Abstract

Harvesting kinetic energy from mechanical vibrations via piezoelectric materials is recently of great interest. Piezoelectric transducers offer not only the ease of direct conversion from kinetic into electrical energy with high power density but, also offer a simple implementation that is attractive for miniaturization and volume-limited applications. Of the many piezoelectric materials available, lead zirconate titanate (PZT) piezoelectric ceramics are often employed in energy harvesting applications due to their high piezoelectric strain \( (d) \) and electromechanical coupling \( (k) \) coefficients. During the last decade, piezoelectric MEMS harvesters fabricated using various film deposition techniques (e.g. sputtering, epitaxial growth, sol-gel, and screen printing) have been developed; however, these films provide lower piezoelectric and electromechanical coupling coefficients than commercially available bulk materials. In order to take advantage of high quality bulk PZT, in this thesis, inertial and impact-type piezoelectric MEMS harvesters based on thinned bulk PZT to harvest energy from low-frequency vibration sources were developed.

Piezoelectric harvesters are often implemented as inertial devices oscillating at their resonant frequencies. Fabricating MEMS scale devices with low resonant frequencies (< 100 Hz) using bulk PZT requires thinning of the piezoelectric layer. Utilizing a high precision mechanical grinder, the first wafer level fabrication of thinned bulk PZT (PZT thickness of 20 µm) harvesters with an electroplated nickel proof mass is presented. This process eliminates the need for individual bonding of PZT layers and proof masses, while still maintaining the excellent properties of bulk PZT. In order to obtain a more detailed description of the electromechanical behavior of the harvesters, an electromechanical model was developed in ANSYS to estimate power output at given input vibration. Harvesters were designed to provide sufficient power for an Ultra-Wideband (UWB) sensor node. A single fabricated harvester with an effective volume of 47.82 mm\(^3\) is capable of generating a normalized power density of 3346 µW cm\(^{-3}\) g\(^{-2}\) with an average power of 1.6 µW (11.8 kΩ) under an excitation of 0.1 g (100 Hz) (1 g = 9.81 m s\(^{-2}\)), and 1723 cm\(^{-3}\) g\(^{-2}\) with an average power of 82.4 µW (9.5 kΩ) at 1 g (96 Hz). Thinned bulk PZT exhibits high power and a useable voltage while maintaining a low optimal
Abstract

Resistive load, demonstrating the potential of high performance piezoelectric MEMS energy harvesters using bulk PZT sheets fabricated at the wafer level.

Natural frequencies of many ambient vibration sources are distributed at the lower end of the spectrum: typically ≤ 10 Hz for human motion and ≥50 Hz for machine-induced vibrations, usually accompanied by considerable frequency variation over time. Using resonant-type device requires a significant mass or a very compliant spring in order to resonate at such low-frequencies, which is difficult to scale down with MEMS technologies. Moreover, average power generated by the harvester operating at resonance drops significantly at low frequencies. Therefore, resonant-type devices do not present a viable option in this case. To efficiently harvest energy from low frequency vibrations, mechanical frequency up-conversion technique, in which low frequency input vibration is converted into high frequency vibration to improve the electromechanical coupling of the transducers, is one of promising solutions.

This thesis also investigates plucking-based frequency up-conversion to harvest energy from a rotating gear using an AFM-like piezoelectric MEMS cantilever based on bulk PZT. In this approach, one or several cantilevers could be placed directly above or below the rotating gear, in order to keep system as compact as possible, such that the tip at the end of the cantilever extends down between the vertically extending gear teeth and is plucked as each tooth passes. Subsequent analytical and FEM modelling of the harvester were also carried out and found to be in good agreement with experimental results. Harvester outputs were studied by investigating the effect of plucking speed, of the tip depth, and of the addition of a proof mass to the harvester on the output energy as well as conversion efficiency. In order to evaluate the conversion efficiency, a novel methodology using a rotational flywheel was implemented. Using this method, the efficiencies of a plucking based frequency-up converting harvester were studied in terms of plucking mechanism (contact and non-contact), the impact speed as well as the coupling geometry between the harvester and the inertial mass. Furthermore, the longevity of the proposed concept was investigated highlighting the importance of the materials used and gear and tip shape. Finally, a rotational, compact, and wearable piezoelectric on-body energy harvesting system utilizing a thinned bulk PZT cantilever and an eccentric mass from common wrist watch is presented.

Keywords: vibrational energy harvesting, piezoelectric energy harvester, low-frequency, resonant, impact, wafer level fabrication, lead zirconate titante (PZT), bulk PZT, thinned PZT, plucking, frequency up-conversion, rotating gear, oscillating mass-gear system.