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THE REQUIREMENT FOR PIEZOELECTRIC SMART MATERIAL FOR CURRENT AND FUTURE APPLICATIONS

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ABSTRACT

This paper shall review and contrast on the current and new emerging smart material technology for power harvesting and application of piezoelectric smart materials. Our reliance and dependency on existing fossil fuel have increased many folds in the last few decades. As we further depend on new emerging technology and increase in global population at an unprecedented rate, no doubt out requirements of energy will further increases, to an extent that we may see our self running out or fossil fuel supply faster than initially predicted. Although investment in nuclear technology will largely replace the energy demand, it too has divided opinions.
One of the aims of this paper is to highlight the advantages of employing smart material piezoelectric material to generate energy, particularly in terms of voltage to power existing battery supply and in certain cases to eliminate the requirement of finite power source entirely. We shall commence by introducing the history of piezoelectricity and materials characteristics for the ceramic based PZT (lead zirconate titanate), polymer membrane PVDF (polyvinylidene fluoride) and polymer foam PP (polypropylene) which is commercially used. Various poling mechanism (to transform standard material into piezoactive) will be discussed, as well as manufacturing methods.
Mostly, PZT piezoelectric material is used in numerous applications due to its superior voltage generating properties. However, PVDF and more recently, PP is being researched and constantly improved to increase the energy output potential since these materials are relatively inexpensive, light, flexible and easily confirms to intricate shapes.
Keywords: Smart materials, piezoelectric, energy harvesting, voltage.

GÜNÜMÜZ VE GELECEK İÇİN İHTİYAÇ DUYULAN PİEZOELEKTRİK AKILLI MALZEME UYGULAMALARI

ÖZET

Bu derleme çalışmasında, mevcut ve gelişmekte olan yeni enerji toplama teknolojileri ve akıllı Piezoelektrik uygulamaları karşılaştırmalı olarak incelenmiştir. Fosil yakıtlarına olan güven ve bağımlılığımız son yıllarda tartışılmaya başlanmıştır. Enerji açığı ve ihtiyacı tahmin edilenden çok daha fazla kendini göstermiş ve şüphesiz enerji kaynaklarına olan ihtiyaç hızlı bir şekilde artmış ve artacaktır. Bu durumun temel nedenleri yeni gelişen teknolojilerin ve nüfusun hızla artmasıdır. Enerji açığını kapatmada en etkili yol nükleer teknoloji olsa da, bu teknolojinin kurulmasında farklı görüşler vardır.
Makalenin yazılmasında ki esas amaçlarından biri, piezoelektrik akıllı malzemeler ile enerji üretimi ve avantajlarının, özellikle gerilim-güç oluşumu, bataryaya aktarılması ve bunun sonucunda sonlu enerji kaynağı gereksiniminin tamamen ortadan kaldırılması açıklanmıştır. Öncelikle piezoelektrik gelişimi tanıtılmış sonrasında ticari olarak üretilen ve kullanılan piezoelektrik malzemeler, seramik esaslı PZT (lead, zirconate titanate), polimer membran PVDF (polyvinylide florur) ve polimer köpük PP (polypropylene) özellikleri açıklanmıştır. Çeşitli poling sistemleri, normal malzemenin piezoaktifle transferi ve üretim yöntemleri ele alınmıştır.
Çoğunlukla, PZT piezoelektrik malzeme üstün gerilim üretimi özelliği nedeniyle sayısız uygulamalarda kullanılır. PVDF ve şimdilerde PP üzerine araştırmalar yapılmaktadır ve umut verici sonuçlara ulaşılmıştır. Nispeten daha hafif, esnek ve ucuz olan bu malzemeler ile enerji elde edilmesinde artış sağlanmıştır.
Anahtar Sözcükler: Akıllı malzemeler, Piezoelektrik, enerji toplama, gerilim.

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1. INTRODUCTION

In 2008, total worldwide energy consumption was 474 exajoules (474×10^{18} J) with 80 to 90 percent derived from the combustion of fossil fuels [1]. This is equivalent to an average power consumption rate of 15 terawatts (1.504×10^{13} W). The estimates of remaining non-renewable worldwide energy resources vary, with the remaining fossil fuels totalling an estimated 0.4 YJ (1 YJ = 1024J) and the available nuclear fuel such as uranium exceeding 2.5 YJ. Fossil fuels range from 0.6-3 YJ if estimates of reserves of methane are accurate and become technically extractable. Mostly thanks to the Sun, the world also has a renewable usable energy flux that exceeds 120 PW (8,000 times 2004 total usage), or 3.8 YJ/yr, dwarfing all non-renewable resources.

Highly insulating polymers have been used extensively in electrical cable insulation since their invention in the first half of the 20th century. One of the most significant advantages of polymeric materials over other materials is their complex structure, which can be physically or chemically tailored for specific applications. In year 2000, pioneering work carried out by Heeger, MacDiarmid and Shirikawa on conducting polymers was awarded with the Nobel Prize in Chemistry [2]. Some fluoropolymers were shown to store injected electrical charges for long period of time [3], even at elevated temperatures. The discovery of piezo and pyroelectricity in polyvinylidene fluoride (PVDF) [4] opened up wide market for electromechanical transducers applications. In recent years non-polar ferroelectrets [5] with high piezoelectric coefficient have received a lot of attention. Already new class of non polar ferroelectrets based on charge storing polymers has become available in the market [6].

Reducing size and power requirements of wearable microelectronics can make it possible to replace batteries with smart systems that capture energy from the user’s environment [7]. The consumer reliance on wearable electronic devices is growing significantly, which is leading to the demand for decreased size and enhanced capabilities of micro power generation devices. Until now batteries have been sufficient, but nuisance in terms of excess weight, rechargeability, replacement and disposal.

An average person spends significant part of the day on foot, dissipating abundant energy into the soles of the foot wear. This wasted energy could be harnessed in an unobtrusive manner to power a variety of low power application systems, such as pagers, health monitors, I-pod and mobile phones. Studies at MIT explored the feasibility of harnessing wasted energy from a variety of body sources; however, heel strike during walking has shown to be the largest untapped source of wasted energy [8]. Scavenging most of the energy unobtrusively would be impossible, but a sizable fraction of it could provide sufficient energy to operate many of the personal micro powered systems on the market today [9].

An MIT study [10], as well as an independent work by Antaki *et al* [11] at another institution, supported and proposed a system of embedded piezoelectric materials and miniature controls. The research observed that a shoe having relatively large volume available in the sole would make an ideal test bed for exploring body energy harvesting.

A recent development demonstrated the feasibility of scavenged shoe power using a simple application circuit [12]. The design is self-powered radio frequency (RF) tag that transmits a short range 12 bit wireless identification (ID) code during walking. Previously, this area of work relied on battery powered IR badges [13]; however, PVDF (Polyvinylidene Fluoride) or PZT staves could be configured into the sole of the shoes to provide the required power for the signal to be transmitted.

It has been calculated that 5W of electrical power can be generated by a 52kg person at a brisk walking pace using a PVDF shoe insert [14]. Similarly, another study used a free falling ball to impact a plate with a piezo ceramic wafer attached to its underside and developed an electrical equivalent model of the PZT transforming mechanical impact energy to electrical power

[15]. Further studies examined using a piezoelectric film in addition to ceramic based piezoelectric material to provide power to light a bulb [16].

2. MATERIALS CHARACTERISTICS

Ceramic fibres in the diameter range of 10-250μm were used in this study [18]. When formed into composite materials they posses all the qualities of conventional ceramics (electrical, mechanical, chemical) and mitigate problems such as weight and brittleness. The piezoelectric fibre composites (PFC) [19] consist of unidirectional aligned piezoelectric fibres in an epoxy matrix, sandwiched between two copper clad polyimide laminates. The PFC devices have higher efficiency than traditional bulk piezoelectric ceramic materials, due to their large length to area ratio [17].

Typically, when in fibrous form crystalline materials have much higher strengths and the polymer shell of the PFC allow the fibres to withstand impacts and harsh environments far better than monolithic piezoelectric ceramic materials. The technique of applying inter-digitated electrodes (IDE) takes advantage of the greater d_{33} piezoelectric constant where full electrode coverage of top and bottom of the sample makes use of the lower d_{31} response, see Table 1(The d_{31} represents piezoelectric charge constant and its the ability of the material to polarise i.e. for a standard material to convert into a piezoelectric material). Whereas the g_{31} is a piezoelectric voltage constant and is the ability of the piezoelectric material to generate voltage. And k_{31} represents electromechanical coupling factor and is an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy, or converts mechanical energy into electrical energy. An energy harvesting system, using flexible fibre composite transducer, is capable of producing and storing typically 880mJ (40V) of energy from a 30Hz vibration over 13 seconds period.

Table 1. Comparison of piezoelectric materials

Property	Units	PVDF Film	PZT
Density	10^3kg/m^3	1.78	7.5
Relative Permittivity	$\varepsilon / \varepsilon_0$	12	1200
d_{31} Constant	(10^{-12})C/N	23	110
g_{31} Constant	(10^{-3})Vm/N	216	10
k_{31} Constant	% at 1 KHz	12	30
Acoustic Impedance	(10^6)kg/m^2-sec	2.7	30

Properties of porous PTFE foams have already been reported some time ago [20, 21]. The high surface charge stability of these materials particularly at elevated temperatures range has been confirmed [22-26]. For a single PTFE films, high piezoelectric coefficient was found [27], but the effect decreased by a factor of 2 when uncharged PTFE films were inserted between the charged films and the electrodes [28]. Consequently, single layer foams were studied and it became clear that part of the piezoelectric effect in this case stems from change in the air gaps between porous electret and disk electrodes [27, 29].

Further work has been conducted where PTFE foam layers have been incorporated into multi layered sandwiches [26, 30], i.e. double layer sandwiches of one hard and one soft layer with an interface charge layer between them [31,32,33]. If two or more separate foams are to be assembled into to such a sandwich, then air pockets have to be avoided.

Since the discovery of piezoelectric PVDF [34], it has been widely used in a range of sensors and actuators applications [35]. In addition, several other polymers have been shown to have potentially useful piezoelectric properties, such as polyamides [36], copolymers of vinylidene cyanide (VDCN) [37], polyureas [38] and polyurethane (PU) [39]. Two layer approach has been investigated with the polypropolene (PP) and PU foams [40], whilst further research has been investigated on stacks of corona charged porous and non porous PTFE [41] and reported piezoelectric d_{33} coefficient of up to 35pC/N as well as a value as high as 150pC/N has been obtained with a single layer of porous PTFE [42].

Cellular polypropylene (PP) foams are usually produced in a modified blow extrusion process [43, 44]. Prior to foam blowing, spherical voids of approximately 10µm are generated by gas injection into the polymer melt. The melt is extruded, cooled down and reheated for foam blowing. Foam formation is accompanied by biaxial orientation, which results in disk or lens shaped voids [45]. In addition, most cellular PP foams have co-extruded outer layer of non voided polymer for higher surface smoothness, better thickness uniformity and improved electrode adhesion [46]. Charging of PP is done by means of corona charging with high corona point voltages around 20kV [36, 47].

The resulting surface charge leads to high electric fields across the thickness of the foam and thus internal breakdown in disk shaped voids [48, 49, and 50]. After breakdown, the voids are charged to top and bottom polarities that are opposite to respective surface charge and electrode polarities of the foam [37]. In addition to corona charging, electrode charging [51, 52, and 53] and electron beam charging [54] have been reported. Figure 1 below depicts typical microstructure of PP foam.

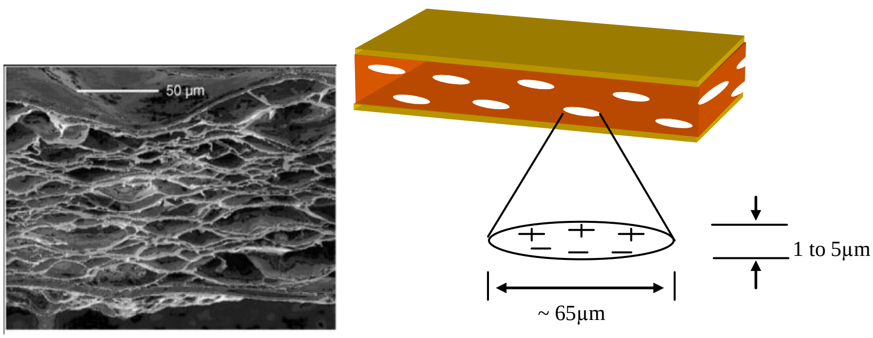

Figure 1. SEM of PP foam with elliptical voids and schematic diagram

2.1. Poling Methods

In order to understand the microscopic mechanism of charge storage, it is important to understand characteristic of fundamental material parameters as well as the measurement of specific sample or device properties. Progress in the area of electrets research has been widely enhanced with the wide range of methods to characterize electrets with respect to their electrical, thermal, mechanical and chemical properties. To date, several characterization techniques have been developed.

Over the past three decades, several techniques for obtaining space charge and polarization depth profiles in insulating materials have been developed [55] and applied to range of topics such as accumulation of space charge in high voltage cable insulations [56], the development and optimization pyroelectric and piezoelectric sensors [57, 58] and basic research into mechanisms of charge storage [59] in electret polymers.

2.1.1. Acoustic Method
2.1.2. Thermal Method
2.1.3. Polarizing (poling) a Piezoelectric Ceramic

2.2. Current and previous work on smart materials

- Silicone Implants for Energy Harvesting
- Paper thin batteries to power
- Flexible nanocrystal fibres for hydrogen fuel

2.3. Piezoelectric Fibre Composite (PFC)

Several actuators that incorporate piezo-fibre technology are commercially available or under development at research institutes, namely the 1-3 composites by Smart Materials Corp. active fibre composite (AFC) actuators developed by MIT [60] and macro-fibre composite (MFC) actuators constructed at NASA Langley Research Centre [61]. In addition the company responsible for the 1-3 composite actuators, Smart Materials Corp. was given the contract from NASA to market the MFC [91].

The 1-3 composite actuator from Smart Material Corp. consists of piezoelectric rods embedded in a polymer matrix. The piezoelectric ceramic material is aligned through the longitudinal direction while the polymer phase is continuous in all three directions, hence its name 1-3 composite. These actuators are constructed using a patented soft mould process that was invented at the Fraunhofer Research Facility in Germany. This process consists of copying a reusable soft mould from a positive form of the final structure then filling the mould with the piezo ceramic material. Once the mould is filled with the piezoelectric material it is fired to sinter the piezo ceramic. Using this process the active pixels can be constructed in either round 70µm diameter with 50µm spaces (Figure 2a) or rectangular form of 80µm with 120µm (Figure 2b).

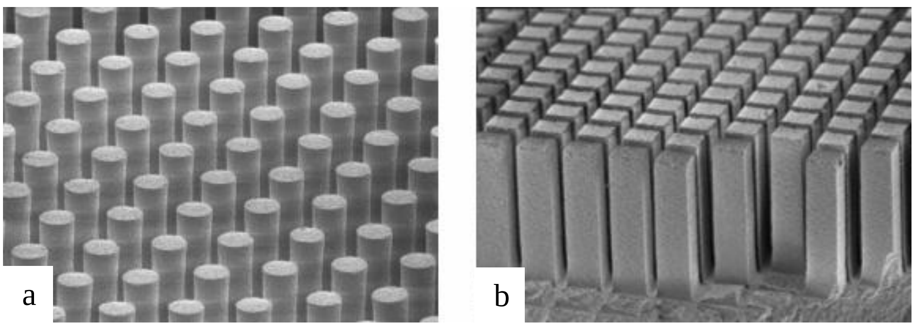

Figure 2. Composite actuators by Smart Materials Corp. piezo ceramic rods with a) round fibres and b) rectangular fibres

After the production of the piezo ceramic fibres, an electrode layer is placed on the top and bottom of the fibres to facilitate the application of an electric field for the collection of current during sensing. The AFC uses inter-digitized electrodes that allow the electrical potential to form along the length of the fibre thereby capitalizing on the higher d_{33} piezoelectric coupling coefficient. A schematic to help visualize the electric field developed along the fibres is shown in Figure 3. The metallic electrodes are normally formed using photolithography, which is a very precise process, however it is a time consuming and expensive process that etches copper strips onto a thin Kapton® film.

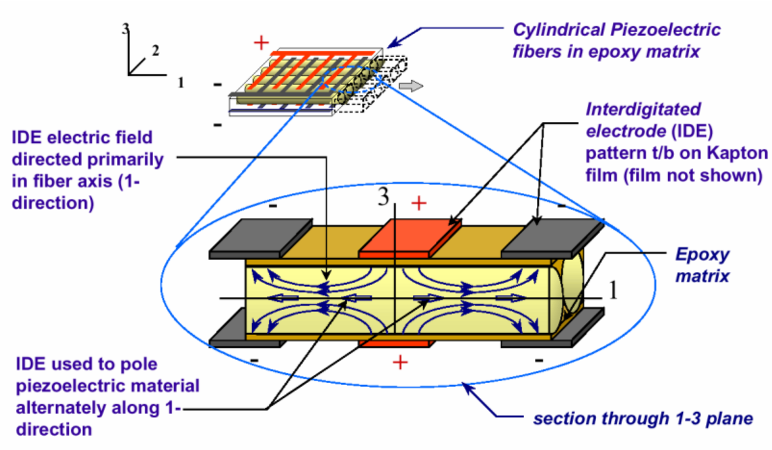

Figure 3. Schematic of the cross section of an AFC actuator [90]

The final assembly of the AFC is fairly complicated. Figure 4 shows the exploded view of the structure. The process begins with the bottom electrode being placed on the aluminium vacuum plate using the locator pins. The piezoelectric fibres are then laid out carefully on the bottom electrode making sure that the fibres are in a single layer and are as parallel to one another as possible. With the piezo ceramic fibres laid out the glass fibres or other material can be included if desired, in order to increase the strength of the actuator.

The next step is to insert the Kapton® moulds along the edges of the electrodes to retain and form the polymer matrix that will be added. With the Kapton moulds in place an epoxy resin doped with an air release agent is applied to the fibres and any inactive material that was added, then the top electrode is aligned on top of the fibres using the positioning holes. With the final layout of the actuator positioned, the plate is placed in a press, where heat and pressure are applied to aid in the curing of the epoxy resin. This process utilizes the vacuum port, which minimizes the amount of void formation in the actuator.

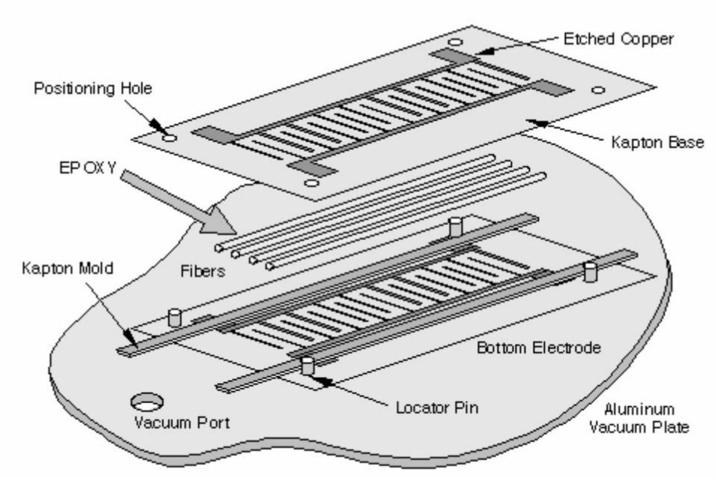

Figure 4. Schematic of the manufacturing process of the AFC [19]

The third and last type of piezo ceramic fibre actuator that is available is the microfiber composite (MFC) actuator that was developed at the NASA Langley Research Center. The MFC is similar to the AFC because both consist of the same three primary components; active piezo ceramic fibres aligned in a unidirectional manner, inter-digitized electrodes, and an adhesive polymer matrix. The layers of the MFC are shown in Figure 5. However, the MFC has one difference that greatly affects the manufacturing process and the performance of the actuator; that is rectangular fibres.

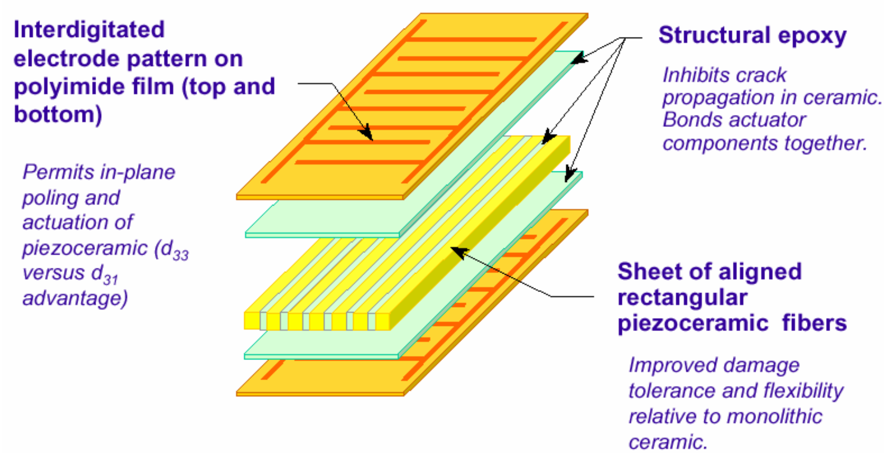

Figure 5. Schematic showing the order of different layers in the macro-fibre composite actuator [19]

2.4. Production of PVDF Film

Rolls of piezoelectric film are produced in a clean room environment. The process begins with the melt extrusion of PVDF resin pellets into sheet form, followed by a stretching step that reduces the sheet to about one-fifth of its extruded thickness. Stretching at temperatures well below the melting point of the polymer causes chain packing of the molecules into parallel crystal planes. These are called “beta phase” materials. To obtain high levels of piezoelectric activity, the beta phase polymer is then exposed to very high electric fields to align the crystallites relative to the poling field. Copolymers of PVDF are polarizable without stretching. Evaporative deposited metals are typically 500 to 1000 Å in thickness, and almost any metal can be deposited. Popular metals are nickel, aluminum, copper, gold and alloys.

2.5. Production of PP Film

An electromechanical film is a thin porous polypropylene (PP) film with biaxially oriented flat voids, with a lateral dimension of 10µm to 100µm and a vertical dimension of 1µm to 5µm [62]. This internal structure is obtained through extrusion, biaxial stretching, and controlled inflation by patented pressure treatments [63]. Under the effect of high electric fields, during the manufacturing process, the heterogeneous foam film acquires a permanent space-charge, with the upper surface of the gas voids with the polarity opposite to the lower surface. The charged voids become perfectly oriented quasi-dipoles, as shown in Figure 6 [64]. These artificial dipoles are responsible for the macroscopic piezoelectric behaviour of these cellular polymers.

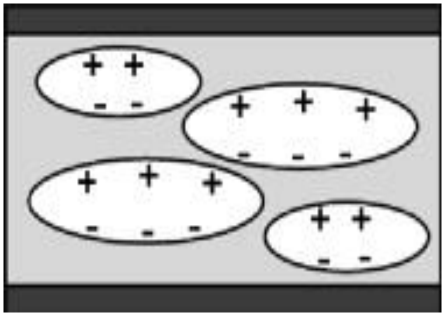

Figure 6. Charged voids in the foam (*which produce the quasi-piezoelectricity*) represent the structure and the inhomogeneous charge distribution.

The transducer is obtained after evaporating or gluing electrodes to the external faces of the charged-foam film. From the application point of view, it is important to take into account that if the metal coat or the glue is too rigid, the quasi-piezoelectric response of the film (a charge) will be small, causing a shift of the quasi-piezoelectric resonance peak [65].

3. TYPICAL PIEZOELECTRIC APPLICATIONS

Based on these piezoelectrets, several applications for large area transducers have been suggested and some are already commercially available. For example, using large mats of these films it is possible to monitor the motion of people and even identify individuals [66] based on single footsteps. Cellular PP foams have also been used for monitoring physiological processes in humans and animals [67]. Another promising area of applications is active vibration and noise control [68].

3.1. Sensors for Motion Control and Pressure Measurement

Motion control to detect, for example, the traffic on the roads or the motion of humans in houses or factory buildings for medical or for safety observations is usually performed by video cameras, infrared detectors, or individual piezoelectric sensors. By placing cellular polymer films on the ground, surveillance of rooms and of the surrounding of machines can be easily achieved [69]. Due to the high transducer sensitivity it is possible to place the sensor film underneath different floor coatings such as polymers, woods, ceramics, or stones.

An example is the implementation of cellular piezoelectric transducers in ski jumping, where cellular polymers allow for the force measurement during the jumpers' takeoff [70]. Besides the monitoring of the pressure distribution on a floor, the pressure distribution in soles of shoes, for example, can be determined during running or walking [71].

The sensitivity of cellular polymer transducers is also high enough for recording the respiration of human patients, even if the transducers are not directly fixed to the skin of the patient [72]. Sensors made of cellular PP have been placed directly on the bed for long-term respiration monitoring. Of course, the sensor signals measured during the movement of the patient are superimposed on the respiration signal. Cellular polymer films also allow for measuring pressure distributions within the body itself.

A current field of development is the sensing of pressure distributions between vocal cords [73]. The high sensitivity of cellular piezoelectric films allows even small forces to be easily detected. Cellular PP films were used for quantitative dynamic-force measurements on dog limbs under their paws [74, 75].

3.2. Control Panels and Keyboards

Push buttons for keyboards, keypads, and control panels with small areas have been made with cellular piezoelectric polymer films. Keypads are commercially produced by the Screentec Company in Finland, and are used for example, in interfaces for information systems in public transportation or as access readers for different applications [76]. The high sensitivity allows the implementation of the sensors behind protective layers of different materials (with a thickness up to 5mm) to achieve vandal-proof control panels usable, for cash dispensers and ticket machines or other systems in public transportation [77].

Based on soft and flexible polymer films, the construction of flexible keypads or keypads covering any shape is also possible if the electronics is separated from the sensor film and connected by flat cables. In long run, flexible keypads including electronic circuitry may become a reality, since organic electronic circuitry is rapidly developing toward commercialization. A mechanical pressure on one of the push buttons with a load of, for example, 2N leads to a sensor voltage signal of around 200mV with a rise time of only 30ms, which is easily detected with standard electronics.

3.3. Electro Acoustic

There is a large potential for applications of internally charged cellular ferroelectrets in electro acoustic applications, where the frequency range from the audio to the ultrasound can be spanned. Microphones and especially pickups based on cellular PP sensors are already on the market, produced by the companies Emfit Ltd. and B-Band Ltd. in Finland [78]. The commercial pick-ups show a bandwidth from 50Hz to 23 kHz, a low distortion of 0.05%, and a good signal-to-noise ratio exceeding 90dB. A sensitivity of 0.7 mV/Pa (Transfer factor for Microphone sensitivity) was determined for cellular polypropylene microphones, which corresponds to a piezoelectric coefficient of around 100pC/N.

Based on optimized preparation methods including the formation of multilayer stacks the sensitivity could be increased significantly [79]. Piezoelectric coefficients between 100pC/N and 1000pC/N are now routinely achieved, depending on the preparation technique, thereby increasing the microphone sensitivity by a similar level [80-87]. Cellular polypropylene films can also be used as microphones in the super audio frequency range up to 40 kHz. A bandwidth exceeding 315 kHz was demonstrated, thereby opening routes for the detection (and generation) of airborne ultrasound [88]. However, the strong sensitivity to pressure changes limits the use of cellular polymer hydrophones to shallow-water applications.

3.4. Switches

The reliability of contact switches is reduced due to contaminate like moisture and dust, which foul the contact points. Piezoelectric film offers exceptional reliability as it is a monolithic structure, not susceptible to this and other conventional switch failure modes. One of the most challenging of all switch applications is found in pinball machines. A pinball machine manufacturer uses a piezoelectric film switch manufactured by MSI, USA, as a replacement for the momentary rollover type switch. The switch is constructed from a laminated piezoelectric film on a spring steel beam, mounted as a cantilever to the end of a circuit board.

The "digital" piezoelectric film switch features a simple MOSFET circuit that consumes no power during the normally-open state. In response to a direct contact force, the piezoelectric film beam momentarily triggers the MOSFET. This provides a momentary "closure" for up to a 50V maximum voltage. The output of this low profile contactless switch is well suited to logic-level switching. The unit does not exhibit the corrosion, pitting or bounce that is normally associated with contact switches. The company has tested these switches in excess of 10 million cycles without failure. The switch solves the nagging problem of fouled contacts in pinball machines, a significant source for machine downtime and lost revenue. The simplicity of the design makes it effective in applications which include:

- Counter switches for assembly lines and shaft rotation
- Switches for automated processes
- Impact detection for machine dispensed products
- Panel switches
- Foot pedal switches
- Door closure switches

The cantilever beam that carries the piezoelectric film can be modified to adjust switch sensitivity for high to low impact forces.

Piezoelectric film switches can be used to measure the amplitude, frequency and direction of an event and are useful in object detection and recognition, counting, wakeup switches and bidirectional encoding applications. Note that the piezoelectric film element is laminated to a thicker substrate on one side, and has a much thinner laminate on the other. This moves the neutral axis of the structure out of the piezoelectric film element, resulting in a fully tensile strain in the piezoelectric film when deflected downward, and a fully compressive strain when deflected in the opposite direction. The neutral axis in the center of the piezoelectric film element would be the case if the two laminate were of equal thickness. The top half of the piezoelectric film would be oppositely strained from the bottom half under any deflection condition, and the resulting signals would therefore be cancelled.

Beam switches are used in shaft rotation counters in natural gas meters and as gear tooth counters in electric utility metering. The beam switch does not require an external power source, so the gas meter is safe from spark hazard. Other examples of applications for the beam switch include a baseball target that detects ball impact, a basketball game where a hoop mounted piezoelectric film sensor counts good baskets, switches inside of an interactive soft doll to detect a kiss to the cheek or a tickle (and the sensor is sewn into the fabric of the doll), coin sensors for vending and slot machines and as digital potentiometer for high reliability.

Piezoelectric materials do not have a true dc response. Very slow events, 0.0001Hz, for example, are not normally possible to detect with piezoelectric film. In switch applications where dc response is required, piezoelectric film in combination with a snap dome provides a high voltage pulse. When the snap device actuates, the film is rapidly strained, typically generating a 10volt pulse into a one mega ohm circuit. This concept is especially well suited for wakeup switches, where an electronic device can be dormant for long periods without power consumption until the snap action device is actuated. Battery operated parking meters, where battery life is very critical, are an example of a piezoelectric snap action switch application. A thermal snap action device also employs this principle.

3.5. Musical Instruments and Traffic Sensors

The popularity of electronics for musical instruments presents a special problem in drums and pianos. The very high dynamic range and frequency response requirements for drum triggers and piano keyboards are met by piezoelectric film impact elements. Laminates of piezoelectric film are incorporated in foot pedal switches for bass drums, and triggers for snares and tom-toms. Piezoelectric film impact switches are force sensitive, faithfully duplicating the effort of the drummer or pianist. In electronic pianos, the piezoelectric film switches respond with a dynamic range and time constant that is remarkably similar to a piano key stroke.

Recent advancements in signal processing open the door to greatly improved real-time vehicle data analysis, provided that inexpensive reliable sensor technologies are developed. Pneumatic road tubing has long been the workhorse of traffic data collection. Road tubes provide a pneumatic pulse to a piezoelectric membrane, which triggers nearby electronics when an axle is detected. The evaluation of alternative sensor technologies has shown piezoelectric cable provides the necessary sensitivity, linearity, noise immunity and environmental stability for high traffic interstate vehicle classification and weight-in motion systems. Piezoelectric cable BL sensors are used for traffic data collection from Saskatchewan to Florida.

"New Jersey barriers", the modern concrete barriers that separate opposing lanes on highways, introduce problems for multilane sensing of four lane highways. Piezoelectric cable can solve this problem with a single sensor that has opposite polarities corresponding to each lane. Vehicles crossing the near lane produce a signal of opposite sign from vehicles in the far lane. This ability to provide lane activity in a single sensor is a significant development. Traffic sensors can monitor vehicle speed, count axles, weigh vehicles, provide direction, and vehicle classification. Recently, these sensors have also proven valuable on airport taxiways. From the output, one can discern the ground speed of an aircraft (time lag between two sensors), its direction, weight, number of axles, and the span of the aircraft (determined from the speed and the known fixed distance between sensors). This information can be used to classify the aircraft and provides taxiway traffic control and safety information at airports.

3.6. Vibration Sensing

One of the first applications for piezoelectric film was as an acoustic pickup for a violin. Later, piezoelectric film was introduced for a line of acoustic guitars as a saddle-mounted bridge pickup, mounted in the bridge. The very high fidelity of the pickup led the way to a family of vibration sensing and accelerometer applications [89].

Music Pickups
Machine Monitoring
Bearing Wear Sensors
Fan Flow Sensor
Thread Break Sensor
Vending Sensors

3.7. Accelerometers and Sensors

A logical outgrowth of the many vibration sensor applications of MSI's piezoelectric technology is accelerometers. These accelerometer designs are based on more traditional piezoelectric ceramic, as well as piezoelectric polymer materials. The choice of base materials allows the product to be tailored for specific applications. Like more conventional sensors, these accelerometers are configured as either compression-design type or beam-design type [110].

Medical Imaging Ultrasound
Non-destructive Testing (NDT)
Acoustic Emission
Fluid Level Sensor
Air Ranging Ultrasound
Audio speakers
Microphones
Sonar

4. FUTURE APPLICATIONS

Piezo film research is underway into an exciting new array of applications. A sampling of this R&D activity is highlighted below:

Active Vibration Damping **-** Piezo film sensor and actuator pairs are in development for active vibration damping. In this application, a piece of piezo film is employed as a strain gauge to detect vibration and another piece of piezo film is employed as an actuator to dampen the vibration noise by applying a 180 degree phase shifted signal. Wide coverage of piezo film, with distributed electrode patterns, can be used to create individual sensor/actuator pairs. Critical damping has been achieved with this piezo film laminate by researchers at Massachusetts Institute of Technology and elsewhere [110]. The applications for this technology include the reduction in harmful vibrations in space-based structures, fuselage for aircraft to cancel engine noise, quiet cars, quiet appliances, and a wide range of other possibilities.

Sensors on Silicon **-** Piezoelectric polymers can be solution cast (spin coated) onto silicon, polarized in place, metalized in pattern arrays, and interconnected with the integrated circuits on the chip. Minor modifications to wafer processing make the silicon suitable for the piezo Polymer Sensor-On-Silicon (PSOS). Early work in PSOS technology at Stanford University was frustrated by the need to adhesively bond thin sheet piezoelectric film onto silicon. The adhesive layer was difficult to apply to the silicon, introducing air bubbles, wrinkles, no uniform thickness layers, etc. The advent of new piezoelectric polymer processing that eliminates the adhesive makes the PSOS technology practical. The R&D work at MSI and elsewhere [110] includes the development of pyroelectric arrays for infrared cameras, fingerprint readers, and thermal imaging devices, ultrasound arrays for high resolution NDT and invasive medical imaging, and integrated accelerometers for micro miniature components.

Smart Skin **-** Piezoelectric film can both sense surface energy and can micro-deflects the surface. These capabilities may be of interest in active surfaces for sound cancellation, extension of laminar to turbulent flow boundaries, etc. Considerable work is under way at university and government laboratories in these and related applications.

5. RESULTS AND DISCUSSION

Recent work has directly compared Piezoelectric material which was ceramic based PZT, polymer membrane based PVDF and polymer foam based PP piezoelectric materials for their ability to generate energy in terms of voltage output. Each category of material behaved differently under varying conditions. The initial vibration experiments using electro mechanical shaker and frequency between 0-120Hz have shown that the single layer of PZT 120µm and 250µm produced larger voltage output when compared with the double layer structures. However, this could have been due to inadequate bonding between the multilayer specimens. Similar conclusions can be drawn from the results for the single and multilayer PVDF specimens subjected to the same experimental procedures.

Overall, the PZT bimorph produced largest voltage output under all experimental conditions, followed by the single layer 250µm sample and 120µm single layer specimen. PVDF based structures produced the lowest voltage output under these conditions.

In order to establish whether impact at various positions of the sample delivered any effect, the samples were subjected to impact analysis using an Instron machine with 1.02kg mass striking the sample on both ends and at the centre. No significant variation in the voltage output was observed due to the positional impact for most of the samples. However, for the PZT Bimorph structure the voltage output was three times greater when the impact was made at the edges than values obtained for the central impact. This is due to the presence of the metal shim between the layers, which produced additional vibrations within the structure. On the other hand the impact at the centre of the material may also have resulted in cancellation of the out-of-phase vibrations.

Controlled vibration of PZT, PVDF and PP materials in contact with a flexible ruler indicated that generally, the metallic ruler provided largest amount of energy due to the better vibration properties compared with the plastic ruler. Again, PZT bimorph specimen displayed the largest voltage output out of the three materials investigated. It was also found that, generally, as the distance of the specimen from the fixed edge increased so did the voltage resonance and the collective total voltage output. Although the overall voltage for PP-based materials was generally lower than PZT and PVDF, it provides more repeatable results.

During temperature elevation experiments, it was found that as the temperature increased, the voltage output dropped for the PZT material, whereas the converse effect was observed with PVDF. This appears to be possibly due to reversion of the PZT material back to the post piezoelectric state, particularly as the polymer matrix in which the PZT piezoelectric fibres are embedded and consequently aids the temperature increase of the structure. As for the PVDF, the internal chains – $(C_2H_2F_2)_n$ are excited and become more mobile, hence, delivering voltage at an increased rate. However, for the PP the voltage output began to climb initially as the sample temperature was raised and reached a maximum value around 80^{o}C. Beyond 80^{o}C the voltage output started to decline probably due to collapsing of internal voids, thus reducing the charge carrying capability of PP.

The subzero temperature experiment (from room to approximately -30^{o}C) showed some interesting phenomena in terms of voltage output. For all of the three piezoelectric materials, energy output generally increased as the temperature began to drop. This may be the result of material shrinkage at sub-zero temperatures - causing compaction of the atoms with within the material and therefore increasing the efficiency of electron transfer processes.

All three materials showed positive and negative attributes in terms of energy output depending on the conditions. In terms of maximum voltage output, the PZT Bimorph specimen generated largest voltage output, however, at a cost of increased weight, lack of flexibility and due to additional manufacturing and production costs. The application PZT piezoelectric material will not be suitable at elevated temperature due to reverse polarisation process and the very nature of the fragile fibres.

Although PVDF piezoelectric material is relatively inexpensive, the repeatability of the material to generate consistent voltage can prove to be a challenging factor. However, while PP may generate least amount of energy, it showed good promise as an engineering material due to its flexibility, cost effectiveness and repeatability characteristics. Furthermore, due to large volume of air (pores) within the material, it would also be beneficial from the weight aspect.

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