Using ionization response maps for SET characterisation in UHF mixers

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Abstract. SEE sensitivity of integrated circuits is characterized by their SEE cross-section vs. linear energy transfer dependencies – $\sigma$(LET) which are obtained through ion tests. Often those $\sigma$(LET) dependencies have such few data points that it’s much trouble to approximate them correctly. In those cases $\sigma$(LET) can be complemented with SEE cross-section vs. laser energy $\sigma$(J) obtained from laser tests. At the same time, $\sigma$(J) rarely follow exactly the shape of $\sigma$(LET) due to the metallization non-uniformly over chip area. Nevertheless, $\sigma$(J) can be corrected against this non-uniformity by examining the ionization response maps $\Delta U(x, y)$. In this work we demonstrate that such corrected $\sigma$(J) correlates better with $\sigma$(LET) by the example of single event transients (SET) in two types of UHF mixers.

1. Introduction
The goal of almost every single event effect (SEE) test is to estimate the frequency of certain single event effect in the device under test (DUT) in space. This frequency $\nu$ can be obtained from the SEE cross-section vs. ion’s linear energy transfer $\sigma$(LET) and the ion’s LET differential spectrum in space $\varphi$(LET):

$$\nu = \int_{0}^{\infty} \varphi(LET) \cdot \sigma(LET) \cdot d(LET),$$

where $\sigma$(LET) is usually obtained from ion accelerator tests. However, the available set of LET values is always limited. Sometimes this leads to very few data point in the final $\sigma$(LET) dependence. In such cases, laser test can help in the reconstruction of the whole $\sigma$(LET) more precisely.

2. Experimental technique
Let’s consider an example. Only three LET values were available in the single event transient (SET) test for the GaAs microwave mixer which was not sufficient for $\sigma$(LET) approximation. To supplement more data to these three data points, a series of laser scanning has been performed (SET locations at different laser energies are shown in Fig. 2) using FEMTO-T laser facility with 870 nm wavelength and 1.0 ps pulse duration [1]. Thus a SET cross-section ($\sigma$) vs. laser energy (J) dependence was obtained. Finally, these to dependencies were overlaid one with another (Fig. 1). This means that $\sigma$(J) curve was scaled both horizontally and vertically (or “shifted” in logarithmic scale) with certain scale factors $K_{\text{LET}}$[MeV·cm$^2$/(mg·nJ)] and $K_{\sigma} = 0.1$ so that finally we have $K_{\sigma} \cdot \sigma(K_{\text{LET}} \cdot J)$ instead of $\sigma$(J).
However, one can note the certain difference between laser and ions data at small LETs. Furthermore, factor $K_\sigma$ is too small which tells us that we have laser SEE cross-section rather overstated in comparison to the ions’ one. The hypothesis is that the $\sigma(J)$ curve obtained with a laser is not quite correct. The fact is that metallization layers covering the chip are opaque for the laser beam. The amount of laser light passing through those layers depends on the metallization density [3,4]. The latter varies over the chip’s area, so the amount of laser energy passing through it at different locations varies as well. This means that if we are scanning the laser beam across the chip with certain pulse energy, the energy deposited in the chip’s SEE-sensitive area is different depending on the location of the laser spot. So we cannot assign any definite energy to the SEE cross-section we obtain in such a scanning.

[2] demonstrates the method of the SEE threshold LET evaluation based on the determination of the SEE threshold laser energy $J_{th}$ and the examination of the so-called ionization response voltage. Ionization response is the voltage pulse which one can observe if he (or she) puts the device to test the so-called photodiode mode and expose it to the laser pulse. Photodiode mode is realized when one connects all input pins of the DUT to the power pin keeping the outputs floating. Power pin and the ground pin of this device are the electrodes of the photodiode, and the ionization response is the voltage pulse which this photodiode generates when being exposed to laser light.
The key point is that the amplitude of the ionization response pulse $\Delta U_{IR}$ is inversely proportional to the laser energy losses which are due to the metallization. Thus the product $J_{th} \cdot \Delta U_{IR}$ is directly proportional to the SEE threshold LET:

$$LET_{th} = K_{LET} \cdot (J_{th} \cdot \Delta U_{IR}),$$

(2)

where $K_{LET}$ is the proportionality coefficient which is the same for every location on the chip.

If we knew the SEE threshold LET in every point of the chip, we could reconstruct the $\sigma(LET)$ curve with as many data points as we want. Indeed for determining SEE cross-section for a particular LET, we need just to sum all the sensitive areas with threshold LETs smaller than that LET.

So we have to determine $J_{th}$ and $\Delta U_{IR}$ for every point of the chip – $J_{th}(x, y)$ and $\Delta U_{IR}(x, y)$. First, we define the grid of points on the chip. To determine $J_{th}$ in each point of the grid, we can use a dichotomy process whose flowchart is shown in Fig. 3. The error of the final $J_{th}$ value in this process is $\Delta J_{th} = J_{\text{start}}/2^{N_{\text{max}}}$, where $J_{\text{start}}$ is the starting laser energy, $N_{\text{max}}$ is the maximum number of iterations in the dichotomy process.

**Figure 3.** The process of SEE threshold energy determination through dichotomy. $J_{\text{start}}$ is a certain starting energy which is set up each time the dichotomy process is started; $N_{\text{max}}$ is the maximum number of iterations in the process.

The $J_{th}(x, y)$ map for GaAs UHF mixer is shown in Fig. 4. From such map, one can obtain $\sigma(J)$ curve with the far larger amount of data points ($2^{N_{\text{max}}}$) than that from a series of scanning (Fig. 5). Nevertheless, that curve still doesn’t take into account optical losses of laser energy due to the metallization and thus it still doesn’t follow exactly the shape of $\sigma(LET)$ curve.

The next step is to determine $\Delta U_{IR}(x, y)$. Ionization response map for GaAs UHF mixer is shown in Fig. 7. Multiplying $J_{th}(x, y)$ and $\Delta U_{IR}(x, y)$, we obtain a value which is directly proportional to the SEE threshold LET (see (2)). The $J_{th}(x, y) \cdot \Delta U_{IR}(x, y)$ map is shown in Fig. 8. Again from this map we can extract the dependence $\sigma(J \cdot \Delta U_{IR})$ though for this time we know that this dependence must follow the shape of the $\sigma(LET)$ curve. Moreover, this is actually the case as shown in Fig. 9 where we see $\sigma(LET)$ overlaid with $\sigma(J \cdot \Delta U_{IR})$ scaled along the horizontal and vertical axis by coefficients $K_{LET}$, $K_{\sigma}$ respectively. Note that $K_{\sigma}$ appeared to be exactly 1.
**Figure 4.** SET threshold energy vs. location (x, y) on the chip for GaAs UHF mixer. d = 2.5 μm, step = 5 μm.

**Figure 5.** SET cross-section vs. laser energy obtained from Jth(x, y) map.

**Figure 6.** σ(LET) and Kσ·σ(KLET·J) for GaAs UHF mixer. K_{LET} = 10 MeV·cm²/(mg·nJ), K_σ = 0.1.

**Figure 7.** ΔU_{experimental} vs. location (x, y) on the chip for GaAs UHF mixer. J=5 nJ, R=50 Ohm, d = 2.5 μm, step = 5 μm.

**Figure 8.** Jth·ΔU_{experimental} vs. location (x, y) on the chip for GaAs UHF mixer.
The technique described above has been applied to a SiGeUHF mixer. In this case, only a part of the whole chip area was tested which was found to be SET sensitive. $J_{th}(x, y)$, $\Delta U_{IR}(x, y)$ and $J_{th}(x, y) \Delta U_{IR}(x, y)$ maps are shown in Figures 10, 11 and 12 respectively. $\sigma(J)$ and $\sigma(J \Delta U_{IR})$ overlapped with $\sigma(LET)$ are shown in Figures 13 and 14.

**Figure 9.** $\sigma(LET)$ and $K_\sigma \cdot \sigma(K_{LET} \cdot J \cdot \Delta U_{experimental})$ for GaAs UHF mixer. $K_{LET} = 2.4 \cdot 10^5 \text{MeV} \cdot \text{cm}^2/(\text{mg} \cdot \text{nJ} \cdot \text{V})$, $K_\sigma = 1.0$.

**Figure 10.** SET threshold energy vs. location $(x, y)$ on the chip for SiGe UHF mixer.

**Figure 11.** $\Delta U_{experimental}$ vs. location $(x, y)$ on the chip for SiGe UHF mixer. $J = 5 \text{ nJ}$, $R = 50 \text{ Ohm}$, $J = 5 \text{ nJ}$, $d = 2.5 \text{ um}$, step = 5 um.

### 3. Conclusion

Laser SEE tests usually complement ion tests because they (laser tests) provide continuous energy range in contrast to the ions’ LETs. Thus laser test provides far more data points in SEE cross-section vs. energy dependence than the accelerator test can provide for SEE cross-section vs. LET. Nevertheless, the laser curve is distorted by the effect of chip metallization nonuniformity. The technique presented in this paper allows not only to correct the SEE cross-section curve against this nonuniformity but also provides almost any number of data points in this curve.
**Figure 12.** $J_0 \cdot \Delta U_{\text{experimental}}$ vs. location (x, y) on the chip for SiGe UHF mixer.

**Figure 13.** $\sigma(\text{LET})$ and $K_{\sigma} \cdot (K_{\text{LET}} \cdot J)$ for SiGe UHF mixer. $K_{\text{LET}} = 110 \text{ MeV} \cdot \text{cm}^2/(\text{mg} \cdot \text{nJ})$, $K_{\sigma} = 1.0$.

**Figure 14.** $\sigma(\text{LET})$ and $K_{\sigma} \cdot (K_{\text{LET}} \cdot J \cdot \Delta U_{\text{experimental}})$ for SiGe UHF mixer. $K_{\text{LET}} = 1.0 \cdot 10^4 \text{ MeV} \cdot \text{cm}^2/(\text{mg} \cdot \text{nJ} \cdot \text{V})$, $K_{\sigma} = 1.0$.

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**References**
[1] Egorov A N, Chumakov A I, Mavritskiy O B, Pechenkin A A, Telets V A and Yanenko A V 2015 Radiation Effects Data Workshop (Boston) (IEEE) art. no. 7004570 pp 247-250
[2] Chumakov A I, Pechenkin A A, Savchenkov D V, Tararaksin A S, Vasil’ev A L and Yanenko A V 2011 Proc. 12th Eur. Conf. on Radiation and Its Effects on Components and Systems (Sevilla) (IEEE) pp 449–453.
[3] Miller F 2011 Applicability of laser methodologies to analog, digital and power electronics (RADLAS, Suresnes, France).
[4] Savchenkov D V, Chumakov A I, Petrov A G, Pechenkin A A, Egorov A N, Mavritskiy O B and Yanenko A V 2013 Proc. of 14th Eur. Conf. on Radiation and Its Effects on Components and Systems (Oxford) (IEEE).