Degradation of polycrystalline silicon TFTs due to alpha particles irradiation stress

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\begin{abstract}
The degradation mechanism of poly-Si TFTs due to alpha particles irradiation is investigated. The tested devices exhibit increase in the density of interface states and grain boundaries traps proportional to the radiation fluence, $\Delta N/N_0 = K \cdot F$. The irradiation introduced defects are responsible for the degradation of major device parameters, such as the threshold voltage, the subthreshold swing, the leakage current and the ON mobility and current. Their degradation is found to obey the same law. The analysis of the thermally activated parameters reveals that the irradiation induced defects are lying deep in the semiconductor band gap. Moreover the negative threshold voltage shift is associated to positively charged oxygen vacancies in the gate insulator, called $E^+$ centers.
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1. Introduction

Thin film transistors (TFTs) fabricated on polycrystalline silicon (poly-Si) films is the most promising active device for the backplanes of future active matrix displays and integration of peripheral circuits on mobile electronics. As a result the reliability of thin film devices and structures has become a topic of vital importance for TFT technology. Beside the hot carriers stress effects that have been intensively investigated\textsuperscript{[1,2]}, the reliability of TFTs in harsh radiation environment, such as in space, has been recently investigated and constitutes a topic of great interest\textsuperscript{[3,4]}. This interest is enhanced by reports that TFTs on flexible substrates are essential for space applications such as solar sails and space based telescopes\textsuperscript{[5]} where they are susceptible to ionizing radiation.

The degradation mechanisms of poly-Si TFTs due to alpha particles irradiation is investigated. The tested devices exhibit increase in the density of interface states and grain boundaries traps proportional to the radiation fluence, $\Delta N/N_0 = K \cdot F$. The irradiation introduced defects are responsible for the degradation of major device parameters, such as the threshold voltage, the subthreshold swing, the leakage current and the ON mobility and current. Their degradation is found to obey the same law. The analysis of the thermally activated parameters reveals that the irradiation induced defects are lying deep in the semiconductor band gap. Moreover the negative threshold voltage shift is associated to positively charged oxygen vacancies in the gate insulator, called $E^+$ centers.

The lattice damage introduced by electron and/or $\gamma$-ray irradiation is restricted to introduction of point defects, the latter through Compton electrons. The ion radiation introduces complex and extended defects due to their large mass and scattering cross section. Presently, the available information on radiation degradation of poly-Si TFTs is restricted on test performed under gamma rays irradiation. Upon gamma rays radiation, TFTs have shown to exhibit negative threshold voltage shift\textsuperscript{[3]} attributed to the generation of positively charged traps in gate oxide, well formed kinks in the subthreshold region\textsuperscript{[3]} and generation of states at interface and grain boundaries\textsuperscript{[4]}. The investigation of particle irradiation effects has been focused on polysilicon films rather than devices. Here it must be pointed out that the equivalent damage due to alpha particles has been found to be one and three orders of magnitude larger than for protons and electrons respectively, due to differences in their effective mass and the probability of collision for the formation of lattice defects\textsuperscript{[6]}.

The radiation tests with alpha particles have been often used because they introduce more primary and cascade complex defects and accelerate the devices degradation. Alpha compose the 9% of cosmic rays and the ionizing stopping power ($-dE/dx$) is large enough to cause under certain conditions the device burnout. They also are often found in radioactive traces in ceramic materials used for packing electronic chips. Therefore it becomes obvious that in the view of future TFT application, their degradation due to alpha particle irradiation is quite relevant.

Aim of the present work is to present a comprehensive study of the influence of alpha particles on the electrical behaviour of poly-Si TFTs and to reveal the degradation mechanisms as it related to device structure.

2. Experimental

Polysilicon n-channel TFTs were fabricated on films formed by crystallization of amorphous silicon. Hydrogenated a-Si films (a-Si:H) were initially deposited at 320 $^\circ$C by plasma enhanced chemical vapor deposition (PECVD) on quartz substrates. The a-Si:H films were then subjected to a 500 $^\circ$C, 2 h anneal to remove the excess hydrogen. The resulting a-Si films were transformed to polysilicon by excimer laser annealing, using the sequential lateral solidification (SLS) process\textsuperscript{[7]}. The SLS process was conducted at room temperature by scanning the samples under an appropriately shaped laser beam, generated by a 4308 Lambda Physik excimer laser (XeCl, 308 nm) with a discharge frequency of 150 Hz. This process results in a polysilicon film having a structure composed of very long crystal grains separated by roughly
parallel boundaries. Films with thicknesses of 30 nm were finally fabricated.

The devices had a non-self-aligned top metal gate structure. Carrier conduction occurred in the direction parallel to the formed grain boundaries. These device orientations presented the minimum energy barrier to conduction, through the anisotropic polysilicon material. The channel length and width were 8 μm and 200 μm, respectively. A 100 nm thick PECVD SiO2 film, formed by plasma decomposition of a SiH4/N2O/N2 gas mixture at 400 °C, was used as gate dielectric. The source and drain regions were formed by ion implantation through the gate oxide, with the channel protected by photore sist and the activation temperature was 800 °C. The device body was not intentionally doped. Thus, material defects and interface states determined the threshold voltage.

The devices have been irradiated, at room temperature with a 5 MeV average energy α-particles obtained from an Am source.

The transfer characteristics at selective temperatures before and after the irradiation process. Additional results are obtained from the application of a modified Levinson [8] analysis on the experimental data.

![Fig. 1. Room temperature transfer characteristics versus irradiation fluence.](image)

![Fig. 2. Transfer characteristics at selective temperatures before and after the irradiation process.](image)

![Fig. 3. The interface state density Nt, the density of states at grain boundaries NGB, and the oxide traps Nox, were found to increase linearly with radiation fluence.](image)

3. Results and discussion

The damage caused by alpha particles in a solid state device arise from partial loss of its energy by disrupting electronic bonds; generating energetic free carriers and by collisions that give rise to lattice atoms displacement generating vacancies and interstitials, which when performed at room temperature may give rise to generation of complex defects. Moreover the material damage is enhanced by the primary knock on atoms which gain enough energy to produce additional vacancies by further collision with the lattice atoms [9].

The irradiation induced defects are responsible for major degradation in the device operation. In poly-Si TFTs the influence of alpha particles on the transfer characteristics at room temperature, after each successive irradiation, as well as at selective temperatures before and after the process presented in Figs. 1 and 2.

It is clearly noted a negative threshold voltage (Vt) shift as well as an increase in the subthreshold swing (S) and in the device leakage current. In a MOS structure the negative threshold voltage shift is associated to the increase of positive charge in the gate insulator [10]. A common irradiation induced defect in SiO2 conventionally identified as positively charged is the E center [11]. The E center consist of two Si atoms joint by a week, strained Si-Si bond with a missing oxygen atom sometimes referred as oxygen vacancy [12]. Except from the irradiation induced ones (Fig. 5), oxygen vacancies pre-exist in its neutral state due to the amorphous nature of SiO2 [12]. When an irradiation induced hole get captured, it appears as positively charged, ≈Si³⁺Si≡ [13] in two distinct configurations, Ec (in two configurations Ec,α and Ec,c) and Ec [14]. The corresponding energy level introduced by Ec and Ec,α is very shallow, while these due to Ec,c, are quite deep [14] and references therein. Electron Paramagnetic Resonance (EPR) data revealed that immediate after irradiation there exist a large concentration of Ec,c. However later, after the end of the process, the holes in the shallow levels re-emitted and re-absorbed by deeper states reducing the concentration of Ec,c centers and increasing the one for the Ec,c [14] and references therein.

On the other hand the increase in the subthreshold swing reveals the increase of positive charge in the gate oxide and the device depleted area in the vicinity of Fermi level. Similar result is obtained from the increase in the leakage current which is directly affected by the density of states in particular close to the drain terminal [15].

The density of introduced states versus irradiation fluence can be extracted by the corresponding device parameter. Thus the interface states density Nt after each successive irradiation is extracted from the subthreshold swing, S as

\[ N_t = \left( \frac{S - S_0}{C_{ox} kT/q} \right) \frac{C_{ox}}{qT} \]  

where \( S_0 \) is the ideal mosfet subthreshold swing, \( S_0 = (kT/q)\ln10 \) and \( C_{ox} \) is the gate insulator capacitance.
The results are presented in Fig. 4 and the corresponding damage coefficients \( Kp \) along with the most important parameters values calculated at room temperature on virgin devices before the irradiation process are summarized in Table 1.

As revealed by the damage coefficient values, supported by the simulation results in Fig. 5, a higher degradation occur in the OFF state operation affecting the device leakage current. As already mentioned, the OFF current in poly-Si TFTs arises by carriers’ generation via band gap states close to the drain terminal, throughout the film thickness. On the contrary, all the other parameters presented in Table 1, are mainly affected by the device interface and channel. This behaviour indicates an enhanced defect creation at the rear part of the poly-Si film, a fact that is supported from the higher concentration of introduction rate of vacancies, as obtained from simulations with the aid of TRIM code (Fig. 5).

Poly-Si TFTs are actually Silicon On Insulator (SOI) structures with polycrystalline body fabricated on glass substrates. Due to the existence of poor crystalline quality and extended defects such as dislocations and grain boundaries in their active area their electrical behaviour differs from the conventional SOI MOSFETs. Regarding the reliability of conventional devices to ion radiation, the effect of 20 MeV alpha particles have been studied by Hakata et al. [16]. Based on the linear degradation of the device parameters with the irradiation fluence, and the proportionality between the experimentally determined damage factors and the theoretically calculated non ionizing energy loss (NIEL), the damage coefficients at different energies is extracted as [9]

\[
K_{(5MeV)} \times K_{(20MeV)}^{-1} = \text{NIEL}(5MeV) / \text{NIEL}(20MeV)
\]

where the calculated values of non ionizing energy loss for alpha particle in silicon have been reported in [17].

The damage coefficient obtained from the experimental values by [16] and Eq. (5) is \( K_{20} = 2.25 \times 10^{-17} \text{Acm}^2/\text{par} \). The result for poly-Si TFTs expressed in the same units as obtained from Table 1 is \( K_{20} = 8.5 \times 10^{-19} \text{Acm}^2/\text{par} \).

For the OFF state current the damage of SOI devices is more than one order of magnitude higher. This difference, with respect to crystalline SOI devices, in the OFF current degradation must be attributed to the nature of polycrystalline silicon film. Due to the presence of grain boundaries and extended defects such as dislocations on TFTs body, a large state density in the semiconductor band gap pre-exist the irradiation. In this case the irradiation induced defects are less or in the same order with the pre-existing, and therefore the device behaviour is less affected by them. Similar behaviour has been obtained on electrical stresses experiments where the thinner more defective polysilicon films are less sensitive to hot carriers stress degradation [1].

![Fig. 4. Influence of alpha particles on the field effect mobility, ON and OFF state currents.](image1)

![Fig. 5. Silicon (solid line) and oxygen (dashed line) introduced vacancies as obtained from TRIM calculations.](image2)
The temperature analysis of leakage current before and after the irradiation process reveals a reduction in the activation energy \(E\) caused by the carriers generated via band gap states, with a similar mechanism as described for the leakage current [15].

\[
S = A_0 + A_1 T + A_2 \exp \left( - \frac{E}{kT} \right)
\]

(7)

where the activation energy \(E\) is also measured with respect to the intrinsic Fermi level.

4. Conclusions

The degradation mechanism of poly-Si TFTs due to 5 MeV alpha particles irradiation has been investigated. The tested devices exhibit increase in the state density proportional to the irradiation fluence. The degradation of major device parameters was found to obey the same law. As revealed by the damage coefficient an enhanced creation of defects occurs in the rear part of the film a result supported by simulation results. Near the top interface of the films the density of irradiation induced defects is comparable with the pre existing defects indicating that the poly-Si TFTs are less sensitive than crystalline SOI devices to alpha particles radiation. Finally the analysis of the thermally activated parameters reveals that the irradiation induced defects are lying deep in the semiconductor band gap.

The same trend is obtained by the temperature dependence of the subthreshold swing (see Fig. 7). In poly-Si TFTs an exponential term emerges at higher temperatures that arise by the carriers generated via band gap states, with a similar mechanism as described for the leakage current [15].

\[
I = I_0 \exp \left( - \frac{E}{kT} \right)
\]

(6)

Regarding the energy distribution of the introduced defects, useful information can be obtained by the thermally activated parameters, such as the leakage current and the subthreshold swing. These parameters are affected by carriers' generated through band gap states and therefore their activation energy is affected by the band gap position of the irradiation induced states [15].

The temperature analysis of leakage current before and after the irradiation process reveals a reduction in the activation energy \(E\) measured from the intrinsic Fermi level (see Fig. 6), thus generation of states deep in the band gap [15].

### Table 1

<table>
<thead>
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<th>(K_i)</th>
<th>Damage coefficient (cm²/par)</th>
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<tr>
<td>(K_{it})</td>
<td>5.2 \times 10^{-12}</td>
<td>3.9 \times 10^{11} (cm⁻² eV⁻¹)</td>
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<tr>
<td>(K_{Car})</td>
<td>3.4 \times 10^{-12}</td>
<td>5.15 \times 10^{13} (cm⁻²)</td>
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<tr>
<td>(K_{thres})</td>
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<td>(K_M)</td>
<td>1.83 \times 10^{-13}</td>
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<td>(K_{ON})</td>
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<td>5.45 \times 10^{-6} (A)</td>
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<tr>
<td>(K_{OFF})</td>
<td>3.25 \times 10^{-10}</td>
<td>8 \times 10^{-11} (A)</td>
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### References


