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ORIGINAL PAPER

# Electrostatic power harvesting for material computing

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**Abstract** We describe a novel wearable energy-harvesting system based on the phenomenon of contact electrification: when two materials are brought into contact and then separated, they are often found to be charged. By patterning circuits out of textiles with specific electronic properties, we can collect and channel these transferred charges to power-harvesting circuitry. As a demonstration of this principle, we have designed and built a garment to display the wearer's ongoing level of physical activity by powering strings of LEDs using only the energy generated in the garment's motion. Finally, the methods we describe are not limited to textiles but are applicable to material computing in general.

## 1 Introduction

In "The Computer for the 21st Century," Mark Weiser suggested that "the most profound technologies are those that disappear. They weave themselves into the fabric of everyday life," [1] yet "ubiquitous computing" dream of wireless sensors everywhere is accompanied by the nightmare of battery replacement and disposal." [2] Taken together, these observations underscore a common need for effective and affordable renewable energy sources in many areas of ubiquitous computation and sensing. Therefore, it is not surprising that pervasive power harvesting is an active and broad area of research with a wealth of applications in medicine, defense, and consumer electronics. It is also especially relevant to the rapidly growing field of electronic textiles, which has evolved from research curiosities [3] into modular construction kits [4] but still requires conventional power sources to operate. A strong interest in pervasive power has led to many promising developments, including piezoelectric nanofibers [5], photovoltaic wires [6], and variable-capacitance generators [7], to name a few emerging technologies that seem particularly well suited to harvesting power from ambient energy sources available to e-textile systems.

Unfortunately, most of this work is still in the early stages and presently unavailable for use in practical designs. Therefore, we endeavored to develop a novel power-harvesting technology that would meet a few simple requirements:

1. Compatibility with electronic textiles and other forms of material computing.
2. Ease of construction using methods and materials available to designers and artists.
3. Exploitation of a well-known, tangible source of power: electrostatic energy.

The first two requirements are self-explanatory. The third requirement comes from the observation that electrostatic energy is most familiar in daily experience as the phenomena collectively known as "static electricity". It is what causes one to build up and retain an electric charge when walking across a carpet in dry weather and then to experience a small spark when touching a doorknob. It is familiar as the "static cling" that can cause fabrics or plastic sheets to stick together, to make a crackling sound

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when pulled apart, and to lift the hairs of the head or forearm when they are brought near. It is quite striking that these effects are strong enough to be tangible and familiar, suggesting that they might be put to use in pervasive power harvesting.

In the remainder of this paper, we describe the development of *Sp4rkl3*, a skirt that uses electrostatic energy to harvest enough power from its own motion to light up several LED displays and thus give a continuous indication of the wearer's level of physical activity.

## 2 Background

### 2.1 The triboelectric effect

Almost everyone has directly experienced the phenomena collectively known as "static electricity", though in modern times it is better known as a destructive nuisance than as the primary indication of electrical charge. These phenomena have been known since at least the time of Thales of Miletus (ca. 600 BC) who conducted the first recorded experiments in which amber was rubbed with silk and shown to attract dust, chaff, and other (small) items. Amber was so noted for this peculiar ability that its Greek name, *elektron*, was used to describe these phenomena until around 1600, when William Gilbert coined the term *electricity* [8]. During the Enlightenment, the properties of electricity were explored further in experiments using charged glass vessels. The ability to quickly gather charge on the glass led to the creation of varied apparati that would rotate glass cylinders against other materials [9]. Electrical scientists of that era (known then as "electricians") expended considerable effort rubbing materials together and classifying them according to their abilities to charge one another in attempts to understand the nature of electricity.

It was not until 1913 that the word *triboelectricity* appeared in the scientific literature, formed by the addition of the Greek root *tribos* (rubbing), and defined as "electricity generated by friction" [10]. It is worth noting that the etymology and definition of this word are misleading because rubbing is not necessary to transfer considerable charge between materials; often, mere contact will suffice. Contact electrification phenomena occur when nearly any combination of metal (conductor), semiconductor, or dielectric (insulator) materials come into contact, and while their mechanisms are fairly well understood in metals and semiconductors, there is still considerable debate over the cause of contact electrification in insulators [11].

The electrostatic interactions between two materials can be estimated from their relative positions in a so-called triboelectric series as in Table 1. A material's position within the series represents its (empirically determined) tendency to accept charge from contact with other materials in the series. The further apart two materials are in the series, the more charge will be transferred between them during contact.

**Table 1** A triboelectric series (adapted from [14])

| |
|---|
| (most positively charged) |
| Air |
| Human skin, Leather |
| Glass |
| Human hair |
| Nylon |
| Wool |
| Cat fur |
| Silk |
| Aluminum |
| Paper |
| Cotton |
| Steel |
| Wood |
| Acrylic |
| Polystyrene |
| Rubber |
| Nickel, Copper |
| Silver |
| Acetate, Rayon |
| Styrofoam |
| Polyurethane |
| Polyethylene |
| Polypropylene |
| Vinyl (PVC) |
| Silicon |
| Teflon (PTFE) |
| (most negatively charged) |

The notion of a triboelectric series is not without its shortcomings, however. For one, it is not always possible to arrange a group of materials into a triboelectric series. For example, it has been found that silk charges glass negatively, glass charges zinc negatively, and zinc charges silk negatively, so these materials form a triboelectric 'ring' [12]. Furthermore, triboelectric series obtained in different studies are often found to be in disagreement for reasons that are not yet fully understood [11, 13]. Nonetheless, we have included a representative triboelectric series here because of its undeniable utility, but caution the reader to consider it to be a rough guide and to seek out corroborating data.

The effects of triboelectric charging are also important to those who work with sensitive electronic devices or flammable materials. Even though there is disagreement among studies of triboelectric series, standards exist to quantify these effects. To quote one:

"Attention has been given to the problem of static electricity because of its ability to damage or destroy certain semiconductor devices, unexpectedly initiate ordnance devices, ignite explosive atmospheres, and surprise workers doing critical jobs causing undesirable consequences and injuries to occur. These hazards associated with electrostatic discharge (ESD) are a continuing safety and financial concern to the scientific, aerospace, and industrial communities. Thin materials like plastic films, foams, and tapes are some of the materials most likely to develop damaging static charge buildup." [15]

## 3 Implementation

### 3.1 Identification of materials

To gain a better understanding of triboelectric effects, we developed the simple instrument illustrated in Fig. 1. This triboelectric testing "paddle" is a cardboard panel with three copper foil electrodes, two diodes, and one neon bulb. The electrodes are covered with one triboelectrically active (triboactive) material, and the paddle is rubbed against a sample of another triboactive material.

The operating principle of this circuit is deceptively simple and not unlike that of the variable-capacitance generator: the diodes allow charge to flow preferentially in one direction across the electrodes, developing a voltage difference across pairs of electrodes. When the breakdown voltage of the neon lamp (typically 100V) is exceeded, a discharge occurs, the lamp lights, and the voltage across the electrode array drops temporarily. When the voltage across the lamp is measured using a probe as shown in Fig. 2, this breakdown effect is seen clearly (Fig. 3) as a series of spikes as the neon lamp discharges multiple times.

When these paddles are brushed rapidly against each other, there is a net charge transfer that is stored in the insulating surface. PTFE is an excellent insulator with a surface resistivity of $>10^{18}\Omega/\square$ (ohms per square) and a high dielectric strength of 18V/μm [16]. Indeed, it is known that charge deposited on a PTFE surface will remain immobile and virtually undiminished for hours [11].

The maximum surface charge density that will be stable on the PTFE surface can be derived from the dielectric strength of air (3V/μm) and the definition of surface charge density $\sigma = \varepsilon E$ to give $\sigma_{\max} = \varepsilon_{\text{air}} E_{\text{breakdown}} = (8.85 \times 10^{-12}\ \text{F/m})(3 \times 10^{6}\ \text{V/m}) = 2.7 \times 10^{-5} \text{C/m}^2$. At this point, the electric field strength at the surface is sufficient to ionize the surrounding air. The surface charge will decrease when oppositely charged ions are attracted and recombination occurs while similarly charged ions are repelled from the surface. This effective current flow through air [17] is known as corona discharge and can be observed by rubbing PTFE and nylon paddles together briefly to build up a charge then slowly pulling them apart. As they separate, a faint crackling will be heard indicating corona discharge. Therefore, we expect the surface charge


**Fig. 1** Triboelectric testing paddle: **a** equivalent schematic; **b** rear of one paddle showing circuitry; **c** PTFE on active face of paddle

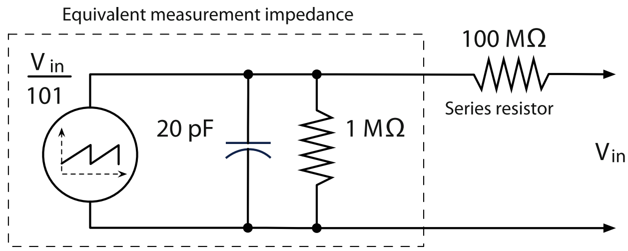


**Fig. 2** Detail of high-voltage measurement technique: a 100 MΩ resistor in series with the 1MΩ measurement impedance forms a 1:101 voltage divider

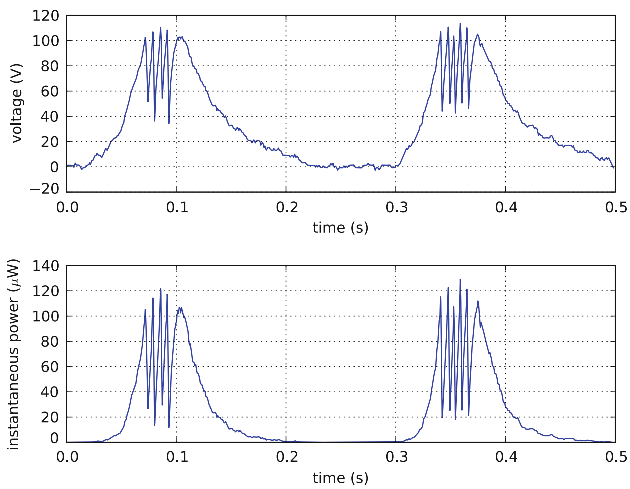


**Fig. 3** Voltage and power output of the nylon test paddle as the PTFE test paddle slides from *left* to *right* and back over it at a frequency of about 4 Hz; two charging events are shown. Note that charging only occurs for relative motion in one direction. Spikes around the voltage peaks correspond to discharges of the neon lamp across the paddle output. Each charging event has an average energy of 5.6 μJ and the average output power is 22.5 μW

density on the insulating surface of a paddle to be on the order of $\sigma_{\max}$.

Because charge is stable for a relatively long time on the dielectric surface, the paddle may be thought of as a self-biasing charge pump that harvests energy from motion, or as a type of variable-capacitance generator [7] biased by triboelectric charging instead of an external source.

With these paddles in hand, we set out to assay materials at local fabric and hobby stores (e.g. Jo-Ann Fabrics, Fabric Place), while at the fabric store, materials were tested with portable tribopositive (nylon-coated) and tribonegative (PTFE-coated) paddles. As bolts of fabric are not universally labeled regarding fiber content, treatments or additives, in-store testing is critical to determine the triboelectric properties of the materials. Experiments with the paddles on available materials identified rip-stop nylon, vinyl, latex rubber, and 0.003" PTFE film as the best candidates for further work. Rip-stop nylon can be found in most fabric stores and is available online from technical fabric retailers. Its stiffness can vary greatly between gossamer fabrics of less than 1oz/yard$^2$ to heavy-duty pack fabrics designed to be used in highly abrasive environments. In any rip-stop fabric, a grid of crossing heavier fibers keeps tears from spreading. The fabric often has a shiny and a rough side from asymmetrical calendaring, so there is a choice of surface texture available.

To estimate the available power, the output voltage was measured through a 100 MΩ series resistance using a Picoscope 2104 USB oscilloscope with a 1 MΩ input impedance, giving an effective probe gain of approximately 1:100. Instantaneous power was then calculated as $P(t) = (V(t))^2/(101\,\mathrm{M\Omega})$.

## 3.2 Prototype skirt panel and display

Encouraged by results from the test paddles, we set out to build a prototype of a panel for the skirt we had in mind. We implemented the same electrode-and-diode ladder circuit used in the test paddles but extended to 10 electrodes and substituted textiles for the substrate and electrodes. Applique and piecework techniques were used to attach the electrodes, diodes, and terminals to the substrate. An inside view of the prototype panel is shown in Fig. 4.

**Fig. 4** Inside view of prototype skirt panel. 10 electrodes (each ~2.5 cm × 10 cm) were cut out of conductive organza and affixed to the nylon substrate using spray fabric adhesive. Diodes were soldered to sections of copper braid and sewn across the organza strips. Two additional sections of copper braid were sewn to the terminal electrodes to allow connection to external circuitry

Power measurements were performed using the same probe gain (1:101) and loading (101 MΩ) as before. A 16 cm × 16 cm square of PTFE was rubbed lightly back and forth across the outer surface of this panel and the output voltage was monitored directly, with a typical charging cycle seen in Fig. 5.

We also developed a simple energy-harvesting circuit and multiple LED display, shown in Fig. 6. Here, diacs S1 and S2 maintain a bias voltage between 100V and 200V across the electrode array, and C1 provides a charge reservoir. Diodes D1-D4 form a full-wave rectifier that drives a string of LEDs. By putting 40 red LEDs in series, each with a nominal forward voltage of $V_f \approx 2$V, we were able to avoid the need to step down the high output voltage ($V_{out} \approx 100$V).

### 3.3 Production skirt panel and display

The final skirt is shown in Fig. 7. Six pairs of panels were constructed. Red rip-stop nylon was used for the electrode substrate, while black rip-stop nylon was used for the outer covering. The diode/electrode ladder pattern of the prototype was extended to a total of 16 electrodes arranged as in Fig. 8. The inner triboelectric panels were made of two layers of 0.003" PTFE sandwiched around a layer of conductive organza. The organza was first stabilized by hemming the edges and then affixing to one sheet of PTFE with spray adhesive. The second PTFE sheet was then added and a whipstitch hem was placed around the edge. Care was taken not to allow the needle or thread to crack the PTFE. Weight-bearing seams (across the top of the panel) were reinforced with stiff interfacing.

Electrodes can be glued onto a backing fabric as long as the glue doesn't fully encase the areas of the electrode

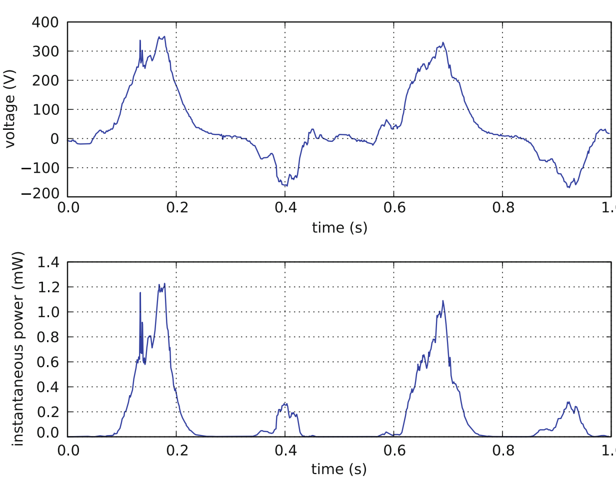


**Fig. 5** Voltage and power output of prototype nylon skirt panel as a PTFE sheet is rubbed (with light pressure) back and forth at a frequency of about 2 Hz across the vertical centerline of the panel as pictured above. Four charging events are shown, and a strong asymmetry is visible in the output voltage due to the diode ladder. Average output power over the entire 1 s interval is 162.2 μW

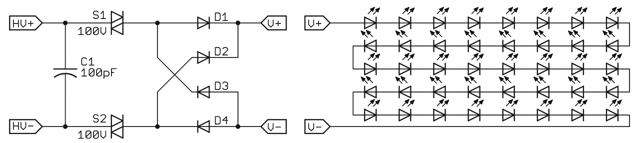


**Fig. 6** Schematic of prototype energy-harvesting circuit and LED display

**Fig. 7** The Sp4rkl3 skirt [photo credit: Mikey Siegel]

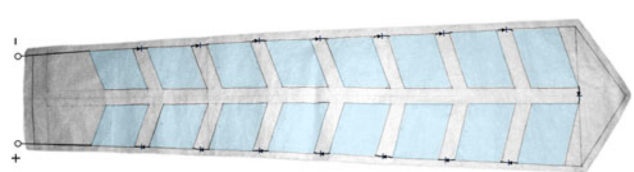


**Fig. 8** Sp4rkl3 skirt panel pattern. Panels were fabricated using similar materials and techniques as in the prototype panel but on a larger scale (16 electrodes with a total area of about 156 $in^2$ ($\approx$0.1 $m^2$). Terminal electrodes (+ and −) were fabricated of folded conductive organza to make robust sewable attachments

contacting the Tribo-surface. This also has the benefit of minimizing fraying, a source of electrical shorts.Each of the six tribogenerator panel pairs attaches by fabric snaps to its own circular power-harvesting circuit and LED display (referred to as a medallion). These medallions were fabricated on single-sided 0.010" FR4 PCB stock using a toner transfer and chemical etch process. A schematic of the medallion is shown in Fig. 9. Note that while the HV+ and

HV − terminals are attached to either side of the electrode/diode ladder, a third common terminal (COM) has been added to connect to the conductive fabric ground plane in the PTFE panel. Bias is maintained at around 100V by diacs S1-S3 as before, and diodes D1-D6 form a three-phase full-wave rectifier. Finally, a capacitive link to the common terminal has been added to the center of the LED string. The common ground planes of the six generators are connected to shield the wearer from unintentional charging and discharge.

The addition of a common terminal to the power-harvesting circuit and display allows it to display three distinct charging events. When the voltage across the electrode array causes any pair of diacs to conduct, the entire string of LEDs (from V+ to V − terminal) will light up. In addition, as the panels separate and come together, they act as a variable-capacitance generator and light up alternate halves of the LED string (from V+ to CT or CT to V −) according to the direction of current flow.

## 4 Results

### 4.1 Performance

A simple measurement of the final power harvester's performance was done by measuring the voltage drop across a 1kΩ resistor inserted between the CT terminals of the circuit shown in Fig. 9. When the skirt is shaken by its test fixture (described in sect. 4.2) the LEDs on the medallions light up as seen in Fig. 10, and Fig. 11 shows the current measured across the resistor during a typical charging cycle as the inner and outer panels are separated by 1 cm and brought back into contact. The measured current through the load resistor was converted to a power measurement and numerically integrated to arrive at a total energy of 657 μJ per charging cycle or an average power of 1.3 mW under these test conditions.

### 4.2 Durability

The Sp4rkl3 skirt is also a durable artifact. It was exhibited at the Boston Museum of Science for 12 weeks between November 2008 and February 2009. It was mounted on a mannequin that had been modified to include a motorized waist to shake the skirt. The stepper motor was programmed to rock the waist sharply 3 times from front to back in 2 s

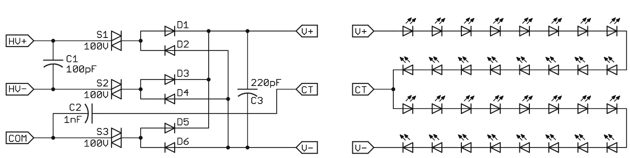


**Fig. 9** Schematic of the Sp4rkl3 skirt LED medallion

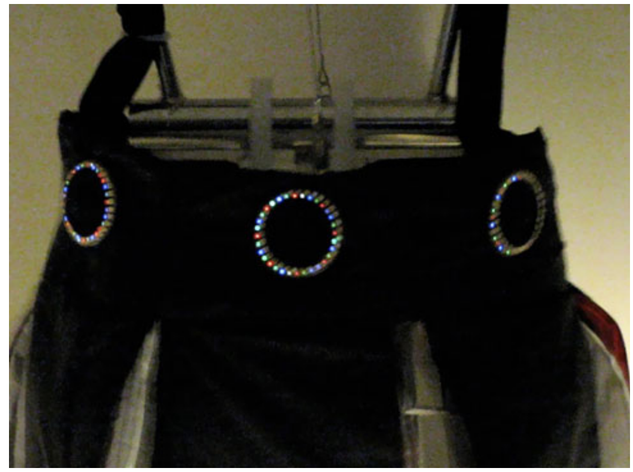

**Fig. 10** Sp4rkl3 lighting up when shaken by the motorized mannequin

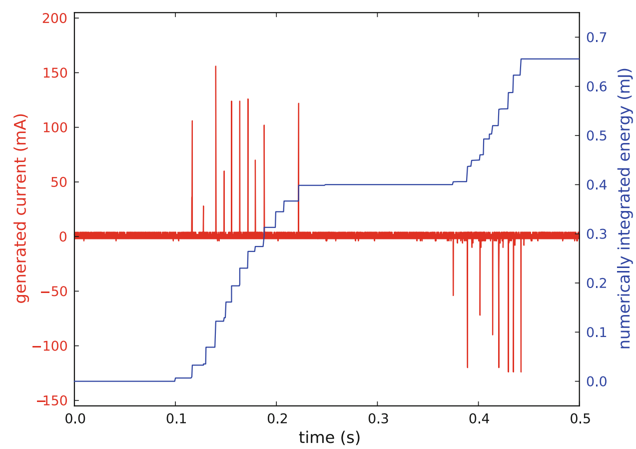


**Fig. 11** Charging event in one panel

through a total arc of about 10 degrees, followed by a pause of 1 s every time an attached button was pressed. The entire assembly was suspended from the ceiling of a display vitrine as shown in Fig. 12. As the display was in a high-traffic area of the museum, we estimate that the button was pressed ~17,000 times during this period (twice every five minutes during opening hours) and therefore the skirt was shaken more than 50,000 times. After the period of this exhibit, neither the performance nor the structural integrity of the skirt were noticeably degraded.

## 5 Contributions and next steps

We have demonstrated a scalable architecture for tribo-electric generation of power in textiles, including:

- Implementation of variable-capacitance and electro-static-induction generators in textiles.

**Fig. 12** The Sp4rkl3 skirt on exhibit at the Boston Museum of Science [photo credit: Emily Roose, Boston Museum of Science]

- Use of triboelectric properties as a charge source for such generators.
- Hand-crafting such generators in wearable form using standard craft materials and techniques.

By combining a multi-mode mechanically driven charge pump with a triboelectric charge source, we have achieved higher conversion efficiency than would be possible with either approach alone. This work has been implemented in a wearable form to recover power from the wearer's motion. Power can be harvested from multiple modes of motion, particularly surfaces sliding over one another as well as surfaces moving together and apart.

These principles are not limited to fabrication in clothing and may be applied to many other media including packaging, enclosures, print media, carpeting, and building construction media to name a few. There are also applications to semi-passive mechanical actuation by selectively harvesting energy from a system's motion in order to cause it to slip and stick as desired.

The major risk in this work going forward is that triboelectricity is well-known to be a difficult phenomenon to model, predict, and control. Furthermore, the majority of current research into triboelectric phenomena seeks to minimize or mitigate its effects, whereas we have sought to maximize and channel these effects. Major areas of work remaining to be done include:

1. Efficient conversion of output power to voltages compatible with standard low-power electronics.
2. Optimization of triboelectric charging and electrostatic induction.
3. Implementation of nonlinear charge pump components (e.g. diodes) as all-fabric or printed structures[18–20], and/or development of semiconductor packages compatible with fabric systems.

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## References

1. Weiser M (1991) The computer for the 21st century. Sci Am 265(3):94–104. September 1991
2. Paradiso JA, Starner T (2005) Energy scavenging for mobile and wireless electronics. IEEE Pervasive Comput 4(1):18–27
3. Post ER, Orth M, Russo P, Gershenfeld N (2000) E-broidery: design and fabrication of textile-based computing. IBM Syst J 39(3–4):840–860. ISSN: 0018-8670
4. Buechley L, Eisenberg M (2007) Fabric pcbs, electronic sequins, and socket buttons: techniques for e-textile craft. Personal Ubiquitous Comput 13(2):133–150. ISSN: 1617-4909. doi: http://dx.doi.org/10.1007/s00779-007-0181-0
5. Yang R, Qin Y, Li C, Zhu G, Wang GL (2009) Converting biomechanical energy into electricity by a muscle-movement-driven nanogenerator. Nano Lett 9(3):1201–1205
6. Lee MR, Eckert RD, Forberich K, Dennler G, Brabec CJ, Gaudiana RA (2009) Solar power wires based on organic photovoltaic materials. Science 324(5924):232–235
7. Yen BC, Lang JH (2006) A variable-capacitance vibration-to-electric energy harvester. Circuits Syst I Regul Pap IEEE Trans 53(2):288–295. ISSN: 1549-8328
8. Ida N (2004) Engineering electromagnetics, 2nd edn. Springer, pp 122–123
9. Priestley J (1775) The history and present state of electricity: with original experiments, Printed for C. Bathurst, and T. Lowndes, p 89
10. "tribo-, comb. form" The Oxford English Dictionary. 2nd ed. 1989. OED online. Oxford University Press. 4 Apr. 2000 http://dictionary.oed.com/cgi/entry/50257487
11. Lowell J, Rose-Innes AC (1980) Contact electrification. Adv Phys 29(6):947–1023. 1980. ISSN: 0001-8732
12. Shaw PE, Jex CS (1928) Tribo-electricity and friction. iii. solid elements and textiles. Proc R Soc London Ser A 118(779): 108–113. ISSN: 09501207
13. Bailey AG (2001) The charging of insulator surfaces. J Electrostat 51–52:82–90
14. URL http://en.wikipedia.org/wiki/Triboelectric_effect
15. Standard test method for evaluating triboelectric charge generation and decay. Kennedy Space Center, Spaceport Engineering & Technology Labs Division, November 15 2002
16. Fluoropolymer comparison: typical properties, 2009. URL http://www2.dupont.com/Teflon_Industrial/en_US/tech_info/techinfo_compare.htm
17. Pratt TH (2000) Electrostatic ignitions of fires and explosions. Wiley, London
18. Maccioni M, Orgiu E, Cosseddu P, Locci S, Bonfiglio A (2006) Towards the textile transistor: assembly and characterization of an organic field effect transistor with a cylindrical geometry. Appl Phys Lett 89(14)http://dx.doi.org/10.1063/1.235703 URL http://dx.doi.org/10.1063/1.235703
19. Hamedi M, Forchheimer R, Inganas O (2007) Towards woven logic from organic electronic fibres. Nat Mater 6(5):357–362. URL http://dx.doi.org/10.1038/nmat1884
20. Lee JB, Subramanian V (2005) Weave patterned organic transistors on fiber for e-textiles. Electron Dev IEEE Trans 52(2):269–275. http://dx.doi.org/10.1109/TED.2004.84133 URL http://dx.doi.org/10.1109/TED.2004.841331