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Design and characterization of miniature piezoelectric generators with low resonant frequency

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ABSTRACT

In this study, both materials selection and device configuration design were considered for developing miniature piezoelectric generators with low resonant frequency. Instead of single crystal Si, stainless steel (SUS) was chosen as the substrate of AlN thin films owing to its higher fracture toughness, which made it possible that millimeter-scale generators had resonant frequency of less than 100 Hz. The device configuration including the aspect ratio (the length of the cantilever to the width of the cantilever) and the thickness ratio (the substrate layer to the AlN film layer) were analyzed for optimizing transverse electromechanical coupling coefficient of generators. Using AlN thin films deposited on stainless steel, millimeter-scale generators were fabricated and their vibration energy harvesting performance was characterized. Output power and resonant frequency of the devices are, respectively, 5.130 μW and 69.8 Hz when they were vibrated at 1 g acceleration and connected with 0.7 MΩ electric loading.

1. Introduction

Ubiquitous networks of wireless sensors have the potential to significantly benefit modern society and create large commercial opportunities. Their network nodes are generally designed to run on batteries, but the replacement of depleted batteries becomes laborious and even impractical as wireless sensors increase in huge number. Therefore, alternative methods for powering these devices are needed. Extracting energy from environmental sources is attractive as inexhaustible replacements for batteries, and has recently received increasing interest within both academic community and industry. There are several power-generating options from environmental sources including vibration, light, temperature gradient and wind, and each type has its benefits for certain applications. Mechanical vibration is one of the most widespread energies in environment which commonly goes unused. Three kinds of generators including electromagnetic, electrostatic and piezoelectric have been suggested for vibration energy harvesting. Piezoelectric generators have taken the most attention due to their simple configuration and high energy converting efficiency [1–4].

Piezoelectric generators convert mechanical energy into electric energy: electric charges are generated when piezoelectric materials are deformed due to a vibration or a force. In the practical application, a good piezoelectric generator is required to hold not only suitably low resonant frequency to match the frequency of vibration sources (usually below 200 Hz), but also high enough output power. These two requirements are easily met for piezoelectric generators with large size [3,4], however, they become challenging for miniature generators with millimeter or smaller size [5–9]. This is because that with the decrease of the device size, the resonant frequency rapidly increases and simultaneously the output power of generators gradually decreases.

In this study, for developing practicable piezoelectric generators with millimeter size, we firstly analyzed what kinds of materials should be adopted for ensuring that the devices with the cantilever structure hold low resonant frequency and high mechanical safety. For further improving the energy conversion efficiency, we calculationally optimized the device configuration including the aspect ratio (the length of the cantilever to the width of the cantilever) and the thickness ratio (the substrate layer to the AlN piezoelectric layer). Finally, AlN thin films deposited on stainless steel (SUS) substrates were prepared with an electron cyclotron resonance (ECR) system, and they were further used to fabricate millimeter-scale piezoelectric generators.

2. Material selection of miniature piezoelectric generators

When a piezoelectric generator works, output power is dependent upon both the converted mechanical energy and the lost energy. The electromechanical coupling coefficient K directly

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quantifies the ability of mechanical–electric energy conversion. The mechanical quality factor Q is related to the mechanical loss, and the dielectric loss $\tan\delta$ is involved into the electric loss (a part of electric energy is dissipated by transforming it into thermal energy). Therefore, K, Q and $\tan\delta$ can be considered as three critical parameters for designing a piezoelectric generator [2]. For miniaturizing the volume of piezoelectric generators, the piezoelectric element in these devices generally takes the form of thin film. Therefore, the material selection is mainly involved into which kinds of substrate and piezoelectric thin film are adopted. The selected materials should ensure that generators hold high Q, K and $\tan\delta$. In addition, because generators continuously work in a vibration environment, the selected materials should have high enough mechanical strength.

2.1. Selection of substrates

A miniature piezoelectric generator is mainly fabricated from the structure of piezoelectric thin film/substrate. The volume of the substrate is much larger than that of the piezoelectric thin film, so Q and mechanical strength of the device are almost determined by the substrate, and to some extent the K value of the device is also affected by the substrate. A stiff substrate is preferred for obtaining high Q and K [10], which means that the substrate needs to have both high elastic modulus and high fracture strength (or yield strength). By considering that the resonant frequency of piezoelectric generators should be low to match the frequency of most vibration sources, the thickness of the substrate should be made to be very thin. Therefore, the vibrational operation environment requires that the substrate should also possess high enough fracture toughness.

In generally, single crystal Si is used as substrates of piezoelectric thin films, because of its easy process, high temperature chemical stability and not high cost. Due to high elastic modulus and fracture strength of Si substrates, piezoelectric thin films deposited on them can be fabricated into generators with high Q and K. However, it should be noted that Si is very brittle and the fracture toughness of (1 0 0) oriented single crystal Si is only 0.95 MPa m$^{1/2}$, which incurs that the resonant frequency of miniature generators cannot be designed to be low enough through the way of thinning the thickness of the substrate. As alternatives, some metals such as SUS and Titanium may be good choices due to their high elastic modulus, yield strength and fracture toughness. Table 1 lists mechanical properties of (0 0 1) oriented single crystal Si and some metals. Among them, it seems that SUS is desirable for being used as substrates of piezoelectric thin films for fabricating miniature generators with low resonant frequency if the compatibility with micromachining technologies is not required. Ti is desirable for being used as the substrate if the micromachining compatibility is considered. Recently, the technology of the metal anisotropic reactive ion etching with oxidation process was successfully developed for fabricating arbitrarily high-aspect-ratio structures from Ti substrates with various thicknesses [11,12]. The miniature structure of Cu and Ni can be made with the electroplating processing. This processing is also compatible with micromachining technologies, but relatively low yield strength of both metals implies that their stiffness is relatively low and thus Q of the fabricated structures is also relatively low. Therefore, it is not suitable to use Cu and Ni as the substrates in piezoelectric generators.

Table 1
Mechanical properties of (0 0 1) oriented single crystal Si and some metals.

Materials	Elastic modulus (GPa)	Yield strength (MPa)	Fracture toughness (MPa m$^{1/2}$)
(0 0 1) oriented Si	130	600–7700 (fracture strength)	0.95
SUS304	197	205	80
Bulk Ti	106	170	75
Bulk Cu	117	100	–
Bulk Ni	204	58	–
Bulk Al	69	15	14–28

2.2. Selection of piezoelectric thin films

For piezoelectric thin films deposited on substrates, there are two work modes: d_{33} and d_{31}. The d_{31} mode implies that the piezoelectric layer is sandwiched between top and bottom electrodes. The d_{33} mode means that a pair of interdigital electrodes is formed on the top surface of piezoelectric thin films. The piezoelectric element cannot be easy to be completely poled and only a partial volume is effectively utilized in the operation. Therefore, although electromechanical coupling coefficient of the d_{33} mode is much higher than that of d_{31} mode, output power of a d_{33} mode generator is normally poorer than that of a d_{31} generator with the similar size [13,14].

For d_{31} mode generators fabricated from piezoelectric thin films, Q is mainly determined by the substrates so the left piezoelectric parameters for selecting piezoelectric materials are k_{31} and $\tan\delta$. The selected piezoelectric materials are also expected to have high mechanical strength such as fracture strength and fracture toughness. Up to now, piezoelectric thin films which can be prepared with matured technologies include lead titanate zirconate (PZT), ZnO and AlN. Tables 2 and 3 list piezoelectric and mechanical properties of these thin films that were reported. It can be seen that PZT thin films have the highest k_{31}, so generators fabricated from them should yield highest output power. However, there are a few unsolvable problems for PZT thin films: (1) the crystallization temperature of PZT is in the range of 600–700 °C, which is not compatible with the CMOS integration; (2) exerting a high electric field for poling is necessary, which may be difficult for PZT thin films that have some defects or pinholes; (3) the performance is gradually deteriorative due to aging effect; (4) high content of lead is unhealthy to human being. For AlN and ZnO thin films, their k_{31} is lower than that of PZT to a certain degree, but they do not

Table 2
Piezoelectric properties of PZT, AlN and ZnO thin films.

Materials	Electromechanical coupling coefficient k_{31}	Dielectric loss $\tan\delta$	Others
PZT 53/47 thin films [15]	20%	0.01–0.04	• High crystallization temperature • Need poling • Aging effect
AlN thin films [16]	14%	0.003	• Low crystallization temperature • No poling • No aging effect
ZnO thin films [17,18]	<18%	0.01–0.1	• Low crystallization temperature • No poling • No aging effect