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Research Article
Hybrid Energy Harvester Based on Radio Frequency, Thermal and Vibration Inputs for Biomedical Devices

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Abstract
Background: Energy harvesting is the process that uses ambient energy from the environment to produce electricity and thus replacing existing sources of power supply especially the battery. Due to increasing demand of energy harvester in the low power electronic applications, the researchers have been encouraged to review and study about this system. Most of them are focusing on improving the rate of efficiency and sensitivity of the system. **Materials and Methods:** In this study, a combination of three sources, which are Radio Frequency (RF), thermal energy and vibration are used as the input of energy harvester. Input of the thermal energy is in the Direct Current (DC) form and the voltage is set to 0.02 V. In contrast, the energy harvester of vibration and RF energy provides inputs of Alternating Current (AC) form. The RF energy harvester using input power as low as -20 dBm, which is equivalent to 32 mV at an operating frequency of 915 MHz while vibration energy harvester is set to 0.5 V at an operating frequency of 10 Hz. A full-wave rectifier is used in the vibration energy harvester to convert AC signal to DC signal. Meanwhile, RF energy harvester uses voltage multiplier circuit because it is capable to double the input voltage and rectify the voltage simultaneously. The voltage multiplier circuit is built using a substrate modulation technique. The voltage adder circuit is one of the most important part of energy harvesting circuit to integrate all the individual energy harvester circuits into a single system. All the circuits are designed, modeled and simulated using PSPICE software. **Results:** This system is able to achieve approximately 2.8 V output voltage across the resistor load of 1 M. **Conclusion:** The combination of all the energy sources; RF, vibration and thermal energy has been able to produce sufficient output voltage to power the biomedical devices.

Key words: Energy harvester, voltage multiplier circuit, full-wave rectifier circuit, thermal energy circuit, voltage adder circuit

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Now a days, most of the electronic devices can generate their own power with low cost and easy maintenance. This factor leads to increasing demand for wireless sensor and wearable devices. There are many ambient sources around us such as thermal energy, vibration, photovoltaic, RF and solar. This technology is an alternative way to replace the battery especially in rural area that often require a risky maintenance process. Development of energy harvesting systems is also a significant work in biomedical field by extending the battery life of the healthcare monitoring sensors. Three types of input energy source are selected for this proposed energy harvesting system; RF, thermal energy and vibration. The combination of these sources is inspired to overcome the problem of limited power produced by a single input source. In addition, it is one of the solution to ensure the energy sources is supplied continuously to achieve operational autonomy[1]. For example, if one of the input source is not available or too low to be detected, another sources will be used. Out of these type of sources, RF input is available everywhere and at anytime either day or night. The RF energy harvester can be defined as the process of absorption of propagation wave from our surrounding and convert it into useful electrical energy without requiring any external power source[2]. In this study, the ultra high frequency is set to 915 MHz as the operating frequency since RF signal could propagate easily at greater distance in this condition. The power loss also low compared to the power loss at higher frequency band[3]. Thermal energy harvester refers to the heat imposed on two different metals. The temperature difference between these two metals will produce a potential voltage which is directly proportional to temperature difference. This effect is known as the Seebeck effect, which was discovered by T.J. Seebeck in 1821. Electrical current will flow continuously in a circuit when junctions on a closed circuit consisting of two different metaNs are maintained at different temperatures[4]. The resulting voltage is relatively low, at only a few millivolt only. Meanwhile, the vibration energy harvester is generated from an operation of engine system or human movement such as walk, run or clapping. There are three methods for generating a vibration energy such as piezoelectric, electrostatic and electromagnetic. The performance of a system is determined by the output voltage, the efficiency and the minimum input power required. Figure 1 shows the basic block diagram of hybrid energy harvester system that combines all the inputs.

MATERIALS AND METHODS

There are several circuits to be emphasized and discussed in this study; 2-stages voltage multiplier circuit, full-wave rectifier circuit, voltage adder circuit, boost converter circuit and voltage regulator circuit. All the circuits are incorporated to produce a hybrid system.

Stages voltage multiplier circuit: For this system, two levels of voltage multiplier circuit has been designed to convert the input voltage of Alternating Current (AC) to Direct Current (DC) and subsequently increase the input to a higher level. The MOSFET acts as a diode when drain and gate terminal connected on the same node[5]. An N-type MOSFET has been selected and is modified for this circuit design. However, there is a constraint such as large threshold voltage of the MOSFET if compared with the amplitude of the input signal[6]. Therefore, modulation substrate technique has been used to reduce the threshold voltage, V_{th}, thus increase the efficiency of the circuit[7]. The parameters of the MOSFETs are programmed according to Predictive Tecnology Model (PTM), which is referring to 0.13 μm CMOS technology. One of the advantages of diode connected transistor is it has low leakage current. The structure of voltage multiplier circuit has been considered for designing the RF to DC converter because it is able to convert both positive and negative wave input signal. Another advantage is it can be arranged in stages to produce a high output. The number of voltage multiplier stages is

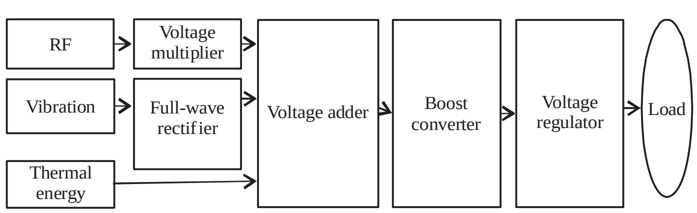

Fig. 1: Basic block diagram of a hybrid energy harvester system

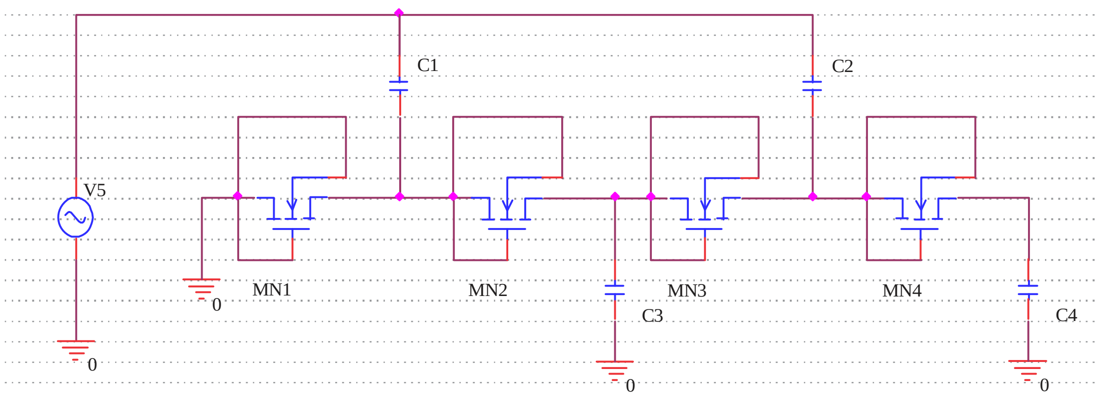

Fig. 2: Two stages voltage multiplier circuit

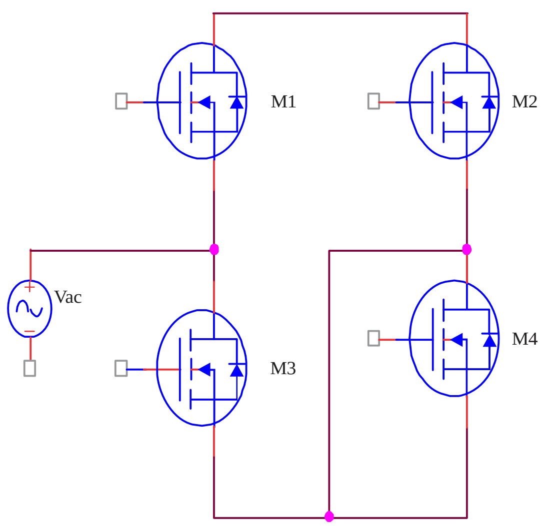

Fig. 3: Full-wave rectifier circuit

important because the parasitic effect is increased if too many stages are used while the voltage generated may not enough if too few[8]. Therefore, the number of stages need to be optimized to obtain the best performance.

Figure 2 shows 2-stages voltage multiplier circuit. The circuit has been designed using two NMOS connected diodes and two capacitors of 10 pF for each stage. The width and length value of the MOSFET have been assigned to 37.5 µm and 130 nm respectively. During the negative half cycle of input, MOSFET MN1 and MN3 is in the ON state while the MN2 and MN4 is in the OFF state and for the next cycle, the process is vice versa, MN1 and MN3 is in the OFF state while MN2 and MN4 is in the ON state.

Full-wave rectifier circuit: The full-wave rectifier is a circuit which has the same function as the voltage multiplier, which will convert AC to DC signal. This is very important because most of the applications use DC source to function. However, the significant difference between the two circuits are the output voltage generated from the rectifier circuit; the output voltage waveform has no effect on the input voltage[9]. There are three types of rectifier; half-wave rectifier, full-wave rectifier and bridge rectifier[10]. Basically, the existing rectifier circuit uses the Schottky diode and capacitor to rectify the voltage. However, the diode is not suitable for vibration energy harvester because there is a decrease in forward voltage as low as 0.1 V and thus reduce the efficiency of the system. To overcome this issue, the MOSFET which has a low constant resistance is selected to replace the diode.

In this study, the full-wave rectifier requires four MOSFETs, a resistor as a load and a capacitor as a filter to get output voltage without a ripple. For the first half cycle, the positive and negative polarity of the voltage source is ranked on the top and bottom, respectively. Figure 3 shows only MOSFET M1 and M4 operate in the positive half-cycle by generating a sine wave signal[11]. Meanwhile, on the negative half cycle, current will flow in the reverse polarity voltage thus the M2 and M3 MOSFETs will function.

Voltage adder circuit: All the input sources are combined using operational amplifier (op-amp) that consists of resistors and transistors on the same silicon. One of the op-amp is used to add or multiply the value of the applied voltage. The input sources are connected to the non inverting (positive terminal) op-amp. The purpose is to get the non inverted wave on the output voltage across the resistor.

Boost converter circuit: The output of op-amp will be used as an input to the boost converter circuit which will raise the low voltage using n-type MOSFET. This MOSFET has few advantages such as fast switching and can operate at a relatively high frequency[12]. This MOSFET is driven by Pulse Width Modulation (PWM) to control the switching duty cycle to obtain a high output voltage. In addition to the MOSFET, Scottky diode and inductor also have been used to avoid large voltage drop. Parameters on PWM controls the duty cycle of the MOSFET and plays an important role for increasing the voltage. The boost converter circuit is divided into two modes; continuous conduction mode and discontinuous conduction mode. During the whole switching cycle in continuous conduction mode, the inductor current flowing continuously and did not reach zero point. While for the discontinuous conduction mode, the inductor current is zero for part of the switching cycle.

Voltage regulator circuit: The output voltage of the boost converter circuit is unstable and is likely to be too high to be connected directly to the load. Therefore, the voltage regulator circuit is used to control and stabilize the output voltage. The voltage drop between the input and the output is controlled using a Bipolar Junction Transistor (BJT) to operate effectively on medium-high speed for voltage, current and low electric power. The resistor load of 1 MΩ is selected to represent biomedical applications and connected to the emitter terminal of BJT.

Hybrid energy harvester circuit: Each of the individual circuits are combined to produce a complete hybrid energy harvester system as shown in Fig. 4. The simulation tests are conducted for the circuit to analyze the efficiency of the system based on the output voltage. The experimental work is then extended to hardware implementation on a Printed Circuit Board (PCB). Test on the PCB is only for the hybrid of thermal energy and vibration because the MOSFETs used in 2-stage voltage multiplier need to go through a different process, namely fabrication on chip. This is due to unavailability of the component in the market. For RF harvester circuit, the process continues with Integrated Circuit (IC) layout to ensure that the simulated design can be fabricated in the future.

RESULTS

Simulation result of 2-stage voltage multiplier circuit: Figure 5 shows the simulation result of RF input, in AC form which valued as low as 32 mV converted into a DC voltage and has improved to 113.95 mV. With the combination of the rectifier circuit and the capacitor, the input has been multiplied to produce the largest DC output.

Simulation result of hybrid input thermal energy and vibration: The simulation for hybrid input of thermal energy and vibration is tested and compared with the hardware on the PCB. Figure 6 shows the simulation result of the input signal AC vibration (0.5 V) that obtains rectified signal DC voltage (0.25 V). The resulting output signal is half of the input signal. This result is better than the full-wave rectifier circuit using a diode. The main drawback of using diode is the voltage drop due to high threshold voltage. Figure 7 is an end result of the process simulation using 1 MΩ resistive load. The graph shows the output voltage proportional to the time and reach the output of 4.0 V after time 1 sec.

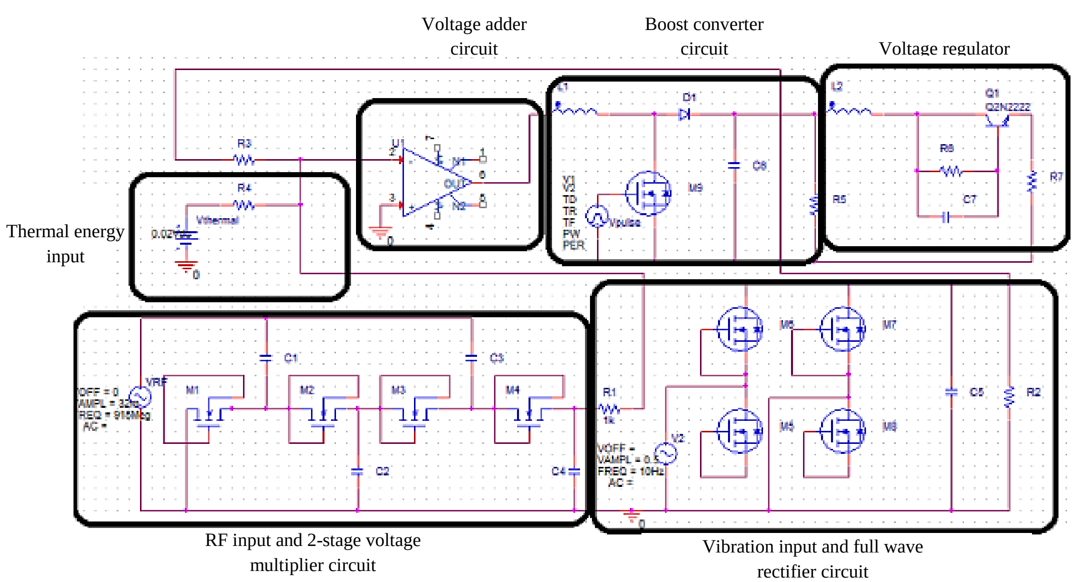

Fig. 4: Complete hybrid energy harvester

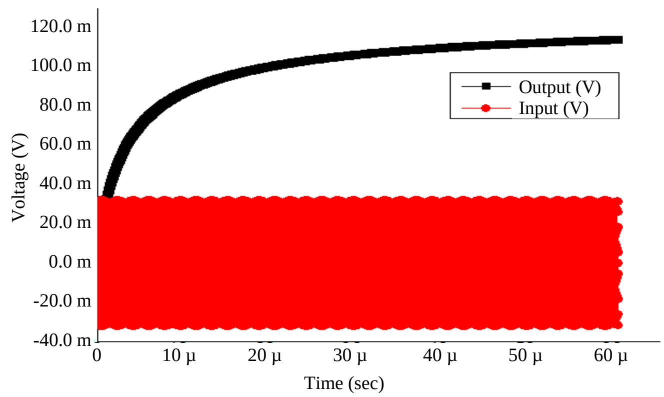

Fig. 5: Output voltage of 2-stage voltage multiplier

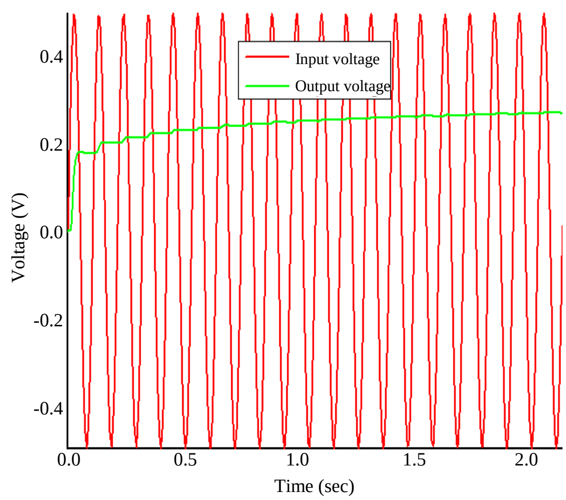

Fig. 6: Input and output voltage of full-wave rectifier

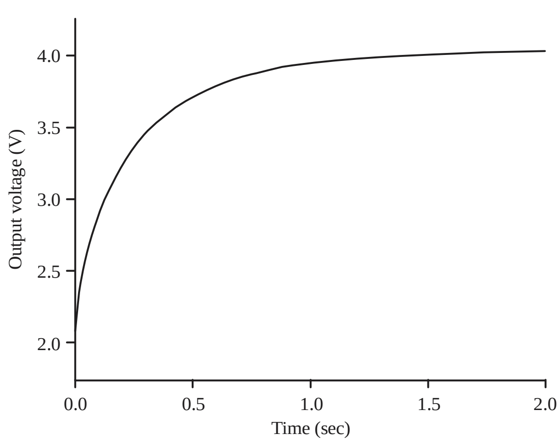

Fig. 7: Output voltage of hybrid thermal energy and vibration

Simulation result of complete hybrid energy harvester circuit: Low input voltage of each individual circuit is not being a big issue in this study because few inputs are combined together to produce more stable and high output voltage. The simulation result is tested for 10 sec and the voltage is initially increased drastically and dropped at time of 1 msec then become a constant after 5 msec. The final result is approximately 2.8 V and is shown in Fig. 8.

Hardware implementation result on PCB of hybrid input thermal and vibration: The simulation of a hybrid of thermal energy and vibration was proceed to the next stage, namely the layout of circuit using Proteus Professional8 software for PCB generation. The circuit is arranged as shown in Fig. 9a with the size of 55×77.5 mm and the results generated on the PCB is shown on Fig. 9b. The result of output voltage is 3.94 V and this value is slightly lower than the simulation result due to the power loss during the experiment.

Implementation result of voltage multiplier circuit on integrated circuit: The proposed design of voltage multiplier

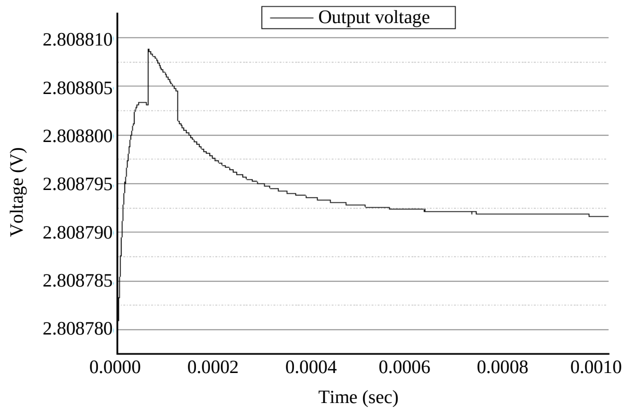

Fig. 8: Output voltage of complete hybrid energy harvester circuit

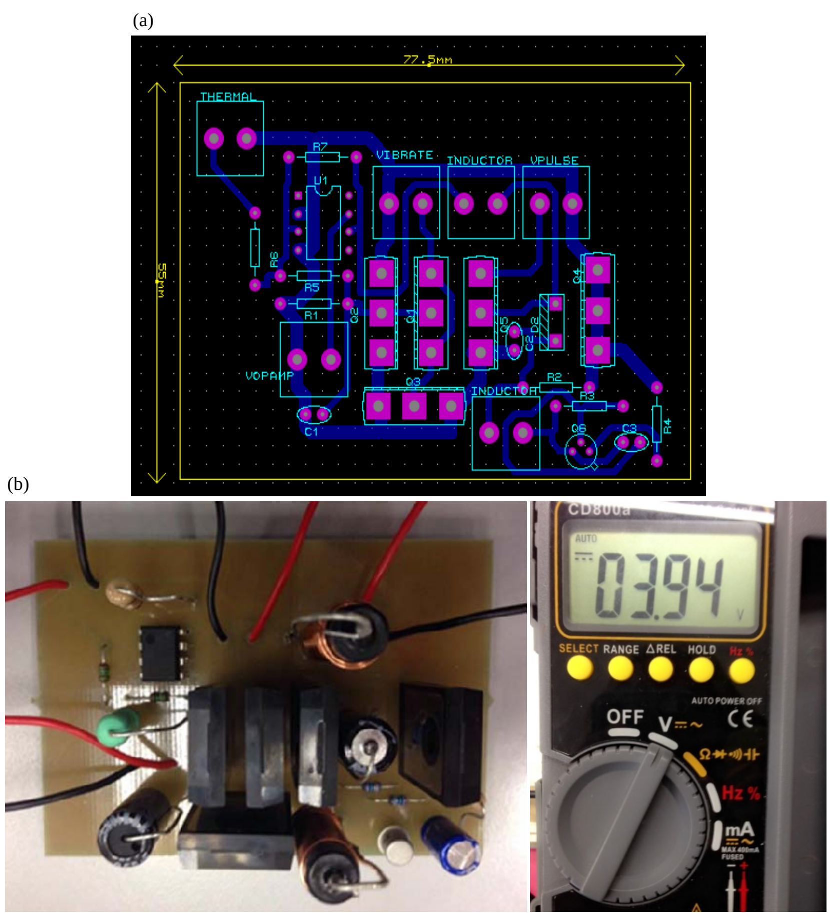

Fig. 9(a-b): (a) Layout and (b) Result of hybrid thermal energy and vibration on PCB board

circuit was transformed into Integrated Circuit (IC) layout on 0.13 µm CMOS process technology under silterra. This step is necessary to ensure that the modulation of substrate built fulfill the criteria for fabrication. Figure 10 illustrates the circuit layout for the single-stage voltage multiplier circuit. For this layout, capacitor fm 5 mL with sp_length valued 2.502 m was used. To represent a capacitor of 10 p, 6 blocks of fm 5 mL were arranged accordingly. Meanwhile for MOSFET, nm_hp has been selected from library of "Sil013 standard cells". Figure 11 shows the layers required for the substrate

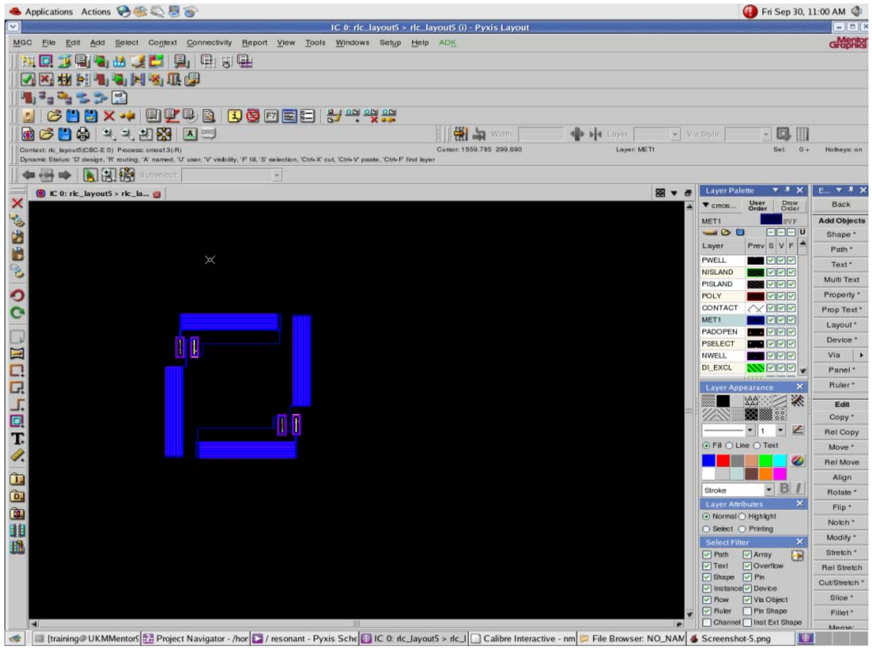

Fig. 10: Result of the integrated circuit for the voltage multipler using Mentor Graphics software

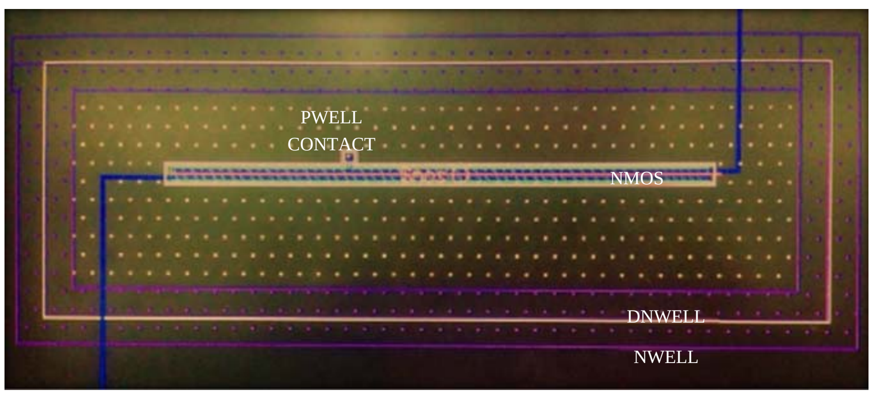

Fig. 11: Layout MOSFET with substrate modulation

Table 1: Comparison of input and output power for each sources

Source	Input power (W)	Output power (W)	Overall output power for hybrid energy harvester (μW)
RF	8.284×10^{-6}	1.47×10^{-7}	
Thermal	1.058×10^{-8}	5.29×10^{-9}	7.889
Vibration	2.414×10^{-8}	1.207×10^{-8}	

modulation. This integrated circuit has been tested through the Design Rules Check (DRC) and Layout Versus Schematic (LVS). The outcome shows error free in terms of size, dimensions and geometric distance. This proves that there is no difference between schematic circuit layout and integrated circuit built.

Comparison between input and output power of RF, thermal and vibration energy harvester: Table 1 shows the comparison between input and output power of every types of sources including RF, thermal and vibration. The overall output power for hybrid energy harvester is also included.

DISCUSSION

Energy harvester system catch high attention recently because it is able to harvest ambient energy from the environment and convert it into useful energy. Therefore, this system has been proposed to improve the existing system in terms of efficiency and sensitivity[13]. A combination of three circuits with different sources is to ensure continuity operation of a system without any interruption. For RF energy harvesting circuit, the modulation substrate technique in this circuit has contributed to low power applications. The number of stages in the circuit also has a significant impact on the DC output. This is because the output voltage is directly proportional to the number of stages[14]. For input of vibration, MOSFETs have been used as an alternative to replace diodes and to avoid voltage drop due to larger threshold voltage[15]. The voltage adder circuit works well for combining more than one source. Although the result is still low, boost converter circuit manage to increase it to the desired output voltage. The main factor that affects the circuit performance is by manipulating the initial value (V1), the pulse (V2), the time delay (TD), the rise time (TR), the fall time (TF), the pulse width (PW) and the period (PER) on the PWM. The voltage regulator circuit at the end of the system manage to control the resulting output voltage so that not exceeding the target value for low-power electronic devices. This energy harvester system is sufficient to supply power for biomedical applications and offers significant benefits over battery-powered solutions in term of low assembly and operational costs[16].

CONCLUSION

The energy harvester system proposed in this study successfully produces an output voltage of 2.8 V input from three ambient sources, namely vibration, thermal energy and RF. This energy harvester circuit is able to supply sufficient power and has potential as an alternative energy source. By combining these full-wave rectifier, voltage multiplier and voltage adder circuit, all ambient sources in our surrounding could be utilized. This system could be implemented in sensor devices for biomedical or other fields.

SIGNIFICANT STATEMENTS

This study introduces one system of hybrid energy harvester as an alternative for powering wireless sensor node. This system combines multiple sources as the inputs to overcome the limitation of single source. Radio Frequency (RF), thermal and vibration energy which are the inputs of this system can be absorbed from our surrounding and human's movement. The voltage adder circuit integrate all the individual energy harvester circuits into a single system. All the circuits are designed, modelled and simulated using PSPICE software. The architecture of simulated circuit is extended to PCB layout for hybrid thermal and vibration energy harvester while IC layout for RF energy harvester. This system is able to achieve approximately 2.8 V output voltage across the resistor load of 1 M. The output voltage is sufficient to prolong battery lifetime or powering biomedical devices.

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