Ferroelectric materials for fusion energy applications

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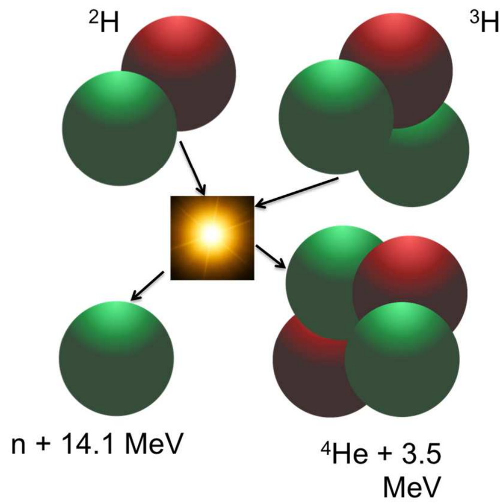
ABSTRACT

A power generating fusion reactor will operate under extreme conditions of temperature and high-energy particle fluences. The energy is produced by the nuclear fusion reaction of deuterium and tritium in a plasma, which can reach temperatures of the order of 100 million °C. The reaction generates helium, high energy (14 MeV) neutrons and gamma rays. The operation of a fusion reactor requires diagnostic equipment for the monitoring of temperature, pressure, magnetic fields, radiation energy and fluence, and other operational parameters. Functional materials, in particular ferroelectrics, can play many useful roles in these types of measurement. Many ferroelectrics are also known for their radiation hardness, which may favour their use in this environment. This review paper describes the functions where ferroelectrics may find useful application in a reactor, the effects of the reactor environment on materials in general, and the effects on ferroelectrics in particular. Though this review is centered on the technology associated with the Joint European Torus (JET), International Thermo-Nuclear Reactor (ITER) and the future planned *DEMOnstration* Power Plant (DEMO) fusion reactor types there are some similar materials related issues associated with the many other systems being explored worldwide. Conclusions are then made about the future for ferroelectric materials in fusion reactors and some of the research challenges that need to be addressed.

1 THE FUSION REACTOR AND THE MATERIALS ENVIRONMENT

A power generating fusion reactor will operate under extreme conditions of temperature and high-energy particle fluences. The energy is produced by the nuclear fusion reaction of deuterium (D) and tritium (T) in a plasma, which can reach temperatures of the order of 100 million °C [1], Figure 1:



$$D + T \rightarrow {}^4He(3.56MeV) + n(14.03MeV)$$

Figure 1: Nuclear fusion reaction of deuterium and tritium in a plasma.

The reaction generates helium, high energy (14 MeV) neutrons and gamma rays. A schematic diagram of a reactor is shown in Figure 2. The helium (alpha particles) needs to be removed to avoid poisoning the plasma, and this is done through the divertors, which also captures their energy. The high energy neutrons carry the major part of the energy generated, and are very penetrating (>30 cm in steel). They are captured in the outer blanket where they typically transfer their energy to liquid lithium. The fluences are of the order of 10^{19} m^{-2} (second mirrors at the divertor port) to 10^{24} m^{-2} (bolometers and magnetic coils near the blanket gap)[2]. The interaction of the neutrons with the lithium also produces tritium, and thereby breeds fuel for the reactor (the deuterium comes from normal water).

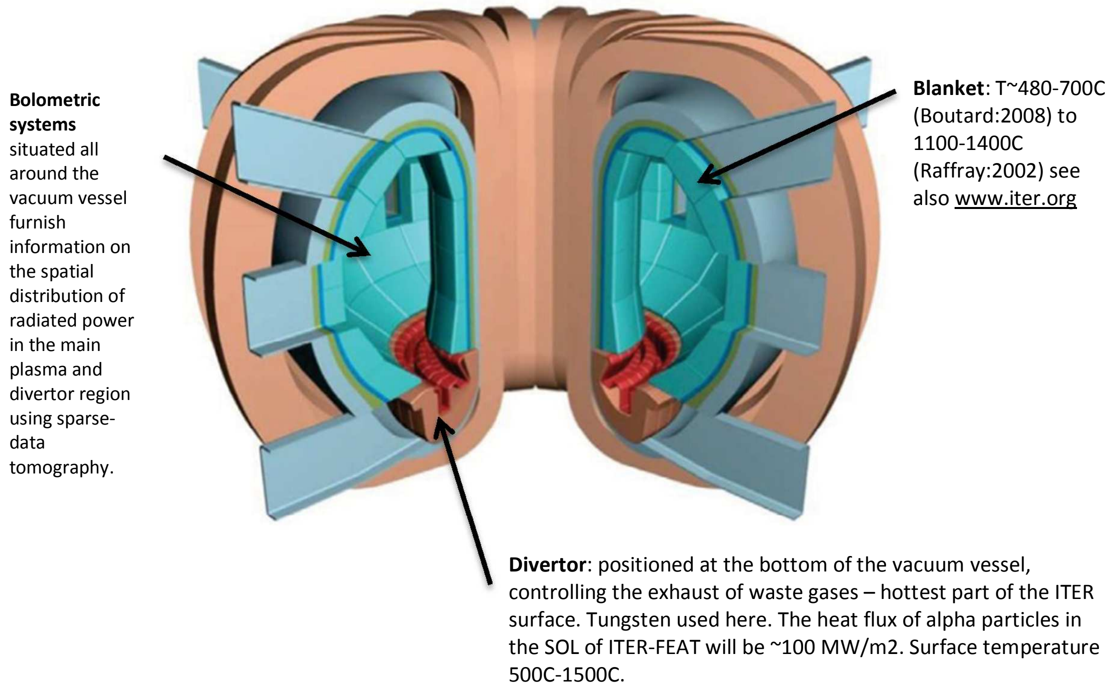


Figure 2: Schematic view of a fusion power plant (total height approximately 20 m). The items for which material performance is particularly crucial are the blanket (shown in blue), and the divertor (red). The vacuum vessel (grey) has access ports for maintenance which pass between the magnets (brown). Example locations for ferroelectric material deployment and typical temperatures envisaged [1,3]. Reprinted from [4] with permission from Elsevier.

The operation of a fusion reactor requires diagnostic equipment for the monitoring of temperature, pressure, magnetic fields, radiation energy and fluence, and other operational parameters. Functional materials, in particular ferroelectrics, can play many useful roles in these types of measurement. Many ferroelectrics are also known for their radiation hardness [5-7], which may favour their use in this environment. Radiation induced damage can be recovered by annealing [8-10], but also by electrical cycling by alternating currents [11].

This review is focused on the general materials requirements associated with the international Tokamak type (JET/ITER/DEMO) reactor development programmes. However, this style of reactor is not the only fusion power generation system being explored – though it does attract most of the global media attention. Though it is not the intention of this article to review the merits and drawbacks of the variety of fusion technologies currently being developed, we feel it important to at least cite the most relevant work. Alternative fusion configurations include: Compact Tokamak/Spheromac (such as the Mega Ampere Spherical Tokamak (MAST) at the Culham Labs in the UK; Field Reversed Configuration[12,13]; Dense Plasma Focus[14]; Reversed Field Pinch[15]; Magnetised Target[16]; Stellarators[17]; Electrostatic Inertial Confinement[18]; and the Laser Inertial Confinement[19]. All technologies will likely face similar (and extended) problems and challenges for space and materials opportunities.

This paper describes the functions where ferroelectrics may find useful application in a (Tokamak) reactor, the effects of the reactor environment on materials in general, and the effects on ferroelectrics in particular. Conclusions are then made about the future for ferroelectric materials in fusion reactors and some of the research challenges that need to be addressed.

2 APPLICATIONS OF FERROELECTRICS IN FUSION TECHNOLOGY

2.1 INTRODUCTION TO FERROELECTRIC MATERIALS

Ferroelectric materials are polar and possess a spontaneous electrical polarization (electrical dipole) in the absence of an electrical field. The direction of the internal electrical polarization (P) can be switched by the application of an external electric field (E). The usual method for identifying and characterizing such materials is to map the hysteretic relationship between these two parameters, known as a PE loop [20]. These materials often exhibit phase transformations dependent on multiple parameters such as chemical composition, temperature, electric field, stress, and history of electric field poling [21-25]. In piezoelectrics, the change in polarization is associated with a mechanical change in shape and vice versa. Many reviews exist that explore the history and background to ferroelectric materials and the reader is referred to the books of Jaffe and Jaffe [26]and Lines and Glass [27] for example.

2.2 DIAGNOSTIC EQUIPMENT

The performance of diagnostic equipment in the radiation environment of a fusion reactor will be an important factor in the operation of ITER [28] and future power generating reactors. For ITER there will be over 40 diagnostic facilities, providing an even greater number of different measurements on materials used in such an environment. These include measurement of strength and brittleness, transport properties (mass, electrical, thermal), heating, optical transmission, parasitic current and light generation during reactor operation. The devices used would typically include coils, mirrors, shutters, windows. Some of the key pieces of diagnostic equipment are:

- Bolometers
- Pressure sensors
- Thermocouples
- Magnetic coils
- Neutron cameras
- LIDAR Thompson scattering
- Impurity monitoring

The piezoelectric properties of ferroelectric materials could be exploited in pressure sensing or in actuation for electromechanical control of mirrors or coils. Piezoelectric properties could also be employed for ultrasound diagnostics. The high permittivity of ferroelectrics makes them suitable for storage of electrical energy for pulse applications. Recent developments in multiferroic and magnetoelectric materials may also present opportunities for new sensing technology, particularly high sensitivity magnetic field detectors [29,30].

Ferroelectrics are also pyroelectrics and can be used to detect temperature changes. They have been proposed for the construction of radiation bolometers and some research work has already been undertaken in this context. This is described below.

Sensor systems increasingly make use of local processing of sensor information and communication. Si electronics, particularly memory, can be susceptible to damage in radiation environments. Ferroelectric materials are used for electronic memory, and they may therefore provide a more radiation-hard system for electronics in fusion, space and power applications.

2.3 FERROELECTRIC BOLOMETER

The plasma in a fusion reactor generates high levels of Bremsstrahlung electromagnetic radiation because of the interaction of the high-energy ions in the plasma. The monitoring of this radiation provides valuable diagnostic information about the condition of the fusion plasma. Bolometers for Tokamak fusion reactors are used to measure the radiation power loss of the fusion plasma. They are positioned, either singly or in arrays, in direct line of sight of the plasma. They measure temperature change from a broad spectrum of radiation emitted by the plasma. The requirements for bolometers are demanding and include [31]:

1. small area (<10 mm^2) for high spatial resolution
2. in-situ calibration
3. fast time response (<5 ms)
4. ultra-high vacuum compatibility
5. high electromagnetic fields and high temperature compatibility
6. reliable over a long period of operation (difficult to access)
7. radiation hardness to avoid damage by neutron and gamma radiation

Bolometers absorb radiation emitted by plasma over a wide range of frequencies (IR to UV). This produces a small change of temperature (<1 °C) that can be measured and used to estimate the total energy incident on the bolometer. Current fusion bolometer technologies include thermocouples or temperature dependent resistance devices, which suffer from slow response and radiation sensitivity. Figure 3 shows the basic structure of a metal foil bolometer used in the JET reactor. Devices based on ferroelectric materials, exploiting either their pyroelectric properties, or strong temperature sensitivity of the permittivity, have a number of properties that will help achieve the requirements listed above. This review examines the properties of ferroelectric materials as they affect their suitability for bolometer and other sensing functions in fusion reactors. There is a developing interest in the use of ferroelectric thin film capacitance bolometers [8]. In these sensors the temperature causes a change in permittivity of the ferroelectric. This is detected as a change in the resonant frequency of an electrical oscillator. To achieve high sensitivity the device can be operated near the Curie point of the ferroelectric, where there is a large change of dielectric permittivity with changing temperature. The advantage of ferroelectric bolometers is that they require the measurement of a resonant frequency and not a voltage. This makes them immune from the electrical noise generated in a fusion reactor. They have the additional advantage that several channels could be combined into one transmission line, which is helpful for remote sensing.

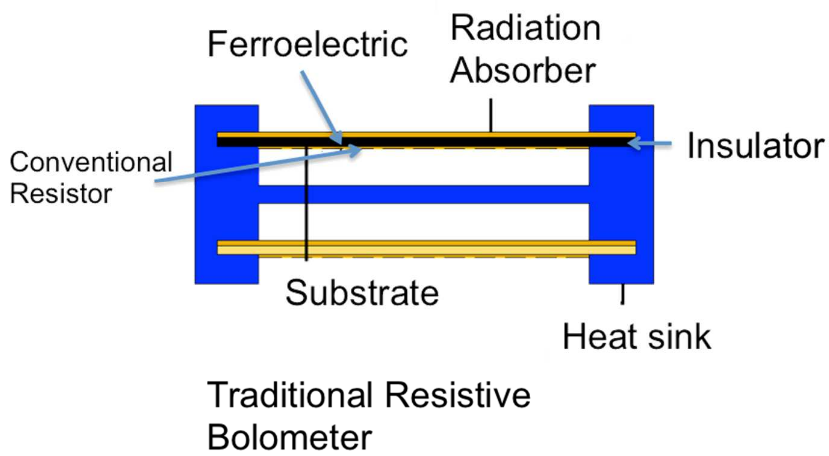


Figure 3: JET type bolometer schematic, with ferroelectric material replacement concepts.

3 MATERIALS ISSUES IN THE FUSION ENVIRONMENT

3.1 MATERIALS REQUIREMENTS

Materials for use in the fusion environment need to [32]:

a) Withstand the high power flux of a fusion reactor and the resultant high temperatures and large temperature gradients (depending on location – see Figure 2). A typical power flux is estimated at 1-10 MW m^{-2} (this is comparable to computer chip power density).

b) Survive and function for a useful length of time (at least 3 years of continuous operation), compared to the fusion reactor's planned maintenance schedule.

c) Not produce long-lived radioactive waste by transmutation.

The International Thermo-Nuclear Reactor (ITER) is currently under construction with international support from China, the European Union (EURATOM), India, Japan, Korea, Russia and the USA. This reactor is designed to obtain new knowledge of the physics of thermo-nuclear plasmas which is essential for the design of future fusion nuclear power plants. The safe, reliable and economic operation of future power plant scale reactors will also require the development of materials and components able to survive and perform in the environment of a fusion reactor. Fusion reactor design concepts are now moving towards consideration of power plant scale, where the selection and performance of suitable materials are a key consideration [1]. However, many aspects of materials selection and performance have not yet been addressed. The materials development program will therefore need to be accelerated and integrated with the on-going intensive international effort aimed at finding optimal regimes for plasma performance [32].

3.2 TRANSMUTATION

Radiation from fusion reactions causes transmutation of the elements used in the construction of the reactor. Most elements irradiated by high-energy neutrons are transmuted into high activation energy radioactive isotopes with a long half-life. Fusion offers the potential for a relatively clean (compared to fission technology) source of nuclear energy. However, this can only be achieved if reactor materials are selected which do not produce long-lived radioactive waste products. There is therefore a requirement for materials used in fusion reactors that they can be recycled “hands-on” after 100 years. These are described as “low activation” materials. For example, carbide forming elements such as Mo or Nb are undesirable but can be replaced by W and Ta in some applications. Alloying elements or impurities such as Ni, Cu, Co, Ag or Al should be kept as low as possible. The low activation requirement means that elements that can transmute to long-lived isotopes need to be kept to a very low level. For steels the low activation requirements are [1] (in ppm by mass): Nb < 0.01, Mo < 1, Ni < 10, Cu < 10, Al < 1, Ti < 200, Si < 400, Co < 10 [33].

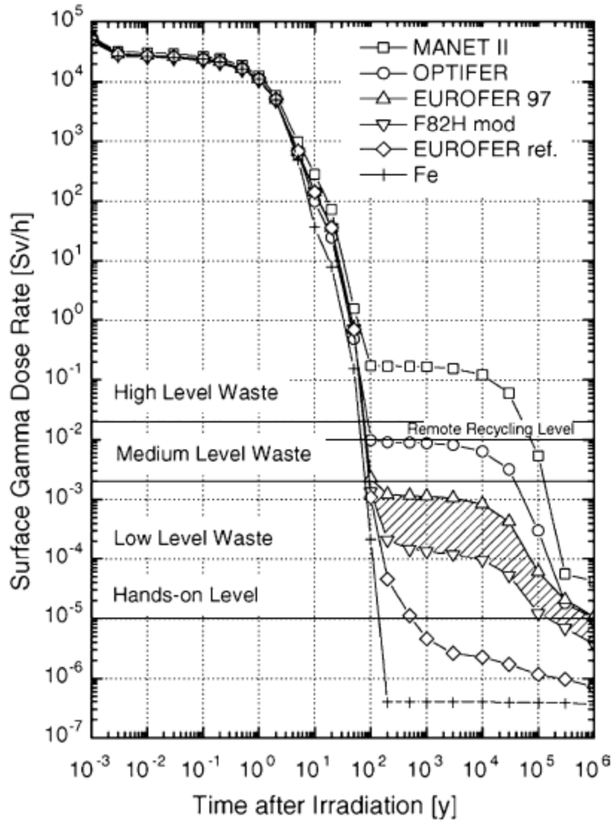


Figure 4: Calculated decay of gamma surface dose rate in iron and ferritic-martensitic steels after irradiation ([33]). (Here, EUROFER 97 is the European 9% CrWVTa steel, RAFM steels are modified compositions of conventional ferritic–martensitic 8–12% CrMoVNb steels and the Japanese reference RAFM steel is labeled F82H mod, other RAFM steels like OPTIFER (70 ppm Nb), EUROFER ref. – an alloy composition containing the theoretical values of undesired elements.) Reprinted from [33] with permission from Elsevier.

Some materials do not form long lifetime radioactive isotopes and can therefore be used without restriction, Figure 4. Unfortunately the number of such elements is very limited, and includes, Fe, V, Cr, Ta, W, C and Si. This is why steels are used extensively for the main structural parts of the reactor, W and C for the divertors and SiC in the outer blanket. Even these materials have problems in a fusion environment because they also transmute, albeit to non-radioactive isotopes. For example, W transmutes into Os and Re. After several years the concentration of these materials is high enough to form the brittle σ phase. The EURATOM/UKAEA Fusion Association have produced a reference source for transmutation data [34].

These limits were formulated for the structural materials such as steels, which form the bulk of the materials used in the reactor. Insulators, including oxides from which most ferroelectrics are formed, have received much less attention due to their relative scarcity in the reactor. The limited availability of elements, such as oxygen, would place constraints on the selection of ferroelectric materials. However, the very small fraction of the total material represented by insulators, and the fact that their functional performance is likely to be degraded before transmuted elements build up, means that it is unlikely to present a serious problem [35]. The choice of ferroelectric compounds also needs to consider the effect of changing composition with transmutation on properties and the functional lifetime of the device.

3.3 RADIATION INDUCED STRUCTURAL CHANGES

One of the main damage mechanisms from neutron irradiation is by neutron collision. An atom or ion is knocked out of its lattice site by the incoming neutron. This ion is still highly energetic and goes on to make other collisions, which result in more ions being ejected from their sites and so resulting in a cascade of collisions. After the cascade there are a number of vacancies from where the ions have been ejected, and a number of interstitial ions where they ended up. These displacements are used as a measure of the radiation dose in "displacements per atom" (dpa). One dpa means that every atom has statistically been displaced once. For fusion reactors, doses of hundreds of dpa will be experienced. However, the material maintains its integrity because the defects created by the neutron collision mostly recombine within a short time by thermally activated diffusion. However, not all of them recombine, and some form defect clusters which remain more or less permanently in the material. It is these that are the main source of damage. Because neutrons interact only weakly with matter their penetration depth is quite large. However, the high neutron energy causes collision cascades which result in defects and can cause localized melting and resolidification [32].

Even though the fusion neutrons are very high energy compared to fission products, the collision still results in displacements of ions so the overall damage pattern from this process is similar - you just get more displacements per neutron in a fusion source. This means that there may be some read across from fission studies with regard to displacement damage.

The neutron collisions can also cause further transmuting nuclear reactions, which produce unstable elements, which decay through alpha particle emission. This produces helium deep within the material[1] which can accumulate at grain boundaries causing embrittlement or even swelling (steel can swell to double its volume). This type of damage is heavily influenced by the neutron energy because the helium is formed from alpha particles during nuclear reactions. Results from fission studies may therefore not be representative of this type of damage.

These effects can be detrimental to mechanical, functional and optical properties. For example, the ductile-brittle transition (DBT) temperature of metals and alloys increases with displacement damage. If it exceeds the local operating temperature of the material, brittle failure can become a problem. In the case of dielectric materials, the Frenkel type lattice defects produced by displacement damage can lead to increased electrical conductivity and long-term electrical degradation. The Oxygen Vacancy-interstitial is likely to be the lowest energy defect [36].

For diagnostic equipment used in a fusion reactor radiation damage can cause a range of effects [28]. Table 1 shows some of the ways in which the radiation environment can affect performance of diagnostic equipment. The problem facing functional components is considerably more complex than that for the structural metallic materials due to the necessity to maintain intact not only the mechanical, but also the far more sensitive physical properties such as electrical insulation, dielectric loss, optical absorption and emission for windows and optical fibres, and even thermal conductivity[2].

This section has focussed on the effects of high-energy neutron irradiation, which is unique to the fusion environment, but it should also be noted that material alteration can occur through a variety of other mechanisms including X-ray damage, high energy charged particles, and exposure to elevated temperatures. For ferroelectric materials, charging effects from the plasma could also affect performance.

Table 1: Effects of the fusion radiation environment affecting the performance of diagnostic equipment

Specific radiation environment	**Materials and locations most affected**
Radiation-induced conductivity (RIC)	When using insulators
Radiation-induced electrical degradation (RIED)	When using insulators held under electric field
Radiation-induced electromotive force (RIEMF)	For any small voltage or current
Radiation-induced thermoelectric sensitivity (RITES)	
Radiation-induced absorption	For optical transmission
Deposition	For any first mirror or any thin metal window close to the plasma
Erosion on any first mirror	
Radioluminescence	For fibres and windows
Nuclear heating	For most front end components with complex consequences
Change in other properties due to transmutation and swelling	

3.4 MATERIALS TESTING

The 14MeV neutrons produced by the fusion reaction are much higher in energy than neutrons from sources such as fission. The radiation damage they cause therefore differs in some respects from that experienced in fission reactors. This makes materials testing difficult, and suitable facilities do not currently exist. A new facility – the International Fusion Materials Irradiation Facility (IFMIF) is planned to address this need [1]. This will use particle accelerator technology to provide a high flux source of 14 MeV neutrons [37,38].

3.5 MATERIALS MODELLING

Modelling of radiation effects on materials properties presents the opportunity to improve our knowledge despite the difficulties in testing. Neutron cascade processes are inherently multiscale [39], requiring a detailed knowledge of the properties of the collision defects, and also the interaction of the neutrons with the lattice. The methods used range from ab initio techniques that study processes occurring on femtosecond timescales and nanometre length scales, to molecular dynamics for intermediate length and timescales and finite element models for macroscopic length scales and experimental timescales [39]. For plasma facing materials, the environment is particularly challenging [39] due not only to the high radiation intensity, but also the high heat flux. Properties such as thermal conductivity and chemical reactivity are important in this area, but are not well modelled using molecular dynamics methods. Electronic effects also create a drag on the neutron providing energy exchange with the lattice in addition to collisions. Whilst a number of sophisticated techniques have been developed to tackle this type of problem, it still poses a significant challenge for modelling techniques.

4 IRRADIATION OF FERROELECTRIC MATERIALS

Research into radiation effects in ferroelectrics dates back to the 1950's and 60's. Much of this early work reported on irradiation of ferroelectrics concerned irradiation typical of fission reactors, with some of the first results reported by Wittels and Sherill [40] in 1957. The effects of radiation damage appear to be similar to the effect of ionically compensating point defects in acceptor doped non-irradiated materials. The point defects generated in both cases produce ageing effects and internal bias fields, which are apparent from the asymmetry of the Polarisation-Electric field (P-E) loops. Wittels and Sherill [40] reported a phase change in neutron irradiated single crystal barium titanate. Lefkowitz and Mitsui [41] found that fast neutrons decreased the coercive field of barium titanate by about 13%, possibly because radiation induced defects provided more nucleation sites for reversed domain formation.

Irradiation of ferroelectric materials provides an interesting opportunity to study the effect of point defects because there is the unique possibility of studying their effect on different domain structures. Chynoweth, [42] studied the effects of electron and X-ray irradiation (39 kV) of single domain and unpoled polydomain triglycine sulphate (TGS). Single domain crystals produced a highly asymmetric loop because of a bias field, similar to what is observed in aged acceptor doped un-irradiated ferroelectric materials. The spontaneous polarisation also reduced (see Figure 5 a,b). If the irradiation is done on a multi-domain crystal with a zero net polarisation a split/double loop is produced (Figure 5c). The effects of irradiation can be temporarily reversed by heating the materials above their Curie point or electrically cycling them many times. This is very similar to the behaviour of acceptor-doped ferroelectrics. If TGS is irradiated above its Curie point, and then returned to room temperature, a split/double loop is produced. At higher radiation doses the ferroelectricity of TGS can disappear [43].

Similar observations to TGS were made for irradiated Rochelle salt, which also forms split/double loops [44-47]. At higher doses the P-E loop became linear with the loss of ferroelectricity [44].

In the 1990's there was renewed interest in radiation effects on ferroelectrics [8] with the advent of ferroelectric memory which was potentially more reliable than semiconductor memory for space and nuclear applications.

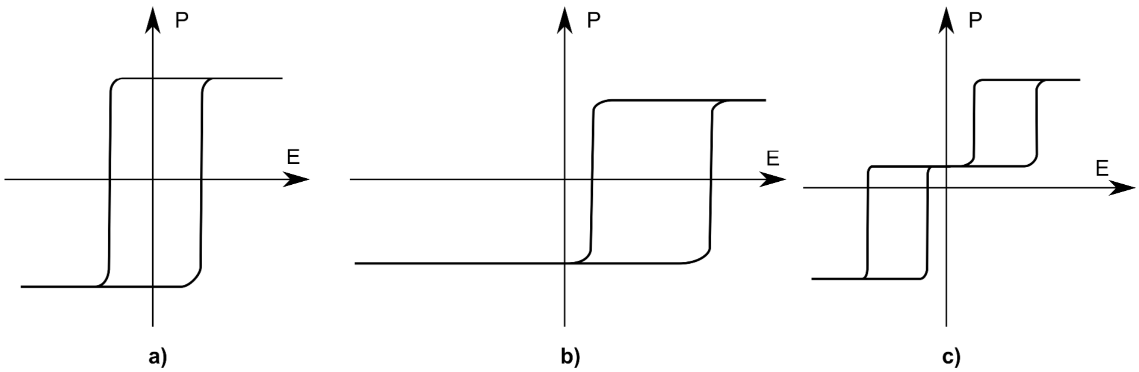


Figure 5: (a) Hysteresis loop of triglycine sulphate before irradiation. (b) Hysteresis loop after irradiation of a single domain crystal of triglycine sulphate. (c) Hysteresis loop after irradiation of a multidomain crystal of triglycine sulphate (redrawn from [48], with permission from Elsevier).

More recently there has emerged an interest in radiation effects on piezoelectric properties of films for piezoelectric MEMS (MicroElectroMechanical Systems) [49-52]. There is potential for MEMS or NEMS (NanoElectroMechanical Systems) switches to replace semiconductor devices for radiation hard logic and memory devices, again for space and nuclear electronic applications. Radiation-induced charge trapping within the gate dielectric of silicon devices can cause failure or loss of data[51]. The problem is exacerbated with the trend to thinner gate dielectrics and reduced size in modern devices. MEMS switches, however, use a metal to metal contact which is inherently radiation hard and is mechanically decoupled from the "gate" circuit. The critical factor for MEMS switches in a radiation environment is not the contact mechanism, but the actuation and the performance of the piezoelectric material. Recent work [51] has shown that PZT (lead zirconate titanate) switches still operate after exposure to over 11 Mrad(Si) of gamma radiation, although some degradation in the properties of the piezoelectric were observed, again attributed to radiation-induced defects leading to domain pinning and a reduction in piezoelectric strain and dielectric constant [51], and an increase in coercive field and remanent polarisation [49]. The sensitivity of PZT to gamma radiation effects appears to be strongly dependent on the fabrication method and quality [49,52], with the effect of the radiation depending on the initial domain pattern [50] and pre-existing defect structures [52]. Neutron irradiation appears to have similar effects with reductions in permittivity and increased switching fields reported [52]. These studies deal with the effects of X-ray [50], gamma ray [49,51] and relatively low energy neutron irradiation [52]. The research on high energy and fluence neutron irradiation of dielectric and ferroelectric materials is limited. For instance, it is not known: what factors effect defect formation; how these defects affect dielectric, ferroelectric and piezoelectric properties; and what materials will have higher radiation hardness. While there are similarities to the behaviour of acceptor-doped ferroelectrics, the mechanisms and their kinetics are not known.

Results have been reported of the effect of fast neutrons (fluence – 5 x 10^{-21} m^{-2}, energy >0.1 MeV) on the dielectric-temperature properties of La-doped PZT (PLZT – Pb_{1-y} La_y Zr_{1-x} Ti_x O_3, ferroelectric), PZT – $PbZr_{1-x}Ti_xO_3$ (ferroelectric) and PZ - $PbZrO_3$ (anti-ferroelectric) films for capacitance bolometer applications [53]. Figure 6a shows the P-E loop of un-irradiated and irradiated PLZT; irradiation increased the coercive field and loss, and induced asymmetry. The remnant polarisations may be similar, but interestingly the high field polarisation is very different. Figure 6b shows the P-E loops for PZT. The pinched loop for the un-irradiated material suggests that it is a hard, acceptor doped ferroelectric composition. The P-E loop of the irradiated material shows similar features, but with reduced high field polarisation. Figure 6c shows the P-E loops for the PZ film, antiferroelectric composition, and shows that for the three compositions the anti-ferroelectric composition is the most stable under irradiation. It is not clear if this is a consequence of its composition or the fact that it is anti-ferroelectric.

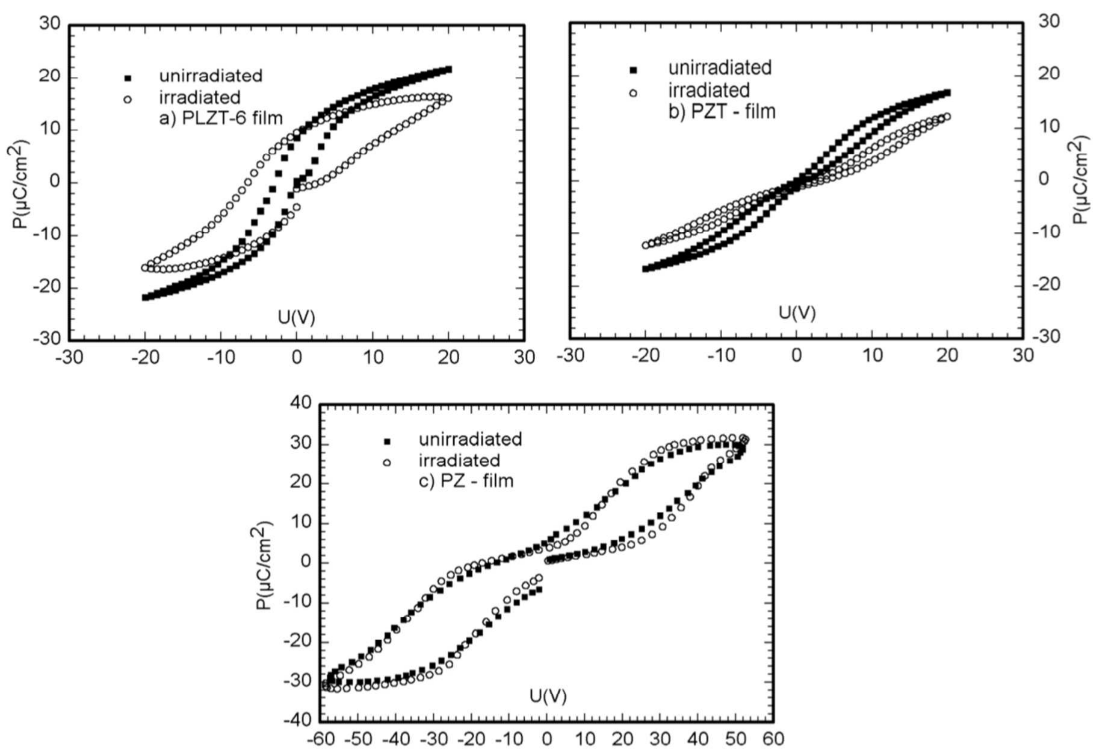


Figure 6: Hysteresis loops for (a) PLZT-6-, (b) PZT-, (c) PZ- films measured at 20Hz and at room temperature before and after irradiation. The contact areas are 0.2mm^2 (a), 0.3mm^2 (b), and 1.0mm^2 (c). From [53], with permission from the IAEA.

Bittner [53],[54] also found that anti-ferroelectric films were more resistant to neutron (5 x 10^{22} m^{-2}) and gamma-ray (1MeV up to 70 MGy) irradiation damage than ferroelectric films (although they do not specify their composition) with changes of less than 5% in the dielectric permittivity in the 25-300 °C range. Sternberg et al [10] reported the interesting observation that the ferroelectrics are more susceptible to irradiation damage near their Curie point.

It is well known that electrode-dielectric interfaces effects are important, producing internal fields and ageing effects in ferroelectric thin films – see for example [55]. It is interesting to note that the effect of irradiation on interfacial effects has not yet been reported in the literature, and this may present an important topic for future research.

There has been increased activity in recent years fuelled by research into fusion, particularly in the area of computational modelling of radiation damage (e.g.[36,37,56]). Molecular modelling of the generation and effect of Frenkel defects in barium titanate allows prediction of the effect of irradiation on their spontaneous polarisation and phase transitions. This work estimated the energy of Frenkel pair formation of Ba, Ti and O as about 9.9, 13.7 and 6.5 eV/pair, respectively [36].

With the advances in understanding of dielectrics and ferroelectrics in the last fifty years, there is a great opportunity to apply this knowledge to advance the fundamental understanding of the effect of irradiation on their properties. This improved knowledge could lead to the development of improved materials for application in the nuclear and space industries.

5 CONCLUSIONS AND PROSPECTS

As fusion technology develops from laboratory experiment towards commercial generation there will be a requirement for many new technologies for diagnostics and control to ensure safe, reliable and economic power plant operation. The materials used for these systems must be capable of reliable, long-term operation within the extreme environment of the reactor. It is likely that ferroelectric materials, because of their versatility and robustness in high radiation environments, will form an important component in these applications. Ferroelectric materials have a number of potential applications in fusion reactors as sensors (radiation, temperature, strain), actuators (control and positioning, ultrasound) and radiation-hard electronic components (logic, switches, and memory). Research to date has focussed on the effects of neutron irradiation (and other irradiation such as gamma-ray) on ferroelectric materials for fission and space applications. This work has shown changes in ferroelectric and piezoelectric properties attributable to radiation-induced defects with effects similar to that observed for ferroelectric fatigue. Whilst some of this work is relevant to the fusion application, little work has been done on the effects of the fusion reactor environment, characterised by higher neutron energies and fluences.

As many ferroelectric materials are based on perovskite oxides, research is required on the “low activation” requirements for insulators and oxides. If the “low activation” requirements of a fusion reactor were to restrict oxygen, this could present a challenge to the use of ferroelectric materials. The emphasis of the low activation requirement has been so far on the structural components that form the bulk of the reactor material. The amount of ferroelectric oxides used, however, will likely be a very small fraction of the total amount of material subject to irradiation. There are likely to be similar issues in a number of other specialised components. It is possible that very small quantities of long-lived radioactive products could be tolerated in specific components, and special procedures will need to be adopted for handling them.

Designs and specifications for new devices for plasma and reactor diagnostics based on ferroelectric materials for sensing and actuation need to be developed in parallel with progress towards practical fusion reactors. Reliable measurement of the effects of the fusion environment on ferroelectric materials is essential for the development of these applications. The established metrology of the functional properties of ferroelectric[57] and increasingly magnetoelectric materials[58] (fatigue, ageing and degradation of electromechanical, magnetoelectric and dielectric coupling) needs to be extended for in-situ measurement in the fusion environment. These measurement techniques will be needed to support both the reliable application of existing materials and the development of new materials optimised for robustness and stability in the fusion environment

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The operation of a fusion reactor requires diagnostic equipment for the monitoring of temperature, pressure, magnetic fields, radiation energy and fluence, and other operational parameters. Functional materials, in particular ferroelectrics, can play many useful roles in these types of measurement. This review paper describes the functions where ferroelectrics may find useful application in a reactor, the effects of the reactor environment on materials in general, and the effects on ferroelectrics in particular.