Effect of Passivation on the Enhanced Low Dose Rate Sensitivity of National LM124 Operational Amplifiers

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Abstract—This paper presents high and low dose rate test results for LM124 operational amplifiers that were fabricated with six passivation layer types. Consistent with previous data, these results confirm that passivation layers play a significant role in determining ELDRS response. SIMS analysis suggests that an influential factor in determining the high and low dose rate response may be the location and concentration of hydrogen at the Si-SiO₂ interface and in the passivation layers.

Index Terms—enhanced low dose rate sensitivity, ELDRS, total dose irradiation, dose rate enhancement factor, passivation, hydrogen, nitride, LM124, operational amplifier, secondary ion mass spectrometer, SIMS.

I. INTRODUCTION

Surface passivation and backend IC processing have been shown to have a major effect on the enhanced low dose rate sensitivity (ELDRS) response of linear ICs [1]-[4]. It was shown that devices fabricated without passivation layers do not exhibit ELDRS, while devices from the same production lot fabricated with passivation layers exhibit ELDRS [2]. In addition, it was shown that removing the passivation layers with a wet etch could mitigate this sensitivity. These results suggested that changing the passivation layer could mitigate ELDRS.

In this work, we continue to explore the role of passivation layers on ELDRS in bipolar linear ICs fabricated by National Semiconductor Corporation. Specifically, we explore ELDRS in LM124 operational amplifiers fabricated by National Semiconductor with a variety of first and second layer passivation combinations. In addition, Secondary Ion Mass Spectrometry (SIMS) analysis is used to explore the location and concentration of hydrogen at the Si-SiO₂ interface and in the passivation layers. The implications of the SIMS results are discussed.
II. EXPERIMENTAL DETAILS

A wafer lot of LM124 devices was fabricated in March 2003 at National Semiconductor’s Arlington, Texas, facility using the commercial LM-series bipolar linear process flow. The LM124 die is shown in Fig. 1. This device used the current LM124 (LM1902TEH) layout. In addition to the LM124, each wafer included special test structures and process monitors designed to study ELDRS effects [3]. All wafers were processed together through metal patterning and etch. The wafers were then passivated with various passivation layers. These passivation layers include no passivation, p-glass (phosphosilicate), p-glass under silicon nitride (the standard non-radiation hardened passivation), TEOS (tetraethylorthosilicate) under nitride, TEOS under p-glass, and TEOS.

Fig. 2 shows the passivation matrix and a cross-section drawing of the location and thickness of each passivation layer.

After fabrication, LM124 die were packaged in 14-pin ceramic dual-in-line packages. These packaged devices were irradiated at NAVSEA Crane using a Shepherd Model 484 Cobalt-60 tunnel irradiator. A total of 10 packaged devices from each passivation split were exposed to total dose. Five devices from each split were irradiated at a high dose rate (HDR) of 90 rd(Si)/s. The remaining five devices were irradiated at a low dose rate (LDR) of 0.022 rd(Si)/s to a total dose of 30 krd(Si). Two LM124 devices were never irradiated, which served both as control samples and indicators of test equipment calibration. During irradiation, all LM124 devices were biased in-situ in a voltage follower configuration with $V_{CC} = 15V$, $V_{EE} = 0V$, and an input of 0V.

After irradiation, HDR-irradiated devices were allowed to anneal (without bias) in electrostatic foam at room temperature. Electrical characterization was performed to look for time dependent effects. The total anneal time was selected to correspond with the amount of time required to irradiate the devices to 30 krd(Si) at LDR.

Electrical characterization was performed using an EAGLE LSI test system. The following electrical parameters were measured: input offset voltage ($V_{OS}$), input offset current ($I_{OS}$), inverting and non-inverting input bias currents ($I_{B+}$ and $I_{B-}$), power supply current ($I_{CC}$), minimum and maximum output voltage ($V_{OL}$ and $V_{OH}$), minimum and maximum output drive currents ($I_{OL}$ and $I_{OH}$), and voltage gain ($AV$).

III. TOTAL DOSE RESULTS

Fig. 3 shows the changes in input offset voltage with increasing total dose for HDR and LDR irradiations. Deltas from pre-irradiated values are plotted for easier comparison of degradation between the passivation splits. The failure level for this parameter is approximately 9mV. The p-glass/nitride passivation is soft at both HDR and LDR with devices failing to operate after 20 krd(Si) at HDR. A very distinct ELDRS signature (HDR degradation suppressed in value from LDR level) is observed on two splits (TEOS/nitride, p-glass) with a slight ELDRS signature seen on TEOS/p-glass. The TEOS and no passivation splits show almost no degradation of input offset voltage at either HDR or LDR. These results clearly confirm that passivation layers have a distinct role in ELDRS. In addition, the results also show that adding nitride to any split tends to soften both the HDR and LDR response.

Changes in the input bias current parameter with total dose are shown in Fig. 4 for HDR and LDR irradiations. Delta absolute values from pre-irradiation are used to allow comparison between passivation splits. Input bias current greater than 100nA is considered to be failure. It is clear that p-glass/nitride passivation is soft at all dose rates and not representative of ELDRS. Again, the TEOS/nitride shows considerable degradation HDR and LDR and shows an ELDRS signature. The p-glass split, although not failing, also shows ELDRS. The remaining splits show almost no degradation of input bias current. The split without passivation is hard at all dose rates.

![Fig. 3. Delta input offset voltage versus total dose for the LM124. For the input offset voltage parameter, the p-glass/nitride passivation is equally soft at both dose rates.](image1.png)

![Fig. 4. Delta input bias current versus total dose for the LM124. Again, the input bias current on the p-glass/nitride split is soft at both dose rates. A strong ELDRS effect is seen on the TEOS/nitride and p-glass splits. Adding a nitride layer enhances the total dose degradation at both dose rates.](image2.png)
Fig. 5. Summary of total dose response of each passivation split.

Test data for the other electrical parameters are not presented, as the total dose effects are most evident in input bias current and input offset voltage.

Fig. 5 summarizes the total dose response for the LM124 for all six passivations. Devices without passivation were hard at both dose rates. A single layer of p-glass (alone) caused a distinct ELDRS response. Adding nitride as a final passivation layer degrades the total dose response at all dose rates. Splits using TEOS (without nitride) are relatively hard, but show a small ELDRS response.

IV. QUANTIFYING ELDRS EFFECTS

Using the data from Figs. 3 and 4, a “figure of merit” was generated to compare each LM124 processing split. This was accomplished by using an enhancement factor calculation, made by dividing the $\Delta$(parameter) at LDR by its $\Delta$(parameter) at HDR counterpart at 30 krd(Si). An enhancement factor of one implied no ELDRS effect. Since the comparisons are made immediately after irradiation, this enhancement factor includes both dose rate and time dependent effects. Fig. 6 summarizes these enhancement factors. Note that since the p-glass/nitride split was soft at both dose rates and these devices failed early, the enhancement factor for this split was computed at 20 krd(Si).

One must exercise caution in using enhancement factor (alone) as a device selection criterion. While certain devices may exhibit a larger enhancement factor (e.g., TEOS/p-glass split), they may still remain within their electrical specification at low dose rate. Other devices with small enhancement factors (e.g., p-glass/nitride) are simply “total dose soft” at all rates and do not show ELDRS.

V. VERIFICATION OF TRUE DOSE RATE EFFECT

To determine if the parameter shifts are associated with true dose rate effects or time dependent effects, one must anneal HDR-exposed parts to the equivalent time of an LDR exposure. If the response is dependent on dose rate, the parameters will not degrade to LDR levels during this anneal. If the total dose effect is time dependent, as found in most CMOS oxides [5]-[6], HDR parameters will degrade to LDR levels.

Figs. 7-8 show the results of the annealing investigation for input offset voltage and input bias current, respectively. In this portion of the experiment, HDR devices were first irradiated to 30 krd(Si) and then allowed to anneal at 25°C with all leads shorted in conductive foam for 26 days, 1.6 times the equivalent time for a 30 krd(Si) LDR exposure. At the 16 day anneal point, the HDR samples have just reached the equivalent LDR exposure time.

<table>
<thead>
<tr>
<th>1st Layer Passivation</th>
<th>2nd Layer Passivation</th>
<th>Total Dose Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>none</td>
<td>hard</td>
</tr>
<tr>
<td>p-glass</td>
<td>none</td>
<td>ELDRS</td>
</tr>
<tr>
<td>p-glass</td>
<td>nitride</td>
<td>soft</td>
</tr>
<tr>
<td>TEOS</td>
<td>nitride</td>
<td>ELDRS</td>
</tr>
<tr>
<td>TEOS</td>
<td>p-glass</td>
<td>ELDRS</td>
</tr>
<tr>
<td>TEOS</td>
<td>none</td>
<td>ELDRS</td>
</tr>
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temperature using the same bias conditions as used during the irradiation. Unfortunately, this was not done. However, we do not believe that the results would differ significantly from those shown in Figs. 7-8. The anneal behavior of similar linear bipolar devices irradiated and annealed using the same bias conditions is not significantly different than the results illustrated here [7]. The solid lines in each figure represent the HDR annealing data. The dashed lines show the LDR irradiation data for comparison. Both figures show no significant change in degradation during the room temperature anneal suggesting that the observed difference in response after the HDR and LDR irradiation is consistent with a true dose rate effect and is not a time dependent effect.

VI. HYDROGEN IN OXIDES AND PASSIVATION LAYERS

It has been well established that protons (positively charged hydrogen) released during irradiation are responsible for positive charge buildup and interface state formation at the Si-SiO₂ interface [8]-[14]. In addition, it has been shown that annealing in a hydrogen ambient after depositing the gate material (e.g., metal or polysilicon) can significantly increase the amount of radiation-induced interface-trap charge [13].

Therefore, it is critical to control the amount of hydrogen at the interface, in the field oxides, and in the passivation layers. Simply knowing the physical location of hydrogen in these layers can be key to developing a hardening strategy for these processes, at both low and high dose rates.

Secondary Ion Mass Spectrometry analysis was used to look for the presence of hydrogen at the Si-SiO₂ interface, in the field oxide, in the vapox, and in each passivation layer. The SIMS analysis was performed starting from the backside of the chip (in the bulk silicon) to increase measurement accuracy for hydrogen. To prepare the samples for SIMS, mechanical lapping was used to remove the bulk silicon to within 1-2 microns of the Si-SiO₂ interface. Only three passivation splits were analyzed with this technique as the effort required to complete this precision lapping and analysis was extensive. SIMS analysis was performed on devices manufactured without passivation which were hard at high and low dose rate, on the p-glass which exhibited ELDRS, and on the p-glass/nitride splits which were soft at all rates.

Fig. 9 shows SIMS profiles for these three key processing splits. The plot was generated by taking the SIMS profile from the thickest split (p-glass/nitride) and overlaying the hydrogen signals from two thinner splits. This visual technique allows for direct comparison of the hydrogen counts from all three splits—using a single plot.

In comparing hydrogen concentrations from the three splits, there is one significant difference at the Si-SiO₂ interface. The hydrogen peak at the Si-SiO₂ interface on the p-glass/nitride sample is 10x greater than in the other two samples. Based on the irradiation data, this was the only split (of the three) that was soft at HDR.

For the p-glass/nitride split, the hydrogen level in the p-glass did not change when nitride was added to the stack. From the irradiation experiments, it was found that both of these splits (p-glass and p-glass/nitride) showed degraded LDR responses. Thus, the SIMS data suggest that the interfacial hydrogen may be responsible for the short-time (HDR) response while the remotely located hydrogen may be responsible for the long-time (LDR) response.

The unpassivated (nopass) split was hard at HDR and LDR. This split shows a small amount of hydrogen at the interface and no hydrogen at a distance from the interface (i.e., no passivation, just air).

The p-glass passivation showed an ELDRS response. It measured low levels of hydrogen at the Si-SiO₂ interface and high levels of hydrogen at a far distance from the interface. This split also showed that ELDRS effects appear by simply adding p-glass over the oxide stack.

The p-glass/nitride split was soft at both HDR and LDR. It contained high hydrogen levels at the Si-SiO₂ interface and high levels of hydrogen at a far distance from the interface. Having two sources of hydrogen in the oxide, one located at the Si-SiO₂ interface and another at some distance away, could be key to understanding the source of the HDR short-time and LDR long-time response. If the movement of radiation-released protons to the interface (during and after irradiation) is creating interface states and degrading transistor gain, efforts must be made to locate the hydrogen and eliminate each source.

VII. SUMMARY AND CONCLUSION

Devices that use nitride passivation were found to be generally soft at all dose rates. These passivations contain a rich source of hydrogen. The data suggest that this source of hydrogen, coupled with high temperature processing cycles, could be responsible for creation of an additional hydrogen peak at the Si-SiO₂ interface. This peak is formed during two post-metallization anneal sequences.

Fig. 9. SIMS profile for three key passivation splits (nopass, p-glass, p-glass/nitride). Devices manufactured with low hydrogen levels at the Si-SiO₂ interface were hard at HDR. Devices with enhanced hydrogen in the passivation layers were soft at LDR. Devices with low hydrogen at the interface and no hydrogen at far distances (i.e., no passivation) were hard both HDR and LDR.
The control split (without passivation) was hard at both high and low dose rates. This split measured very low hydrogen levels at the Si-SiO₂ interface and contained no hydrogen at far distances (as it had no far-distance passivation). Fabricating devices without passivation is not a practical hardening solution because a moisture barrier of some material (like silicon nitride) is required to protect the die after packaging. However, this split demonstrated that passivation layers play a role in the ELDRS effect.

The split with p-glass passivation showed a strong ELDRS signature. SIMS analysis indicated low hydrogen levels at the Si-SiO₂ interface and high hydrogen levels in the p-glass. As this was the ELDRS split, it supports the hypothesis that the source for the HDR short-time response could be the close-at-hand interfacial hydrogen and the source for the LDR long-time response could be the remotely located hydrogen in the first-level passivation. In this technology, the first-level p-glass layer is located at distances of 12,200Å to 21,200Å from the interface.

Previous experimenters [2] have shown that wet chemical removal of passivation layers suppressed the LDR response on many device types. SIMS analysis shows that these same layers contain elevated levels of hydrogen and further support the hypothesis that remotely-located hydrogen is responsible for the LDR response.

The fact that LM124 post-irradiation HDR parameters did not show any significant change with 25°C annealing also suggests that ELDRS is a true dose rate effect in this technology. This true dose rate effect is explained with the space charge model [14] as a buildup of positive charge in the field oxide at HDR, impeding the movement of protons from remote locations to the Si-SiO₂ interface.

While not conclusive, the data suggest that the hydrogen located at the Si-SiO₂ interface may contribute to the HDR response while the hydrogen located at greater distance may contribute to the LDR response. Understanding the physical location of the hydrogen in bipolar technology oxides could be key to developing hardening solutions for ELDRS.

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REFERENCES


