Research Article

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Piezoelectric-driven Charging Supercapacitors for Biomedical Sensor Applications

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ABSTRACT

Piezoelectric materials can be fabricated as a generator to convert mechanical energy emitted by ambient vibrations into electrical energy that may be stored and utilized to power some ultra-low-power devices such as radio frequency identification (RFID) tags. Since most of the ultra-low-power devices are wireless, it becomes essential to have their independent power supplies. In tradition, the power supplies come from bulky lead-acid and lithium batteries, which have environment-unfriendly chemical ingredients. Most importantly, the lead-acid and lithium batteries have a limited life of 500-1000 cycles compared to millions or more for most commercially available carbon-based supercapacitors. With the introduction of many portable electronic device and health monitor device using piezo-based energy harvesting has become one of the fascinating subjects of interest to provide portable electrical power.

Keywords: Piezoelectric; Supercapacitor; Ultra-low-power devices; Wireless

1. INTRODUCTION

In distant power supply applications, piezoelectric energy harvesting has proved to be an innovative way to replace lead-acid and lithium batteries (Hofmann *et al.* 2003). Unfortunately, as shown in Fig. 1, the restricted power capacity and low output power efficiency limit the practical uses of energy harvesting in daily life. Following a review of current research on piezoelectric energy harvesting from the standpoint of power management, a circuit design focusing on low-frequency mechanical vibration is presented. Piezoelectric energy can be used for small-scale energy harvesting because of its high energy storage density. Energy harvesting involves harvesting electrical power convert and storing the harvested power. The reason for choosing piezoelectricity is because of its higher energy storage density, as it has been justified earlier, as shown in Fig. 4. In piezoelectric energy harvesting, the piezoelectric sensor is used as a harvesting element, and the storage element is a supercapacitor. Recent advancements in ultralow-power microcontrollers have resulted in devices with remarkable levels of integration for the amount of power used. These are chip systems that employ aggressive power-saving strategies such as turning-off power to idle functions. In fact, because these devices require so little power to operate, many sensors are becoming wireless since they can easily run on batteries. Unfortunately, batteries must be replaced on a regular basis, which is an expensive and time-consuming maintenance undertaking. Harvesting ambient mechanical, thermal or electromagnetic energy in the sensor's nearby surroundings may be a more effective wireless power solution (Fig. 2).

Analog devices have a large selection of ultra-low-power integrated circuits (ICs) for energy harvesting applications (Ottman *et al.* 2002). High-efficiency conversion to regulated voltages or to charge batteries and supercapacitor storage components is provided by power management devices that convert energy from vibration (piezoelectric), photovoltaic (solar) and thermal (TEC, TEG, thermopiles, thermocouples) sources. Industrial automation and control, wireless sensor, transportation, automotive and building management applications all benefit from boost converters that function from as little as 20 mV or battery chargers with maximum power point capabilities. Additional building elements for autonomous systems include ultra-low quiescent current linear regulators, op-amps, comparators, voltage supervisors, ADCs, DACs and micro-power voltage references, as shown in Fig. 3.

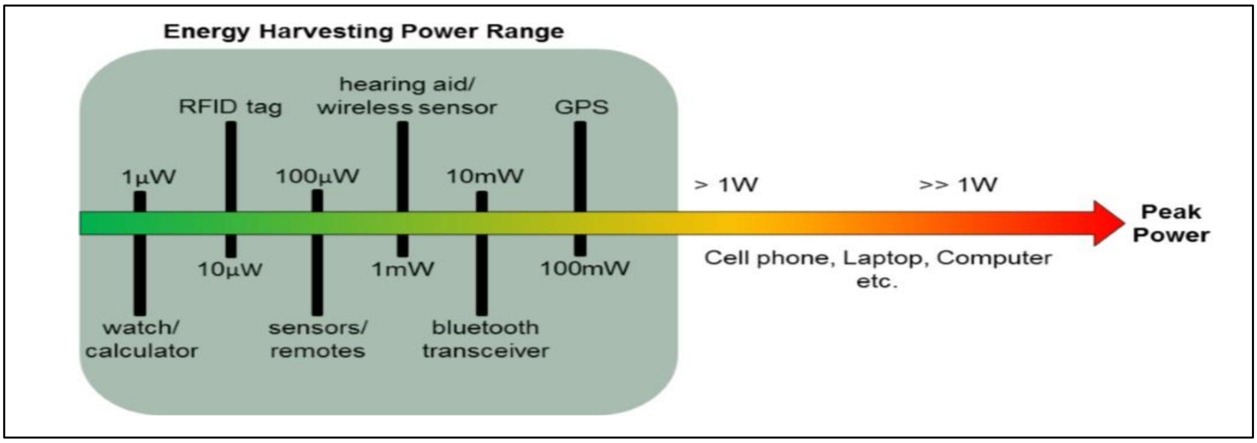

Fig. 1: Schematic diagram of Energy harvesting power range

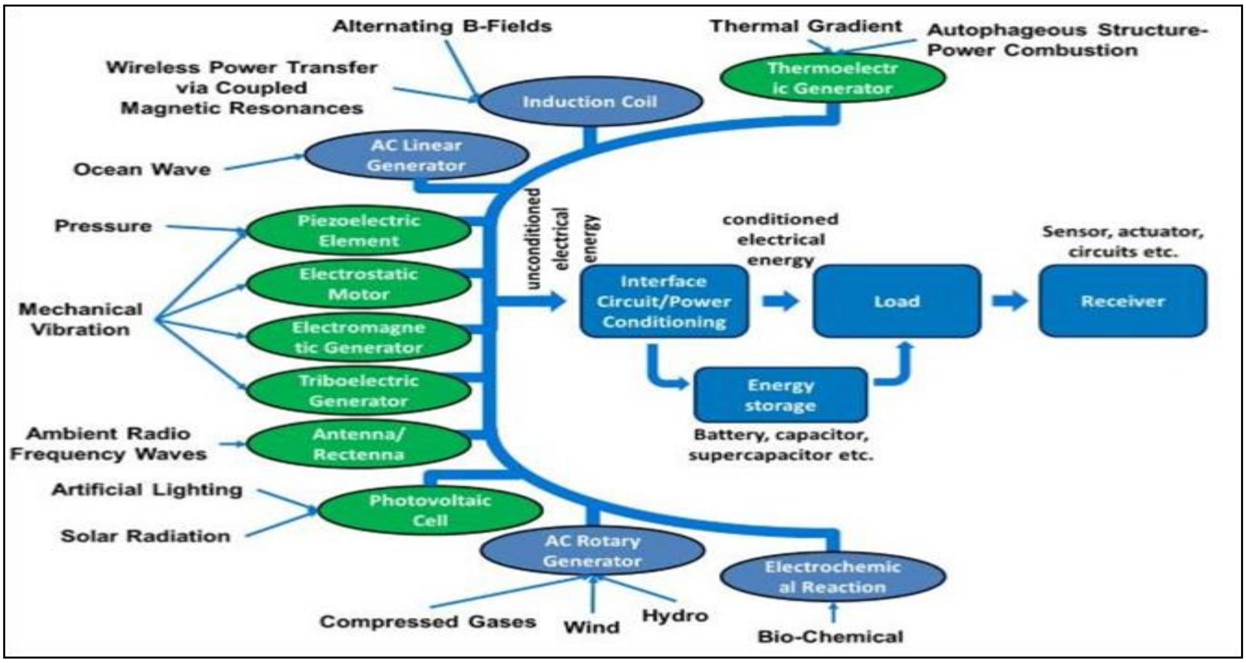

Fig. 2: Schematic diagram of ambient energy sources for energy harvesting technologies

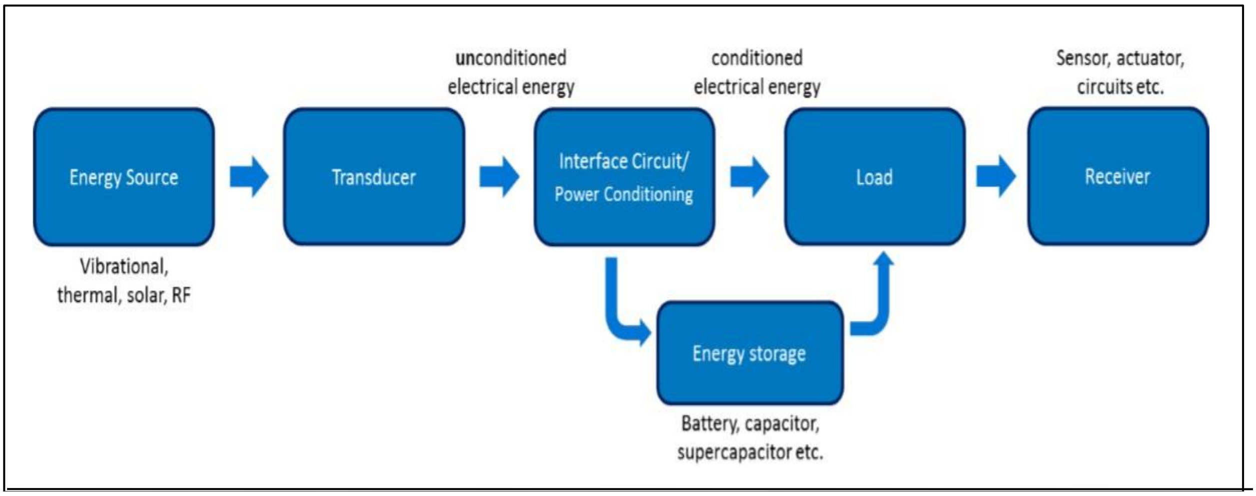

Fig. 3: Block diagram of Energy harvesting system

The environment has abundant energy, so energy harvesters are an ideal power source for IoT applications, eliminating the need to replace and dispose of batteries. However, small energy harvesters often cannot provide the peak power required to collect and transmit data. This article will show how to use a supercapacitor, charged from an energy harvester to provide the peak power required using a small solar cell as a case study. The typical power architecture has an energy harvester supplying a supercapacitor charging circuit with the supercapacitor directly supplying the load. The high carbon and low equivalent series resistance (ESR) of the supercapacitor maintain a sufficiently stable voltage for the load to function during peak power bursts.

2. MATERIALS AND METHODOLOGY

Light, heat differentials, vibrating beams, transmitted RF signals and any other source that may create an electrical charge through a transducer are examples of ambient energy sources. Some example are given below:

- Hand-held electronic gadgets have been powered by small solar panels for years; they can produce 100 s of mW/cm^2 in direct sunshine and 100s of $\mu W/cm^2$ in indirect light.
- When a temperature gradient exists, Seebeck devices transform heat energy into electrical energy. The sources of heat energy range from body heat, which produces 10 s of $\mu W/cm^2$, to a furnace exhaust stack, which produces 10 s of mW/cm^2.
- Piezoelectric devices generate energy either through compression or deflection. Depending on their size and manufacture, piezoelectric components may yield 100 s of $\mu W/cm^2$.
- An antenna collects RF energy, which may yield hundreds of pW/cm^2.

Power-saving microcontrollers and transducers that use minimum electrical energy from low-energy situations are required for creating a totally self-contained wireless sensor system (Le *et al*. 2006). The missing link is a high-efficiency power conversion product capable of converting the transducer output to a useful voltage, which is now easily accessible.

The LTC3588-1 is a full energy harvesting system, tailored for high impedance sources such as piezoelectric transducers (Fig. 6). It has a low-loss full-wave bridge rectifier and a high-efficiency synchronous buck converter that transfer energy from an input storage device to an output at a regulated voltage that can sustain loads up to 100 mA. The LTC3588-1 is available in 10-lead MSE and 3 mm × 3 mm DFN packages.

The energy source/transducer, an energy storage device and a mechanism to transform the stored energy into a well-regulated voltage are shown in Fig. 5. In the case of a piezoelectric device, a voltage rectifier network between the energy transducer and the energy storage element may be required to prevent energy from back-feeding into the transducer or to correct an AC signal.

Illustrations of use: The output voltage of the transducer must be greater than the under-voltage lockout increasing threshold limit for the particular output voltage defined at the D0 and D1 input pins, according to LTC3588-1. The energy transducer must have an open circuit voltage of double the input operating voltage and a short-circuit current of double the input current necessary for optimal energy transfer. To obtain continuous output power, these conditions must be satisfied at the source's minimum excitation level.

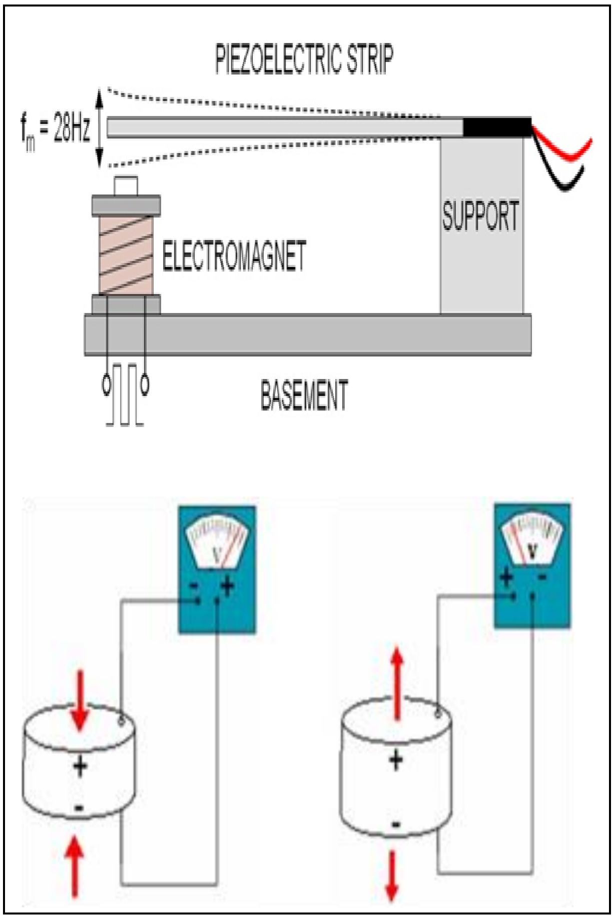

Fig. 4: Working principle of Piezoelectric materials

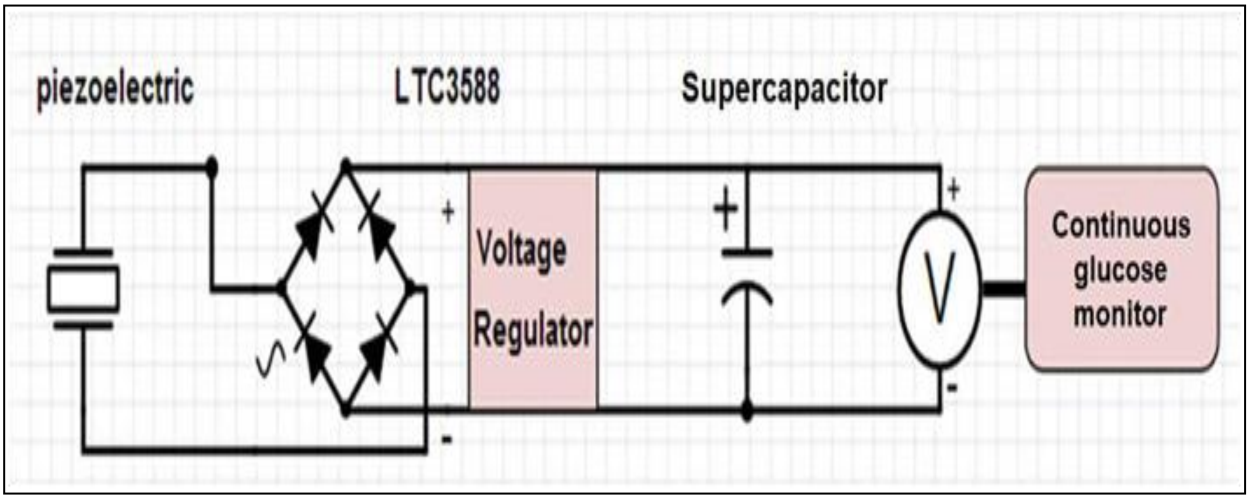

Fig. 5: Equivalent circuit diagram of Piezoelectric-driven charging Supercapacitor

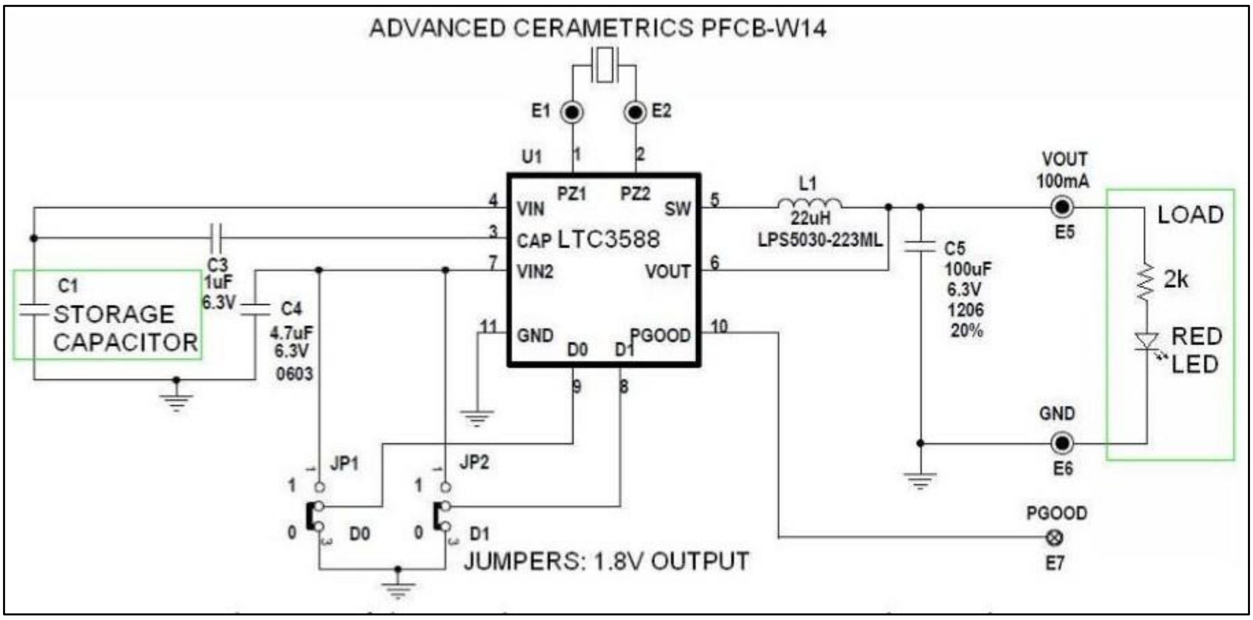

Fig. 6: Charging circuit diagram of Piezoelectric-driven charging Supercapacitor

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Fig. 1 depicts a piezoelectric device that produces 100 W of electricity at 3.3 V when put in an airstream. At a frequency of 50 Hz, the piezoelectric element deflects 0.5 cm.

Harvesting mechanical energy from human motion is an attractive approach for obtaining clean and sustainable electric energy. Piezoelectricity is electrical energy produced from mechanical pressure (such as walking and running). When pressure is applied to an object, negative charge is produced on the expanded side and a positive charge on the compressed side of the piezoelectric crystal. Once the pressure is relieved, electrical current flows across the material. The commonly used sources are solar power, wind energy, and piezoelectricity. This study is focused on piezoelectricity as it depends on the mechanical pressure or strains to obtain electrical energy, while the other sources are not reliable at all times. Piezoelectric technique has more energy storage density when compared with the other techniques.

3. RESULTS AND DISCUSSION

Piezoelectric sensors have to be positioned in two main parts of the shoe sole, where the maximum pressure is applied. A Piezoelectric generator is placed inside a shoe. A shoe has two points where the pressure exerted is maximum, and they are the heel and the toe, where the piezoelectric unit is placed. Fig. 7 shows the arrangement of the piezoelectric generator inside a shoe. A single sensor is capable of generating 3-5 V on the application of pressure consistently. In this work, four sensors were connected in parallel to increase the probability of getting maximum output. Piezo-polymeric materials are more advantageous to use than piezo-ceramic materials in sensor applications because polymeric films can be easily fabricated into different shapes. In spite of this fact, piezoceramic sensor has been used in this work since it was commercially available at a lower cost.

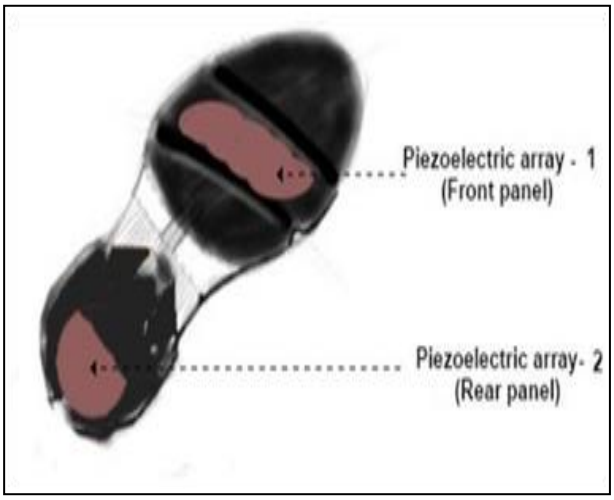

Fig. 7: Arrangement of piezoelectric generator inside a shoe

The design consists of a pair of an array of piezoelectric generator units connected in series. The Front panel has an array of piezoelectric generators in a linear arrangement and the rear panel has a circular arrangement. The receiving and charging sides collected intermittent or continuous energy input from the piezo-generator and efficiently stored their energy in the capacitor bank. During the charging process, the capacitor voltage was continuously monitored. When it reached 5.2 V, the module output was enabled to supply power to a rectifier and a charging unit.

A Piezoelectric disk-type generator was placed in the shoe. When a person walks, pressure is exerted on the ground, and this pressure can be converted into electrical energy, and it can be used to charge the Supercapacitor. This energy storage system can be used in biomedical sensor applications.

There are many researches that successfully realize energy harvesting in the labs, but the total power efficiencies of the designed systems are constrained by the trade-off among efficiencies of each subsystem. Some researchers pay more attention to maximizing the output power of the piezoelectric source, but the useful power stored in the energy buffer is degraded by the significant power dissipation of the regulator. Based on a systematic analysis of piezoelectric energy harvesting from a power management perspective, the maximum charging current of a supercapacitor with an optimized duty cycle was investigated.

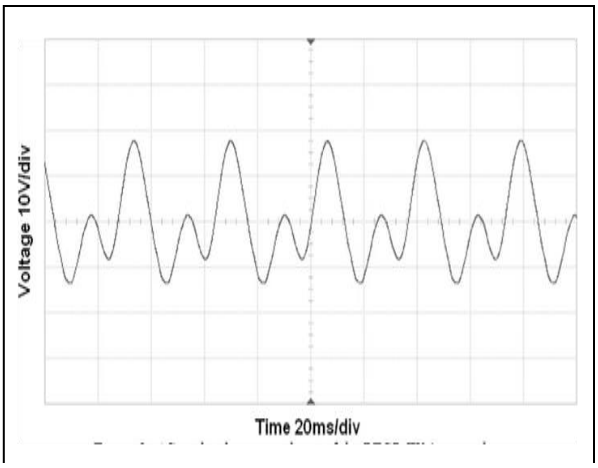

Fig. 8: Piezoelectric generator output voltage

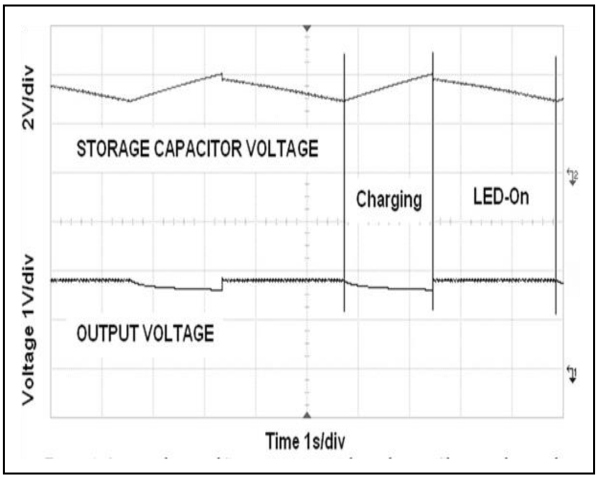

Fig. 9: Piezoelectric-driven Supercapacitor - charging and discharging characteristics

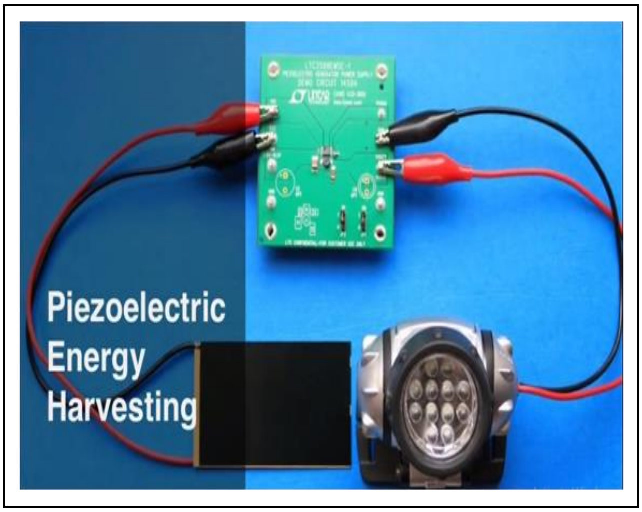

Fig. 10: Hardware implementation Piezoelectric-driven Supercapacitor setup.

Fig. 11: Piezoelectric-driven charging Supercapacitor

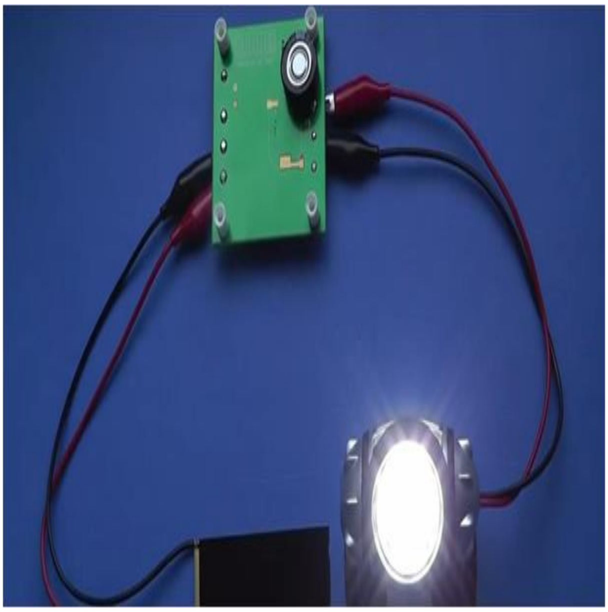

Fig. 12: Piezoelectric-driven charging Supercapacitor for LED Flash application

Fig. 13: Continuous Glucose Monitoring (CGM) Sensor, Receiver and Transmitter

The maximum charging current of a supercapacitor may be reached by adjusting the duty cycle of a buck regulator using software-applied pulse width modulation using a Piezoelectric disc type generator. Fig. 8 and Fig. 9 demonstrate the experimental findings, proving the capacitive electric model of the piezoelectric generator, the presence of the supercapacitor's maximum charging current and the adaptive control of the planned circuits.

Continuous Glucose Monitoring (CGM) systems track glucose levels throughout the day. CGM users insert a tiny sensor wire just under their skin using an automatic applicator is shown in Fig. 13. An adhesive patch holds the CGM sensor housing in place so the sensor can measure glucose readings in interstitial fluid throughout the day and night. A small, reusable transmitter connects to the sensor wire and sends real-time readings wirelessly to a receiver so that the user can view the information. With some systems, a compatible smart device with the CGM system app can serve as the display device. The receiver or compatible smart device displays current glucose levels, as well as historical trends in levels. The CGM receiver and/or compatible smart device can also be set to send custom alerts to the user when certain glucose thresholds are reached.

4. CONCLUSION

With the development of wireless sensor network and micro-electromechanical system technologies, intelligent sensors are developed to be embedded in remote locations, such as structural health monitoring sensors embedded in the bridges and medical sensors implanted in the human body, A CGM (Continuous Glucose Monitor) device that provides "real-time" glucose readings and data about trends in glucose levels, reads the glucose levels under the skin every 1-5 minutes (10-15 minute delay) and provides alarms for high and low glucose levels and trend information for diabetes management (Simjee *et al*. 2008). Obtaining the sensors to replace the batteries could be very time-consuming and expensive. In the embedded case, accessibility is even impossible and destructive. If a strain energy scavenging technology is realized, the life spans of the sensors could be extended significantly, or even the batteries themselves could be replaced.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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