Applications of MEMS-MOSFET Hybrid Switches to Power Management Circuits for Energy Harvesting Systems

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Abstract

A hybrid switch that uses a microelectromechanical system (MEMS) switch as a gate driver of a MOSFET is applied to an energy harvesting system. The power management circuit adopting the hybrid switch provides ultralow leakage, self-referencing, and high current handling capability. Measurements show that solar energy harvester circuit utilizing the MEMS-MOSFET hybrid switch accumulates energy and charges a battery or drive a resistive load without any constant power supply and reference voltage. The leakage current during energy accumulation is less than 10 pA. The power management circuit adopting the proposed hybrid switch is believed to be an ideal solution to self-powered wireless sensor nodes in smart grid systems.

Key words: MEMS-MOSFET hybrid switch, Energy harvesting, Power management circuit, Ultralow leakage, Self-referencing, Wireless sensor nodes, Smart grid

I. INTRODUCTION

Batteries are widely used to power wireless sensor nodes and mobile devices, but they require periodic exchange or recharge. Instead of batteries or as an energy source for recharge, the harvested energy from light, heat, or vibration available in our environments can be utilized for low average power electronic devices that have a very low (< 1%) operation duty cycle [1], [2]. Power monitoring sensors in a smart grid system require power source, but it is impractical to intervene the high voltage power line to draw low power necessary to drive each low voltage sensors. Recently, researchers in power electronics pay attentions to power management circuits for energy harvesting due to the particular characteristics of environmental energy [3]-[7]. However, most of these reports can be applied when the harvested power is high enough to drive the system. In realistic environments, the harvested power is usually on the order of microwatt that is less than or equal to the same order of sleep mode power, and it varies significantly over time and is sporadic in some cases [8]. Therefore, the harvested power should be accumulated in a storage capacitor over time and the

storage capacitor should be disconnected from the load during the energy accumulation stage to prevent energy leakage to the load. The storage capacitor is supposed to be connected to the load only if the accumulated energy is large enough to drive it. This means that the accumulated energy should be monitored all the time. Furthermore, in case of a wireless sensor node, after it completes sensing, data processing, and RF data transmitting, the storage capacitor should be disconnected again from the sensor node for the next energy accumulation stage. The serious problem in this autonomous scenario is that all of these functionalities require a certain amount of energy, but the only available energy is the precious harvested energy. Some of these functionalities without any stable voltage source have been partially realized by the MIT Media Laboratory group using a bipolar junction transistor (BJT), a zener diode, a MOSFET, and the low-battery-out function of a voltage regulator for a shoe-mounted piezoelectric harvesting system [9]. In this case, however, the energy loss due to the leakage currents flowing through the BJT and zener diode is inevitable during the energy accumulation stage. The electrostatically actuated microelectromechanical system (MEMS) switch might be a good candidate to provide these functionalities without any constant voltage source. Yet, it suffers from a low current handling capability and a short lifetime at the elevated currents [10]. The MEMS-switch-based power management architecture has been reported recently, but it requires reference

voltage of -20 V [11].

In this paper, we introduce the operation of the electrostatically actuated MEMS switch that has a low actuation voltage, and an autonomous operation of the harvesting circuit utilizing the MEMS-MOSFET hybrid switch for capacitive and resistive loads, without any stable power source. In the MEMS-MOSFET hybrid structure, the MEMS switch is used as a gate driver of a MOSFET. The typical example of a capacitive load is a rechargeable battery used in wireless devices such as wireless sensor nodes and mobile electronics. The result for a resistive load has been published in our previous paper [12], but it is included here again to introduce more detailed analysis and to cover up all the possible applications of the hybrid switch to the energy harvesting system. Using a fabricated MEMS switch, the MEMS-MOSFET hybrid switch is constructed and two major application circuits of energy harvesting, which are a battery charging circuit and a load driving circuit, are built and experimental results are presented.

II.   MEMS-MOSFET HYBRID SWITCH

Fig. 1 shows a schematic diagram of a MEMS-MOSFET hybrid switch in which the MEMS switch works as a gate driver of the MOSFET switch. The MEMS switch consists of a single crystal silicon moving part and a glass substrate. The basic structure and fabrication process of MEMS switch is similar to those reported, and the MEMS switch was used as an RF signal switch [13], but in this work, the process is modified to reduce further the actuation voltage.

In the MEMS switch shown in Fig. 1, A and B are the signal lines which are separated physically with a 2.5-μm gap, and A is connected to the moving part. As a contact area, gold is deposited on the bottom of the moving part. The moving part is suspended by an elastic force of the springs, and C is connected to an electrical ground.

When the voltage between the moving part and C is increased to a certain voltage, the electrostatic force becomes larger than the elastic force of the springs; hence, the moving
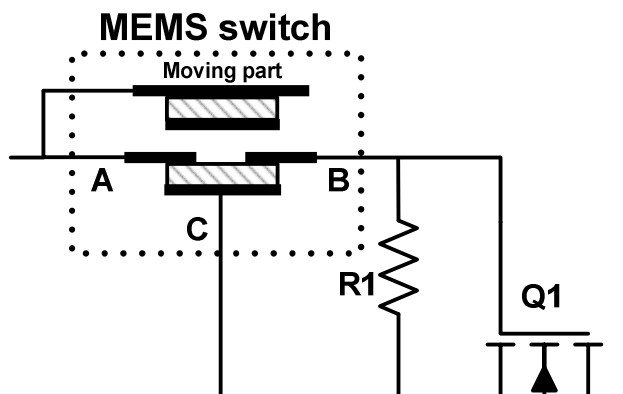
part goes down and the contact area connects A and B. This voltage is called the pull-in voltage of the MEMS switch. It enables the electrical signal to be delivered from A to B. When the voltage decreases under a certain level, the electrostatic force becomes smaller than the elastic force of the springs. Consequently, the moving part goes up, which disconnects A from B. This voltage is called the release or pull-out voltage of the MEMS switch.   Since the signal lines are fabricated on a glass substrate and physically separated, the leakage current is almost zero during the off-state of the MEMS switch. Furthermore, since the pull-in voltage is always higher than the release voltage, the MEMS switch has a hysteretic property.

As shown in Fig. 1, the moving part is at the same potential with A and the MEMS switch works as a gate driver of the MOSFET. Therefore, as long as the voltage between A and C is lower than the pull-in voltage, the gate-source voltage is 0 V and keeps the MOSFET in the off-state. When the voltage between A and C increases to the pull-in voltage, A is connected to B and the gate-source voltage increases abruptly and the MOSFET switch turns on. When the voltage decreases under the release voltage, A is isolated from B and the gate-source voltage is discharged through R1 (a few MΩ) to 0 V and the MOSFET switch turns off. Due to the hysteresis of the MEMS switch, the MEMS-MOSFET hybrid switch does not require the pulse generating circuit to control the MOSFET switch.

Fig. 2 shows a photograph of a (a) fabricated and (b) mounted MEMS switch. Dimensions of the designed MEMS switch are as follows: thickness of the spring = 15 μm, width of the spring = 4 μm, thickness of the membrane = 70 μm, gap between the electrode and switch = 2.5 μm, and size of
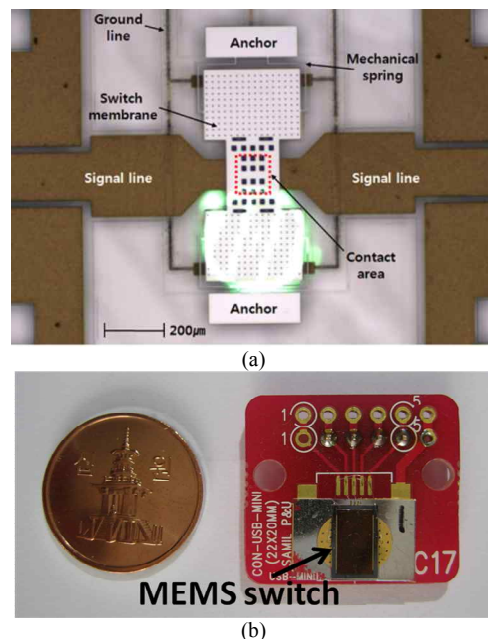

(a)

(b)

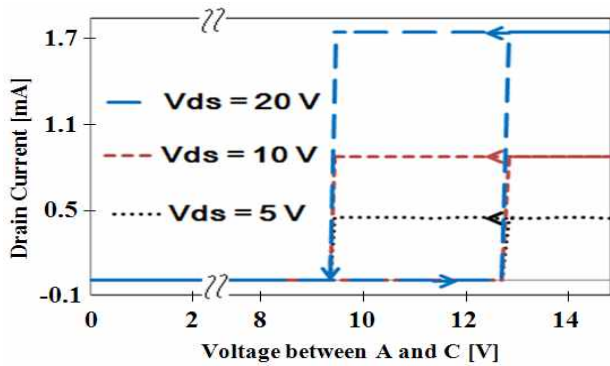Fig. 2. Photograph of a (a) fabricated [12] and (b) mounted MEMS switch.

Fig. 1. Schematic diagram of the MEMS-MOSFET hybrid switch. A and B are signal lines.

Fig. 3. Measured hysteresis characteristics of a fabricated MEMS-MOSFET switch.

the bottom electrode = 300 μm × 400 μm. Measured pull-in and pull-out voltages of the fabricated MEMS switch were 10 ~ 13 V and 8 ~ 9.5 V, respectively. These values are almost half of the values reported in [13].

The measured hysteretic property of a MEMS-MOSFET hybrid switch is shown in Fig. 3. In practice, the transition width would be zero volts, but the figure shows finite transition width due to the resolution limit of the dc power supply. The pull-in voltage and the release voltage of the MEMS-MOSFET hybrid switch are measured to be 12 V and 9.2 V, respectively. Since they are determined by the mechanical structure and properties of the MEMS switch, in contrast to Schmitt trigger or comparator, the hybrid switch does not require the use of stable dc power supply and reference voltage. Therefore, employing the hybrid switch can greatly simplify a circuit and save energy.

III. CIRCUIT OPERATION AND RESULTS

For the first demonstration, to simulate a rechargeable battery, a 470 μF capacitor is used as a capacitive load and a diode is included to prevent reverse leakage as shown in Fig. 4. As an energy harvester, we use four solar cells (with a total size of 55 mm × 27 mm) taken from commercial calculators. They are connected in series, generating an open-circuit voltage of 15 V on an office desk under indoor lighting conditions (300 lux).

Since the output power from the solar cells in this condition is very low, it should be firstly accumulated over
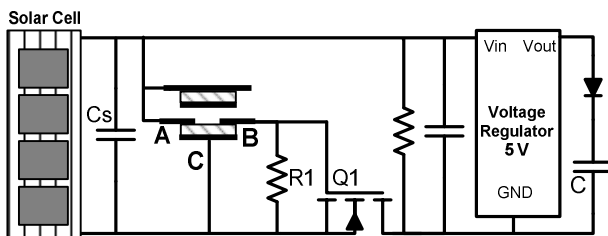

Fig. 4. A capacitor (rechargeable battery) charging circuit employing MEMS-MOSFET switch.

time in a storage capacitor CS (100 μF) until the accumulated energy is sufficiently high to drive the voltage regulator and the storage capacitor CS should be isolated from the following circuitry during this accumulation stage. Since the MEMS switch is normally off and gate of the MOSFET is grounded through R1 (5 MΩ), deactivated MOSFET Q1 makes the ground of the regulator floating (as shown in Fig. 3) and the stored energy is not discharged to the following part of the circuit. The resistor (750 kΩ) and capacitor (100 nF) on the input side of voltage regulator are used for impedance matching [9]. As long as the solar cells convert the light power to electric power, the capacitor voltage (upper trace) gradually increases toward the solar cell's open circuit voltage as shown in Fig. 5. This voltage is also applied to the MEMS switch so that the silicon membrane starts to deflect downward due to an electrostatic force between silicon membrane and electrodes, but it does not touch the disconnected signal lines. When the storage capacitor voltage reaches the pull-in voltage (12 V) of the MEMS switch, the switch membrane suddenly collapses down and the gold contact on the bottom of silicon membrane closes the signal lines underneath. The voltage of C_S, at this moment, is applied to the gate of the MOSFET and the MOSFET is turned on. Afterward, the grounds of the storage capacitor and the voltage regulator are connected through the MOSFET, and the stored energy is delivered to the voltage regulator to charge the load capacitor. The accumulated energy in the storage capacitor is transferred to the load capacitor, resulting in rapid decrease of storage capacitor voltage (upper trace) as shown in Fig. 5. It takes 15 ms (not resolved in this figure due to the long time scale) for the storage capacitor voltage to deceases from 12 V to 9.2 V (the pull-out voltage), but most of this time is the turn-on delay time of the voltage regulator (~14 ms).

When the storage capacitor voltage is reduced to the pull-out voltage of the MEMS switch, the switch membrane returns to the up-state position and opens the signal lines. The charges on the gate are discharged through R1 to ground and the MOSFET is turned off. Then the ground reference to the voltage regulator ceases, which makes the storage capacitor open-circuited and the next energy accumulation process resumes. Fig. 5 shows that this cycle autonomously repeats until the load capacitor voltage (lower trace) increases stepwise to reach the final full-charge voltage and then the charging process ceases.

The final full-charge voltage (4.4 V) is determined by the regulator voltage (5 V) and forward voltage drop (about 0.6 V) of the diode. Whenever the voltage of the load capacitor (or rechargeable battery) decreases for some reason, the cycle repeats except when the storage capacitor is charged again starting from the last voltage of it. The advantage of this circuit is that the energy accumulating and charging is possible under the very low illumination. During the accumulation stage, since the signal lines fabricated on glass substrate are physically separated, the leakage through the glass substrate is less than 1 pA and out of measurement
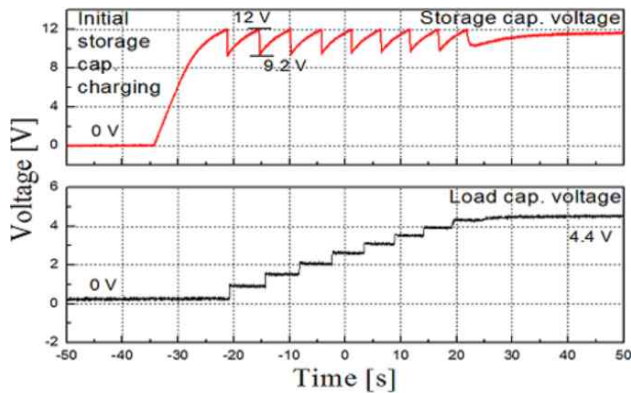
Fig. 5. Photograph Storage capacitor voltage (upper trace) and load capacitor voltage (lower trace).

Fig. 6. A resistive load driving circuit employing MEMS-MOSFET switch and measurement circuit.

range of picoammeter. In addition, since the gate of MOSFET is grounded through R1 during the accumulation stage, the drain-source leakage current is negligible. Measurements show that the leakage current is less than 10 pA, which means it is almost completely isolated.

If the solar cells are directly connected to the voltage regulator without the MEMS-MOSFET hybrid switch under very low lighting conditions, all of the output power generated by the solar cells is consumed to supply the quiescent power of the regulator without any output; therefore, the load capacitor (battery) can never be charged. Also, when the semiconductor automatic connection circuit [9] is used, a few tens of nA leakage through BJT and zener diode develops a few mV on the gate. In spite of the fact that this gate voltage is lower than the threshold voltage of the MOSFET, the sub-threshold drain-source leakage current flows. This sub-threshold current exponentially increases as the gate voltage increases, which also results in the failure of energy harvesting. Moreover, when the MEMS switch is used alone as a main power line switch without the MOSFET, the MEMS switch fails after a few cycles due to the initial high peak charging current.

During the on-time of the MEMS switch, when the 100 µF storage capacitor voltage decreases from 12 V to 9.2 V in 15 ms, it discharges 3 mJ while R1 consumes only 0.3 µJ (0.01%). Therefore, the energy harvesting circuit with our MEMS-MOSFET hybrid switch makes it possible to harvest energy and recharge the battery even if the generated power is extremely low in solar, piezoelectric, or thermoelectric energy harvesting systems.

The second demonstration with a resistive load, which was published in our previous paper [12], is presented here again to introduce more detailed analysis and to cover up all the possible applications of the hybrid switch to the energy harvesting system. In this demonstration, a series-connected current limiting resistor and an LED are used as a resistive load as shown in Fig. 6. The LED and resistor draw a current of 20 mA at 5 V. In a practical application, this resistive load can be a sensor circuitry that includes sensors, a microprocessor, and an RF transmitter. As long as the solar cells convert the light power to electric power, the capacitor
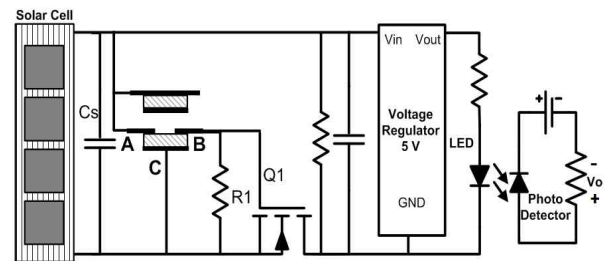
voltage increases to the solar cell's open circuit voltage. As soon as the storage capacitor voltage reaches the pull-in voltage (12 V), the MEMS switch and MOSFET are turned on as in the first demonstration. Since the voltage regulator supplies constant voltage to the resistive load in this case, the storage capacitor voltage decreases linearly due to the constant power dissipation of the resistive load. The MEMS switch, however, does not return to its original position immediately because the electrostatic force is still larger than the restoring force of the mechanical springs. As the storage capacitor reduces closer to the pull-out voltage of the MEMS switch, the MEMS switch turns off, followed by the deactivation of MOSFET as in the first case.

Fig. 7 shows the storage capacitor voltage (upper trace) and the LED output (lower trace) measured with a photodetector as shown in Fig. 6. This LED/photodetector measurement configuration is used as a photocoupler in order to keep ground isolation during the synchronous measurement of two waveforms as shown in Fig. 7. Note that the whole cycle of accumulation, energy delivery and next energy accumulation processes are autonomously repeated as long as the light is incident to the solar cells. The higher the incident light power is, the higher the repetition rate is. To accomplish this operation without our MEMS-MOSFET hybrid switch, a comparator [14] or Schmitt trigger circuit can be used; however, these components require another external stable power source for the operation and reference voltage, which consumes energy all the time. In this demonstration, the discharging time is about 300 ms and predominantly determined by the impedance of the resistive load rather than the turn-on delay time of the voltage regulator. During the discharge of the 100 µF storage capacitor from 12 V to 9.2 V in 300 ms, it discharges energy of 3 mJ and while R1 consumes 6 µJ since on-time of the hybrid switch is 20 times longer than that of the first demonstration. Therefore, when the load is capacitive, a regulator with short turn-on delay time should be used for the efficient charging. When the load is resistive, the operation time should be minimized for the efficient operation, which means that high frequency data transmission is more beneficial in wireless sensor nodes if the power consumption RF transmitter is constant over the carrier frequency.

Using the results mentioned above, the hybrid switch seems to be applied to reduce the standby power. Absolute
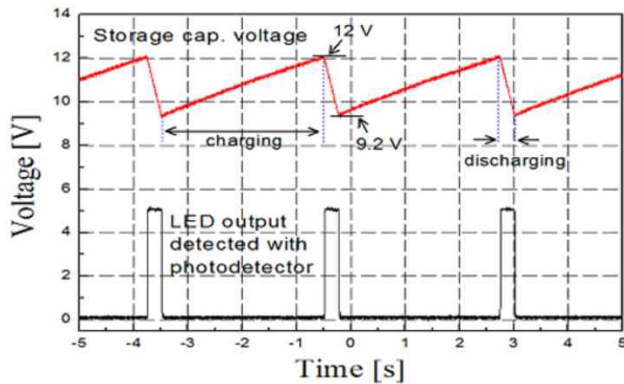
Fig. 7. Storage capacitor voltage (upper trace) and LED output measured with a photodetector (lower trace).

zero standby power has been achieved using laser light power transmission in [15]. Since semiconductor switches were used to control the power relay that switches 220 V power line in that report, it took several seconds to turn on/off the appliance due to the losses in semiconductor switch. We are working to replace the semiconductor switches with hybrid switch and it is believed that the turn on/off time and required laser power would be further reduced.

The first advantage of the MEMS-MOSFET hybrid switch is near-zero power loss in the energy accumulation process. Since the signal lines of the MEMS switch are fabricated on the glass substrate and physically disconnected, the leakage through the glass substrate is negligible (less than 12 pA). When semiconductor devices are used as in the MIT circuit, the inevitable leakage current (order of 1 nA) through a BJT and a zener diode prolongs the storage time. To make the matter worse, charge buildup on the gate of MOSFET and following gate voltage increase due to this leakage current force the MOSFET operate in the subthreshold or triode region, which could result in the failure of ground floating and, consequently, the failure of energy accumulation. The second advantage is its simplicity and ultralow operation power. The pulse forming circuit composed of a few devices is replaced with a single MEMS switch for gate driving and, more importantly, MEMS switch requires neither any external power supply nor any reference voltage that consume power all the time. Finally, since the main power is delivered to the load via the MOSFET and not the MEMS switch, a sufficient amount of current can be handled with this hybrid switch. We believe that these advantages make the MEMS-MOSFET hybrid switch a solution component in developing the practical energy harvesting power circuit for the self-sustaining wireless ubiquitous sensor network (WUSN), where sensor nodes are in standby mode for almost 99% of the time and harvested energy is limited. Power dissipation in the gate resistor R1 during on-state of the MEMS switch might be problematic, but the operation duty cycle is so small in the practical WUSN that the dissipation in the resistor has little effect on the performance.

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