Journal of Nuclear Materials 386–388 (2009) 999–1001

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Insulator degradation due to radiation induced ion and dark currents in vacuum

E.R. Hodgson *, A. Moroño, S.M. Gonzalez

Euratom/CIEMAT Fusion Association, Avda. Complutense 22, 28040 Madrid, Spain

A B S T R A C T

Ceramic insulators and windows in ITER will be bombarded by H isotope and He ions due to ionization of the residual gas and acceleration by local electric fields. Most of the energy will be deposited at or near the surface giving rise to possible electrical and optical degradation. To quantify the problem gases at low pressure have been irradiated and the induced ion currents measured. The current decreases with decreasing pressure as expected, however it reaches an unexpected constant saturation level for pressures <10^{-1} mbar (10 Pa). Modification of the irradiation chamber indicated that the saturation was due to electrons, i.e., a radiation induced dark current from the metal surfaces. With the modified system it was possible to suppress this dark current and measure ion currents down to <10^{-4} mbar (10^{-2} Pa). In this low pressure region ion currents of about 10^{-6} A/m^3/Gy/s may be generated. In addition dark currents of the order of 10^{-8} A/m^2/Gy/s may be produced from metallic surfaces. The ion and electron currents are potentially high for large systems and must be considered as possible sources of insulator degradation.

1. Introduction

Severe electrical surface and optical degradation has recently been observed when oxide insulator materials are implanted to low doses (<10^{20} ions/m^2) with keV H and He ions at 50 to 450 °C as shown in Fig. 1 [1]. The mechanism giving rise to such surface degradation is the loss of oxygen from the vacuum insulator surface region due to preferential radiolytic sputtering [2,3]. Similarly in future fusion devices such as ITER ceramic insulators and windows may also degrade, as they will be bombarded by energetic H isotope and He ions due to ionization of the residual gas by gamma radiation and acceleration by local electric fields. To assess this potential problem one must determine the magnitude of radiation generated ion currents at low residual gas pressures. Earlier work on radiation induced conductivity due to ion currents in NBI insulator gases had shown that unacceptably high currents were generated at and above atmospheric pressure, and extrapolation indicated that high ion currents may also be produced even at low pressures [4].

Initial experiments for residual air, H, and He indicated, as anticipated, a decreasing ion current on lowering the pressure. However the measured current reached an unexpected constant saturation level for pressures below about 10^{-1} mbar (10 Pa), as may be seen in Fig. 2 [5]. As reported here, by modifying the irradiation chamber the source of this pressure independent current has been shown to be due to a radiation induced electron dark current from the metal surfaces. With the modified system it was possible to suppress most of this dark current and measure ion currents down to <10^{-4} mbar (10^{-2} Pa). Even at this low pressure the radiation induced ion currents were about 10^{-6} A/m^3/Gy/s, i.e., potentially high ion currents for large systems.

2. Experimental procedure

These experiments have been carried out in a special closed gas chamber mounted in the beam line of a Van de Graaff electron accelerator, which permits selected gases at controlled low pressures to be irradiated through an 0.05×10^{-3} m thick aluminium window with 1.8 MeV electrons [4,5]. Within the chamber a guarded volume between copper electrodes with a voltage applied, permitted the electric current flowing through the ionized gas to be measured as a function of dose rate, electric field, and residual gas pressure. The guarded volume is defined between two parallel square copper plate electrodes separated by 1.5×10^{-2} m (Fig. 3). One of the square plates, $2.5 \times 2.5 \times 10^{-4}$ m^2 formed the common high voltage electrode, while the opposite plate consisted of an inner $1.5 \times 1.5 \times 10^{-4}$ m^2 square central electrode and an outer square guard electrode separated from the central electrode by 2×10^{-3} m and with an external dimension equal to the opposite common electrode. A variable HV power supply was connected to the common electrode, and the central and guard electrodes were connected to ground via picoamperimeters. In the present experiments the gas chamber was modified to allow it to be electrically insulated and allow polarization of the chamber relative to the guarded volume (Fig. 4). The irradiating electron beam, defined

* Corresponding author.
E-mail address: hodgson@ciemat.es (E.R. Hodgson).

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doi:10.1016/j.jnucmat.2008.12.198

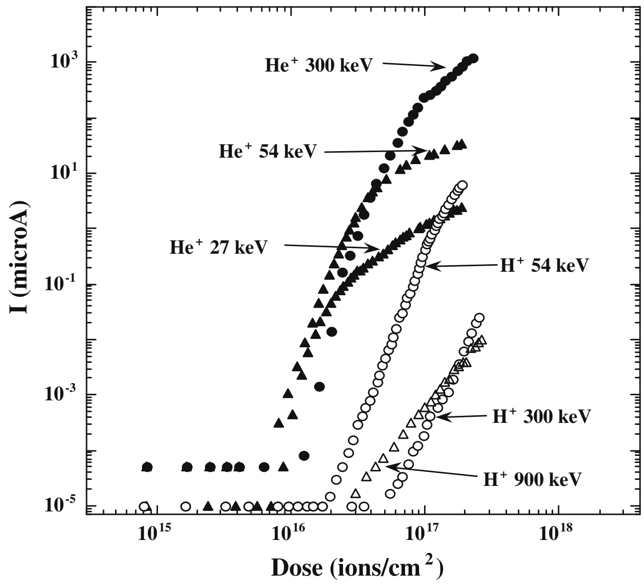

Fig. 1. Surface electrical current as a function of dose for SiO_2 samples implanted with He^+ at 27, 54 and 300 keV, and H^+ at 54,300 and 900 keV, at 50 °C.

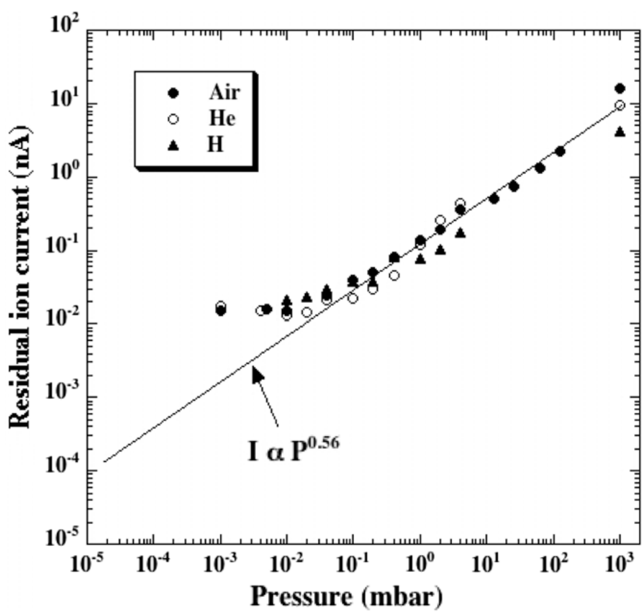

Fig. 2. Radiation induced ion conductivity for air, helium, and hydrogen with 100 V applied as a function of pressure.

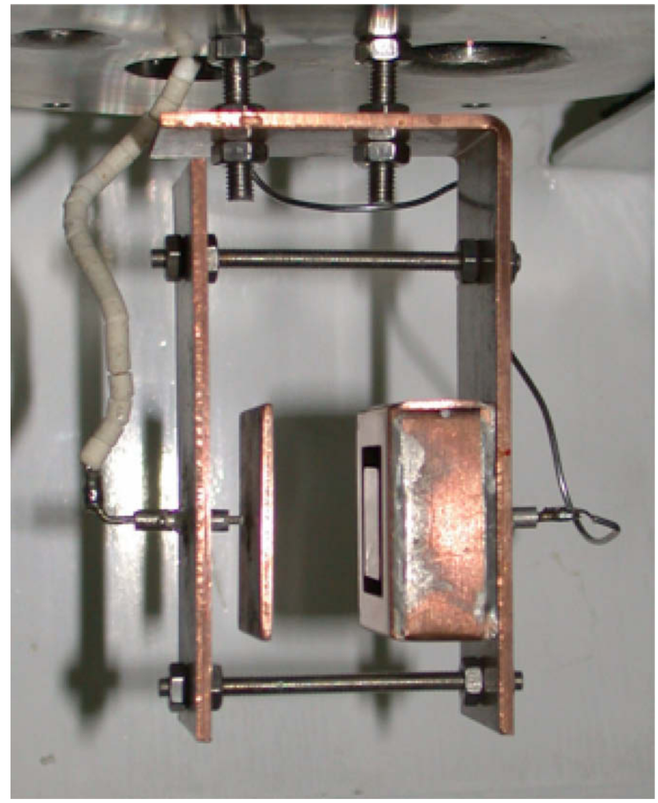

Fig. 3. Guarded cell to measure radiation induced conductivity for gases.

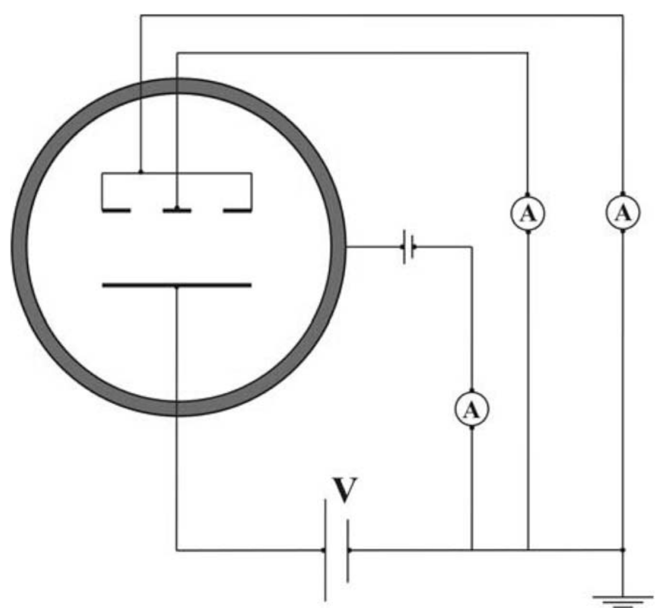

Fig. 4. Experimental set-up.

by an 8×10^{-3} m diameter collimator in front of the aluminium window, was perpendicular to the electric field direction. The gas chamber was continuously evacuated with a turbo molecular pump and at the same time the gas to be studied was introduced into the irradiation chamber by means of a needle valve. In this way radiation induced ion currents for air were measured at 3 Gy/s, gas pressures between about 1000 and $<10^{-4}$ mbar (10^5 to 10^{-2} Pa), and applied voltages up to 1500 V (10^5 V/m).

3. Results and discussion

Trial observations with the modified system reproduced earlier results for air, H, and He (Fig. 2) [5]. A decreasing ion current was observed on lowering the pressure, reaching a constant saturation level of about 10^{-2} nA for pressures below 10^{-1} mbar (10 Pa), independent of the type of gas, but increasing linearly with dose rate. The possibility of scattered electrons or sputtered aluminium from the thin aluminium window reaching the electrodes and perturbing the measurement was examined by introducing an additional thick steel collimator inside the gas chamber behind the thin aluminium window. However, the saturation level remained unaltered.

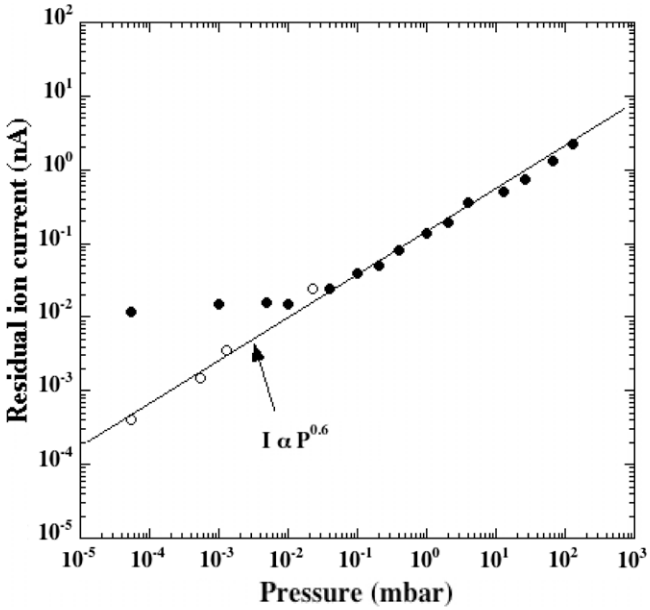

Fig. 5. Radiation induced ion conductivity for air with 100 V applied as a function of pressure, without (closed circles) and with (open circles) electron dark current suppression.

To examine the saturation level, all further experiments were carried out using air. The gas cell needle valve was completely closed reducing the irradiation chamber pressure down to <10^{-4} mbar (10^{-2} Pa). At the lowest pressure with the insulated irradiation chamber unpolarized (grounded), and +100 V applied to the common high voltage electrode a current of the order of 10^{-2} nA at the central electrode was measured (Fig. 5). Then the insulated irradiation chamber was polarized with up to ±500 V. For negative polarization no change was observed in the measured current, but for positive polarization the current was reduced (suppressed), reaching a constant lower value of about 3×10^{-4} nA for polarization $\geqslant$+100 V. Once the additional current was suppressed it was possible to measure the radiation induced conductivity for the gas at pressures increasing from below 10^{-4} mbar. As one can see in Fig. 5, the results fit very well with those measured above 10^{-2} mbar indicating an $I \propto P^{0.6}$ dependence. In the low pressure region the radiation induced ion currents are about 10^{-6} A/m^3/Gy/s, i.e., potentially high ion currents for large systems in good agreement with earlier results [5].

The results for the saturation current; independent of pressure and type of gas, proportional to dose rate, suppressed by positive polarization of the chamber wall, strongly suggest that is due to a radiation induced electron dark current (photoelectrons) produced from the chamber walls. Although it is difficult to quantify, the observed values indicate that radiation induced dark currents of the order of 10^{-8} A/m^2/Gy/s may be generated from metal surfaces in vacuum. Dark currents occur in large high voltage systems under vacuum even in the absence of radiation, and can themselves produce Bremsstrahlung (X-ray) radiation. In some cases they have been observed to degrade insulation performance in high voltage NBI test rigs [6]. To date radiation enhanced dark currents in fusion systems have not been considered as a potential problem. However they may be a serious additional source of electrical insulation degradation. Not only will they produce a Bremsstrahlung X-ray background increasing the radiation induced conductivity, RIC in the insulator volume [7], the accelerated electrons may directly irradiate insulator surfaces producing permanent surface electrical degradation in a similar way to energetic ion bombardment [8].

4. Conclusions

Ion currents from residual gas and electron currents generated from metallic surfaces in vacuum systems at low pressures have been separately identified. Ion currents of about 10^{-6} A/m^3/Gy/s may be generated for pressures below 10^{-4} mbar (10^{-2} Pa). In addition dark currents of the order of 10^{-8} A/m^2/Gy/s independent of the pressure may be produced from metallic surfaces. These currents are potentially high for large systems and must be considered as possible sources of insulator degradation.

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