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Sub-30-mV-Supply, Fully Integrated Ring Oscillator Consisting of Recursive Stacking Body-Bias Inverters for Extremely Low-Voltage Energy Harvesting

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Abstract—This paper presents a ring oscillator (ROSC) consisting of recursive stacking body-bias inverters (RS-BBIs) for low-voltage energy harvesting. The RS-BBI is based on the conventional stacked body-bias inverter and consists of additional inverters stacked at the top and bottom of the inverter recursively. The RS-BBI increases the transconductance of MOSFETs and suppresses the leakage current due to its stacking structure, and increases the on-current of MOSFETs with the body-bias technique. The minimum supply voltage $V_{DD,min}$ can be reduced by increasing the number of stacking inverters. Measured results indicate that our ROSCs using the RS-BBIs were able to operate at lower supply voltage as the number of stacking inverters increased. The measured lowest $V_{DD,min}$ was 26 mV even though not all chips were able to oscillate. All chips oscillated successfully at 30 mV.

Index Terms—Energy harvesting, Ring oscillator, Inverter, Recursive stacking, Body-bias technique

I. INTRODUCTION

Energy harvesting (EH) techniques using thermoelectric generators (TEGs) have attracted much attention as excellent candidates for powering Internet-of-Things edge node devices. TEGs produce electric energy from a slight difference in temperature; therefore, we can use them as power sources for wearable electronics devices. However, it is quite difficult to operate them stably because their power and voltage are limited for application systems. Hence, highly efficient power management circuits (PMCs) that can operate with an extremely low voltage have been extensively investigated [1]–[8].

Fig. 1(a) is a diagram of a PMC capable of starting an operation at extremely low input voltage [9]–[11]. The PMC consists of a TEG, oscillator using off-chip transformer and capacitors, rectifier, and application-load circuits. The oscillator plays the role of the DC-AC converter and converts the TEG's low voltage V_{IN} to a boosted AC voltage, where the boost ratio is determined by a transformer turns ratio (i.e., 1:100). The rectifier rectifies the boosted AC voltage; thus, we obtain a boosted DC voltage. Even though the PMC can start up at extremely low voltage (e.g., 20 mV), it requires an off-chip and bulky transformer and capacitors. In addition, the PMC architecture cannot achieve high-power conversion efficiency because maximum-power-point tracking techniques cannot be developed with this architecture.

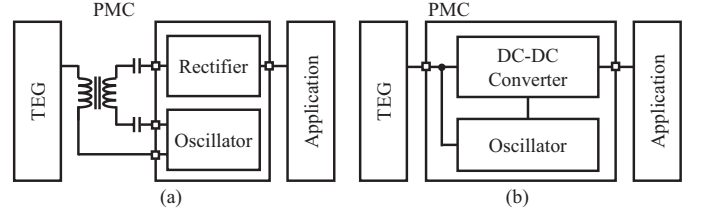


Fig. 1. Block diagrams of (a) conventional PMC and (b) PMC equipped with our ROSC.

To cope with this limitation, fully on-chip PMCs have been studied. Fig. 1(b) shows a block diagram of an integrated PMC. The PMC is composed of a TEG, oscillator (OSC), DC-DC voltage boost converter (VBC), and application circuits. The OSC generates a clock signal from the TEG's low voltage input V_{IN} and the clock is used to enable and start up the DC-DC VBC. However, the OSC is not able to oscillate correctly when the V_{IN} becomes low. This is because the voltage gain $|A_{INV}|$ of inverters, which are used in the OSC, decreases as the V_{IN} decreases.

Fully on-chip and extremely low-voltage OSCs have been reported [12]–[15]. Bose *et al.* presented a ring oscillator (ROSC) that can oscillate at supply voltage V_{DD} of 40 mV [12]. This ROSC uses stacked inverters (SIs). The $|A_{INV}|$ of the SI is enhanced by the stacked additional inverters at the top and bottom of the main inverter [13]. Matsuzuka *et al.* reported an ROSC that can operate at $V_{DD} = 42$ mV [14]. This ROSC uses body-bias inverters (BBIs). The $|A_{INV}|$ of a BBI is increased with the body-bias technique using a feedback inverter. On the basis of these achievements, Nishi *et al.* developed an ROSC that can oscillate at $V_{DD} = 35$ mV [15]. This ROSC uses stacked body-bias inverters (SBBIs) that use the low-voltage advantages of SIs and BBIs. As seen above, dedicated low-voltage CMOS inverters have been intensively studied to develop extremely low-voltage EH systems.

In light of this background, we propose an ROSC capable of operating at extremely low V_{DD} . It consists of recursive stacking body-bias inverters (RS-BBIs) that are based on prior studies on SI, BBI, and SBBI. The impact of our RS-BBI is in the combined use of the conventional low-voltage SI-, BBI-, and SBBI-circuit-design techniques and their ability to operate at extremely low V_{DD} . We also fabricated and measured a

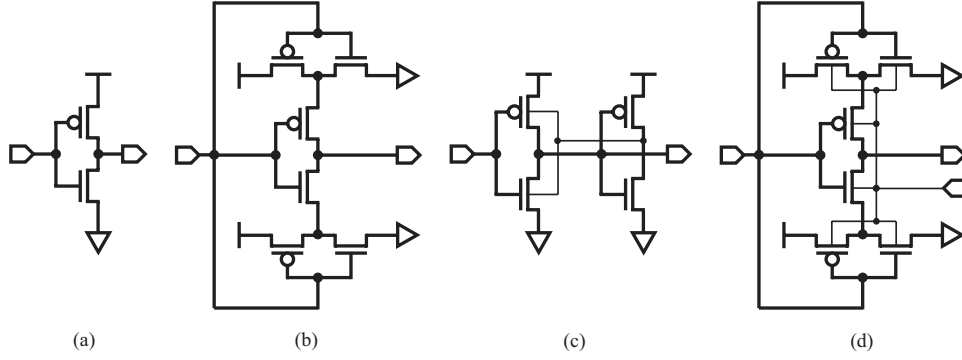


Fig. 2. Schematics of (a) NI, (b) SI [12], (c) BBI [14], and (d) SBBI [15].

prototype chip by using 180-nm CMOS process technology to show the extremely low voltage performance of our ROSC.

II. CONVENTIONAL LOW-VOLTAGE INVERTERS

An ROSC consisting of delay cells, or inverters, oscillates when the voltage gain $|A_{INV}|$ is greater than unity. However, the $|A_{INV}|$ decreases as the V_{DD} decreases. Thus, a CMOS inverter that has a higher $|A_{INV}|$ is needed. We briefly review normal and dedicated low-voltage inverters as follows.

Fig. 2(a) shows a schematic of a normal inverter (NI). The $|A_{INV}|$ of this inverter operating in the subthreshold region can be given by

$$|A_{INV}| = \frac{1}{\eta} \left\{ \exp \left(\frac{V_{DD}}{2V_T} \right) - 1 \right\}, \quad (1)$$

where η is the subthreshold slope factor and V_T is the thermal voltage [14]. As shown in (1), the $|A_{INV}|$ exponentially decreases as V_{DD} decreases. To operate an ROSC at lower V_{DD} , dedicated low-voltage inverters have been developed.

Fig. 2(b) shows a schematic of an SI consisting of three inverters [12]. Two inverters are stacked at the top and bottom of the main inverter. The input voltage V_{IN} is applied to all inverters, and the output voltages of SIs are connected to the sources of the main inverter's MOSFETs. By using the SI, the transconductance of the nMOSFET and pMOSFET in the main inverter increases; thus, the $|A_{INV}|$ increases. An ROSC using SIs oscillated at a 40-mV power supply [12].

Fig. 2(c) shows a schematic of a BBI consisting of main and feedback inverters [14]. The output voltage of the feedback inverter is connected back to the body terminals of the main inverter's MOSFETs. The feedback voltage controls the threshold voltages V_{THS} of the main inverter's MOSFETs. Compared with (1), the $|A_{INV}|$ of a BBI increases by a factor of

$$\left(1 - \frac{1}{2} \cdot \frac{\partial(\Delta V_{TH})}{\partial V_{IN}} \right), \quad (2)$$

where ΔV_{TH} is the threshold-voltage difference between the nMOSFET and pMOSFET in the main inverter. The $|A_{INV}|$ increases because $\partial(\Delta V_{TH})/\partial V_{IN}$ becomes negative. An ROSC using BBIs oscillated at a 42-mV power supply [14].

Fig. 2(d) shows a schematic of an SBBI [15]. An SBBI combines the architecture of an SI (Fig. 2(b)) and BBI (Fig.

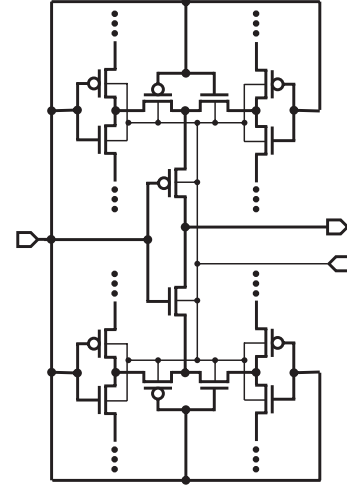


Fig. 3. Simplified schematic of RS-BBI.

2(c)) (note: a feedback inverter is not shown in Fig. 2(d)). The $|A_{INV}|$ of the SBBI increases effectively because two techniques do not interfere with each other. An ROSC using SBBI oscillated at a 35-mV power supply [15]. Note that in this ROSC, the body-bias voltage is connected to the output of the next stage inverter to save the feedback inverter.

III. RECURSIVE STACKING BODY-BIAS INVERTER

To achieve lower voltage oscillation of an ROSC, we propose a recursive stacking body bias inverter (RS-BBI). Fig. 3 shows a simplified schematic of the RS-BBI. The RS-BBI is based on the SBBI [15] and additional inverters are stacked at the top and bottom of the inverter recursively. It is expected that the transconductance of MOSFETs in the recursive stacking inverters as well as in the main inverter will increase by increasing the number of stacking inverters. In addition, leakage current, which degrades the output voltage of the main inverter, can be reduced effectively thanks to the recursive-stacking technique. Note that our RS-BBI achieves low-voltage operation at the cost of increased number of transistors, area and power penalty.

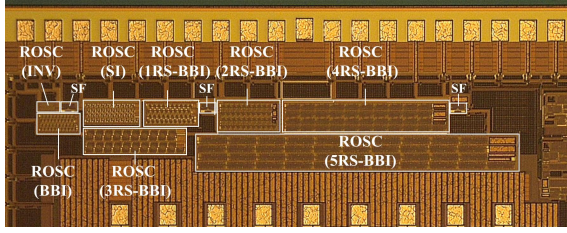


Fig. 4. Chip micrograph.

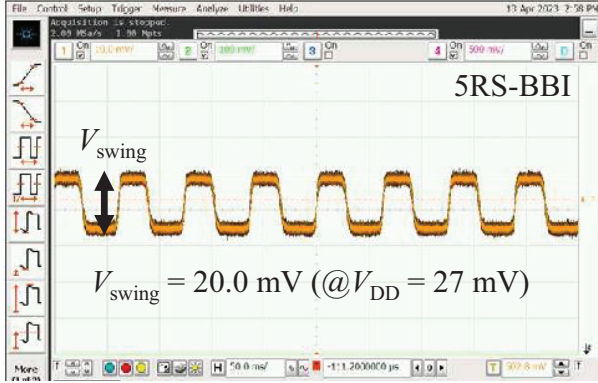


Fig. 5. Measured waveform of ROSC using 5RS-BBIs at $V_{DD} = 27$ mV

IV. RESULTS

We designed and fabricated a prototype test chip equipped with five of our ROSCs using a 180-nm, 1-poly, 6-metal CMOS process technology with deep n-well option, each with 1 to 5 RS-BBIs, i.e., ROSC (1RS-BBI), ROSC (2RS-BBI), ROSC (3RS-BBI), ROSC (4RS-BBI), and ROSC (5RS-BBI) as well as ROSCs using NIs, SIs, and BBIs for comparison. Fig. 4 is a micrograph of this chip. The area of ROSCs occupied 0.013, 0.018, 0.029, 0.055, and 0.12 mm², respectively. In the measurement, source-follower (SF) buffers were used to adequately drive non-ideal parasitics.

Fig. 5 shows the measured waveform of ROSC using 5RS-BBIs at $V_{DD} = 27$ mV. The swing was 20 mV. We confirmed the low-voltage oscillation of this ROSC.

Fig. 6 shows the measured normalized amplitudes as a function of V_{DD} . ROSC using 5RS-BBIs showed the highest amplitude among all ROSCs. It was also able to operate at an extremely low V_{DD} of 27 mV.

To examine the minimum supply voltage $V_{DD,min}$ of our ROSCs in detail, we conducted further experiments. Tab. I summarizes the measured number of chips when all ten ROSCs were able to operate successfully at different V_{DD} s and room temperature. We defined the $V_{DD,min}$ as the voltage when all ten samples oscillated successfully. As shown in Tab. I, the $V_{DD,min}$ s can be reduced by using our proposed RS-BBIs, compared with those using NIs, BBIs, and SIs, and ROSC using 5RS-BBIs was able to operate successfully at

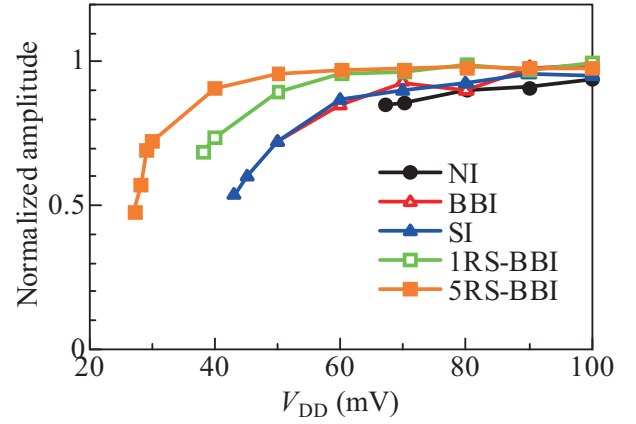


Fig. 6. Measured normalized amplitude

TABLE I
MEASURED NUMBER OF CHIPS WHEN ROSCs WERE ABLE TO OPERATE AT DIFFERENT V_{DD} S (10 SAMPLES IN TOTAL).

V_{DD} (mV)	NI	BBI	SI	1RS- BBI	2RS- BBI	3RS- BBI	4RS- BBI	5RS- BBI
70	10	10	10	10	10	9	10	10
65	9	10	10	10	10	9	10	10
60	7	9	10	10	10	9	10	10
55	2	5	10	10	10	9	10	10
50	1	1	10	10	10	9	10	10
45	0	0	6	10	10	9	10	10
40	0	0	0	6	10	9	10	10
35	0	0	0	0	7	9	10	10
30	0	0	0	0	0	4	8	10
29	0	0	0	0	0	2	6	9
28	0	0	0	0	0	0	2	7
27	0	0	0	0	0	0	1	5
26	0	0	0	0	0	0	1	1
25	0	0	0	0	0	0	0	0

$V_{DD} = 30$ mV and achieved the lowest $V_{DD,min}$ among all our ROSCs. Note that the number of successful operations using 3RS-BBIs was nine. One chip could have been damaged due to electrostatic breakdown.

Tab. II summarizes the performances of all ROSCs. As discussed in Sect. III, the number of transistors, area, and current dissipation increased as the number of stacking inverters increased. However, ROSC using 5RS-BBIs achieved the lowest $V_{DD,min}$ of 30 mV.

Fig. 7 shows the measured $V_{DD,min}$ as a function of the number of stacking inverters. For comparison, simulated $V_{DD,min}$ s with and without the body-bias technique are also plotted. By stacking inverters recursively, the $V_{DD,min}$ decreased as the number of stacks increased. We also found that the $V_{DD,min}$ can be reduced with the body-bias technique. The measured $V_{DD,min}$ s were higher than the simulated ones. One possible reason for the difference could be the effect of process variation.

Tab. III summarizes the results of the $V_{DD,min}$, where N

TABLE II
PERFORMANCE SUMMARY OF ROSCS

Inverter	# of stacks	# of Trs.	Area (mm ²)	I_{total} (nA)	$V_{\text{DD,min}}$ (mV)	f_{ROSC} (Hz)
NI	0	2	0.0018	2.57	68	9.0k
BBI	0	4	0.0083	2.41	62	870
SI	1	6	0.013	6.42	49	1.6k
1RS-BBI	1	6	0.013	6.70	44	340
2RS-BBI	2	14	0.018	13.8	38	160
3RS-BBI	3	30	0.029	28.8	33	85
4RS-BBI	4	62	0.055	68.0	32	37
5RS-BBI	5	114	0.12	135	30	3.0

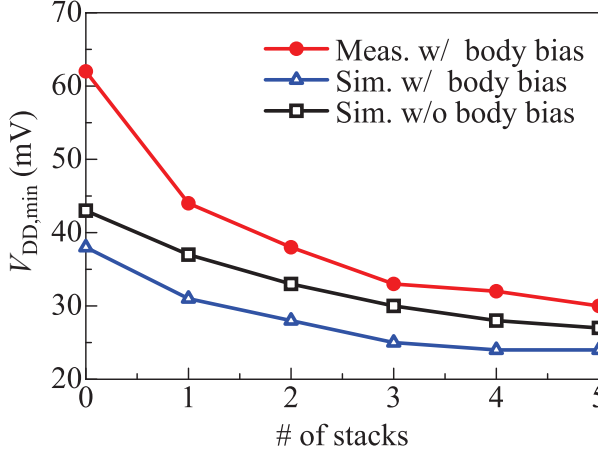


Fig. 7. Measured $V_{\text{DD,min}}$ as function of number of stacking inverters.

is the stage number of an ROSC. ROSC using 5RS-BBIs achieved the lowest V_{DD} of 30 mV.

V. CONCLUSION

We presented ring oscillators capable of operating at extremely low supply voltage. These oscillators consist of recursive stacking body-bias inverters. These inverters increase the transconductance of MOSFETs and suppress the leakage current by the stacking inverters, and increases the on-current of MOSFETs by using the body-bias technique. The minimum supply voltage can be reduced by increasing the number of stacking inverters. Measurement results indicate that our oscillators were able to oscillate at lower supply voltage. The minimum supply voltage was 30 mV. These oscillators will be advantageous for extremely low-voltage energy harvesting systems.

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TABLE III
PERFORMANCE COMPARISON

Ref.	Year	Type	Tech. (nm)	Area (mm ²)	N	$V_{\text{DD,min}}$ (mV)
[4]	2012	V_{TH} tuned	65	0.123	NA	82
[12]	2018	Stack	180	<0.003	21	50
[13]	2018	Redundant	65	NA	11	45
[14]	2020	BBI	180	0.0153	31	42
[15]	2021	SBBBI	180	0.026	27	35
This work	2023	5RS-BBI	180	0.123	41	30

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