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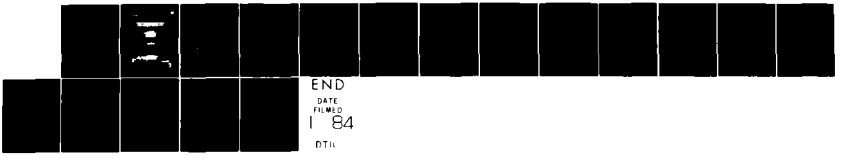

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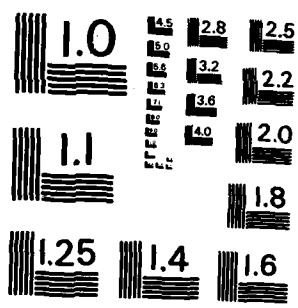

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Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-82-C-0083 with the Space Division, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by D. H. Phillips, Director, Electronics Research Laboratory. 1st Lt. Lawerence J. Zappone, SD/YKXL, was the project officer for the Mission Oriented Investigation and Experimentation Program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SD-TR-83-97	2. GOVT ACCESSION NO. AD-A136 [illegible]	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ELECTRIC FIELD DISTORTION IN ELECTRO-OPTICAL DEVICES SUBJECTED TO IONIZING RADIATION		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER TR-0084(4753-06)-1
7. AUTHOR(s) Lee Aukerman		8. CONTRACT OR GRANT NUMBER(s) F04701-83-C-0084
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Aerospace Corporation El Segundo, Calif. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Space Division Los Angeles Air Force Station Los Angeles, Calif. 90009		12. REPORT DATE 26 December 1983 13. NUMBER OF PAGES 13
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Electro-optical devices
Optical filters
Radiation effects
Trapped charge
Tunable filters

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Insulators exposed to the combined effects of an intense electric field and ionizing radiation frequently exhibit trapped-charge effects, the most notable example being the oxide in MOSFET devices. This report explores a heretofore neglected radiation damage mechanism in electro-optically tunable filters (EOTF) and other electro-optical devices requiring high field strengths. This mechanism is the gross perturbation of the electric field as a result of trapped space charge.

DD FORM 1473 (FACSIMILE)

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19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

We set up the equations for calculating the changes in electric field under irradiation for two different models: (1) for blocking contacts with negligible trapping in the bulk, and (2) for ohmic contacts with bulk trapping. The results are expressed in terms of physical parameters, some of which are not known for $AgGaS_2$, the material most likely to be used for the infrared EOTF. More experimental work is needed in order to make accurate predictions, but by estimating reasonable values for the unknown physical parameters, using SiO_2 as a guideline, we find that for either model a dose of about 10^5 rad is consistent with a field degradation of 50%. From the uncertainty in physical parameters, the effect described could equally well occur at both higher and lower dosages. However, such a large variation in field would have a strong impact on the operation of EOTF devices.

Additional experimental and analytical studies are recommended in order to determine more accurately the needed physical parameters and to explore the behavior of the electro-optical material under conditions of a nonuniform electric field resulting from ionizing radiation.

CONTENTS

FIGURE

I. INTRODUCTION

The purpose of this report is (a) to consider models for calculating the effects of ionizing radiation on an elecro-optical tunable filter[1] (EOTF) and other electro-optical devices requiring a large electric field and (b), on the basis of such models, to estimate the magnitude of the electric field distortion that could be expected to occur in the ionizing environment of space. The quantitative effect of such field distortions on an EOTF will be considered in a later report. Here, it is considered quite likely that a field distortion of 50% would have a very deleterious effect on the operation of the EOTF.

Although radiation tests are planned for silver thiogallate ($AgGaS_2$), a promising candidate for the EOTF, none of these tests are designed to pick up the effects, if any, of trapped space charge. The buildup of trapped space charge in insulators exposed simultaneously to a large electric field and ionizing radiation is a frequent occurrence, one that most commonly results in the positive charge buildup in the SiO_2 layers of MOSFET devices.[2,3] Since the EOTF changes its bandpass frequency in response to changes in the electric field strength, it seems quite obvious that changes in the internal field of this layered structure resulting from space charge buildup will seriously affect the operation of this device.

Figure 1 is a schematic of one layer of such a device. The fields in adjacent layers are directed in opposite directions. The shaded contact regions are highly doped compared to the insulating bulk region. The resistivity of the bulk region is expected to be $\sim 10^{13}$ Ω cm or greater at the temperature of operation (40°K). The thickness ℓ is about 25 μm, that of the contact layers about 4 μm. A typical applied bias V_a would be about 1000 V, making the strength of the applied field about 4×10^5 V/cm.

The presence of ionizing radiation generates electrons and holes that will either recombine, be swept out of the crystal, or be trapped at impurity centers or other crystal defects. We will consider two cases: (1) a model of blocking contacts with no trapping and (2) a model of ohmic contacts with trapping present. The bulk material will be assumed to be slightly n-type.

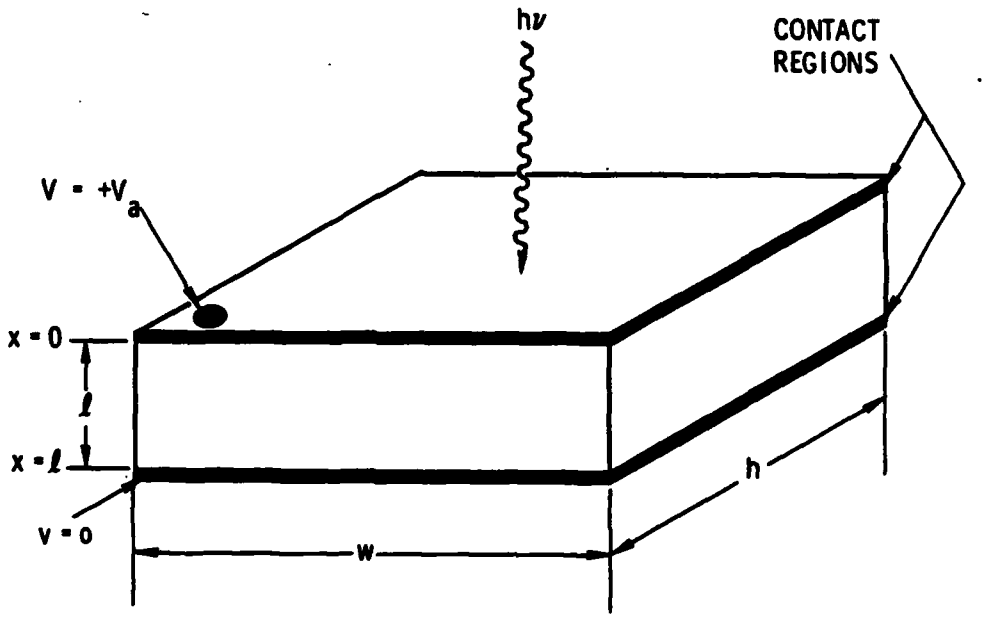

Fig. 1. Geometry of a Single Layer of an EOTF

II. CASE I: BLOCKING CONTACTS, WITH NEGLIGIBLE TRAPPING IN THE BULK

In the case of blocking contacts, the electrons and holes are swept out of the crystal but are trapped close to the anode and cathode, respectively. Although the low-resistivity regions are fabricated with the intent of providing ohmic contacts, we cannot be certain at this stage that this will indeed be the case. Furthermore, the calculation for blocking contacts is relatively easy to make and provides a crude illustration of the magnitude of field degradation that could occur.

The rate per unit volume at which electrons and holes are generated is $\dot{N} \equiv g_0\dot{D}$, where g_0 is the generation rate (number of carriers generated/cm^3/rad) and $\dot{D}$ is the dose rate in rad/sec. If the electric field E is large enough to sweep the electrons and holes to the electrodes before they have a chance to recombine or get trapped, the current, which is also the rate of charge buildup at or near the blocking contacts, is

$$I = \frac{dQ_t}{dt} = qg_0\dot{D}\,\ell wh \tag{1}$$

The quantity g_0 is related to the density δ and to the average energy ε_i required to generate a hole-electron pair by $g_0 = \delta/(1.6 \times 10^{-14}\varepsilon_i)$. ε_i is usually about 3 times the band gap. If the mobile charge is trapped a distance Δ from the contacts, one can show by Gauss' law that the field in the bulk, E_B, becomes

$$E_B = (V_a/\ell) - \frac{Q_t}{A\varepsilon\varepsilon_0}\quad\frac{2\Delta}{\ell} \tag{2}$$

Next, we define D_p to be the total dose ($\dot{D}t$) required to decrease E_B to p% of the applied field (V_a/ℓ). Then, from (1) and (2)

$$D_p = \left(1 - \frac{p}{100}\right)\ \frac{V_a\varepsilon\varepsilon_0}{2\Delta q g_0 \ell} \tag{3}$$

In order to get a value for the dose required to degrade E_B by, say, 50%, we need to make some assumptions for the values of Δ and g_0, since these values are not known for $AgGaS_2$. We therefore take the values characteristic for holes in SiO_2: $\Delta \sim 100$ Å and $g_0 = 7.6 \times 10^{12}/cm^3$ rad. This gives, for a 50% field reduction

$$D_{50} = 0.75 \times 10^5 \text{ rad}$$

Since we have only estimated the values of Δ and g_0, the calculation can only suggest that a total dose of 10^5 rad might be sufficient to produce a large degradation in the internal field of this device if blocking contacts are present.

III. CASE II: OHMIC CONTACTS

Ohmic contacts on insulators tend to result in space-charge-limited currents.[4] In the trap-free case, electrons injected at the cathode give rise to very large currents, which are inconsistent with the measured resistivity of 10^{13} Ω cm. The presence of a large trap density N_T tends to pin the Fermi level so that the traps are partially occupied; the injected electrons become mostly trapped and thus unavailable as current carriers. In this case the current increases linearly with voltage until the traps are filled, then it jumps up very rapidly to the trap-free limit. The voltage at which the trap-free limit takes over is about[4] 5600 V for $N_T = 10^{16}/cm^3$. The measured high resistivity for $AgGaS_2$ samples is more consistent with the presence of traps than is the trap-free case. In what follows, we assume a single, donor-like trapping level slightly above the Fermi level.

We need to solve the transport equation along with Poisson's equation:

$$\frac{dn}{dt} = g_0\mathring{D} + \mu_n \mathrm{div}(nE) - nC_n(1 - f)N_T \tag{4a}$$

$$\frac{dp}{dt} = g_0\mathring{D} - \mu_p \mathrm{div}(pE) - pC_pN_Tf \tag{4b}$$

$$\frac{dE}{dx} = \frac{q}{\epsilon\epsilon_0}\left[N_T(1 - f) + (p - n)\right] \tag{4c}$$

Here μ_n and μ_p, respectively, are the electron and hole mobilities, f is the probability of occupation by an electron, and C_n and C_p are capture probability constants. In Eq. (4) we have neglected the electron and hole emission terms because the trap is considered to be a deep level at low temperature (~40°K). In steady state, $\frac{dn}{dt} = 0$, $\frac{dp}{dt} = 0$, div j = 0, and

$$f = \frac{nC_n}{pC_p + nC_n} \quad \text{(steady state)} \tag{5}$$

In the present case, because of the large field and small device thickness, the fate of most of the electrons and holes is to be swept out by the field. This means we can get a quasistatic solution to Eqs. (4a) and (4b) by neglecting the trapping terms. Since the sample is n-type, no holes will be injected at the anode, so $p(0) \approx 0$, and enough electrons (n_ℓ) will be injected at the cathode to support the current density of j:

$$j = qn_\ell \mu_n E_\ell = qg_0 \mathring{D} \ell \tag{6}$$

when n_ℓ and E_ℓ are, respectively, the carrier density and electric field at the cathode, $x \approx \ell$ (actually at the "virtual" cathode). The quasistatic solution of Eqs. (4a) and (4b) becomes

$$n = g_0 \mathring{D} (2\ell - x)/\mu_n E \tag{7a}$$

$$p = g_0 \mathring{D} x/\mu_p E \tag{7b}$$

However, Eq. (5) is not yet satisfied; instead, the concentration of trapped holes, $p_T \equiv N_T (1 - f)$, is determined by the following:

$$\frac{dp_T}{dt} = pC_p N_T - p_t(pC_p + nC_n) \tag{8}$$

For small t such that $p_T << pC_p N_T/(pC_p + nC_n)$, Eq. (8) becomes simplified, and solving Poisson's equation gives

$$E_\ell^2 - E_0^2 = \frac{q}{\epsilon\epsilon_0} g_0 \mathring{D} \left(\frac{1 + N_T C_p t}{\mu_p} - \frac{3}{\mu_n} \right) \ell^2 \tag{9}$$

The capture probability C_p is the thermal velocity times the capture cross section σ. Since the site is not ionized when it captures a hole, σ is quite small, say $\sim 10^{-14}$ cm^2, so at 40°K, $C_p \sim 2 \times 10^{-8}$ cm^3/sec. For $N_T \approx 10^{15}$/cm^3, the quantity $(N_T C_p t/\mu_p)$ very quickly ($\sim 10^{-7}$ sec) becomes the dominant term in the parenthesis of Eq. (9); hence, we get

$$\frac{\Delta E}{\bar{E}} \simeq \frac{q}{\varepsilon\varepsilon_0} \frac{g_0 D\, N_T\, C_p \ell^2}{2\mu_p (\bar{E})^2} \qquad (10)$$

where $\Delta E = E_\ell - E_0$ and $\bar{E} = V_a/\ell \simeq (E_\ell + E_0)/2$. From Eq. (10) the dose to make $(\Delta E/E) = 0.5$, a severe perturbation in the field, is again about 10^5 rad, assuming the trap density N_T to be 10^{15}. Actually, in typical insulators it is extremely difficult to achieve trap densities this low. Therefore, a dose considerably less than 10^5 rad might suffice to create a large, possibly catastrophic degradation in the internal electric field of a $AgGaS_2$ EOTF.

In the analysis presented above, only the electric-field-sensitive electro-optical effect has been considered. However, radiation can cause effects on the passive optical transmission of an EOTF. For example, radiation can cause the formation of color centers whose absorption properties could cause reduced transmission in wavelengths of interest. Furthermore, in the specific case of silver salts such as $AgGaS_2$, there is the possibility of the nucleation and growth of microscopic particles of silver metal, as happens when silver halide crystals of the sort used for photographic purposes are exposed to energetic radiation. Such particles would, by scattering, reduce the transmission of the filter.

IV. RECOMMENDATIONS

Although the above calculations illustrate the possibility that severe internal field degradation will occur in an ionizing environment, more quantitative results are needed and other likely models should be explored. More experiments are needed to determine the parameters more accurately and to determine which model is correct. Furthermore, we need to explore the effect of field degradation on the operation of an actual EOTF device. Since the present device model assumes a constant electric field, a careful reworking of the device physics is required. Experiments to measure changes in optical constants before and after irradiation at 40°K in the presence of an electric field should be given a high priority.

The following experimental and analytical studies are proposed:

1. Ellipsometry measurements at 40°K on single layers of $AgGaS_2$ with ohmic contacts and electric field applied, both before and after Co^{60} irradiation at doses of 10^4, 10^5, and 10^6 rad ($AgGaS_2$).
2. Measurement of V-I curves before, during, and after Co^{60} irradiation at 40°K. The purpose of this experiment is to determine trapping constants C_p, N_T, and carrier generation rate g_0.
3. A literature search.
4. Analytical studies to improve the model and enable a more quantitative prediction.
5. Consideration of hardening methods (such as decreasing N_T) if a potential problem is shown to exist.
6. Measurement of radiation effects on optical transmission of EOTF materials in wavelengths of interest.

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