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Charging behavior of Al_2O_3 and AlN under positive and negative charge injection using a kV electron beam

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ABSTRACT

Under electron irradiation, insulating materials may charge either negatively or positively depending on their electron emission properties and characteristics of the incident electrons. The electrical behavior of these materials is linked to the sign of the injected charge. The aim here is to describe an electron beam based method that can be used to study the electrical behaviors of insulators under either positive or negative charge injection. The method was tested on ceramics samples, Al_2O_3 and AlN. It was shown that the electrical behaviors of both materials under e-irradiation are very different according the sign of the injected charge. Negative charging results to stable space charge for Al_2O_3 and on the contrary it leads to a fast charge-decay for AlN. Remarkably, reversed trends are observed for positive charge injection. The practical consequences of these results are then discussed.

1. Introduction

Charging of insulating materials or floating conductors under electron irradiation is a commonly encountered problem in many space applications. Spacecraft charging due to solar and cosmic radiations may lead to critical discharge phenomenon [1]. Indeed, under irradiation (especially electron irradiation), insulators as well as floating conductors may charge negatively or positively depending on the incident electron properties (energy [2], incidence angle [3], flux [3–5]) and on the specific material properties (composition, surface roughness, contamination [6], temperature [7,8], etc.). The knowledge of the electrical properties (electron emission yield, conductivity and radiation induced conductivity) under electron irradiation for each material of the spacecraft is needed for spacecraft plasma interaction software [9,10].

Several experimental methods have been developed to measure the trapped charge or the associated surface potential under and after electron irradiation. These methods are usually base on the following measurements: the absorbed or influence current [11,12], electron spectrometry and X-ray spectroscopy [13,14], electron beam deflection [15–17] and kelvin probe [18,19]. Most of these techniques are restricted to the analysis of negatively charged materials. Indeed, when electron beam is used to charge the sample, the electrical properties such as the characteristic charge relaxation time or electrical resistivity were generally extracted from negative charging situation. However, it is generally admitted that charge localization and transport properties of holes and electrons may be very different depending on intrinsic material properties and nature of defects and impurities. This was illustrated for instance in many works dealing with corona discharge, where it was clearly shown that the surface potential decay kinetics is highly dependent on the sign of the deposited charge [20,21]. Hence, it is expected that, under electron irradiation, charge relaxation of insulators will be very different whether the net deposited charge is negative or positive. In many cases and in particular in the invert gradient situation frequently encountered on satellites, a net positive charge is injected. Therefore, it is necessary to make a clear distinction between electrical properties under negative charging and positive charging. From the fundamental point of view, the use of an electron beam as charging source allows preventing the use of injecting electrodes. Indeed, the interfering effect of electrodes may in some cases screen the intrinsic electrical behavior of the material [22].

In this paper, we address the problem of measuring the charge localization and transport in insulators with the help of an electron beam. We first describe the experimental method and set-up for the injection of either positive or negative charge. The results presented on Al_2O_3 and on AlN demonstrate the ability of this method to characterize charging properties discrepancies between negative and positive charge injection. We can prove that negative charges are durably stable for Al_2O_3, while positive charges decay

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rapidly. It was interesting to notice as well that behavior of the AlN sample is the opposite: positive charges are deeply trapped while negative charges decay rapidly.

2. Experimental and methods

2.1. Samples

The investigated samples are pure polycrystalline Al_2O_3 (99.995%; 5 μm mean grain diameter) and AlN (99.5%; 7 μm average grain diameter) obtained from NEYCO companies.

The samples are 40 mm diameter and 2 mm thick disks. The samples have been heated at 350 °C in situ for more than 2 h under high vacuum condition before the measurements. The vacuum level is about 2×10^{-6} mbar. To avoid hydrocarbon contamination from the diffusion pump, a cryogenic trap was used.

2.2. Experimental setup

The experimental setup is shown in Fig. 1. An electron beam produced by a 2 keV–22 keV STAIB electron gun is focused on 0.8 μm Al foil biased at +10 kV. The Al foil is used to diffuse the incident electron beam, allowing the irradiation of the entire sample surface. A combination of 5 Faraday cups can be rotated in front to the Al foil in order to check the spatial homogeneity of the diffused electron flux and to measure the incident current density. The typical current densities used in this work are in the nA/cm^2 range. The sample holder (Cu) can be independently biased up to 6 kV (negative or positive). An electrically isolated heater is fastened on the sample holder. The surface temperature of the sample can be monitored with the help of a calibrated pyrometer. A Monroe Kelvin probe attached to motorized translation arm is used to measure the surface potential along the sample surface.

2.3. Charge injection procedures

When the primary electrons (PEs) with incident energy E_L and incident current I_0, impacts the surface of the sample, secondary electrons (SEs), with low energies (few eV), and backscattered electrons (BSEs), with energies ranging from few eV to E_L, are emitted in the vacuum leading to an electron emission current I_E. The total electron emission yield, σ is defined as:

$$\sigma = \frac{I_E}{I_0} \quad (1)$$

The general behavior of σ as a function of E_L is shown in Fig. 2. The injected charge characteristics (implantation depth, sign, and amplitude) depend on E_L. This phenomenon is at the basis of the charge injection procedure described in this work. A comprehensive description of this dependence can be found in Cazaux Work [2].

2.3.1. Positive charge injection

If the PEs impact the insulator surface with energy comprised between $E_{C1}$and E_{C2}, the number of the generated holes is higher than the incoming electrons. Therefore, a positive charge builds up. However, only slight positive charging is expected due to the SEs potential barrier effect [2,4]. Indeed, as the surface potential becomes positive the emission yield falls down rapidly resulting to a surface potential of only few volts. To overcome this charge limitation, one solution consists in applying an extraction electron field (suppressing the SEs potential barrier). In this study, this was done by biasing negatively the sample holder at few kV. It should be noted that, as the mean escape depth of SEs does not exceed few nm [2,4], the injected positive charge is located at near-surface region (the few first nm of depth of the insulator).

2.3.2. Negative charge injection

The straightforward way to inject a net negative charge consists in the use of incident electrons of energies higher than the second crossover energy, E_{C2}, (i.e. $\sigma < 1$). Indeed, according to the total yield approach higher the initial incident electron energy and higher the magnitude of charging [2–4]. As E_{C2} exceed few keV for most insulators, the incident electron energy must to be set at also few keV (typically 10 keV at the minimum). The maximum penetration depth of electrons of 10 keV in Al_2O_3 is about 1 μm, which is much higher than the SEs mean escape depth (few nm). This will produce a negative space charge with a centroid much more generated in

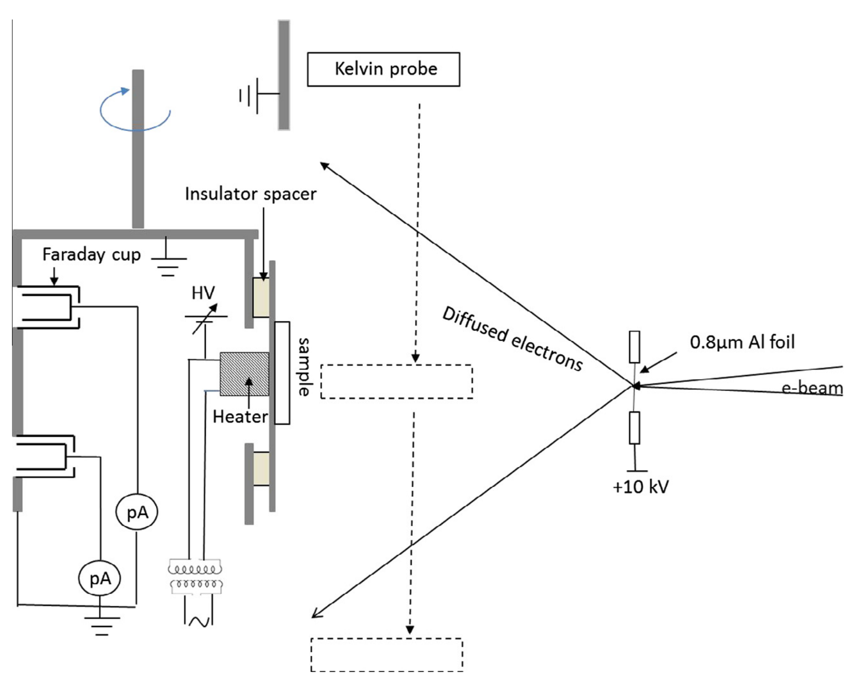

Fig. 1. Experimental setup.