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Radiation enhanced electrical breakdown in fusion insulators from dc to 126 MHz

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Serious electrical degradation occurs in Al_2O_3 when subjected to concurrent electron irradiation and an applied electric field. The process occurs from dc to at least 126 MHz and a voltage threshold has been observed for the effect.

1. Introduction

Both near-term and future fusion reactor devices will require the extensive use of insulating materials under a wide range of dc and ac/rf electric fields, temperatures, and radiation levels. Work on MgO, Al_2O_3, and $MgAl_2O_4$ studying the enhancement of the dc electrical conductivity during irradiation, the so-called radiation induced conductivity (RIC), has shown that although considerable increase is observed in the conductivity it is a problem which can be accommodated by the design engineers [1–3].

The results show that the RIC may be described at any given temperature by $\sigma_{RIC} = \sigma_0 + KR^{\delta}$, where σ_0 is the conductivity in the absence of radiation (the base conductivity), R the dose rate, and K and δ constants.

However, recent work has highlighted a hitherto unconsidered problem which will severely condition the use of electrical insulators in fusion devices, namely radiation enhanced electrical breakdown [4–9]. This phenomenon has been observed to occur under moderate conditions of temperature and dc electric fields during electron, proton, and neutron irradiation [4,8,9]. It was observed that the degradation process is due to a permanent increase in the base conductivity σ_0 [4]. An extensive study at different radiation dose rates and temperatures has shown that the electrical degradation only occurs under concurrent ionizing radiation, displacement damage, and applied electric field, and that the process shows a marked similarity to colloid production in alkali halides [4–7]. No similarity was observed with ordinary (i.e. no radiation field) dielectric breakdown in which polarization plays a key rôle. It was hence felt necessary to study the process under an alternating applied electric field.

In the work presented here for Al_2O_3, results are given for the effect of applying alternating fields at frequencies from 33 Hz to 126 MHz. Again, serious electrical degradation is observed, with little or no frequency dependence. Relative to the dc results the degradation is slightly retarded. This difference has been shown to be related to a voltage threshold for the degradation process at approximately 50 kV/m. However, even below this threshold degradation still occurs, although at a slower rate, down to at least 18 kV/m. The importance of the observed radiation induced degradation in Al_2O_3, a prime fusion insulator candidate, from dc to at least 126 MHz needs hardly be stressed. The implications for any future fusion device are serious and wide ranging.

2. Experimental procedure

The experimental work reported here has been performed in a sample chamber mounted in the beam line of a HVEC 2 MeV Van de Graaff accelerator. The system permits samples to be irradiated in high vacuum with electrons at any temperature between about 15 and 750°C. The electrical conductivity is measured in situ with or without irradiation by means of a voltage applied across the sample. Full details are given elsewhere [3,10]. In this way samples of single crystal Al_2O_3 (Roditi-Union Carbide UV grade) have been irradiated with 1.8 MeV electrons at 10^6 Gy/h, 2×10^{-6} dpa/h, 450°C, with both dc and ac applied fields. Experiments have been performed with dc fields of 18, 36, 72 and 130 kV/m and with ac fields of 130 kV/m rms at 33, 5×10^3, 3.3×10^6, and 126×10^6 Hz. The sample electrical degradation with irradiation time has been obtained in all cases by switching off the accelerator beam every 8 h and by measuring the dc base conductivity σ_0 at 130 kV/m.

3. Results

Fig. 1 shows the increase in σ_0 with irradiation time for both the 130 kV/m dc and ac applied fields. One

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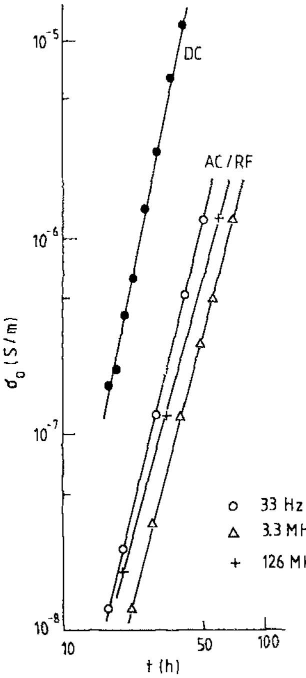

Fig. 1. Increase in conductivity σ_0 with irradiation time for dc and ac/rf applied fields for Al_2O_3 at 450°C, 1.8 MeV electrons, 10^6 Gy/h. For clarity results at 5×10^3 Hz are not shown as they are almost indentical to the 3.3 MHz results.

observes that the ac results are all very similar, and that relative to the dc results the degradation is retarded and the rate of degradation slightly reduced. In fig. 2 the time for the sample current to reach 10^{-6} A ($\sigma_0 = 1.7 \times 10^{-6}$ S/m) is plotted as a function of frequency. Little if any frequency dependence is observed, the differences most probably being due to slight variations in the dose rate which cause marked differences in the degradation rate [5].

The results for the different dc applied fields are given in fig. 3, where the base conductivity σ_0 following

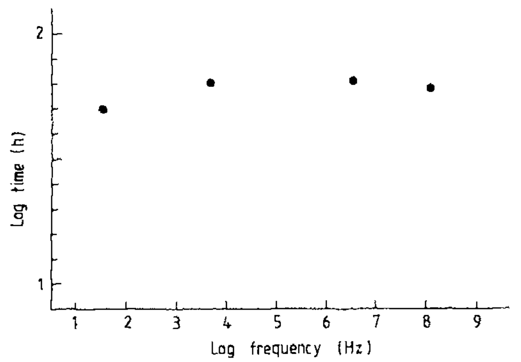

Fig. 2. Time for the sample current to reach 10^{-6} A ($\sigma_0 = 1.7 \times 10^{-6}$ S/m) as a function of applied field frequency. Irradiation at 450°C, 10^6 Gy/h.

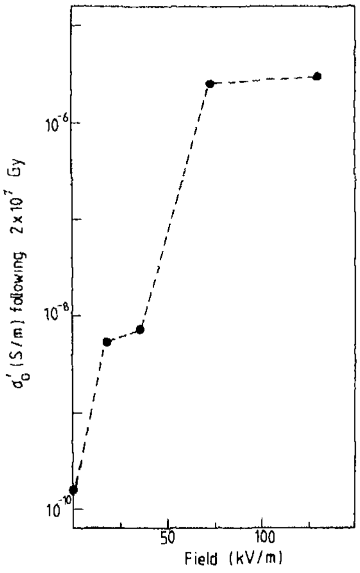

Fig. 3. Sample conductivity measured at 130 kV/m following irradiation to 2×10^7 Gy with applied fields of 18, 36, 72 and 130 kV/m.

a total dose of 2×10^7 Gy (20 h of irradiation), is plotted as a function of the applied electric field. The value plotted at zero field corresponds to an unirradiated sample, i.e. the initial σ_0 value. One observes a clear threshold effect for degradation at around 50 kV/m. Above this threshold rapid degradation is observed. However, even below the threshold degradation still occurs, samples degrading to the same value as those above threshold after about 100 h, i.e. 10^8 Gy.

4. Discussion

Single crystal Al_2O_3 is highly resistant to dielectric breakdown, samples at 1000°C, 10^6 V/m, show no degradation whatsoever after over 100 h [11]. However, recent results [4–9] have shown that under irradiation the material rapidly degrades at temperatures down to at least 350°C and electric fields lower by more than one order of magnitude. The degradation occurs by the formation of precipitates (aluminium colloids) throughout the bulk material [6]. This contrasts sharply with the well known process of dielectric breakdown, observed for example in MgO, in which polarization plays a key rôle and sample degradation begins from one electrode [11–14]. For MgO, samples which readily broke down under a dc field did not do so under an ac field, confirming the rôle of polarization [14]. However given the marked differences observed for the radiation induced breakdown and the varied uses envisaged for fusion insulators under both dc and ac/rf fields it was felt necessary to observe the behaviour under an ac applied field.

The results given in fig. 1 show that radiation induced degradation occurs under both dc and ac conditions thus confirming that the mechanism involved is different to that involved in ordinary dc breakdown. All the ac results from 33 Hz to 126 MHz are very similar and as may be seen in fig. 2 show little if any frequency dependence. However relative to the dc case the ac degradation is delayed and the rate reduced. A similar behaviour has been observed for dc degradation on lowering the dose rate [5]. This similarity led one to consider the existence of a voltage threshold for the degradation process. Such a threshold would reduce the effective time for the degradation process to be operative when an ac voltage is used, and would hence be equivalent to reducing the dose rate. The results obtained by irradiating with different dc fields are given in fig. 3. One observes a clear voltage threshold at around 50 kV/m. However, even below the threshold, at fields down to 18 kV/m degradation still occurs although at a slower rate.

The implications of these results for fusion devices are serious. DC degradation must be taken into account in uses such as neutral beam injectors, active coils and diagnostics. The observation of degradation even at very low fields is serious for proposed uses of insulators as induced current breaks in the torus and liquid breeder blankets. The results on ac/rf show that right through the ion cyclotron frequency range problems may well arise.

From the results at 126 MHz and the observed threshold one can set an upper limit of $< 3 \times 10^{-9}$ s on the time scale for the mechanism involved in the degradation process. (The mechanism must operate within one-half cycle, $\sim 4 \times 10^{-9}$ s, and only during the part of the half cycle above threshold, i.e. $\sim 3 \times 10^{-9}$ s.) The results given in fig. 2 strongly suggest that degradation will also occur in the GHz range, i.e. $< 10^{-9}$ s. This would imply that lower hybrid heating systems could also be affected.

Earlier work has pointed to a possible perturbation of the basic damage process (production of vacancies and interstitials) by the applied field [6,7]. Such processes generally occur in $< 10^{-12}$ s, beyond the electron cyclotron frequency range. Work is now in progress to study the effect of the field on the F-type vacancy production.

5. Conclusions

Radiation induced electrical degradation has been observed to occur in Al_2O_3 from dc to 126 MHz. A voltage threshold exists for the degradation process at about 50 kV/m. However degradation still occurs down to at least 18 kV/m. The consequences for future fusion devices are serious.

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