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Recent developments in electroceramics: MEMS applications for energy and environment☆

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Abstract

Thin films of ferroelectric materials such as polar polymers and polymer ceramic composites show unique properties for a wide range of applications in the field of microelectronics, communications, biomedical engineering, energy conservation, micro-electromechanical system (MEMS) and others. Interest in these materials for devices having high permittivity induced by electrostatic polarization, has been revived in the past few years. The work on development of acoustic transducers, vibration sensors and pyroelectric arrays with integration of MEMS structures by bulk micromachining has begun in number of organizations in India. In this paper, recent developments in ferroelectric materials, advancements in poling and characterization techniques as well as materials considerations for integration with microelectronics in MEMS structures are briefly discussed. A review of status of the ongoing research work and the future prospects for application of MEMS devices in energy and environment are presented.

Keywords: Electroceramic materials; Ferroelectric polymers; Electric poling; Polarization; MEMS applications

1. Introduction

Ever since Jacques and Pierre Curie discovered ferroelectric effect in Rochelle salt way back in 1880, field of applications of ferroelectric materials has been growing. Ferroelectricity in single crystals was observed in 1920s, but it was the discovery of ferroelectricity in polycrystalline ceramics like barium titanate, that has led to several new possibilities. Ferroelectric ceramics are non-centro symmetric polar materials and dipoles in them are randomly oriented. Electrical charging or poling process aligns the dipoles. Induced polarization responds to changes in thermal and mechanical stresses resulting in pyroelectric or piezoelectric responses. This was a transition point in the history of ceramic materials observed during World War II. It was seen that an external electric field could orient domains, within the grains of a polycrystalline material, thus producing a material similar in behavior to single crystals as far as its ferroelectric and piezoelectric properties are concerned. Dipole switching and piezoelectric behaviour in polyvinyledene fluoride polymer was observed in 1969. Another breakthrough occurred in early 1980s, when ferroceramics thin films were developed using sol–gel wet chemical methods as well as vacuum deposition techniques. Integration of ferroelectric films to silicon chip was demonstrated in 1993 [1]. Since then, electroceramics have come to the threshold of a technological revolution preparing towards nano-composite intelligent materials.

2. Recent developments in ferroelectrics

Ferroelectricity is a property of certain dielectrics, which exhibit a spontaneous polarization. Ferroelectric ceramics, polymers and their composites form a class of functional materials, that are being increasingly utilized for their specific dielectric, ferroelectric, piezoelectric, pyroelectric, electro-optic and electro-chromic as well as superconducting properties in microdevices. Recent developments taking place in these are discussed below.

☆ The view expressed here need not necessarily represent views of the organization.

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Table 1
Dielectric, piezoelectric and pyroelectric properties of PZT modified with rare earths materials

Material properties	PLZT	PSZT	PEZT	PGZT	PYZT
Dielectric constant, ε'	1600	420	392	283	675
Piezo d_{33} (pC/N)	400	240	225	220	75
Piezo d_h (pC/N)	37	83	55	26	–
Piezo g_h (mV m/N)	2.6	23.3	15.4	12	–
Piezo figure of merit, $d_h g_h$ (fm^2/N)	96	1851	877	312	–
Density, ρ (g/cm^3)	7.4	7.2	6.8	6.8	6.8
Curie temperature, T_c (°C)	110	225	299	324	327
Pyroelectric coefficient, P_i (μC/m^2 K)	170	350	401	100	70
Ionic radii (A^0)	1.06	0.096	0.95	0.94	0.93
Dopant (%)	8.0	4.0	5.0	5.0	5.0

PLZT, lanthanum doped; PSZT, samarium doped; PEZT, europium doped; PGZT, gadolinium doped; PYZT, ytterbium doped.

2.1. Electroceramic materials

The electroceramics are proving most promising for use in miniature devices for industrial and commercial applications, because of their unique properties, namely high piezoelectric and electro-mechanical coupling on poling, very high dielectric permittivity in Relaxor system and high pyroelectric as well as electro-optic coefficients in some. The dielectric, piezoelectric and pyroelectric properties of barium titanate (BT), lead zirconium titanate (PZT) and modified PZT with rare earths (Table 1) have been studied extensively [2]. These high permittivity ceramics have proved to be excellent materials in monolithic multiplayer capacitors (MLCs), resonators and delay lines in communication applications, in noiseless printing heads for bubble jet printers, ultrasonic imaging, accelerometers, hydrophones and high resolution tomography. The lanthanum doped PZT (PLZT) is transparent and can be sensitized by optical signal. Developments in thin film deposition techniques to synthesize materials on micro scale with controlled stoichiometry, integration of electroceramic functions with microelectronics and further miniaturization in micro-electromechanical system (MEMS) devices using substrates other than quartz and silicon are the current R&D activities in electroceramics worldwide [3].

2.2. Ferroelectric polymers

Ferroelectric polymers though semi-crystalline in nature show piezoelectric properties in niche areas where ceramics are incapable of performing. Ferroelectric dipole orientation occurrence in polyvinyledene fluoride (PVDF) was confirmed in 1978 and since then it is the most studied polymer for piezoelectric transducer related applications. It has high voltage sensitivity and makes excellent pressure sensor material [4]. Its copolymer with trifluoroethylene (TrFE) and tetrafluoro-ethylene (TFE) increase crystallinity up to 90% and represent state-of-the-art piezoelectric and pyroelectric polymers for use in telecommunication applications such as miniature microphones, cellular phones and hearing aids. The PVDF films have good pyroelectric response over a useful range −50 to 100 °C, making them suitable candidate for infrared sensors as low cost uncooled IR detectors. Other promising semi-crystalline polymers being investigated for ferroelectric behaviour are polyureas, polyamides and biopolymers (like keratin, peptides, collagen, etc.). Recent research is directed towards thin films of polyurea grown by vapor deposition method, piezoelectricity of polyurethane produced by coupling of electro restriction and applied electric field and investigation of ferroelectricity in amorphous polymers without crystal lattice structure [5].

2.3. Polymer: ceramic composites

Benefits of combining polymers with piezoelectric ceramics have been reported by different researchers from the study of polarization in them. Polymers are flexible and light weight, but their piezoelectric strain constant is lower than that of ceramics. They have high breakdown strength and their density is close to water as well as human body tissue and they make good sensors for underwater and biomedical applications. On the other hand, ceramics have good piezoelectricity; they can have high dielectric constant and good electrical impedance matching, but are rigid. A comparison of dielectric and mechanical properties of PVDF and PZT is shown in Table 2. When combined, electroactive polymers are much lighter and exhibit as much as hundred times the piezoelectric strain in comparison to electroactive ceramics. Ceramic nanoparticles dispersed in the ferroelectric polymer matrix are also known to show much higher electromechanical coupling coefficient and higher critical temperatures. The major advantages of polymer-ceramic composites are not only improved performance, higher dielectric breakdown, high electro-mechanical coupling, but also better integration of sensor and actuator functions and ability to pattern electrodes on to film surface for poling selective regions. Such patterns can pave the way for development of electro-optic and non-linear optical microdevices and form current area of research.

The properties of composites depend on the connectivity of different phases and their improved processibility for incorporation into devices is being investigated. One of the

Table 2
Comparison of a standard piezoelectric polymer and a ceramic material

	d_{31} (pm/V)	g_{31} (mV m/N)	k_{31}	Salient features
Polyvinylidene fluoride (PVDF)	28	240	0.12	Flexible, lightweight, high dielectric breakdown, low acoustic and mechanical impedance
Lead zirconium titanate (PZT)	175	11	0.34	Brittle, heavy, high dielectric constant, fast domain polarization switching, broad temperature stability

Source: [5]. d_{31} is piezoelectric strain constant; g_{31} is piezoelectric stress constant; k_{31} is electromechanical coupling coefficient.

most innovative applications of such composites in biomedical field is artificial muscle actuator for robots. At NASA's Jet Propulsion Laboratory multi-finger electroactive polymer grippers (MFEGs) have been made for robotic hands. Miniature intelligent robots with such grippers for internal inspection in manufacturing systems as well as in medical prosthesis and active implants to stimulate the tissue are nor far in future.

2.4. Electrical poling

Electrical poling of ferroelectrics is at 'heart' of device applications and miniaturization. For poling the material is heated and a high electric field is applied across it for a given duration. The domains within grains of the polycrystalline material rotate in the direction of the field and get frozen when the material is cooled in the presence of the field. The 'electret' so formed has stable polarization for a long period (sometimes years). A number of ceramics crystallize with the perovskite structure and when poled they show extremely high piezoelectric coefficient. This 'thermal poling' is the oldest method, which has been extensively adopted for polymers and other dielectrics. The charge transport in such dielectrics is strongly dependent on temperature. In materials where charge dynamics is sensitive to light, 'optical poling' is adopted. It is similar to thermal poling except that light is used in place of heat. It has been found that amount of stored electric charge in dielectric materials increases with poling time and poling field, till it saturates.

Two other charging methods, viz. corona charging and electron beam injection can also be adopted for materials with higher melting point. In corona charging, a corona grid is placed over the material and the current flowing through the sample is maintained at a constant value. In electron beam charging an electron gun is used. The sample is biased under the high electric field and interstitial polarization is detected. A number of variations in these poling methods, as depicted in Fig. 1, have been developed to suit the materials and applications in view. The correlation of poling technique and polarization dynamics is a subject of analysis and further studies.

2.5. Characterization methods

The polarization dynamics in ceramics, both PZT and Relaxor type system, encompasses very broad time scales from pico-seconds for dipolar fluctuations to almost 10 years for retention of polarization. Polarization switching occurs on a time scale of few nanoseconds and Relaxor phenomena takes place in few seconds (Fig. 2). Wide range of old and new characterization methods are being used for study of polarization in electroceramics. Temporal fluctuations and spatial responses of dielectric response poled films can be measured by scanning microwave microscopy and femtosecond optical spectroscopy. The remnant polarization can be measured or scanned by relaxing the frozen charge using light, thermal and pressure induced probes. Thermally stimulated current measurement is well known quasi-static method carried out by heating the poled material at a uniform slow rate of 1–3 °C/min. The characterization by this method has proved to be an extremely useful to study dipolar behavior or charge trapping characteristics within domains as well as to get information on different phase transitions and charge retention time. The charge stored per unit area is determined by integration of current with respect to time. Other methods include direct strain or charge measurements and resonance analysis. The role of trapped charges, dipolar orientation and the effect of forming conditions on electromechanical prop-

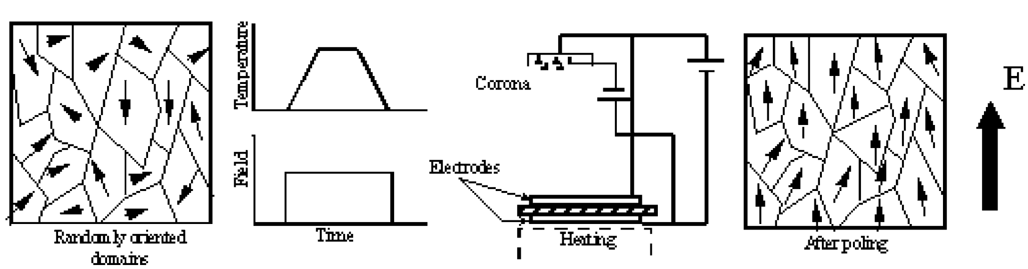

Fig. 1. The electrical poling methods and ferroelectric material with orientation of grains before as well as after poling.

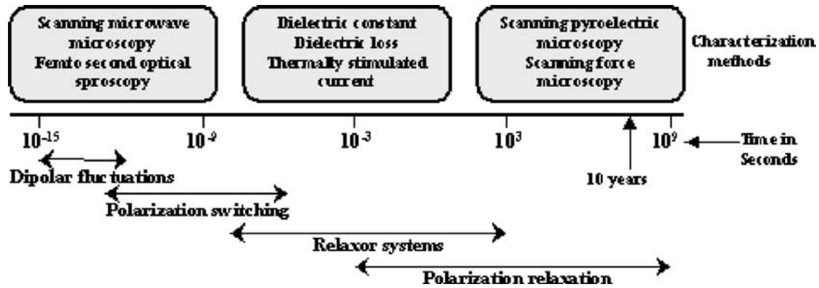

Fig. 2. Polarization dynamics and characterization methods [9].

erties of PVDF like ferroelectric polymers and PZT type ceramics have been widely investigated [6,7].

Scanning pyroelectric microscopy (SPM) measures pyroelectric current due to heating by focused laser beam scanned across the film. Using this technique, it is possible to study domain switching of ferroelectric thin films. In the laser intensity modulation method (LIMM), the diffusion of heat inside the material though modulated Nd:YAG laser pulse of energy 1–10 mJ traversing through the samples, leads to thermal expansion and changes in the temperature dependent physical properties of the materials like the observation of pyroelectric current [8]. The SPM techniques can be used to probe the crystallites and the domain structure in thin films with fine spatial and temporal resolution.

Another type of force used to study the effect of perturbations on polarization dynamics is through a pressure or piezoelectric transducer, which generates pulsed mechanical force to characterize three dimensional space charge profiles to a good sensitivity [9]. It uses a low frequency ac signal imposed on the metallized atomic force microscope (AFM) tip to generate a piezoelectric response, which results in a height change on surface depending on the sign of polarization. Regions of bright and dark contrast are created to represent positive and negative polarization states and can be used to image polarization relaxation. Electric force microscopy (EFM) is seen to be of immense value in understanding the relaxation of polarization with high spatial resolution. These novel techniques are being adopted to understand the role of interfaces and complex polarization dynamics in thin ferroelectrics for applications in devices.

3. Indian scenario

The area of electroactive polymers and ceramics is fast growing. The research work in ferroelectric materials for device applications began in 1970s at the Indian Institute of Technology, Kanpur, Delhi University and National Physical Laboratory, Delhi. The idea of blending ceramics with polymers for study of polarization behaviour for device applications was conceived in the Physics Department of IIT Delhi in early 1980s. Since then, a large number of compositions of thin films of barium titanate (BT), lead zirconium titanate (PZT), modified and doped PZT, PMN type Relaxor and ceramic: polymer composites have been prepared and tested for different applications in the advanced ceramics laboratory of the Institute [10].

The research on electroceramics and polymers thin films as well as silicon based MEMS is being carried out in number of other organizations [11]. For example at Indian Institute of Science (IISC), Bangalore, techniques of thin film deposition such as multi-ion beam reactive sputtering, plasma assisted growth, excimer laser ablation and MOCVD have been tried. Backward switching effect observed in PZ and PZS thin films show promising result for microelectronics applications in high-speed charge coupling capacitor [12]. Low energy ion induced effects in multi-component oxide films, ion-surface interactions and epitaxial growth in ferroelectrics and high permittivity oxide films for dynamic random access memories (DRAMs), development of epitaxial pyroelectric thin films for IR detection using ECR plasma are some of the ongoing areas of research. Technical expertise exists here and at other institutions for growing several types of non-linear optical crystals of requisite size and quality. The research work carried out at IIT Mumbai has focused on the amorphous and nano-crystalline thin films of elemental semiconductors and their alloys such as Si–H, Si–C, Si–N, etc. Dielectric properties of thin films of PZT ceramics and lead magnesium niobate (PMN) have been the recent studies for correlation with grain size, thickness, etc. at IIT Kanpur. Using chemical vapor deposition enhanced by either a hot filament, i.e. HFCVD, or r.f. plasma, i.e. RFCVD, development of devices and material modification by low energy ion immersion technique has been targeted. Quantum-dot materials based on semiconductor nanoscale have been prepared at IIT Chennai.

At IIT Kharagpur, a large number of electroceramic materials have been characterized such as lead germinate oxide (PG), PZT, PLZT, lead magnesium niobate-lead titanate (PMN-PT), barium titanate (BT), barium strontium titanate (BST). Compounds with K_2SO_4 structure have also been investigated exhibiting successive ferroelectric, paraelectric commensurate-incommensurate phase transitions. Work on synthesis of the doped $BaTiO_3$ materials in bulk and thin film forms for their applications in transducers and other piezoelectric devices has been pursued as well as studies on PVDF and other piezoelectric polymers have been carried out at Universities of Allahabad, Burdwan, Delhi, Jabalpur and Benaras Hindu University. The Center for Advanced Technology, Indore has developed transparent PLZT ceramic crystals for electro-optic applications. Several other laboratories in the country have made important contributions to understanding of NLOs processes and materials.

Work on temperature and frequency characterization of dielectric and electromechanical properties of electroceramics for transducer applications in soft PZT materials developed at National Physical Laboratory (NPL), New Delhi for low power applications was reported in 1980s [13]. The Solid State Physics Laboratory (SSPL), New Delhi has carried out fabrication of, La doped PZT, PCT and BST ceramics prepared by high temperature solid state reaction and pulsed laser deposition (PLD) techniques. The MEMS devices based on silicon technology are also the main thrust area of this laboratory. The MEMS research is being carried out at a few other places including Central Electronics and Engineering Research Institute, Pilani and C-Met Trissur.

The work on integration of electroceramics with MEMS based structures has recently begun at very few Institutions. First MEMS vibration sensor having lanthanum doped PZT (PLZT) thin films with composition 8/60/40 was fabricated at IIT Delhi using silicon micro machining technology. Calcium doped PT and ferroelectric Relaxor ternary system has been studied for development of infrared detectors and MLCs. The scientists at Naval Materials Research Laboratory (NMRL), Mumbai have developed advanced technologies for SONAR system design, acoustic signal processing, information technology displays and underwater transducers by using a variety of electroceramic materials [14]. Currently, NMRL, Mumbai and National Physical Oceanographic Laboratory (NPOL), Cochin are engaged in research on micro-miniaturization of electroceramics.

Noteworthy is the Government of India initiative to launch nationally coordinated programmes, such as the National Smart Materials Programme (NSMP) and Nanomaterials Science and Technology Initiative (NSTI). The NSMP has identified separate tasks for development of materials for sensors and actuators and for development of devices. It is also addressing packaging and is aiming to promote ‘smart’ sensor development. The NSTI has supported advance characterization facilities such as atomic force microscope, scanning tunneling microscope, tunneling electron microscope and matrix assisted laser deposition ionization spectroscope to gear up development of technology for nanofabrication, nanolithography, nanosensors, nanotubes and nanowires, nanosize ceramics and nanocrystalline intermetallic compounds.

4. MEMS applications and future considerations

The MEMS are miniature array of devices that combine electronics with mechanical operations using integrated processing technology. For a number of applications, MEMS concept facilitates better quality control, less material use

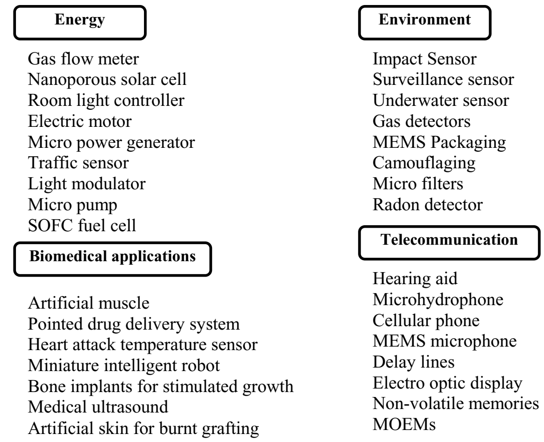

Fig. 3. Potential applications of ferroelectric MEMS in energy and environment.

and low energy consumption. The potential applications ferroelectric microdevices in energy, communication, environment and biomedical engineering are summarized in Fig. 3.

Among different category of functional materials being studied for MEMS, thin films of poled ferroelectric compositions with large piezoelectric and electromechanical coupling coefficient are most important candidate materials for MEMS devices, having low cost of fabrication and possibility of integrating sensor, actuator and control functions. Here we briefly discuss thin film deposition techniques for electroceramics and electroactive polymers and critical challenges in MEMS devices, viz. effect of thinning on electrical properties and integration of piezoelectric layer with the substrate as well as rest of the electronics.

4.1. Thin film deposition techniques

The drive towards miniaturization has led to development of new routes of fabrication of ceramics and controlling grain size in them as opposed to bulk compacting, tape casting and sintering processes. Thin film deposition techniques such as sol–gel method, hydrothermal route, r.f. sputtering, metal-organic chemical vapor deposition (MOCVD) and pulsed laser deposition have been developed and are being adapted in commercial devices. Table 3 lists the advantages and disadvantages of different film deposition techniques. Three major categories are sol–gel, physical vapor deposition and chemical vapor deposition. In wet chemical methods, sol gel techniques uses fine powder in gel form in a liquid like mixture of metal allcoxides and organic salts to grow transparent ceramic films. It is low energy consuming process at lower crystalline temperature and has better control of chemistry of mixing of precursors in liquid state at molecular level. Most electroactive ceramics and polymers are amenable to this technique. Physical vapor deposition requires vacuum and uses D.C. or r.f. magnetron sputtering and pulse laser deposition to provide high quality, uniformity, and stability but low deposition rates of

Table 3
Merits and demerits of different thin film deposition techniques for ceramics

S. No.	Deposition techniques	Advantages	Disadvantages
1	Sol–gel	Lower crystallization temperature, lower cost, better control of mixing of precursors, quickly produce new materials	Lack of phase and composition control, morphology, reproducibility
2	Physical vapor deposition	Compatibility with IC processing	High equipment cost
	(i) dc sputtering	Uniformity and scalability, high quality	Low deposition rate, high point defect concentration
	(ii) Pulsed laser deposition	Rapid sampling of materials, quickly produce new materials	Lack of uniformity, high residual stresses
	(iii) MBE	Composition control, precise atomic layering, extreme flexibility and scalability	Expensive, development stage
3	Chemical vapor deposition	High deposition rate, good stoichiometry control, low point defect concentration, high conformity and scalability	Low precursor stability, expensive

materials. The chemical vapor deposition, i.e., MOCVD on the other hand, uses volatile chemical precursors, which are vaporized on heated substrates. It is proving suitable for conformational deposition of high quality three-dimensional structures on bottom electrodes. and is characterized by high deposition rates. The application of molecular beam epitaxy (MBE) to ferroelectrics is in research stage.

4.2. Effect of thinning on polarization behaviour

Thinning has given rise to flexibility in processing, control of orientation through choice of substrate material and boost to fabrication of microdevices from ferroelectrics. Nanostructural features such as grain size, grain boundaries and pinning of domain-wall introduced during processing steps have been shown to significantly affect dielectric, pyro or piezoelectric behaviour in ceramics. Domain-walls are known to be less active in thin films in comparison to bulk ceramics. As particle size reduces to nanosize it can become a single domain, with domain-wall at the grain boundary itself, and the movement of domain walls is restricted. Shift in phase transition temperature with grain size, enhancement of conductivity and increased domain-wall contribution to dielectric response in fine grain ceramics have been observed [15]. Relaxor ferroelectrics show unusual properties as a consequence of having compositional inhomogenity on a nanometers scale. Ferroelectric Relaxor have large permittivity over a wide temperature range and are shown to possess electro-mechanical coupling efficiency exceeding 90%. More and more applications of nonlinear electrorestrictive Relaxor materials in piezoelectric microdevices have been conceived and demonstrated such as micro-accelerators, micro-pumps, micro-filters and micro-actuators using electroceramics. Further research is being pursued for developing thin films that exhibit properties similar to Relaxor-ferroelectric single crystals and understanding as well as modeling of their response. In anti-ferroelectric materials below a critical thickness ferroelectric behaviour is exhibited. It is attributed to self-polarization during the growth of the film and with advances in processing techniques, possibility of growing self-poled films is not ruled out.

A phenomenon such as appearance or disappearance of spontaneous polarization is ceramics below a critical thickness is of fundamental importance in future integrated devices. Factors influencing piezoelectric response in polymeric thin films are status of polarization, its mechanical coupling to the substrate, presence of defects and their influence of crystallite boundaries. The lack of finite size effects on Langmuite–Blodgett films of P(VDF-TrFE) thinner than 15 nm has been reported [16]. There is no suppression of the ferroelectric phase and the phase transition temperature is seen to be independent of thickness in polymers. However, using variable temperature scanning tunneling microscopy and spectroscopy, a well-ordered chain structure with atomic resolution indicated intra- and inter-chain lattice constants to be slightly smaller than for the bulk structure. The polarization switching times in polymer films [17] are longer, taking 10–100s for polarization reversal, unlike ferroelectric ceramics. Efforts are being made to bridge this gap by merger of two fields.

4.3. Interface with the substrate

Optimization of piezoelectric performance of a device is strongly influenced by the mechanical boundary conditions, besides grain size effect, defect chemistry, orientation of crystallites or domains, etc. In microelectronics, silicon is the base material. In MEMS, a substrate serves an additional purpose of acting as transducer and becomes an active substrate material. Hence the scope of materials research is widened. A great deal of interest in use of different materials like; metals, quartz, polymers and ceramics, besides silicon dioxide exists. Silicon nitride has many superior properties and is being considered attractive.

Techniques like scanning probe microscopy and transmission electron microscopy can be applied to determine the contact potential between ceramics and electrodes, simultaneously with the structure, potential at grain boundaries, atomic dimensions. While considerable success could be achieved in development of non-volatile ferroelectric random access memories (NVFRAMs) using switchable polarization in poled material on silicon substrate, most ceramics are thermodynamically unstable in contact with silicon. Both PZT based oxide ceramics and Relaxor systems integration with microelectronics for MEMS is complicated because of presence of lead. The interface-trapped charges can interact electrically with silicon and attempts to reduce trap sites by annealing results in loss of polarization. There are difficulties associated with domain-wall pinning and use of alternative substrates such as platinum or metal oxides and novel film deposition methods are being investigated.

In order to overcome the stability problem of oxides with silicon, metal–ferroelectric–insulator–semiconductor (MFIS) devices have been fabricated. Using a two-step MBE process a thin insulation layer is deliberately placed between the semiconductor and the ferroelectrics. Another emerging issue is introduction of nanoscale pores in ceramics. Very large surface area films of nanoporous titanium oxide coated with layer of a photosensitive insulating dye in a metal–insulator–semiconductor composition make a high efficiency solar photochemical cell. Such nanoporosity has been achieved in silica and is being developed for ferroelectric perovskites.

5. Conclusions

Over the last 10 years, the field of ferroelectrics and electroactive ceramics has progressed rapidly. This paper reviews recent developments in ferroelectrics, as it is a growing research area in the technical institutions worldwide. The research and development on ceramics and dipolar polymers started in late 1960s. The work on MEMS based piezo-restrictive, piezo-capacitive and pyro-electric materials has begun in 1990s. Research trends are; study of polarization dynamics, optical switching and non-uniform charge distribution as well as integration with microelectronics for application in devices. Nanotechnology methods offer new challenges for materials integration as well as properties (optical, electrical and mechanical) and modeling studies. New domain configurations would lead to development of micro-optic-electro-mechanical systems (MOEMS) with unprecedented applications.

In India, field of electroceramic materials is beginning to unfold new application domains through basic and applied research. The work on combining desirable properties of PZT and different piezoelectric polymers to forms electro active materials for advance sensors was started 15 years ago. With the current research focus on new compositions, new processes and new device concepts in ceramic: polymer and silicon integration using micro machining, material integration approaches in ceramics–polymers–silicon have become the center of attraction for emergence of niche applications in actuators and smart sensors. Finally, while this trend will continue, it would be desirable to have state-of-the-art MEMS fabrication facility at more than one academic institutions in country for technological advancement and indigenous capability building.

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