gate of transistors are connected to their source terminals, however we think it is better to connect those to the drain terminals. So type(e) in Fig. 8 is proposed in this paper. For a reference, type(d) of the grounded body is prepared in addition to type(a)–(c) in Fig. 4. The way to determine the parameters of these rectifiers is the same as the one explained in the previous subsection.

Comparison of the simulation results among type(c), (d), (e) are shown in Fig. 9. Though both (d) and (e) applies threshold-compensated technique [7], only (e) connecting its body to drain, exceeds (c) when the load resistance is relatively high. From this result, body connecting technique of [6] is found to be more effective when combined with the threshold-compensated technique of [7].

Some comparison results are extracted and listed in Table II, where maximum output voltage value and ratio to the type(a) of the conventional rectifier are shown. When the load resistance is large, both (c) and (e) are much better than the conventional one, for example, (c) is 128% of (a) and (e) is 135% of (a) with the load resistance 4000 kΩ. On the other hand, when the load resistance is small, (e) is still better than (a), but (c) is almost the same as (a). And (d) is relatively better than (a) with the load resistance 40 kΩ, but is as the same as (a) and worse than (c) when the load resistance is 4000 k. In summary, type(e) is the best.

![Simulation results among type(a), (b), and (c). Solid lines show the maximum output voltage of each load resistance. Dotted lines show the area of the rectifiers at the conditions of the optimal. Type(c) is the best especially when the load resistance is large.](image)

**Fig. 7.** Simulation results among type(a), (b), and (c). Solid lines show the maximum output voltage of each load resistance. Dotted lines show the area of the rectifiers at the conditions of the optimal. Type(c) is the best especially when the load resistance is large.

### 3.3 Proposal of new configuration

In order to realize better rectifier performance, threshold compensation method is combined with the body connection which utilizes the back bias effect. By connecting the gate terminal with drain terminals of second neighbor transistors, a higher voltage with the same phase of the original voltage is applied to the gate terminal and apparent threshold voltage becomes lower [7]. In the original paper, back gate of transistors are connected to their source terminals, however we think it is better to connect those to the drain terminals. So type(e) in Fig. 8 is proposed in this paper. For a reference, type(d) of the grounded body is prepared in addition to type(a)–(c) in Fig. 4. The way to determine the parameters of these rectifiers is the same as the one explained in the previous subsection.

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![The gate terminals are connected to the drain terminals of the second neighboring transistors, where voltage phase is the same as the original drain and the DC voltage is higher.](image)

**Fig. 8.** The gate terminals are connected to the drain terminals of the second neighboring transistors, where voltage phase is the same as the original drain and the DC voltage is higher.
When designing the rectifiers, we decided the antenna resistance $R_A$ to be 50 $\Omega$ and the coupling capacitance $C$ is 500 fF in section 3. However, these design parameters, including the load resistance and required output voltage, may vary depending on RF energy harvesting applications and circumstances. If these parameters can be unified, there is no need to redo the tedious design simulations in order to optimize the rectifier depending on the situation. To make this realize, we deeply analyzed the simulation results. We designed a type(c) rectifier under the same conditions as section 3 (AC peak amplitude is 50 mV, frequency is 539 MHz and $C_L = 10$ pF), except the values of the antenna resistance $R_A$ and the coupling capacitance $C$. Sets of $(R_A, C)$ are $(R_A = 5 \Omega, C = 1000$ fF), $(R_A = 50 \Omega, C = 100$ fF), $(R_A = 500 \Omega, C = 10$ fF), $(R_A = 50 \Omega, C = 1000$ fF), and $(R_A = 500 \Omega, C = 100$ fF). These sets are chosen to make the product of $R_A$ and $C$ be constant. The product of first three sets is 5 ps and that of the rest two sets is 50 ps. In Fig. 10, the maximum output voltage of those rectifiers are shown, and the horizontal axis shows the load resistance $R_L$. All lines seem to have no relationship at the first

### Table II. Output voltage values and ratios

<table>
<thead>
<tr>
<th>$R_L$ (k$\Omega$)</th>
<th>40 k$\Omega$</th>
<th>400 k$\Omega$</th>
<th>4000 k$\Omega$</th>
</tr>
</thead>
<tbody>
<tr>
<td>type (a)</td>
<td>80 mV (100%)</td>
<td>378 mV (100%)</td>
<td>938 mV (100%)</td>
</tr>
<tr>
<td>type (b)</td>
<td>67 mV (83%)</td>
<td>344 mV (91%)</td>
<td>997 mV (106%)</td>
</tr>
<tr>
<td>type (c)</td>
<td>82 mV (102%)</td>
<td>417 mV (110%)</td>
<td>1199 mV (128%)</td>
</tr>
<tr>
<td>type (d)</td>
<td>91 mV (113%)</td>
<td>400 mV (106%)</td>
<td>963 mV (103%)</td>
</tr>
<tr>
<td>type (e)</td>
<td>95 mV (118%)</td>
<td>464 mV (123%)</td>
<td>1270 mV (135%)</td>
</tr>
</tbody>
</table>

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**Fig. 9.** Simulation results among type(c)(d)(e). Type(e) is the best.

**Fig. 10.** Maximum output voltage of each conditions by showing the horizontal axis as the load resistance.

### 4 Output voltage universal curves

When designing the rectifiers, we decided the antenna resistance $R_A$ to be 50 $\Omega$ and the coupling capacitance $C$ is 500 fF in section 3. However, these design parameters, including the load resistance and required output voltage, may vary depending on RF energy harvesting applications and circumstances. If these parameters can be unified, there is no need to redo the tedious design simulations in order to optimize the rectifier depending on the situation. To make this realize, we deeply analyzed the simulation results. We designed a type(c) rectifier under the same conditions as section 3 (AC peak amplitude is 50 mV, frequency is 539 MHz and $C_L = 10$ pF), except the values of the antenna resistance $R_A$ and the coupling capacitance $C$. Sets of $(R_A, C)$ are $(R_A = 5 \Omega, C = 1000$ fF), $(R_A = 50 \Omega, C = 100$ fF), $(R_A = 500 \Omega, C = 10$ fF), $(R_A = 50 \Omega, C = 1000$ fF), and $(R_A = 500 \Omega, C = 100$ fF). These sets are chosen to make the product of $R_A$ and $C$ be constant. The product of first three sets is 5 ps and that of the rest two sets is 50 ps. In Fig. 10, the maximum output voltage of those rectifiers are shown, and the horizontal axis shows the load resistance $R_L$. All lines seem to have no relationship at the first
glance, however, replacing horizontal axis with the quotient of $R_L$ divided by $R_A$, graphs with the same $R_A C$ value depict a single line as seen in Fig. 11.

In this way, with normalizing $R_L$ by $R_A$, it is possible to draw the output voltage universal curve for each $R_A C$. If the sufficient number of these curves are drawn, selecting the curve of $R_L$ and the output voltage is the only necessary task for the rectifier optimizations.

5 Conclusions

In this paper, we compared rectifier circuits based on Dickson charge pump by SPICE simulation and the best configuration of rectifiers is confirmed that the body terminals of FETs are connected to their drains. This configuration utilizes body bias effect to overcome the disadvantages of a Dickson charge pump. When the load resistance is relatively higher, performance of the best circuit is particularly better than the others because high output voltage provides a positive impact to its body bias effect while a negative impact to the body bias effect of other types. We also studied new derivative circuits of the best configurations that the gate terminals are connected not to their own drain terminals but to their second neighbor transistors. Its performance is better than the others even when the load resistance is not high.

In addition to this, we are proposing a new design guideline for determining the optimal design parameters of rectifiers by using output voltage universal curves. It helps us to find the optimum rectifier design parameters depending on the specification of the application targets, without difficulties to re-find parameters by tedious SPICE simulations.

Fig. 11. Maximum output voltage of each conditions by showing the horizontal axis as the load resistance normalized by the antenna resistance. If the product of the antenna resistance and the coupling capacitance is constant, a single line, the universal curve, is drawn.