Asian Journal of Scientific Research

ISSN 1992-1454

science alert
http://www.scialert.net

ANSInet
an open access publisher
http://ansinet.com

Asian Journal of Scientific Research 6 (1): 1-15, 2013
ISSN 1992-1454 / DOI: 10.3923/ajsr.2013.1.15

Investigation on MEMS-based Piezoelectric Energy Harvester Design with Aspect of Autonomous Automobile Sensors

[1]M.S. Bhuyan, [2]Masuri Othman, [3]Sawal Hamid Md Ali, [1]Burhanuddin Yeop Majlis and [1]Md. Shabiul Islam

[1]Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia, 43000 UKM, Bangi, Malaysia
[2]Ministry of Science, Technology and Innovation (MOSTI), Federal Government Administrative Centre, 62662, Putrajaya, Malaysia
[3]Department of Electrical, Electronic and Systems Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43000 UKM, Bangi, Malaysia

Corresponding Author: M.S. Bhuyan, Micro and Nanoelectronics System (MNS), IMEN, UKM, Malaysia

ABSTRACT

Exponential progress in Microelectromechanical Systems (MEMS) miniaturization feasibility and ultra-low-power electronics to date, micro sensors require so small energy that may be simply harvested from sensors ambient environment. To power-up sensors, batteries and chemical fuel sources may be considered. However, it is impractical to power-up automotive sensors through wired means because they derive their self-worth through their distribution and mobility. Moreover, if battery is used, questions of lifetime, design complexity, costs etc arise. The key objective of our research was to design and fabricate a micro piezoelectric energy harvester for converting low-frequency vibrations into electrical power. In this review paper, we have investigated most recent micro piezoelectric harvesters at depth, with focus on design structure and output characteristics. Contrary to designs that follow cantilever structure to use the bending strain on the piezoelectric beam, a novel design is required to be investigated as sensors power source instead of conventional batteries. As in automotive ambient environment, energy harvesting device will be in direct contact with driving force and ambient acceleration amplitudes will be large enough for previously reported cantilever based design. In this regards, this research will explore new geometries to utilize tensile stress/strain on piezoelectric film instead of cantilever bending strain. The harvester will be modeled in CoventorWare. To realize an efficient autonomous energy harvesting platform, it is also necessary to integrate ultra-low-power electronic circuitry with harvesting device. The electrical schematic will be simulated in Cadence Virtuoso Spectre. A short discussion on energy harvester under development followed by research methodology is presented.

Key words: Automotive sensors, energy harvesting, microelectromechanical system, complementary metal-oxide semiconductor, ultra-low-power electronics, wafer-level fabrication

INTRODUCTION

Under strict environmental regulations and incentive polices for eco-friendly vehicles in every countries, fuel economy is becoming a critical commercial issue. Demands for plug-in hybrid and Electric Vehicle (EV) are emerging as an effective way to lower global warming emissions, oil use

Fig. 1: The evSAT sensor detects accidents involving electric and plug-in hybrid vehicle and shuts off their high voltage batteries. Series production of the sensor will begin in 2012. 1: evSAT (Sensor for high-voltage battery cut-off), 2: Air bag control unit, 3: High-voltage battery, 4: Battery management system, 5: Motor and transmission

and smog (Maggetto and Van Mierlo, 2000). The advent of plug-in hybrid and EV are accelerating the trend in employing more and more new integrated Microelectromechanical System (MEMS) sensors to improve performance and comfort as well as to enhance passenger's safety in an unobtrusive way during driving, finding in their way into systems such as air bags, tire-pressure monitoring and vehicle stabilization control etc. (Hussain *et al*., 2006). As an example, Continental Automotives evSAT acceleration sensor when detects an accident it can immediately shut-off the high voltage traction batteries (up to 400 volts) thus protects passengers from possible electric shock as shown in Fig.1 (http://www.conti-online.com/generator/www/start/com/en/index_en.html).

Automotive MEMS sensors powered (by means of wires) from vehicle main battery immediately undermine the value of sensor devices being random and mobile in distribution and implementation. Often these sensors are not easily accessible, so battery replacement is not practical. Even if access is possible, the more number of sensor devices needed in automotive sensing network make the cost of replacement too high. The need to monitor a large amount of parameters causes the proliferation of wires, increasing the complexity of vehicle design, adding significant to vehicle weight and cost that leading to very complicated sensing architectures and other problems related to the maintenance and the reliability. Towards the vision of future ubiquitous autonomous automotive sensing network, supplying power appears to be the most challenging technological hurdle still to be overcome (Hannan *et al*., 2008).

Integrated micro sensing devices combine ultra-low-power electronics with MEMS-sensors. However, the actual implementation and application of such technologies is limited by the ability of remote power-up. Although, at present reported macro and mesoscale energy harvesting devices can produce power at mW level, but insufficient power is still a major issue during miniaturizing into micro-scale (Najafi *et al*., 2011). To overcome the remote power-up problem, researchers to this end have examined many different methods of energy harvesting technologies including simple combustion in micro-reactors, ambient vibration harvesting by electrostatic transducers as well as electromagnetic transducers, Micro-direct Methanol Fuel Cells (DMFCs) and micro-solar cell arrays etc. (Najafi *et al*., 2011). One of the most studied methods to date and one of the most appealing due to its potential simplicity, involves the use of piezoelectric energy harvesters in combination with ambient vibration. The integration of MEMS piezoelectric energy harvesting functionality with automotive sensor devices becomes of interest from the evidence of large amount of mechanical vibration that result during automotive operation. Moreover, vibration-based energy harvesting is especially attractive because the associated harvesters can be scaled to incredibly small sizes and do not require the constant addition of fuel, such as with combustion reactors and DMFCs. Furthermore, unlike solar energy harvesting technology, vibration-based energy harvesters may be packaged away from the ambient environment to increase their device lifetimes and they can be operated at all times throughout the day. In addition, this environmentally friendly energy harvester can have life of more than twenty years that can provide safety, security of supply and other benefits including ongoing life-cycle expenses of automotive sensing network.

In this review paper we have studied the works carried out by researchers during the past one decade followed by a discussion on the different types of approaches that are being pursued. The most prominent MEMS-based piezoelectric energy harvesters are examined at depth, with a focus on their device structure and the best device output characteristics, to provide insight into the best methods to capture vibration energy. Our research will explore new energy harvester geometries to utilize tensile stress/strain on piezoelectric film. This research will use CoventorWare (3-D MEMS model schematic editor) software to model the harvest (Dennis *et al.*, 2011). The ultra-low-power electrical schematic will be created and simulated in Cadence Virtuoso Spectre and UltraSim circuit simulator. Results from simulations will be viewed in the MEMS+Scene3D module for 3-D inspection. Finally, the paper provides concluding remarks.

INVESTIGATION ON PAST RESEARCHERS WORKS

In the early 2000, researchers started to focus on the modeling and fabrication of MEMS scale piezoelectric energy harvester and demonstrated MEMS devices capable of generating useful power and have shown a great deal of inventiveness and originality in the design of piezoelectric energy harvester, with the realization of many different geometries, configurations and device types. Williams and Yates (1995) analyzed a piezoelectric micro energy harvester with a dimension of $5\times5\times1$ mm^3. The predicted power output was 1 μW at 70 Hz and 0.1 mW at 330 Hz assuming a displacement of 50 μm. Researchers concluded that the power output is proportional to the cube of frequency of vibration source and to maximize power output for any particular application, the resonant frequency of the energy harvester should be designed to match the dominant frequency of the source vibration and the maximum possible deflection of the device should be made as large as possible.

One of the first thin film MEMS piezoelectric energy harvesting devices was fabricated by Marzencki *et al.* (2005). The researchers used piezoelectric Aluminum Nitride (AlN) layer, because AlN films can be fabricated by a much simpler sputtering process in contrast to the sol-gel film formation and high temperature anneal usually used with Lead Zirconate Titanate (PZT) films. This allowed greater control in film quality and greater compatibility with standard micro fabrication processes. The energy harvesting device generated 0.038 μW of power from 0.5 g ($g = 9.81$ m sec^{-2}) vibration at its resonant frequency of 204 Hz. However, the output power of the device was limited due to the low power levels by the properties of AlN material. Through FEM simulation, researchers estimated that higher power could be obtained by much higher piezoelectric constant. In a later work, Marzencki *et al.* (2007a) developed a custom circuitry to charge capacitors by unimorph piezoelectric cantilevers and achieved 1 volt output by charging a 1 μF capacitor using only 0.05 g acceleration amplitudes at cantilever resonant frequency of 1511 Hz Marzencki *et al.*

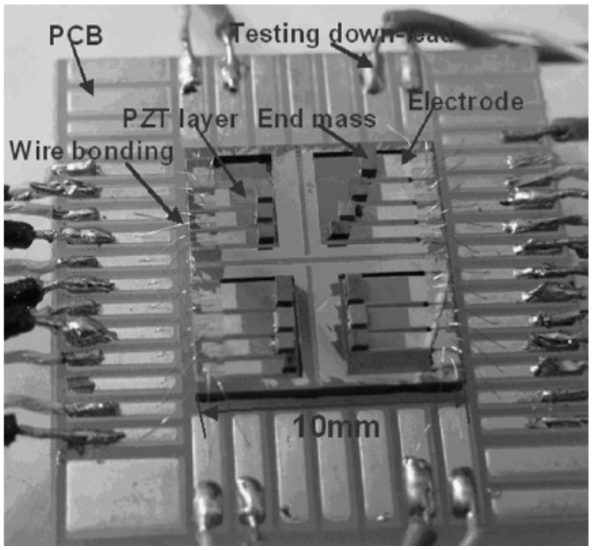

Fig. 2: Energy harvester array prototype

(2007b). In a more recent work, Marzencki *et al.* (2009) have demonstrated an adaptive device that can shift its resonant frequency up to 36% to best match the vibrations in a system of interest. This was an important development because both the ambient vibrations as well as the resonant frequency of the cantilever are susceptible to shifting over time and during operation. By tuning the resonant frequency, one can match the cantilever device to the ambient vibrations in order to enhance harvesting efficiency. Unfortunately, since this method relies on nonlinear resonance effects that require very large cantilever oscillation amplitudes, it is not immediately useful for applications in ambient vibration energy harvesting where vibrations are typically less than 1 g. Researchers noted a feasible application area of industrial machinery, where acceleration amplitudes can exceed 25 g at frequencies of several kHz.

Shen *et al.* (2008) fabricated a Pt/PZT/Pt/Ti/SiO_2/Si cantilever structure with dimensions of 3200×400 μm, the added (1360×940) μm proof mass (Si), allowing for a resonant frequency of 462.5 Hz. The researchers were able to achieve 2.15 μW and ~200 mV output with a load resistance of ~6 kΩ while using a 461.25 Hz vibration source at 2 g acceleration magnitude.

Fang *et al.* (2006) fabricated a Ti:Pt/PZT/Ti:Pt/SiO_2/Si composite cantilever structure with a non-integrated Nickel (Ni) metal proof mass. Upper PZT thick film layer was sandwiched between a pair of metal electrodes (Pt/Ti) and a lower non-piezoelectric element. The beam dimension was $2000\times600\times13.64\ \mu m^3$ and proof mass dimension of $600\times600\times500\ \mu m^3$. Ni proof mass was added to the top of the device after the complete formation of the cantilever. This allowed to use a rather harsh KOH (Soin and Majlis, 2006) wet etch to remove the backside of the wafer instead of backside RIE. However, the downside to this approach was the added difficulty of adding the Ni mass to the cantilever by glue without damaging the device. The metal mass on tip of the cantilever was used to decrease the structure's natural frequency for the applications under low-frequency vibration. The prototype fabricated acts as AC current source, its voltage increases with increased load, up to 898 mV at 112 kΩ. Researchers achieved a peak of 2.16 μW for 21.4 K resistance and a 608 mV peak-peak AC voltage under resonant frequency of about 609 Hz from a 1 g vibration.

Liu *et al.* (2008) developed an energy harvesting array (three cantilevers) device to improve power output and frequency flexibility as shown in Fig. 2. The size of the cantilevers were, 12 mm

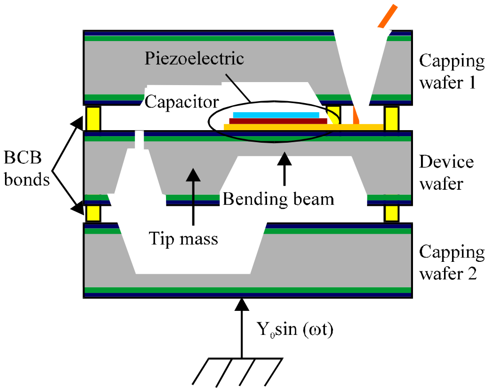

Fig. 3: Schematic diagram of the fabricated devices

silicon layer thickness, 3.2 mm PZT layer thickness, length and width were in range of 2000-3500 mm and 750-1000 mm, respectively. At 229 Hz the array device produced about 3.06 V (direct serial connection), which is less than the actual total value of the cantilevers i.e., 5.256 V. After rectification, the DC voltage was 3.93 V across the capacitor and the maximum power obtained was about 3.98 μW. The bandwidth covers from 226-234 Hz, which indicates the cantilevers array has wider bandwidth than that of single cantilever. This device is promising to support networks of ultra-low-power wireless nodes. However, researchers noticed that the output voltage drops-off when the excited frequency deviates from the resonant frequency for the available bandwidth of only just 2-3 Hz.

Renaud *et al.* (2008) focused their analysis on the case of the piezoelectric unimorph cantilever which, consists of an elastic cantilever supporting one piezoelectric capacitor as shown in Fig. 3. An additional mass (Si) was attached to the tip of the unimorph. PZT and AlN were used as piezoelectric materials. The PZT-based energy harvester has a Pt/PZT/Pt/Si multi-layer structure and the PZT was deposited by sol-gel process. The piezoelectric capacitor was connected to an electrical load in which energy is stored or dissipated. The fabricated PZT-based cantilever generated maximum 40 μW at its resonant frequency of 1.8 kHz with amplitude of 180 nm.

Elfrink *et al.* (2009a) developed a unimorph Al/AlN/Pt/Ta/SiO_2/Si cantilever. The output power from mechanical vibrations was measured with different geometries. The resonance frequencies ranged from 200 Hz up to 1200 Hz. A maximum output power of 60 μW was achieved from an unpackaged device at 2.0 g acceleration and resonance frequency of 572 Hz. Glass wafers were used for the top and bottom covers. The device was packaged with top and bottom glass substrates within the cavities to allow mass displacement up to about 400 μm. The packaged devices had limited output powers and quality factors due to air damping caused by the package. One such packaged cantilever experienced a decrease in output power from 60-2.1 μW. The device for which the package is partly opened at the mass tip generated 22 μW. Researchers noted that packaging the devices resulted in significantly greater damping losses due to squeeze forces/air displacement effects and the associated limitation in the maximum cantilever displacement. Recently, Elfrink *et al.* (2009b) measured 85 μW from an unpackaged device at 325 Hz and 1.75 g acceleration. This work has led to the most efficient micro-machined piezoelectric vibration energy harvester to date.

Lee *et al.* (2007) fabricated two modes of piezoelectric energy harvesters to incorporate a 3000×1500 μm^2 cantilever beam structure with 11 μm thickness comprised of a 5 μm PZT layer and a 1 μm SiO2 at the bottom of the beam structure. In the d33 mode, the interdigitated electrodes were fabricated with 30 μm widths and 30 μm gaps. The proof masse for the two piezoelectric harvesters was fabricated under the beam structure with dimensions of 500×1500×500 μm^3 for the d31 mode and 750×1500×500 μm^3 for the d33 mode. The different proof mass dimension was used in the two devices to demonstrate the ability of the structure to adjust the resonant frequency. Experimental results showed that d31 mode device possesses a maximum open circuit output voltage of 2.675 V and a maximum output power of 2.765 μW with 1.792 V output voltages excited at a resonant frequency of 255.9 Hz under a 2.5 g acceleration level. The d33 mode device possessed a maximum open circuit output voltage of 4.127 V and a maximum output power of 1.288 μW with 2.292 V output voltages at its resonant frequency of 214 Hz at 2 g acceleration. Lee *et al.* (2009) in a later work developed a bimorph 3000×1500 μm^2 piezoelectric cantilever beam. The 10 μm thick cantilever was formed by laminating two 5 μm upper and lower PZT layers that comprised of a thin electrodes in between and also at the top and bottom of PZT layers. To demonstrate the tuning of the resonant frequency of the device, the proof mass was fabricated under the beam structure at the tip with a dimension of 500×1500×500 μm^3 for parallel poling device and 750×1500×500 μm^3 for serial poling device. Researchers reported that the device possessed a maximum open-circuit output voltage of 1.91 V and 3.42 V for a parallel polarization device and a serial polarization device, respectively with 2 g vibration. At an optimal resistive load, the maximum output power was 1.548 μW and 1.778 μW for the parallel polarization device and the serial polarization device, respectively. The MEMS piezoelectric bimorph energy harvester with serial polarization could generate higher output voltage than that of the device with parallel polarization under identical output level. The optimal resistive load of the device with serial polarization was higher than that of the device with parallel polarization. In choosing a series-configured bimorph, the researchers allowed for large load resistances, granting potentially large open circuit voltages, at the cost of slightly higher resonant frequencies, feasibly reducing operational efficiency in a given ambient environment.

Muralt *et al.* (2009) designed and fabricated a thin film sol-gel PZT laminated cantilever with proof mass which could harvest energy by resonant inertial oscillation of the cantilever. The active part with 2 μm thick PZT on 5 μm silicon was equipped with interdigitated electrodes to achieve higher voltages. At optimal load impedance, a voltage of 1.6 V and an output power of 1.4 μW were measured with the 0.8×1.2 mm cantilever having an active area of 0.8×0.4 mm excited with 2 g acceleration at 870 Hz.

Aktakka *et al.* (2010) developed the first wafer-level micro-scale energy harvester integrating a bulk piezoelectric ceramic (PZT). Researchers described the harvester with a Si proof mass, which generated 1.82 μW from an input acceleration of 0.1 g at 427 Hz. The unpackaged active volume of the energy harvester (beam+mass) was 12.1 mm^3. However, the design faced a large residual stress due to the temperature coefficient of expansion mismatch between the top PZT layer and the bottom AuIn layer. The resultant beam bending caused a large static tip deflection, which affected the mechanical integrity and prevented packaging of the harvester. Additionally, the tensile stress in the PZT layer caused a decrease in the piezoelectric coupling and also reduced the yield stress. In a later work, Aktakka *et al.* (2011a) used Si (instead of AuIn) as the bottom layer of the unimorph structure to avoid beam bending. This enabled the compressive residual stress in the bond layer to be equally distributed through the beam thickness and minimizes static beam

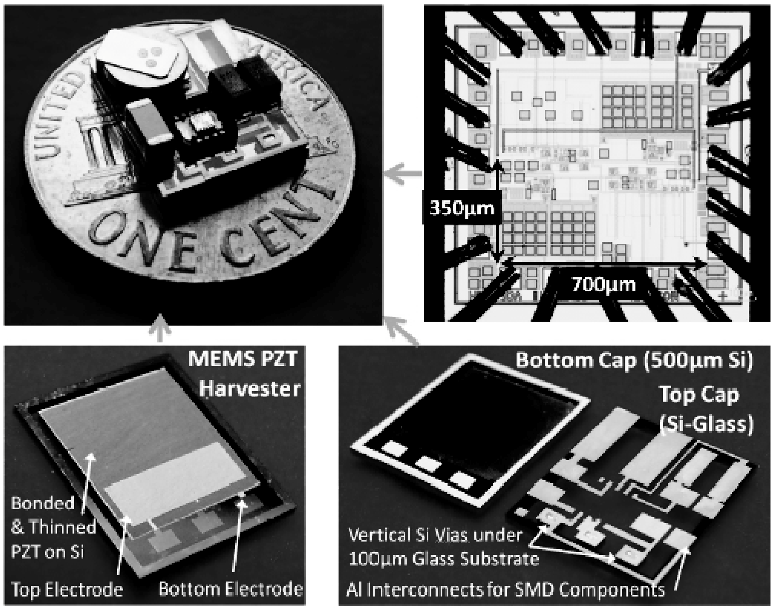

Fig. 4: Photo of the generator, with MEMS harvester, its packaging, placement of the chip and SMD components and chip micrograph

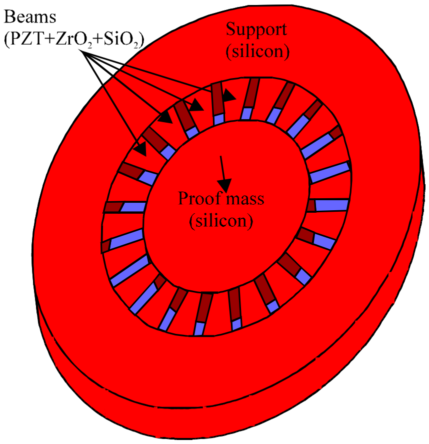

Fig. 5: Schematic structure of wide-bandwidth MEMS-scale piezoelectric energy harvester

bending. An unpackaged harvester with a tungsten (W) proof mass produces 2.74 μW at 0.1 g (167 Hz). Vertical Si vias enable the integration of the harvester to its power management IC, which allows autonomous charging of an ultra-capacitor from 0 V to a regulated voltage level of 1.85 V (Aktakka *et al*., 2011b) shown in Fig. 4. The overall system is completely self-supplied by vibration energy and has no dependence on a previously charged battery.

Hajati and Kim (2011) designed and fabricated a pie-shaped ultra wide-bandwidth resonating thin film PZT Pb(Zr,Ti)O_3 energy harvester by exploiting the nonlinear stiffness of a doubly clamped MEMS resonator as shown in Fig. 5. The device was micro-fabricated by a combination of surface and bulk micro-machining processes. Contrary to the high-Q linear cantilever based

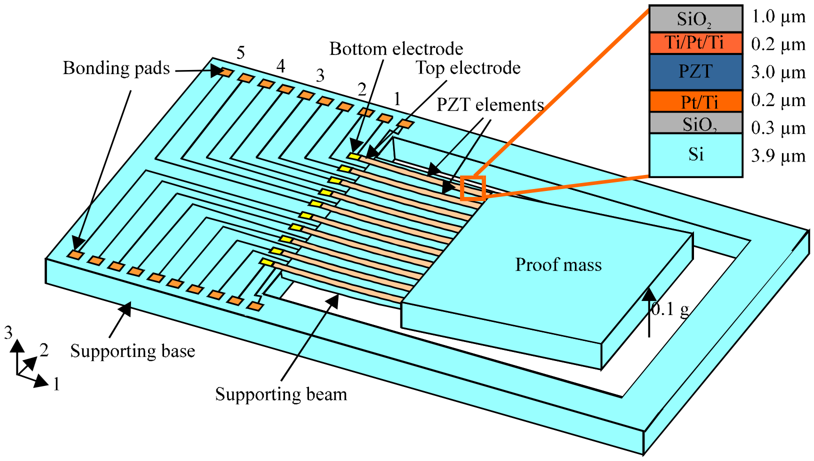

Fig. 6: Schematic drawing of the energy harvester cantilever with a large proof mass to gain in low resonant frequency

design the researchers utilized the tensile stretching strain in doubly-anchored beams. The resultant stiffness nonlinearity due to stretching provided a passive feedback and consequently a wide-band resonance. This design always generated positive tension on the PZT layer and mono-polarity output charge without using any additional bridge rectifier circuitry. Based on the open circuit voltage measurement, researchers claimed more than one order of magnitude improvement in both bandwidth (more than 20% of the peak frequency) and power density (up to 2 W cm^{-3}) by comparing the frequency response of the system with that of an equivalent linear harvester with a similar Q-factor. The power measurement from the device was 45 μW with a fixed load plain circuit.

Liu *et al.* (2011) designed and fabricated a piezoelectric MEMS energy harvester with low resonant frequency and wide operation bandwidth. The energy harvester cantilever consists of a silicon beam integrated with PZT elements parallel arranged on top and a silicon proof mass resulting in a low resonant frequency of 36 Hz as shown in Fig. 6. The whole chip was assembled into a metal carrier with a limited spacer such that the operation frequency bandwidth can be widened to 17 Hz at the input acceleration of 1.0 g during frequency up-sweep. Moreover, the energy harvester device had a wideband and steadily increased power generation from 19.4 nW to 51.3 nW within the operation frequency bandwidth ranging from 30-47 Hz at 1.0 g. The researchers claimed based on theoretical estimation that a potential output power of 0.53 μW could be harvested from low and irregular frequency vibrations by adjusting the PZT pattern and spacer thickness to achieve an optimal design.

Park *et al.* (2010) design and fabricated a piezoelectric MEMS energy harvester using sol-gel spin-coated PZT thin film and bulk micromachining for d33 piezoelectric mode operation. To scavenge low-level vibration energy with frequencies of several hundreds of hertz and a low acceleration of less than 0.5 g, it was optimally designed with a multilayered cantilever structure having a volume of 1000×800×10 μm^3 with a Si proof mass having a volume of 1000×1000×525 μm^3 by reducing the spring constant and adjusting the resonant frequency. To achieve a large output voltage, an interdigital shaped electrode was employed to achieve a large output voltage. A $PbTiO_3$

seed layer was applied as an interlayer between the ZrO_2 and Pb (Zr: 0.52, Ti: 0.48)O_3 (PZT) thin films to improve the piezoelectric property of the sol-gel spin-coated PZT thin film. The fabricated energy harvester device generated an electrical power of 1.1 μW for a load of 2.2 MΩ with 4.4 V from a vibration with an acceleration of 0.39 g at its resonant frequency of 528 Hz (Park *et al*., 2009).

Composite plot in Fig. 7 shows the frequency spectra of vibrations in typical environments where energy harvester applications may be found, along with the Volume Figure of Merit of vibration energy harvester devices reported to date. The plot in Fig. 7 highlights the relative importance of the low-end of the frequency spectrum, in terms of applications, versus the small amount of work that has gone into addressing these applications. Because the discrepancy is quite evident between the energy harvesting efforts to date as most of the academic and industrial efforts have focused on harvesting energy from relatively high-frequency periodic vibrations. Despite all of the gains in the field in the last 10 years, most research only apply to one specific type of vibration typically produced by man-made sources such as motors and other machinery (above 100 Hz). However, it is at these low-frequencies that available vibration energy can be found in many practical applications including automotives (interest of this research), environmental monitoring, agricultural automation, structural monitoring, security, military applications and of course medical and body-worn devices. At low-frequencies vibration frequencies, it is hard to harvest reasonable energy and it is even harder to regulate the harvested power. The summary of the MEMS-based piezoelectric energy harvester on our literature survey is shown in Table 1.

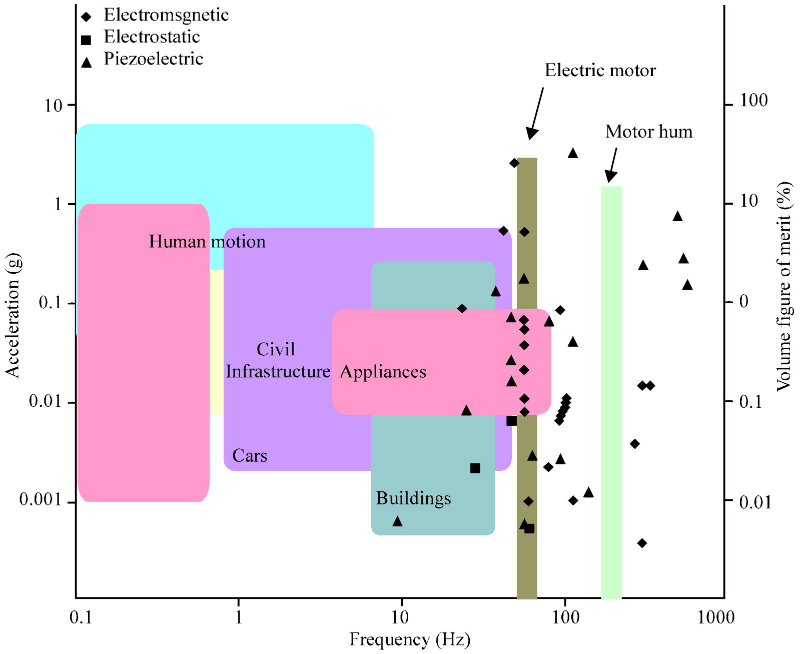

Fig. 7: Frequency spectra of the vibrations in typical environments and volume figure of merit of energy harvester devices, Left axis: Boxes area showing frequency response of vibrations, Right axis: Dots showing efficiency achieve to date

Table 1: Summary of the MEMS based piezoelectric energy harvester

Piezoelectric material	Prof mass	Input vibration (g)	Resonance frequency (Hz)	Mode	Power output (μW)	References
AlN cantilever	Si	0.5	204	d31	0.038	Marzencki *et al*. (2005)
PZT cantilever	Ni	1	608	d31	2.16	Fang *et al*. (2006)
AlN cantilever	Si	4	1368	d31	1.97	Marzencki *et al*. (2007a)
Sol-gel PZT	Si	2	461	d31	2.15	Shen *et al*. (2008)
Sol-gel PZT	Si	2.35	1.8 k	d31	40	Renaud *et al*. (2008)
Aerosol PZT	Si	2.5	256	d31	2.77	Lee *et al*. (2007)
Sputtered AlN	Si	1.75	325	d31	85	Elfrink *et al*. (2009b)
Sputtered AlN	Si	2	572	d31	60	Elfrink *et al*. (2009a)
Sol-gel PZT	Si	2	870	-	1.4	Muralt *et al*. (2009)
Sol-gel PZT	Si	0.39	528	d33	1.1	Park *et al*. (2009)
Thinned PZT	Si	0.1	167	d31	2.74	Aktakka *et al*. (2011a) Aktakka *et al*. (2011b)
Thinned PZT	Si	0.1	427	d31	1.82	Aktakka *et al*. (2010)
PZT cantilever	Si	1	36	d31	0.53	Liu *et al*. (2011)
Sol-gel PZT	Si	-	-	d33	45	Hajati and Kim (2011)

PROPOSED ENERGY HARVESTER DESIGN

Our present work is to design and fabricate a novel vibration-based MEMS energy harvesting device with integrated power conversion circuitry. The important parameters in the performance analysis of the energy harvester (i.e., stiffness and effective mass etc.) will be derived analytically from theoretical analysis. The derived equations will be formulated by considering bending moment and shear effect etc. The equations will be then used to predict the natural frequencies and the stiffness constants of the energy harvester. The results obtained will be comparable with other published results and those obtained from the FEA analysis (Wai-Chi *et al*., 2010). A hybrid simulation approach in CoventorWare design environment which combines Finite Element Analysis (FEM) and circuit simulation modeling to obtain the optimal performance of the energy harvester. The integration of both FEM and circuit simulation solvers in CoventorWare will enable the optimization of MEMS energy harvester with faster simulation time (Rahim *et al*., 2009). One new MEMS scale cymbal like structures energy harvesting device is under development in our laboratory as shown in the Fig. 8. This device will be made with micro-machining (Yunas and Majlis, 2008) techniques that will supply ultra-low-power IC through some secondary energy storage like capacitor or micro-batteries.

The device will be sealed packaged to keep the inner empty areas of the cymbal structure vacuumed. We are considering anisotropic etch and simple MEMS processing techniques for fast and reliable fabrication (Yunas *et al*., 2010) of the energy harvester structure for the EV application. In this device, the downward force on the outer metallic frame will causes tensile stress/strain on the piezoelectric film to generate energy. Such a device is mechanically robust compared to the cantilever like structure. Similar to the EV environment it is also suited to applications where the energy harvesting device is in direct contact with some driving force or where the ambient acceleration amplitudes may be too large for the previously examined cantilever devices. Design proposed by substitution of the usual membrane shape electrode with a wide beam structure and a T-shape, rectangular base protrusion on transverse symmetry axis will be followed. It was shown that protrusion eliminated free edges undesirable deformation and also increased wide beam axial deflection (Damghanian and Majlis, 2009).

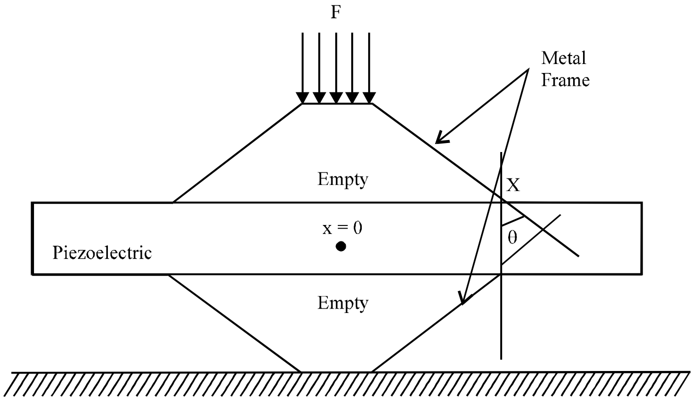

Fig. 8: Cymbal-type structure for MEMS energy harvesting in EV application

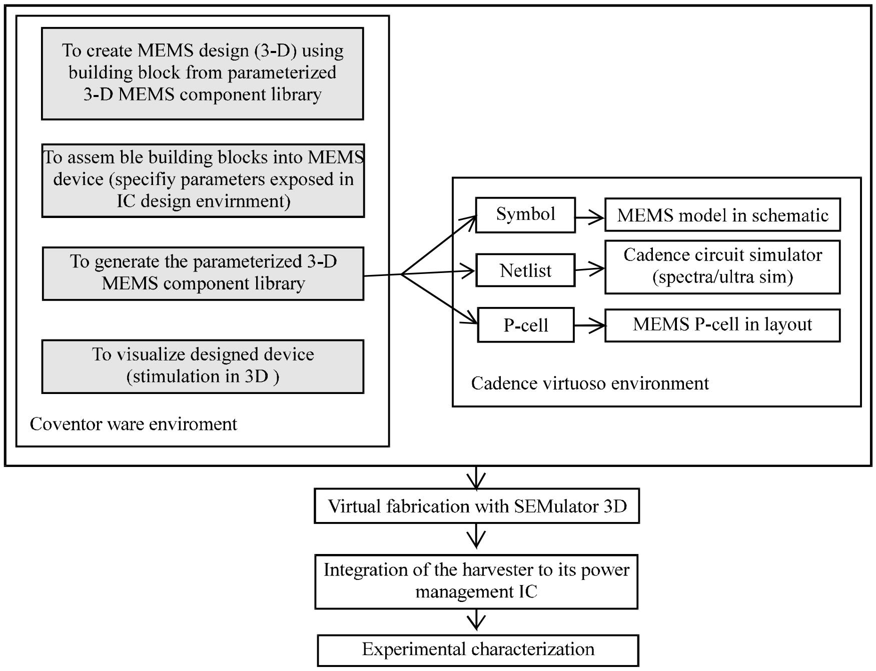

Fig. 9: Co-design flow of CMOS and MEMS

The purpose of the MEMS energy harvester is to be placed in EV environment and to perform some measurement on long period of time without the need of wiring or batteries. Some alternative solution based on the use of piezoelectric materials will also be targeted. This is expected to provide the optimal desired dc output power characteristics with high efficiency satisfying all the desired parameters and also maintain an output power that can be used to power EV sensor networks instead of the conventional batteries.

IMPLEMENTATION PROCESS OF THE PROPOSED HARVESTER DEVICE

As described in Fig. 9, firstly, wafer-level fabrication process will be selected and then the design modules of the energy harvester will be modelled in 3-D MEMS Model Schematic Editor (namely

Coventor Innovator). All building blocks of the energy harvester device will be selected and combined from the model library of behavioural model building blocks. Electrical and mechanical ports will be defined at this stage. Next the schematic symbol will be created for connecting electronic components and then simulated in Cadence Virtuoso Spectre and UltraSim circuit simulators. Results from simulations will be viewed in the MEMS+Scene3D module for 3-D inspection. Lastly, a parametric layout cell will be created (P-Cells) for Cadence Virtuoso layout environment.

ARCHITECTURE OF THE PROPOSED SYSTEM MODULES

A complete Wireless Sensor Network (WSN) node in signal processing and communication area will typically have a power budget of 100 μW. Achieving this requires good application knowledge and well designed energy harvester to enable an optimal balance between power and resolution. The ultimate goal of this research work is to design a micro-power module that can be integrated into WSN node. Therefore, in this research work we will be investigating ways to design MEMS energy harvester to integrate with WSN node. For the most promising concepts, we will build fully integrated demonstrators including micro-energy harvester, conditioning, storage and power management systems as shown in Fig. 10. By employing MEMS CMOS co-designed energy harvester technology, several advantages will be achieved over traditional batteries or power supplies, which will include small size, low cost, high reliability and the capability of integrating with WSN node. This research will focuses on the conversion of air turbulence (i.e., car vibration) flow to electrical energy via a piezoelectric energy harvester for EV sensing systems. Common piezoelectric designs in recent years observe a small microchip with layers of PZT glued to the top of a tiny cantilever beam, the beam moves up and down like a wobbly diving board. As the beam bends it stresses the PZT layers, which build up an electric charge that can be picked up by arrays of tiny electrodes. As with everything, the cantilever beam has a frequency at which it wobbles the most. This is known as the resonant frequency and outside of it, the beams wobbling response drops off along with the amount of power the device can generate. In the lab, moving and shaking the devices at the desired frequencies is easier but in reality, the source of vibration is not constant and very little power is generated if the frequency is not matching with the resonant frequency. Many researches were conducted to resolve the problem by increasing the number of cantilever beams and PZT layers on a chip however this approach is not only wasteful, but also expensive. The key

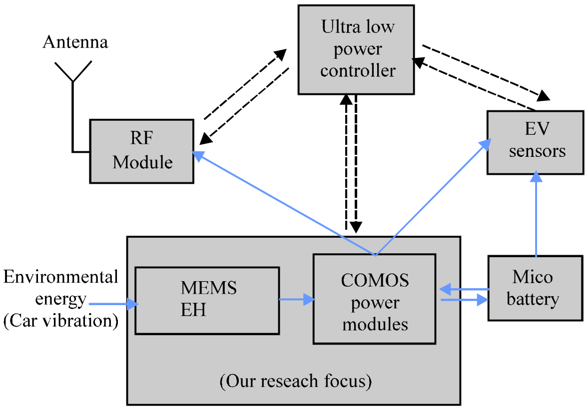

Fig. 10: Proposed architecture of a general autonomous micro-system for energy harvester modules

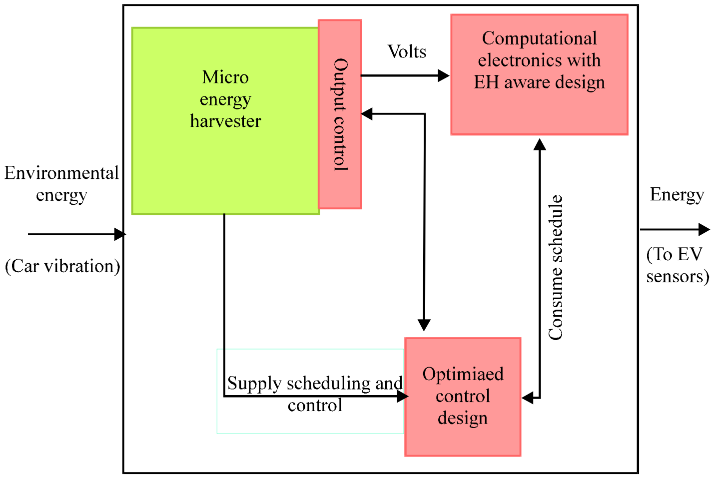

Fig. 11: Proposed system modules of the MEMS based energy harvester and CMOS power electronics in our research work

objectives of our research is to come up with a low cost energy harvester specially for EV applications by single-layer MEMS device to lower down the fabrication cost which will eventually lower down the price of the device in the market.

In this research work an integrated MEMS-CMOS micro energy harvester system as shown in Fig. 11 will be developed. The chip will be only dedicated to scavenging functions, which co-integrate the MEMS based micro energy converter along with the CMOS low power conditioning circuitry. Whole chip mass will act as inertial mass and integration of array of harvesting transducers in the full chip surface will be analyzed. The design and fabrication results of the proof of concept system integrated in a CMOS technology will be reported.

CONCLUSION

The literature survey on vibration-based piezoelectric energy harvester show that MEMS based energy harvesters achieved significant improvements in a very small period of time. In our investigation, most of the critical milestones in piezoelectric energy harvesting research have been done using 31-mode rectangular unimorph cantilevers. The properties of these cantilevers allow the resonant frequencies in order of 100-1000 Hz range for ambient vibration energy harvesting. Furthermore, it is noted that a proof mass to be added to cantilevers in order to reduce their resonant frequencies and enhance amplitudes of deflection. In addition, the feasibility of multiple cantilever arrays, including arrays of varying dimensions to allow for a larger energy harvesting bandwidth.

We conclude that our present research is focused to design and fabrication of a cymbal type structure instead of cantilever structure and engineered a microchip with just one layer of PZT on a bridge hke structure anchored at both ends of the chip to lower down the fabrication cost. Because such a device will be mechanically robust that will perfectly suit to harvest energy from vehicle low frequency vibration (>100 Hz), as the device will be in direct contact with driving force and with high automotive ambient acceleration amplitudes. To design a self-powered automotive sensor device, this research work is also focused to hybridly integrate the ultra-low-power CMOS power management circuitry on the same silicon die by utilizing TSMC nanotechnology.

REFERENCES

Aktakka, E.E., R.L. Peterson and K. Najafi, 2010. A CMOS-compatible piezoelectric vibration energy scavenger based on the integration of bulk PZT films on silicon. Proceedings of the IEEE International Electron Devices Meeting, December 6-8, 2010, San Francisco, CA., USA., pp: 1-4.

Aktakka, E.E., R.L. Peterson and K. Najafi, 2011a. A self-supplied inertial piezoelectric energy harvester with power-management IC. Proceedings of the IEEE International Solid-State Circuits Conference, February 20-24, 2011, San Francisco, CA., USA., pp: 120-121.

Aktakka, E.E., R.L. Peterson and K. Najafi, 2011b. Thinned-PZT on SOI process and design optimization for piezoelectric inertial energy harvesting. Proceedings of 16th International Solid-State Sensors, Actuators and Microsystems Conference, June 5-9, 2011, Beijing, China, pp: 1649-1652.

Damghanian, M. and B.Y. Majlis, 2009. Analysis and design of a wide micro beam as a pressure gauge for high sensitivity MEMS fingerprint sensors. Microsyst. Technol., 15: 731-737.

Dennis, J.O., M.S.B.M. Sihat, A.Y. Ahmed and F. Ahmad, 2011. Piezoresistive pressure sensor design, simulation and modification using coventor ware software. J. Applied Sci., 11: 1426-1430.

Elfrink, R., V. Pop, D. Hohlfeld, T.M. Kamel and S. Matova, 2009a. First autonomous wireless sensor node powered by a vacuum-packaged piezoelectric MEMS energy harvester. Proceedings of the IEEE International Electron Devices Meeting (IEDM), December 7-9, 2009, Baltimore, pp: 1-4.

Elfrink, R., T.M. Kamel, M. Goedbloed, S. Matova, D. Hohlfeld, Y. van Andel and R. van Schaijk, 2009b. Vibration energy harvesting with aluminum nitride-based piezoelectric devices. J. Micromech. Microeng., Vol. 19.

Fang, H.B., J.Q. Liu, Z.Y. Xu, L. Dong and L. Wang *et al*., 2006. Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting. Microelectron. J., 37: 1280-1284.

Hajati, A. and S.G. Kim, 2011. Ultra-wide bandwidth piezoelectric energy harvesting. Applied Phys. Lett., Vol. 99.

Hannan, M.A., A. Hussain, A. Mohamed and S.A. Samad, 2008. TPMS data analysis for enhancing intelligent vehicle performance. J. Applied Sci., 8: 1926-1931.

Hussain, A., M.A. Hannan, H. Sanusi, A. Mohamed and B.Y. Majlis, 2006. Characterization of MEMS automotive sensor for tire pressure monitoring system. J. Applied Sci., 6: 810-815.

Lee, B.S., W.J. Wu, W.P. Shih, D. Vasic and F. Costa, 2007a. P2E-3 power harvesting using piezoelectric MEMS generator with interdigital electrodes. Proceedings of the IEEE Ultrasonics Symposium, October 28-31, 2007, New York, USA., pp: 1598-1601.

Lee, B.S., S.C. Lin, W.J. Wu, X.Y. Wang, P.Z. Chang and C.K. Lee, 2009b. Piezoelectric MEMS generators fabricated with an aerosol deposition PZT thin film. J. Micromech. Microeng., Vol. 19.

Liu, H., C.J. Tay, C. Quan, T. Kobayashi and C. Lee, 2011. Piezoelectric MEMS energy harvester for low-frequency vibrations with wideband operation range and steadily increased output power. J. Microelectromech. Syst., 20 1131 1142-10.1109/JMEMS.2011.2162488.

Liu, J.Q., H.B. Fang, Z.Y. Xu, X.H. Mao and X.C. Shen *et al*., 2008. A MEMS-based piezoelectric power generator array for vibration energy harvesting. Microelectronics J., 39: 802-806.

Maggetto, G. and J. Van Mierlo, 2000. Electric and hybrid electric technology: A survey. Proceedings of the IEE Seminar on Electric, Hybrid and Fuel Cell Vehicles, April 11, 2000, Durham, UK., pp: 101-111.

Marzencki, M., B. Charlot, S. Basrour, M. Colin and L. Valbin, 2005. Design and fabrication of piezoelectric micro power generators for autonomous microsystems. Proceedings of the DTIP'05 Symposium on Design Testing Integration and Packaging of MEMS/MOEMS, June 1-3, 2005, Switzerland, pp: 299-302.

Marzencki, M., Y. Ammar and S. Basrour, 2007a. Design, fabrication and characterization of a piezoelectric microgenerator including a power management circuit. Proceedings of the Dans Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS-DTIP 2007, April 25-27, 2007, EDA Publishing, Stresa, Italy.

Marzencki, M., Y. Ammar and S. Basrour, 2007b. Integrated power harvesting system including a MEMS generator and a power management circuit. Proceedings of International Solid-State Sensors, Actuators and Microsystems Conference, June 10-14, 2007, Lyon, pp: 887-890.

Marzencki, M., M. Defosseux and S. Basrour, 2009. MEMS vibration energy harvesting devices with passive resonance frequency adaptation capability. J. Microelectromech. Syst., 18: 1444-1453.

Muralt, P., M. Marzencki, B. Belgacem, F. Calame and S. Basrour, 2009. Vibration energy harvesting with PZT micro device. Proc. Chem., 1: 1191-1194.

Najafi, K., T. Galchev, E.E. Aktakka, R.L. Peterson and J. McCullagh, 2011. Microsystems for energy harvesting. Proceedings of the 16th International Solid-State Sensors, Actuators and Microsystems Conference, June 5-9, 2011, Beijing, China, pp: 1845-1850.

Park, J.C., D.H. Lee, J.Y. Park, Y.S. Chang and Y.P. Lee, 2009. High performance piezoelectric MEMS energy harvester based on D33 mode of PZT thin film on buffer-layer with PBTIO3 inter-layer. Proceedings of the International Solid-State Sensors, Actuators and Microsystems Conference, June 21-25, 2009, Denver, CO., USA., pp: 517-520.

Park, J.C., J.Y. Park and Y.P. Lee, 2010. Modeling and characterization of piezoelectric d_{33} mode MEMS energy harvester. J. Microelectromech. Syst., 19: 1215-1222.

Rahim, R.A., B. Bais and B.Y. Majlis, 2009. Hybrid simulation approach on MEMS piezoresistive microcantilever sensor for biosensing applications. Adv. Mater. Res., 74: 283-286.

Renaud, M., K. Karakaya, T. Sterken, P. Fiorini, C. Vanhoof and R. Puers, 2008. Fabrication, modeling and characterization of MEMS piezoelectric vibration harvesters. Sens. Actuators A Phys., 145-146: 380-386.

Shen, D., J.H. Park, J. Ajitsaria, S.Y. Choe, H.C. Wikle and D.J. Kim, 2008. The design, fabrication and evaluation of a MEMS PZT cantilever with an integrated Si proof mass for vibration energy harvesting. J. Micromech. Microeng., 10.1088/0960-1317/18/5/055017

Soin, N. and B.Y. Majlis, 2006. Design and fabrication of perfect silicon corrugated diaphragm using KOH etching technique. J. Solid State Sci. Technol. Lett., 13: 42-47.

Wai-Chi, W., A.A. Azid and B.Y. Majlis, 2010. Formulation of stiffness constant and effective mass for a folded beam. Archiv. Mechan., 62: 405-418.

Williams, C.B. and R.B. Yates, 1995. Analysis of a micro-electric generator for Microsystems. Proceedings of the 8th International Conference on Solid-State Sensors and Actuators, June 25-29, 1995, Sweden, pp: 369-372.

Yunas, J. and B.Y. Majlis, 2008. Comparative study of stack interwinding micro-transformers on silicon monolithic. Microelectron. J., 39: 1564-1567.

Yunas, J., J. Johari, A.A. Hamzah, Mimiwaty, I.C. Gebeshuber and B.Y. Majlis, 2010. Design and Fabrication of MEMS micropumps using double sided etching. J. Microelectron. Electron. Packag., 7: 44-47.