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Measurements of Electronic Properties of Conducting Spacecraft Materials with Application to the Modeling of Spacecraft Charging

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Abstract

Introduction

Many spacecraft system anomalies and component failures are known to result from spacecraft charging which is due to the bombardments of spacecraft by energetic electrons, ions, and photons in natural space surrounding [Hastings and Garrett, 1996; Bedingfield *et al.*, 1996; Leach *et al.*, 1995]. To assist spacecraft designers in accommodating and mitigating the harmful charging effects on spacecraft, NASA has developed an extensive set of engineering tools to predict the extent of charging in various spacecraft environments (for example, NASCAP/LEO, NASCAP/GEO, and POLAR) [Mandell *et al.*, 1993]. However, current NASCAP databases lack electronic properties of most spacecraft materials in use (only nine basic materials are presently incorporated) and many new spacecraft bulk materials and coatings need to be characterized. In an effort to improve the reliability and versatility of these models, the NASA Space Environments and Effects (NASA/SEE) Program has funded a study to measure the electronic properties of spacecraft materials related to NASCAP parameters [Dennison, 1998]. The objectives of the study are (i) to provide more accurate measurements together with sufficient materials characterization and (ii) to significantly extend the database to include a wider range of materials that are more representative of the myriad materials used in spacecraft design and incorporates newly developed materials.

This paper describes the results of the first stage of this project, measurements of the electronic properties of conducting spacecraft materials. We begin with a description of the required measurements and specifics of the experimental methods used. Representative measurements for gold are described in detail. This is followed by a complete list of the conducting materials studied, justification of their selection for study, and a summary of the important results of the measurements. We end with a description of incorporation of these measurements into the NASCAP database.

Experiment

The NASCAP code uses 19 parameters to characterize the electronic properties of a given material used to model spacecraft charging [Mandell *et al.*, 1993]. For each sample studied, measurements are made to determine these 19 parameters. Table I identifies the experimental methods and apparatus employed to determine these physical properties. The measurements can be grouped under three headings:

- (1) *sample characterization*, used to fully identify the specific materials tested and to allow end users to more accurately assess which material is most closely related to their specific spacecraft materials;
- (2) *conduction related properties*, used to model the response of materials to accumulated charge; and
- (3) *electron emission* (induced by electrons, ions, photons) which determine a material's response to space environment fluxes.

A number of additional property measurements, highlighted in italics in column three of Table I, are included in the study; the intent of these additional measurements is to extend the description of the electronic properties of the materials with the goal of improving the modeling of spacecraft charging in future codes.

Specific of the measurement methods and instrumentation for conducting samples is given below for each of the three categories. An overview of the instrumentation used for these measurements is found elsewhere [Chang *et al.*, 1999].

Sample Preparation and Characterization

Sample size, polishing, and cleaning

Ex situ characterization: bulk composition, surface morphology (Optical microscope, SEM, STM/AFM)

In situ characterization: vacuum mount, vacuum environment, surface morphology (SEM), surface contamination (AES)

Conduction Related Properties

4-point probe measurements of bulk and surface conductivity

Electron Emission Measurements

Electron-induced Emission Measurement: BS/SE total yield versus incident electron energy (Emission current from sample for 5 eV to 30 keV monoenergetic electrons using hemi-spherical retarding field analyzer). Analysis: Maximum SE yield $\delta_{\max}$ [5].

Energy for $\delta_{\max}$, $E_{\max}$ [6].

Parameterless fit for $\eta(E_0)$.

Extended parameter fits for $\delta(E_0)$ and $\eta(E_0)$.

Incident angle dependence of $\delta(E_0)$ and $\eta(E_0)$. Stopping power data--4-parameter bi-exponential range law fit for primary electron energy range derived from stopping power data: b_1 , n_1 , b_2 , n_2 [7-10].

Measurement: Energy- and angle-resolved BS/SE cross-sections (Energy and angle dependent emission cross-sections using rotatable Faraday cup retarding field analyzer. Monoenergetic electrons from <100 eV to 30 keV.) Analysis: *Parameters for BS/SE angular distributions used by NASCAP at various incident energies.*

Deviation from NASCAP BS/SE angular emission distributions.

Ion-induced Emission Measurement: Total electron yield versus incident photon energy (Emission current of biased sample from discharge lamps, 0.5-11 eV) Analysis: SE yield due to 1 keV proton impact δ^H [11].

Incident proton energy for $\delta_{\max}^H$ and $E_{\max}^H$ [12].

Measurement: *Energy spectra of emitted electrons.*

Photon-induced Emission -- Measurement: Total electron yield versus incident photon energy (Emission current of biased sample from discharge lamps, 0.5-11 eV, Analysis: **Total electron yield from solar spectrum [13]. Measurement:** *Photon energy dependence of emitted electron yields.*

Representative Measurements for Gold

So far, our measurements related to NASCAP parameters have been performed on polycrystalline gold material. A distribution of the emitted electrons as a function of emission energy is shown in Figure I. The secondary electrons (≤ 50 eV) intensity has a peak in the range of 2-5 eV and is much stronger than that of backscattered electrons (> 50 eV). Figure II shows an angular distribution of secondary electron emission. The data was fitted with a theoretical cosine dependence of secondary electron yield, $\delta(\theta) = \delta(0) \cdot \cos(\theta)$.

Materials Studied

Need a paragraph describing selection criteria. See Quarterly report #2 (?)

Have text listing these conductors as grouped:

Elemental metal Al,Ag,Au,Be,Cu, Ti,Mg

Alloys Al 6061-T6, Al 2024-T3, Al 7075-T6SS 316, Ti/Al ???

Semiconductors a-Si, Ge, GaAs

Carbon materials HOPG, evaporated a-C, d-C, soot, aquadag

Conductive coatings: vapor-deposited ITO (In-Sn Oxide)

*Materials characterized in current NASCAP database.

Say something about measurements made for all of these materials

Discussion

Brief discussion of incorporation of measurements into NASCAP database and use of database.

Acknowledgements (copy from SCC paper, omit RMSGC and Grad fellowship)

References

Start by copying SCC refs.

Table I: Property measurements related to NASCAP modeling parameters.

Property Category	Measured Property (Methods and Apparatus)	Related NASCAP Parameters [(a),(b)]
Sample Characterization	Density (Gravimetric).	Density ρ [9,19].
	Bulk composition (AA, IPC).	Mean atomic number $\langle Z \rangle$ [4]. Mean atomic weight $\langle A \rangle$ [10].
	Surface contamination (AES, AES mapping plus UPS, SIMS, EDX, ESD as needed).	
	Surface morphology (<i>in situ</i> LEED, SEM; <i>ex situ</i> STM, AFM, SEM, optical microscopy).	
	Coating thickness (<i>in situ</i> HEED, quartz micro-balance; <i>ex situ</i> STM, AFM, optical microscopy).	Dielectric film thickness d [2].
Conduction Related Properties	Dielectric constant (<i>ex situ</i> capacitive measurements).	Relative dielectric constant ϵ_r [1].
	Bulk and surface conductivity (4- point resistance probe measurements).	Bulk conductivity σ_0 [3]. Surface resistivity ρ_s [14]. <i>Temperature dependence of conductivity.</i>
	Electrostatic discharge (I-V profiles of non-conducting films on conducting substrates).	Maximum potential before discharge to space $V_{\max}$ [15]. Maximum surface potential difference before dielectric breakdown discharge V_{punch} [16].
	High energy plasma-induced conductivity (4-point probe measurements of non-conducting samples for flux of 5-30 keV electrons).	Two parameter fit of radiation-induced conductivity σ_r : k and Δ [17,18].

Electron-induced Emission	BS/SE total yield versus incident electron energy (Emission current from sample for 5 eV to 30 keV monoenergetic electrons using hemi-spherical retarding field analyzer).	Maximum SE yield $\delta_{\max}$ [5]. Energy for $\delta_{\max}$, $E_{\max}$ [6]. Parameterless fit for $\eta(E_0)$. <i>Extended parameter fits for $\delta(E_0)$ and $\eta(E_0)$.</i> <i>Incident angle dependence of $\delta(E_0)$ and $\eta(E_0)$.</i>
	Stopping power data.	4-parameter bi-exponential range law fit for primary electron energy range derived from stopping power data: b_1 , n_1 , b_2 , n_2 [7-10].
	Energy- and angle-resolved BS/SE cross-sections (Energy and angle dependent emission cross-sections using rotatable Faraday cup retarding field analyzer. High resolution energy dependent emission current using HSA or TOF. Monoenergetic electrons from 5 eV to 30 keV.)	<i>Parameters for BS/SE angular distributions used by NASCAP at various incident energies.</i> <i>Deviation from NASCAP BS/SE angular emission distributions.</i>
Ion-induced Emission	Total electron yield versus incident ion energy (Emission current of biased sample from cold cathode ion guns, 500 eV to 5 keV, or PHI ion guns, 100 eV to 5 keV).	SE yield due to 1 keV proton impact δ^H [11]. Incident proton energy for $\delta_{\max}^H$ and $E_{\max}^H$ [12]. <i>Energy spectra of emitted electrons.</i>
Photon-induced Emission	Total electron yield versus incident photon energy (Emission current of biased sample from discharge lamps, 0.5-11 eV, or He resonance lamp, 21.2 and 40.8 eV).	Total electron yield from solar spectrum [13]. <i>Photon energy dependence of emitted electron yields.</i>

(a) Mandell et al., 1993.

(b) The numbers of the materials database parameters used in the current version of NASCAP are indicated in square brackets. Proposed additions to the database are indicated in italics.

Figures to include for Au:

1. SE total yield vs incident energy with fits (see Clint's senior project)
2. BS yield vs incident energy
3. Energy-resolved SE/BSE spectr (your Fig I)
4. Angle resolved SE/BSE distributions (your fig II)
5. Total electron yield vs incident ion energy
6. Energy spectra of electrons emitted due to ion bombardment
7. Total electron yield vs incident photon energy
8. Energy spectra of electrons emitted due to photon bombardment

Figure I Energy distribution of secondary and backscattered electrons at an emission angle of 17° and 1500 eV normal incident electron beam energy from a polycrystalline gold surface.

Figure II Angular distribution of secondary electron yield at 1500 eV incident energy for argon sputtered polycrystalline gold.