INFLUENCE OF PARASITIC CAPACITANCE ON OUTPUT VOLTAGE OF SERIES-CONNECTED PZT ELEMENTS

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Abstract: Electrically series-connected PZT (Pb(Zr,Ti)O\textsubscript{3}) generates high output voltage when the elements are subjected to stress. For the application of series-connected PZT elements to power harvesters, the influence of parasitic capacitances on the output voltage and the generating output power are investigated numerically and experimentally. Numerical calculations using a circuit simulator, SPICE validated that the output voltage is multiplied for the series-connected PZT elements. The investigations about the influence of parasitic capacitance indicate that there is an optimum number of series-connection. From measurements of the output voltage of the series-connected PZT, it is verified that a proper choice of electric resistance generates the best output power. We conclude that a proper design of the SC-PZT and the peripheral circuit realize a power harvester with high output power using SC-PZT.

Keywords: PZT thin film, series-connected PZT, high output voltage

INTRODUCTION

For sensor networks and integrated sensing systems, various types of power harvesters have been reported for this decade [1]. Piezoelectric power harvesters have great potential for their high responsibility and applicability to MEMS [2]. However, integration and miniaturization of the device result in small voltage output. In addition, the obtained voltage needs to be rectified, and a voltage larger than the voltage drop for rectifying is required. For the integration of power harvesters to an electric circuit system, not only high power generation but also high voltage generation is significantly important.

An enhancement in the output voltage makes the circuit design simple and flexible. Itoh et al. reported digital output accelerometer using series-connection of PZT elements [3]. The authors reported a concept of series-connection of PZT elements (SC-PZT) for sensor applications that provides the generation of higher output voltage [4]. A well-established fabrication technique of PZT realized SC-PZT and it was verified that the output voltage from vibrating cantilever with SC-PZT is multiplied with the number of series-connection. Figure 1 shows a conceptual diagram of SC-PZT. Electrically series-connected PZT elements generate a high output voltage when the structure deforms.

The objective in this work is the application of SC-PZT to energy harvester device. The output voltage multiplication for SC-PZT is validated using numerical simulation. In addition, the influence of the parasitic capacitance is evaluated. Furthermore, a generating power from SC-PZT and the effects of parasitic capacitances are numerically and experimentally investigated.

Fig. 1: Conceptual illustration of SC-PZT.

OUTPUT VOLTAGE MULTIPLICATION

Validation of Output Voltage Multiplication

For the SC-PZT with ten series connection, the equivalent circuit is expressed as Fig.2. PZT elements are modeled as simple capacitors with the capacitance $C_n$. The parasitic capacitances $C_m$ are SiO\textsubscript{2} layers between substrates and lower electrodes of PZT. $C_b$ and $C_m$ are parasitic capacitances under bonding pads and the load capacitance, respectively. Although the output voltage of the equivalent circuit can be obtained analytically, it becomes more difficult when there is numerous number of series-connection with capacitances, $C_n$ designed to have different values.

We used transient analyses in a circuit simulator, SPICE to estimate the output voltage of SC-PZT device. The nodal point voltages in the equivalent circuit in Fig. 2 are analyzed. The electrons generated from PZT deformation are modeled as “initial
voltage” at the PZT capacitors. The electric potential on each PZT capacitor immediately decreases because of the parasitic capacitances. Parasitic capacitance decreases the voltage on the PZT capacitor and the resultant output is the equilibrium voltage. The equilibrium potentials obtained from the transient analysis at the nodes indicate the output voltage between ground and the corresponding node numbers of PZT element.

For a SC-PZT device illustrated in Fig. 3, the output voltage is calculated. The details of the fabrication have been reported in Ref. [3]. In the calculation, the parasitic capacitances are estimated from actual dimensions and material properties. Output voltages measured from each element are employed as initial voltages of the PZT elements. The calculated values clearly correspond to the measured ones as indicated in Fig. 4. The line in Fig. 4 indicates the total summation of output voltage obtained from single element. This result demonstrates that the difference between the summation voltage and measured voltage from series-connected PZT is due to the parasitic capacitance.

**Influence of Parasitic Capacitances**

To investigate the affects of parasitic capacitances, the output voltages for SC-PZT devices with various ratio of $C_{pn}/C_n$ are calculated. The ratio of $C_{pn}/C_n$ depends on the thicknesses, the areas and the dielectric constants of PZT and SiO$_2$ located under the electrodes. Therefore an intended ratio can be obtained by controlling the process rules and device designs. For the analyses, the capacitance values for PZT, SiO$_2$, bonding pad, and wiring are based on an actual device [3]. The initial voltages are set to 1 V to evaluate the multiplying factor which defined as the
ratio of an initial voltage to net output voltage. Figure 5 shows the relationship between the multiplying factor of output voltages and number of PZT elements for the ratio of the parasitic capacitance to the PZT capacitance. The net output voltage significantly decreases with the increase of the capacitance ratio. The voltage drops to almost half values expected when the value of parasitic capacitance is 20% of SC-PZT.

The reduction in the parasitic capacitance prevents from voltage drops. The reduction of the parasitic capacitance is realized from the utilization of the material with a low dielectric coefficient or from the thickening of the SiO$_2$ layer. We focused on the thickness of the SiO$_2$ layer and estimated the output voltages. The parasitic capacitance for the same model as used in Fig. 4 is altered to various values that correspond to SiO$_2$ thicknesses. Figure 6 presents the calculation result. The output voltage for the SiO$_2$ thickness of 0.2 μm reduced, while that for 1.0 μm is proportional to the series-connection. The reduction in the parasitic capacitance is crucially important for the multiplication of the output voltage.

**ESTIMATION OF OUTPUT POWER**

For the power harvester application of SC-PZT, the output power is estimated using SPICE. A load resistance is connected in parallel to the system shown in Fig. 2. The potential difference at both ends of the resistance is output voltage. The PZT elements are modeled as ideal capacitors, although the each PZT elements should be modeled as equivalent circuits composed of resistances and capacitances in actual case. In the transient analyses, the initial voltages on PZT capacitances decrease with time because of a transfer of electrons to parasitic capacitances. The generated power is consumed in the resistance, resulting in zero equilibrium voltages. The net energy, $E$ generated from the initial voltage can be calculated from

$$E = \int_0^\infty \left( V(t)^2/R \right) dt,$$

where $V(t)$ and $R$ are the voltage at the time $t$ and resistance, respectively.

To investigate a proper number of series-connection of PZT elements, a generated net energy and multiplying factor, defined as the ratio of an initial voltage to net output voltage, are calculated when the number of series-connection is changed. The calculations are conducted for the SC-PZT with various number of series-connection under the condition of the same summation area of the PZT elements. The parasitic capacitances are calculated from the area and the material properties. The initial voltages are 1 V to evaluate the multiplying factor which is the ratio between an initial voltage to net output voltage. The load resistance is set to 1 kΩ. Figure 7 indicates the multiplying factor and net energy obtained from the calculations. There is a clear peak for the output voltage. However, monotone decreasing of the output energy indicates that series-connection of PZT elements results in a degradation of output power. The output power and output voltage is in a trade-off relationship. This result implies that the optimum number of series-connection depends on
other conditions, such as the peripheral circuits and the systems.

The best number of series-connection about the output voltage for SC-PZT was discussed in this chapter. Although the PZT elements are modeled as ideal capacitors, actually they should be modeled as equivalent circuits composed of resistances and capacitances due to leak currents. For the further discussion about the net energy, the leak currents should be taken into consideration. The internal impedance of the SC-PZT can be measured and modeled.

MEASUREMENTS

The output power for SC-PZT with nine series-connections on a cantilever (with the dimensions of length: 13 mm, width: 10 mm, substrate thickness: 500 µm, and PZT thickness: 3 µm is measured. The output voltages of the PZT elements when the cantilever is oscillated with a peak-to-peak amplification of 50 µm at the resonant frequency of 4.2 kHz using a bulk PZT are measured. A resistance is connected to PZT element in parallel and the output voltage is measured using an oscilloscope. The output power is obtained from the square of root-mean-square voltage divided by the resistance. Figure 8 indicates the results. The output power has a peak around 10 kΩ of the resistance, while the output voltage decreases with the resistance. The net impedance of SC-PZT measured with a LCZ meter was about 27 kΩ at the same frequency. In this work, the output-voltage measurements at 27 kΩ of the resistance were not conducted. However, this result demonstrates that the impedance matching provides a maximum power for SC-PZT.

In this work, the net peak-to-peak output voltage was less than 160 mV and the output power was about 50 nW. However, thinning the cantilever enlarges the output voltages. An optimum design of SC-PZT and the structure by eliminating parasitic capacitance and considering the peripheral circuit realizes the energy harvester with a high output voltage.

CONCLUSIONS

The influence of the parasitic capacitance on the output voltage is investigated for the application of the series-connection of PZT elements to energy harvester. The numerical calculations using a circuit simulator, SPICE validated the output voltage is multiplied when the PZT elements are serially connected. The numerical indications for the parasitic capacitances of SiO₂ layers between the substrates and the lower electrodes of PZT elements demonstrate that the degradation of output voltage due to parasitic capacitances is avoidable by thickening the SiO₂ layer. The output power of the SC-PZT is also investigated numerically and experimentally. Numerical calculations indicate that there is an optimum number of the series-connection for the output voltage and that the output power decreases with the number of series-connection. Measurements of the output power for a vibrating cantilever with SC-PZT clarified that the proper resistance of the peripheral circuit maximize the output power. We concludes that a proper design of the SC-PZT and the peripheral circuit realize a power harvester with high output voltage using SC-PZT.

REFERENCES