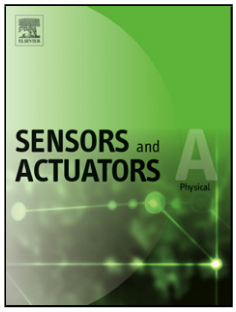
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Title	Shock-induced aluminum nitride based MEMS energy harvester to power a leadless pacemaker
Authors	Jackson, Nathan;Olszewski, Oskar Zbigniew;O'Murchu, Cian;Mathewson, Alan
Publication date	2017-08-03
Original Citation	Jackson, N., Olszewski, O. Z., O'Murchu, C. and Mathewson, A. (2017) 'Shock-induced aluminum nitride based MEMS energy harvester to power a leadless pacemaker', Sensors and Actuators A: Physical, 264, pp. 212-218. doi:10.1016/j.sna.2017.08.005
Type of publication	Article (peer-reviewed)
Link to publisher's version	10.1016/j.sna.2017.08.005
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Download date	2026-11-02 00:51:10
Item downloaded from	https://hdl.handle.net/10468/4681



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PII: S0924-4247(17)30702-1
DOI: http://dx.doi.org/doi:10.1016/j.sna.2017.08.005
Reference: SNA 10259

To appear in: *Sensors and Actuators A*

Received date: 21-4-2017
Revised date: 10-7-2017
Accepted date: 2-8-2017

Please cite this article as: Nathan Jackson, Oskar Z.Olszewski, Cian O'Murchu, Alan Mathewson, Shock-induced aluminum nitride based MEMS energy harvester to power a leadless pacemaker, Sensors and Actuators: A Physicalhttp://dx.doi.org/10.1016/j.sna.2017.08.005

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Shock-Induced Aluminum Nitride based MEMS Energy Harvester to Power a Leadless Pacemaker

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Submitted to:
Sensors and Actuators A: Physical

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Highlights

- *Demonstrated PiezoMEMS device to power implantable pacemaker*
- *Validated shock-induced vibration method of the heart*
- *Off resonance excitation due to large acceleration force*
- *Increased power density due to increased heart rate*

Abstract:

The next generation of implantable leadless pacemakers will require vibrational energy harvesters in order to increase the lifetime of the pacemaker. This paper reports for the first time the use of a piezoelectric MEMS linear energy harvester device that fits inside a pacemaker capsule. The silicon based MEMS cantilever device uses CMOS compatible Aluminum Nitride as the piezoelectric layer. The developed harvester operates based on a shock-induced vibration that is generated from the low frequency

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(60-240 beats per minute) high acceleration (>1 g) vibration of the heart. The high g impulses force the high-frequency harvester to oscillate at its resonant frequency. A power density of 97 and 454 μW cm^{-3} g^{-2} was achieved for a heart rate of 60 and 240 beats per minute respectively. The forced oscillation causes the linear harvester to dampen after 100-200 ms which reduces the average power compared to a typical sinusoidal excitation. A two and four cantilever system occupies 35% and 70% of the overall volume of the capsule while obtaining 2.98 and 5.96 μW respectively at a heart rate of 60 bpm respectively and 1 g acceleration. The results in this paper demonstrate that a shock-induced linear MEMS harvester can produce enough electrical energy from the vibration of a heart to power a leadless pacemaker while maintaining a small volume.

Keywords: Aluminum Nitride, Energy Harvesting, MEMS, Pacemaker, Heart

1. Introduction:

Pacemakers are lifesaving implantable devices that help sustain a normal heart beat for patients that have arrhythmias. Current pacemakers have large batteries, which allow them to operate for long periods of time. These devices are implanted in the clavicle region so replacing the battery is feasible. Leadless pacemakers are the next generation of devices, which are encased in a small cylindrical capsule and implanted in the heart wall of the right ventricle, so replacing the battery of these devices is not feasible. Leadless pacemakers have several advantages over current pacemakers such as the procedure for implanting them is less invasive and they have fewer complications due to common failures from the leads. Current leadless pacemakers have small batteries which allow them to operate from 2-10 years depending on their usage. However, a pacemaker should be able to perform for the lifetime of the patient which could be 20-40 years. Therefore a self-sustainable pacemaker is ideal for a leadless pacemaker.

The heart is a highly efficient pump, which has inexhaustible sources of energy throughout the patient's life, which requires approximately 0.93W of mechanical power to

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function at 60 beats per minute (bpm) [1]. The heart is therefore a good source of reliable mechanical energy. A vibrational energy harvester is used to convert mechanical energy into electrical energy. By integrating such a device on or in the heart will allow it to harvest a small amount of the mechanical energy into a useable electrical energy, which can be used to power an implantable device such as a pacemaker [2]. Pacemakers used to require large amount of power (30-100 μW) [3]. However, in recent years the power requirements have significantly decreased to approximately 5-10 μW due to optimization of electronics and stimulation methods [4, 5], which makes developing a self-sustainable pacemaker feasible.

The leadless pacemaker is in the form of a cylindrical capsule with maximum dimensions of approximately 6 mm in diameter and 40 mm in length. This capsule needs to incorporate the electronics as well as the power management, therefore the size of the devices is critical. Macro-scale piezoelectric assembled devices using bulk lead zirconate titanate (PZT) have been demonstrated in a laboratory environment previously [6], but these require large masses which are difficult to fit within the capsule dimensions. There are two possible strategies for trying to develop prototype devices to be used as implantable energy harvesters: i) develop macro-scale device concept that demonstrates high power density and then try and scale down the size to fit inside the pacemaker, or ii) build a micro-scale device that fits inside the pacemaker and then try to develop methods for increasing power density. The challenge with developing a macro-scale device is that the power density does not scale down linearly to the micro-scale, and fabrication of the device at the MEMS level can be difficult. The issue with developing a micro-scale device is that increasing the power density can be challenging. This paper focuses on the latter approach, because if the device does not meet the size limitations it cannot be used, whereas if a device does not meet the maximum power requirements it could still be used in conjunction with a battery, which could prolong the life of the pacemaker.

Microelectromechanical systems (MEMS) energy harvesters are desired for this application as the size of the devices needed to fit within the capsule are small. The three main methods of harvesting energy from vibrations are electromagnetic, electrostatic, and

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piezoelectric. Electromagnetic is not possible in implantable devices because permanent magnets are required, which are not MRI compatible. Design of MEMS electrostatic energy harvesters have been reported but to obtain the high power density, complex 3D structures are necessary and difficult to fabricate [7, 8]. Piezoelectric ribbons and films have been developed that attach on the outside of the heart to harvest energy. However, integrating these into an implantable pacemaker is difficult, requires leads which defeats the purpose of the leadless pacemaker, and requires invasive surgery [2, 9]. Linear and non-linear macro-scale manufactured piezoelectric cantilever devices using PZT harvesters have been developed but these have low power density of <1 μW cm^{-3}, due to large mass and displacements required [10, 11]. An off resonance method using AlN was previously reported for optimization of the cantilever shape [12]. Leadless pacemakers typically require around 5-10 μW of power to operate. There are two challenges in regard to power density for this application: 1) the heart does not have a sinusoidal vibration so the average power is significantly reduced compared to sinusoidal harvesters, because of the low duty cycle (60 bpm) and 2) the targeted frequency spectrum of the vibrations are low (20-30 Hz) [13].

Developing ultra-low frequency micro-scale based energy harvesters that have a >10 Hz bandwidth is very difficult. Typically large masses or thin beams are needed to reduce the frequency [6], but a large mass then limits the displacement due to the size constraint of the capsule. Widening the bandwidth usually involves reducing the Q-factor, which has the negative side effect of reducing the power [14]. There has been numerous methods developed for widening the bandwidth for macro-scale devices such as using repelling forces and mechanical stoppers [15, 16], but these significantly reduce the output power. New techniques using a sliding liquid mass have been demonstrated at the macro-scale to widen bandwidth without reducing power, but this is yet to be validated at the micro-scale [17]. Developing either an ultra-low frequency or a wide bandwidth device is challenging at the MEMS scale, but creating a device that has both aspects is extremely complex. Therefore developing a method

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that excites a high frequency linear MEMS device that is independent of the resonant frequency of source is of significant importance.

This paper investigates for the first time the use of a linear Aluminum Nitride (AlN) based MEMS piezoelectric energy harvester to power a leadless pacemaker. AlN was chosen because, i) it has a high power figure of merit [18], ii) it is CMOS and MEMS fabrication compatible, iii) it is biocompatible [19, 20] , and iv) methods are continuously being developed to enhance material properties in order to increase performance [21-23], which will enhance power densities values in the future. This paper demonstrates a shock-induced method of exciting a MEMS linear cantilever off resonance, by using high g accelerations from the heart. In order for the MEMS cantilever to operate the device was designed to have maximum displacement at resonance with low g acceleration (< 0.25 g) [24]. By using this excitation method the device eliminates the need to match the resonant frequency of the cantilever to the frequency spectrum of the heart, so an ultra-low frequency harvester with wide bandwidth is not necessary.

2. Materials and Methods

2.1 Concept

A leadless pacemaker is implanted in the right ventricle towards the apex of the heart as shown in Fig. 1(a). The pacemaker is in the form of a cylindrical capsule which contains a screw, two electrodes, and the inside of the capsule contains the electronics and power module, which currently consist of batteries. However, this paper aims to replace the batteries with vibrational energy harvesters as shown in Fig. 1(b). The orientation of capsule and how it is implanted will have a significant impact on the acceleration that is applied to the harvester. A cantilever based energy harvester operates efficiently when the force applied is out of plane. The dynamics of the heartbeat causes forces in all three directions but some directions will have larger forces as was previously demonstrated [25]. The capsule dimension used in this paper

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has a length of 40 mm and a diameter of 6 mm. The power module should occupy less than 75% of the volume to ensure enough space for the electronics. MEMS based energy harvesters are ideal because they can meet the size limitations. As the heart beats the mechanical force generated will cause the capsule to resonate, which will excite the vibration energy harvester inside the capsule. The excitation of the energy harvester will oscillate causing stress/strain in the piezoelectric layer, which will convert the mechanical energy into an AC voltage. A power management circuit such as a rectifier would be needed to convert the voltage from AC to DC.

---------- Insert Figure 1----------

2.2 Shock-Induced Excitation

The frequency spectrum of the heart has been previously demonstrated [13] to have a high peak at 1-3 Hz, which represents the heart rate, and then a secondary peak at 20-30 Hz. Previous attempts to develop linear or non-linear energy harvesters from the heart focus on developing techniques to create an ultra-low frequency device that has a resonance frequency that covers the 20-30 Hz frequency ranges [6, 10, 11, 13] . This requires an ultra-low frequency device with a wide bandwidth, which is challenging to create at the MEMS scale. Developing an ultra-low frequency cantilever requires a i) thin beam, ii) huge mass, or iii) low stiffness beam according to the formula for estimating the frequency of a rectangular beam Eq. (1). All of these methods lead to a decrease in reliability, and they are difficult to fabricate at the MEMS level.

$$f = \frac{1}{2\pi} * \sqrt{\frac{3E}{m}} * \sqrt{\frac{wt^3}{L^3}} \qquad (1)$$

Where E is the elastic modulus of the beam, m is the mass, w is the width, t is the thickness, and L is the length.

Instead of creating an ultra-low frequency device this paper investigates the use of an off resonance excitation method by using the shock-induced impulse from the heart. Linear energy

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harvesters have high Q-factors and typically require a vibration source to operate at the same frequency as the resonant frequency of the energy harvester in order to obtain high power density [18, 26, 27]. However, shock-induced vibration allows the device to operate off resonance by applying a high acceleration impulse over a small period of time thus forcing the device to oscillate at its resonant frequency. Shock-induced vibration of an energy harvester has been previously applied to tire pressure monitoring systems [28]. However, in order for the cantilever structure to oscillate with significant displacement a high acceleration force is needed as determined by Eq. (2).

$$X = \frac{F_o}{k} \frac{1}{\sqrt{\left(1-r^2\right)^2 + \left(2\xi r\right)^2}} \qquad (2)$$

Where X is the amplitude, F_o is the applied force, k is the spring constant, ζ is the damping ratio, and r is the ratio between frequency of the applied pulse and resonant frequency of cantilever. Using the 20-30 Hz as the applied pulse frequency we can estimate how much force is required to cause significant displacement of a given resonant frequency beam cantilever. Assuming a damping ratio of 0.05-0.03 for a silicon cantilever we can determine that to achieve maximum displacement off resonance with r <0.3 (f_n > 90 Hz) we would need approximately 10x increase in acceleration as shown in Fig. 2. Lower damping ratios would require even larger acceleration force as demonstrated in Fig. 2. Previous reports demonstrate that the heart produces about 1-2 g acceleration, [11, 29], so if a 10x force is needed to displace the cantilever off resonance then a harvester that has maximum displacement at resonance with approximately 0.1-0.2 g applied force is optimal for this application. As the power obtained with 0.1 g at resonance should be similar to 1-2 g acceleration off resonance.

---------- Insert Figure 2----------

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2.3 Fabrication

Typical mechanical damping factors of silicon based MEMS devices range from 0.005 to 0.05, so the device would need at least a 10x increase in excitation force to operate off resonance according to Fig.2. The authors previously designed a low acceleration AlN based energy harvesting device using a silicon-on-insulator substrate, which produced high power density (2.5 mW cm^{-3} g^{-2}) at 0.2 g acceleration [24], and was the base design of the device used in this paper. The cantilever dimensions were modified in order for the device to fit and operate within the required dimensions of the capsule. The resonant frequency of the cantilever is not critical because of the shock induced method of excitation. Anything with a $r<0.3$ requires a similar force to achieve the same displacement, therefore the exact resonant frequency is not critical.

The design of the MEMS harvester was modified to fit within the capsule, and the fabrication process was previously described in detail as shown in Fig. 3 [24, 30]. An SOI wafer with 40 µm thick device silicon and 400 µm handle silicon were used to define the beam and mass thickness. A thermal oxide was initially deposited and patterned to act as the mask during the DRIE etching of the silicon. Layers of Ti/AlN/Al were deposited and patterned using a DC sputtering technique and patterned using a combination of dry and wet etch techniques. The AlN was deposited using DC sputtering with a thickness of approximately 500 nm as previously described [22]. A compressively stressed silicon nitride layer was deposited in order to compensate for the tensile stressed AlN layer in order to prevent buckling. DRIE of the silicon was used to release the structure and to define the beam dimensions. After fabrication the devices were diced and wire bonded onto a custom made PCB.

---------- Insert Figure 3----------

The fabricated devices consist of a 2 or 4 cantilever system, which is shown in Fig. 4(a). The individual cantilever device has dimensions of 8 mm (length) and 4.8 mm wide, in

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order to allow for space for a frame to fit into the capsule. The device easily fits within the capsule with plenty of space for the electronics as shown in Fig. 4(b). The average occupancy volume for the energy harvester is 35% and 70% for a two or four cantilever system respectively. The small thickness of the device with silicon mass will allow the cantilever tip to displace up to 5.5 mm peak-to-peak inside the capsule, thus allowing the device to harvest significant amount of power.

---------- Insert Figure 4----------

2.4 Characterization

The AlN quality was analyzed using X-ray diffraction (Philips X'Pert Pro 45 kV, 40 mA) and a piezometer (PM 300, Piezotest) as previously described [31, 32]. After the devices were wire bonded onto a PCB they were tested using a vibration shaker (Labworks Inc.). A load resistance was connected to the cantilever that matched the impedance of the device (approximately 300kΩ), in order to calculate the RMS power. Initially testing was performed to determine the resonant frequency of the device by sweeping the frequency at low acceleration. The device performance was first measured with a typical sinusoidal excitation at resonant frequency. In order to mimic the vibration of the heart a custom waveform sent to the shaker using a signal generator. The waveform shape and durations were taken from data from an accelerometer that was implanted in the heart previously [25, 29] as shown in Fig. 5(c). A 35-50 ms vibration impulse with frequency of 1-4 Hz representing 60-240 bpm and varying acceleration was used to mimic the heartbeat.

3. Results and Discussion

The acceleration of the heart was measured by implanting a 3-axis accelerometer in the heart of a sheep which was performed by Brancato et al [25]. Fig. 5(a) demonstrates the location of the capsule in the right ventricle. Fig. 5(b) demonstrates the z-axis acceleration of the heart, which has an average peak-to-peak acceleration of 1.22 ± 0.19 g. However, the acceleration

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can vary significantly due to location of the capsule, orientation of the capsule (different axis), and the condition of the heart [25, 29]. Previous reports have demonstrated that the acceleration can vary from 0.5g to > 3g depending on the orientation [29]. The frequency spectrum demonstrates a peak at 20-30 Hz which corresponds to the 30-50 ms period of the peak acceleration pulse as shown in Fig. 5(c). Knowing the frequency spectrum and acceleration are usually critical pieces of information that are required in order to design an energy harvester. However for shock-induced excitation the acceleration and width of the pulse is the most useful information as shown from Eq. (2) and Fig. 2.

---------- Insert Figure 5----------

The quality of the AlN can have a significant effect on the device performance [23]. XRD results shown in Fig. 6 demonstrate a highly crystalline c-axis textured (002) oriented AlN film, with a relatively narrow omega scan full width half maximum value of (002) AlN of 1.8º (Fig. 6(b)). The piezoelectric properties (d_{33}) of the AlN film were 5.1 pm V^{-1}, which is in good agreement with typical values. Enhanced piezoelectric properties of AlN have been demonstrated by optimizing the underlying layers[22] and doping the AlN with Sc[21], which could be used to enhance the device performance.

---------- Insert Figure 6----------

Initially the fabricated cantilevers were experimentally tested to investigate their performance at resonance using a standard sinusoidal excitation method. The results for the power as a function of frequency at varying accelerations is shown in Fig. 7. The devices were tested in an open atmosphere environment. The resonant frequency of the devices was approximately 376 Hz and they were able to achieve powers of approximately 14 μW at 0.15 g with a bandwidth of approximately 3.7 Hz. This results in a power density of 0.842 mW cm^{-3} at 0.15 g. However, significant amplitude of 3 mm was visually demonstrated at 0.25 g, and

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device failure was observed at higher accelerations at resonant frequency. The cantilever had a resonant frequency of 376 Hz, which corresponded to an r-value of 0.08 for a 30 Hz source vibration according to Eq. (2).

---------- Insert Figure 7----------

The devices were then validated for an off-resonance shock-induced impulse excitation method. The results comparing the on-resonance and off-resonance are shown in Fig. 8. The off-resonance power measurements demonstrate the peak power that was measured across a 300 kΩ load. As expected the power as a function of acceleration curve is shifted to the right for the off-resonance mode. The power obtained from the energy harvester is dependent on the amplitude of the beam, which creates stress in the piezoelectric film. Therefore to achieve similar peak power a 10x acceleration force is required. In addition the energy harvester was able to operate at much higher acceleration without failure when operating in off-resonance mode, because the amplitude was significantly lower than when operated at resonance for any given acceleration input. Fig. 8 demonstrates that the peak power of the energy harvester with impulse accelerations of 1-1.5 g were 17-27 µW per cantilever. However, due to the cantilevers mechanical damping the power harvested diminishes quickly and within 100-200 ms the cantilever stops oscillating and obtaining significant amount of power.

---------- Insert Figure 8----------

After the devices were characterized for their peak power as a function of acceleration, the devices were validated for their power as a function of heart rate. The same impulse based waveform was used but the frequency or duty cycle of the impulse was altered. A 1 g acceleration was used and the frequency varied between 1-4 beats per second to represent a normal heart rate (60 bpm) and an accelerated heart rate of up to 240 bpm. The impulses were

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evenly spaced. A normal heart rate of 60 bpm allows for 1 beat per second, which if the device dampens within 100-200 ms that means the device is not harvesting power for 80-90% of the time. Therefore the peak power needs to be significantly higher in order to achieve an average of 5-10 μW, which is needed to power the pacemaker. Fig. 9 demonstrates the effects of increasing the heart rate. As the heart rate increased the average power increased and the resulting waveform more closely resembles a sinusoidal waveform. The amount of power harvested was also increased due to the superposition principle. However, this high heart rate is not realistic in a typical real-life application as typically pacemaker patients have bradycardia (low heart rate), so a high peak power is necessary to counteract the downtime in between heart beats.

---------- Insert Figure 9----------

The average power per cantilever as a function of acceleration and heart rate is shown in Fig. 10. This demonstrates that our MEMS energy harvester was able to obtain an average power of 1.49 and 2.81μW at 1 to 1.5 g at a heart rate of 60 bpm. This corresponds to a power density of 97 μW cm^{-3} g^{-2}, whereas the power density at 240 bpm increases to 454 μW cm^{-3} g^{-2}, because of the increased peak power and the number of shocks in a second. Therefore a 2 cantilever system which takes up 35% of the volume of the capsule (taking into account the maximum displacement of the beam) can generate 5.62 μW and a 4 cantilever system occupying 70% volume can generate 11.24 μW, which should be sufficient to have a self-sustaining system or at least prolong the lifetime of a rechargeable battery. The power obtained was prior to rectification which will decrease the overall power. Therefore there is still a need to enhance device performance.

---------- Insert Figure 10----------

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As demonstrated in Eq. (2), if the resonant frequency of the cantilever is reduced to approach the shock impulse frequency (r -> 1) the displacement of the cantilever increases and thus the power density would be enhanced. However, creating a low frequency MEMS harvester with resonant frequency of 20-30 Hz is challenging and will likely reduce the reliability of the device, as displacement/stress would also increase. Reliability of the MEMS device is another critical component that is often overlooked. Operating in off-resonance mode at a higher frequency allows the energy harvester to be fabricated with a thicker beam substrate, which will be more robust and will increase the lifetime of the device. Reliability and optimal design to enhance power density needs to be further investigated.

4. Conclusions

This paper demonstrates for the first time the capability of using a piezoelectric MEMS based device to power an implantable leadless pacemaker using vibrations from the heart while maintaining a small enough footprint to fit within the pacemaker capsule. The capability of fitting inside the capsule allows the energy harvester to be used to increase the lifetime of a battery or it can be used to create a self-sustaining system. The PiezoMEMS device is able to harvest mechanical energy by converting it into electrical energy through the use of a thin film piezoelectric layer. AlN was used as the piezoelectric material because it has a high power figure of merit, biocompatible, and it is CMOS compatible, which allows the electronics to be integrated into the chip in the future. The issues with matching the resonant frequency of the cantilever to that of the heart were eliminated with the use of a shock-induced vibration method, which allows the energy harvester to be designed for optimal power efficiency without the need to match the resonant frequency to the ultra-low frequency impulses of the heart. The use of linear MEMS energy harvesters based on shock-induced vibration opens up new possibilities for harvesting energy for implantable or wearable systems, as high frequency devices offer numerous advantages such as i) lower impedance, ii) increased stiffness, which leads to iii)

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increased reliability. Further designs need to be investigated in order to enhance device performance.

Acknowledgements

The authors would like to thank entire Fabrication Facility staff at Tyndall National Institute for their help, along with the entire MANpower consortium. This work was performed under the financial support from the European Union Seventh Framework Program under grant agreement no. 604360.

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References:

[1] J. Gonzalez, A. Rubio, M. Francesc, Human powered piezoelectric batteries to supply power to wearable electronic devices, International journal of the society of materials engineering for resources 10/1 (2002) 34.
[2] C. Dagdeviren, B. Yang, Y. Su, P. Tran, P. Joe, E. Anderson, J. Xia, Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm, Proceedings of the National Academy of Sciences 111/5 (2014) 1927.
[3] X. Wei, J. Liu, Power sources and electrical recharging strategies for implantable medical devices, Frontiers of energy and power engineering 2/1 (2008) 1.
[4] H. Mond, G. Freitag, The cardiac implantable electronic device power source: evolution and revolution, Pacing and Clinical Electrophysiology 37/12 (2014) 1728.
[5] J. Paulo, P. Gaspar, Review and future trend of energy harvesting methods for portable medical devices, Proceedings of the world congress on engineering 2 (2010) 168.
[6] M. Colin, S. Basrour, L. Rufer, Design, fabrication and characterization of a very low frequency piezoelectric energy harvester designed for heart beat vibration scavenging, SPIE Microtechnologies, International Society for Optics and Photonics, 2013, p. 87631P.
[7] E. Lefeuvre, S. Risquez, M. Woytasik, M. Deterre, B. Boutaud, R. Dal Molin, Energy harvesting devices as long lasting power sources for next generation pacemakers, International Conference in Microelectronics, 2013, p. 1.
[8] S. Risquez, M. Woytasik, J. Wei, F. Parrain, E. Lefeuvre, Design of a 3D multilayer out-of-plane overlap electrostatic energy harvesting MEMS for medical implant applications, Design, Test, Integration and Packaging of MEMS/MOEMS, 2015, p. 1.
[9] G. Hwang, H. Park, J. Lee, S. Oh, K. Park, M. Byun, H. Park, G. Ahn, C. Jeong, K. No, H. Kwon, Self-powered cardiac pacemaker enabled by flexible single crystalline PMN-PT piezoelectric energy harvester, Adv Mater 26/28 (2014) 4880.
[10] M. Ansari, M. Karami, Modeling and experimental verification of a fan-folded vibration energy harvester for leadless pacemakers, J. Appl. Phys. 119/9 (2016) 094506.
[11] A. Karami, D. Inman, Powering pacemakers from heartbeat vibrations using linear and nonlinear energy harvesters, Appl Phys Lett 100/4 (2012) 042901.
[12] N. Jackson, O. Olszewski, C. O'Murchu, A. Mathewson, Powering a leadless pacemaker using a PiezoMEMS energy harvester, SPIE Microtechnologies, 2017, p. 102469V.
[13] M. Deterre, B. Boutaud, R. Dal Molin, S. Boisseau, J. Chailout, E. Lefeuvre, E. Dufour, Energy harvesting system for cardiac implant applications, Design, Test, Integration and Packaging of MEMS/MOEMS, 2011, p. 387.
[14] A. Hajati, S. Kim, Ultra-wide bandwidth piezoelectric energy harvesting, Appl Phys Lett 99/8 (2011) 083105.
[15] H. Liu, C. Lee, T. Kobayashi, C. Tay, C. Quan, Investigation of a MEMS piezoelectric energy harvester system with a frequency widened bandwidth mechanism introduced by mechanical stoppers, Smart Mater Struct 21/3 (2012) 035005.
[16] O. Olszewski, R. Houlihan, A. Blake, A. Mathewson, N. Jackson, Evaluation of vibrational PiezoMEMS harvester that scavenges energy from a magnetic field surronding an AC current-carrying wire, J. Microelectromech S. (2017).

ACCEPTED MANUSCRIPT

[17] N. Jackson, F. Stam, O. Olszewski, H. Doyle, A. Quinn, A. Mathewson, Widening the bandwidth of vibration energy harvesters using a liquid-based non-uniform load distribution, Sensor Actuat A-Phys 246 (2016) 170.
[18] R. Andosca, T. McDonald, V. Genova, S. Rosenberg, J. Keating, C. Benedixen, J. Wu, Experimental and theoretical studies on MEMS piezoelectric vibrational energy harvesters with mass loading, Sensor Actuat A-Phys 178 (2012) 76.
[19] N. Jackson, L. Keeney, A. Mathewson, Flexible-CMOS and biocompatible piezoelectric AlN material for MEMS applications, Smart Mater Struct 22/11 (2013) 115033.
[20] B. Murphy, Wayne State University, 2008.
[21] M. Akiyama, T. Kamohara, K. Kano, A. Teshigahara, Y. Takeuchi, N. Kawahara, Enhancement of piezoelectric response in scandium aluminum nitride alloy thin films prepared by dual reactive cosputtering, Adv Mater 21/5 (2009) 593.
[22] N. Jackson, Influence of silicon crystal orientation on piezoelectric textured aluminum nitride deposited on metal electrodes, Vacuum 132 (2016) 47.
[23] N. Jackson, A. Mathewson, Enhancing the piezoelectric properties of flexible hybrid AlN materials using semi-crystalline parylene, Smart Mater Struct (2017).
[24] N. Jackson, R. O'Keeffe, F. Waldron, M. O'Neill, A. Mathewson, Evaluation of low-acceleration MEMS piezoelectric energy harvesting devices, Microsyst Technol 20/4-5 (2014) 671.
[25] L. Brancato, T. Weydts, W. Oosterlinck, P. Herijgers, R. Puers, Biocompatible packaging of an epicardial accelerometer for real-time assessment of cardiac motion, Eurosensors, 2016.
[26] Y. Jia, A. Seshia, Power optimization by mass tuning for MEMS piezoelectric cantilever vibration energy harvesting, J. Microelectromech S. 25/1 (2016) 108.
[27] A. Rivadeneyra, J. Soto-Rueda, R. O'Keeffe, J. Banqueri, N. Jackson, A. Mathewson, J. Lopez-Villanueva, Tunable MEMS piezoelectric energy harvesting device, Microsyst Technol 22/4 (2016) 823.
[28] R. Elfrink, S. Matova, C. De Nooijer, M. Jambunathan, M. Goedbloed, J. Van de Molegraft, R. Van Schaijk, Shock induced energy harvesting with a MEMS harvester for automotive applications, Electron Devices (IEDM), 2011.
[29] L. Brancato, T. Weydts, H. De Clercq, T. Dimiaux, P. Herijgers, R. Puers, Biocompatible packaging and testing of an endocardial accelerometer for heart wall motion analysis, Eurosensors, 2015, p. 840.
[30] N. Jackson, R. O'Keeffe, F. Waldron, M. O'Neill, A. Mathewson, Influence of aluminum nitride crystal orientation on MEMS energy harvesting device performance, J. Micromech. Microeng. 23/7 (2013) 075014.
[31] N. Jackson, R. O'Keeffe, R. O'Leary, M. O'Neill, F. Waldron, A. Mathewson, A diaphragm based piezoelectric AlN film quality test structure, Microelectronic Test Structures (ICMTS), 2012, p. 50.
[32] N. Jackson, O. Olszewski, L. Keeney, A. Blake, A. Mathewson, A capacitive based piezoelectric AlN film quality test structure, Microelectronic Test Stuctures (ICMTS), 2015, p. 193.

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Shock-Induced Aluminum Nitride based MEMS Energy Harvester to Power Leadless Pacemaker



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Dr. Jackson is a senior member of IEEE and IEEE Engineering in Medicine and Biology Society.



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Figure Captions:

Figure 1- (a) Schematic of the location of the implanted leadless pacemaker in the right ventricle, (b) Schematic of the capsule contents with four MEMS energy harvesters and electronics/storage with dimensions of 40 mm by 6 mm diameter

Figure 2- Simulated results from Eq. (1) demonstrating amplitude ratio as a function of the resonant frequency ratio with f=30 Hz to match the width of the impulse peak of the heart.

Figure 3- Cross section schematic of the fabrication process for the MEMS energy harvesters

Figure 4- (a) fabricated AlN based MEMS energy harvester with a two cantilever device, (b) image showing the two cantilever MEMS energy harvester inside a Perspex capsule with exact dimensions of a leadless pacemaker.

Figure 5- (a) Schematic of the location of a leadless pacemaker and the orientation of acceleration, (b) transient acceleration of an implanted accelerometer in the z-direction, (c) zoomed in data of the impulse waveform demonstrating the width which corresponds to a frequency of 20-30 Hz in the frequency spectrum

Figure 6- X-ray diffraction results of the AlN/Ti stacked layer (a) 2θ-ω scan showing crystalline peaks of AlN (002) and Ti (002), (b) ω scan of the AlN (002) peak and its corresponding FWHM value.

Figure 7- Measured power harvested from a single cantilever when operating at resonant frequency with low acceleration forces.

Figure 8- Optimal peak power generated as a function of acceleration for a cantilever structure operating at resonance frequency (black) and with a shock induced excitation off resonant frequency (red).

Figure 9- Transient power obtained from energy harvester for various heart rates.

Figure 10- Average power of shock induced vibration as a function of acceleration for various heart rates for a single cantilever.

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Figures:

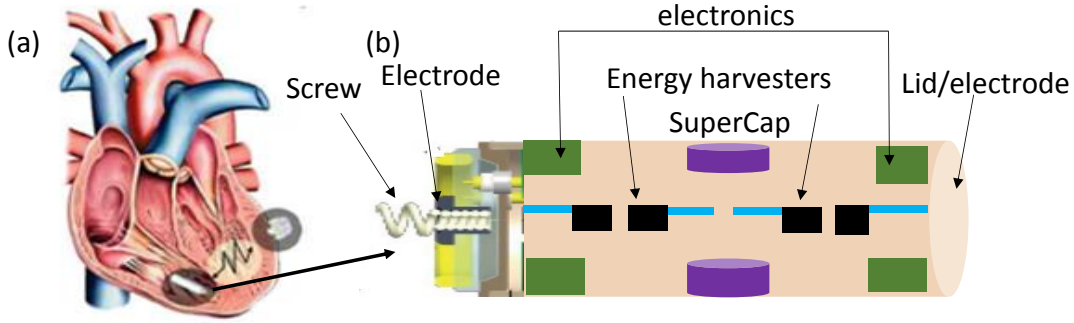


Figure 1

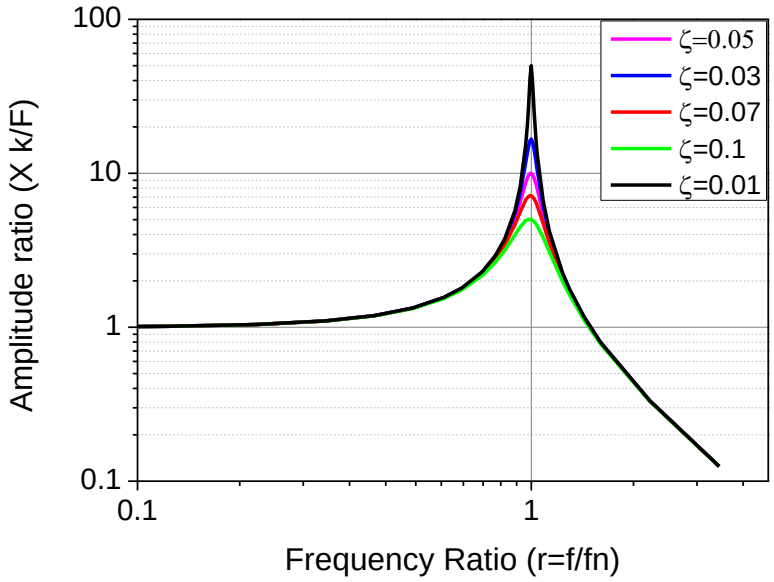


Figure 2

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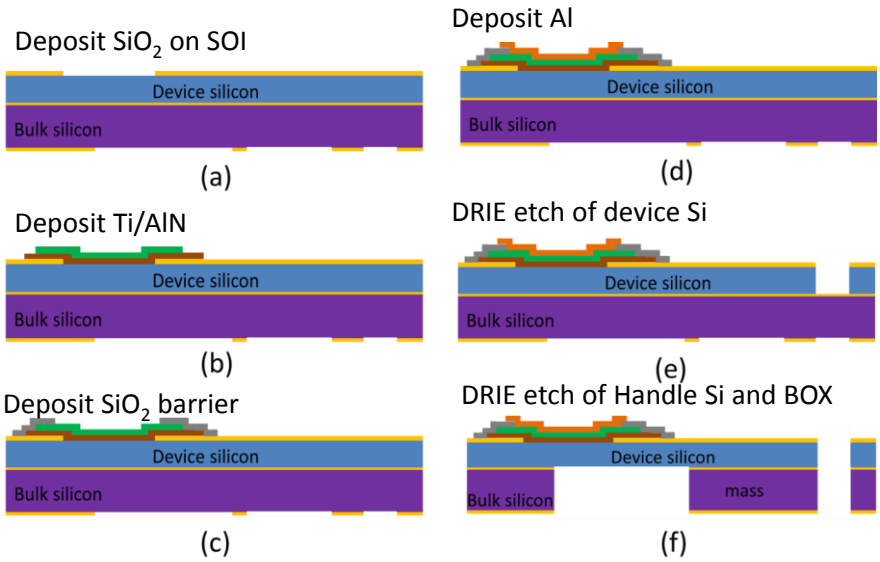


Figure 3

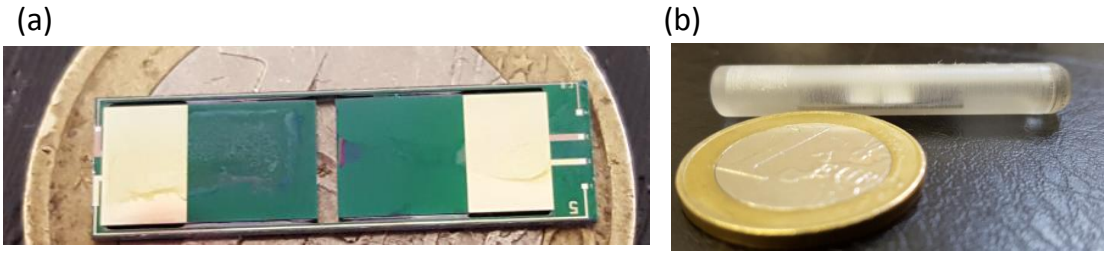


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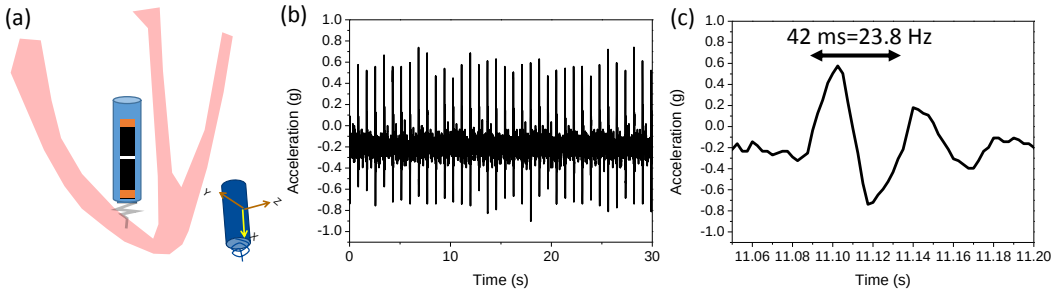


Figure 5

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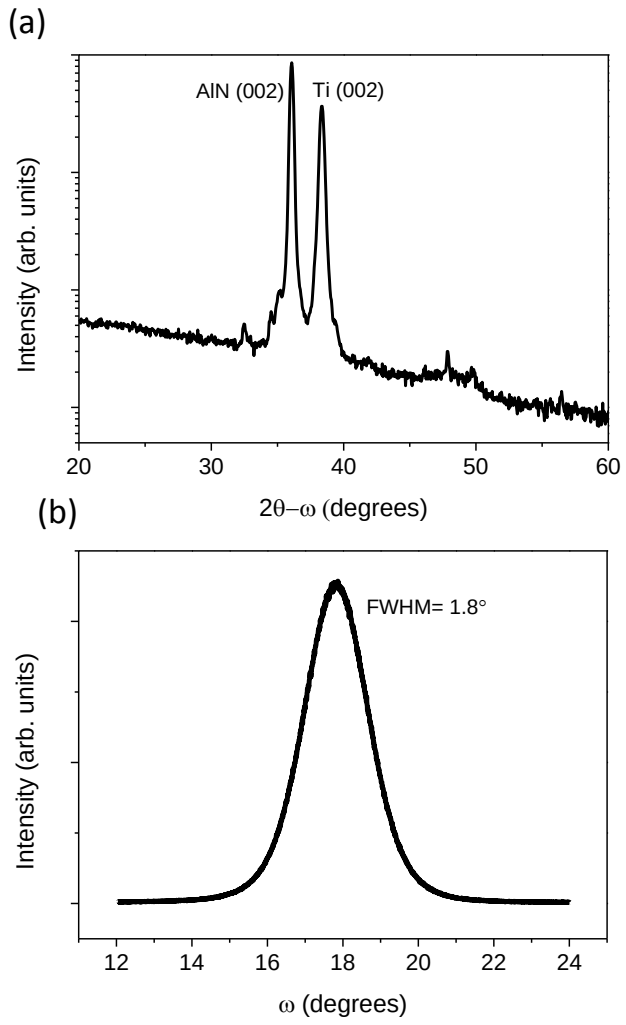


Figure 6

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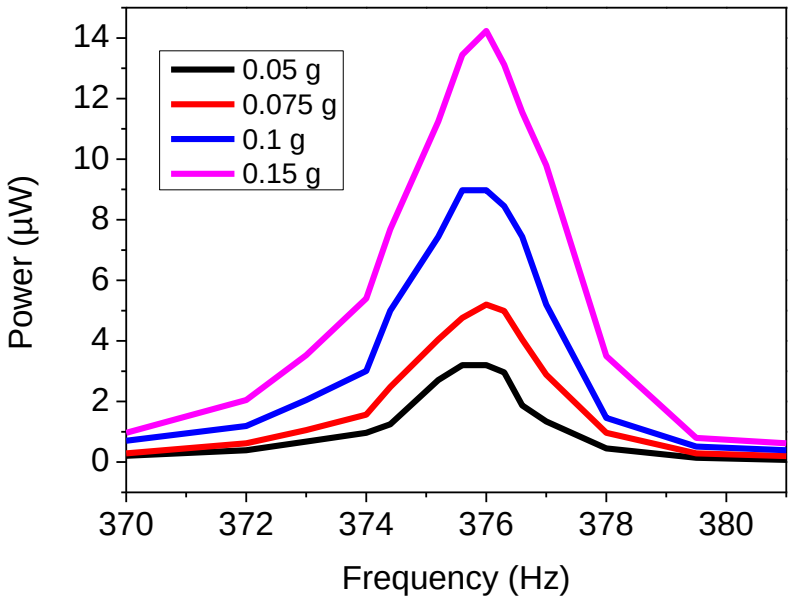


Figure 7

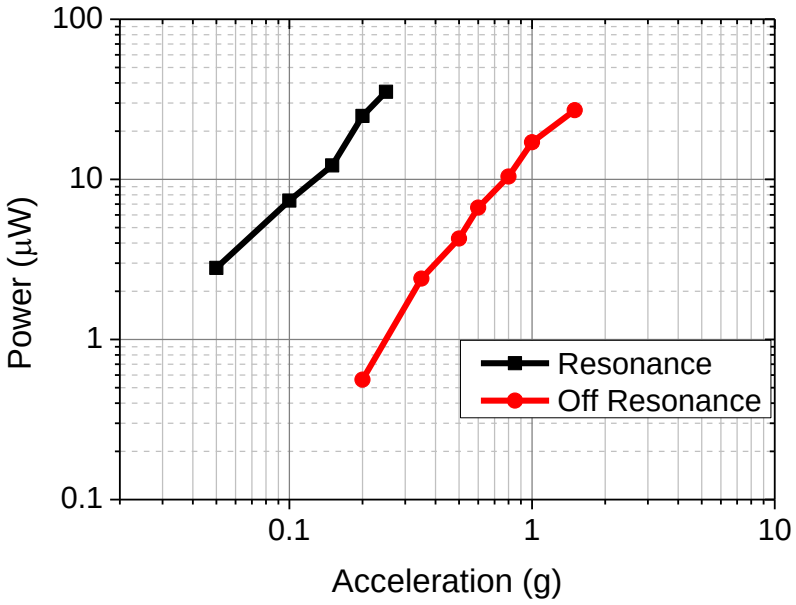


Figure 8

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Shock-Induced Aluminum Nitride based MEMS Energy Harvester to Power Leadless Pacemaker

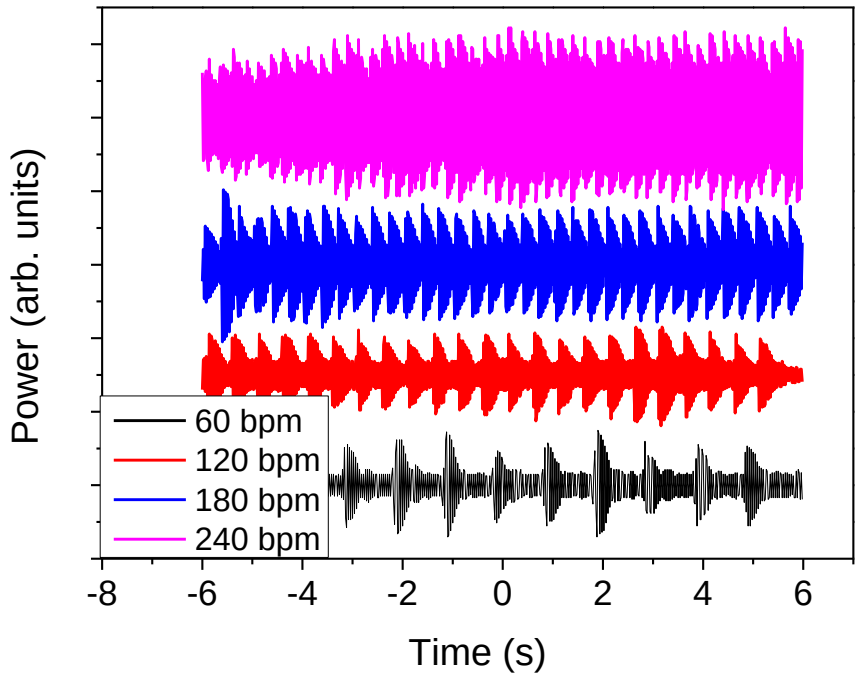


Figure 9

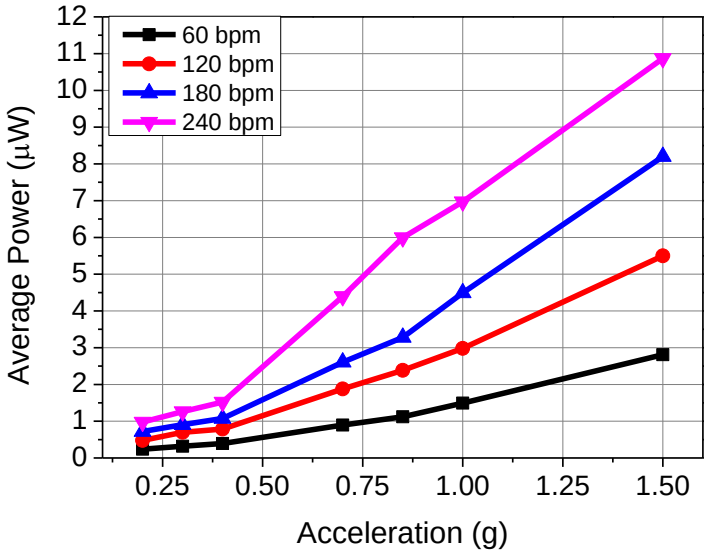


Figure 10