Combined Space Environmental Exposure Tests of Multi-junction GaAs/Ge Solar Array Coupons

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A set of multi-junction GaAs/Ge solar array test coupons were subjected to a sequence of 5-year increments of combined environmental exposure tests. The purpose of this test program is to understand the changes and degradation of the solar array panel components, including its ESD mitigation design features in their integrated form, after multiple years (up to 15) of simulated geosynchronous space environment. These tests consist of: UV radiation, electrostatic discharge (ESD), electron/proton particle radiation, thermal cycling, and ion thruster plume exposures. The solar radiation was produced using a Mercury-Xenon lamp with wavelengths in the UV spectrum ranging from 230 to 400 nm. The ESD test was performed in the inverted-gradient mode using a low-energy electron (2.6 – 6 keV) beam exposure. The ESD test also included a simulated panel coverglass flashover for the primary arc event. The electron/proton radiation exposure included both 1.0 MeV and 100 keV electron beams simultaneous with a 40 keV proton beam. The thermal cycling included simulated transient earth eclipse for satellites in geosynchronous orbit. With the increasing use of ion thruster engines on many satellites, the combined environmental test also included ion thruster exposure to determine whether solar array surface erosion had any impact on its performance. Before and after each increment of environmental exposures, the coupons underwent visual inspection under high power magnification and electrical tests that included characterization by LAPSS, Dark I-V, and electroluminescence. This paper discusses the test objective, test methodologies, and preliminary results after 5 years of simulated exposure.

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Introduction

A set of multi-junction GaAs/Ge solar array test coupons were subjected to a sequence of 5-year increments of combined environmental exposure tests. The purpose of this test program is to understand the changes and degradation of the solar array panel components, including its ESD mitigation design features in their integrated form, after multiple years (up to 15) of simulated geosynchronous (GEO) space environment. These tests consist of: simulated UV radiation, electrostatic discharge (ESD), electron/proton particle radiation, thermal cycling, and simulated ion thruster exposures. The solar radiation simulation was produced using a Mercury-Xenon lamp with wavelengths in the UV spectrum ranging from 230 to 400 nm. The ESD test was performed in the inverted-gradient mode using a low-energy electron (2.6 – 6 keV) beam exposure. The ESD test also included a simulated panel coverglass flashover for the primary arc event. The electron/proton radiation exposure included both 1.0 MeV and 100 keV electron beams simultaneous with a 40 keV proton beam. The thermal cycling included simulated transient earth eclipse for satellites in geosynchronous orbit. With the increasing use of ion thruster engines on many satellites, the combined environmental test also included ion thruster exposure to determine whether solar array surface erosion had any impact on its performance. Before and after each increment of environmental exposures, the coupons underwent visual inspection under high power magnification and electrical tests that included characterization by LAPSS, Dark I-V, and electroluminescence. This paper discusses the test objective, test methodologies, and preliminary results after 5 years of simulated exposure.

Test Coupon Configuration

Three test coupons are being used in this test program. Each coupon consists four (4) Emcore Advanced Triple Junction GaAs/Ge (ATJ) solar cells. The solar cell area is 30.49cm^2. The coverglass is Qioptiq CMG coverglass, 100-µm thick with a single-layer MgF_2 anti-reflective coating. Each solar cell assembly (SCA) has a discrete Silicon bypass diode. As a part of the ESD mitigation design, the cell laydown included room-temperature vulcanizing (RTV) silicone adhesive grout along the cell parallel gaps (gaps between cell strings). The SCA interconnectors and bustabs were conformal coated with RTV silicone adhesive. The small quantity of solar cells per coupon was due to the limited beam area of the Proton particle radiation. Figure 1 is a photograph of a test coupon.

Figure 1. Solar Array Coupon Test Configuration

Test Plan/Environments

Test Phase 1:
In parallel with the coupons' combined environmental tests, a set of solar array material coupons were subjected to combined environmental tests, at their material component level, as shown by Test Phase 1 in the test flow diagram below. Test Phase 1 is designed to generate material property data as a function of on-orbit life. Data from Test 1 are required to support simulated ion thruster erosion of solar array coupons in Test Phase 2.

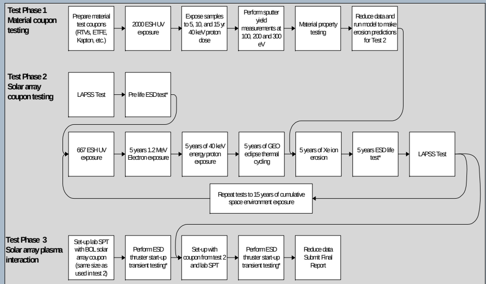

Figure 2. Test Flow Diagram

Materials under investigation are Wacker S-691 adhesive, Nusil CV1-1142-1 adhesive, Dow Corning DC93-500 adhesive, Kapton HN, Carbon-doped Kapton, Tefzel and Silverized Teflon. Material samples in Test Phase 1 were subjected to 2000 hours of equivalent UV and then 5, 10 and 15 years of low-energy Proton (LEP) particle exposures. The UV exposure was from a Xenon light source with equivalent UV suns from 200-400nm in wavelengths. The low-energy Proton energy was 30keV, and the test fluence was 9.4E15 p$^+$/cm^2 to simulate a 15-yr exposure. Figure 3 below shows a coupon sample configuration of Test Phase 1 pre and post UV and LEP exposures.

BOL — After UV exposure of 2010 ESH — After UV and 15-yr proton exposure

Figure 3. Test Phase 1 Coupon Configuration (ETFE samples pre and post UV and LEP exposures)

Post UV and LEP, or simulated EOL combined environmental exposures, material samples were then subjected to an erosion exposure test by a monoenergetic Xenon ion source at Colorado State University. The ion thruster source simulates the plume of the Stationary Plasma Thruster (SPT) that Space Systems/Loral deploys on many of its spacecraft. The plume of the simulated ion thruster erosion exposures were performed at 100 eV, 200 eV, and 300 eV.

Test Phase 2:
In this test phase, the solar array coupons, as shown in Figure 1, are subjected to three increments of 5-yr combined environmental exposures (see Figure 2). Inspection and electrical tests are performed post each environmental exposure. The first environmental test was an ESD test using guidelines from ISO-11221 [1]. Details of the ESD test setup and experimental results are further presented in references 2 and 3. Subsequent environmental tests were UV, LEP and Electron irradiation. Note that in our test program, we limit the equivalent UV Suns exposure to 2000 hours. The UV exposure was from a Xenon light source with equivalent UV suns from 200-400nm in wavelengths. The LEP energy was 40 keV, and the test fluence was 7.8E15 p+/cm2 to simulate a 15-yr exposure. Two Electron energies were used, 0.1MeV and 1MeV; and their equivalent 15-yr fluence were 1.3E16 e+/cm2 and 8.0E14 e+/cm2, respectively. At each 5-year test increments, the test coupons were exposed to 1/3 of the radiation fluence specified above.

After ESD and irradiation test, the coupons are then subjected to thermal cycling test. The typical thermal cycling test profiles are shown in Figure 4.

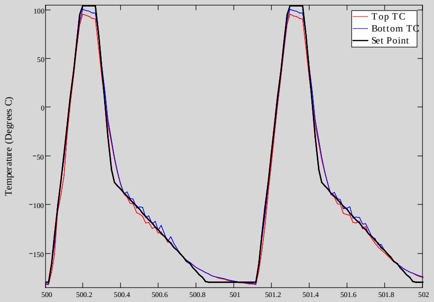

Figure 4. Thermal Cycling Profile from 5-yr test

It is essential for the thermal cycling profile to match the predicted rapid on-orbit thermal variation in order to properly produce the 'aged' condition of the solar array coupon materials. The thermal cycling test was performed in a partial vacuum condition, 3.3 - 5.3 Pascal, to facilitate the desired on-orbit thermal cycling profile. The temperature limits were 95C +10C/-0C and -180C +0C/-10C. The target for the total number thermal cycles is 1320 which simulates earth eclipse cycles of a 15-yr GEO mission. After each 5-yr increment of thermal cycling, the coupons are exposed to a simulated 5-yr SPT erosion using a Xenon ion source. The exposure time for a given Xenon ion energy and flux is provided by test data acquired from Test Phase 1.

Test Phase 3:
After the complete 15th-yr combined environmental exposures, the coupons are subjected to EOL ESD and ESD/SPT interaction tests. The purpose of the ESD/SPT interaction test is to evaluate if the presence of an SPT plume can induce an ESD sustained arc. With the exception of Test Phase 1 material erosion tests, all of the environmental exposures tests are being performed in the NASA Marshall Space Flight Center test facilities.

Experimental Results

To date, with the exception of the simulated SPT erosion test, the Loral/NASA team has completed 5 years of combined environmental exposures to the three solar array test coupons. Detailed inspection showed slight coloration (yellowing) of the ETFE wires. Note that the Proton beam size was approximately 127 mm in diameter; therefore, none of the Proton beam exposure reached the ETFE wires. However, the key area of interest is the RTV grouted area between the solar cells. After thermal cycling, the S-691 RTV adhesive grout shows hairline cracks in several locations, as shown by the close-up view in Figure 5. The condition is believed to be caused by embrittlement of the RTV adhesive due to the combined irradiation and the thermal cycling exposures. The coupons, however, successfully passed a partial ESD test post 5-years of combined environmental exposures (the ion erosion component has not been performed yet). During the ESD test, the ESD primary arc threshold voltage was observed to decrease from 2900V to 200V. More details of these findings are presented in reference [3]. Figure 6 shows the solar array coupon #10 LAPSS I-V characteristics to date.

The measured I-V data on Coupon #10-string B and both strings on both Coupons #8 and #9 were as predicted. Coupon #10-string A shows higher-than-expected degradation. On one of the solar cell coverglass, a small hole exists in the glass which we believe resulted from an ESD event from buried charge deposited by the 100 keV electron beam. The most probable cause was the high radiation test flux which is several orders of magnitude above on-orbit conditions. In subsequent irradiation tests, we plan to reduce the 100 keV flux by an order of magnitude.

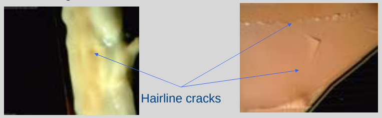

Figure 5. Microscopic pictures of RTV on Phase 2 Solar Array Coupon #9 (post 5-yr without simulated SPT erosion)

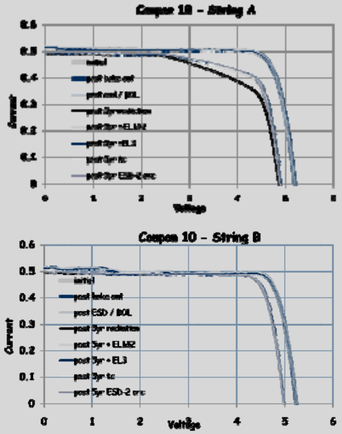

Figure 6. Solar Array Coupon #10 I-V Characteristics (post 5-yr without simulated SPT erosion). I-V response of Coupons #8 and #9 are like Coupon #10 String B.

Summary

A combined environmental test program of solar array coupons is on-going. Test results post 10-year and post 15-year aging are scheduled for completion in the first and second quarter 2011, respectively. Initial test results for post 5-year aging show degradation of solar array materials (e.g., hairline cracks in the coupon RTV adhesives) not shown by previous qualification tests in which thermal cycling was the only environmental exposure. This combined environmental test program has further shown a renewed emphasis in understanding space material properties as a function of on-orbit life and their effects to the solar array design and performance.

References

[1] ISO-11221, "Space systems -- Space solar panels -- Spacecraft Charging Induced Electrostatic Discharge Test Methods", May 2010.

[2] B.Hoang, F. Wong, Victor V. Funderburk, M. Cho, K.Toyoda, H.Masui, "Electrostatic Discharge Test With Coverglass Flashover Simulation For Multi-Junction GaAs/Ge Solar Array Design", *35th IEEE Photovoltaic Specialist Conference, June 2010.*

[3] K. H. Wright, T.Schneider, J. Vaughn, B. Hoang, V. Funderburk, F. Wong, G.Gardiner , "Electrostatic *Discharge Test of Multi-Junction Solar Array Coupons after Combined Space Environmental Exposures", 11th Spacecraft Charging Technology Conference, September 2010.*