A High Voltage Generator Utilizing a Single PZT Element with Series-Connected Electrodes

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***Abstract*—This paper presents a high voltage generator utilizing a single piezoelectric element (PZT, 5 mm in diameter, 740 µm thick) with electrodes series-connected via a flexible Kapton cable. High voltage pulses over 1 kV are generated in response to transient mechanical input loads. The response of high voltage generator is evaluated for stress range from 1 MPa to 5 MPa. The high voltage generator is successfully used to operate a microdischarge-based chemical vapor sensor by providing high voltage pulses to enable microdischarge sparks across a 75 µm anode-cathode gap.**

I. Introduction

For self-powered devices in microelectromechanical systems (MEMS), substantial efforts have been made to scavenge mechanical ambient energy and convert it into electric energy using piezoelectric materials [1, 2]. To date, most energy harvesting devices are designed to work in vibration mode and gather induced charges from piezoelectric materials. In general, the output voltages are limited within several volts or even less than 1 V. Lead zirconate titanate (PZT) is the most widely used piezoelectric materials due to its high piezoelectric coefficients and good electro-mechanical coupling. Research in energy harvesting using piezoelectric materials directed primarily at improving conversion efficiency of the energy harvesting system by selecting piezoelectric materials, optimizing electrode pattern, changing coupling modes and tuning the resonant frequency of the devices [1]. However, the study on energy scavenging with high output voltage and high power density has not been fully investigated.

High voltage (HV) sources are required for a number of microsystem requirements, ranging from electrostatic [3] and piezoelectric actuation [4] to microdischarge-based sensing. Miniaturized HV sources that scavenge ambient mechanical energy are of particular interest for microdischarge-based sensors in long term and self-powered integrated microsensing systems. A variety of sensors based on microdischarges, like radiation detector, pressure sensor in harsh environment, chemical sensor for gas chromatography etc., have been reported [5-10]. In those applications, the threshold voltages to initiate discharges are typically between 500 V to 1 kV.

Past efforts on microsystems with HV outputs based on piezoelectric materials were series-connecting several individual PZT elements together [11, 12]. This method increases the output voltage to some extent, but the voltage is still much lower than the threshold voltage for microdischarges due to limited amount of energy converted from vibration. In addition, the fabrication of multiple PZT elements can increase the system complexity.

This paper presents a new approach to HV generation utilizing a monolithic PZT51 element attached to series-connected electrode pattern through a flexible Kapton cable. The structure is used to initiate microdischarges in a chemical vapor sensor.

II. Device Design

A. Concept and Modeling

A schematic representation of the HV generator is shown in Fig. 1. A monolithic PZT disk (PZT51, 5 mm in diameter, 740 µm thick) is patterned with Au electrodes on both surfaces. The patterned disk is then sandwiched between a 75 µm thick flexible Kapton cable. Each pair of opposite electrodes on two PZT surfaces aligning along thickness direction forms one electrode pair. All three electrode pairs are series-connected by this cable, i.e., the top electrode of one pair is connected to the bottom electrode of another electrode pair. The bottom electrode of the first pair and the top electrode of the last pair are connected to the output pads on the Kapton cable. The output signal is measured at these output pads.

The PZT element operating in d33 orientation generates positive and negative charges along the polarization direction in response to the external mechanical stress applied in the same direction. For the PZT element used in this paper, the polarization direction is parallel to the thickness direction, which provides an electric potential difference between two sides of surfaces. In theory, the top and bottom surfaces of the PZT element are equipotential, so each of the three electrode pairs provides the same contribution to the total output voltage. When three electrode pairs are connected in series, the equivalent voltage output is the summation of every individual voltage.

The equivalent circuit model of the HV generator is also shown in Fig. 1. Each pair of electrodes is modeled as an individual capacitor with capacitance C_0. In generalized and ideal cases, this design concept could obtain output voltage up to $N \cdot V_0$, in which N is the total number of electrode pairs on the PZT element, V_0 is the voltage across each electrode pair. In the current configuration, the total output voltage is

Xin Luo was supported, in part, by a fellowship from the Department of Mechanical engineering, University of Michigan, Ann Arbor.

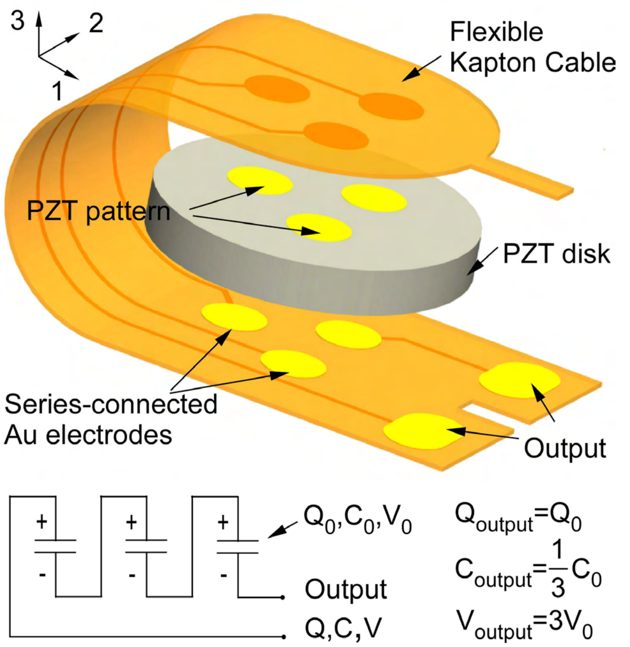

Fig. 1. Device concept. Electrodes on the PZT disk are series-connected through a flexible Kapton cable.

$3V_0$. However, the fringe capacitance diminishes the performance to some extent. Thinning the PZT element increases the equivalent capacitance of the device and reduces the fringe capacitance influence.

B. Fabrication and Assembly

The fabrication of the HV generator begins with a 1 mm thick, 5 mm in diameter PZT51 disk, as shown in Fig. 2, followed by a lapping step which thins the disk down to 740 µm. Then, both sides of the thinned PZT disk are patterned with 100 nm Cr/500 nm Au electrodes by evaporation. A 75 µm thick flexible Kapton cable (Sierra Circuits, Inc., CA, USA) with Cu leads embeded within it and Au contacts exposed is wrapped around three sides of the PZT disk. A narrow slot and a flat pin with the same dimension at two ends of the cable are designed as alignment marks for assembly process. The patterned PZT is sandwiched by the folded flexible Kapton thin film cable along the alignment mark. The sandwiched structure is then bonded using both superglue in the field regions and conductive silver epoxy at the cable contacts. The assembled HV generator is shown in Fig. 3 against a U.S. penny.

III. EXPERIMENTS AND RESULTS

A. Experimental Setup

The experimental setup is depicted in Fig. 4. The assembled HV generator is mounted on a load cell (208C01, PCB Piezotronics Inc., NY, USA) to determine the applied mechanical load. In order to protect the PZT element and uniformly transfer the mechanical load, a 500 µm thick glass cover with the same lateral dimension as the device was attached to the device surface. A transient mechanical load in the experiment was applied by dropping a stainless steel ball (6.8 mm in diameter) directly on the glass cover. The ball is guided by a glass tube held vertically above the device. By adjusting the height of release position, the applied mechanical load was well controlled. Fig. 4 (b) shows the readout circuits for electrical measurement. A resistive divider was used to measure a fraction of the generated voltage through an oscilloscope probe. The measured voltage was then converted to the generated voltage by considering the division factor. Using this readout circuit instead of directly measuring the full output voltage reduces the influence of the capacitance of the oscilloscope probe.

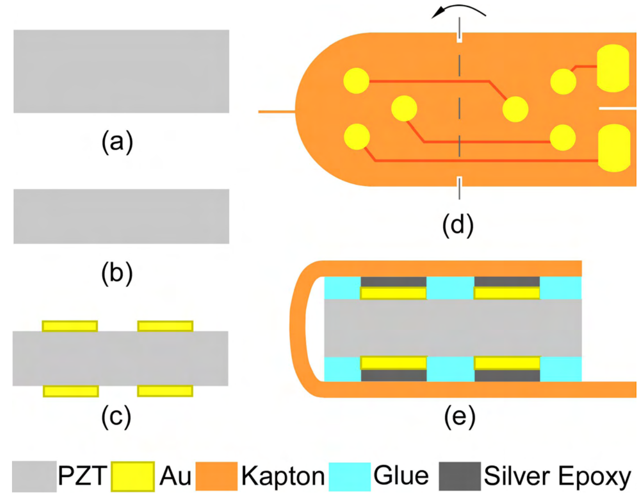

Fig. 2. Fabrication and assembly process. (a) 1mm thick PZT51 disk. (b) Lapping the PZT disk down to 740 µm. (c) Pattern electrodes on both sides of the PZT. (d) Layout of the customized flexible Kapton cable, top view. (e) Sandwich the PZT disk in the cable, bonding using both superglue and silver epoxy, cross sectional view.

B. Characterization Experiments

The HV generator was characterized in the mechanical stress range of 1 MPa to 5 MPa using the experimental setup in Fig. 4. Electrical response to the transient mechanical loads was experimentally obtained and plotted in Fig. 5. It is evident that the HV generator yields an increasing output voltage as the external stress increases. The peak output voltage reaches 900 V when the stress is near 5 MPa. In these measurements, the range of applied mechanical stress is limited by the measurement capability of load cell.

C. Experiments on Chemical Vapor Sensor

To demonstrate the potential application of the HV generator, the HV generator was used to power a microdischarge-based chemical vapor sensor that uses optical emission spectroscopy [7]. As shown in Fig. 6 (a), the HV generator is connected to the anode and cathode of the chemical vapor sensor chip across a 19.8 kΩ current-limiting resistor. The core component of the chemical vapor sensor is a 1×1 cm^2 glass chip with electrodes patterned on the surface. The anode and cathode of the chip have a 75 µm gap, where microdischarges occur when voltage higher than the break down voltage is applied. Microdischarge sparks are guided by an optical fiber to a portable spectrometer. The spectral data are read out from a computer connected to the spectrometer. The chemical vapor around the microdischarge electrodes determines the optical emission characteristics, which are unique for specific elements and chemical bonds. By

Fig. 3. The high voltage generator against a U.S. cent.

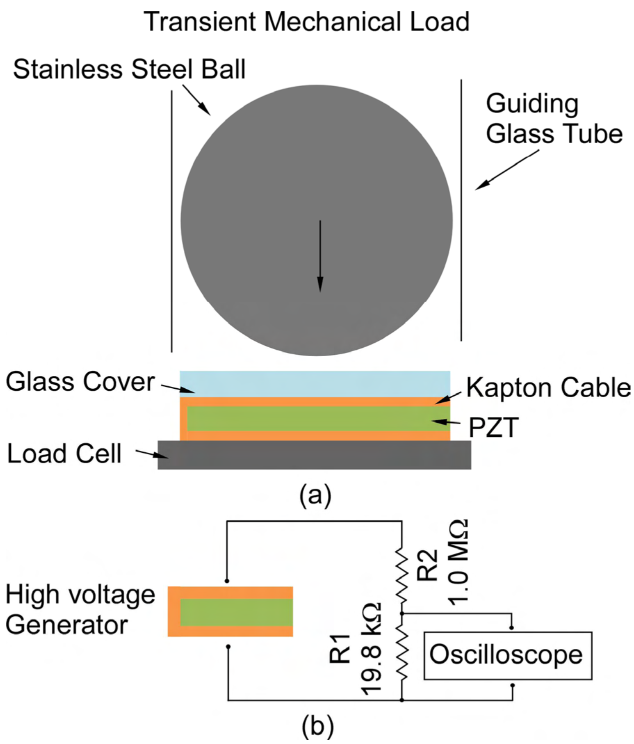

Fig. 4. Experimental setup. (a) Transient load is applied by dropping a stainless steel ball (OD 6.8 mm) guided by a glass tube; (b) Readout circuits.

analyzing the spectra, the chemical vapors under the test are sensed and studied.

Fig. 6 (b) is an optical image of the sensor electrodes before the onset of a microdischarge, whereas Fig. 6 (c) shows a transient microdischarge that was triggered by the HV generator. In these experiments, the voltage across a 19.8 kΩ resistor was monitored by an oscilloscope. A typical transient pulse is shown in Fig. 7. One peak is as high as 1.35 kV, and voltage pulses oscillate with amplitude decaying. This oscillation and the decay profiles reflect the important features. The inset of Fig. 7 shows the highest voltage pulse appears at the beginning and is built up within several nanoseconds. This first and highest voltage pulse initiated the microdischarge across the anode and cathode in the chemical vapor sensor chip. From the voltage response profile,

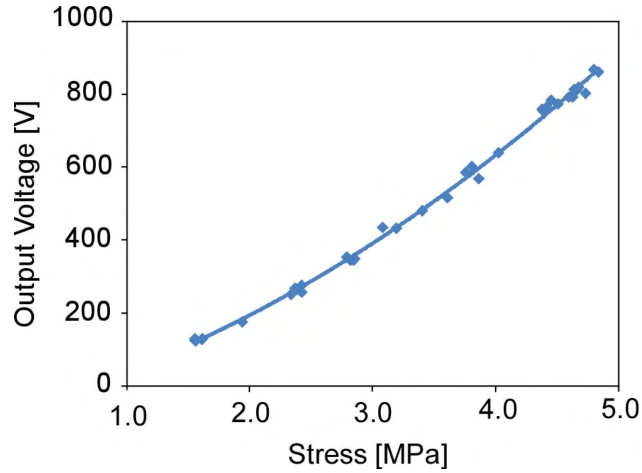

Fig. 5. Experimental results. Measured peak output voltage from the device vs. the applied stress.

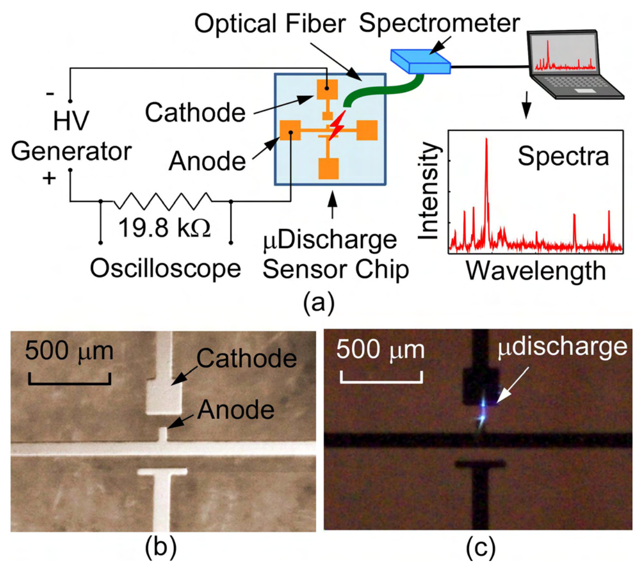

Fig. 6. Scheme of demonstration experiments on a microdischarge-based chemical sensor that detects surrounding chemical vapors using optical emission spectroscopy. (a) Experimental setup. (b) Sensing electrodes before and during (c) discharge.

calculated charge delivered to the sensor chip is about 34 nC in each discharge. The equivalent capacitance of the test HV generator is 25 pF.

IV. CONCLUSION

In this paper, a pulsed HV generator is designed, fabricated, assembled and tested. The HV generator utilizes a monolithic PZT51 element (5 mm in diameter, 740 µm thick) with series-connected electrodes via a flexible Kapton cable. The HV generator is characterized in the mechanical stress range from 1 MPa to 5 MPa. Corresponding peak output voltage varies from 100 V to 900 V. Experimental results validate the capability of pulsed high voltage generation for this new design of HV generator. Potential applications on microdischarge-based microsensors are demonstrated in further experiments. The HV generator successfully powers a microdischarge-based chemical vapor sensor and initiates sparks between sensor electrodes. The peak voltage during

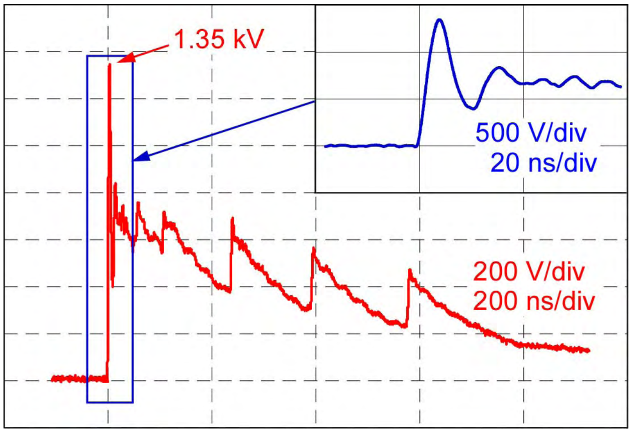

Fig. 7. Measured transient voltage response across a 19.8 kΩ resistance during the discharge.

the discharges reaches up to 1.35 kV and 34 nC charges are delivered to the sensor in one spark.

ACKNOWLEDGMENT

The authors thank Dr. Christine Eun for help with the electrode evaporation process. Facilities used for this research include the Lurie Nanofabrication Facility (LNF), the University of Michigan, Ann Arbor.

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