Towards Optimized Triboelectric Nanogenerators

R.D.I.G. Dharmasena, S.R.P. Silva*

Advanced Technology Institute, Department of Electrical and Electronic Engineering, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom. Email: s.silva@surrey.ac.uk

Abstract

The rapid progression of electronic technologies is predicted to enhance the quality of life of the people around the world. A key challenge in achieving these targets is the need to develop sustainable power sources, which can support the ubiquitous and mobile operation of next generation electronic devices. Energy harvesting from ambient mechanical movements is seen as one of the main approaches in powering autonomous low power electronic systems such as wearables and IoT technology. Triboelectric nanogenerators (TENGs) have attracted significant attention in recent years as an emerging mechanical energy harvesting technology, due to numerous advantages over conventional mechanical energy harvesters. In this paper, we present a comprehensive review on the structural, material, motion and environmental parameters affecting the power output of triboelectric nanogenerators. The optimisation strategies for these energy harvesters are discussed, based on the theoretical and experimental studies in the literature. Finally, we discuss the major challenges in this research field, along with the future outlook.

1. Introduction

The advancement of novel technologies such as the Internet of Things (IoT), 5G technology and big data capture and analysis are envisioned to immerse the lives of the people in a digitally connected world, with improved productivity for society. Everyday objects visualised via sensors, displays, logic & communications will help enhance functionality with exchange of data to develop a smart network, realising improved usage and efficiency in real world applications. This opens countless opportunities worldwide, in areas of education, governance, health, transportation, disaster management, food and security, among many others. Powering the next generation electronic devices, in particular, the sensors and transducers that need to be mobile and ubiquitous, is a key challenge the world is facing today.[1,2] Many of these devices contain a large number of electronic components that might be located remotely, therefore, using individual power units for each system, along with their replacement or recharging becomes challenging. Specially, the novel electronic technologies contain various performance requirements such as flexibility, stretchability, reliability, safety and autonomy. The success of future electronic technologies is heavily dependent on the design and construction of versatile self-powered energy supplies.

The power demands for some of the common electronic devices are summarized in Fig. 1a [3]. Harvesting ambient energy forms such as solar energy, heat and mechanical motion, targeting low power electronics has been increasingly popular in recent years.[2,4] Some of these energy harvesting technologies typically produce micro-Watt to milli-Watt range power outputs using small scale devices.[5] The overall energy harvesting market amounted for approx. £ 500 million in 2009, whereas this value is predicted to exceed £ 2.5 billion by 2020, mostly consisting of consumer products.[5] Therefore, finding suitable material

Figure 1. (a) The reported energy consumption of some of the common portable electronic devices. Reprinted with permission from ref [3]. (b) Schematic showing the average mechanical power produced at different regions of the human body when a person is walking. Adopted from ref [9] and [7]. (c) Schematic of main working modes of TENGs, showing (i) Vertical Contact Separation mode TENG (VCSTENG), (ii) Lateral Sliding mode TENG (LSTENG), (iii) Single Electrode mode TENG (SETENG), and, (iv) Free Standing triboelectric layer mode TENG (FSTENG).

systems and designing optimized energy harvesting technologies are considered a high priority in the scientific community as well as in the industry.

Among various ambient energy types, mechanical energy has attracted significant attention due to wide availability in forms such as wind, natural and machine vibrations, water waves, human motion etc.[6–8].

As an example, an average person can produce a mechanical power output ranging up to several Watts,

at different locations of the body (Fig. 1b) [9][7]. Other natural movements such as wave energy and wind energy can act as potential energy sources for energy harvesting, for instance, the kinetic energy generated by ocean waves worldwide is estimated around 2-3 TW, with the wind power estimated to be of similar order of magnitude.[10,11] The existing methods for mechanical energy harvesting include piezoelectric, triboelectric, electromagnetic and electrostatic technologies.[7,12–15]

Triboelectric Nanogenerator (TENG), first introduced in 2012 by Z.L. Wang's research group[16], is an upcoming mechanical energy harvesting technology, with the potential to scavenge multiple ambient mechanical energy forms.[17,18] TENGs depend on the triboelectric effect, the static charge separation between two material surfaces upon contact, and the electrostatic induction resulting from the movement of such charged surfaces, to convert mechanical motion into electricity.[1,19–24] The instantaneous peak output power density of some of the TENG designs has been reported to be as high as 500 W/m², with instantaneous power conversion efficiencies reaching 85%.[25] Apart from high output performance, TENGs have been demonstrated to contain many advantages over other energy harvesting technologies, such as the low cost, simple fabrication, scalability, and the ability to operate using low frequency movements. [1,17,25]

TENGs with various architectures have been reported in the literature with different applications. However, developing output optimisation strategies for TENG designs has been challenging, mainly due to the lack of understanding about their output behaviour in real life applications [1][19]. This calls for a detailed analysis on the effect of device parameters such as the material and structural parameters, the motion profiles driving the TENG device, and the environmental parameters, on its outputs. In this work, we discuss the main types of TENG architectures, their applications, and working principles. A detailed review is provided on the theoretical and experimental reports regarding the effect of key device and environmental parameters on TENG outputs, along with their optimisation strategies. Furthermore, we discuss the major challenges in realising practical TENG applications, along with a perspective on potential solutions which can be helpful for the development of this research area.

2. TENG Working Modes and Applications

TENGs are fabricated in many different architectures, however, these can be divided into four main working modes; vertical contact separation mode (VCSTENG), lateral sliding mode (LSTENG), single electrode mode (SETENG), and, free-standing triboelectric layer mode (FSTENG) (Fig. 1c). [1] VCSTENG is arguably the most popular TENG architecture due to its simplicity and potentially high output power.[26–28] The electrical outputs generated during periodic vertical contact and separation of triboelectric surfaces are obtained through electrodes deposited on the opposite sides of the contact surfaces. The basic architecture of LSTENG is relatively similar to VCSTENG, with the relative sliding movement of triboelectric layers in a parallel direction being used to induce the outputs.[29]–[30] LSTENG working mode has been used in many device designs which include planar[1], cylindrical rotation[31], disc rotation[32] and grating structured[33]–[34] device types. SETENG typically consists of a grounded bottom electrode, and relies on the electron transfer between the ground and the electrode to convert mechanical movement into electricity.[1] Contact electrification is maintained between a freely moving triboelectric surface and the electrode, and the movement of triboelectric layers can be either contact separation motion[35] or sliding motion[36]–[37]. Although the output performance of SETENG is typically lower in comparison to other TENG types, it has been specifically used where the mobility of the moving component is important, such as in harvesting energy from human body movements.[1,20,25,28] FSTENG

contains a pair of symmetric electrodes with a freely moving triboelectric layer between them, where the triboelectric charging takes place between the moving TENG layer and the electrodes.[38] The movement of the free-standing triboelectric layer causes an asymmetric charge distribution on electrodes, inducing a charge flow between them to balance the potential difference.[34] This mode can operate using contact motion as well as sliding movement.

TENGs have been demonstrated in a broad range of applications, as energy harvesters and self-powered sensors. A large variety of energy harvesters have been developed in the literature, capable of harvesting different energy types with high power outputs (Fig. 2). Zhu et al. reported a shape adaptive thin film based LSTENG, which utilizes the sliding movement between triboelectric layers (Fig. 2a) [39]. The device consisted of a micro grated architecture with Polytetrafluoroethylene (PTFE) and metal surfaces. Subjected to a sliding velocity of 10 m/s, the device produced an average power density of 500 W/m² with an overall energy conversion efficiency of 50%, and, demonstrated the capability of powering light bulbs. Wind energy harvesting has been a popular application for TENGs [40–43]. As an example Wang et al. [42] presented a FSTENG for wind energy harvesting, using Copper (Cu) and fluorinated ethylene propylene (FEP) (Fig. 2b). The wind flow caused the FEP to vibrate, resulting in an open circuit voltage (V_{oc}) of 375 V, peak current density (J_{sc}) of 98.5 mA/m², and peak output power (P_{out}) of around 9.8 W/m², at wind speed of 15 m/s.

A number of TENG designs have been demonstrated for their capability in vibration energy harvesting [27,44–49]. Zhu et al.,[45] developed a VCSTENG consisting of PDMS and gold nanoparticles on the triboelectric surfaces, with springs connected as the restoring mechanism (Fig. 2c). The TENG produced peak V_{oc} of 1200 V, peak J_{sc} of 751.2 mA/m², and peak P_{out} of around 313 W/m² (through 1 M Ω load), lighting 600 LED bulbs, under the influence of human footfalls applying a force of 500 N to 600 N. The mechanical energy generated from the water waves, tidal and ocean current has been harvested using TENG architectures [10][50][51]. Wen et al.,[51] proposed a TENG with a wavy structured Cu-Kapton-Cu triboelectric layer sandwiched between nanostructured PTFE layers, capable of harvesting water wave energy (Fig. 2.d). The water waves cause pressing and releasing on the TENG structure, resulting in lateral extension and relaxation of wavy Cu electrode. This results in the contact electrification and relative movement between Cu electrodes and PTFE surfaces, causing an output current flow. The TENG was subjected to an artificial wave condition of wave height 0.2 m and speed of 1.2 m/s, producing a peak voltage of 30 V, peak output current of 6 μ A. The same device was subjected to a vibration of 100 Hz, resulting in a peak power density of 0.4 W/m².

TENGs can be constructed using a broad range of materials and structures due to its versatility, resulting in a range of wearable textile based TENG designs. These include fibre, yarn and fabric based TENGs [52–56]. Zhong et al.,[56] fabricated a modified fiber structure to develop wearable TENGs (Fig. 2e). Cotton threads were covered with carbon nanotube (CNT) ink which acted as triboelectric surfaces and electrodes. The second TENG surface was fabricated by applying a PTFE coating on the CNT coated yarns. These yarns were twisted to construct single fiber-based generators, and, interwoven into a fabric. The fiber-based TENG was used to harvest energy from finger movement, resulting in a peak output power density of around 1 mW/m², through a load of 80 M Ω . Pu et al.,[57] modified a polyester fabric using Nickel (Ni) and Parylene to develop a wearable energy harvester (Fig. 2f). Strips of polyester fabrics were covered with a Ni coating, whereas a set of Ni covered fabric strips were again coated using Parylene. These strips were interwoven into a fabric. Parylene coated surfaces and the Ni coated surfaces act as the triboelectric contact surfaces, whereas the Ni coatings act as the electrodes for both the TENG surfaces.

Figure 2: Energy harvesting examples for TENGs. (a) Schematic of a shape adoptive thin film based TENG, which utilizes sliding motion. Reprinted with permission from ref. [39], Copyright © 2014, Wiley-VCH GmbH & Co. (b) Photograph of a double side fixed flutter driven TENG. Reprinted with permission from ref. [42], Copyright © 2016, American Chemical Society. (c) Schematic of a spring based TENG for vibration energy harvesting, consisting of PDMS and gold nanoparticles. Reprinted with permission from ref. [45], Copyright © 2013, American Chemical Society. (d) Schematic of a TENG consisting of a wavy electrode for energy harvesting from water waves. Reprinted with permission from ref. [51], Copyright © 2014, American Chemical Society. (e) A fibre based TENG design for applications in wearable energy harvesting. Reprinted with permission from ref. [56], Copyright © 2014, American Chemical Society. (f) Wearable TENG constructed using modified fabric strips woven into a fabric. Reprinted with permission from ref. [57], Copyright © 2015, Wiley-VCH GmbH & Co.

130 The output performance of the TENG was evaluated at low frequency movement (<1 Hz), where peak V_{oc}
 131 of 50 V, peak I_{sc} of around 2 mA/m², and a peak P_{out} of 0.4 W/m² were reported.

Self-powered TENG sensors have been shown useful in wearable electronics, IoT, and portable electronics, where a number of remote sensors are deployed to collect information, enabling users to detect and respond to their surroundings.[58] Pressure and tactile sensing is a key application for TENG sensors.[59–62] Zhu et al.[60] reported a TENG capable of measuring tactile responses at low pressure regimes (Fig. 3a). A PET layer was sandwiched between two Indium tin oxide (ITO) layers acting as the electrodes, and the pressure sensitive surface was constructed using a vertically aligned fluorinated ethylene propylene (FEP) nanowire surface. An example for the operation of this device is shown in the voltage output graph of Fig. 3a. When the device is compressed using finger contact, the voltage increases accordingly, and returns to the reference state when the finger contact is removed. The output performance of the TENG indicated a pressure sensitivity of 44 mV/Pa ($0.09\% \text{ Pa}^{-1}$), touch sensitivity of 1.1 V/Pa ($2.3\% \text{ Pa}^{-1}$), capable of operating at low pressure ranges ($<0.15 \text{ kPa}$). Fan et al.[61] used a similar concept to construct a VCSTENG with micro-patterned PDMS and PET contact surfaces (Fig. 3b), along with ITO back electrodes.

Figure 3: Use of TENGs in self-powered sensing. (a) Schematic of the structure of a TENG designed for tactile sensing (left), and, the voltage response to the touch of a finger (right). Reprinted with permission from ref. [60]. Copyright © 2014, American Chemical Society. (b) A VCSTENG composed of a micropatterned PDMS surface for pressure sensing (left), and the voltage output during the drop of a feather (right). Reprinted with permission from ref. [61]. Copyright © 2012, American Chemical Society. (c) Schematic of a membrane based self-powered vibration sensor. Reprinted with permission from ref. [63]. Copyright © 2014, Wiley-VCH GmbH & Co. (d) Schematic of a self-powered TENG UV sensor. Reprinted with permission from ref. [64]. Copyright © 2014, Wiley-VCH GmbH & Co.

This device demonstrated a lower detection limit of 13 mPa, sensing the fall of a feature and a water droplet. A membrane-based TENG vibration sensor was developed by Bai et al.,[63] capable of detecting pressure changes for health monitoring applications. This device uses a latex membrane and a FEP nanorod array as triboelectric contact surfaces, and a pair of copper electrodes for the exchange of induced charges (Fig. 3c). The TENG device detected a minimum air pressure variation of 0.16 Pa, and used to detect human footsteps, respirations, and heartbeat, showing the potential to be used in medical applications.

Apart from the dynamic physical parameters, TENGs have also been used in detecting environmental and chemical properties. Lin et al. [64] proposed a VCSTENG which acts as an active UV photodetector, fabricated using titanium dioxide nanostructures (Fig. 3d). The irradiation of UV radiation affected the resistance of the active layer, and in turn, the triboelectrification process. Therefore, the current and voltage variations of the TENG were used as an indicator to determine the intensity of UV radiation, with a response of 280 A/W, rise time of 18 ms, and a light intensity detection range of 20 $\mu\text{W}/\text{cm}^2$ to 7 mW/cm². Lin et al.[50] developed a VCSTENG architecture composed of gold (Au) nanoparticles, capable of sensing mercury (Hg²⁺) ions.

3. Working Principles of TENGs

The power generation of TENGs is a combination of the triboelectric effect, and, electrostatic induction resulting from the relative movement of triboelectrically charged surfaces [19][24][23]. In this section, existing theories regarding the origin of triboelectric effect are briefly discussed, followed by the theoretical models explaining the output behavior of TENGs.

3.1 Triboelectric Effect

Triboelectric charging occurs when two material surfaces are contacted or rubbed against each other[65–69]. **Triboelectric series is constructed through the empirical classification of triboelectric materials according to their capability of being positively or negatively charged (Fig. 4a).[70][71][68]** The origin of the triboelectricity is considered to be due to the transfer of electrons [72][73], ions [68][74][75], mass [76][66] or a combination of these effects [67].

Triboelectric charging of metals and semiconductors correlates with their work function or contact potential difference.[67,77] However, charging of insulators does not typically indicate such a clear trend [78]. Electron transfer theory supports the idea of electron transfer during triboelectric charging. Liu *et al.* conducted a series of experiments on the contact charging of polytetrafluoroethylene (PTFE) against poly(methyl methacrylate) (PMMA), proving the presence of electrons on PTFE surface after contact electrification, using a set of electro chemical reactions[79][80]. More recently, Xu et al.,[77] reported the charging behaviour of inorganic insulating surfaces against increasing temperature, supporting electron transfer theory.

Harper et al.[68] presented a theoretical model to explain the contact electrification through ion transfer, considering an electret containing larger fixed ions and mobile counter ions. When the surfaces are in van der Waals contact, smaller mobile ions will move between the two surfaces experiencing a single potential well, which becomes an asymmetric double potential well When the surfaces start to separate. When the potential barrier created between the surfaces is too high, the ions would be trapped on one of the

183 surfaces. Diaz et al.,[74][75] reported a study relating the magnitude and polarity of the contact
 184 electrification with the structure and concentration of the ionic species on the contact surfaces.

Figure 4: (a) An example of a triboelectric series, where the materials are listed according to their capability of triboelectrically charged with respect to a liquid metal reference. Reprinted from ref. [70] (b) Schematic showing the dimensions of a charged TENG layer which was used to derive the DDEF model, with length (L), width (W), charge density (σ), and the axis (z) perpendicular to its midpoint. Reprinted with permission from ref. [19] Copyright © 2017, Royal Society of Chemistry. (c) Schematic representation of a TENG device with m number of contact surfaces. In this demonstration, the electric field behaviour of i^{th} triboelectric surface is considered, and the distance to electrode a ($x_{a,i}$) and electrode b ($x_{b,i}$) are marked. The electrodes are separated by a distance y , and the dielectric constants are shown as ϵ_a and ϵ_b respectively. Reprinted with permission from ref. [20] Copyright © 2018, Elsevier Ltd.

185 Mass transfer related to contact electrification was first proposed by Clark et al. [76] by studying the
 186 contact electrification of PTFE and PET films. Transfer of the opposite material was detected on both
 187 surfaces using X-ray Photoelectron Spectroscopy analysis, and higher material transfer was correlated
 188 with larger charge transfer. More recently, Baytekin et al. [66] highlighted the significance of material

transfer during contact electrification of insulators, reporting the triboelectrically charged surface as a random mosaic of positively and negatively charged nano-scale areas.

3.2 Simulating TENG Outputs

The relative movement of triboelectrically charged surfaces causes the electric fields acting on electrodes of TENG devices to vary, inducing an output current, which is driven through an external load to harvest energy. The fundamental output behaviour of TENGs has been explained using Maxwell's displacement current [14], given by:

$$J_D = \frac{\partial D}{\partial t} = \varepsilon \frac{\partial E}{\partial t} + \frac{\partial P_S}{\partial t} \quad (1)$$

Where J_D is the displacement current density, D is the displacement field, t is time, E is electric field, and, P_S is the polarization of the medium.

The conventional theoretical models depend on the parallel plate capacitor approximation to simulate TENG outputs, by developing the relationship between the voltage, charge and the separation (V-Q-x). This relationship is typically represented by,

$$V = -\frac{1}{C}Q + V_{OC} \quad (2)$$

Where, V_{OC} indicates the open circuit voltage and C is the overall capacitance of the TENG. This concept has been expanded to represent contact mode as well as sliding mode TENG architectures [33][24][81][37]. However, the theoretical models based on the parallel plate capacitor approximation contain a number of drawbacks. These include the inability to fully explain the polarization of dielectrics, induction of output charges, and the electric field behaviour inside a TENG device, as well as the relatively low accuracy in predicting output trends [19][20][21]. Furthermore, bespoke circuit models have been presented to explain different TENG working modes, affecting the consistency and the comparability of between different models [20].

We presented the distance-dependent electric field (DDEF) model, the first analytical theoretical model based on Maxwell's equations, as a universal platform to fully describe the working principles of majority of TENG architectures. Instead of the parallel plate capacitor approximation, the distance-dependent electric field model takes into account the finite dimensions of triboelectric layers and evaluates the overall electric fields acting in a TENG. Considering a charged layer with dimensions L and W , and a uniform charge density of σ , placed in a medium with a permittivity of ε (Fig. 4b), the electric field perpendicular to the layer ($E_{z,plane}$), against the distance (x) can be calculated as,

$$E_{z,plane} = \frac{\sigma}{\pi\varepsilon} \arctan \left[\frac{\frac{L}{W}}{2\left(\frac{x}{W}\right)\sqrt{4\left(\frac{x}{W}\right)^2 + \left(\frac{L}{W}\right)^2 + 1}} \right] = \frac{\sigma}{\pi\varepsilon} f(x) \quad (3)$$

Considering a typical TENG device consisting of m triboelectrically charged surfaces, triboelectric charge density (of i^{th} surface) $\sigma_{T,i}$, output charge density σ_u (Fig. 4c), eqn (3) can be applied to each of the triboelectrically charged surfaces as well as dielectric electrode interfaces, to calculate the overall electric field acting on the electrodes. Considering the TENG shown in Fig. 4d, the potential of the electrodes a (Φ_a) and b (Φ_b) is evaluated as [20]:

$$\Phi_a = \frac{-\sigma_u}{\pi\epsilon_a} \int_0^y f(x)dx + \frac{1}{\pi} \sum_{i=1}^m \left(\frac{\sigma_{T,i}}{\epsilon_a} \int_{x_{a,i}}^{\infty} f(x)dx \right) \quad (4)$$

$$\Phi_b = \frac{\sigma_u}{\pi\epsilon_b} \int_0^y f(x)dx + \frac{1}{\pi} \sum_{i=1}^m \left(\frac{\sigma_{T,i}}{\epsilon_b} \int_{x_{b,i}}^{\infty} f(x)dx \right) \quad (5)$$

During the operation of the TENG, triboelectric layers will move relative to each other using the mechanical energy available in the environment. This causes the distance between the TENG layers to change. The electric fields from the charged surfaces are distance-dependent, therefore, the magnitude of the electric fields on the respective electrodes changes accordingly. As a result, the potentials of the electrodes vary depending on the separation distance of TENG layers, as described by eqn (4) and eqn (5). The potential difference can be evaluated as [20]:

$$V = \Phi_a - \Phi_b \quad (6)$$

This causes an output charge exchange between the electrodes, attempting to balance the potential difference between them. Considering the short circuit scenario, the output current (I_{sc}) can be evaluated as [20]:

$$I_{sc} = LW \frac{d\sigma_u}{dt} \quad (7)$$

Where, the output charge density (σ_u) is given by,

$$\sigma_u = \frac{\sum_{i=1}^m \left(\frac{\sigma_{T,i}}{\epsilon_a} \int_{x_{a,i}}^{\infty} f(x)dx - \frac{\sigma_{T,i}}{\epsilon_b} \int_{x_{b,i}}^{\infty} f(x)dx \right)}{\left(\frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} \right) \int_0^y f(x)dx} \quad (8)$$

Assuming the electrodes are connected via a load resistor of resistance R, the output current, hence, the power output of the TENG can be evaluated using Ohm's law with the use of following equation [20]:

$$LWR \frac{d\sigma_u}{dt} + \frac{\sigma_u}{\pi} \left(\frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} \right) \int_0^y f(x)dx - \frac{1}{\pi} \left[\sum_{i=1}^m \left(\frac{\sigma_{T,i}}{\epsilon_a} \int_{x_{a,i}}^{\infty} f(x)dx - \frac{\sigma_{T,i}}{\epsilon_b} \int_{x_{b,i}}^{\infty} f(x)dx \right) \right] = 0 \quad (9)$$

Therefore, DDEF model not only provides a full and adequate explanation of the working principles of different TENGs, but also provides an estimation of their output trends and magnitudes, with a higher accuracy in comparison to the capacitor based theoretical models [19–22]. Furthermore, the DDEF model acts as a universal platform to compare the output trends between different TENG architectures.

4. Output Trends and Optimization Methods for TENGs

The power generation of a TENG depends on the triboelectric charging process as well as electrostatic induction, as discussed in section 3. The design and construction of efficient TENG architectures involve the understanding of the output trends of TENGs, and the factors affecting their output behaviour, in terms of their impact on the triboelectric charging and the output induction process.

4.1 Characteristics of Triboelectric Charging

Triboelectric charging strongly depends on the material properties of the contact surfaces. One of the primary indicators of the polarity and the amount of charge is the relative position of the materials in the triboelectric series.[68][71] The materials further apart in the triboelectric series typically generate higher amounts of surface charges, where the material ranked higher in the series shows the positive

polarity.[71] Moreover, chemical composition, pre-treatment, processing history, and surface roughness of contact surfaces can affect triboelectric charge density [25,61,71,82–84].

For a given pair of triboelectric surfaces, the triboelectric charging depends on the number of contacts between them during initial charging phase.[68,78,85,86] The triboelectric charge separation start from a low value, increase gradually with a decreasing, and saturates after a finite number of (typically several hundred) contact cycles (Fig. 5a). After this initial dynamic period, the triboelectric charge density remains relatively stable at the saturated value. Other experimental parameters such as different charging steps and the pressure applied during triboelectrification affects the surface charge density. Application of adequate pressure between triboelectric contact surfaces has been demonstrated to increase effective contact area, resulting in higher charge separation especially for structured surfaces.[87–89]

Figure 5: (a) The gradual increase, and, eventual saturation of triboelectric surface charge, against the number of contacts of triboelectric surfaces. Charge curves for a PDMS sheet (1 cm*1 cm) contacted against (i) another PDMS surface, where the charge output of both sheets are shown, (ii) polycarbonate, (iii) silicon wafer, (iv) PTFE. In (i) to (iv), open markers show charge outputs for the experiments conducted inside a non-polar oil medium, and the solid markers indicate the experiments conducted in air. Reprinted with permission from ref. [86] Copyright © 2011, Wiley-VCH GmbH & Co. (b) DDEF model simulations for the effect of triboelectric charge density on the output power, against increasing load resistances. Reprinted with permission ref. [21]

The saturated triboelectric charge density is a dynamic balance between the charge separation (discussed above) and charge recombination.[68] Charge recombination occurs from three main mechanisms;

electron tunnelling, field emission and dielectric breakdown of the surrounding gases, among which the dielectric breakdown is considered to be the dominant factor.[68] A number of studies have been presented in the literature regarding the discharge patterns of tribo charged insulators.[66],[86] Baytekin et al.,[66] evaluated the kinetics of discharge for triboelectrically charged PDMS surfaces. The discharge rate constant for the PDMS surface in air was estimated to be around 0.001 s^{-1} to 0.00001 s^{-1} . Furthermore, the charges do not show lateral migration. These results indicated the capability of triboelectric charges to remain unaltered for relatively long durations of time. [67]

Triboelectric charges separated during metal-metal contact typically get discharged before the surfaces are separated, due to the presence of high mobility electrons. On the other hand, Insulating materials are capable of retaining triboelectric charges on contact surfaces.[67,68] Therefore, triboelectricity between metal-insulator and insulator-insulator materials forms the basis of triboelectric energy harvesting considering the stability of separated static charges.[1,13,19]

4.1.1 Enhancing TENG Outputs Through Triboelectric Charging

As evident from eqn (6) to (8), triboelectric charge density is directly proportional to the voltage and current outputs. Therefore, the power output of the TENG has a quadratic relationship against the charge density [21], as depicted by the DDEF model simulations (Fig. 5b). Hence, enhancing the charge density plays a critical part in optimising the outputs of a TENG. Apart from the fundamental optimisation characteristics such as the appropriate material selection from the triboelectric series and sufficient repetitive contact between surfaces, a number of strategies have been used in the literature to enhance the triboelectric charge density.

Physical surface modification of TENG layers through micro and nano-scale patterning has been frequently used to enhance the outputs of TENGs.[1,13,17,58] Patterning the contact surfaces enhances the effective contact area confined in a given space, therefore improves the effective charge density. Fan et al.[90] developed a series of micro-patterned PDMS surfaces as triboelectric contact layers, to study their effect on TENG outputs (Fig. 6a). Several designs including lines, cubes and pyramid structures were compared with a flat triboelectric surface of the same material. The output trends were consistent with the increase in effective contact area (pyramid>cube>line>flat) caused by surface structuring, resulting in enhanced outputs. Zhu et al.,[45] reported a VCSTENG where the triboelectric surface modified with gold nanoparticles (Fig. 2c), resulting in significantly enhanced outputs. Similarly, nanoparticles, nanowires and other nanomaterials have been regularly used to enhance the output performance of different TENG architectures.[26,44,91] Furthermore, some studies focussed on increasing the triboelectric charge density through the engineering of friction layer [92]. For example, Cui et al. presented a TENG with a composite friction layer to adjust the charge distribution depth, and, obtained an improvement of a factor of 11.2 in triboelectric charge density.

Different chemical surface modification techniques have been reported in literature, which were used to enhance the triboelectric charge density of TENG contact surfaces.[17,82,83,93] Many of these studies focused on introducing functional groups that encourage the triboelectric charge transfer. Shin et al. [82] reported a surface modification technique for PET films, in which poly-L-lysine solution was used to introduce positively charged amino ($-\text{NH}_3^+$) groups. Similarly, trichloro (1H, 1H, 2H, 2H-perfluorooctyl) silane (FTOS) was used to introduce nonpolar trifluoromethyl ($-\text{CF}_3$) groups. VCSTENG devices were constructed using non-functionalized PET and the functionalized films as shown in Fig. 6b. Both V_{oc} and J_{sc} trends were comparable, where the functionalized PET films showed improved performance ((ii), (iii),

and (iv) in Fig. 6b), in comparison to the case of non-functionalized PET ((i) in Fig. 6b). The maximum output performance was observed for $(-\text{NH}_3^+)$ modified and $(-\text{CF}_3)$ modified triboelectric contact surface pair. These improvements were discussed with relation to the surface functionalization, where $(-\text{NH}_3^+)$ group improves the positive triboelectric charging whereas the $(-\text{CF}_3)$ encourages negative triboelectric charging, which results in improved charge density of contact surfaces. A similar output enhancement was

Figure 6: Strategies used to enhance the triboelectric charge density for TENGs. (a) Micropatterned PDMS surfaces consisting of line, cube and pyramid patterns, and, their corresponding current and voltage outputs compared with a corresponding flat surface. Reprinted with permission from ref. [61]. Copyright © 2012, American Chemical Society. (b) Effect of chemical functionalisation on TENG contact surfaces using different functional groups, and their corresponding voltage outputs. Reprinted with permission from ref. [82]. Copyright © 2015, American Chemical Society. (c) Enhancing triboelectric charge density thorough ion injection, and the corresponding voltage and current improvements. Reprinted with permission from ref. [94] Copyright © 2014, Wiley-VCH GmbH & Co. (d) Schematic of the concept of an additional TENG device acting as the charge pump to enhance triboelectric charge density. Reprinted with permission from ref. [100] Copyright © 2018, Elsevier Ltd. (e) A block diagram explaining the concept of integrating external charge excitation and self-charge excitation to increase the triboelectric charge density. Reprinted with permission from ref. [102]

reported by Li et al., where the introduction of fluorine containing groups onto a PET triboelectric surface through inductively coupled plasma etching resulted in a significant enhancement in output voltage, current and charge density.[83]

In a relatively different approach, Wang et al.,[94] reported a technique where single polarity charged ions were injected directly on TENG contact surfaces using an air ionization gun. A FEP film was injected with negatively charged ions using this method (Fig. 6c), reaching triboelectric charge densities of around $630 \mu\text{C}/\text{m}^2$. The FEP layer was coupled with an Al sheet to construct a VCSTENG. The performance comparison before ion injection and after injection clearly indicate a significant enhancement of V_{oc} and J_{sc} , with an improvement of around 4 to 5 times, resulting in an improvement of 25 times in the power output. In a more recent study, Wang et al.,[95] reported a significant enhancement in triboelectric surface charge density, by placing the TENG in a vacuum. They presented a VCSTENG using PTFE and Cu as triboelectric contact surfaces. A Change in the surrounding conditions of the TENG from the atmospheric pressure to high vacuum (around 10^{-6} Torr) increased the triboelectric surface charge density from $50 \mu\text{C}/\text{m}^2$ up to $660 \mu\text{C}/\text{m}^2$. Moreover, this charge density was further increased up to $1003 \mu\text{C}/\text{m}^2$ by coupling the PTFE layer with a ferroelectric material. The current, voltage and output power increased significantly as a result of the increase in triboelectric charge density.

Several other techniques have been reported in the literature to encourage conformal contact between the triboelectric surfaces, hence, to increase triboelectric charge separation. Hard surface contact between TENG layers is known to produce relatively low TENG outputs, due to inadequate contact between triboelectric surfaces [96]. Consequently, some researchers have engineered the triboelectric surfaces to obtain soft contact targeting increased contact surface area [96–99]. This resulted in higher contact charge transfer, providing increased output performance of the TENGs. Such techniques include the utilisation of contact electrification between liquid metal triboelectric layers[98,99], and the use of soft core TENG surfaces [96][97]. In one example, Tang et al. [98] suggested a liquid-solid contact TENG to ensure nanometer scale conformal contact between triboelectric surfaces, using liquid metals (mercury and gallium) as one of the triboelectric layers. The contact between the solid triboelectric layer (Kapton) provided a triboelectric charge density of around $430 \mu\text{C}/\text{m}^2$, resulting in a 4 to 5 times improvement compared to a solid-solid contact TENG.[98] More recently, Cheng et al. [96] developed a TENG for water wave energy harvesting, consisting of an acrylic hollow sphere as the shell component. The second triboelectric material was contained within this shell, and the relative rolling action between the two components was used to generate the TENG output. In this design, the conventional PTFE spheres, which results in hard contact between triboelectric surfaces, were replaced by a liquid/silicone soft core material. This led to an increase in the contact area, and hence the triboelectric charge transfer, resulting in a 10 fold increment in maximum output charge, and significant improvement in TENG outputs.

A novel approach has been suggested where two TENGs are used in tandem, acting as a floating layer structure and a charge pump (Fig 6d) [100], reporting an output charge density of $1020 \mu\text{C}/\text{m}^2$ in ambient conditions. In a relatively different approach, TENGs were combined with voltage multiplying circuits consisting of capacitors and diodes, to construct a self-improving TENG design [101]. As a hybridisation and a further development of these two concepts, a TENG architecture which utilises the external charge excitation using a charge pump mechanism as well as self-charge excitation mechanism consisting of a self-voltage multiplying circuit was presented more recently (Fig. 6e) [102]. This new device was able to achieve an effective output charge density of $1250 \mu\text{C}/\text{m}^2$. Furthermore, a number of studies have highlighted the influence of the contact force or pressure between the triboelectric contact surfaces,

during the operation of the TENG [21][88][89][87]. Therefore, obtaining a proper contact between triboelectric surfaces is essential to increase the charge density, especially when the surfaces are structured.

4.2 The Output Induction of a TENG and Its Optimisation

Once TENG contact surfaces are triboelectrically charged, the relative movement of these layers result in the generation of TENG outputs, as discussed in section 3. The electric fields of the charged triboelectric surfaces propagate through the TENG layers, causing the dielectric layers to polarize, and acts on the dielectric electrode interfaces which drives the output charges. This output induction process is affected by a number of device and motion parameters of the TENG, and some of the main parameters are discussed in this section.

4.2.1 Device Parameters

The output characteristics of a TENG device depend on a number of device parameters, which include structural parameters such as the shape, surface area and thickness of TENG layers, as well as material parameters such as the dielectric constant and charge density.

The effect of the surface area of a TENG contact surface was analysed in our previous studies, using the DDEF model (Fig. 7a) and experimental results (Fig. 7b) [19][21]. This study used a pair of square shaped TENG layers consisting of PDMS and PET contact surfaces, and the current, voltage and power output at different surfaces areas were evaluated. The current and voltage outputs increased when the surface area increased [19]. As a result, the power output was higher for the larger surface area device, which was observed at a relatively lower load resistance (Fig. 7a,b), both which are favourable for practical TENG applications [21]. Similarly, Wang et al.,[103] reported the effect of triboelectric layer size on the outputs of a VCSTENG, with superimposed multiple electrode layers. As expected, the increase in the triboelectric layer size significantly increases both V_{OC} (Fig. 7c) and I_{SC} (Fig. 7d). Furthermore, the same study indicated the significance of the edge effects from the TENG layers towards its electrical outputs, when the maximum separation of the TENG movement is of a comparable scale with respect to TENG layer dimensions.

The thickness of the TENG layers affects the electric field propagation, therefore, impacts the power generation capability of the TENG during the output induction process [19][21]. Assuming a given triboelectric charge density on a dielectric TENG layer, the electric fields have to propagate through a shorter distance when the thickness of the layer is low, and according to the DDEF model, they will easily propagate towards the electrode interfaces without significantly reducing their intensity. Therefore, in the output induction point of view, reducing the thickness of dielectric TENG layers to a minimum increases the output power, and, reduces the corresponding load resistance from which the maximum power output is obtained, as demonstrated through DDEF model simulations (Fig. 7e) and experimental results (Fig. 7f) [21]. On the other hand, a recent study by Cui et al [92] revealed details about the effect of the thickness of the triboelectric layer on the transportation and distribution of triboelectric surface charges, and its charge storage capability, using a VCSTENG with a PVDF contact layer. The outcomes of this study suggested that the triboelectric charge density decreases towards the inner volume of the dielectric layer (Fig. 7g). When the thickness of the dielectric layer is increased, the storage thickness of triboelectric charges also increases, and gradually maximizes at a threshold thickness. Further increasing the thickness of the dielectric layer above this threshold value does not contribute to the triboelectric

Figure 7: Effect of device parameters on TENG outputs. (a) DDEF model simulation results, and, (b) corresponding experimental outputs for the output power against increasing loads, considering different TENG layer surface areas. Reprinted with permission from ref. [21] The output trends of a VCSTENG against different surface areas showing (c) voltage and (d) current output trends. Reprinted with permission from ref. [103] Copyright © 2017, Elsevier Ltd. The power output of a TENG against increasing TENG layer thickness, indicated through (e) DDEF model simulations, and (f) experimental results. Reprinted with permission from ref. [21] (g) A theoretical simulation for effect of triboelectric layer thickness on triboelectric charge distribution on the contact layer. Reprinted with permission from ref. [92]. Copyright © 2016, American Chemical Society. (h) The DDEF model simulations indicating the effect of increasing dielectric constant on the output power of a TENG. In this simulation, dielectric constant is systematically increased, while keeping all other parameters constant. Reprinted with permission from ref. [21]

charge accumulation. In a triboelectric surface charge density perspective, triboelectric charges maximize above this threshold thickness, therefore, having the minimum threshold thickness becomes essential. Hence, the optimum thickness of TENG layers can be considered as a balance between the reduction of thickness to obtain maximum electric field propagation, and, providing enough thickness to ensure maximum stable triboelectric surface charge accumulation.

Moreover, the shape of the TENG layers has an influence on the electric field propagation and the output induction of the TENG. As an example, the theoretical and experimental output trends of a planar TENG device were compared against a comparable convex-concave TENG design, proving a relatively higher output performance for the planar architecture [19].

Considering the materials parameters, the triboelectric charge density depends directly on the contact surface material selection as discussed in detail in section 3. This selection depends on the relative position of the pair of materials in the triboelectric series, where the material ranked towards the top of the series provides a positive charge against the material ranked lower, which will charge negatively [70]. Utilising material pairs which are placed further apart in the triboelectric series can be considered a suitable approach for the selection of material type to increase the triboelectric charging. The recent literature contains a number of quantitative triboelectric series consisting of a large range of materials typically used for the construction of TENGs, which can be used as a guide in this process [70,71].

On the other hand, dielectric constant also depends on the material type which affects the electric field propagation of the TENG, however, contradictory views exist on the effect of the dielectric constant on TENG outputs. According to the theoretical simulations from the DDEF model as well as the capacitor-based model, when the dielectric constant is lower, higher output power can be obtained (Fig. 7h) [21]. These simulations assume the surface charge density and all other parameters to be similar, and purely investigate the effect of dielectric constant change on the power output of TENG. However, some of the experimental studies[104][105] have suggested an increase in the TENG outputs while using high dielectric constant material surfaces, citing an increase in the triboelectric charge density. Therefore, further investigation is necessary to verify the effect of the dielectric constant on TENG outputs.

4.2.2 Motion Parameters

The nature of input motion profile affects the magnitude and the rate of the induced outputs of the TENG. Sinusoidal and constant velocity periodic motion profiles are commonly used to characterise TENGs, of which, the magnitude of the movement (amplitude) and the motion rate (frequency) are considered key parameters.

The effect of the rate of movement on TENG outputs was analysed in our previous studies (at fixed amplitude), using sinusoidal and constant velocity periodic motion profiles [21]. Considering the sinusoidal motion profiles, the power output of the TENG increases proportionally to the frequency, when the other parameters are kept constant. Increasing the frequency of the movement increases rate at which the TENG layers move relative to each other, and hence increases the rate of charge transfer (current), resulting in an increase in the output power (Fig. 8a) [21,106–110]. It is important to notice that the load resistance corresponding to the peak power decreases with a linear trend, as the frequency is increased, which is desirable for practical applications. A similar trend can be observed for constant velocity contact and separation movements considering the DDEF model simulations (Fig. 8b) and experimental results (Fig. 8c). Similarly, Yang et al.,[111] investigated the effect of frequency on the output power, which indicated an increase in the power output when the frequency is increased (Fig. 8d). Wang et al.[27] investigated the effect of increasing frequency (at constant amplitude) on the TENG output trends, using a VCSTENG device (Fig. 8e-f). As indicated in Fig. 8d, V_{OC} does not show a significant variation against increasing frequency of the movement (Fig. 8e). However, I_{SC} increases significantly as the frequency of the movement is increased (Fig. 8f), whereas Q_{SC} remains almost constant (Fig. 8f inset).

Therefore, having a higher rate of movement for TENGs is advantageous in obtaining higher outputs as well as reducing the impedance of the energy harvester. This approach can be challenging as the frequency of ambient movements can be limited to physical restrictions, however, frequency up conversion mechanisms have been suggested in literature to overcome this issue. For example, a mechanical system composed of a spiral spring, great train, cam and a fly wheel was suggested by Bhatia

Figure 8: The effect of the motion rate on TENG outputs. (a) Simulation (DDEF model [solid triangles] and TENG power transfer equation [hollow circles]) and experimental results [solid circles] for the effect of increasing frequency of sinusoidal movement on TENG power output. (b) DDEF model simulations, and, (c) experimental results, indicating the effect of increasing rate of movement on TENG power output, when the TENG is subjected to constant velocity motion. Reprinted with permission from ref. [21]. (d) The effect of increasing frequency of movement on TENG output power. Reprinted with permission from ref. [111] Copyright © 2018, Elsevier Ltd. Effect of increasing frequency on (e) Open circuit voltage (V_{oc}) and (f) Short circuit current (I_{sc}) outputs. Inset of (f) shows the effect of frequency on the charge output. Reprinted with permission from ref. [27] Copyright © 2012, American Chemical Society.

signals (50 Hz). A significant power output improvement was reported by Kim et al.[113] through the use of a gear train to enhance the frequency of input motion for the TENG. Additionally, cantilever type layer designs have been suggested as a potential method to increase the rate of movement for TENG layers [21].

Amplitude of the movement has a significant impact on the output trends of a TENG. The effect of the increasing amplitude of a sinusoidal motion (at fixed frequency) on the power generation of the TENG was reported using the DDEF model simulations (Fig. 9a) and experimental results (Fig. 9b). For both scenarios, the output power increases with a decreasing trend when the amplitude is increased. A similar output behaviour was reported by Wang et al.,[62] using a FSTENG, where an increase in the current and voltage outputs were observed, under increasing amplitude of movement Fig. 9c-d. A similar analysis was presented by Zhong et al.,[46] for a VCSTENG, indicating an increase in the current output profiles (Fig. 9e), as well as peak current and charge outputs (Fig. 9f), at a fixed frequency. Increasing the amplitude results in increasing the gap distance between the electrodes, causing a larger potential difference. This results in the increased voltage and current outputs.

Due to the gradually saturating outputs, deciding the optimum separation distance (amplitude for the case of contact mode TENGs) for a given TENG can be challenging. An optimisation criteria for amplitude has been demonstrated by Dharmasena et al. [21] which considers the saturation of the peak output power, the separation distance corresponding to the peak output power, and the energy transfer during the movement of TENG layers.

The importance obtaining conformal contact between TENG layers towards the triboelectric surface charge density was discussed in section 4.1.1. Sufficient contact between TENG contact surfaces also affects the electrostatic induction process. The effect of the minimum separation distance (h) of pre-charged triboelectric contact surfaces, on the power output of a TENG was reported in our previous work [21], where h was varied from contact ($h=0$) up to different separations. When the gap distance increased, the power output reduced significantly, and the load corresponding to maximum power increased as suggested by the DDEF model simulations (Fig. 9g) and experimental results (Fig. 9h). These results indicate the importance of sufficient contact between TENG layers towards the output induction. Similarly, several other experimental studies confirmed the importance of conformal contact between the TENG layers during the contact phase [27,61].

4.3 Environmental Parameters

Environmental parameters such as temperature, humidity and atmospheric pressure are known to impact the behaviour of triboelectric charging [71,77], as well as electrostatic induction process [114], therefore affects the output performance of a TENG.

The temperature affects the triboelectric charging process as well as the material characteristics of TENG layers [77,114–116]. The behaviour of the triboelectric charging against temperature was reported by Xu et al. [77] using TENG consisting of inorganic insulating surfaces, where the charge, voltage, and current decreased when the temperature was increased (293 K to 473 K). These trends were explained using an electron cloud potential well model, where the atoms of the materials were represented by a potential well with outer shell electrons loosely bound, forming an electron cloud. When the atoms are apart, a distance (d) exists between the clouds, and the occupied energy levels

of the materials (E_A and E_B) are less than the required energy for electrons to escape from the surface of materials (E_1 and E_2) (Fig. 10a i). Therefore, electrons cannot transfer before contact, due to local

Figure 9: Effect of increasing amplitude on TENG output power. (a) DDEF model simulations, and, (b) corresponding experimental results, for the effect of increasing amplitude of movement (considering a sinusoidal motion profile) on the power output of a VCSTENG. Reprinted with permission from ref. [21]. Effect of increasing amplitude of the movement on (c) V_{oc} and, (d) I_{sc} output trends. Reprinted with permission from ref. [62] Copyright © 2014, American Chemical Society. Output results for the effect of increasing amplitude on (e) Current, (f) Peak current (blue) and charge (black). Reprinted with permission from ref. [46] Copyright © 2013, Elsevier Ltd. (g) DDEF model simulations, and, (g) Experimental results for the effect of increasing minimum separation (gap distance - h) between TENG layers on the power output. Reprinted with permission from ref. [21].

trapping of electrons in potential wells. These electron clouds overlap during the contact electrification creating an asymmetric double well potential, and, allows the electrons to transfer between the surfaces (Fig. 10a ii). When the surfaces are separated, an energy barrier is created, and the transferred electrons are trapped in subsequent surfaces at relatively low temperatures (Fig. 10a iii). However, the thermal energy of the material increases when the temperature is increased, enabling electrons to move out of this potential well to transfer to the other material or to the air, which results in the reduced triboelectric charging at adequately elevated temperatures (Fig. 10a iv).

The overall effect of increasing temperature on the TENG outputs depends on how the triboelectric charging is affected, as well as on the structural and material changes of the TENG that may be caused by the temperature increment. As an example, Wen et al.[114] studied the effect of temperature on the current and voltage outputs of a TENG composed of PTFE and Aluminium contact surfaces. The temperature of the surrounding was changed from 77 K to 500 K, while recording V_{OC} and I_{SC} . Both the V_{OC} (Fig. 10b) and I_{SC} (Fig. 10c) depict relatively similar output trends, where an increase in the output performance is initially observed (77 K to 260 K). The outputs maximised around 260 K and decreased significantly when the temperature was further increased. When the temperature is increased, the thermal fluctuation on the contact surfaces cause the triboelectric charge density to reduce, imposing a negative impact on the TENG outputs, as discussed in the previous paragraph. At the same time, the elevated temperatures cause the TENG surfaces to soften, enhancing the triboelectric contact area. This enhances the effective triboelectric charge transfer between TENG layers. In the initial phase (77 K – 260 K), the latter is dominant, therefore, the outputs show an increasing trend. However, when the temperature is further increased, the reduction in the triboelectric charge density causes the TENG outputs to reduce significantly. Therefore, the overall effect on changing the temperature on TENG outputs depends on how the triboelectric charge density is affected, as well as the effect on the material and structural characteristics of TENG layers.

The effect of humidity or water on the TENG output performance was presented by Zhang et al. [59] using a series of hydrophobic and hydrophilic triboelectric contact surfaces. The influence of humidity on a given triboelectric surface depends on the amount of humidity and the wettability of the surface.[115] Considering hydrophilic surfaces such as Nylon 6,6 and Kapton, the triboelectric charges are almost nullified as the water spreads in a large area and prevents the triboelectric charge transfer. For example, the output performance of a VCSTENG consisting of a Nylon 6,6 layer, before adding water to the surface (Fig. 10d) and after the addition of water (Fig. 10e) were compared, where a significant reduction of the voltage was observed at the presence of water. When the surfaces are hydrophobic, the water is assumed to roll off the contact surfaces or remain with a small contact area on the triboelectric surface, therefore has a minimum effect on the triboelectric charge density and TENG output performance. The voltage for a hydrophobic PTFE layer with no water (Fig. 10f) and after adding water (Fig. 10g) does not indicate a significant change in output performance. A similar effect is observed at increasing relative humidity, where a hydrophilic surface (Nylon 6,6) shows an exponential drop in the output voltage (Fig. 10h), and the hydrophobic surface (PTFE) does not show a notable reduction in output performance (Fig. 10i). Therefore, Increasing the humidity generally has a negative effect on triboelectric charge density specially for hydrophilic surfaces, as polymers tend form a microscale water layer on the contact surfaces, disturbing the charge separation as well as encouraging lateral charge dissipation.[71,115] However, some studies suggested the importance of maintaining substantial humidity conditions due to the charge stabilizing effect of moisture present in air [86].

Figure 10: (a) Electron cloud potential well model explaining contact electrification of two materials. Schematic showing electron cloud and potential energy profiles of material A and B, (i) before contact, (ii) in contact, (c) after contact showing electron transfer between atoms at low temperature, and, (d) release of charges from atoms when the temperature (T) is increased as kT approaches barrier height (k -Boltzmann constant). Reproduced with permission from ref. [77] Copyright © Wiley-VCH GmbH & Co. The effect of increasing temperature on the (b) peak voltage and, (c) peak current of a TENG. Reprinted with permission from ref.[114] Copyright © 2014, Elsevier Ltd. The influence of adding water on the voltage performance of a TENG, showing a hydrophilic surface (nylon 6,6) (d) before, and, (e) after the addition of water, and, a hydrophobic surface (PTFE) (f) before, and, (g) after adding water. The effect of increasing humidity on the voltage output for (h) a hydrophilic (nylon 6,6) and, (i) a hydrophobic (PTFE) surface. Reprinted with permission ref. [59] Copyright © 2013, Elsevier Ltd.

charge separation, in comparison to atmospheric pressure conditions.[71] While significant output performances have been reported in the atmospheric pressure conditions, low vacuum conditions have reported relatively high output performances for TENGs as discussed in section 4.1.1 [95].

4.4 Power Output Extraction of TENG

Extracting the output power generated in a TENG energy harvester is a challenging task, due to a number reasons [21]. TENGs produce periodic output pulses corresponding to their input motion profiles, therefore, obtaining a constant and consistent output signal is difficult. These sporadic output pulses and generally not suited for powering electronic devices, as most of them require a constant direct current input [117]. Furthermore, TENGs are inherently high impedance devices, therefore, they require matching high external loads to deliver high output power, which again deviates for most of the day to day electronic applications [19][21].

One of the leading studies on the analysis of output power extraction of a TENG was presented by our group in 2018 through the development of TENG power transfer equation [21], using the DDEF model and Norton's Theorem. This technique segments the power generation characteristics of a TENG into its current (source current) and impedance (internal impedance) characteristics, and, uses the characteristic i-ratio (the ratio between the TENG internal impedance and the external load) to determine the output power generation and its optimisation (Fig. 11a). The source current and the i-ratio are evaluated using the DDEF model, and the TENG equivalent circuit to the Norton's theorem is used to approximate the output current of the device.

This study resulted in the development of unique visualisation strategy, TENG impedance plots, which represents the trends in i-ratio and the source current using the same time scale (Fig. 11b). Based on the maximum power transfer theorem, as the peak source current coincides with i-ratio of 0.5, optimum load matching condition is achieved, where the maximum output power can be extracted from the TENG. TENG power transfer equation and TENG impedance plots have been theoretically and experimental demonstrated for their capability of detecting peak power generation conditions, corresponding load matching, variation of outputs against different parameters and power output optimisation techniques, therefore, provides a step by step guidance for designing and fabricating optimised TENG energy harvesters.

Apart from the device optimisation, external circuit designs have been used to modulate the output of TENGs. These approaches include combining rectifier circuits, capacitor and inductor elements, to modify the output signal as well as to store the energy [118][119][120][121]. Zi et al. reported an inductor-free power management strategy, which involves automated switching between series and parallel arrangement of capacitors, resulting in the conversion of low current high voltage TENG output into a high current low voltage output signal (Fig. 11c) [122]. This strategy was used to demonstrate the improved performance, achieving five times higher charging rate for a supercapacitor. More recently, Ryu et al. presented a multi-phase rotation type TENG, capable of producing a near direct output current (Fig. 11d) [123]. This device used the sliding motion between triboelectric layers to generate output current, and the electrodes of the TENG were arranged to obtain a calculated phase shift between their output signals. These outputs were then rectified and superimposed to obtain a near direct current output from the energy harvester.

4.5 Hybrid Energy Harvesting Approaches

Figure 11: (a) Developing TENG power transfer equation: Transformation from the conventional TENG circuit model (i) which consists ideal voltage source ($V(t)$), variable capacitor ($C(t)$) and load (R), in to Norton's equivalent circuit model for TENGs (ii) representing source current $I_s(t)$, internal impedance $Z_s(t)$, and, load impedance Z_L . (b) Example of a TENG impedance plot. The source current and impedance-ratio (i -ratio) are plotted against the same time axis for different load values, and the optimum load is located at the intersection of i -ratio=0.5 and peak source current. Reprinted with permission from ref. [21]. (c) Schematic representation of the inductor-free power management system consisting of a mechanism to shift between series and parallel capacitor configurations, along with a comparison of its applicability to charge a supercapacitor. Reprinted with permission from ref. [122] Copyright © 2016, Elsevier Ltd. (d) Multi-phase rotation type TENG capable of producing a direct current output, showing schematic of the (i) device, (ii) the connection of the electrodes to obtain phase shift, and, the corresponding (iii) voltage and (iv) current outputs at different number of phases. Reprinted with permission from ref. [123]. Copyright © 2018, Royal Society of Chemistry.

578 The desirable properties of TENGs such as flexibility, stretchability, light weight, are extremely useful for
 579 their applicability for different purposes, as discussed in section 2. However, successful integration of
 580 TENGs into practical applications require them to be incorporated with different components of electronic

systems, such as energy storage and management, in a compact and compatible manner [1]. A number of TENG architectures have been presented in the literature with the objective of integrating energy harvesting and storage units into the same module, as well as to combine different energy harvesting methods, to maximise the space consumption and provide multiple functionality [4,124–128].

As an example, a shape adaptive self-charging power package suitable for wearable electronic applications was reported by Guo et al. [124], by integrating a flexible and stretchable TENG and a supercapacitor (Fig. 12a). Silicone rubber was used as the triboelectric material for the TENG, which was used to cover a silver nanowire-based electrode. Triboelectric charging occurred between the skin of the wearer and the silicone layer. The supercapacitor was fabricated on by depositing graphite on a gold coated paper substrate, and the stretchable properties were introduced to the structure using Kirigami patterns. The TENG was able to generate around 4 mW/m^2 power density, at an operating frequency of 1.5 Hz, and the specific capacitance of the supercapacitor was 12 F/g at a scan rate of 10 mV/s. The hybrid energy harvesting and storage unit produced a charging current to of 1.6 μA . A wearable solar cell – TENG hybrid design was reported by Wen et al., to simultaneously harvest and store energy from mechanical movement and light energy (Fig. 12b) [126]. The energy harvester consisted of a dye-sensitized solar cell, a fibre shaped TENG device and a supercapacitor. Considering a single pair of fibre-based devices, the solar cell component of this hybrid device was capable of producing $J_{sc}=1.92 \text{ mA/cm}^2$ $V_{oc}=0.74 \text{ V}$, fill factor of 0.64, and overall power conversion efficiency of 5.64%. The TENG unit was capable of producing a current output of 910 nA, and the supercapacitor showed a specific capacitance of 1.9 mW/cm. These elements were combined in to fabrics and demonstrated to power LEDs, digital watches and sensors.

5 Summary and Outlook

TENGs have emerged as one of the leading candidates for mechanical energy harvesting, in the last few years. These devices depend on the triboelectric effect coupled with electrostatic induction resulting from the relative movement of such charged layers, to convert movement into electricity. Four basic working modes have been identified for TENGs, and a large number of different architectures have been presented in the literature. The applicability of TENGs has been extensively demonstrated with various prototypes, as energy harvesters to power LEDs, smart watches, LCD screens, low power sensors, as well as self-powered active sensors to detect pressure, force, movement and physiological parameters. This technology is shown to contain advantages such as high output power, high efficiency, compatibility with low frequency ambient movements, low cost, light weight, flexibility and stretchability among many others.

The power generation of the TENG depends on the triboelectric effect and electrostatic induction. Triboelectric charging occurs between two surfaces when they are contacted, and, believed to be due to the transfer of electrons, ions or mass transfer between them. Explanation of the working principles of TENGs due to electrostatic induction has been based on two main approaches, the parallel plate capacitor based model, and the DDEF model. Among these models, the capacitor model provides a simple approach to estimate of the output trends of TENGs. The DDEF model provides a detailed understanding of the working principles of TENGs, along with a relatively accurate approximation of the output trends of practical devices.

A number of parameters can affect the output trends of a TENG, which can affect its triboelectric charge density as well as the output induction. These parameters have been categorized into device parameters, motion parameters and environmental parameters, and, the optimisation strategies for each of these

Figure 12: Some example for integrated TENG designs. (a) Shape adaptive self-charging power package, fabricated using (i) TENG and (ii) supercapacitor, resulting in a stretchable and flexible integrated power unit. Reprinted with permission from ref. [124] Copyright © 2016, American Chemical Society. (b) Fibre shaped hybrid energy harvester, capable of harvesting solar energy, mechanical energy and energy storage. The components include (i) dye sensitized solar cell, (ii) supercapacitor, and, (iii) TENG constructed at the interface of the solar cell and the supercapacitor. Reprinted with permission from ref. [126].

categories have been discussed in this review. The power management and storage strategies were also discussed briefly in this review. Furthermore, the optimisation tools which can be used to enhance the output power extraction such as the TENG power transfer theory and TENG impedance plots were explained. The importance of the effective integration of TENGs into low power electronic applications was discussed, along with several examples from literature.

Despite its impressive and rapid progress within the last few years, a number of challenges still need to be addressed to enable the maximum potential of this technology, and some of these challenges can be listed as follows.

The current, charge and power outputs of TENGs are in forms of positive and negative pulses, corresponding to the contact-separation or sliding motion inputs. This sporadic and discontinuous nature of their power generation makes it difficult to be used in directly powering many of the electronic devices which require a direct current output to operate. Addressing this discontinuity remains a key challenge in constructing practical TENG devices. Current approaches in this regard include the combination of energy storage and output modulation circuits with TENG energy harvesters, however, these circuit elements might consume significant amounts of energy in comparison to the energy scavenged. Moreover, many of the circuit elements are rigid and relatively high weight in comparison to TENGs, therefore, they may disturb the functionality of the energy harvesters specially when flexibility, stretchability and wearability is necessary. Energy storage methods compatible with such applications need to be further developed to address this issue. More recently, the construction of near direct current output TENGs was demonstrated for a rotary type sliding mode TENG, which provides a novel approach to solve this issue, however, these primary solutions need to be further developed and expanded to other working modes.

TENGs are inherently high impedance devices due to their structure, and many of their applications, which include output loads or energy storage units, contain relatively low load resistance values. The impedance mismatch between the TENG and the output load causes an issue in extracting the power, where the majority of power dissipated without being used. Several strategies have been presented to address this problem through structural optimisation, however, further studies are necessary to provide inventive solutions.

The outputs of a TENG consist of low currents and high voltages, and, in order to modify these outputs for practical applications, the voltage needs to be decreased and the current increased. Different electrical transformation methods have been demonstrated to overcome this issue, however, the circuit elements used can consume significant portions of energy. Novel approaches are necessary to overcome this issue, probably using passive circuit elements, and with high efficiency.

The understanding of the working principles needs to be further improved for TENGs. Despite significant research, the exact mechanism and details of triboelectric charging remains to be uncovered, which needs to be further investigated. Moreover, approaches similar to the DDEF model, which is capable of fully explaining the working principles are estimating output trends with relatively higher accuracy, need to be further expanded to represent real life TENG architectures. Some of the simulation results related to material parameters, such as the independent effect of triboelectric charge density, dielectric constant has to be investigated experimentally. Developing experimental strategies for this purpose is difficult, since many material properties are highly inter-related, and changing a single parameter would cause change in many other subsequent properties.

The robustness and durability of TENG architectures need to be improved for some device designs. TENGs are constantly subject to abrasion, pressure and mechanical deformation, which can cause wear and defects on their structure. While some of the TENG designs have been demonstrated to operate for a large number of working cycles, the durability of many of these devices need to be improved. One possible way of doing this is through novel material and structural developments, which can help boost the output performance as well as the robustness.

Environmental parameters such as humidity, temperature and atmospheric pressure cause significant variations in the triboelectric charge density and TENG output behaviour. TENGs need to be designed to withstand these conditions, and, maintain substantial and consistent power generation and sensing

capabilities. For example, wearable TENGs will be subjected to sweat and other body fluids, which can significantly reduce its output performance. TENGs deployed in extreme environments might be subjected to high temperatures and pressure scenarios, which again could reduce their output generation capabilities. These issues may be overcome through design and fabrication of protective layers, material selection and encapsulation.

Developing more efficient, application compatible material and device architectures is essential. This will ensure highly efficient energy harvesting and self-powered sensing architectures with high output generation. Moreover, attention needs to be extended towards the integration of TENGs at the system level, by combining energy harvesting, power conditioning, energy storage and transducers etc. Integrating these different functionalities as well as hybridising various energy harvesting methods can be a useful strategy in advancing TENG energy harvesting field.

Due to the effort of the researchers around the world, TENGs have undoubtedly become one of the most promising energy technologies to power the next generation of electronic devices. With the issues listed above resolved through innovative solutions, this technology is likely to expand and progress becoming a major component in our day to day lives, in near future.

Acknowledgements:

R.D.I.G.D. acknowledges the support for the ORS and URS studentships from the University of Surrey and Advanced Technology Institute. The authors acknowledge the support from the EPSRC for the research funding for this work.

Author Contributions:

R.D.I.G.D. designed the concept and framework of the paper, organised the figures and wrote the manuscript. S.R.P.S. supervised the project. All authors revised, commented and constructed the final manuscript.

Conflict of Interest:

The authors declare no conflict of interest.

Keywords:

Triboelectric nanogenerators, Energy Harvesting, Flexible Electronics, Device optimization.

References:

- [1] Z.L. Wang, Triboelectric nanogenerators as new energy technology and self-powered sensors - Principles, problems and perspectives, *Faraday Discuss.* 176 (2015) 447–458. doi:10.1039/c4fd00159a.
- [2] G.-Z. Yang, J. Bellingham, P.E. Dupont, P. Fischer, L. Floridi, R. Full, N. Jacobstein, V. Kumar, M. McNutt, R. Merrifield, B.J. Nelson, B. Scassellati, M. Taddeo, R. Taylor, M. Veloso, Z.L. Wang, R. Wood, The grand challenges of *Science Robotics*, *Sci. Robot.* 3 (2018) eaar7650. doi:10.1126/scirobotics.aar7650.
- [3] K.-E. Byun, M.-H. Lee, Y. Cho, S.-G. Nam, H.-J. Shin, S. Park, Potential role of motion for enhancing maximum output energy of triboelectric nanogenerator, *APL Mater.* 5 (2017) 074107.

710 doi:10.1063/1.4979955.

711 [4] J.-H. Lee, J. Kim, T.Y. Kim, M.S. Al Hossain, S.-W. Kim, J.H. Kim, All-in-one energy harvesting and
712 storage devices, *J. Mater. Chem. A* 4 (2016) 7983–7999. doi:10.1039/C6TA01229A.

713 [5] K. Dervojeda, D. Verzijl, E. Rouwmaat, Clean Technologies, Energy Harvesting - European
714 Commission Business Innovation Observatory Contract No 190/PP/ENT/CIP/12/C/N03C01, 2014.
715 [http://ec.europa.eu/enterprise/policies/innovation/policy/business-innovation-](http://ec.europa.eu/enterprise/policies/innovation/policy/business-innovation-observatory/files/case-studies/32-clt-energy-harvesting.pdf)
716 [observatory/files/case-studies/32-clt-energy-harvesting.pdf](http://ec.europa.eu/enterprise/policies/innovation/policy/business-innovation-observatory/files/case-studies/32-clt-energy-harvesting.pdf).

717 [6] F.R. Fan, W. Tang, Z.L. Wang, Flexible Nanogenerators for Energy Harvesting and Self-Powered
718 Electronics, *Adv. Mater.* 28 (2016) 4283–4305. doi:10.1002/adma.201504299.

719 [7] F. Invernizzi, S. Dulio, M. Patrini, G. Guizzetti, P. Mustarelli, Energy harvesting from human
720 motion: materials and techniques, *Chem. Soc. Rev.* 45 (2016) 5455–5473.
721 doi:10.1039/C5CS00812C.

722 [8] L. Lin, Micro Energy Harvesting & Storage, *lab.* (2011) 459–468.

723 [9] R. Riemer, A. Shapiro, Biomechanical energy harvesting from human motion: theory, state of the
724 art, design guidelines, and future directions, *J. Neuroeng. Rehabil.* 8 (2011) 22. doi:10.1186/1743-
725 0003-8-22.

726 [10] Z.L. Wang, T. Jiang, L. Xu, Toward the blue energy dream by triboelectric nanogenerator
727 networks, *Nano Energy* 39 (2017) 9–23.

728 [11] Global Wind Energy Council, Global Wind Report, 2011. [http://gwec.net/wp-](http://gwec.net/wp-content/uploads/2012/06/Annual_report_2011_lowres.pdf)
729 [content/uploads/2012/06/Annual_report_2011_lowres.pdf](http://gwec.net/wp-content/uploads/2012/06/Annual_report_2011_lowres.pdf) (accessed July 12, 2018).

730 [12] Y. Suzuki, D. Miki, M. Edamoto, M. Honzumi, A MEMS electret generator with electrostatic
731 levitation for vibration-driven energy-harvesting applications, *J. Micromechanics*
732 *Microengineering* 20 (2010) 104002. doi:10.1088/0960-1317/20/10/104002.

733 [13] Z.L. Wang, Triboelectric Nanogenerators as New Energy Technology for Self-Powered Systems
734 and as Active Mechanical and Chemical Sensors, *ACS Nano* 7 (2013) 9533–9557.
735 doi:10.1021/nn404614z.

736 [14] Z.L. Wang, On Maxwell’s displacement current for energy and sensors: the origin of
737 nanogenerators, *Mater. Today* 20 (2017) 74–82. doi:10.1016/j.mattod.2016.12.001.

738 [15] A. Khan, M. Ali Abbasi, M. Hussain, Z. Hussain Ibupoto, J. Wissting, O. Nur, M. Willander,
739 Piezoelectric nanogenerator based on zinc oxide nanorods grown on textile cotton fabric, *Appl.*
740 *Phys. Lett.* 101 (2012) 193506. doi:10.1063/1.4766921.

741 [16] F.R. Fan, Z.Q. Tian, Z. Lin Wang, Flexible triboelectric generator, *Nano Energy* 1 (2012) 328–334.
742 doi:10.1016/j.nanoen.2012.01.004.

743 [17] J. Chen, Z.L. Wang, Reviving Vibration Energy Harvesting and Self-Powered Sensing by a
744 Triboelectric Nanogenerator, *Joule* 1 (2017) 480–521. doi:10.1016/J.JOULE.2017.09.004.

745 [18] Z.L. Wang, J. Chen, L. Lin, Progress in triboelectric nanogenerators as a new energy technology
746 and self-powered sensors, *Energy Environ. Sci.* 8 (2015) 2250–2282. doi:10.1039/C5EE01532D.

747 [19] R.D.I.G. Dharmasena, K.D.G.I. Jayawardena, C.A. Mills, J.H.B. Deane, J.V. Anguita, R.A. Dorey,

748 S.R.P. Silva, Triboelectric nanogenerators: providing a fundamental framework, *Energy Environ.*
749 *Sci.* 10 (2017) 1801–1811. doi:10.1039/C7EE01139C.

750 [20] R.D.I.G. Dharmasena, K.D.G.I. Jayawardena, C.A. Mills, R.A. Dorey, S.R.P. Silva, A unified
751 theoretical model for Triboelectric Nanogenerators, *Nano Energy*. 48 (2018) 391–400.
752 doi:10.1016/j.nanoen.2018.03.073.

753 [21] R.D.I.G. Dharmasena, J.H.B. Deane, S.R.P. Silva, Nature of Power Generation and Output
754 Optimization Criteria for Triboelectric Nanogenerators, *Adv. Energy Mater.* (2018) 1802190.
755 doi:10.1002/aenm.201802190.

756 [22] J.H.B. Deane, R.D.I.G. Dharmasena, G. Gentile, Power computation for the triboelectric
757 nanogenerator, *Nano Energy*. 54 (2018) 39–49.
758 <https://www.sciencedirect.com/science/article/pii/S2211285518307080> (accessed October 18,
759 2018).

760 [23] S. Niu, Z.L. Wang, Theoretical systems of triboelectric nanogenerators, *Nano Energy*. 14 (2015)
761 161–192. doi:10.1016/j.nanoen.2014.11.034.

762 [24] S. Niu, S. Wang, L. Lin, Y. Liu, Y.S. Zhou, Y. Hu, Z.L. Wang, Theoretical study of contact-mode
763 triboelectric nanogenerators as an effective power source, *Energy Environ. Sci.* 6 (2013) 3576–
764 3583. doi:10.1039/c3ee42571a.

765 [25] Y. Wang, Y. Yang, Z.L. Wang, Triboelectric nanogenerators as flexible power sources, *Npj Flex.*
766 *Electron.* 1 (2017) 10. doi:10.1038/s41528-017-0007-8.

767 [26] G. Zhu, C. Pan, W. Guo, C.-Y. Chen, Y. Zhou, R. Yu, Z.L. Wang, Triboelectric-Generator-Driven
768 Pulse Electrodeposition for Micropatterning, *Nano Lett.* 12 (2012) 4960–4965.
769 doi:10.1021/nl302560k.

770 [27] S. Wang, L. Lin, Z.L. Wang, Nanoscale Triboelectric-Effect-Enabled Energy Conversion for
771 Sustainably Powering Portable Electronics, *Nano Lett.* 12 (2012) 6339–6346.
772 doi:10.1021/nl303573d.

773 [28] Y. Zi, S. Niu, J. Wang, Z. Wen, W. Tang, Z.L. Wang, Standards and figure-of-merits for quantifying
774 the performance of triboelectric nanogenerators, *Nat. Commun.* 6 (2015) 8376.
775 doi:10.1038/ncomms9376.

776 [29] S. Wang, L. Lin, Y. Xie, Q. Jing, S. Niu, Z.L. Wang, Sliding-Triboelectric Nanogenerators Based on In-
777 Plane Charge-Separation Mechanism, *Nano Lett.* 13 (2013) 2226–2233. doi:10.1021/nl400738p.

778 [30] G. Zhu, J. Chen, Y. Liu, P. Bai, Y.S. Zhou, Q. Jing, C. Pan, Z.L. Wang, Linear-Grating Triboelectric
779 Generator Based on Sliding Electrification, *Nano Lett.* 13 (2013) 2282–2289.
780 doi:10.1021/nl4008985.

781 [31] Q. Jing, G. Zhu, P. Bai, Y. Xie, J. Chen, R.P.S. Han, Z.L. Wang, Case-Encapsulated Triboelectric
782 Nanogenerator for Harvesting Energy from Reciprocating Sliding Motion, *ACS Nano*. 8 (2014)
783 3836–3842. doi:10.1021/nn500694y.

784 [32] L. Lin, S. Wang, Y. Xie, Q. Jing, S. Niu, Y. Hu, Z.L. Wang, Segmentally Structured Disk Triboelectric
785 Nanogenerator for Harvesting Rotational Mechanical Energy, *Nano Lett.* 13 (2013) 2916–2923.
786 doi:10.1021/nl4013002.

- 787 [33] S. Niu, Y. Liu, S. Wang, L. Lin, Y.S. Zhou, Y. Hu, Z.L. Wang, Theory of Sliding-Mode Triboelectric
788 Nanogenerators, *Adv. Mater.* 25 (2013) 6184–6193. doi:10.1002/adma.201302808.
- 789 [34] S. Niu, S. Wang, Y. Liu, Y.S. Zhou, L. Lin, Y. Hu, K.C. Pradel, Z.L. Wang, A theoretical study of
790 grating structured triboelectric nanogenerators, *Energy Environ. Sci.* 7 (2014) 2339.
791 doi:10.1039/c4ee00498a.
- 792 [35] Y. Yang, Y.S. Zhou, H. Zhang, Y. Liu, S. Lee, Z.L. Wang, A Single-Electrode Based Triboelectric
793 Nanogenerator as Self-Powered Tracking System, *Adv. Mater.* 25 (2013) 6594–6601.
794 doi:10.1002/adma.201302453.
- 795 [36] Y. Yang, H. Zhang, J. Chen, Q. Jing, Y.S. Zhou, X. Wen, Z.L. Wang, Single-Electrode-Based Sliding
796 Triboelectric Nanogenerator for Self-Powered Displacement Vector Sensor System, *ACS Nano.* 7
797 (2013) 7342–7351. doi:10.1021/nn403021m.
- 798 [37] S. Niu, Y. Liu, S. Wang, L. Lin, Y.S. Zhou, Y. Hu, Z.L. Wang, Theoretical Investigation and Structural
799 Optimization of Single-Electrode Triboelectric Nanogenerators, *Adv. Funct. Mater.* 24 (2014)
800 3332–3340. doi:10.1002/adfm.201303799.
- 801 [38] S. Wang, Y. Xie, S. Niu, L. Lin, Z.L. Wang, Freestanding Triboelectric-Layer-Based Nanogenerators
802 for Harvesting Energy from a Moving Object or Human Motion in Contact and Non-contact
803 Modes, *Adv. Mater.* 26 (2014) 2818–2824. doi:10.1002/adma.201305303.
- 804 [39] G. Zhu, Y.S. Zhou, P. Bai, X.S. Meng, Q. Jing, J. Chen, Z.L. Wang, A Shape-Adaptive Thin-Film-Based
805 Approach for 50% High-Efficiency Energy Generation Through Micro-Grating Sliding
806 Electrification, *Adv. Mater.* 26 (2014) 3788–3796. doi:10.1002/adma.201400021.
- 807 [40] B. Chen, Y. Yang, Z.L. Wang, Scavenging Wind Energy by Triboelectric Nanogenerators, *Adv.*
808 *Energy Mater.* 8 (2018) 1702649. doi:10.1002/aenm.201702649.
- 809 [41] Y. Yang, G. Zhu, H. Zhang, J. Chen, X. Zhong, Z.-H. Lin, Y. Su, P. Bai, X. Wen, Z.L. Wang,
810 Triboelectric Nanogenerator for Harvesting Wind Energy and as Self-Powered Wind Vector
811 Sensor System, *ACS Nano.* 7 (2013) 9461–9468. doi:10.1021/nn4043157.
- 812 [42] S. Wang, X. Wang, Z.L. Wang, Y. Yang, Efficient Scavenging of Solar and Wind Energies in a Smart
813 City, *ACS Nano.* 10 (2016) 5696–5700. doi:10.1021/acs.nano.6b02575.
- 814 [43] Z. Zhao, X. Pu, C. Du, L. Li, C. Jiang, W. Hu, Z.L. Wang, Freestanding Flag-Type Triboelectric
815 Nanogenerator for Harvesting High-Altitude Wind Energy from Arbitrary Directions, *ACS Nano.* 10
816 (2016) 1780–1787. doi:10.1021/acs.nano.5b07157.
- 817 [44] J. Chen, G. Zhu, W. Yang, Q. Jing, P. Bai, Y. Yang, T.-C. Hou, Z.L. Wang, Harmonic-Resonator-Based
818 Triboelectric Nanogenerator as a Sustainable Power Source and a Self-Powered Active Vibration
819 Sensor, *Adv. Mater.* 25 (2013) 6094–6099. doi:10.1002/adma.201302397.
- 820 [45] G. Zhu, Z.-H. Lin, Q. Jing, P. Bai, C. Pan, Y. Yang, Y. Zhou, Z.L. Wang, Toward Large-Scale Energy
821 Harvesting by a Nanoparticle-Enhanced Triboelectric Nanogenerator, *Nano Lett.* 13 (2013) 847–
822 853. doi:10.1021/nl4001053.
- 823 [46] J. Zhong, Q. Zhong, F. Fan, Y. Zhang, S. Wang, B. Hu, Z.L. Wang, J. Zhou, Finger typing driven
824 triboelectric nanogenerator and its use for instantaneously lighting up LEDs, *Nano Energy.* 2
825 (2013) 491–497. doi:10.1016/j.nanoen.2012.11.015.

- 826 [47] J. Yang, J. Chen, Y. Yang, H. Zhang, W. Yang, P. Bai, Y. Su, Z.L. Wang, Broadband Vibrational
827 Energy Harvesting Based on a Triboelectric Nanogenerator, *Adv. Energy Mater.* 4 (2014)
828 1301322. doi:10.1002/aenm.201301322.
- 829 [48] J. Yang, J. Chen, Y. Liu, W. Yang, Y. Su, Z.L. Wang, Triboelectrification-Based Organic Film
830 Nanogenerator for Acoustic Energy Harvesting and Self-Powered Active Acoustic Sensing, *ACS*
831 *Nano.* 8 (2014) 2649–2657. doi:10.1021/nn4063616.
- 832 [49] X. Fan, J. Chen, J. Yang, P. Bai, Z. Li, Z.L. Wang, Ultrathin, Rollable, Paper-Based Triboelectric
833 Nanogenerator for Acoustic Energy Harvesting and Self-Powered Sound Recording, *ACS Nano.* 9
834 (2015) 4236–4243. doi:10.1021/acsnano.5b00618.
- 835 [50] Z.-H. Lin, G. Zhu, Y.S. Zhou, Y. Yang, P. Bai, J. Chen, Z.L. Wang, A Self-Powered Triboelectric
836 Nanosensor for Mercury Ion Detection, *Angew. Chemie Int. Ed.* 52 (2013) 5065–5069.
837 doi:10.1002/anie.201300437.
- 838 [51] X. Wen, W. Yang, Q. Jing, Z.L. Wang, Harvesting Broadband Kinetic Impact Energy from
839 Mechanical Triggering/Vibration and Water Waves, *ACS Nano.* 8 (2014) 7405–7412.
840 doi:10.1021/nn502618f.
- 841 [52] K.N. Kim, J. Chun, J.W. Kim, K.Y. Lee, J.-U. Park, S.-W. Kim, Z.L. Wang, J.M. Baik, Highly Stretchable
842 2D Fabrics for Wearable Triboelectric Nanogenerator under Harsh Environments, *ACS Nano.* 9
843 (2015) 6394–6400. doi:10.1021/acsnano.5b02010.
- 844 [53] M. Zhu, Y. Huang, W.S. Ng, J. Liu, Z. Wang, Z. Wang, H. Hu, C. Zhi, 3D spacer fabric based
845 multifunctional triboelectric nanogenerator with great feasibility for mechanized large-scale
846 production, *Nano Energy.* 27 (2016) 439–446. doi:10.1016/j.nanoen.2016.07.016.
- 847 [54] L. Liu, J. Pan, P. Chen, J. Zhang, X. Yu, X. Ding, B. Wang, X. Sun, H. Peng, A triboelectric textile
848 templated by a three-dimensionally penetrated fabric, *J. Mater. Chem. A.* 4 (2016) 6077–6083.
849 doi:10.1039/C6TA01166G.
- 850 [55] L. Zhang, Y. Yu, G.P. Eyer, G. Suo, L.A. Kozik, M. Fairbanks, X. Wang, T.L. Andrew, All-Textile
851 Triboelectric Generator Compatible with Traditional Textile Process, *Adv. Mater. Technol.* 1
852 (2016) 1600147. doi:10.1002/admt.201600147.
- 853 [56] J. Zhong, Y. Zhang, Q. Zhong, Q. Hu, B. Hu, Z.L. Wang, J. Zhou, Fiber-Based Generator for
854 Wearable Electronics and Mobile Medication, *ACS Nano.* 8 (2014) 6273–6280.
855 doi:10.1021/nn501732z.
- 856 [57] X. Pu, L. Li, H. Song, C. Du, Z. Zhao, C. Jiang, G. Cao, W. Hu, Z.L. Wang, A Self-Charging Power Unit
857 by Integration of a Textile Triboelectric Nanogenerator and a Flexible Lithium-Ion Battery for
858 Wearable Electronics, *Adv. Mater.* 27 (2015) 2472–2478. doi:10.1002/adma.201500311.
- 859 [58] S. Wang, L. Lin, Z.L. Wang, Triboelectric nanogenerators as self-powered active sensors, *Nano*
860 *Energy.* 11 (2015) 436–462. doi:10.1016/j.nanoen.2014.10.034.
- 861 [59] H. Zhang, Y. Yang, Y. Su, J. Chen, C. Hu, Z. Wu, Y. Liu, C. Ping Wong, Y. Bando, Z.L. Wang,
862 Triboelectric nanogenerator as self-powered active sensors for detecting liquid/gaseous
863 water/ethanol, *Nano Energy.* 2 (2013) 693–701. doi:10.1016/J.NANOEN.2013.08.004.
- 864 [60] G. Zhu, W.Q. Yang, T. Zhang, Q. Jing, J. Chen, Y.S. Zhou, P. Bai, Z.L. Wang, Self-Powered,
865 Ultrasensitive, Flexible Tactile Sensors Based on Contact Electrification, *Nano Lett.* 14 (2014)

866 3208–3213. doi:10.1021/nl5005652.

867 [61] F.-R. Fan, L. Lin, G. Zhu, W. Wu, R. Zhang, Z.L. Wang, Transparent Triboelectric Nanogenerators
868 and Self-Powered Pressure Sensors Based on Micropatterned Plastic Films, *Nano Lett.* 12 (2012)
869 3109–3114. doi:10.1021/nl300988z.

870 [62] S. Wang, S. Niu, J. Yang, L. Lin, Z.L. Wang, Quantitative Measurements of Vibration Amplitude
871 Using a Contact-Mode Freestanding Triboelectric Nanogenerator, *ACS Nano*. 8 (2014) 12004–
872 12013. doi:10.1021/nn5054365.

873 [63] P. Bai, G. Zhu, Q. Jing, J. Yang, J. Chen, Y. Su, J. Ma, G. Zhang, Z.L. Wang, Membrane-Based Self-
874 Powered Triboelectric Sensors for Pressure Change Detection and Its Uses in Security
875 Surveillance and Healthcare Monitoring, *Adv. Funct. Mater.* 24 (2014) 5807–5813.
876 doi:10.1002/adfm.201401267.

877 [64] Z.-H. Lin, G. Cheng, Y. Yang, Y.S. Zhou, S. Lee, Z.L. Wang, Triboelectric Nanogenerator as an Active
878 UV Photodetector, *Adv. Funct. Mater.* 24 (2014) 2810–2816. doi:10.1002/adfm.201302838.

879 [65] G.R. Freeman, N.H. March, Triboelectricity and some associated phenomena, *Mater. Sci. Technol.*
880 15 (1999) 1454–1458. doi:10.1179/026708399101505464.

881 [66] H.T. Baytekin, A.Z. Patashinski, M. Branicki, B. Baytekin, S. Soh, B.A. Grzybowski, The mosaic of
882 surface charge in contact electrification., *Science*. (2011) 1201512. doi:10.1126/science.1201512.

883 [67] F. Galembeck, T.A.L. Burgo, L.B.S. Balestrin, R.F. Gouveia, C.A. Silva, A. Galembeck, Friction,
884 tribochemistry and triboelectricity: recent progress and perspectives, *RSC Adv.* 4 (2014) 64280–
885 64298. doi:10.1039/C4RA09604E.

886 [68] L.S. McCarty, G.M. Whitesides, Electrostatic Charging Due to Separation of Ions at Interfaces:
887 Contact Electrification of Ionic Electrets, *Angew. Chemie Int. Ed.* 47 (2008) 2188–2207.
888 doi:10.1002/anie.200701812.

889 [69] A.D. Moore, *Electrostatics: Exploring, Controlling, and Using Static Electricity: Including the Dirod*
890 *Manual, Electrostatic Applications*, 1997.

891 [70] H. Zou, Y. Zhang, L. Guo, P. Wang, X. He, G. Dai, H. Zheng, C. Chen, A.C. Wang, C. Xu, Z.L. Wang,
892 Quantifying the triboelectric series, *Nat. Commun.* 10 (2019) 1427. doi:10.1038/s41467-019-
893 09461-x.

894 [71] A.F. Diaz, R.M. Felix-Navarro, A semi-quantitative tribo-electric series for polymeric materials: the
895 influence of chemical structure and properties, *J. Electrostat.* 62 (2004) 277–290.
896 doi:10.1016/j.elstat.2004.05.005.

897 [72] J. Lowell, A.C. Rose-Innes, Contact electrification, *Adv. Phys.* 29 (1980) 947–1023.
898 doi:10.1080/00018738000101466.

899 [73] B.A. Grzybowski, M. Fialkowski, J.A. Wiles, Kinetics of Contact Electrification between Metals and
900 Polymers, *J. Phys. Chem. B*. 109 (2005) 20511–20515. doi:10.1021/jp053532g.

901 [74] A.F. Diaz, J. Guay, Contact charging of organic materials: Ion vs. electron transfer, *IBM J. Res. Dev.*
902 37 (1993) 249–260. doi:10.1147/rd.372.0249.

903 [75] A.F. Diaz, D. Fenzel-Alexander, An ion transfer model for contact charging, *Langmuir*. 9 (1993)
904 1009–1015.

- 905 [76] W.R. Salaneck, A. Paton, D.T. Clark, Double mass transfer during polymer-polymer contacts, *J.*
906 *Appl. Phys.* 47 (1976) 144. doi:10.1063/1.322306.
- 907 [77] C. Xu, Y. Zi, A.C. Wang, H. Zou, Y. Dai, X. He, P. Wang, Y.-C. Wang, P. Feng, D. Li, Z.L. Wang, On the
908 Electron-Transfer Mechanism in the Contact-Electrification Effect, *Adv. Mater.* 30 (2018)
909 1706790. doi:10.1002/adma.201706790.
- 910 [78] J.A. Wiles, B.A. Grzybowski, A. Winkleman, G.M. Whitesides, A Tool for Studying Contact
911 Electrification in Systems Comprising Metals and Insulating Polymers, *Anal. Chem.* 75 (2003)
912 4859–4867. doi:10.1021/ac034275j.
- 913 [79] C. Liu, A.J. Bard, Electrostatic electrochemistry at insulators, *Nat. Mater.* 7 (2008) 505–509.
914 doi:10.1038/nmat2160.
- 915 [80] C. Liu, A.J. Bard, Electrons on dielectrics and contact electrification, *Chem. Phys. Lett.* 480 (2009)
916 145–156. doi:10.1016/j.cplett.2009.08.045.
- 917 [81] S. Niu, Y. Liu, X. Chen, S. Wang, Y.S. Zhou, L. Lin, Y. Xie, Z.L. Wang, Theory of freestanding
918 triboelectric-layer-based nanogenerators, *Nano Energy.* 12 (2015) 760–774.
919 doi:10.1016/j.nanoen.2015.01.013.
- 920 [82] S.-H. Shin, Y.H. Kwon, Y.-H. Kim, J.-Y. Jung, M.H. Lee, J. Nah, Triboelectric Charging Sequence
921 Induced by Surface Functionalization as a Method To Fabricate High Performance Triboelectric
922 Generators, *ACS Nano.* 9 (2015) 4621–4627. doi:10.1021/acs.nano.5b01340.
- 923 [83] H.Y. Li, L. Su, S.Y. Kuang, C.F. Pan, G. Zhu, Z.L. Wang, Significant Enhancement of Triboelectric
924 Charge Density by Fluorinated Surface Modification in Nanoscale for Converting Mechanical
925 Energy, *Adv. Funct. Mater.* 25 (2015) 5691–5697. doi:10.1002/adfm.201502318.
- 926 [84] C.K. Jeong, K.M. Baek, S. Niu, T.W. Nam, Y.H. Hur, D.Y. Park, G.-T. Hwang, M. Byun, Z.L. Wang, Y.S.
927 Jung, K.J. Lee, Topographically-Designed Triboelectric Nanogenerator via Block Copolymer Self-
928 Assembly, *Nano Lett.* 14 (2014) 7031–7038. doi:10.1021/nl503402c.
- 929 [85] M.M. Apodaca, P.J. Wesson, K.J.M. Bishop, M.A. Ratner, B.A. Grzybowski, Contact Electrification
930 between Identical Materials, *Angew. Chemie.* 122 (2010) 958–961. doi:10.1002/ange.200905281.
- 931 [86] H.T. Baytekin, B. Baytekin, S. Soh, B.A. Grzybowski, Is Water Necessary for Contact
932 Electrification?, *Angew. Chemie Int. Ed.* 50 (2011) 6766–6770. doi:10.1002/anie.201008051.
- 933 [87] C. Jin, D.S. Kia, M. Jones, S. Towfighian, On the contact behavior of micro-/nano-structured
934 interface used in vertical-contact-mode triboelectric nanogenerators, *Nano Energy.* 27 (2016)
935 68–77. doi:10.1016/J.NANOEN.2016.06.049.
- 936 [88] M.-L. Seol, J.-W. Han, D.-I. Moon, M. Meyyappan, Hysteretic behavior of contact force response
937 in triboelectric nanogenerator, *Nano Energy.* 32 (2017) 408–413.
938 doi:10.1016/j.nanoen.2016.12.055.
- 939 [89] M.-L. Seol, S.-H. Lee, J.-W. Han, D. Kim, G.-H. Cho, Y.-K. Choi, Impact of contact pressure on
940 output voltage of triboelectric nanogenerator based on deformation of interfacial structures,
941 *Nano Energy.* 17 (2015) 63–71. doi:10.1016/J.NANOEN.2015.08.005.
- 942 [90] B. Meng, W. Tang, Z. Too, X. Zhang, M. Han, W. Liu, H. Zhang, A transparent single-friction-
943 surface triboelectric generator and self-powered touch sensor, *Energy Environ. Sci.* 6 (2013)

944 3235. doi:10.1039/c3ee42311e.

- 945 [91] P. Bai, G. Zhu, Z.-H. Lin, Q. Jing, J. Chen, G. Zhang, J. Ma, Z.L. Wang, Integrated Multilayered
946 Triboelectric Nanogenerator for Harvesting Biomechanical Energy from Human Motions, *ACS*
947 *Nano*. 7 (2013) 3713–3719. doi:10.1021/nn4007708.
- 948 [92] N. Cui, L. Gu, Y. Lei, J. Liu, Y. Qin, X. Ma, Y. Hao, Z.L. Wang, Dynamic Behavior of the Triboelectric
949 Charges and Structural Optimization of the Friction Layer for a Triboelectric Nanogenerator, *ACS*
950 *Nano*. 10 (2016) 6131–6138. doi:10.1021/acsnano.6b02076.
- 951 [93] S. Wang, Y. Zi, Y.S. Zhou, S. Li, F. Fan, L. Lin, Z.L. Wang, Molecular surface functionalization to
952 enhance the power output of triboelectric nanogenerators, *J. Mater. Chem. A*. 4 (2016) 3728–
953 3734. doi:10.1039/C5TA10239A.
- 954 [94] S. Wang, Y. Xie, S. Niu, L. Lin, C. Liu, Y.S. Zhou, Z.L. Wang, Maximum Surface Charge Density for
955 Triboelectric Nanogenerators Achieved by Ionized-Air Injection: Methodology and Theoretical
956 Understanding, *Adv. Mater.* 26 (2014) 6720–6728. doi:10.1002/adma.201402491.
- 957 [95] J. Wang, C. Wu, Y. Dai, Z. Zhao, A. Wang, T. Zhang, Z.L. Wang, Achieving ultrahigh triboelectric
958 charge density for efficient energy harvesting, *Nat. Commun.* 8 (2017) 88. doi:10.1038/s41467-
959 017-00131-4.
- 960 [96] P. Cheng, H. Guo, Z. Wen, C. Zhang, X. Yin, X. Li, D. Liu, W. Song, X. Sun, J. Wang, Z.L. Wang,
961 Largely enhanced triboelectric nanogenerator for efficient harvesting of water wave energy by
962 soft contacted structure, *Nano Energy*. 57 (2019) 432–439. doi:10.1016/J.NANOEN.2018.12.054.
- 963 [97] J. Wang, S. Li, F. Yi, Y. Zi, J. Lin, X. Wang, Y. Xu, Z.L. Wang, Sustainably powering wearable
964 electronics solely by biomechanical energy, *Nat. Commun.* 7 (2016) 12744.
965 doi:10.1038/ncomms12744.
- 966 [98] W. Tang, T. Jiang, F.R. Fan, A.F. Yu, C. Zhang, X. Cao, Z.L. Wang, Liquid-Metal Electrode for High-
967 Performance Triboelectric Nanogenerator at an Instantaneous Energy Conversion Efficiency of
968 70.6%, *Adv. Funct. Mater.* 25 (2015) 3718–3725. doi:10.1002/adfm.201501331.
- 969 [99] Y. Yang, N. Sun, Z. Wen, P. Cheng, H. Zheng, H. Shao, Y. Xia, C. Chen, H. Lan, X. Xie, C. Zhou, J.
970 Zhong, X. Sun, S.-T. Lee, Liquid-Metal-Based Super-Stretchable and Structure-Designable
971 Triboelectric Nanogenerator for Wearable Electronics, *ACS Nano*. 12 (2018) 2027–2034.
972 doi:10.1021/acsnano.8b00147.
- 973 [100] L. Xu, T.Z. Bu, X.D. Yang, C. Zhang, Z.L. Wang, Ultrahigh charge density realized by charge
974 pumping at ambient conditions for triboelectric nanogenerators, *Nano Energy*. 49 (2018) 625–
975 633. doi:10.1016/J.NANOEN.2018.05.011.
- 976 [101] J. Cheng, W. Ding, Y. Zi, Y. Lu, L. Ji, F. Liu, C. Wu, Z.L. Wang, Triboelectric microplasma powered by
977 mechanical stimuli, *Nat. Commun.* 9 (2018) 3733. doi:10.1038/s41467-018-06198-x.
- 978 [102] W. Liu, Z. Wang, G. Wang, G. Liu, J. Chen, X. Pu, Y. Xi, X. Wang, H. Guo, C. Hu, Z.L. Wang,
979 Integrated charge excitation triboelectric nanogenerator, *Nat. Commun.* 10 (2019) 1426.
980 doi:10.1038/s41467-019-09464-8.
- 981 [103] Q. Wang, M. Chen, W. Li, Z. Li, Y. Chen, Y. Zhai, Size effect on the output of a miniaturized
982 triboelectric nanogenerator based on superimposed electrode layers, *Nano Energy*. 41 (2017)
983 128–138. doi:10.1016/J.NANOEN.2017.09.030.

984 [104] Y.J. Kim, J. Lee, S. Park, C. Park, C. Park, H.-J. Choi, Effect of the relative permittivity of oxides on
985 the performance of triboelectric nanogenerators, *RSC Adv.* 7 (2017) 49368–49373.
986 doi:10.1039/C7RA07274K.

987 [105] J. Chen, H. Guo, X. He, G. Liu, Y. Xi, H. Shi, C. Hu, Enhancing Performance of Triboelectric
988 Nanogenerator by Filling High Dielectric Nanoparticles into Sponge PDMS Film, *ACS Appl. Mater.*
989 *Interfaces.* 8 (2016) 736–744. doi:10.1021/acsami.5b09907.

990 [106] Q. Shen, X. Xie, M. Peng, N. Sun, H. Shao, H. Zheng, Z. Wen, X. Sun, Self-Powered Vehicle
991 Emission Testing System Based on Coupling of Triboelectric and Chemoresistive Effects, *Adv.*
992 *Funct. Mater.* 28 (2018) 1703420. doi:10.1002/adfm.201703420.

993 [107] L. Han, M. Peng, Z. Wen, Y. Liu, Y. Zhang, Q. Zhu, H. Lei, S. Liu, L. Zheng, X. Sun, H. Li, Self-driven
994 photodetection based on impedance matching effect between a triboelectric nanogenerator and
995 a MoS₂ nanosheets photodetector, *Nano Energy.* 59 (2019) 492–499.
996 doi:10.1016/J.NANOEN.2019.02.072.

997 [108] X. Xie, Z. Wen, Q. Shen, C. Chen, M. Peng, Y. Yang, N. Sun, P. Cheng, H. Shao, Y. Zhang, Q. Zhu, X.
998 Chen, X. Sun, Impedance Matching Effect between a Triboelectric Nanogenerator and a
999 Piezoresistive Pressure Sensor Induced Self-Powered Weighing, *Adv. Mater. Technol.* 3 (2018)
1000 1800054. doi:10.1002/admt.201800054.

1001 [109] Z. Wen, J. Fu, L. Han, Y. Liu, M. Peng, L. Zheng, Y. Zhu, X. Sun, Y. Zi, Toward self-powered
1002 photodetection enabled by triboelectric nanogenerators, *J. Mater. Chem. C.* 6 (2018) 11893–
1003 11902. doi:10.1039/C8TC02964D.

1004 [110] Q. Tang, M.-H. Yeh, G. Liu, S. Li, J. Chen, Y. Bai, L. Feng, M. Lai, K.-C. Ho, H. Guo, C. Hu, Whirligig-
1005 inspired triboelectric nanogenerator with ultrahigh specific output as reliable portable instant
1006 power supply for personal health monitoring devices, *Nano Energy.* 47 (2018) 74–80.
1007 doi:10.1016/J.NANOEN.2018.02.039.

1008 [111] X. Yang, W.A. Daoud, Design parameters impact on output characteristics of flexible hybrid
1009 energy harvesting generator: Experimental and theoretical simulation based on a parallel hybrid
1010 model, *Nano Energy.* (2018). doi:10.1016/J.NANOEN.2018.05.073.

1011 [112] D. Bhatia, J. Lee, H.J. Hwang, J.M. Baik, S. Kim, D. Choi, Design of Mechanical Frequency Regulator
1012 for Predictable Uniform Power from Triboelectric Nanogenerators, *Adv. Energy Mater.* 8 (2018)
1013 1702667. doi:10.1002/aenm.201702667.

1014 [113] W. Kim, H.J. Hwang, D. Bhatia, Y. Lee, J.M. Baik, D. Choi, Kinematic design for high performance
1015 triboelectric nanogenerators with enhanced working frequency, *Nano Energy.* 21 (2016) 19–25.
1016 doi:10.1016/J.NANOEN.2015.12.017.

1017 [114] X. Wen, Y. Su, Y. Yang, H. Zhang, Z.L. Wang, Applicability of triboelectric generator over a wide
1018 range of temperature, *Nano Energy.* 4 (2014) 150–156. doi:10.1016/J.NANOEN.2014.01.001.

1019 [115] V. Nguyen, R. Zhu, R. Yang, Environmental effects on nanogenerators, *Nano Energy.* 14 (2015)
1020 49–61. doi:10.1016/J.NANOEN.2014.11.049.

1021 [116] C. Xu, A.C. Wang, H. Zou, B. Zhang, C. Zhang, Y. Zi, L. Pan, P. Wang, P. Feng, Z. Lin, Z.L. Wang,
1022 Raising the Working Temperature of a Triboelectric Nanogenerator by Quenching Down Electron
1023 Thermionic Emission in Contact-Electrification, *Adv. Mater.* 30 (2018) 1803968.
1024 doi:10.1002/adma.201803968.

- 1025 [117] C. Wu, A.C. Wang, W. Ding, H. Guo, Z.L. Wang, Triboelectric Nanogenerator: A Foundation of the
1026 Energy for the New Era, *Adv. Energy Mater.* 9 (2019) 1802906. doi:10.1002/aenm.201802906.
- 1027 [118] F. Xi, Y. Pang, W. Li, T. Jiang, L. Zhang, T. Guo, G. Liu, C. Zhang, Z.L. Wang, Universal power
1028 management strategy for triboelectric nanogenerator, *Nano Energy*. 37 (2017) 168–176.
1029 doi:10.1016/J.NANOEN.2017.05.027.
- 1030 [119] D. Bao, L. Luo, Z. Zhang, T. Ren, A power management circuit with 50% efficiency and large load
1031 capacity for triboelectric nanogenerator, *J. Semicond.* 38 (2017) 095001. doi:10.1088/1674-
1032 4926/38/9/095001.
- 1033 [120] H. Qin, G. Cheng, Y. Zi, G. Gu, B. Zhang, W. Shang, F. Yang, J. Yang, Z. Du, Z.L. Wang, High Energy
1034 Storage Efficiency Triboelectric Nanogenerators with Unidirectional Switches and Passive Power
1035 Management Circuits, *Adv. Funct. Mater.* 28 (2018) 1805216. doi:10.1002/adfm.201805216.
- 1036 [121] X. Liang, T. Jiang, G. Liu, T. Xiao, L. Xu, W. Li, F. Xi, C. Zhang, Z.L. Wang, Triboelectric
1037 Nanogenerator Networks Integrated with Power Management Module for Water Wave Energy
1038 Harvesting, *Adv. Funct. Mater.* (2019) 1807241. doi:10.1002/adfm.201807241.
- 1039 [122] Y. Zi, H. Guo, J. Wang, Z. Wen, S. Li, C. Hu, Z.L. Wang, An inductor-free auto-power-management
1040 design built-in triboelectric nanogenerators, *Nano Energy*. 31 (2017) 302–310.
1041 doi:10.1016/J.NANOEN.2016.11.025.
- 1042 [123] H. Ryu, J.H. Lee, U. Khan, S.S. Kwak, R. Hinchet, S.-W. Kim, Sustainable direct current powering a
1043 triboelectric nanogenerator *via* a novel asymmetrical design, *Energy Environ. Sci.* (2018).
1044 doi:10.1039/C8EE00188J.
- 1045 [124] H. Guo, M.-H. Yeh, Y.-C. Lai, Y. Zi, C. Wu, Z. Wen, C. Hu, Z.L. Wang, All-in-One Shape-Adaptive
1046 Self-Charging Power Package for Wearable Electronics, *ACS Nano*. 10 (2016) 10580–10588.
1047 doi:10.1021/acsnano.6b06621.
- 1048 [125] Y. Fang, J. Tong, Q. Zhong, Q. Chen, J. Zhou, Q. Luo, Y. Zhou, Z. Wang, B. Hu, Solution processed
1049 flexible hybrid cell for concurrently scavenging solar and mechanical energies, *Nano Energy*. 16
1050 (2015) 301–309. doi:10.1016/J.NANOEN.2015.06.029.
- 1051 [126] Z. Wen, M.-H. Yeh, H. Guo, J. Wang, Y. Zi, W. Xu, J. Deng, L. Zhu, X. Wang, C. Hu, L. Zhu, X. Sun,
1052 Z.L. Wang, Self-powered textile for wearable electronics by hybridizing fiber-shaped
1053 nanogenerators, solar cells, and supercapacitors, *Sci. Adv.* 2 (2016) e1600097.
1054 doi:10.1126/sciadv.1600097.
- 1055 [127] X.-S. Zhang, M. Han, B. Kim, J.-F. Bao, J. Brugger, H. Zhang, All-in-one self-powered flexible
1056 microsystems based on triboelectric nanogenerators, *Nano Energy*. 47 (2018) 410–426.
1057 doi:10.1016/J.NANOEN.2018.02.046.
- 1058 [128] C. Xu, C. Pan, Y. Liu, Z.L. Wang, Hybrid cells for simultaneously harvesting multi-type energies for
1059 self-powered micro/nanosystems, *Nano Energy*. 1 (2012) 259–272.
1060 doi:10.1016/j.nanoen.2012.01.002.

1061

1062

Dr R. D. I. G. Dharmasena is a Research Fellow at the Advanced Technology Institute (ATI), University of Surrey. He received his B.Sc. (Engineering) degree from the University of Moratuwa, Sri Lanka in 2014, where obtained the best academic performance and the best overall performance awards in his discipline. He completed the PhD degree at the ATI specializing in energy harvesting and wearable electronics in 2019. Ishara worked at Sri Lanka Institute of Nanotechnology (SLINTEC) as a research scientist prior to moving to Surrey, developing nanotechnology enhanced textiles. His research interests include mechanical energy harvesting, fundamentals of triboelectric nanogenerators, and wearable electronics.

Prof. S.R.P. Silva is the Director of the Advanced Technology Institute at University of Surrey. He is also the Director of the EPSRC sponsored Nano-Manufacturing Hub. He joined Surrey in 1995 after completing undergraduate and postgraduate degrees at Cambridge University. His research interests include nanoelectronics, large-area electronics and renewables, and resulted in over 600 presentations at conferences, and over 550 journal papers. He has over 18,000 citations to his output with an H-index of 68, and won research funding in excess of £30m. He is the inventor of 30 patents, including a key patent on low temperature growth of carbon nanotubes, and fabrication of large area nanotube-organic solar cells. He is a Fellow of the Royal

Academy of Engineering, UK and a Fellow of the National Academy of Sciences Sri Lanka.