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SYNERGISTIC MODELS OF ELECTRON EMISSION AND TRANSPORT MEASUREMENTS OF DISORDERED SIO_2

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ABSTRACT

An important way for the spacecraft charging community to address the expanding necessity for extensive characterization of electron emission and transport properties of materials is to expand the role of more fundamental materials physics. This includes the development of unifying theoretical models of the charge transport equations based on the creation, distribution, and occupancy of defect densities of states. Models that emphasize the synergistic relation between fitting parameters for diverse measurements can also lead to a better understanding of materials and facilitate solutions to spacecraft charging issues. As an example of this approach, we present results of many different measurements on similar samples of a single common insulating spacecraft material, disordered silicon dioxide. Measurements include time-, field-, and temperature-dependent conductivity, radiation induced conductivity, electron emission yields and spectra, surface voltage accrual and decay, cathodoluminescence, electrostatic discharge, endurance time, and optical transmission.

1. INTRODUCTION

A critical component in the prediction and mitigation of spacecraft charging issues is an accurate model of the charging, charge transport and electron emission properties of a broad array of materials used in the construction of spacecraft.[1,2] The increased sensitivity, longer-duration missions, and ventures into more demanding environments only serve to heighten this need. One important way for the spacecraft charging community to address this issue is to expand the role of more fundamental materials physics. This includes the development of unifying theoretical models of the charge transport equations based on the creation, distribution, and occupancy of defect densities of states.[3] Models of electron emission and transport measurements that emphasize the synergistic relation between fitting parameters for diverse measurements—for example, defect energies or distributions and transition rates from one state to another—can also lead to a better understanding of materials and facilitate solutions to spacecraft charging isuues.

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This paper is intended to illustrate the advantages of such a synergistic approach, which focuses on the basic materials physics of highly disordered insulating materials through their defect structure at the microscopic level and an understanding of the interactions of electron, ion and photon fluxes from the space environment with the materials.

2. SYNERGISTIC MODEL

As an example of this approach, we present results of many different measurements on similar samples of a single common insulating spacecraft material, disordered silicon dioxide. We emphasize the emerging—though, as yet, incomplete—band structure and density of states model of disordered silicon dioxide that can be pieced together and crosschecked through careful consideration of the diverse results.

Fig. 1 shows a greatly simplified electron energy level diagram of disordered silicon dioxide. It depicts the complimentary response of electrons in the material when exposed to high energy radiation. These electron responses to radiation are dominated by valence band (VB) excitation into the conduction band (CB), since there is a high concentration of both filled VB states and empty CB states. These excited electrons most often relax into shallow trap (ST) states, then thermalize into lower available long-lived ST. At this point, there are four possible paths to consider. ST electrons can:

- Remain in (short lived) shallow traps, which contributes to charge accumulation;
- Relax into deep traps (DT), with concomitant photon emission, which again contributes to accumulation;
- Thermally re-excite into the CB, leading to radiation induced conductivity (RIC); or
- Undergo non-radiative transitions or electron-hole recombination with VB holes.

The various electron states involved in these paths are depicted schematically in Fig. 1.

3. SYTHESIS OF MEASUREMENTS

Measurements considered here include electron emission yields and spectra,[4] cathodoluminescence (CL),[5,6] and optical transmission. These provide information about the acquisition of charge in spacecraft materials. Also consider here are electron transport studies of conductivity,[7,8,9] radiation induced conductivity,[10] surface voltage accrual and decay,[9] electrostatic

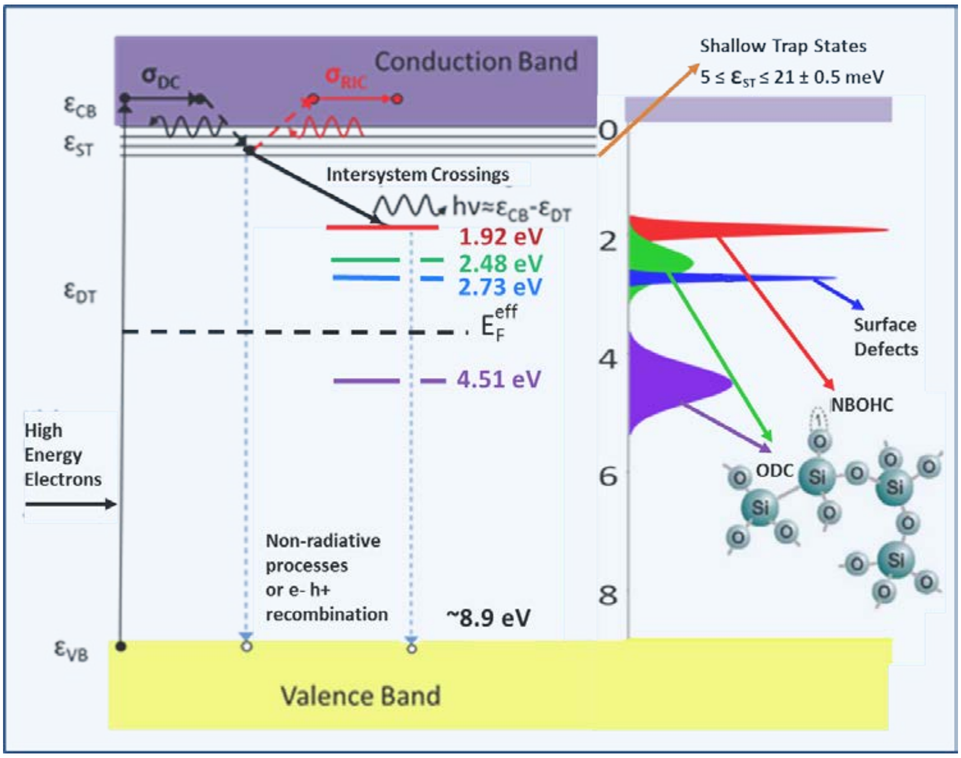

Figure 1. Energy band level diagram of fused silica SiO_2 derived from compilation of results from various electron emission and transport measurements. Shown are transitions between the extended state valence (VB) and conduction (CB) bands, shallow trap (ST) states at binding energies of ε_{ST} within ~k_BT below the CB edge, and deep trap (DT) distributions centered at ε_{DT}. Energy depths are exaggerated for clarity. The diagram at right depicts the approximate energy depths, widths and magnitudes of the four observed bands and their defect origins.

discharge (ESD),[11] and endurance time under applied voltages prior to ESD.[11] These properties largely determine the dissipation of charge acquired by spacecraft materials. For all of these measurements, time-, field-, and temperature-dependent behaviour is also considered. All of these measurements can contribute to the understanding of the electron band structure, the energy and spatial distribution of the defects, and the density and occupancy of these defects.

Optical transmission and reflection measurements of optical edges provide information about the direct band gap of the materials through photoexcitation of electrons to higher states.[5] Additional structure in these spectra can also provide information about defect structure within the band gap.

Cathodoluminescence measurements[5,6] study the emission of light as electrons excited into trapped states by incident electrons generate light emission as they relax to lower energy states. Measurements in the UV/VIS/NIR of the intensity and spectral radiance of spacecraft materials provide information about ST and DT densities of states and their occupation. The number of CL emission peaks and their wavelengths, amplitudes and widths provide information about the ST and DT density of states. The specific type of defect can often be determined, by comparison with the peak positions of previous luminescence studies of similar materials. Measurements of the relative intensity of the different bands as functions of temperature, time, and charge accumulation provide information about the occupation of states and the transition probabilities and state lifetimes. Detailed models of CL on incident current, energy and power, emission wavelength, charge deposition, and temperature have been developed to explain these results.[5]

Measurements of the time evolution of constant voltage conductivity[8] and surface voltage charging and discharge curves[9] at different temperatures can often be analyzed to separate contributions from polarization, dark current or drift conductivity, and diffusion-like or dispersive transport. These provide information about the average and ST defect densities, energies, lifetimes and occupation, as well as the dielectric function. Conductivity measurements, particularly surface voltage decay, can be related to the electron yield curves[4] and emission spectra, as well as the electron range.[12] Measurements of the ESD behavior provide information on the defect densities, energies and occupation.

4. CONCLUSIONS

There is a demonstrated need to address dynamic materials issues in spacecraft charging,[1] including:[2]

- Myriad spacecraft materials
- New, evolving materials
- Many materials properties
- Wide range of environmental conditions
- Evolving materials properties
- Feedback, with changes in materials properties affecting changes of environment

To mitigate the overwhelming demand for such measurements requires a conscious awareness of dynamic nature of materials properties, which can be used with available modeling tools to foresee and mitigate many potential spacecraft charging problems**.** For dynamic materials issues in spacecraft charging, as with most materials physics problems, synthesis of results from different studies and techniques, and development of overarching theoretical models allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space**,** to predict behavior outside of measured parameters, and to predict behavior in future useful materials.

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