UNIVERSITY OF CAMBRIDGE

Connection Configurations to Increase Operational Range and Output Power of Piezoelectric Vibration Energy Harvesters

Sijun Du, Yu Jia, Shao-Tuan Chen, Emmanuelle Arroyo and Ashwin A. Seshia

Nanoscience Centre, University of Cambridge, 11 JJ Thomson Avenue, Cambridge, CB3 0FF, UK

Introduction

- Vibration energy harvesting (VEH) aims to realise self-powered micro-electronics, in order to minimise battery maintenance for ubiquitous sensing.
- Piezoelectric materials are widely used due to their high power density and compatibility with conventional IC technologies. [1] [2]
- Full-bridge rectifiers (FBR) are usually used as the interface circuit to rectify power from AC to DC and store it in an intermediate storage capacitor. [3]
- The efficiency of the FBR is limited by the voltage at the output and the forward voltage drop of the diodes. MEMS piezoelectric VEHs usually generate open-circuit voltages of a few volts, which is hard to overcome the threshold set by the FBR.

Background on a full-bridge rectifier

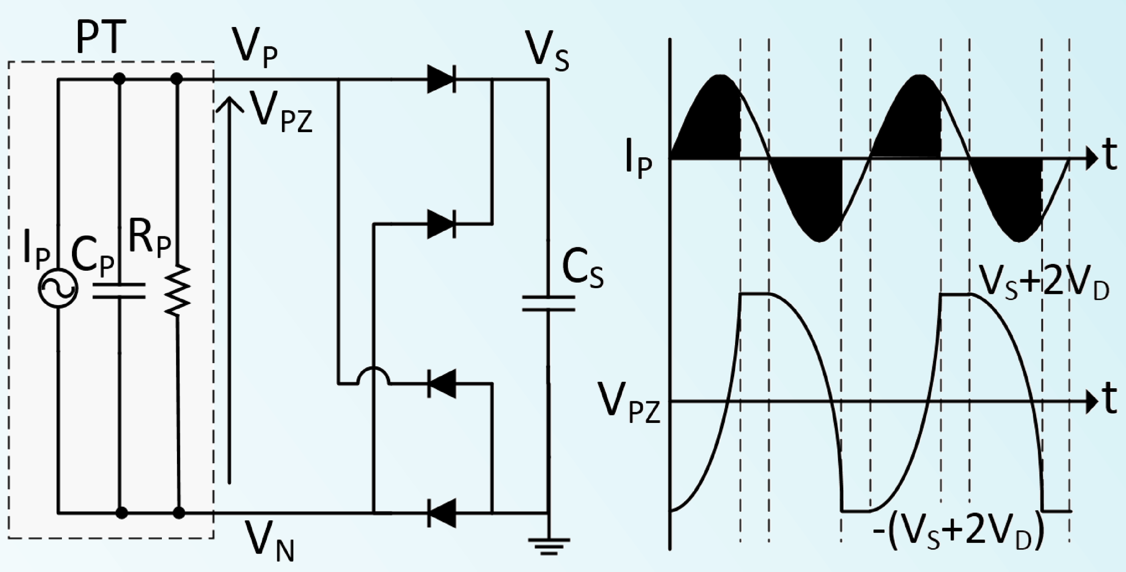

Figure 1: Full-bridge rectifier and the associated waveforms

Figure 1 shows the circuit diagram of a full-bridge rectifier and the associated waveforms. A FBR usually consists of four diodes and a storage capacitor C_S. The piezoelectric harvester is modeled as a current source I_P in parallel with a capacitor C_P and a resistor R_P, which are connected at the input of the FBR.

Assuming the voltage across the capacitor C_S is V_S, the voltage across the piezoelectric harvester (PH) should generated a voltage higher than voltage V_S+2V_D or lower than $-(V_S+2V_D)$ prior to any energy transfer from the PH to C_S, where V_D is the forward voltage drop of the diode Hence, the amplitude of the open circuit voltage generated form the PH should be greater than V_S+2V_D to overcome the threshold set by the FBR. However, this threshold is usually hard to attain for most of MEMS piezoelectric harvesters. For some devices that can slightly overcome this threshold, most of harvested energy is wasted due to charging the internal capacitor C_P from V_S+2V_D to $-(V_S+2V_D)$, or vice-versa.

In this poster, a connection configuration scheme is proposed to split the electrodes of a PH into multiple regions connected in series [4]. The work is especially useful for MEMS energy harvesters as they have relatively low open-circuit voltage. In this case, the open-circuit voltage from all regions can sum up to a much higher level to easily overcome the voltage threshold set by the FBRs. The enables the FBR to start extracting energy from the PH at lower excitation levels. However, while the open-circuit voltage is high enough, parallel connection may be suitable to output higher power. The trade-off for different series stages is presented in the following part.

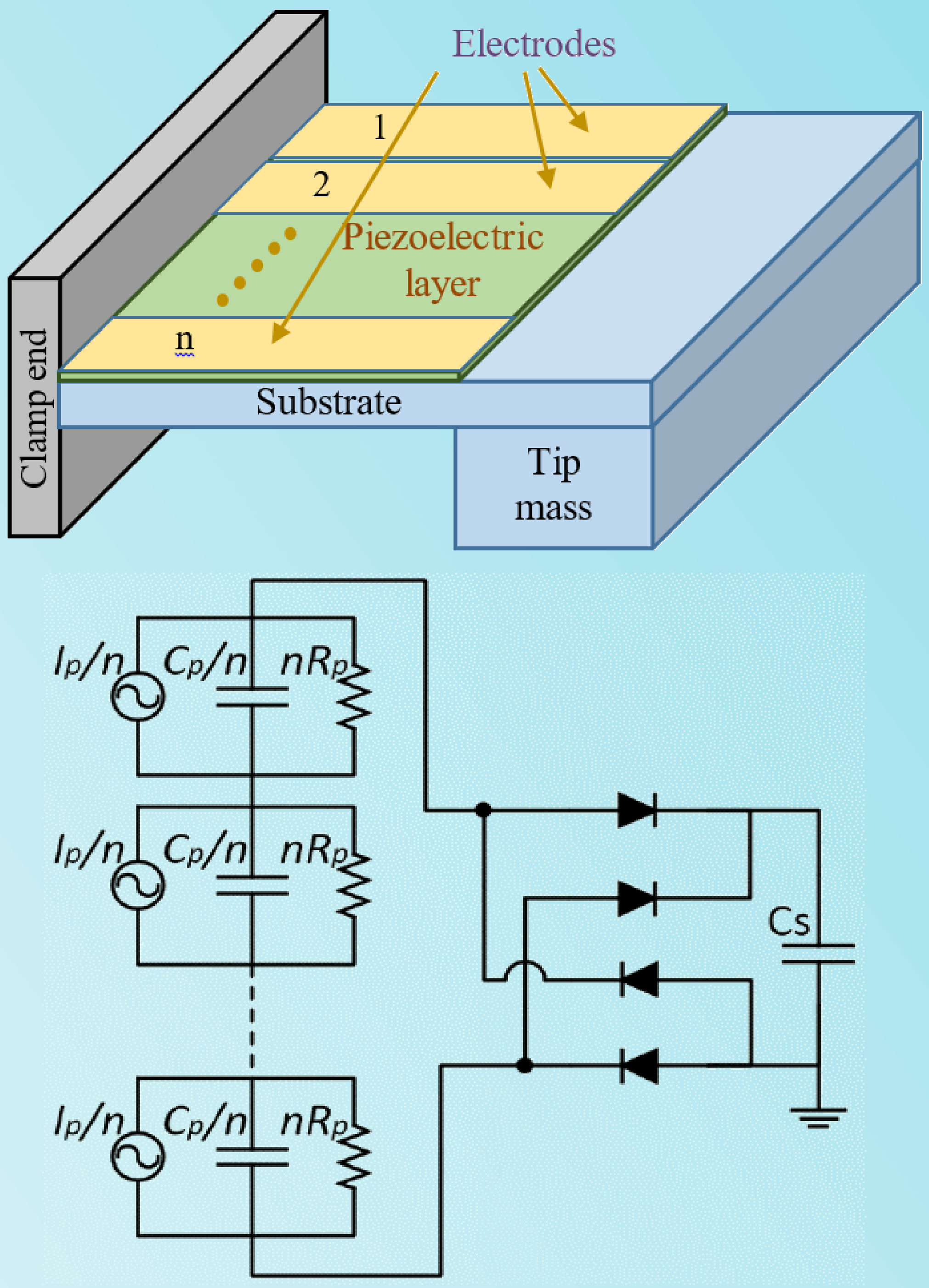

Figure 2: A monolithic PH split into n equal regions and connected in series with a FBR

Theoretical calculations

The total charge generated in a half cycle of the current source I_P is:

$$Q_{total} = \int_0^{\frac{T}{2}} I_0 \sin(\omega t) \mathrm{d}t = \frac{2I_0}{\omega}$$

Assuming the monolithic PH is split into n equal regions, the charge that can be transferred into the storage capacitor C_S is:

$$Q_{S(n)} = \sum_n Q_{S1} = \frac{2C_P}{n}\left(\frac{I_0 R_P}{\sqrt{1+\omega^2 R_P^2 C_P^2}} - \frac{V_S + 2V_D}{n}\right)$$

So that the voltage increase in V_S for a half cycle of I_P is:

$$\Delta V_{S+(n)} = \frac{2C_P}{C_S}\left(\frac{V_{pp(open)}}{2n} - \frac{(V_S+2V_D)}{n^2}\right)$$

The energy transferred into C_S can then be calculated by the voltage increase and hence, the output power of the FBR can be written as:

$$P = \frac{\Delta E_{\frac{T}{2}}}{T/2} = 2f_P \Delta E_{\frac{T}{2}} = f_P C_S((V_S+\Delta V_S)^2 - V_S^2)$$

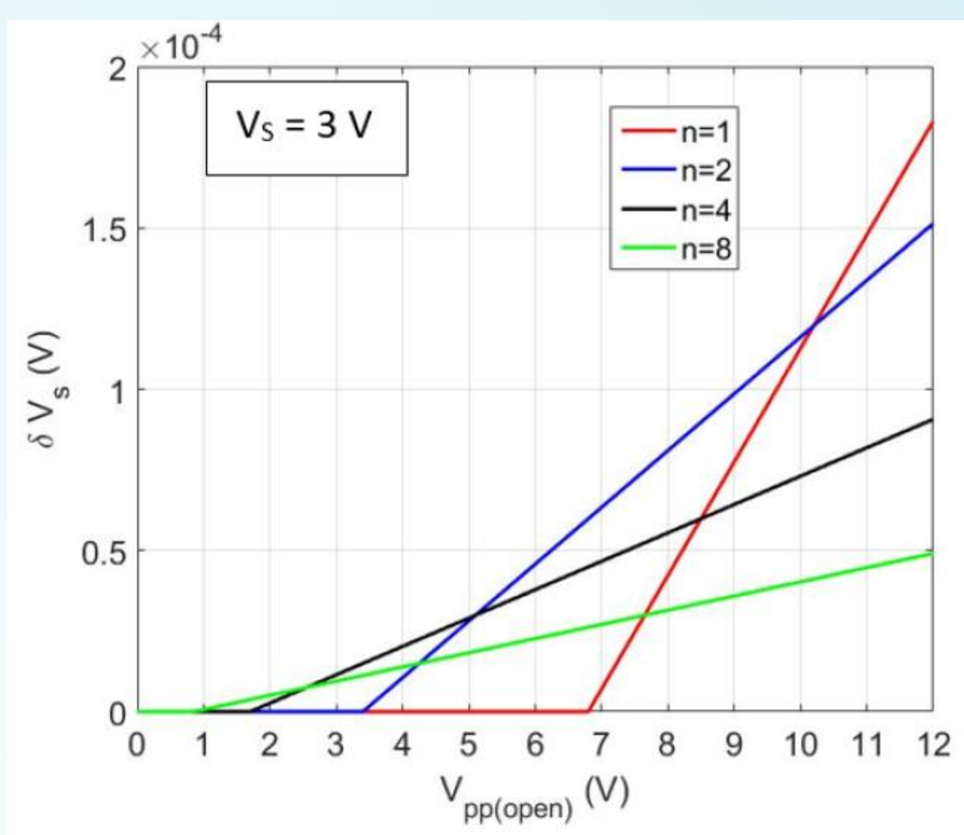

Figure 3: Output power for different series stages

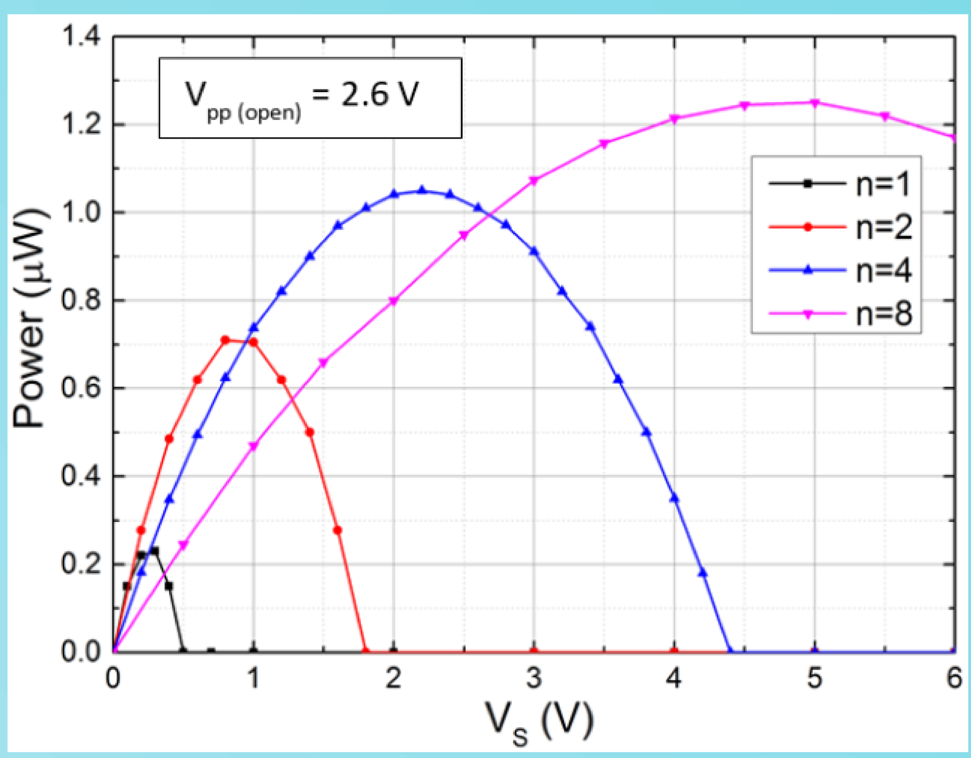

Figure 4: theoretical (4a, left) and measured (4b, right) output power for different series stages

Figure 3 and 4a present the theoretical output power in a range of excitation level and V_S voltage values, respectively.

Experimental setup and results

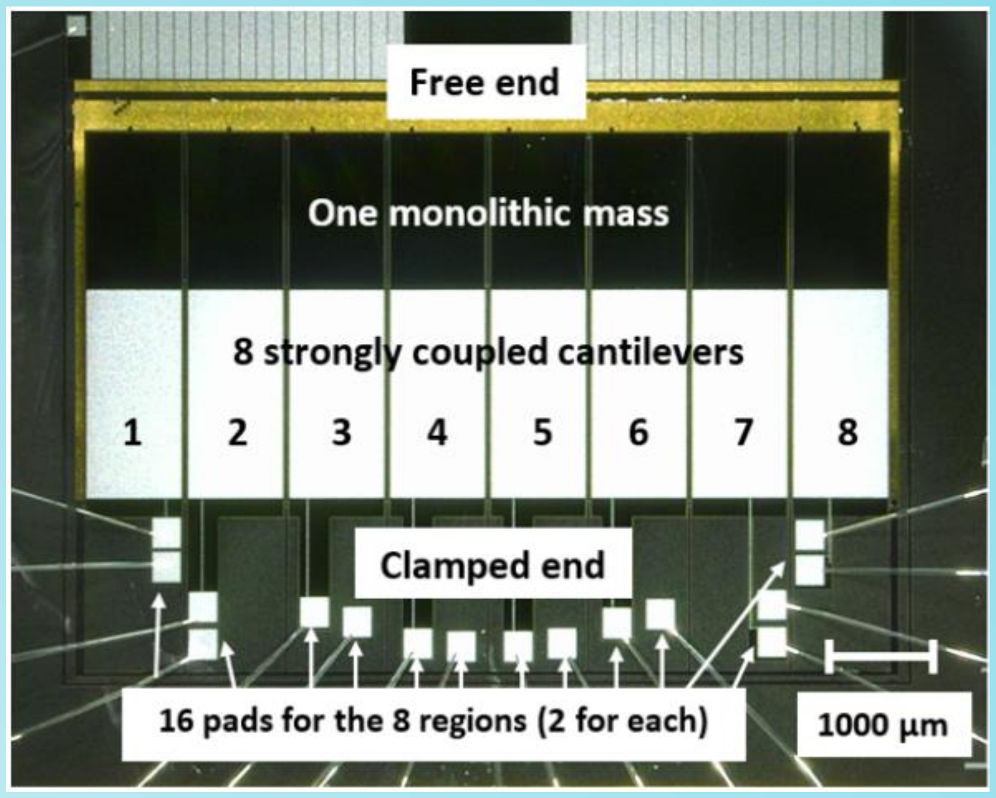

Figure 5: Optical micrograph of the test MEMS device

Figure 5 shows the optical micrograph of the test MEMS device. The device consists of 8 cantilevers, which are strongly coupled with a monolithic proof mass at their free ends. Hence, the eight cantilevers vibrate in the same amplitude, phase and frequency and their electrodes can be perfectly connected in series or in parallel. The cantilever is excited on a shaker at its natural frequency of 211 Hz under an excitation level of 2:0 g. The open-circuit peak-to-peak voltage generated by the cantilever while all the 8 regions are connected in parallel is 2:6V.

Figure 4b shows the measured output power for n=1, 2, 4 and 8. It can be seen that connecting more regions in series can output more power and the resulting summed-up voltage is easier to overcome the FBR threshold even at low excitation levels.

Conclusion

- Splitting a monolithic PH into multiple equal regions connected in series allows the PH easily transfer energy through a FBR.
- Connecting PHs in series increases the output power while using a FBR.
- Compared to active circuits, this topology does not consume any extra energy and is very stable.

References

[1] S. R. Anton et al., Smart Mat. Struct., 2007
[2] A. G. A. Muthalif et al., Mech. Sys. Sig Proc., 2015
[3] N. G. Elvin, J. Intel. Mat. Syst. Str., 2014
[4] S. Du et al., J. Intel. Mat. Syst. Str., 2016

Research Centres

Cambridge Nanoscience Centre

CSIC Cambridge Centre for Smart Infrastructure and Construction – An Innovation and Knowledge Centre

UNIVERSITY OF CAMBRIDGE Department of Engineering

Funding Bodies

Innovate UK Technology Strategy Board

EPSRC Engineering and Physical Sciences Research Council