New active diode with bulk regulation transistors and its application to integrated voltage rectifier circuit

Ryoichi Miyauchi¹, Koichi Tanno², Hiroki Tamura³

¹Interdisciplinary Graduate School of Agriculture and Engineering, University of Miyazaki, Japan
²Department of Electrical and Systems Engineering, Institute of Education and Research for Engineering, University of Miyazaki, Japan
³Department of Environmental Robotics, University of Miyazaki, Japan

ABSTRACT

This paper describes new active diode with bulk regulation transistors and its application to the integrated voltage rectifier circuit for a biological signal measurement system with smartphone. The conventional active diode with BRT has the dead region which causes leak current, and the output voltages of the application (e.g. voltage rectifier circuit) decrease. In order to overcome these problem, we propose new active diode with BRT which uses the control signal from the comparator of active diode to eliminate the dead region. Next we apply the proposed active diode with BRT to the integrated voltage rectifier circuit. The proposed active diode with BRT and voltage rectifier circuit were fabricated using 0.6 µm standard CMOS process. From experimental results, the proposed active diode with BRT eliminates the dead region perfectly, and the proposed voltage rectifier circuit generates +2.86 V (positive side) and -2.70 V (negative side) under the condition that the amplitude and frequency of the input sinusoidal signal are 1.5 V and 10 kHz, respectively, and the load resistance is 10 kΩ.

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Corresponding Author:

Koichi Tanno,
Department of Electrical and Systems Engineering,
Institute of Education and Research for Engineering,
University of Miyazaki,
1-1 Gakuenkibanadai-Nishi, Miyazaki 889-2192, Japan.
Email: tanno@cc.miyazaki-u.ac.jp

1. INTRODUCTION

Improving the quality of life and increasing healthspan is become global concern and challenges, therefore, measuring the own vital data is necessary for management of health on a daily basis. Many researchers focus on realizing the biological signal measurement systems [1]-[7]. Our research group tries to realize the battery less measurement system for biological signals by using a smartphone. This system positively use the function of a smartphone, which are the earphone output and the microphone input with A/D converter. In detail, the conditioning of the biological signal is done by an amplifier and filter, and this signal is inputted through the microphone terminal of the smartphone. This analog signal is converted to digital signal by A/D converter built-in a smartphone and this signal is analyzed by the application program on the smartphone. On the other hand, the outer circuits for conditioning the analog signal are needed the supply voltage. The supply voltages are generated by the smartphone as follows. The sinusoidal signals are generated by application program on the smartphone and its signals are outputted through the earphone terminal. These sinusoidal signals (AC signals) are converted to DC voltages using a voltage rectifier circuit designed by our research group. The voltage rectifier circuit consists of diodes, and in many cases, the parasitic diodes of MOSFET are used for integrated version. In this way, the proposed system can be fabricated using conventional CMOS process.
connected to signal conditioning circuits through the earphone and microphone terminals only. However, the conventional voltage rectifier circuit has disadvantages. The diodes have a potential barrier which is approximately 0.7 V, therefore, using parasitic diodes is difficult to apply for the low voltage applications. Furthermore, in the case of using the parasitic diodes of MOSFET, the bulk terminal of MOSFET should be connected to $V_{SS}$ (or lowest voltages of the circuit), however, since the input of the parasitic diodes of MOSFET is sinusoidal signal in many cases, the polar of the input signal is changed every second. In order to these problems, the active diode with bulk regulation transistors (BRT) was proposed [8]-[10]. However, the conventional active diode with BRT has the dead region that the output voltage is indeterminate value. Therefore, the leak current is occurred in the conventional active diode with BRT. As the results, the performance of the application circuit using the conventional active diode with BRT such as the operation range, current consumption etc degrades.

In this research, we propose new active diode with BRT firstly. The proposed active diode with BRT can be realized adding an inverter to conventional one and has no dead region. Next, we propose the new integrated voltage rectifier circuit using the proposed active diode with BRT. The proposed circuits were implemented by using 1-poly, 3-metal, single n-well, 0.6 $\mu$m CMOS process. The effectiveness of the proposed circuits are shown in this paper through the experimental results.

2. CONVENTIONAL ACTIVE DIODE WITH BRT

Figure 1 shows the circuit schematic of conventional active diode with BRT which is consisted of three MOSFETs and one comparator [8]-[10]. The operation of the active diode with BRT shown in Figure 1 is different in the two voltage ranges that are $V_A > V_B$ and $V_A < V_B$, where $V_A$ is terminal voltage of A and $V_B$ is terminal voltage of B.

In the case of $V_A > V_B$, the terminals A and B are become the source and drain terminals respectively. As the results, the output of comparator becomes high, then $M_1$ turns off, and $M_2$ and $M_3$ turn on and off respectively. Therefore the terminal C is connected to terminal A (it is indicated the bulk of $M_1$ connect to own source terminal). In the case of $V_A > V_B$, the terminals A and B are become the drain and source terminals respectively. As the results, the output of comparator becomes low, then $M_1$ turns on, $M_2$ and $M_3$ turn off and on respectively. Therefore, the terminal C is connected to own source terminal.

From the above explanation, the terminal C, which is bulk terminal of $M_1$, is always connected to own source terminal. In this way, the leak current through the bulk terminal (the parasitic diodes of $M_1$) can be prevented. That is to say, the conventional active diode with BRT behaves like a diode with the threshold voltage of 0 V.

However, the conventional active diode with BRT shown in Figure 1 has a problem in the switching operation of $M_2$ and $M_3$. Because Vin is AC signal (sinusoidal wave), $M_j$ and $M_l$ operate not only stable states of ON and OFF but also in the transitional region (dead region) which is not ON and OFF states. That is to say, the voltage of terminal C ($V_C$) is an indeterminate value in the dead region and the dead region is depend on the threshold voltage of MOSFET ($V_T$).

![Figure 1. Conventional active diode with BRT](image)

3. PROPOSED ACTIVE DIODE WITH BRT

Figure 2 shows the circuit schematic of the proposed active diode with BRT. In order to overcome the dead region, the output of the comparator ($V_{comp}$) is used for the switching signal of $M_2$ and $M_3$ because
Vcomp does not output a voltage in the dead region but outputs the digital signal of High (\(V_{DD}\)) or Low (\(V_{SS}\)). In the actual design, an inverter is added for the switching control of \(M_2\), as shown in Figure 2.

The operation of the proposed active diode with BRT is almost same with conventional one. The differential of the operation of the proposed and conventional circuits is switching of BRT. Vcomp is a digital signal, therefore the gate voltages of \(M_2\) and \(M_3\) are also digital signal. As the results, \(M_2\) and \(M_3\) turn ON or OFF in the moment. In this way, we can overcome the dead region problem.

![Figure 2. Proposed active diode with BRT](image)

4. APPLICATION TO INTEGRATED VOLTAGE RECTIFIER CIRCUIT

Figure 3 shows the circuit schematic of the conventional voltage rectifier circuit [8]-[10]. This circuit has two functions; one is conversion of the AC voltages to the DC voltages and the other is voltage doubler. Therefore, the output voltage of this circuit becomes the twice DC voltage of the amplitude of the input sinusoidal signal ideally. As shown in Figure 3, the circuit consists of four diodes and four capacitors. This circuit operates as follows. \(D_1\) and \(C_2\) constitute the well-known half-wave voltage rectifier circuit. The voltage rectifier circuit with voltage doubler can be realized by adding to \(D_2\) and \(C_1\). By adding \(D_2\) and \(C_1\) in the negative half cycle of the input sinusoidal signal, \(C_1\) is charged and in the next positive half cycle, \(C_2\) is charged with adding the voltage of \(C_1\). As the results, the positive voltage doubler can be achieved. In the same way, the circuit of the bottom side in the voltage rectifier circuit shown in Figure 3 also operates as the negative voltage doubler because the circuit has complementary structure of the upper side one. However, the output voltage of this circuit is decrease because the diodes has a threshold voltage. Furthermore, the problems of the stable operation and leak currents remain even if the conventional active diode with BRT is employed in stead of diode shown in Figure 3.

Figure 4 shows the circuit schematic of the proposed voltage rectifier circuit. In the Figure 4, the proposed active diode with BRT is employed in order to overcome the above problems. The voltage rectifier circuit is realized by replacing four diodes with the proposed active diode with BRT and the conventional active diode with BRT. Because the proposed circuit is designed by using single n-well process, the proposed active diode with BRT is applied to \(D_2\) and \(D_3\) and the conventional active diode is applied to \(D_1\) and \(D_4\). On the other hand, the proposed circuit can be divided to two circuit blocks as mentioned previously; positive and negative voltage doublers. Therefore, we can reduce the number of the comparators because the output signals of comparators can be shared since the circuit blocks of positive and negative voltage doublers have complementary structure each other. This contributes the reduction of the chip area and power consumption.

In the proposed circuit, two diodes can be replaced with the proposed active diodes with BRT, however, the remain two diodes cannot be replaced as mentioned previously. Therefore, the output voltage of the proposed rectifier circuit is slightly decrease compared with the ideal output. However, the output voltage of Figure 4 is drastically improved as compared with that of Figure 3.
Figure 3. Conventional voltage rectifier circuit

Figure 4. Proposed voltage rectifier circuit

5. SIMULATION AND EXPERIMENTAL RESULTS

The proposed active diode with BRT shown in Figure 2 and the proposed rectifier circuit shown in Figure 4 were designed and fabricated by using 1-poly, 3-metal, single n-well, 0.6μm CMOS process. The design parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Width (μm) / Channel Length (μm) of $M_1$, $M_2$, $M_5$, $M_8$</td>
<td>40 / 1 (10$^0$)</td>
</tr>
<tr>
<td>Channel Width (μm) / Channel Length (μm) of $M_1$, $M_2$, $M_5$, $M_8$</td>
<td>10 / 1 (2$^*$)</td>
</tr>
<tr>
<td>$C_1-C_4$ (μF)</td>
<td>4.7</td>
</tr>
<tr>
<td>$V_{GS}$ (V)</td>
<td>2.5</td>
</tr>
<tr>
<td>$V_{LS}$ (V)</td>
<td>-2.5</td>
</tr>
<tr>
<td>Amplitude of $V_{in}$ (V)</td>
<td>1.5</td>
</tr>
<tr>
<td>Frequency of $V_{in}$ (kHz)</td>
<td>10</td>
</tr>
</tbody>
</table>

* This value means the number of parallel connection of MOSFET.
Figure 5 shows photograph of the proposed voltage rectifier. The area is 305 \( \mu m \times 355 \mu m \). Firstly, we confirmed the I-V characteristics of the proposed and conventional active diodes shown in Figure 1 and 2, respectively. As the results, we confirmed the threshold voltage of both circuits are the same and its value equals 0. Figure 6 shows the DC transfer characteristics of the the conventional and proposed active diode with BRT. In the Figure 6, the vertical and horizontal axes mean \( V_C \) and the input voltage \( V_{in} \), respectively. From this experimental results, the dead region exist in the conventional circuits and its range is from -0.6 V to 0.6V. In contrast the results, we can confirmed that the dead region is perfectly eliminated in the proposed one. Figure 7 shows the oscilloscope photograph of the proposed voltage rectifier circuit. In this experiment, the amplitude and frequency of \( V_{in} \) were 1.5 V and 10 kHz, respectively, and \( R_{OUT} = 10 \, k\Omega \). From this graph, we can find the proposed voltage rectifier circuit generate the positive and negative power supply voltages, and its values are +2.88 V and -2.72 V.

6. CONCLUSION

In this paper, new active diode with BRT and its application to integrated voltage rectifier circuit have been proposed. We could confirmed that the proposed active diode with BRT can eliminate the dead region perfectly. Additionally, its application to integrated voltage rectifier circuit can reduce the chip area and the power consumption by sharing the output voltage of comparator, furthermore, the chip area and the output voltage of the proposed voltage rectifier circuit are 305 \( \mu m \times 355 \mu m \) and +2.86 V (positive side) and -2.70 V (negative side), respectively.

Future work is to apply the startup method for the proposed voltage rectifier circuit. In the experiment shown in Figure 7, external battery was used for power supply voltage of the comparator and inverter. However, our goal is to operate without external battery, therefore we should try to improve for the self-startup of the proposed voltage rectifier circuit.
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REFERENCES


BIOGRAPHIES OF AUTHORS

Was born in Kagoshima, Japan, on March 3rd, 1986. He received B. E. and M. E. degrees from Faculty of Engineering, University of Miyazaki, Miyazaki, Japan, in 2008 and 2010, respectively. He is currently studying to get Dr. Eng. degree at University of Miyazaki. From 2010 to 2015, he joined the Hitachi ULSI Systems Co., Ltd., Tachikawa, Japan. He was engaged in development of application software for Windows and development of voice recognition system for car navigation system. His research interests are biological signal measurement system and analog integrated circuit.

Was born in Miyazaki, Japan, on April 22, 1967. He received B. E. and M. E. degrees from the Faculty of Engineering, University of Miyazaki, Miyazaki, Japan, in 1990 and 1992, respectively, and Dr. Eng. degree from Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan, in 1999. From 1992 to 1993, he joined the Microelectronics Products Development Laboratory, Hitachi, Ltd., Yokohama, Japan. He was engaged in research on low-voltage and low-power equalizer for read channel LSI of hard disk drives. In 1994, he joined University of Miyazaki, where he is currently a Professor in the Department of Electrical and Systems Engineering. His main research interests are in analog integrated circuit design and multiple-valued logic circuit design. Dr. Tanno is a member of IEEE.

New active diode with bulk regulation transistors and its application to integrated... (Ryoichi Miyauchi)
Received the B. E. and M. E. degree from Miyazaki University in 1998 and 2000, respectively. From 2000 to 2001, He was an Engineer in Asahi Kasei Corporation, Japan. In 2001, He joined Toyama University, Toyama, Japan, where He was a Technical Official in Department of Intellectual Information Systems. In 2006, He joined Miyazaki University, Miyazaki, Japan, where He was an Assistant Professor in Department of Electrical and Electronic Engineering. In 2012, He is currently a Professor in the Department of Environmental Robotics. His main research interests are Neural Networks and Optimization Problems. In recent years, He has the interest in Biomedical Signal Processing using Soft Computing.