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Electrical behaviour of carbon nanotubes under low-energy proton irradiation

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ABSTRACT

Several applications for carbon nanotubes (CNT) have been proposed for space applications in the last years. However, their behaviour in the harsh space environment is mostly unknown. Energetic particles such as protons can influence the material degradation in space. This material damage could result in a system failure of space systems. Therefore it is necessary to investigate the performance of new materials under proton irradiation.

Screen and jet printed disordered single-walled carbon nanotubes (SWNT), multi-walled carbon nanotubes (MWNT) and multi-walled carbon nanotubes/resin composites (ME) were exposed to 1 keV, 15 keV and 100 keV protons. The electrical behaviour of the CNT conductor paths was measured during the experiment. After this exposure, the CNTs were analyzed using Raman scattering and a scanning electron microscope (SEM).

Their is a clear evidence that proton radiation can destroy carbon nanotubes and influence their electrical performance.

1. Introduction

Currently various characteristics (e.g. electrical and mechanical) of carbon nanotubes are studied by many groups [1–3]. Their tensile strength is superior to carbon fibers and their ballistic electron conduction makes them interesting for electronic applications [4]. Because of their predicted properties, different areas of application e.g. in electrical or medical applications or for new nano-designed composite materials are discussed. However, the production, unbundling and the preparation of stable and optimized CNT dispersions are challenging [4–6].

Particularly the high demands of aerospace engineering for operational safety and reliability demand testing of CNTs under real conditions to determine if the theoretical properties are achievable.

Currently a large number of applications for space technologies are discussed and investigated in detail [7,8]. These include sensors [9,10], electrostatic discharge coatings [11,12], CNT based electronics [13], deep black optical coatings [14] and composite materials [15]. Most of these technologies are in an early stage of development and their behaviour in space environment is still unknown.

In space there are a lot of factors which can influence the behaviour and structure of CNTs. This includes electromagnetic radiation, vacuum, atomic oxygen, space debris and ionizing radiation [16,17]. Ionizing radiation consists of corpuscular (e.g. proton irradiation) or electromagnetic radiation. Corpuscular irradation can separate electrons from atoms or displace atoms from the lattice structure. This can cause degradation effects in materials over a period of months or years. Hence this material damage can result into a system failure. Therefore, it is important to examine the material behaviour under ionizing radiation. The focus of the following investigation is low energy proton irradiation ($E_p \leq$ 100 keV). Recent publications have studied and simulated the effect of ionizing irradiation on carbon nanotubes [18–24]. They focus on the damage of the tubes and the resulting morphological changes [25]. They often use imaging techniques and simulations to

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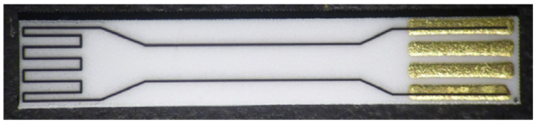

Fig. 1. Image of an aerosol jet printed SWNT-Tuball-conductor path.

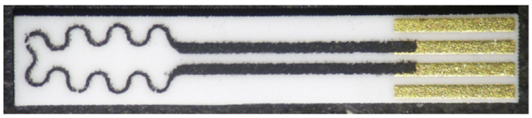

Fig. 2. Image of a screen printed MWNT/resin conductor path.

visualize the impact effects on carbon nanotubes [21,26]. The effect on other particular properties of CNTs, such as the electrical conductivity, have been left out of focus. Our work studies the electrical behaviour of single-walled carbon nanotubes (SWNT), multi-walled carbon nanotubes (MWNT)and multi walled carbon nanotubes/resin composites (ME) under 1 keV, 15 keV and 100 keV proton irradiation. This emulates as a first approach the proton distribution in low earth orbit. Healing effects of carbon nanotubes as reported by Jee et al. [27] or Suzuki et al. [28,29] can not be observed separately with our measuring method.

2. Materials and method

The nanotubes used in this study are commercially available (Suppliers: OCSiAl, Nanocyl and Covestro). The nanotubes are printed on a 20 × 3 mm^2 Al_2O_3 substrate. Two types of sample preparation were used: aerosol jet printing and screen printing. The first type is manufactured by an aerosol jet printing system (see Fig. 1). The aerosol jet printing ink is a dispersion of SWNT (Tuball™; diameter: 1.7 nm; length: more than 5 μm) and water or MWNT (Nanocyl7000™, diameter: 9.5 nm; length: more than 1.5 μm) and water. The layer thickness is up to 8 μm.

The second type is printed via a screen printing procedure. A mixed material from INVENT GmbH was dispersed into a screen printable paste (see Fig. 2). This composite material contains Baytubes C150 HP (diameter: 13 nm, length: more than 1 μm) and epoxy resin. These screen printed circuits can achieve a layer thickness up to 27 μm.

All samples were connected to the electronics through screen printed gold contact pads. The electronic box is connected to a computer with analysing software. The error of the electrical resistance is ± 1% (see Fig. 3).

For a satellite life time of 10 years a protons flux of $0.9 \cdot 10^9$ up to $2.0 \cdot 10^9$ protons/cm^{2}s will be assumed [16,30]. The simulation tool SPENVIS only provides data for proton irradation with an energy of 100 keV and more. Lower energies are not taken into account. It might be reasonably assumed that the flux increases with lower proton energies. To make the three tests comparable we defined the same proton flux for all three energies. (siehe Table 1). Therefore the samples were irradiated with a fluence of $4.0 \cdot 10^{17}$ protons/cm^2 to achieve a representative lifetime-dose. Three experiment series with different ion energies were carried out (see Table 1). Ion irradiation was done using Danfysik Model 1050 and 1090 ion implanters, with maximum acceleration voltages of 40 and 200 kV, respectively.

The implanter creates a proton beam, which is raster scanned over the samples surface. The scanning area is 5 × 5 cm^2. All experiments were carried out in a vacuum chamber at a pressure of $2 \cdot 10^{-6}$ mbar. Before the experiments started the samples were kept in vacuum for several hours to ensure that the vacuum indicated desorption processes is finished and a stable resistance was

Table 1
Test parameters for proton irradiation.

Test	1	2	3
Energy [keV]	100	15	1
Ion species	H^+	H_2^+	H_2^+/H^+
Proton fluence [cm^{-2}]	$4.0 \cdot 10^{17}$	$4.0 \cdot 10^{17}$	$4.0 \cdot 10^{17}$
Ion implanter [kV]	200	200	40

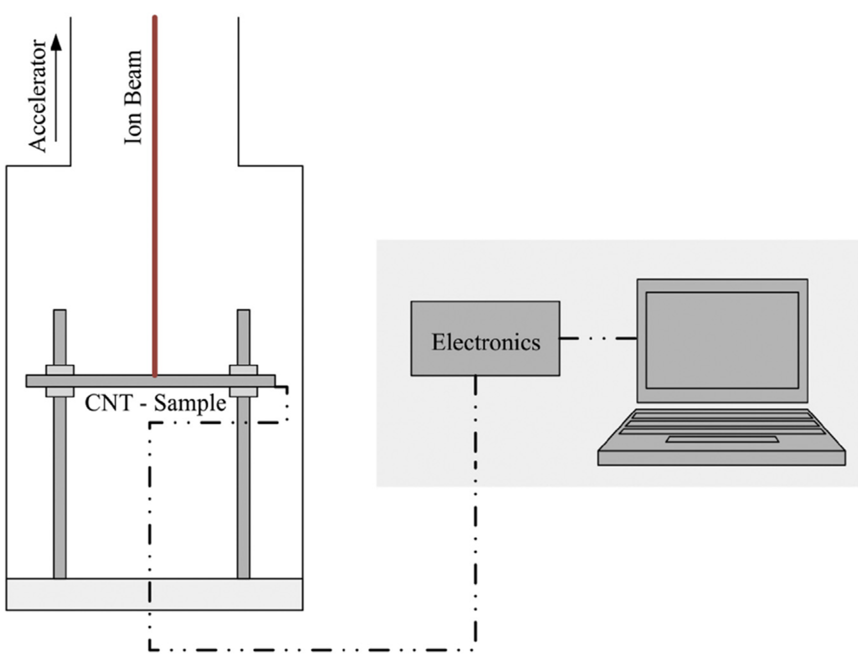

Fig. 3. Experimental setup.