248pW, 0.11mV/°C Glitch-Free Programmable Voltage Detector With Multiple Voltage Duplicator for Energy Harvesting

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***Abstract*—A glitch-free programmable voltage detector is proposed for RF energy harvesting. In energy harvesting applications, ultra-low power (< 1nW), PVT-variation tolerant, and glitch-free voltage detectors are required to turn on or off the output switch which connects an output capacitor of the energy harvester and the load circuits. The proposed multiple voltage duplicator (MVD) enables the ultra-low power (248pW at 1V) feature, detection voltage programmability (< 49-mV step), and temperature-variation tolerant (0.11mV/°C in -20°C to 80°C) operation in 250-nm CMOS. In the conventional voltage detectors, when the input voltage is increased from 0V, a glitch of the output is observed, which mistakenly turns on the output switch and spoils the energy harvesting. To remove the glitch, the glitch-free programmable voltage detector is proposed.**

I. Introduction

In the applications of Internet of Things (IoT), the energy harvesting is strongly required to enable energy autonomous IoT nodes. Fig. 1 shows a block diagram of an IoT node with the RF energy harvesting [1]. The charge pump converts the input RF signal (e.g. 920MHz) to the DC voltage (V_{DD}). At the start-up, the charge pump charges the output capacitor (C_1) from 0V. During the charging, the output switch (M1) [2-3] should be turned off to prevent the load circuits (e.g. MCU and RF circuits) from discharging C_1. M1 is very important in the energy harvesting, because the charging current (e.g. 1μA [4] and 1nA [1]) of the charge pump is much smaller than the load current (e.g. 1mA). When V_{DD} is increased to the pre-defined voltage (V_{DETECT}) of a voltage detector (VD), VD turns on M1 and the load circuits start the operation. This paper focuses on VD. In the RF energy harvesting, ultra-low power (< 1nW), PVT-variation tolerant, and glitch-free VDs are required. The supply current of VD should be less than the charging current of the charge pump, because VD is directly connected to C_1. V_{DETECT} of VD should be constant over PVT variations. When a glitch is observed in V_{OUT}, M1 is mistakenly turned on, which spoils the energy harvesting. In this paper, a low power (248pW at 1V), PVT-variation tolerant, and glitch-free VD is proposed and implemented in 250-nm CMOS.

II. Conventional Voltage Detectors

A. Glitch-Free and Programmable Operation

In this section, conventional VDs are reviewed and it is shown that all the conventional VDs do not achieve both the glitch-free and the programmable operation.

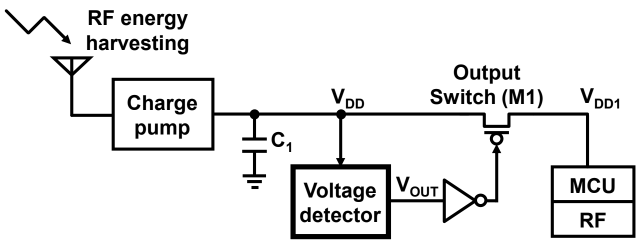

Fig. 1. Block diagram of IoT node with RF energy harvesting.

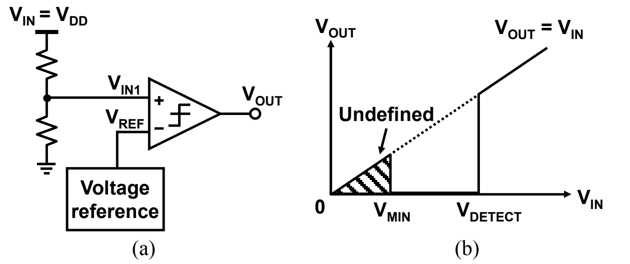

Fig. 2. (a) Circuit schematic and (b) input-output characteristic of commercially available voltage detector [5-7].

Figs. 2 (a) and (b) show a circuit schematic and an input-output characteristic of a commercially available VD [5-7], respectively. When, the input voltage (V_{IN}) is lower or higher than V_{DETECT}, V_{OUT} is low or high, respectively. V_{DETECT} is factory-trimmed by changing the resistive divider. As shown in Fig. 2 (b), when V_{IN} is between 0V and V_{MIN}, V_{OUT} is undefined due to the metastability of the comparator, which is the cause of the glitch of V_{OUT}. To hide the glitch, the minimum V_{IN} (e.g. 0.8V to 1V) (> V_{MIN}) is specified in the commercially available VDs [5-7]. The VDs cannot be applied to the energy harvesting where V_{IN} increases from 0V.

Fig. 3 shows a conventional programmable VD. A resistive ladder and a selector are added to enable the programmable V_{DETECT} to compensate for the die-to-die process variations. As shown in Fig. 3 (b), however, the glitch is observed.

Fig. 4 shows a glitch-free VD. By replacing the comparator in Fig. 2 (a) with two stacked pMOSFETs, the glitch is removed. In this work, VD [3] with two stacked pMOSFETs with the same threshold voltage (V_{TH}) is modified to two stacked pMOSFETs with different V_{TH} to achieve temperature-variation tolerant V_{DETECT}. After the optimization of the transistor sizes, V_{DETECT} of the glitch-free VD is given as follows.

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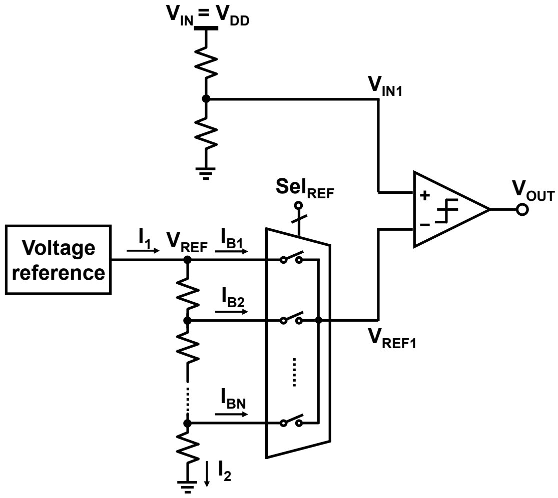
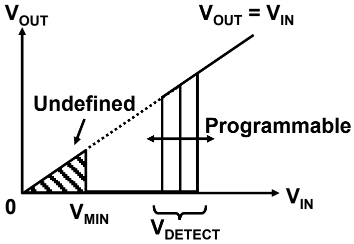
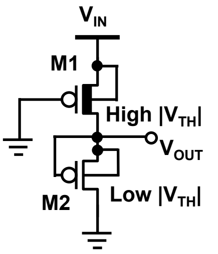


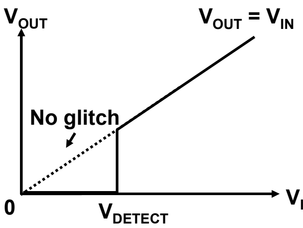
(a)



(b)

Fig. 3. (a) Circuit schematic and (b) input-output characteristic of conventional programmable voltage detector.





(a) (b)

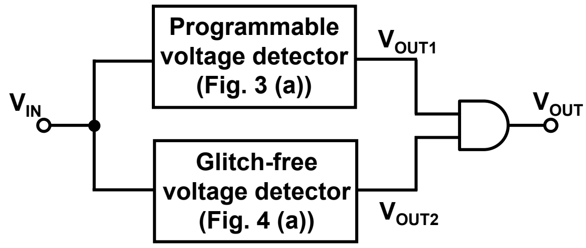
Fig. 4. (a) Circuit schematic and (b) input-output characteristic of glitch-free voltage detector.

$$V_{DETECT} = |V_{TH1}| - \frac{m_1}{m_2}|V_{TH2}| \quad (1)$$

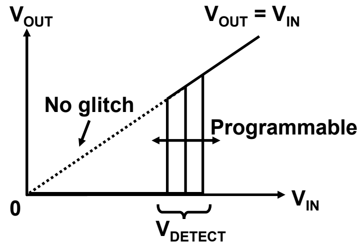
where V_{TH1} and V_{TH2} are V_{TH} of M1 and M2, and m_1 and m_2 are the body-effect coefficient of M1 and M2, respectively. Eq. (1) shows that the temperature-dependent term is not included and V_{DETECT} is temperature-variation tolerant. Though V_{DETECT} varies due to the process variations of V_{TH1} and V_{TH2}, V_{DETECT} is not programmable, which is a problem of the glitch-free VD.

B. *Low Power and Temperature-Variation Tolerant Operation*

In this section, the power consumption to generate V_{REF1} and the temperature dependence of V_{REF1} in the conventional programmable VD in Fig. 3 (a) are discussed. The voltage reference need to drive the leakage current (I_{B1}, I_{B2}, and I_{BN}) of the switches in the selector. In an ideal case of the leakage current = 0 and $I_1 = I_2$, the temperature dependence of V_{REF1} is the same of that of the voltage reference. In reality, however, when the leakage current is comparable to I_1, the temperature dependence of V_{REF1} is worse than that of the voltage reference. To improve the temperature dependence, I_1 should be increased. Therefore, the power consumption and the temperature dependence are the tradeoff. Later, the tradeoff is quantitatively shown in Fig. 9.



(a)



(b)

Fig. 5. (a) Block diagram and (b) input-output characteristic of proposed glitch-free programmable voltage detector.

III. Proposed Glitch-Free Programmable Voltage Detector

A. *Glitch-Free and Programmable Operation*

Figs. 5 (a) and (b) show a block diagram and an input-output characteristic of a proposed glitch-free programmable VD, respectively. As shown in Fig. 5 (b), by combining the programmable voltage detector with the glitch (Fig. 3) and the glitch-free un-programmable voltage detector (Fig. 4), both the glitch-free and the programmable operation are achieved, when $V_{MIN(Fig.\ 3(b))} < V_{DETECT(Fig.\ 4(b))} < V_{DETECT(Fig.\ 3(b))}$. Table I summarizes the four VDs in Figs. 2 – 5 regarding the glitch-free and the programmable operation. Fig. 6 shows a circuit schematic of the proposed glitch-free programmable VD. The voltage reference is implemented with two stacked pMOSFETs with different V_{TH}, which is the similar concept to [8] with two stacked nMOSFETs implementation. The V_{TH} difference is approximately 0.4V. To reduce the step of the programmable V_{DETECT}, the voltage dividers are added to both V_{IN} and V_{REF}.

TABLE I Summary of Four Voltage Detectors

		Programmable V_{DETECT}	Glitch-free V_{OUT}
Conventional	Commercial VD (Fig.2)	No	No
	Programmable VD (Fig.3)	Yes ✓	No
	Glitch-free VD (Fig.4)	No	Yes ✓
Proposed glitch-free programmable VD (Fig.5)		Yes ✓	Yes ✓

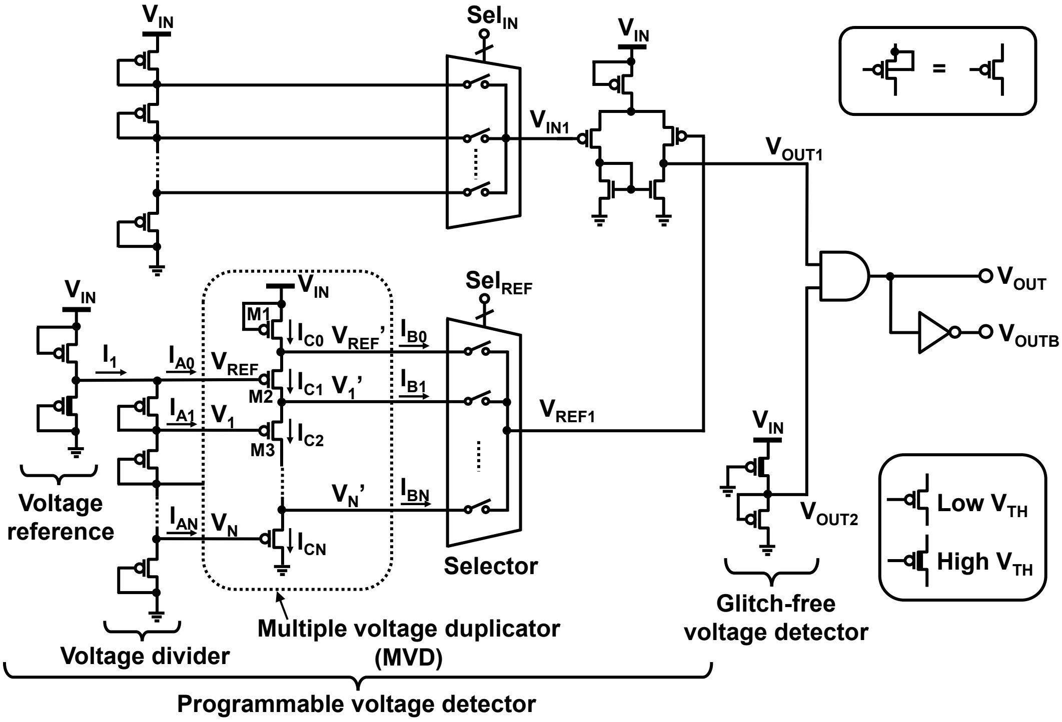


Fig. 6. Circuit schematic of proposed glitch-free programmable voltage detector.

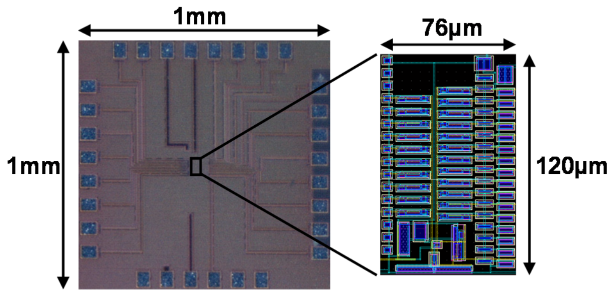


Fig. 7. Die photo and layout of proposed glitch-free programmable voltage detector in 250-nm CMOS.

B. *Multiple Voltage Duplicator for Low Power and Temperature-Variation Tolerant Operation*

To solve the tradeoff between the power consumption to generate V_{REF1} and the temperature dependence of V_{REF1} in the conventional programmable VD (Fig. 3 (a)), a multiple voltage duplicator (MVD) is newly proposed and inserted between the voltage divider and the selector as shown in Fig. 6. MVD is a multiple-input multiple-output voltage buffer. In MVD, M1 is the current source with the subthreshold leakage current (V_{GS} = 0V) of I_{C0}, and the other transistors (M2, M3) are serially stacked. When the source current (I_{C0}, I_{C1}, I_{C2}, and I_{CN}) is sufficiently larger than the leakage current (I_{B0}, I_{B1}, and I_{BN}) of the switches, an interesting characteristic of MVD is that each input voltage equals to each output voltage ($V_{REF} = V_{REF}'$, $V_1 = V_1'$, and $V_N = V_N'$), because $I_{C0} = I_{C1} = I_{C2} = I_{CN}$ and V_{GS} of all transistors in MVD (M1, M2, and M3) are 0V. Thus, in MVD, multiple input voltages are simultaneously duplicated to multiple output voltages. The power overhead of MVD is 56pW at 0.8V. Different from Fig. 3 (a), by inserting MVD between the voltage divider and the selector, $I_{A0} = I_{A1} = I_{AN} = 0$ and I_1 can be greatly reduced by reducing the transistor size of the voltage reference and the voltage divider. Thus, the tradeoff between the power consumption to generate V_{REF1} and the temperature dependence of V_{REF1} in the conventional programmable VD is solved with MVD.

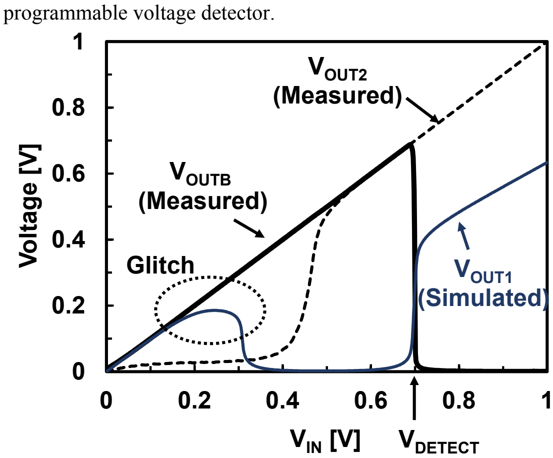


Fig. 8. Simulated and measured input-output characteristics of proposed glitch-free programmable voltage detector.

IV. Measured Results

Fig. 7 shows a die photo and a layout of the proposed glitch-free programmable VD fabricated in 250-nm CMOS process. The core area is 76μm by 120μm. Fig. 8 shows simulated and measured input-output characteristics of V_{OUT1}, V_{OUT2}, and V_{OUTB} of the proposed glitch-free programmable VD in Fig. 6. The glitch in V_{OUT1} is successfully removed in V_{OUTB} thanks to the proposed glitch-free VD. To clarify the tradeoff between the power consumption to generate V_{REF1} and the temperature dependence of V_{REF1}, Fig. 9 shows the power supply current dependence of the temperature coefficient (TC) of V_{REF1} with and without MVD. For V_{REF1} without MVD, the results are obtained by SPICE simulations of the circuits in Fig. 3 (a), where the voltage reference shown in Fig. 6 is used and the transistor

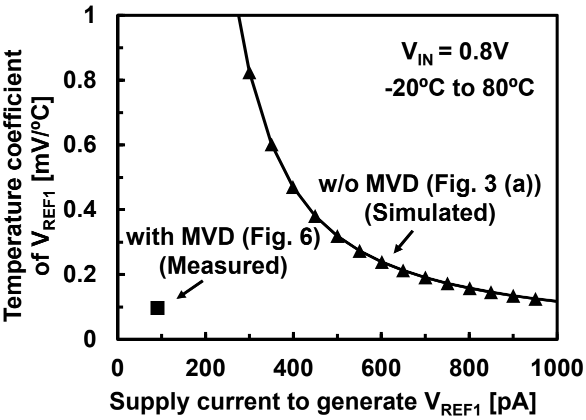


Fig. 9. Power supply current dependence of temperature coefficient of V_{REF1} with and without proposed multiple voltage duplicator (MVD).

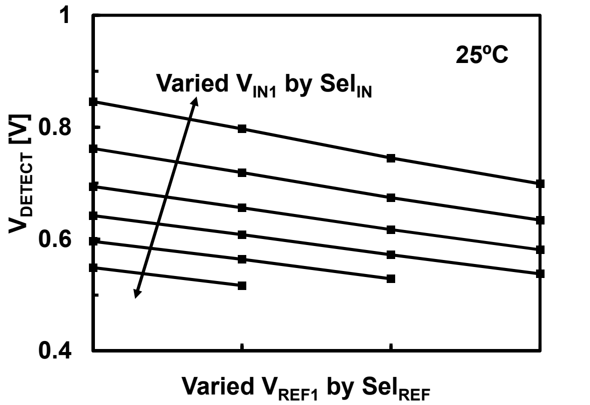


Fig. 10. Measured programmable V_{DETECT} in proposed glitch-free programmable voltage detector.

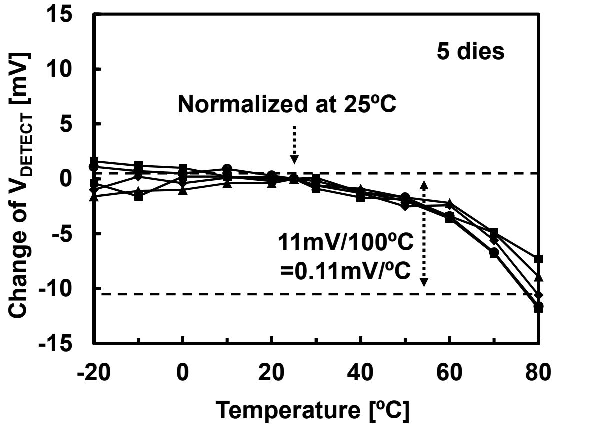


Fig. 11. Measured temperature dependence of V_{DETECT} among 5 dies of proposed glitch-free programmable voltage detector.

TABLE II COMPARISON WITH PREVIOUS VOLTAGE DETECTORS

		TPS3839 [5]	AP4400A [7]	JSSC'12 [3]	VLSI'12 [9]	This Work
CMOS process		N/A	N/A	65nm	180nm	250nm
Operating supply voltage	Max	6.5V	5.5V	N/A	N/A	1.0V
	Min	0.9V	0.8V	0V		0V
Detection voltage (V_{DETECT})	Max	4.38V	4.2V	0.46V (Fixed)	3.58V (Fixed)	0.85V
	Min	0.9V	2.0V			0.52V
	Step	< 130mV (Trimming)	100mV (Trimming)			< 49mV (Programmable)
Power (25°C)		180nW @1.2V	68nW @3.4V	1.6nW @0.46V	286pW @3.6V	248pW @1.0V
Temperature coefficient of V_{DETECT}		0.055mV/°C	0.75mV/°C	2.0mV/°C (Calculated)	1.5mV/°C	0.11mV/°C
Temperature range		-40°C to 85°C	-15°C to 85°C	N/A	0°C to 80°C	-20°C to 80°C

gate width of the voltage reference is varied to change I_1 in the simulation. As the power supply current is reduced, TC increases, which is the tradeoff between the power consumption and TC. For V_{REF1} with MVD, a measured result is shown. By introducing MVD, the tradeoff is solved, and both the low supply current (92pA) and low TC (0.10mV/°C) are simultaneously achieved. Fig. 10 shows a measured programmable V_{DETECT} in the proposed glitch-free programmable VD. The range of V_{DETECT} is from 0.52V to 0.85V and the step of the programmable V_{DETECT} is less than 49mV. Fig. 11 shows a measured temperature dependence of V_{DETECT} among 5 dies. The results are normalized at 25°C. The measured TC of V_{DETECT} is 0.11mV/°C in - 20°C to 80°C.

In Table II, this work is compared with the previously published VDs. This work achieves the minimum operating voltage of 0V thanks to the glitch-free operation, which is essential for the energy harvesting. This work demonstrates the programmable VD with less than 49-mV step to compensate for the die-to-die variations for the first time. The proposed MVD enables the programmable VD with the lowest power of 248pW and the competitive TC of 0.11mV/°C.

V. CONCLUSIONS

For the RF energy harvesting, ultra-low power, PVT-variation tolerant, and glitch-free VD is proposed and implemented in 250-nm CMOS. This work achieves the minimum operating voltage of 0V thanks to the glitch-free operation, which is essential for the energy harvesting. This work demonstrates the programmable VD with less than 49-mV step to compensate for the die-to-die variations for the first time. The proposed MVD enables the programmable VD with the lowest power of 248pW and the competitive TC of 0.11 mV/°C.

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