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A Nano-power Wake-up Circuit for Energy-driven IoT Applications

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***Abstract*—Owing to the advancement of vibration energy harvesting technology, many motion-powered battery-free Internet of things (IoT) applications have been reported in recent years. Since the ambient energy is usually weak, these IoT devices mostly operate in intermittent or burst mode. The operation of these devices heavily depends on the level of stored energy. Conventional energy-aware solutions are carried out based on discrete general-purpose comparators or analog-to-digital converters (ADC) inside the system on chip (SoC) to monitor the storage level. Their power consumption is considerable in a low-power system. This paper presents a new energy-aware circuit, which can wake up or turn off the IoT devices according to the stored energy. Its standby quiescent current is at the sub-μA level. The proposed circuit also provides a regulated output voltage for IoT applications. This design is built with discrete analog components. It is low cost and has high feasibility. It is compatible with different kinds of micro-power generators.**

I. Introduction

In recent years, emerging market demand and technological advances have led to an increasing number of IoT devices. The performance of battery-powered IoT nodes are subjected to a big challenge, given the possible exhaustion and failure of batteries [1]. The vibration energy harvesting (VEH) technology offers a promising power solution for powering ubiquitous and everlasting IoT devices by obtaining the kinetic energy in their surroundings. By reducing the maintenance of power supply, the cost of the whole system might be largely cut down. The general power solution for electrical devices is shown in Fig. 1(a). The existing VEH systems usually give a power output at mW or sub-mW levels. However, the operating power of a micro-controller unit (MCU) exceeds 10 mW. As a result, it is difficult for a VEH generator to directly and continuously power an MCU-based embedded system. On the other hand, vibration sources are sporadic in nature. They are heavily influenced by the environment, requiring storage components to buffer or store the harvested energy. For this reason, the intermittent operation mode is a better choice under the condition of uncertain power supplement [2]. Only if the stored energy is sufficient, the device can start up and run a specific routine without browning-out. If the preset task is completed or the energy is insufficient, the device must be turned off or enter low-power mode, to accumulate energy for the next round of operation. Recent studies on VEH mostly focused on the maximization of its harvesting capability. It should be emphasized that, the power management unit is also

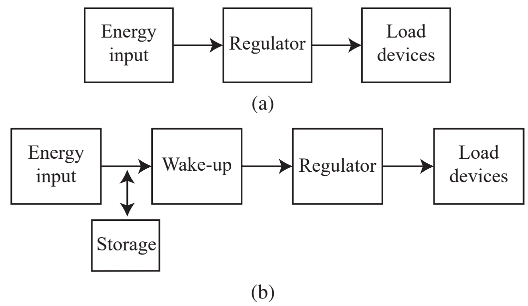

Fig. 1: Power supply architecture of (a) general IoT devices, (b) battery-free IoT devices.

an essential part for properly running an VEH-powered IoT device.

A lot of the previous works, like battery-free wireless sensor nodes (WSN) [3] and VEH-powered wearable devices [4], utilized a commercial chip LTC-3588 for power management. LTC-3588 integrates an internal full-bridge rectifier as the interface circuit. A buck converter to regulate the output voltage at a specific level. The internal under-voltage-lockout (UVLO) block in LTC-3588 only provides a fixed threshold. It is not convenient for the tailor-making or flexible designs of different IoT applications. To make a complement, an external comparator with voltage reference (MIC841) was used to provide a configurable on/off threshold in an IoT design [5]. Another work utilized a voltage sensing chip to carry out the UVLO function [6]. Commercial integrated circuits are rarely designed under the premise of unstable power supply. It is difficult to find a general comparator or voltage sensor with the capability of low power consumption and high voltage rating. Analog-to-digital converter (ADC) integrated in SoC is also a solution to detect the storage voltage level, so that to schedule the computing tasks [7]. Only if the SoC is powered on with a stable supply voltage, the on-chip ADC can be enabled. The ADC solution is a polling-based method. It is difficult to make a good trade-off among sampling rate, power consumption, and sensing accuracy. Some previous works use discrete devices to enhance the harvesting capability and realize the power management [8]. But the circuit utilized numerous discrete semiconductor components. Other works designed custom integrated circuits for carrying out both energy harvesting and management, to support the practical

IoT applications [9], [10].

VEH sources might have very strong dynamics in general. They have raised several unique demands to their power management circuit. These specific features include

- **Energy awareness:** The power management circuit should keep an eye on the energy storage level. It should immediately turn on/off the IoT devices according to the energy condition;
- **Low-power standby:** The power consumption of the power management circuit should be extremely low during the standby or deep-sleep period, to enable the effective energy build-up process;
- **Effective and efficient voltage regulation:** Once in the active condition, it should effectively stabilize the output voltage at a relatively constant digital level with a relative high efficiency before the stored energy is used out;
- **Flexibility and adaptability:** The thresholds of turn-on and turn-off should be easily re-configurable to adapt to different source and load conditions.

In this paper, a power management circuit meeting most of the aforementioned criteria is proposed. The circuit can provide the essential on/off signal and regulate the output voltage for battery-free IoT devices. It is built with a few discrete components, without the need of integrated circuits and additional electronic modules. The static power consumption of the proposed circuit is extremely low. The whole system only consumes 55 nA and 268 nA current during the off and on states, respectively, at 4 V storage voltage. In addition, the circuit is compatible with different VEH interface circuits, which convert fluctuating ac voltage into dc. It might also be applicable to other micro-power energy sources.

II. Circuit Design

The block diagram of battery-free device shown in Fig. 1(b) is embodied with the circuit topology shown in Fig. 2. It consists of several parts. The energy source is summarized by a dc current source I_{IN}. A capacitor C_{S} acts as the energy storage. The main part is a low-power start-up circuit. The regulation circuit is simplified into a depletion-mode MOSFET. The circuit is built with four MOSFETs, a pair of bipolar transistors, and several resistors.

A. Nano-power UVLO

The core part of the proposed energy management circuit is a low-power UVLO. It provides the on/off signals for external devices. The on/off threshold voltages are defined by three resistors R_1, R_2, and R_3. A depletion-mode NMOS Q_1 acts as the current limiter at high storage voltage. An enhanced-mode NMOS Q_2, resistors R_4 and R_5, and a PNP transistor Q_5 form a common-source amplifier. Another PNP transistor Q_6 mirrors the current of Q_5 with an artificial mismatch introduced by R_5. A general PMOS Q_3 acts as a power switch, which is controlled by the common-source amplifier. A depletion-mode NMOS Q_4 is utilized as an easy voltage regulator.

When the voltage across the storage capacitor C_{S} is low, almost no current flows through the resistor R_1. So the depletion NMOS operates in linear region. The gate voltage of Q_2, i.e.,

$$V_{\mathrm{gs2}} = V_{\mathrm{S}} \frac{R_1}{R_1 + R_2 + R_3} \tag{1}$$

is lower than the threshold voltage. Therefore, Q_2 is biased in the sub-threshold region. The current flowing through Q_2 is expressed as follows

$$I_{\mathrm{Q2}} = I_{\mathrm{Q5}} = I_{\mathrm{ON2}} \exp\left(\frac{V_{\mathrm{gs2}} - V_{\mathrm{th2}}}{n_2 kT/q}\right), \tag{2}$$

where V_{th2} is the intrinsic threshold voltage of NMOS Q_2. I_{ON2} is the drain current at threshold voltage. n_2 is the ideality factor. k is the Boltzmann constant. T is the absolute temperature of the MOSFET. q is the charge of an electron. The value of V_{th2} and I_{ON2} can be found in the SPICE model of the device. In this condition, the gate node of Q_3 is pulled up. The output is turned off. With the charges accumulated in the storage capacitor C_{S}, V_{S} keeps rising. The current I_{Q6}, which is mirrored from I_{Q5}, rises too. With the artificial mismatch introduced by R_5, I_{Q6} increases quicker than I_{Q5}. So Q_6 starts to share current with R_3, the circuit enters a critical condition. Such a current sharing can increase I_{R2} and the gate voltage of Q_2; therefore, further magnify the current I_{Q5}. Via such a positive feedback, the transistor Q_6 can finally short the resistor R_3. After that, the circuit enters a new steady state. As the gate node of Q_3 is pulled down by Q_2, the depletion-mode Q_4 is powered on. It supplies a regulated output voltage V_{O} to the load device.

At the critical condition, we have $V_{\mathrm{gs3}} = V_{\mathrm{th3}}$. Assuming that the voltage drop across the diode-connected bipolar transistor Q_5 can be neglected, and designing $R_5 \ll R_4$, we have

$$I_{\mathrm{Q5}} R_4 \approx |V_{\mathrm{th3}}|. \tag{3}$$

By solving (2) and (3), we can find the critical gate-to-source voltage of Q_2, over which the UVLO circuit switches between its on and off conditions. This critical gate-to-source voltage of Q_2 can be defined as follows

$$V_{\mathrm{gs2}}^{*} = V_{\mathrm{th2}} + \frac{n_2 kT}{q} \ln\left(\frac{|V_{\mathrm{th3}}|}{I_{\mathrm{ON2}} R_4}\right). \tag{4}$$

The resistor R_3 is used to define the hysteresis between on and off threshold voltages. By solving (1) and (4), the turn-on

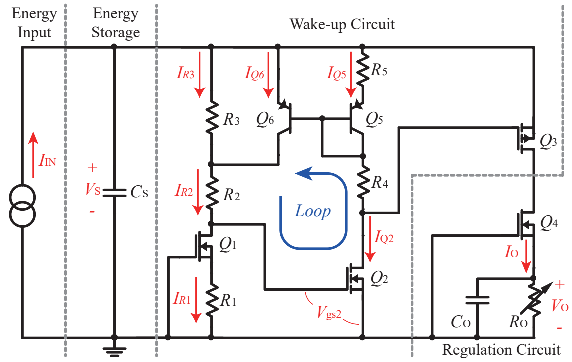

Fig. 2: The proposed power management circuit.

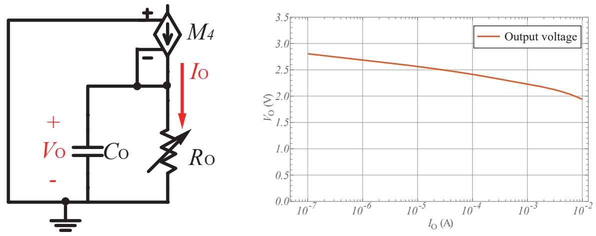

Fig. 3: (a) The proposed power management circuit. (b) The output voltage versus output current with BSS159N.

threshold of the UVLO circuit is

$$V_{\mathrm{S,ON}} = \frac{R_1+R_2+R_3}{R_1} V_{\mathrm{gs2}}^{*}. \quad (5)$$

Based on the same principle, the turn-off threshold of UVLO circuit is

$$V_{\mathrm{S,OFF}} = \frac{R_1+R_2}{R_1} V_{\mathrm{gs2}}^{*}. \quad (6)$$

By setting the proper ratios among R_1, R_2, and R_3, the on/off threshold voltages of the UVLO can be determined.

Selecting large resistance for R_1, R_2, and R_3 helps reduce the quiescent current of the circuit. But if a high voltage is biased across R_1, the current consumption is still considerable. So we add a depletion-mode NMOS Q_1 to reduce the maximum current through R_1. When the voltage across R_1 reaches the threshold voltage of Q_1, Q_1 enters the saturation region. So the maximum current through R_1 can be expressed as follow

$$I_{R_1,\mathrm{max}} \approx \frac{|V_{\mathrm{th1}}|}{R_1}. \quad (7)$$

By adding such a depletion-mode NMOS in this design, the quiescent current can be effectively reduced.

B. Regulation Mechanism

The electronic load devices, such as sensors and MCU, require a stable supply voltage to work. In normal cases, the supply voltage is provided by LDOs (low-dropout regulator) or switched-mode dc/dc converters. When powered on, a general regulator chip consumes quiescent current, which induces extra dissipation. To eliminate the quiescent current and reduce the component number, we use a depletion NMOS Q_4 as a low-cost regulator. Since all the current through Q_4 also flows through the load, such a simple regulator has zero quiescent current for regulation. The equivalent circuit of the depletion MOSFET is given in Fig. 3(a). The drain current of the gate-grounded depletion MOSFET is:

$$I_O = K_{p4}\frac{W}{L}(-V_{\mathrm{O}} - V_{\mathrm{th4}})^2. \quad (8)$$

where the K_{p4}, W, L, V_{th4} are the transconductance, width, length, and threshold voltage of the depletion mode N-channel MOSFET, respectively. Since V_{th4} is negative, the output voltage can be calculated as follows

$$V_{\mathrm{O}} = |V_{\mathrm{th4}}| - \sqrt{\frac{I_O L}{K_{p4} W}}. \quad (9)$$

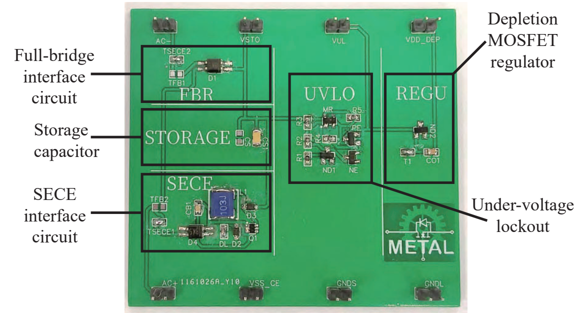

Fig. 4: Evaluation PCB of the proposed power management circuit.

Most SoCs for IoT applications can run within a wide voltage range. When use BSS159N depletion-mode NMOS as a simple regulator, for example, the simulation result of output voltage versus output current is given in Fig. 3(b). At open-circuit condition, the regulator can provide a voltage no higher than 2.8 V. When the load current is 10 mA, a heavy load condition for a normal SoC, the output voltage is about 2 V. The 2∼2.8 V regulated output voltage interval falls within the acceptable voltage range of the SoC in use.

C. Design Considerations

The applications of the proposed circuit is not limited to those in piezoelectric energy harvesting (PEH). It can be reconfigured to fit other energy sources and interface circuits. In the front end, the interface circuit can be replaced with SECE (synchronized electric charge extraction) or SSHI (synchronized switch harvesting on inductor) interface circuits to enhance the harvesting capability for PEH. The proposed circuit solutions are also applicable to other micro-power sources, such as small solar cells and thermal energy harvesting devices. In the downstream end, if the load device draws higher instantaneous current, the regulator should be replaced with a general dc/dc converter or a commercial LDO, which has stronger load driving capability.

III. Experiments

To evaluate the effectiveness of the proposed power management circuit, we design several experiments. The PCB prototype is shown in Fig. 4. Component information is provided in Table I. These experiments cover several aspects. a) The effectiveness of proposed wake-up circuit. b) The performance of the proposed power-management solution, in particular, its improvement compared with a commercial PEH chip LTC-3588.

A. Under Voltage Lockout

First, the voltage hysteresis of the wake-up circuit can be obtained based on the default parameter provided in Table I. The voltage across the storage capacitor is swept back and forth, to record the regulated output voltage. The result is given in Fig. 5(a). With the default parameters, the UVLO circuit can turn on and off at certain voltage thresholds. It provides the voltage at a suitable logic level and the sufficient energy

TABLE I: Circuit parameters in experiment.

Parameter	Value/Type	Parameter	Value/Type	Parameter	Value/Type
Q_1	BSS169N	Q_2	BSS123	Q_3	BSS84
Q_4	BSS159N	$Q_{1,2}$	BCV62C	R_1	10 MΩ
R_2	15 MΩ*	R_3	62 MΩ*	R_4	33 MΩ
R_5	1 MΩ	C_S	47 μF**	C_O	1 μF
C_p	32 nF	V_{OC}	7.5 V	f	26.4 Hz

* Resistance can be tuned to define the on/off threshold.
** Capacitance can be used to define the stored energy.

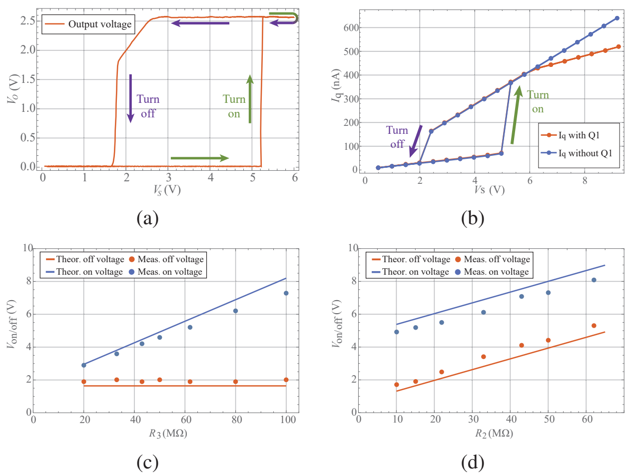

Fig. 5: (a) Output voltage, and (b) quiescent current under storage voltage sweep. Theoretical and measured on/off voltages under different (c) R_3 and (d) R_2.

gap for running a specific load event. In addition, the output voltage is relative stable at around 2.5 V during the on-state, which satisfies the design.

Fig 5(b) shows the quiescent current of the proposed wake-up circuit. Take the condition of $V_S = 4$ V for example, the quiescent current is 55 nA at off-state, and 268 nA at on-state. Such a low dissipation can satisfy the demand in battery-free scenarios. By comparing the blue and orange curve in Fig. 5(b), the improved implementation with depletion NMOS Q_1 can effectively reduce the quiescent current when the storage voltage is higher than 6 V.

Fig. 5(c) and (d) shows that the threshold voltage can be tuned by changing the resistance values of R_2 and R_3. R_3 defines the gap between the on/off thresholds. R_2 defines the absolute value of turn-off threshold. The theoretical and measured results in Fig. 5(c) and (d) show a good agreement. They validate the effectiveness and predictability of the proposed UVLO circuit.

B. Performance

To evaluate the performance of the proposed wake-up circuit, we used a Bluetooth transmitter in the EH-IoT development platform ViPSN [5] as the load IoT device. ViPSN sends out one package per second when powered on. The parameters of the evaluation circuits and piezoelectric sources are provided in Table I. The waveform of the proposed

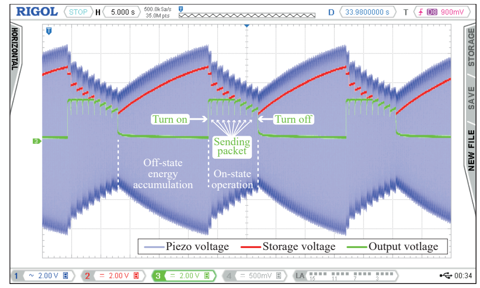

Fig. 6: Waveform in operation when using the piezoelectric source and FBR as the ac/dc interface circuit.

TABLE II: Transmitted packets in 140 s under the same excitation.

Interface circuit	PM solution	Transmitted packets
FBR	LTC-3588	20
FBR	Proposed	48
SECE	Proposed	70

wake-up circuit using a full-bridge rectifier (FBR) as the piezoelectric interface circuit is given in Fig. 6. When the storage voltage (red curve) reaches 5 V, the wake-up circuit start to provide a regulated voltage (green curve) to the IoT transmitter. When the transmitter is activated, the stored energy is consumed gradually. When the storage voltage drops below 2 V, the wake-up circuit turns off the output. Another energy build-up process starts; therefore, energy is accumulated again in the storage capacitor.

We compare the three power management setups by counting the number of packets transmitted by ViPSN. Under the same excitation condition during the same period, the more transmitted packets imply better performance. The circuit setup and the packet numbers are listed in Table II. From the table, the FBR and LTC-3588 combination scores the lowest performance. The UVLO inside LTC-3588 has a relative higher on-threshold voltage and a narrower hysteresis window. Therefore, the load is frequently turned on and off. More power is consumed because of the frequent initialization. We also investigate the performance of the combinations of different interface circuits and the proposed wake-up circuit. SP-SECE (self-power SECE) interface circuit can achieve better performance than FBR.

IV. Conclusion

This paper has proposed a nano-power wake-up and regulation circuit. The proposed circuit can be applied to IoT devices powered by low-power sources in energy harvesting scenarios. It is built with only a few discrete components and manages to reduce the size, cost, and quiescent current. The circuit can wake up or turn off the IoT load devices according to the handily configurable voltage thresholds. When being activated, it also provides a regulated output voltage to power the IoT devices without consuming extra quiescent current. The experimental results have validated the effectiveness and good performance of the proposed design.

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