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Charging and characterization of non-patterned organic micro electret arrays

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Abstract. This paper presents the charging and characterization of organic micro electret array for vibration energy harvesting. Micro sized electrets with stable and high surface potential are essential for long-term effectiveness of micro electrostatic power generators which harvest low-level vibration energy. In this study, a localized corona charging method to obtain micro sized electret areas on non-patterned macro sized dielectric thin film has been proposed to solve the problem of low charging efficiency and fast charge decay of micro sized electrets. This method involves using a shadow mask to transfer charge patterns and a triode corona charging configuration to facilitate charge penetration. Charging efficiency of 93.6% is achieved on an electret area of $100\mu\text{m} \times 100\mu\text{m}$, and 87% of its initial surface potential remains on the shrunken area of $50\mu\text{m} \times 50\mu\text{m}$ after 240 days of storage. A technique combining SEM surface topography and non-contact measurement of the average surface potential has been developed to map the charge distribution on locally charged dielectric thin film and measure the surface potential on the micro sized charged area by incorporating the layout characteristic of an micro electret array.

1. Introduction

Vibration energy harvested from the ambient environment offers a promising sustainable alternative or complementary source of power for electronic devices and systems, such as wireless integrated sensor (WINS) nodes that require low power consumption [1]. Among the power generators based on one of the three major energy conversion principles, i.e. electrostatic, electromagnetic, piezoelectric, the electrostatic ones have the advantage of easy implementation with silicon micromachining technology for batch fabrication [2]. In addition, by integrating electrets, which are dielectric material implanted with charges, into the device, electrostatic power generators are fully self-sustaining without the need of charge pumps [3].

In order to harvest energy from low-level vibration sources with small acceleration ($<1\text{g}$) that are ubiquitous in the environment [4], the size of capacitive electret cells in the power generator devices is designed from dozens to hundreds of micro meters to produce capacitance change at small travel length [5-7]. One commonly adopted method for charging micro sized electrets is to pattern dielectric thin film into micro sized arrays and then to implant charges by corona charging [8-10]. However, low charging efficiency and fast charge decay have been reported [11]. Leonov et al [12] have reported that a charging efficiency of less than 10% can be achieved on $500\mu\text{m}$ wide SiO_2 strips. For strips that are narrower than $400\mu\text{m}$, it is impossible to effectively implant charges into the material. It has also been

reported that even if charges could be successfully implanted in strips narrower than 1mm, they would completely drain after two days. Another way to charge micro sized electrets is to charge selected electret area on dielectric thin film without patterning the material. The emphasis of the reported work on selective charging has been placed on achieving high surface potential after charging. In the work reported by Naruse et al [13], charging is aided by aluminium electrodes patterned on top of certain areas of SiO₂ thin film. During charge implantation, it is observed that the charges in areas with aluminium electrodes tend to leak, and the charges in areas without aluminium electrodes remain. This selective charging method results in higher surface potential than the conventional charging-after-patterning method. Another way to guide charges into the selected area can be found in [14], in which the silicon mass of the inertial power generator is used as the charging grid. Local charging on a whole piece of CYTOP polymer thin film is conducted after the device is assembled. This charging process sacrifices the mass which is a crucial factor for the power generation of inertial power generators, as the mechanical energy available to be converted into the electrical energy is proportional to the mass. Etching away a portion of the mass material to create slits not only decreases the weight of the mass, but also increases air damping that prevents the mass from vibrating. Wang et al [15] conducted selective charging by selectively treating the whole charged SiO₂ electret thin film surface with an FDTS layer, turning the electret surface hydrophobic and protecting the charges from later exposure to humidity. In these various methods of selective charging, the charging efficiency still needs further improvement. In addition, the characterization of the stability of micro sized electrets in long-term observation is of concern and in need of more investigation and study, because the instability of micro sized electrets will inevitably impair the harvesting effectiveness of electret power generators deployed for long-term use.

The objective of this work is to achieve high charging efficiency and obtain stable micro sized electret arrays by a proposed triode localized corona charging system. The charge distribution and charge migration of micro sized electret arrays over the long term will be discussed. Our work has manifested the application of this localized charging method in the fabrication of micro electret power generators and prototype testing [16].

2. Methodology

2.1 The modelling of charging micro sized electrets

Electrets can be obtained either from inorganic material such as SiO₂/Si₃N₄ multilayers, or organic dielectric material, such as polymer material CYTOP, PTFE, and Teflon AF [17]. Inorganic thin films can be either thermally grown [18, 19] or deposited via plasma-enhanced chemical vapour (PECVD) [20]. However, the low deposition speed and high residual stress of these techniques lead to difficulties to prepare thick inorganic layers (>2μm). Organic electrets can be easily manufactured with a thickness more than 10μm, which is beneficial for maintaining low parasitic capacitance in power generator devices [21]. In order to analyse the cause of low charging efficiency and fast charge decay occurring in the charging process of micro sized electrets, we conducted the modelling of the electric field inside and outside of micro sized dielectric material during charging, as the movement of charges is directed by the electric field.

Figure 1 shows a corona charging system on which an ANSYS model is based. The charging voltage V_c applied on the metal grid for uniform charging is 600V. A two dimensional 8-node element of Plane 121 which depicts the cross section of dielectric material is meshed by a mapping scheme. The thickness d of the dielectric material is set at 50μm. The length L_0 of the material is allowed to vary while the gap between the grid and the surface material is set at 200μm. Since the dielectric constant of organic material commonly used for power generators is around 2 (2.2 for parylene HT®, 2.1 for CYTOP, 1.9 for Teflon AF and 2.1 for PTFE) [22], the dielectric constant ϵ is set as 2 in the model. In the model, E_c denotes the central surface electric field inside the material, while E_f refers to the fringing field near the edge of the material as shown in figure 1(a). The electric field gradient across the material, ΔE ,

is determined by $\Delta E = E_f - E_c$, a difference between the central surface electric field and the fringing field.

The electric fields are investigated in two conditions, uncharged and slightly charged. The uncharged condition is the initial stage of charging when the surface potential V_s on dielectric material is equal to 0. In the uncharged condition, the central surface electric field is E_{c-0} , and the fringing field is E_{f-0} . In the slightly charged condition, a small amount of charges are implanted into the shallow surface of the material and the surface potential is assumed as 30V. The central surface electric field and the fringing field change to E_{c-30} , and E_{f-30} , respectively. Figure 1(b) shows the electric field distribution in and out of electret material when L_0 is 100 μm .

Figure 1. (a) Corona charging model; (b) Modelled electric field distribution for dielectric material with L_0 of 100 μm

Percentage change of central surface electric field, ρ , is represented by $(E_{c-30} - E_{c-0})/E_{c-0}$. Negative ρ indicates a drop of central surface electric field, whereas positive ρ indicates an increase of central surface electric field. Figure 2 plots ρ with respect to L_0 . If the value of L_0 is greater than 400 μm , ρ has a positive value. This indicates an increase in the central surface electric field owing to the accumulated charges. If L_0 is reduced to a size less than 400 μm , ρ registers a negative value, and the central surface electric field inside the material records a drop owing to charge accumulation on the surface.

Figure 2. Percentage change of the central surface electric field E_c as a function of the length, L_0 , of dielectric material during charging

Figure 3 shows the electric field gradient, ΔE , as a function of L_0 . The electric field gradient is observed to decrease with L_0 in both charged conditions. A smaller electric field gradient is desired during charging, as a large electric field gradient generates a fringing field that is stronger than the central electric field. This limits the charge implantation, as the stronger fringing field would either divert the majority of the incoming charges to the material edges or to the surrounding air. This restricts the charges from penetrating deeply into the bulk of the material. This therefore accounts for the low charging efficiency in the process of charging micro sized dielectric material. In addition, the close proximity of the charges at the edges to the surrounding air in micro sized dielectric material would cause neutralization with the atmospheric ions, leading to charge leakage from the material during storage.

Figure 3. The electric field gradient, ΔE , as a function of the length, L_0 , of dielectric material during charging

From the above analysis, the inference is that ρ and ΔE are size-dependent. Macro sized ($>1000\mu\text{m}$) dielectric material is more effective than micro sized material ($<100\mu\text{m}$) in capturing and holding charges in the charging process, and selectively charging micro sized areas on macro sized dielectric material will reduce the size effect. Hence our proposed charging method will be based on this mechanism.

2.2 The triode localized charging system

In order to achieve high charging efficiency, two properties of organic dielectric material are considered, namely density of trap level and dielectric strength. A high density of trap level in dielectric material denotes that there are a significant number of traps per unit area. This material would have a high capacity to trap more charges thereby providing a higher charge density or surface potential. Dielectric strength of the material is another important property as it relates to the amount of charges that a material can hold before electric breakdown occurs. According to Table 1, LDPE (low density polyethylene) is found to have the highest density traps and dielectric strength amongst commonly used polymer materials for electrets. LDPE is also readily available and more environmentally friendly, compared with soluble fluoropolymers (CYTOP, PTFE and Teflon AF) which emit toxic substances when heated up during the production cycle [23]. Hence LDPE, in thin film form, purchased from Goodfellow Cambridge Limited, is chosen as the electret material for this work.

Table 1. Properties of polymer materials

Polymer material	Electron trap density $N_{et}(\times 10^{18} \text{ m}^{-3})$	Hole trap density $N_{ht}(\times 10^{18} \text{ m}^{-3})$	Dielectric strength $E_m(\text{MV/m})$
LDPE(Low density polyethylene)	1.2992 [24]	1.1900 [24]	200 [25]
PP(polypropylene)	0.3441 [24]	0.2262 [24]	200 [25]
PTFE(Polytetrafluoroethylene)	0.6797 [24]	0.5768 [24]	18 [26]
CYTOP	/	/	110 [26]
Teflon AF	/	/	21 [26]

Before charging, macro sized LDPE thin films are first manually cut from the LDPE sheet. Figure 4 shows the schematic configuration of the proposed triode localized positive corona charging system. During the charging process, the LDPE thin film is sandwiched between a shadow mask (top) and a silicon substrate (bottom) with patterned gold electrodes. Each gold electrode on the bottom silicon substrate is mapped to the shadow mask opening. To ensure that charges are uniformly implanted into micro sized areas, the LDPE thin film should be fully flat on the substrate plate. A 5 μm thick spun-on epoxy layer is used as a bonding adhesive layer between the LDPE thin film and the silicon substrate plate. After charging, the shadow mask is removed and can be repeatedly used for charging. DC voltage supply is set at 10 kV and connected to a Beryllium copper needle of high electrical conductivity and low resistivity of 6 $\mu\Omega/\text{cm}$ to ionize the air. The distance between the needle tip and the shadow mask is set at 5mm. The shadow mask is biased by a positive voltage V_c , which is the charging voltage and equal to the targeted surface potential on electrets. The holes under shadow mask openings have vertical sidewalls and are conductive. This is to make sure ions arriving at the shadow mask can move through the holes and implanted into the thin film below the shadow mask. The back side of the thin film is biased by a negative voltage V_e , for the purpose of facilitating the charge movement inside the thin film. It should be noted that the charging system can be changed to a negative triode corona charging system by switching the polarity of voltages.

Figure 4. Schematic configuration of the triode localized charging system

In this localised charging method, the shadow mask will be made of silicon. This is because the shadow mask fabricated from silicon wafers are rigid and flat and can be micro machined to a good degree of accuracy by MEMS technology. The thickness of the silicon shadow mask is kept thin ($200\mu\text{m}$) and yet has adequate strength to deal with handling and fragility problems. After a DRIE process of creating through-holes, a sputtering process is then applied to deposit Cr(20nm)/Au(300nm) layer on the surface of the mask facing the needle and the sidewalls of through-holes. Compared with the evaporation process, sputtering is preferred as it has a better step coverage, faster deposition rate, better uniformity, and better adhesion to the substrate [27]. Figure 5 shows SEM images of a sputtered shadow mask designed with openings of $100\mu\text{m} \times 100\mu\text{m}$. The metallic layer, which is the bright area in the images, covers the surface of the shadow mask and the side wall of through-holes.

Figure 5. (a) SEM image of the top view of a shadow mask designed with an array of $100\mu\text{m} \times 100\mu\text{m}$ openings; (b) SEM image of the cross section of through-holes in the shadow mask

3. Experimental

3.1 Evaluation of the triode corona charging system

In the triode system for localized charging, $V_e = -V_c$ will be applied. By biasing the dielectric material, the electric field crossing the material is larger than the value when the dielectric material is merely grounded. To examine the effect of the larger electric field on the trap level occupation of charges, experiments are carried out to globally charge samples of $10\text{ mm} \times 10\text{ mm} \times 15\mu\text{m}$. Globally charged samples will have the whole surface areas exposed for charge implantation by using a metal grid which is biased by the charging voltage. Two charging voltages are applied: 1 kV and 2 kV . Samples are charged for 30 minutes under

different conditions (S1-S4). The initial surface potential V_0 of samples are then measured immediately after charging and presented in Table 2. The samples are stored in an environment with a constant temperature of $25\text{ }^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and a humidity of 48%-51% Rh. The surface potential is measured using a noncontact electrostatic voltmeter (Model 542, Trek).

Table 2. Initial surface potential V_0 on samples charged under varied conditions

Charing conditions				
	S1: $V_c=1\text{ kV}$, $V_e=0\text{ kV}$			
	S2: $V_c=1\text{ kV}$, $V_e=-1\text{ kV}$			
	S3: $V_c=2\text{ kV}$, $V_e=0\text{ kV}$			
	S4: $V_c=2\text{ kV}$, $V_e=-2\text{ kV}$			
	S1	S2	S3	S4
V_0	630V	800V	1300V	1700V
V_0/V_c	0.63	0.8	0.65	0.85

Table 2 shows that charging conditions S3 and S4 result in higher surface potentials on samples than S1 and S2, due to the higher charging voltage V_c . Sample (S2) and sample (S4) charged with a larger electric field have higher charging efficiencies V_0/V_c than the other samples (S1 and S3). The initial charge stability of the various samples is plotted in figure 6. The surface potential has been normalized against the initial value of each sample and is expressed as a ratio of r .

Figure 6. Normalized surface potential decay in the first 600s

A model based on the isothermal relaxation current theory in reference [28] is applied numerically in the initial charge decay stage to determine the distribution of trapped charges at different energy levels after charging. At constant temperature, the decreasing current $I_e(t)$ inside the electret caused by charge detrapping relates to the decay of surface potential: $I_e(t) = C dV_s(t)$, where C is the capacitance of electret. The current density J therefore is written as follows:

$$J = \frac{\varepsilon_0 \varepsilon}{d} \frac{\partial V_s(t)}{\partial t} \quad (1)$$

Where ε_0 is the dielectric constant of vacuum and ε is the dielectric constant 2.2 of LDPE[25]. The energy level E_t , and the density of the trapping energy levels $N_t(E_t)$ and J can be derived from the following equations [24]:

$$E_t = kT \ln(\gamma) \quad (2)$$

$$J = \frac{qdkT}{2t} f_0(E_t) N_t(E_t) \quad (3)$$

Where $f_0(E_t)$ is the initial occupancy of trapping levels, assuming as 1/2, q the electron charge, k the Boltzmann's constant, γ the attempt-to-escape frequency, usually of the order 10^{11} to 10^{12} sec^{-1} [28], assumed as 10^{11} , T the temperature, and t is the time.

Based on the measurement of surface potential in figure 6, the density of trapping levels are plotted against the energy level of trap based on the above three Equations (1), (2) and (3). Graphs in figure 7(a) and (b) show the distribution of trap density in samples over a range from 0.8eV to 0.9eV, where energy trap levels of LDPE are located [29]. By performing the integral of the density of the trapping energy level, the number of traps occupied by charges are determined and listed in the column graph figure 7(c), in which S3 and S4 charged with 2kV have more trap levels occupied than S2 and S1 charged with 1kV. S2 and S4, charged with a larger charging electric field, are also found to trap more charges than S1 and sample S3, resulting in higher surface potential.

Figure 7. (a) Density of the trapping energy level as a function of the energy level of trap of samples charged under S1 and S2 conditions; (b) Density of the trapping energy level as a function of the energy level of trap of samples charged under S3 and S4 conditions; (c) Number of occupied trap levels in different samples

3.2 Characterization of micro sized electret arrays

Charge distribution on electret is an important characteristic for studying the stability of electret. The conventional approach to map charge distribution is to conduct a two-dimensional line scan of discrete points of surface potential on electret thin film by means of a non-contact voltmeter probe [15, 22, 30]. This approach can only obtain a low resolution contour map of charge distribution due to the spatial resolution limited by the probe's aperture size that is in the range of hundreds of micro meters to millimetres. For a spot electret area of diameter 100 μm and less, this scanning method would not be able to provide good measurement of the actual surface potential on the micro sized electret area or the accurate charge distribution.

To overcome the problem of low resolution, SEM (scanning electron microscope), which is a commonly used metrology method to image fine details of surface structure of micro-machined parts, is utilized for mapping charge distribution of a micro sized electret array. Electret samples are devoid of sample preparation (e.g. metal coating) for the SEM imaging process. The existing charges in the pre-charged sample will interact with the incident electrons and affect the produced secondary electrons collected for imaging. Figure 8 illustrates the imaging process of a locally positive-charged sample. The incoming incident electrons are neutralized on the charged areas, and therefore the induced secondary electrons are diminished. Figure 9 presents the SEM images of 1cm $\times$ 1cm $\times$ 50 μm LDPE samples either negative-charged (figure 9 (a) and (b)) or positive-charged (figure 9 (c) and (d)) by a voltage of 900V, using shadow masks with different opening sizes. The dimension of charged areas is very similar to that of designed opening areas.

Figure 8. Schematic diagram of a scanning electron microscope (SEM) applied to map charge distribution on locally positive-charged sample

Figure 9. SEM images of charge patterns on LDPE thin films (a) opening area designed as $200\mu\text{m} \times 200\mu\text{m}$, $V_{acc} = 5\text{kV}$; (b) opening area designed as $50\mu\text{m} \times 100\mu\text{m}$, $V_{acc} = 1\text{kV}$; (c) opening area designed as $200\mu\text{m} \times 200\mu\text{m}$, $V_{acc} = 5\text{kV}$; (d) opening area designed as $100\mu\text{m} \times 100\mu\text{m}$, $V_{acc} = 1\text{kV}$

The images are taken immediately after charging. Acceleration voltage V_{acc} of 5kV is applied in the imaging process of samples of figures on the left side, while V_{acc} of 1kV is applied in figures on the right side. In the SEM imaging process, a bigger difference in the amount of

secondary electrons induced from charged areas and non charged areas can create a higher contrast. It can be seen that SEM images taken under small V_{acc} of 1kV (figure 9(b) and (d)) have higher contrast between charged and non-charged areas than images taken under relatively higher acceleration voltage V_{acc} of 5kV (figure 9(a) and (c)). Fast disappearance of patterns is also observed when V_{acc} of 5kV is applied. This is because a strong electron beam when high V_{acc} is applied reduces the difference between the amount of secondary electrons generated from charged and non-charged areas and makes it difficult to enhance the contrast of the fine boundary of charged and non charged areas, and the quick electron charge-up can easily destroy the original charge pattern on the sample. Moreover, we also found that acceleration voltage lower than 0.5kV makes it difficult to capture images due to insufficient difference in secondary electrons. Therefore, for characterization of charge patterns on micro sized electrets with surface potential around several hundred volts which is often applied in micro electret power generators, acceleration voltage around 0.5~1kV is suggested. It should be noted that the image must be taken immediately after the focus of electron beam. This is because the focused area will get charged by the incoming electron beam within a few minutes, which destroys charge patterns.

As the aperture of voltmeter covers charged and non-charged areas, the surface potential registered in the voltmeter is the average value over the covered area, and this value is a function of the actual surface potential on charged areas and the area ratio factor which reflects the relation between charged and non-charged areas. To verify this relation, we conduct global charging and localized charging on samples with the same size ($1\text{cm} \times 1\text{cm} \times 50\mu\text{m}$) by the same charging voltage V_c of 900V for 1 minute. Globally charged samples having the whole surface area exposed for charging are used as references. For the locally charged samples, a shadow mask with a total number of 2965 openings ($100\mu\text{m} \times 100\mu\text{m}$), spaced $160\mu\text{m}$ apart, is used. The area ratio of the total area of locally charged areas to the whole area of LDPE thin film is 3.37. The voltmeter gives an average surface potential reading, V_{as} , of 250V from the locally charged samples immediately after charging. The surface potential V_s on samples globally charged is measured to be 800V. Voltage ratio of V_s to V_{as} is equal to 3.2. This similarity between the voltage ratio and the area ratio has proven that the voltmeter registers the average surface potential on the thin film. Area ratio, together with measured V_{as} can be combined to derive the surface potential on the micro sized electret area. The derived V_s on $100\mu\text{m} \times 100\mu\text{m}$ area is 842V, and the charging efficiency is therefore 93.6%

Samples charged by 900V for 30 minutes are stored for long-term observation. After 20 days of storage, figure 10(a) shows that the shape of the charge patterns remain in-tact but with a reduced length of $95\mu\text{m}$. The area ratio becomes 3.8, resulting in a surface potential of 800V on the charged areas, according to a measured V_{as} of 210V. Figure 10 (b) shows the SEM image of a sample taken after 240 days of storage. The charges remain concentrated in the locally charged areas but with a side length of $50\mu\text{m}$. The surface potential on the $50\mu\text{m} \times 50\mu\text{m}$ area is 730 V, computed by multiplying measured V_{as} of 60V and area ratio of 12.1, representing 87% of its initial surface potential.

(a)

(b)

Figure 10. SEM images of locally charged samples: (a) 20 days after charging; (b) 240 days after charging [31]

Unlike charges in globally charged electrets where they migrate laterally due to the self-field [32], charges in locally charged samples are not found to have such movement. This could be owing to the distance separation in micro meters between the charged regions; and the electric field distributed within these charged regions prohibits charge migration and leakage at the surface. It is also found that charges retain more at the centre than at the edges of the locally charged areas. This could be explained by the fact that, during charging, moving charges in the centre of the through-holes of the shadow mask have higher acceleration energy than moving charges close to the through-holes' sidewall, which exerts a repelling force on charges and results in a loss of the acceleration energy of charges. Therefore, those charges close to the sidewall tend to reside at the shallow parts of the material surface. As such, they are more easily displaced, released and neutralized by atmospheric ions. The results of charges stability provide a motivation for future work to optimize the localized charging system, by considering the influence of the dimension of openings and the charging voltage on the charge motion and charge stability.

4. Conclusion

This work has reported the charging and characterization of micro sized electret arrays for energy harvesting application. Charging efficiency of 93.6% has been achieved by localized charging through the use of a shadow mask to transfer charge pattern, and the use of a triode corona system to facilitate charge penetration. SEM surface topography combined with non-contact measurement of average surface potential is employed to map the charge distribution on locally charged dielectric thin film, observe long-term charge migration, and measure the surface potential on the micro sized area by incorporating the layout characteristic of electret arrays. For a charged micro sized electret array of $100\mu\text{m} \times 100\mu\text{m}$ on $1\text{cm} \times 1\text{cm} \times 50\mu\text{m}$ LDPE thin films, 87% of the initial surface potential remains on the shrunken area of $50\mu\text{m} \times 50\mu\text{m}$ 240 days after charging.

Reference

- [1] Beeby S P, Tudor M J and White N M 2006 Energy harvesting vibration sources for microsystems applications *Meas. Sci. Technol.* **17** R175-R95
- [2] Shad Roundy P K W, and Jan M. Rabaey 2004 *Energy scavenging for wireless sensor networks with special focus on vibrations*: Springer)
- [3] Suzuki Y 2011 Recent Progress in MEMS Electret Generator for Energy Harvesting *Ieej Transactions on Electrical and Electronic Engineering* **6** 101-11
- [4] Roundy S, Wright P K and Rabaey J 2003 A study of low level vibrations as a power source for wireless sensor nodes *Computer Communications* **26** 1131-44

- [5] Crovetto A, Wang F and Hansen O 2013 An electret-based energy harvesting device with a wafer-level fabrication process *Journal of Micromechanics and Microengineering* **23**
- [6] Sato N, Ono K, Shimamura T, Kuwabara K, Ugajin M and Sato Y 2012 Analysis of electret-based mems vibrational energy harvester with slit-and-slider structure *J. Microelectromech. Syst.* **21** 1218-28
- [7] Suzuki Y, Miki D, Edamoto M and Honzumi M 2010 A MEMS electret generator with electrostatic levitation for vibration-driven energy-harvesting applications *Journal of Micromechanics and Microengineering* **20**
- [8] Sakane Y, Suzuki Y and Kasagi N 2008 The development of a high-performance perfluorinated polymer electret and its application to micro power generation *Journal of Micromechanics and Microengineering* **18**
- [9] Wang F, Bertelsen C, Skands G, Pedersen T and Hansen O 2012 Reactive ion etching of polymer materials for an energy harvesting device *Microelectronic Engineering* **97** 227-30
- [10] Meng X, Zhang H and Zhu J 2008 A general empirical formula of current-voltage characteristics for point-to-plane geometry corona discharges *Journal of Physics D: Applied Physics* **41**
- [11] Genda T, Tanaka S and Esashi M 2005 Charging method of micropatterned electrets by contact electrification using mercury *Japanese Journal of Applied Physics Part 1- Regular Papers Brief Communications & Review Papers* **44** 5062-7
- [12] Leonov V and Van Schaijk R 2010 Patterning of inorganic electrets *Ieee Transactions on Dielectrics and Electrical Insulation* **17** 994-1000
- [13] Naruse Y, Matsubara N, Mabuchi K, Izumi M and Suzuki S 2009 Electrostatic micro power generation from low-frequency vibration such as human motion *Journal of Micromechanics and Microengineering* **19**
- [14] Fujii K, Toyonaga T, Fujita T, Jiang Y G, Higuchi K and Maenaka K 2011 Electret based energy harvester using a shared si electrode. In: *Solid-State Sensors, Actuators and Microsystems Conference (TRANSDUCERS), 2011 16th International*, pp 2634-7
- [15] Wang F and Hansen O 2013 Invisible surface charge pattern on inorganic electrets *IEEE Electron Device Letters* **34** 1047-9
- [16] Liu S W, Miao J M and Lye S W 2013 High Q and low resonant frequency micro electret energy harvester for harvesting low amplitude harmonic of vibration. pp 837-40
- [17] Sessler G M 2001 Electrets: Recent developments *Journal of Electrostatics* **51-52** 137-45
- [18] Mescheder U, Muller B, Baborie S and Urbanovic P 2009 Properties of SiO₂ electret films charged by ion implantation for MEMS-based energy harvesting systems *Journal of Micromechanics and Microengineering* **19**
- [19] Leonov V, Fiorini P and Van Hoof C 2006 Stabilization of positive charge in SiO₂/Si₃N₄ electrets *Dielectrics and Electrical Insulation, IEEE Transactions on* **13** 1049-56
- [20] Yang Z, Wang J and Zhang J 2011 A high-performance micro electret power generator based on microball bearings *Journal of Micromechanics and Microengineering* **21**
- [21] Jinwen Zhang Z C, Yilong Hao, Zhongquan Wen, Yufeng Jin, Zhiyu Wen 2007 PECVD SiO₂/Si₃N₄ double layers electrets for application in MEMS power generator. In: *powerMEMS 2007*, cFreiburg, Germany pp 105-8
- [22] Lo H W and Tai Y C 2008 Parylene-based electret power generators *Journal of Micromechanics and Microengineering* **18**
- [23] Rychkov D, Alberto Pisani Altafim R, Qiu X and Gerhard R 2012 Treatment with orthophosphoric acid enhances the thermal stability of the piezoelectricity in low-density polyethylene ferroelectrets *Journal of Applied Physics* **111**

- [24] Zhang G J, Yang K, Dong M, Zhao W B and Yan Z 2007 Surface electroluminescence phenomena correlated with trapping parameters of insulating polymers *Applied Surface Science* **254** 1450-5
- [25] www.goodfellow.com
- [26] Takumi Tsutsumino Y S, Nobuhide Kasagi, and Yukinori Tsurumi 2005 High-Performance Polymer Electret for Micro Seismic Generator. In: *The Fifth International Workshop on Micro and Nanotechnology for Power Generation and Energy Conversion Applications*, (Tokyo, Japan
- [27] Franssila S 2010 *Introduction to microfabrication*: John Wiley&Sons)
- [28] Simmons J G and Tam M C 1973 Theory of isothermal currents and the direct determination of trap parameters in semiconductors and insulators containing arbitrary trap distributions *Physical Review B* **7** 3706-13
- [29] Sahli S, Bellel A, Ziari Z, Kahlouche A and Segui Y 2003 Measure and analysis of potential decay in polypropylene films after negative corona charge deposition *Journal of Electrostatics* **57** 169-81
- [30] Sato N, Ono K, Shimamura T, Kuwabara K, Ugajin M, Mutoh S, Morimura H, Ishii H, Kodate J and Sato Y 2009 Energy harvesting by MEMS vibrational devices with electrets. pp 513-6
- [31] S.w. Liu Z Y S, S.W. Lye, J.M. Miao 2012 Stable micro sized electret array produced by localised charging using a silicon shadow mask *Micro & Nano Letters* **7** 1094-6
- [32] Baum E A, Lewis T J and Toomer R 1978 The lateral motion of charge on thin films of polyethylene terephthalate *Journal of Physics D: Applied Physics* **11** 963-77