Charge Yield at Low Electric Fields: Considerations for Bipolar Integrated Circuits

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***Abstract* - A significant reduction in total dose damage is observed when bipolar integrated circuits are irradiated at low temperature. This can be partially explained by the Onsager theory of recombination, which predicts a strong temperature dependence for charge yield under low-field conditions. Reduced damage occurs for biased as well as unbiased devices because the weak fringing field in thick bipolar oxides only affects charge yield near the Si/SiO_2 interface, a relatively small fraction of the total oxide thickness. Lowering the temperature of bipolar ICs – either continuously, or for time periods when they are exposed to high radiation levels – provides an additional degree of freedom to improve total dose performance of bipolar circuits, particularly in space applications.**

***Index terms* – bipolar integrated circuit, ionizing radiation, recombination, radiation effects.**

I. Introduction

The yield of electron-hole pairs in SiO_2 was the subject of many studies during the early years of research on total dose effects. Older work in the Physical Review was used to develop theories for columnar and geminate recombination, as summarized in the books by Ma and Dressendorfer (eds.) and Oldham [1,2].

For electrons in space (as well as cobalt-60 gamma rays), the electron-hole pair density is sufficiently low so that the geminate recombination model for initial recombination applies, while the columnar model applies to protons with energies below about 5 MeV as well as low-energy X-rays.

Most early research was done on oxides with thicknesses between 70 and 95 nm, the approximate gate thickness of mainstream MOS transistor technology in the late 1970's. The main concern was with effects at high electric fields; the charge yield was so much lower at reduced fields it was not necessary to know it very accurately for the practical problem of dealing with total dose effects in MOS transistors.

Figure 1 shows a summary of those results [3], which has been referenced in numerous papers. The charge yield for electrons and gamma rays at low fields is approximately 0.2, considerably higher than suggested in later work.

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Oxides between 70 and 95 nm showed little temperature dependence for charge yield, although transport time was strongly affected [4]. However, the lowest electric field used in those earlier experiments was 0.5 MV/cm, much higher than the electric field in the oxides of bipolar integrated circuits.

In the mid-1980's Boesch and McLean studied oxides with thicknesses up to 790 nm, with electric fields as low as 0.1 MV/cm [5]. They found that some of the charge appeared to be stuck in the bulk region during the 1000-second time interval used in their experiments, which affected their interpretation of charge yield in the presence of low electric fields.

This paper examines charge yield indirectly, using input current degradation of a bipolar integrated circuit. We performed radiation tests at several temperatures, using a cryostat to maintain a constant temperature throughout the irradiation. Those results are compared with predictions of recombination developed by Onsager for electrolytes [6], and extended by Ausman to silicon dioxide [7].

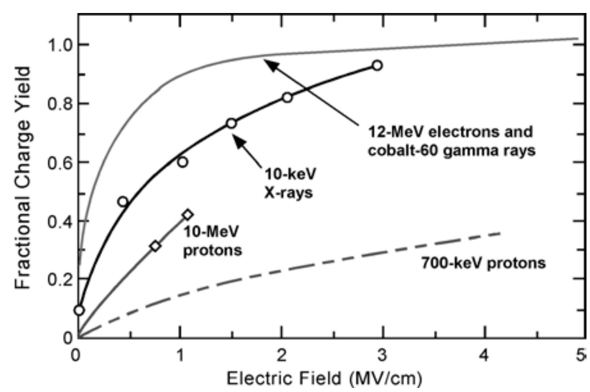

Fig. 1. Charge yield for various radiation sources [3].

II. Experimental Approach

The samples that were tested were LM111 comparators from National Semiconductor. A schematic of the input stage is shown in Fig. 2. A modified measurement of input bias current, using an offset voltage of 300 mV, was used to determine damage in the substrate input transistor. Applying the offset voltage shifts the loading effect of the second stage to only one of the input transistors. This allows first-order calculations of the gain of the input substrate transistor with the lower input voltage. It is also possible to calculate the gain of the second-stage npn transistor, using the difference in the input currents of the two pnp input transistors, along with the value of the second-stage current source. Measurements were made with an Agilent Technologies 4156 parameter analyzer.

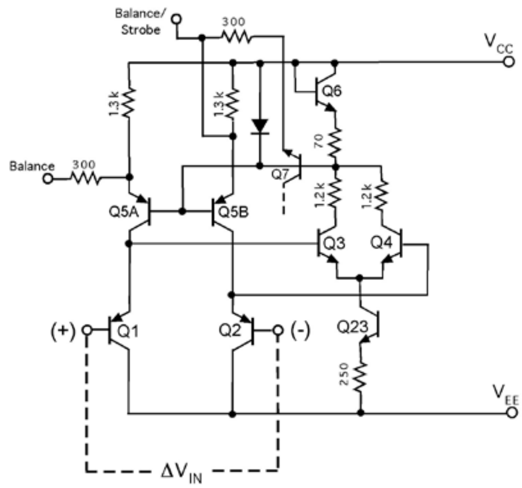

Fig. 2. Input schematic diagram of the LM111 comparator, including the second stage. Applying a differential input voltage shifts loading from the second-stage amplifier to only one of the input transistors.

Devices were irradiated and measured in vacuum (to avoid icing) in a small Dewar, cooled with a CryoTiger refrigeration system that allowed the device to remain at a stable low temperature for extended periods. The device under test was placed in a hole within an aluminum block within the Dewar. A thermocouple attached to the block was used to measure temperature. Temperature stability was typically within 0.5 °C.

A cobalt-60 room irradiator was used, with a dose rate of 5 mrad(SiO_2)/s. Additional tests were done at a higher dose rate. An ionization chamber was used for dosimetry. The source was calibrated by placing the ionization chamber behind an aluminum plate with the same thickness as the walls of the Dewar, adding a small additional thickness to account for the effective shielding of the Kovar package.

Irradiations were done using two different bias conditions. The majority was done using unbiased devices (all pins grounded), which is usually the worst-case condition for these types of devices [8]. A second set of experiments was done on samples that were biased with power supplies of +6 (V_{CC}), -6 (V_{EE}), and a differential input voltage of 0.2 V.

III. Basic Considerations and Background

A. Selection of Total Dose for Damage Comparisons

Nonlinearities in the degradation of circuit parameters affect comparisons under different irradiation conditions and temperature. Thus, the selection of a total dose level for comparison is an important factor in planning experiments and interpreting the results. Older work on various circuits and test structures made comparisons of circuit degradation at approximately 30 krad(SiO_2) [9], but this turns out to be well above the range where internal transistor damage is linear with total dose for most bipolar ICs. Although it is certainly legitimate to make comparisons at higher total dose levels, it leads to confusion in studies such as this one that attempt to relate circuit damage to more basic phenomena.

Figure 3 shows results for the dependence of input bias current on total dose for the LM111 comparator at a dose rate of 0.005 rad[(SiO_2)/s] where the irradiation was done at room temperature. Although there is a slight nonlinear region at low dose levels, the slope is approximately linear between 6 and 8.5 krad(SiO_2) which is the region where damage comparisons were made in the present work. Note the large change is slope that takes place at higher total dose levels, which approaches saturation. If conventional measurements of input bias current are used – without applying the small offset voltage used in this work – loading of the second amplification stage reduces the nonlinearity at higher total dose levels, masking the fact that damage in the input pnp transistor is saturating. Thus, the region where damage comparisons are made and the circuit parameters used to make those comparisons must be carefully selected.

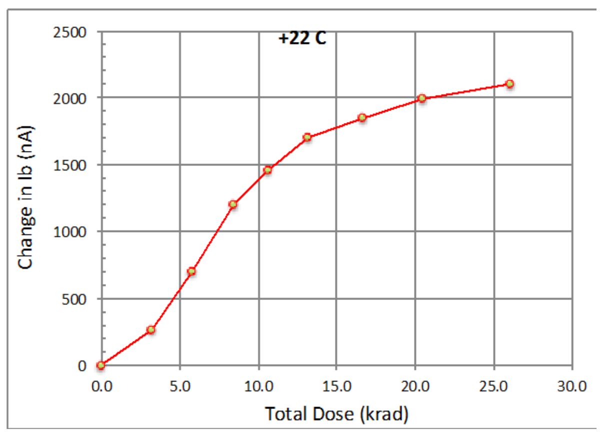

Fig. 3. Increase in input bias current of LM111 comparators showing a reduced slope at low total dose levels.

The results in Fig. 3 appear to be straightforward, but the first data point appears to be too low. A second experiment, using smaller incremental irradiations, showed that the initial slope at low total dose levels is about 1/3 that of data for total dose levels above 3.5 krad(SiO_2). Those results are shown in Fig. 4. Although this nuance is unimportant when devices are tested for the higher levels that apply to most space applications, it is important when we compare data at different temperatures because of reduced charge transport.

Note that there are three regions in this response curve: a linear region at low total dose levels, a superlinear region with higher slope at intermediate levels, and a saturation region above approximately 10 krad(SiO_2).

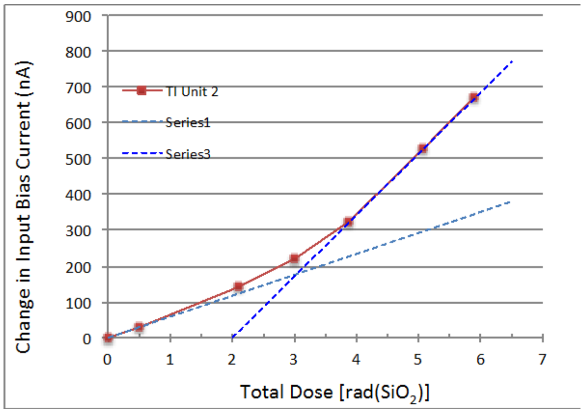

Fig. 4. Data for an LM111 at 0.005 rad(SiO_2)/s with small incremental radiation levels showing a distinctly reduced slope at low levels.

B. Annealing

Although it has received little attention, annealing occurs in bipolar linear devices. It turns out that approximately ½ of the damage that is observed immediately after irradiation with a short-duration radiation exposure anneals afterwards [10]. The earlier data is repeated here because annealing plays an important role when damage comparisons on bipolar devices are made at various temperatures.

Figure 5 shows damage in an LM111 comparator as a function of time. The radiation source was a 1-s pulse of 1.3 MeV electrons. Measurements were made at various time intervals after the irradiation, using a pulsed technique, applying bias for only 20 ms during each measurement to reduce the effects of biasing on annealing. There appear to be two distinct components to the damage: a recoverable component, which anneals with a log(t) dependence for a time period extending to about 10^7 s, and a stable component (annealing in the recoverable component likely continues for longer times, but the small changes that occur are masked by the relatively large amount of damage in the stable component).

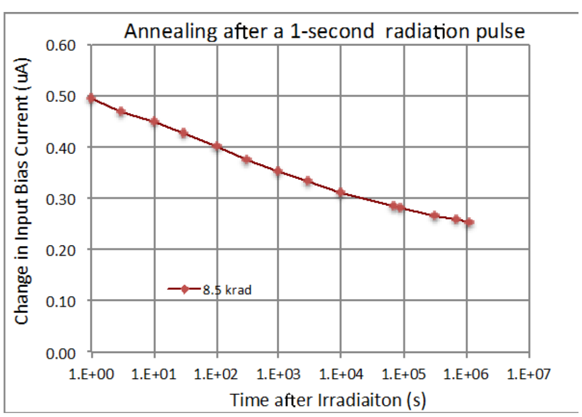

Fig. 5. Annealing of input bias current in an LM111 comparator after exposure to a 1-s radiation pulse [10].

The stable component is nearly unchanged after storage for several months at room temperature, but anneals at higher temperature. Isochronal annealing tests (unpublished) show gradual recovery, up to temperatures of 320 °C, similar to the temperature dependence reported by other workers for interface states [11]. This is consistent with the interpretation that the recoverable component is due to trapped holes, while the stable component is due to interface states.

In the present work, the key factor is the relatively rapid annealing of a significant fraction of the damage after irradiation. For irradiations at low dose rate, nearly all of the damage that is susceptible to annealing does so during the lengthy irradiation period. This is illustrated in Fig. 6 (the slight fluctuations are due to temperature changes of approximately 3 °C in the laboratory over extended time periods for this particular experiment).

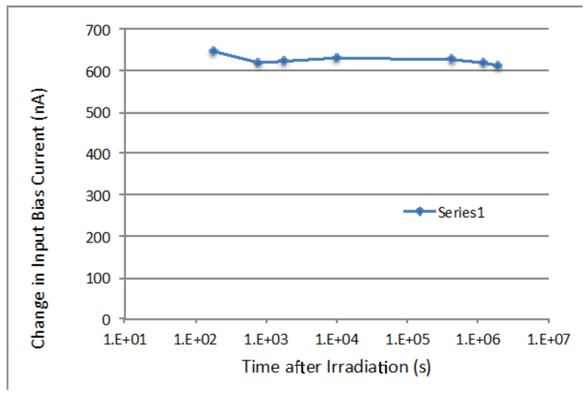

Fig. 6. Post-radiation stability of an LM111 comparator irradiated to 6 krad (SiO_2) at a dose rate of 0.005 rad(SiO_2)/s.

Devices irradiated at low temperature show significant *increases* in damage after irradiation when they are warmed to higher temperature. The reason is that hole transport time is so much longer at low temperature that part of the radiation-induced charge is still in the bulk region of the oxide, even when the irradiations are done at low dose rate. That fraction of the charge floods the interface region when the temperature increases. That part of the charge will also be susceptible to annealing, beginning at the end of the irradiation cycle when the temperature increases. Thus, the behavior during warm-up is a complex interaction between the increased number of hole and interface traps, and annealing of the new trapped holes that arrive during warm up.

C. Hole Transport

Most of the features of hole transport in SiO_2 after irradiation are consistent with the continuous time random walk (CTRW) model [12]. This transport process is highly dispersive, extending over several orders of magnitude, as shown in Fig. 7. Time is referenced to the midpoint (t_o), which is the time required for 50% of the charge to transport through the oxide.

Although the scaled time to is affected by temperature and electric field, the CTRW relationship fits a wide variety of conditions. For our purposes we need to note that scaled time decreases by more than five orders of magnitude at the lower temperature values used in our experiments. This means that although tests at room temperature extend over time periods >> t_o, tests at low temperature extend over time periods << t_o, due to the strong dependence of t_o on temperature.

The shape of the CTRW curve depends on the disorder parameter, α. Boesch and McLean reported a higher α value for thick steam oxides [5], with comparable thicknesses to the oxides in bipolar ICs. We will assume that also applies to our devices, and use the corresponding curve in Fig. 7 in analyzing our results.

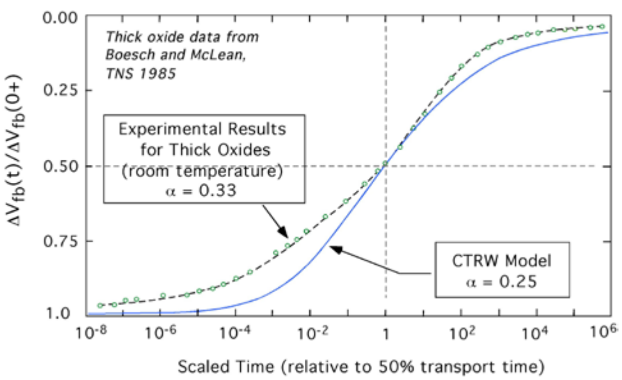

Fig. 7. CTRW model for hole transport in SiO_2 [5].

D. Electric Fields in Bipolar Oxides

The gate oxide in an MOS transistor can be approximated by a parallel plate capacitor. In contrast, oxides in bipolar transistors are far more complex. There is no electrode at the top surface, except for cases where metallization stripes overlap. Steps in the oxide are present because of cuts in the oxide during fabrication, required to diffuse the emitter and contacts, resulting in non-uniform thickness. The "bottom electrode" consists of various semiconductor regions with different doping levels and built-in potentials; lateral fringing fields are present, even for unbiased devices.

It is possible to estimate the electric field from the work function of the various semiconductor regions and the oxide thickness, but this is not very accurate for bipolar devices because of the complex geometry and absence of a top oxide contact.

The Synopsys device analysis program was used to determine the electric field. The results after irradiation to a total dose of 200 rad(SiO_2) are shown in Fig. 8. The simulation assumed 100% hole trapping. At that total dose level, the field was only slightly higher than the field with no radiation. The field extends laterally as well as vertically. The average value in the vertical direction, varying from about 1,000 V/cm near the top of the oxide to about 10,000 V/cm at the bottom.

At a total dose of 1,000 rad(SiO_2), the trapped charge at the interface increases, causing the field to extend further in the lateral direction. As shown in Fig. 4, this is about the same total dose level where the damage starts to depart from linear behavior.

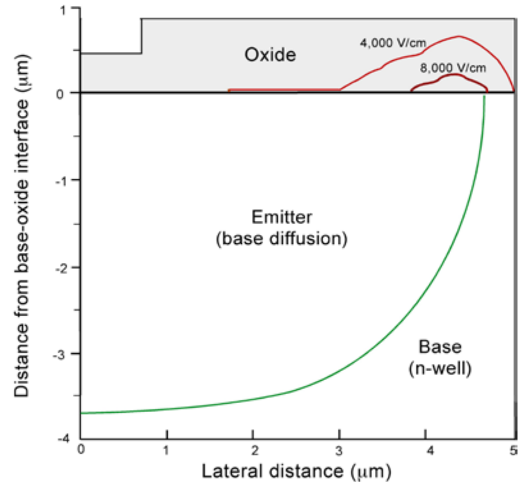

Fig. 8. Electric field in the oxide above a substrate pnp transistor obtained with the Synopsys device analysis program after irradiation to a dose of 200 rad(SiO_2).

IV. Radiation Tests at Low Temperature

A. Initial Measurements During Irradiation

Figure 9 shows how the change in input bias current depended on dose for irradiations at three different temperatures. These measurements were made at the temperature used for irradiation, not room temperature. The dose rate was 0.005 rad(SiO_2)/s. Damage was linear with dose at the two lower temperatures, but becomes slightly super-linear for the irradiation at -35 °C above 2.5 krad(SiO_2). Significantly less damage occurred for parts where the irradiations were done at lower temperature. However that is consistent with the reduction in charge transport from the CTRW model.

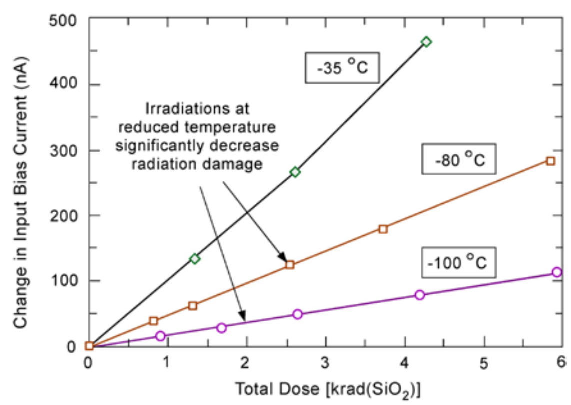

Fig. 9. Increase in input bias current vs. dose for irradiations at low temperature (all pins were grounded during irradiation).

The slopes in the linear region for the three temperatures are shown in Table 1.

Table 1. Slope of ΔI_b at Different Temperatures

Temperature (°C)	Slope [nA/krad(SiO_2)]
-35	106
-80	48.8
-100	19.8

B. Response During Warm-Up and Annealing

Our previous work (using a 1-s radiation pulse) showed that charge transport, which depends on temperature, was sufficiently retarded at temperature below -50 °C so that the charge was effectively frozen in place for the duration of the experiment [10]. That allowed direct observation of delayed transport in a bipolar device, consistent with expectations of transport with the CTRW model. Those results also showed that charge was collected from nearly all the oxide, not just from regions close to the Si/SiO_2 interface region.

Although there are clear differences in the slope of the increase in bias current at various temperatures, the gain depends on temperature. Thus, a different way to compare low-temperature irradiations is to evaluate devices that are irradiated to the same total dose level after they are warmed to room temperature. Figure 10 compares the damage observed for devices irradiated at -80 and -100 °C after they were warmed to room temperature with damage in a similar part that was irradiated at room temperature. The warm-up time was about one hour. Damage for the parts irradiated at low temperature were reduced by a factor of 2.9 for the -80 °C case, and by 5.6 for the irradiation at -100 °C compared to damage in the part that was irradiated at 22 °C.

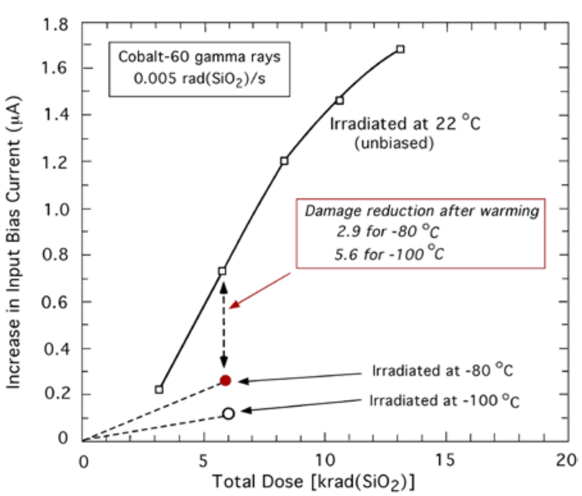

Fig. 10. Comparison of damage in devices irradiated at low temperature to a dose of 6 krad(SiO_2) with a device irradiated at room temperature. The cooled devices were warmed to room temperature after irradiation. All samples were grounded during irradiation.

Although this seems straightforward, it is complicated by two factors: first, damage anneals afterwards; and second (discussed earlier), during the warm-up period a significant number of the radiation-induced holes within the oxide will be transported to the interface because the scaled time increases by several orders of magnitude.

Evidence of the latter factor is shown in Fig. 11, covering the approximate one-hour period required to warm the devices at room temperature (solid symbols) and the extensive period afterwards, where damage annealed at room temperature (open symbols). For the -100 °C irradiation, the damage increases about 15% during the warm-up period, but starts to decrease later in the temperature cycle due to annealing. The same trend can be seen in the results for the -80 °C irradiation, but the damage during warm-up never exceeds the damage observed when the part was at the -80 °C temperature.

When we consider these effects, there are three different ways to evaluate the effect of temperature on radiation damage:

1. Measurements at low temperature, applying corrections for the temperature dependence of gain. That approach is appropriate for applications where the devices remain at low temperature.
2. Measurements immediately after warm-up. However, it is clear from Fig. 11 that those values are affected by the time and temperature conditions during the warm-up period, lending some confusion to the comparisons.
3. Measurements long after warm-up when the fraction of the damage that can anneal has essentially recovered.

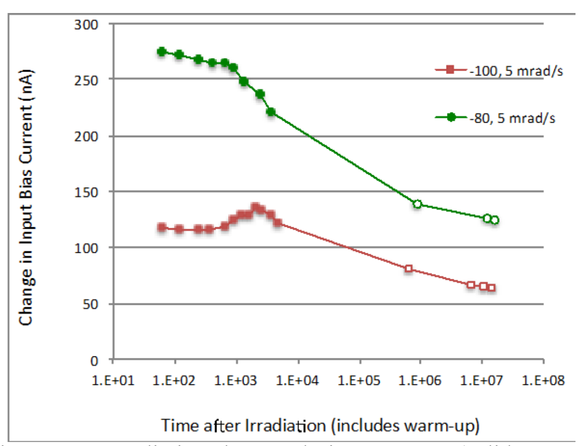

Fig. 11. Post-radiation changes during warm-up (solid symbols) and extended annealing at room temperature (open symbols).

The reduction in damage (compared to room temperature values) for these three approaches is shown in Table 2.

Table 2. Reduction in Damage at Various Temperatures

	-100	-80	-35
After 6 krad	5.71	2.38	0.97
After warm-up	5.13	3.02	0.97
After annealing	9.12	5.31	1.03

C. Dependence on Total Dose

It is interesting to compare the dependence of damage on total dose at different temperatures, extending the radiation level to the point where nonlinearities start to occur. Figure 12 makes such a comparison for a room temperature irradiation and an irradiation at -80 ^oC. The slope starts to increase at about 15 krad(SiO_2), but is very gradual compared to the response for the room-temperature irradiation. Thus, for the practical case where a device has to withstand a radiation level that is much higher than the region where the damage is linear, the extended total dose level for the change in slope adds an additional improvement factor for the net amount of radiation damage.

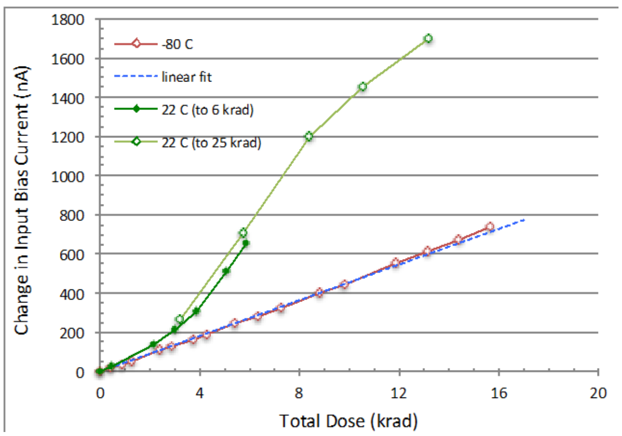

Fig. 12. Radiation damage (measured at the irradiation temperature) for a room temperature experiment and an experiment at -80 ^oC.

V. Discussion

A. Theoretical Considerations

Initial recombination is an important mechanism for the reduction in damage at low temperature. A number of papers have dealt with electron-hole recombination [13-17]. Nearly all have assumed that initial recombination is independent of temperature. However, that is inconsistent with the Onsager theory [6], particularly in the presence of low electric fields.

The Onsager theory (originally developed to explain recombination of charges in electrolytes) points out that thermal energy provides a mechanism to separate the initial positive and negative ions after they are produced. Ausman extended this to electron-hole pairs in SiO_2, assuming that the charged pairs are widely separated, and that geminate recombination applies [1, 2, 7]. The theory assumes the charges will escape recombination if they are separated by a critical distance, r_{crit}, the Onsager radius. At low electric fields r_{crit} is given by [18]

$$r_{crit} = \frac{q^2}{4\pi\varepsilon_r\varepsilon_o kT} \qquad [1]$$

where q is electronic charge, ε_r is the relative permittivity, ε_0 is free space permittivity, and k is Boltzmann's constant.

The probability Y that an electron-hole pair, separated by an initial distance r after creation, will escape recombination is

$$Y = \exp\left(\frac{-r_{crit}}{r}\right) \qquad [2]$$

There is a distribution of separation distances, For a large number of e-h pairs we can use an average value, r_o. Most analyses have assumed that r_o is independent of temperature and electric field. There is considerable uncertainty in what value to use for r_0. Ausman used a range of 5 to 10 nm, but did not discuss the underlying rationale. Boch, *et al.*, did not directly address the question of what value to use, but made computer calculations over a wide range of r_o values [19]. Their work only included temperatures above 200 K (-73 °C), somewhat higher than the range of temperatures for our experimental work. A third analysis of recombination by Murat, *et al.*, used a much smaller value, 0.5 nm, without explanation [20].

B. Older Experimental Results

A variety of devices and experimental conditions were used in previous experimental studies. Most of the earlier work was focused either on charge yield at relatively high fields – 0.5 MV/cm and higher – or on comparisons between different types of radiation sources, including comparisons between cobalt-60 gamma rays and 10-kV X-rays over a wide range of electric fields.

An important distinction can be made between the capacitor studies used by the group at Harry Diamond Laboratory, and other groups: the early HDL experiments used short pulses of radiation, along with a rapid C-V technique that was sensitive to the total charge remaining in the oxide. Most other experiments used longer irradiation times, and were affected by annealing as well as the time required to develop interface traps. Even more important, many of the charge yield experiments at HDL were done on samples that were cooled to 77K, a temperature that is low enough to eliminate hole transport. With no hole transport, those experiments provide the least ambiguous measure of net charge after recombination.

A widely cited recombination study on capacitors by Dozier and Brown was done at room temperature, using a dose rate of 0.07 rad(SiO_2)/s [15]. That work, which did not recognize the strong temperature dependence of recombination at low fields, has been used in several later studies. Note however that the main purpose of the paper was to compare recombination in cobalt-60 and 10-kV X-ray environments, not to investigate recombination at low fields.

With the present knowledge that recombination has a strong temperature dependence, the older work can be re-evaluated. For example, Fig. 11 from [16] includes results from the Dozier and Brown study at room temperature [15], along with data at a temperature of 77 K at a higher dose rate [3]. Data from X-ray sources in the original figure have been removed; all data in the revised figure used cobalt-60 sources. The line in this figure appears to be a "guide to the eye" rather than a mathematical fit. The three data points at low field (taken at room temperature) are well below the line.

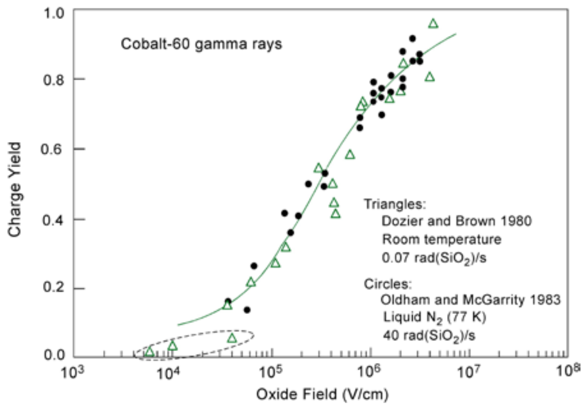

Fig. 11. Hole yield vs. electric field for ^{60}Co irradiations (after [16]). The original figure included X-ray data as well, which tended to obscure the low data points.

When plotted with a logarithmic ordinate (Fig. 12), the inconsistency of those three values becomes even more apparent. The lines in Fig. 12 are calculations of charge yield using various values of r_o in the Onsager recombination model at room temperature. Those lines should apply to the triangles (at room temperature), but not to the circles, which represent data at 77 K. However, nearly all the low temperature data is for high electric fields, where temperature effects are less important.

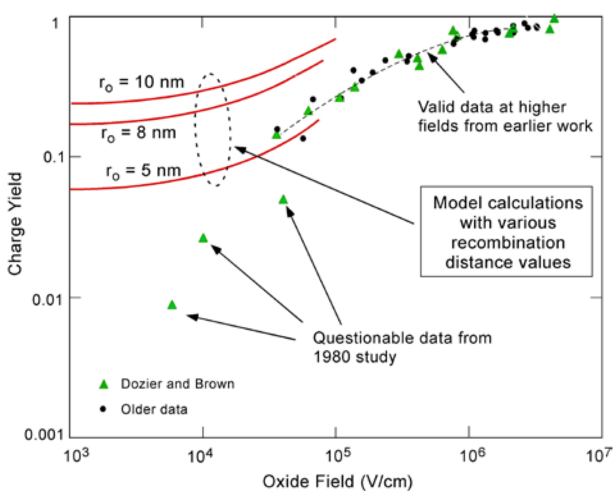

Fig. 12. Results of Fig. 5 plotted with a logarithmic vertical axis.

The region where the two sets of data are consistent at higher fields corresponds to the case where r_o is about 5.1 nm. Although the abnormal data at low fields could be fitted to a much smaller r_o value, recombination at higher fields would be much too high, additional justification for the argument that those three data points are anomalies. As discussed later, those three data points are particularly important because they have been used in subsequent papers on charge yield.

With our current understanding of charge transport, there are important fundamental differences in the two experiments represented in Fig. 11 that make direct comparisons difficult. No charge transport occurs at 77K (as noted in the original work), while the second experiment was done at low dose rate and at room temperature. Thus, most of the charge in the second experiment had sufficient time to reach the Si/SiO_2 interface during the extended irradiation time. Annealing (which from our experiments occurred at much shorter time periods than considered in the original paper) may be a contributing factor for the reduced charge yield in their experiments, but cannot explain the very low values they observed at low field.

The lines in Fig. 12 were calculated using Ausman's model for the field dependence of charge yield [7]. The charge yield flattens out at low fields, depending on the value used for r_0. This allows us to apply an average value for charge yield to the oxides in bipolar structures where the fields vary in the vertical direction, as long as they are on the order of 10^4 V/cm or less.

Estimates of r_o can be made from the value of charge yield at low field (where the field dependence is low) as well as the value at approximately 2 x 10^5 V/cm, where the data are more consistent. However, we still have to deal with the widely different temperature used in the two experiments

C. Effect of Temperature

Ausman's work was the first to recognize that temperature had a strong influence on charge yield in SiO_2, particularly at low electric fields [7]. Calculated values of charge yield based on his work are shown in Fig. 13 for various temperatures, using 5.1 nm for r_0. The calculations include the first 160 terms of the power series expansion in his paper.

For electric fields above 2 x 10^5 V/cm the temperature dependence is very small. At lower fields, the temperature dependence is quite strong, but it flattens out at low electric fields; this is the region that applies to the pnp transistors in bipolar ICs (see Fig. 8).

We can compare those results with our experimental values for low-temperature irradiations of the LM111 comparator, shown in Table 3; the comparisons are made for measurements at the irradiation temperature. The results are in reasonable agreement with recombination calculations from the model, lending experimental credibility to the temperature dependence of charge yield predicted by Ausman at low field.

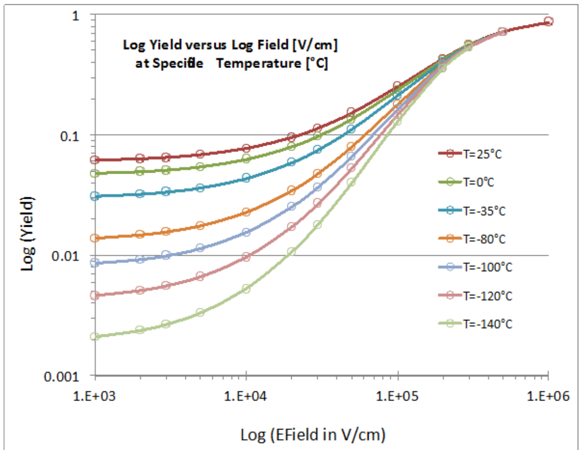

Fig. 13. Effect of electric field on charge yield at various temperatures, using r_0=5.1 nm, obtained by fitting earlier work on charge yield at room temperature.

Table 3. Comparison of Yield Calculations and Experimental Results, Assuming r_o = 5.1 nm

Temperature (°C)	Yield for E = 3000 V/cm	Ratio to Yield at 20 °C	Experimental Ratio (from Fig. 9)
20	0.0622	1	1
-80	0.0157	3.9	2.9
-100	0.0099	6.3	5.6

They also explain why such a significant reduction in total dose damage is achieved in bipolar devices by operating them at low temperature during radiation exposure.

D. Charge Yield

Only a few experiments have been done on charge yield at low fields, a region that is particularly important for the bipolar transistors in linear integrated circuits. The pioneering work at HDL was done at low temperatures, and verified the strong dependence on field. However, as discussed earlier, the main focus was at electric fields > 10^5 V/cm, not the low-field region.

Two later papers compared charge yield from cobalt-60 gamma rays with the charge yield from 10-keV gamma rays [16, 17]. Although a considerable amount of additional data was added, the low-field results from Dozier and Brown [15] noted in Figs. 11 and 12 have been added to the new sets of data, and appear to be the only available data for cobalt-60 gamma rays for fields below 3 x 10^4 V/cm. Shaneyfelt, *et al.*, used those results to arrive at revised charge yield data for cobalt-60 in their paper comparing charge yield in 10-keV and cobalt-60 environments [17]. They show charge yield values of about 1% at 3 x 10^4 V/cm, and include a line that implies even lower yields as the field is reduced. It should be emphasized that (1) their paper includes new data for 10-keV X-rays at lower fields, which are undoubtedly correct; and (2) the primary purpose of the work was to compare charge yield in the two environments, not to get accurate charge yield values at low fields.

Nevertheless, the Onsager recombination model predicts higher values for low-field recombination. Using our estimates of r_o recombination for cobalt-60 should be about 6% at low field, well above the nearly zero values shown in that work. This is further supported by the recent work of Adell, *et al.*, which used gated pnp transistors to measure hole and interface traps in bipolar oxides [21]. The values at low temperature and room temperature obtained in that work are consistent with estimates from the Onsager model.

The Onsager model assumes that geminate recombination applies, a reasonable assumption for high-energy electrons and cobalt-60 gamma rays, but not for 10-keV X-rays or low-energy protons [1,2]. The model does not take clusters into account (see Bradford [22]). Other potential complications include the effect of electron traps, and variations in the concentration of oxygen atoms in oxides from the different processes represented in various experiments, which can affect the number of interface states [23]. Additional experimental work should be done to further investigate yield at low electric fields.

VI. Conclusions

This paper shows that less damage takes place in bipolar integrated circuits when they are irradiated at low temperature. This provides a way to extend the failure levels of these devices to significantly higher radiation levels, either by operating them continuously at low temperature, or by cooling them to low temperatures during time periods when higher radiation levels are expected, such as orbital insertion in planetary missions with trapped radiation belts.

The results can be explained by the temperature dependence of initial recombination of the electron-hole pairs, which is much higher at low temperature. We expect the results can be applied to all bipolar devices, although the magnitude of the improvement depends on oxide thickness.

Existing charge yield data can be fitted using the Onsager model proposed by Ausman with a mean separation distance of about 5 nm. For that r_0 value, charge yield at low fields (for geminate recombination) is 0.06 at room temperature. This is considerably higher than the low-field value given in several later interpretations of charge yield. Our experimental results for bipolar devices at -80 and -100 °C are consistent with the lower value of r_0, and further support the assumption that the yield at low field can be described by the Onsager model.

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