N94-31029

DEGRADATION OF OPTICAL COMPONENTS IN SPACE

M. D. Blue
Georgia Tech Research Institute
Atlanta, Georgia 30332
Phone: (404) 894-3646 Fax: (404) 894-3628

ABSTRACT

This report concerns two types of optical components: multilayer filters and mirrors, and self-scanned imaging arrays using charge coupled device (CCD) readouts. For the filters and mirrors, contamination produces a strong reduction in transmittance in the ultraviolet spectral region, but has little or no effect in the visible and infrared spectral regions. Soft substrates containing halides are unsatisfactory as windows or substrates. Materials choice for dielectric layers should also reflect such considerations. Best performance is also found for the harder materials. Compaction of the layers and interlayer diffusion causes a blue shift in center wavelength and loss of throughput. For sensors using CCD's, shifts in gate voltage and reductions in transfer efficiency occur. Such effects in CCD's are in accord with expectations of the effects of the radiation dose on the device. Except for optical fiber, degradation of CCD's represents the only ionizing-radiation induced effect on the Long Duration Exposure Facility (LDEF) optical systems components that has been observed.

INTRODUCTION

Several reports covering various aspects of our postrecovery measurements of the set of optical components on the tray prepared by GTRI have already been published (refs. 1–3). Here we wish to provide additional information on two subjects: multilayer filters and mirrors, and self-scanned imaging arrays using CCD readouts.

A review of the reports of other LDEF investigators concerning performance of optical filters and mirrors indicates some common degradation effects in these components. In the first part of this report, we discuss and summarize some of these effects, and attempt to provide some general guidelines. In the following section, we present the results of measurements of the performance of silicon devices forming part of the signal conditioning circuitry for a Pd_2-Si imaging array with a CCD serial readout register. Here, the results are in agreement with a radiation-induced degradation mechanism.

OPTICAL FILTERS AND MIRRORS

Contamination

All trays were coated with a contamination layer (silicates and hydrocarbon compounds) of a thickness which varied with tray location and substrate characteristics. The amount of contamination varied from a few monolayers (ref. 4) to as much as 2 gm/ft^2 from an LDEF end plate scraping (ref. 5). The optical effects of the contamination layer are of interest. Figures 1 to 3, taken from other

LDEF reports, show transmittance in the visible and ultraviolet spectral regions for a Mg-F_2 window (ref. 6), quartz windows (ref. 7), and ultra-low-expansion glass (ref. 8). These figures illustrate the general result that attenuation of radiation is very strong in the ultraviolet region, but drops to much lower values in the visible and infrared regions. Our measurements in the visible region indicated no measurable change in transmittance after cleaning the contamination layer from optical filters (ref. 2). A similar result was reported for the Reading University experiment (ref. 9).

The transmittance of window materials with a contamination layer is similar to the transmittance of substrate materials after irradiation. As an example, Figure 4 shows spectral transmittance of fused quartz after irradiation by neutrons at a temperature of 500 °C (ref. 10).

While the ram-facing surfaces of the LDEF were scrubbed by atomic oxygen affecting material such as metal mirrors, no effects on other optical components caused by atomic oxygen have appeared in NASA reports at this time. Nonetheless, the potential for degradation by atomic oxygen erosion appears to be present.

Materials

The University of Reading experiment contained a group of uncoated substrate materials (ref. 9). The materials were distributed among two locations; near the leading edge and on the Earth-facing end. Comparison of average prelaunch and postrecovery transmittance for these samples indicated no major changes within the accuracy of the spectrometer except for the soft materials KRS-5 and KRS-6 (Tl-Br-I and Tl-Cl-Br respectively). For these soft materials, postrecovery transmittance was irregularly lower.

KRS-5 windows were used on several pyroelectric detectors used in a NASA Langely Research Center LDEF experiment (ref. 11). Postrecovery examination showed nonuniform cloudy (white) or slightly metallic-appearing regions on the front surface of the windows. Transmittance losses ranged from 17 to 50 percent with the larger losses corresponding to regions with greater physical damage. The KRS-5 window on a control detector was unchanged. Surface analysis indicated the presence of silicon (in the form of silicates) on the space-exposed windows with higher concentrations on the regions of least damage, lower concentrations in the regions of highest damage. The conclusion, supported by measurements of the Th:Br ratio at the surface, was that the presence of silicates inhibited the general loss of bromine from the surface.

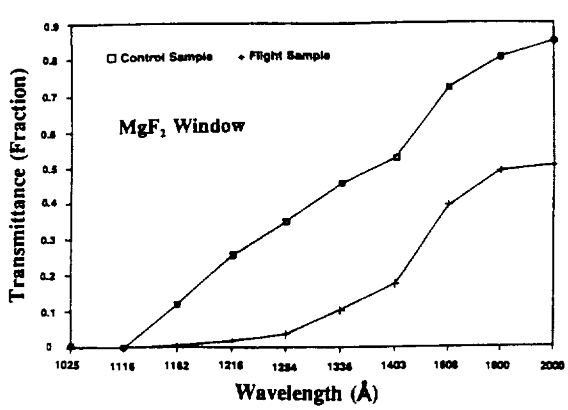


Figure 1. Spectral transmission of a Mg-F_2 window with contamination at the front surface (ref. 5).

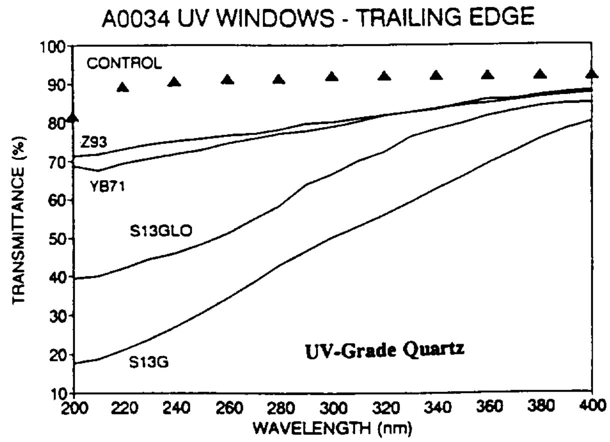


Figure 2. Spectral transmittance of ultraviolet-grade quartz windows from the trailing edge of the LDEF. Contamination produced even greater reductions in transmittance for the leading-edge windows (ref. 6).

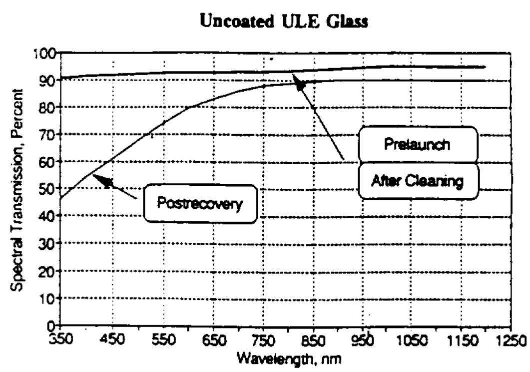


Figure 3. Spectral transmittance for an uncoated ULE-glass sample (ref. 7).

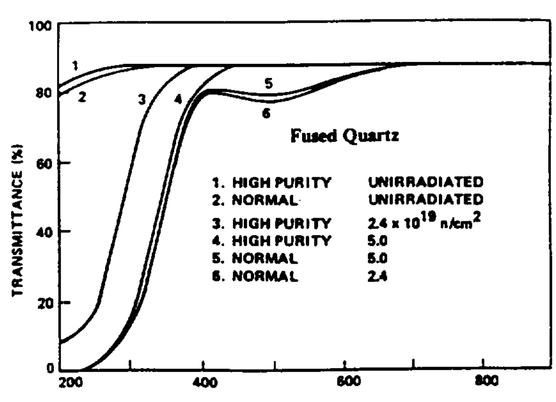


Figure 4. Spectral transmittance of fused quartz irradiated by neutrons at a temperature of 500 °C (ref. 9).

Several LDEF experiments contained multilayer dielectric filters and mirrors. The common degradation effects included the following:

Small shift of center wavelength toward the blue,
Reduction in peak transmittance,
Disruption in design tolerances,
Soft substrate material degradation.

Figures 5 to 7 show prelaunch and postrecovery transmittance of narrow-band filters from the GTRI (ref. 2), Reading University (ref. 9), and FRECOPA (ref. 12) experiments respectively. In all cases, a small shift of the peak transmittance wavelength in the range of a few nanometers was a typical result for these filters. Even the control filters showed a shift in many cases. The effect is in agreement with the effect of a slight compaction of the deposited layers with time (aging effect). On-orbit temperature cycling may aid in attaining equilibrium more rapidly but the effect should, and does, take place in the control filters as well. For the GTRI filter, Figure 5, the shift in peak transmittance corresponds to a reduction of 1/55 Å in the thickness of a layer. The effect will only be significant for the very narrow-band filters.

Reduction in peak transmittance was a typical result for filters on LDEF. Reductions of about 5 to 10 percent were typical. Degradation of $Mg\text{-}F_2$ was suggested as a possible source of deterioration for the filters in the FRECOPA experiment (ref. 12). A study by Fogdall et al. (ref. 13) was performed to simulate expected degradation effects of ultraviolet and charged particle radiation on multilayer dielectric mirrors at the Boeing Radiation Effects Laboratory. As pointed out by Donovan et al. (ref. 14), the results indicated that anticipated stability of the optical properties varies greatly among different material combinations. Degradation of $Zn\text{-}S/Th\text{-}F_4$ mirrors in the Boeing work was suspected as being the result of the reaction of Zn-S with water impurities in the coating. Materials such as $Si\text{-}O_2$, $Al_2\text{-}O_3$, and Si performed well.

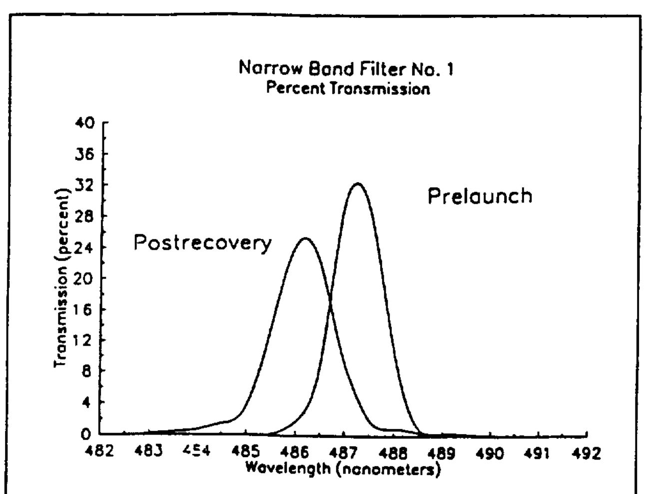


Figure 5. Prelaunch and postrecovery spectral transmittance of a narrow-band filter from the GTRI tray. (ref. 2).

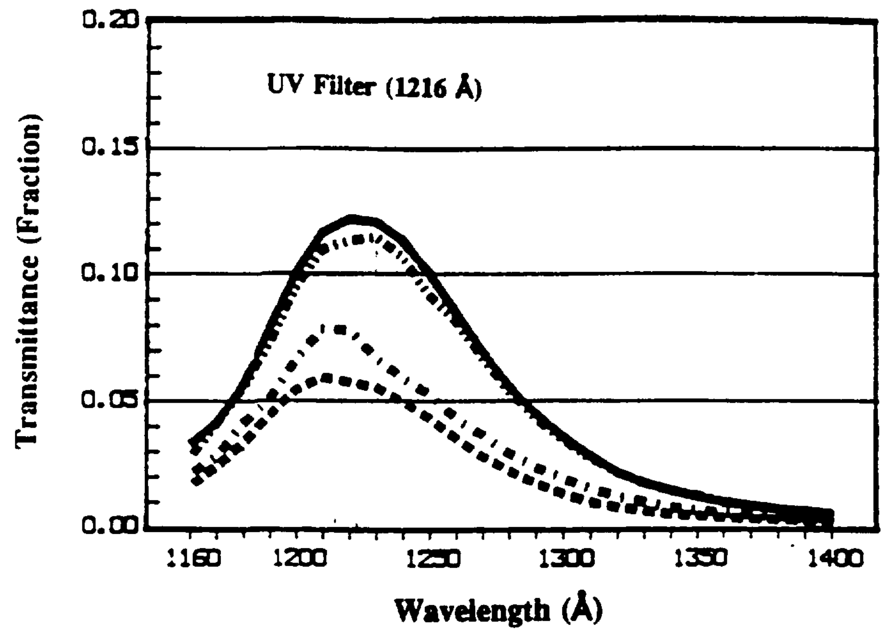
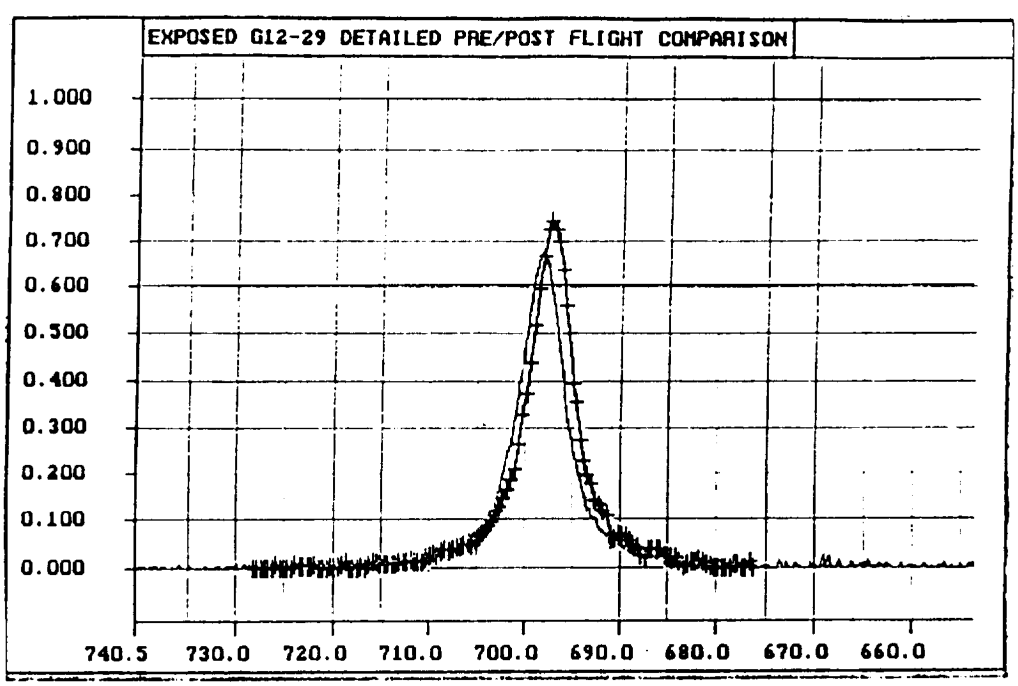


Figure 6. Spectral transmittance of a narrow-band ultraviolet filters before and after Earth orbit. The outer pair of curves refer to a filter exposed directly to space, the inner pair of curves refer to a filter mounted to look inward (ref. 11).



Wavelength^{-1} (Wavenumbers, cm^{-1})

Figure 7. Prelaunch and postrecovery for one of the narrow-band optical filters from the Reading University set (ref. 9).

The GTRI narrow-band filters (i.e., Fig. 5) tended to have a somewhat larger reduction in transmittance than the typical result. These filters were constructed with a cover glass cemented over the dielectric stack for protection. We believe that deterioration of the cement used to attach the cover glass gives rise to additional loss in transmittance.

Again, substrate choice is important. Quartz and ULE glass performed well. Reading University filters using KRS-5 and KRS-6 substrates had much lower transmittance in the infrared region and showed substantial physical degradation such as "delamination of the coatings and/or substrate materials."

CCD PERFORMANCE

Discussion

In the early 1980's, silicon Schottky-barrier detector arrays represented a promising new technology for imaging arrays operating in the near- and mid-infrared spectral region. The potential for this technology is now being largely fulfilled. While normal operating temperatures for these arrays is 77K or lower, degradation effects at ambient temperatures are also of interest, and the devices were not cooled in this experiment. Two different chips were used. The first was an integrated circuit containing process test devices. The second chip contained the Pd_2-Si Schottky-barrier 32 by 64-pixel IRCCD imaging array. The arrays were produced and characterized by the RCA Advanced Technology Laboratories which was later disbanded following the purchase of RCA by GE. The postrecovery characterization of the arrays was carried out by the David Sarnoff Research Center, and their data are discussed in the section. The sample from the LDEF tray and a control sample (prepared from the same wafer as the spaceborne sample) were compared for shift of threshold bias voltage, dark current, and transfer inefficiency.

Ionizing radiation produces three different types of permanent degradation on CCD arrays. First, radiation effects can increase the thermal generation rate of minority carriers which increases the dark current and shortens the storage time of the device. Second, because of a tendency for some charge to be left behind in each transfer step from gate to gate, there is an inherent charge transfer loss in CCD's. This transfer loss or transfer inefficiency is enhanced by radiation and works to degrade image resolution. Finally, irradiation of a CCD causes a shift in the range of bias voltages in the propagation and transfer gates over which satisfactory operation can be obtained.

The major radiation damage mechanism in these devices is the production of positive charge which can be trapped in the Si-O_2 insulator or at the semiconductor-insulator interface. The amount of energy required to create a hole-electron pair in Si-O_2 is 18 ev/pair. Thus, the total effective radiation dose must be adjusted to reflect the lack of pair production by lower energy radiation. However, because of the high energy of the electrons and protons incident on the LDEF, this correction is negligible. For 18 ev/pair, one calculates that 7.6×10^{12} pairs/cm^3 are created per rad (Si) dose (ref. 15).

The devices were mounted on the tray so as to allow backside illumination. Ionizing radiation reached the arrays by passing through the holes in the sunscreen as well as by penetrating the solid aluminum portions of the screen. The total dose for these devices was calculated to be 68 krads (Si)/cm^2. As a result, the maximum possible density of hole-electron pairs created during space exposure would be 5.2×10^{17} pairs/cm^3. Of these, 95 percent would recombine quickly, and most of the defects produced by the remaining 5 percent would be expected to be removed by annealing. A reasonable estimate is that 1 percent of the total radiation flux results in trapped charge. Thus, 5×10^{15} traps/cm^3 would be expected in the silicon dioxide gate insulators which could shift the bias potentials and provide traps to reduce the CCD transfer efficiency.

This estimated dose is about two orders of magnitude greater than the planned dose because of the extended time in orbit and a higher radiation flux than originally expected. A realistic spaceborne sensor using an array of this type would mount the sensor in a cryogenic dewar at the focal plane of a telescope, and the assembly would likely be contained within additional structure providing additional radiation protection. Therefore, the results reported here represent manifestly worst case conditions.

Pt_2-Si CCD Transfer Efficiency

Figures 8 and 9 show the construction and operation of the input and output stage of the serial output C-register of the array. The C-register was operated in a two-phase clocking mode with a data rate near 2×10^5 to determine the effects of the space environment on transfer efficiency and operating voltages. The two-phase mode provides better transfer efficiency than the usual four-phase mode. A dc charge component could be added to the input charge at the input end of the C-register (fat zero injection) as a means of improving charge transfer efficiency by filling fast trap states. Bias voltages were adjusted for maximum transfer efficiency. Each charge packet received 128 transfers (64 stages by 2 transfers/stage).

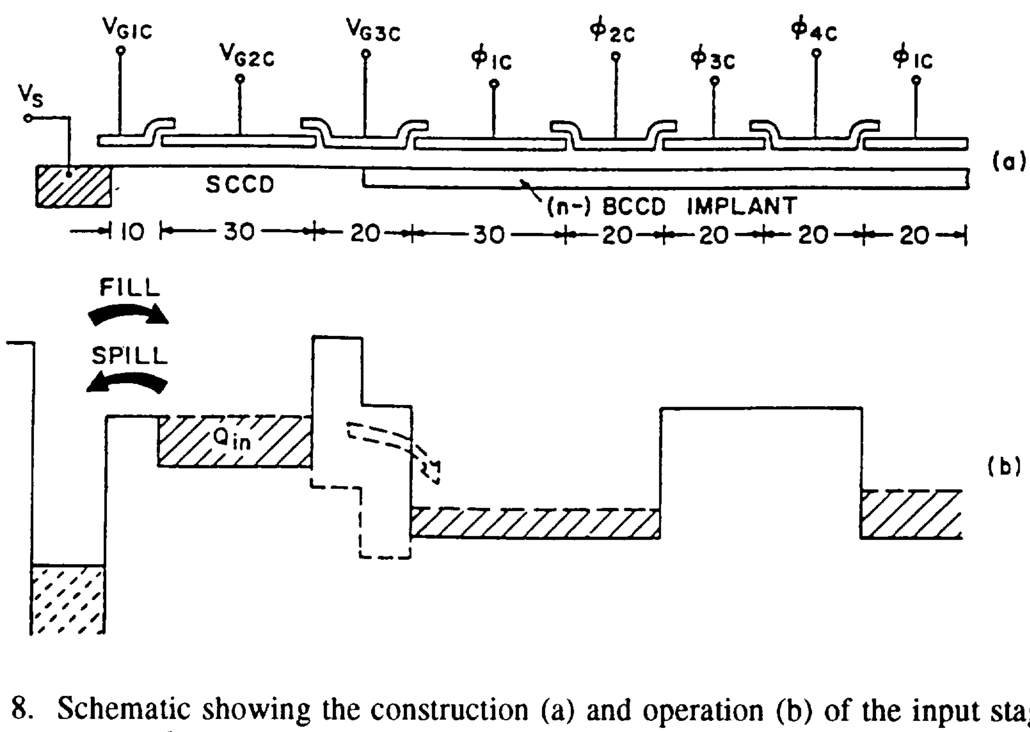


Figure 8. Schematic showing the construction (a) and operation (b) of the input stage of the serial-output C-register of the imaging array.

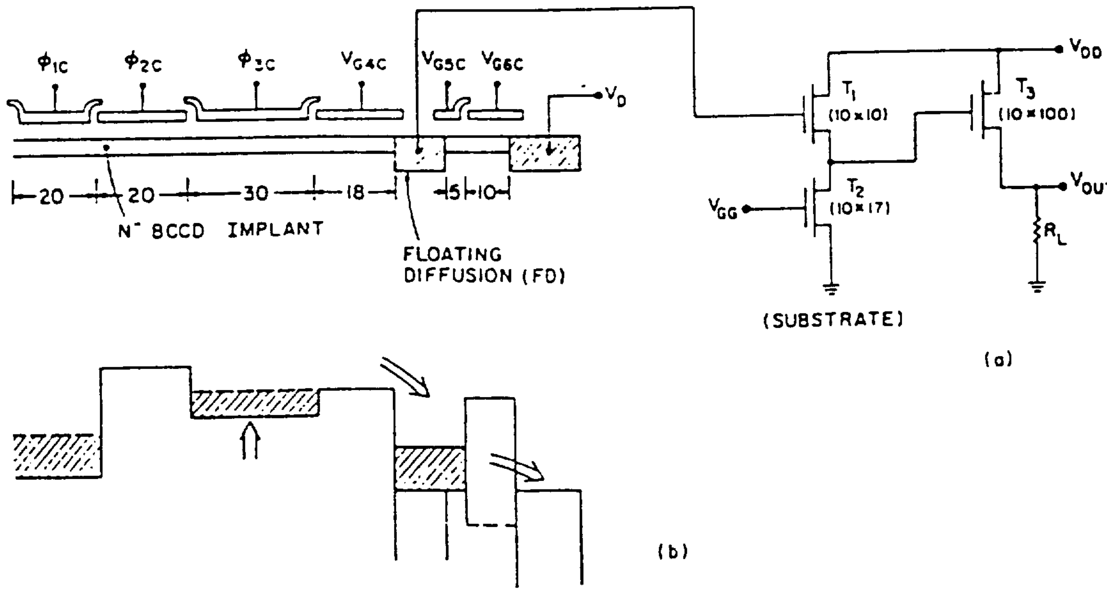


Figure 9. Schematic showing the construction (a) and operation (b) of the output stage of the serial-output C-register of the imaging array.

The spaceborne array required a more positive bias (2.5 V and 4.8 V) than the control array. The cause of these shifts is not understood, and the direction of the shifts is opposite to the expected direction. Also, the magnitude of the shifts is greater than the threshold shifts measured in the test transistors included on the die. Transfer efficiencies exceeding 0.999 (or an inefficiency of 10^{-3}) will provide acceptable resolution. The control sample showed a transfer inefficiency of 10^{-4} at room temperature, and 2×10^{-3} at 80 K.

For the spaceborne sample, the transfer inefficiency at room temperature was 5×10^{-3}, and at 80 K the inefficiency had degraded to 10^{-2}, indicating very poor operation. Injection of additional charge to fill the traps in the C-registers improves operation. With a charge injection equivalent to 2×10^{6} electrons per pixel, the transfer efficiency at 80 K improved to 0.998, equivalent to an inefficiency of 2×10^{-3}.

The density of ionizing-radiation-induced trap density can be estimated from the area of the CCD electrode (80-μm by 30-μm), the electrode thickness (1,200-Å), and the calculated density of charge created by the ionizing radiation (5×10^{15} cm^{-3}). The product of these factors gives an estimated 1.5×10^{6} traps per cm^3. This number is to be compared with the 2×10^{6} electrons per pixel used as a fat zero charge injection to increase transfer efficiency. The agreement tends to support the conclusion that the loss of transfer efficiency is the result of the rather excessive radiation dose received by the array while in orbit.

Dark Current Increase

Dark current in the control and spaceborne samples was significant, equivalent to 1.3×10^{6} and 2.5×10^{6} electrons per pixel respectively at room temperature. At 80 K, dark current drops by a factor of 5. The dark current in the control sample was very probably caused by defects in an adjacent register causing a current leak into the C-register. The additional dark current in the spaceborne sample is believed to result from degradation caused by the ionizing radiation dose.

Threshold Potential Shifts

Threshold measurements for separate FET transistors on the chip provide an indication of process variations and the effects of space exposure. The measured values for threshold voltages for control and spaceborne devices are listed in Table 1. The threshold differences between control and spaceborne samples for the buried and surface channel devices were less than 0.5 V, which would have a minimal effect on device operation. While some of this shift may be caused by radiation induced charging of the gate oxide, shifts of about half or less of this value would be expected from normal die-to-die process variations within a wafer. The test structures also allowed the potential difference between the buried channel potential minimum and the substrate to be measured. For the space-borne sample, the zero-bias values are very close to one of the reference samples, although this value also varies by a volt between the reference samples.

The drain diffusion of the output transistor of the spaceborne array had a reverse-bias leakage current of about 10 μA. While leakage current of this magnitude would have little effect on the amplifier operating point and transfer characteristics because the normal operating current is about 1 mA, additional noise from this source could be important. There was no leakage current in other diffusion regions such as the C-register drain and test structures. Since the leakage current in this transistor is the exception, it may be caused by a defect and not related to the radiation dose.

Table 1. FET threshold voltages.

Device Location	Control Sample Voltage	Spaceborne Sample Voltage
Surface Channel	–0.119 V	–0.214 V
Polysilicon 1 Buried Channel	–8.33 V	–7.92 V
Polysilicon 2 Buried Channel	–7.55 V	–7.11 V

In summary, several differences between control and spaceborne samples were observed. FET transistor threshold voltages exceeded normal process variations by a small amount; there was junction leakage in at least one case. The optimal CCD operating voltages changed in the spaceborne sample, and CCD transfer efficiency degraded.

The changes in operating voltage are of a magnitude that can be accommodated by the drive electronics. As the parameters of the imaging system change, periodic calibration would allow for gradual changes in drive parameters.

The degradation in CCD transfer efficiency is the most serious issue to be addressed. A very large fat zero injection was necessary to provide minimal transfer inefficiency in the spaceborne device. The magnitude of the fat zero used in these measurements is in agreement with the estimated trap density and the resulting charge density arising from the received radiation dose.

The construction of these chips represents technology over 10 years old. Since these arrays were produced in the early 1980's, alternative insulating systems have been developed which provide greater radiation hardness. Newer devices also have shorter gate lengths and better transfer efficiency, which suggests better performance in a radiation environment. Also, because of the known sensitivity of CCD registers to radiation, radiation protection must be provided sufficient to hold the total dose to an acceptable level. Because of the protection provided by the metal cryogenic dewar and mounting structure, this requirement should pose no significant problem to the system designer.

REFERENCES

1. Blue, M.D., and Perkowitz, S.: "Space-Exposure Effects on Optical-Baffle Coatings at Far-Infrared Wavelengths." Appl. Optics, vol. 31, No. 21, July 20, 1992, pp. 4305–4309.

2. Blue, M.D., and Roberts, D.W.: "Effects of Space Exposure on Optical Filters." Appl. Optics, vol. 31, No. 25, September 1, 1992, pp. 5299–5303.

3. Blue, M.D.: "Effects of Space Exposure on Electro-Optic Components." Ga. J. Sci., vol. 49, No. 3, 1991, pp. 107–116.

4. Preuss, Ludwig: "Evaluation of LDEF Experiment S 1002." Final Report, LDEF-69 Months in Space, NASA Conf. Pub. 3134, 1992, pp. 1405–1417.

5. Harvey, Gale A.: NASA Langley Research Center, Hampton, VA, personal communication, March 1991.

6. Harvey, Gale A.: "Effects of Long-Duration Exposure on Optical System Components." LDEF-69 Months in Space, NASA Conf. Pub. 3134, 1991, pp. 1327–1328.

7. Linton, R.C., Kamenetzky, R.R., Reynolds, J.M., and Burris, C.L.: "Atomic Oxyten Simulated Outgassing." LDEF-69 Months in Space, NASA Conf. Pub. 3134, 1991, pp. 763–767.

8. Havey, Keith, Mustico, Arthur, and Vallimont, John: "Effects of Long Term Space Exposure on Optical Substrates and Coatings." Presented at the Second LDEF Post-Retrieval Symposium, Sponsored by the National Aeronautics and Space Administration, June 1–5, 1991.

9. Seeley, J.S., Hunnemen, R., and Harkens, G.J.: "Exposure to Space Radiation of High-Performance Infrared Multilayer Filters and Materials Technology Experiment (A0056)." Final Report, Reading University, 1991.

10. Suzuki, H., Iseki, T., and Yamamoto, A.: "Effect of Reactor Irradiation on the Physical Properties of Fused Quartz." Bull. Toky. Inst. of Tech., No. 121, 1974, pp. 83–88.

11. Robertson, James B.: "Effects of Space Exposure on Pyroelectric Infrared Detectors." LDEF Materials Workshop '91, NASA Conf. Pub. 3162, 1992, pp. 501–506.

12. Charlier, Jean: "Vacuum Deposited Optical Coatings Experiment." LDEF-69 Months in Space, NASA Conf. Pub. 3134, 1991, pp. 1343–1360.

13. Fogdall, L.B.: "Natural and Induced Space Radiation Effects on Optical Coatings and Materials, Final Report." Contracts N00123-78-C-0989 and N60530-79-C-0263. Naval Weapons Center, Boeing Radiation Effects Laboratory, April 1981.

14. Donovan, T.M., Bennett, J.M., Dalbey, R.Z., Burge, D.K., and Gyetvay, S.: "Space Environmental Effects on Coated Optics." LDEF-69 Months in Space, NASA Conf. Pub. 3134, 1992, pp. 1361–1375.

15. Duffey, J.R., Powell, W.W., Song, S.H., Manpearl, D.G., and Kalma, A.H.: "Gamma Radiation Tests of Bulk and IBC Si: As Mosaic Detector Arrays." Proc. IRIS Detector, vol. II, 1986, pp. 147–162.