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Process management for avionics – Atmospheric radiation effects – Part 4: Design of high voltage aircraft electronics managing potential single event effects

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International Standard IEC 62396-4 has been prepared by IEC technical committee 107: Process management for avionics.

This International Standard is to be used in conjunction with IEC 62396-1:2012.

This first edition cancels and replaces IEC/TS 62396-4 published in 2008. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) Change to title.

b) Clause 4 inclusion of SEGR.

c) Inclusion of 6.5 concerning SEB due to thermal neutrons.

d) Consideration of alternative materials to silicon in 6.6.

The text of this international standard is based on the following documents:

FDIS	Report on voting
107/211/FDIS	107/221/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts in the IEC 62396 series, published under the general title *Process management for avionics – Atmospheric radiation effects,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual edition of this document may be issued at a later date.

INTRODUCTION

This industry-wide international standard provides guidance and requirements to design high voltage aircraft electronics for electronic equipment and avionics systems. It is intended for avionics system designers, electronic equipment manufacturers, component manufacturers and their customers to manage the single event effects produced in semiconductor devices operating at high voltage (nominally above 200 V) by atmospheric radiation. It expands on the information and guidance provided in IEC 62396-1:2012.

The internal elements of semiconductor devices operating at high applied voltage will be subject to high voltage stress. The incident radiation causes ionisation charge within the device, and the high voltage stress may cause a large increase (avalanche) in this charge, which may be destructive. Within this part of IEC 62396 two effects are considered: single event burnout (SEB), and single event gate rupture (SEGR).

PROCESS MANAGEMENT FOR AVIONICS – ATMOSPHERIC RADIATION EFFECTS –

Part 4: Design of high voltage aircraft electronics managing potential single event effects

1 Scope

This part of IEC 62396 provides guidance on atmospheric radiation effects and their management on high voltage (nominally above 200 V) avionics electronics used in aircraft operating at altitudes up to 60 000 ft (18,3 km). This part of IEC 62396 defines the effects of that environment on high voltage electronics and provides design considerations for the accommodation of those effects within avionics systems.

This part of IEC 62396 provides technical data and methodology for aerospace equipment manufacturers and designers to standardise their approach to single event effects on high voltage avionics by providing guidance, leading to a standard methodology.

Details are given of the types of single event effects relevant to the operation of high voltage avionics electronics, methods of quantifying those effects, appropriate methods to provide design and methodology to demonstrate the suitability of the electronics for the application.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62396-1:2012, *Process management for avionics – Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62396-1:2012 apply.

4 Potential high voltage single event effects

An N-channel power MOSFET can have two different types of destructive effects induced by the deposition of charge from a single energetic particle, single event burnout (SEB) and single event gate rupture (SEGR). Different tests performed on several devices show that is difficult to induce SEB in P-channel MOSFET [1], [2][1]. In addition to this kind of power MOSFET, other power devices, such as insulated gate bipolar transistors (IGBTs), bipolar power transistors and diodes, which have large applied voltage biases and high internal electric fields, are susceptible to SEB.

In SEB, the penetration of the source-body-drain region by the deposited charge can forward bias the thin body region under the source. If the bias applied to the drain exceeds the local

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[1] Numbers in square brackets refer to the Bibliography.

breakdown voltage of the parasitic bipolar elements, the single event induced pulse initiates avalanching in the drain depletion region that eventually leads to destructive burnout SEB. SEB can be induced by heavy ions, high energy protons [3] and high energy neutrons [4].

SEGR applies to N- and P-channel MOSFETs. It is explained via the transient plasma filament created by the energy deposition track when the MOSFET is struck through the thin gate oxide region. As a result of this transient track filament, there is a localized increase in the oxide field which can cause the oxide to break down, leading first to gate leakage and finally to gate rupture. The SEGR failure mechanism has been widely studied by heavy ion testing and effects have been identified on different devices with various levels of sensitivity [2]. For the time being, experiments show also that SEGR induced by heavy ions is more an issue for space systems, and guidance for heavy ion SEGR testing is available [5]. As a consequence of the atmospheric neutrons, SEB is the major threat to high voltage electronics.

There remains a paucity of data on the question of neutron-induced single event gate rupture (SEGR) in power devices. In the late 1990s one study looked for, but did not find, SEGR in 500 V power MOSFETs during accelerated spallation neutron testing [1]. Shortly afterwards, however, dielectric breakdown was observed in 60 V power MOSFETs during 44 MeV and 200 MeV proton irradiation [6]. As the gate ruptures in these devices were almost certainly caused by charge deposition from recoil ions, rather than by direct ionisation from the very low LET protons, sensitivity to neutrons was implied.

Data published more recently show more direct evidence of neutron-induced SEGR in devices rated at ~1 kV. Hands *et al.* observed significant gate damage to a 1 kV power MOSFET at a spallation neutron facility, with a dependence on gate bias consistent with SEGR [7]. Griffoni *et al.* tested a variety of devices, including IGBTs, SiC MOSFETs and superjunction (SJ) MOSFETs in quasi-monoenergetic neutron environments, and observed SEGR only in the SJ MOSFETs [8]. Interestingly, in this latter case the SEGR failure rate was sometimes higher than the SEB failure rate, though no dependency on gate bias condition was investigated to characterise the relative susceptibilities. These results demonstrate that fast neutrons (and protons) are very capable of causing damage to the gate regions of power devices and, where conditions are right, this damage can lead to dielectric breakdown and catastrophic failure. Therefore this failure mode should be considered and, where appropriate, quantified during accelerated testing of HV devices.

Although at the outset this threat to the power system in an aircraft from SEB from the atmospheric neutrons may appear to be remote or even far-fetched, the experience of breakdowns in the high voltage electronics on electric trains in Europe before 1995 shows that SEB can be real and has happened in the field. In that case, European and Japanese manufacturers of high voltage semiconductors noticed that some of their devices were undergoing burnout failures in the field during normal operation of newly developed train engines [9, 10]. The diodes and GTO thyristors (gate turn-off thyristors) used on the trains were rated at 4 500 V, and were normally operated at 50 % to 60 % of rated voltage. They were designed for terrestrial use for > 35 years, so when the failures first appeared in the field after only a few months, this was puzzling. The failure mode was investigated in great detail and eventually a set of experiments was carried out at three different locations (salt mine, top-floor laboratory and basement); the results convinced the investigators that the cause of the failures was the cosmic ray neutrons. Since that time, the manufacturers of these very high voltage devices have been careful in recommending the voltage at which the devices can be operated safely without SEB.

In addition, these manufacturers have followed the methodology established by an experienced radiation effects group [1] by carrying out tests in the WNR beam at Los Alamos National Laboratory to characterize the response of their devices to a simulated high-energy neutron environment. Because the atmospheric neutron flux is higher by about a factor of 300 at aircraft altitudes compared to sea level, it is clear that the same effect can occur in high voltage electronics in aircraft. The reason that, as far as is known, such failures have not been experienced previously in the field in aircraft power electronics is that the bus voltage used in aircraft systems has always been low enough to preclude SEB or SEGR.

Generally, the highest voltage used in aircraft power systems has been 270 V, and a practical lower onset limit for most high voltage devices is 300 V. This practical lower limit stems from the fact that with SEB there is a threshold voltage for the effect to occur; if V_{ds} is kept below the threshold voltage, there will be no SEB. Thus for 270 V operation, devices rated at 400 V or 500 V would be used, resulting in a situation in which the devices are being operated at a derating factor of 67,5 % and 54 % respectively. Since the devices are being used at < 300 V and with a derating factor of < 70 %, these conditions are sufficient to preclude any single event burnout in the high voltage electronics.

However, in advanced designs for avionics systems significantly higher voltages are being considered for the bus voltage in order to reduce the overall weight of the system. The voltage will thus be > 300 V and in fact 600 V has often been mentioned as a practical bus voltage. Thus, in order to preclude SEB from occurring in the high voltage electronics of such advanced avionics systems, a sufficiently low derating factor will have to be used, and the adequacy of the derating factor will have to be demonstrated through testing.

5 Quantifying single event burnout in avionics for high voltage devices

Thus, the problem becomes that avionics vendors are asked to provide systems that will operate at higher voltages, e.g., 600 V, and there has been virtually no guidance for them to use in developing the designs that will avoid the potential of SEB in the high voltage devices such as power MOSFETs and IGBTs.

In reality, the situation with SEB in high voltage electronics is relatively similar to that of single event upset (SEU), in low voltage devices (< 5 V) such as random access memories (RAMs), microprocessors and FPGAs. The threat of SEU from the atmospheric neutrons in the low voltage devices has been dealt with very extensively in the technical literature and in IEC 62396-1:2012. The approach in IEC 62396-1:2012 is that the rate of the single event effect, in this case SEU, in the devices, can be estimated by the following equation:

$$\text{SEE rate per device (per hour)} = 6\,000\ (\text{n/cm}^2\text{h}) \times \text{SEE cross section (cm}^2\text{ per device)} \qquad (1)$$

The 6 000 n/cm^2 per hour flux is a nominal value for the cosmic ray neutrons with energy > 10 MeV, at 40 000 ft (12,2 km) altitude and 45° latitude. It shall be adjusted for different altitudes and latitudes using the data tables in Annex D of IEC 62396-1:2012. For RAMs especially, a great deal of SEU cross section data has been published, allowing users of the standard to estimate the SEU rate, and some SEU cross section data is also available for microprocessors and FPGAs.

The same Equation (1) shall be used for SEB rates in high voltage devices provided that SEB cross sections are known for specific devices operated at a specified voltage. This part of IEC 62396 recommends the use of Equation (1) for calculating SEB rates even though it is recognized that this is conservative. There is very little published data on the SEB cross sections, but the data that does exist [1], [4] suggests that the SEB cross section is significantly reduced at lower neutron energies compared to e.g. 200 MeV. The most suitable facilities for measuring SEB cross sections are spallation sources with maximum energy above 200 MeV. Thus the minimum neutron energy threshold for calculating the SEB rate (energy at which the SEB cross section is similar to that at high energy, e.g., 200 MeV) is 100 MeV. The available SEB cross section data is documented in Clause 6.

For avionics applications it should be recognized that assuming the high voltage electronics will be operating at a single voltage is unrealistic. First, the airplane power system is expected to experience power transients and spikes during flight. The transients typically last for less than 1 s, during which time V_{ds} could increase from 270 V to 350 V. The cascading power spikes can increase the voltage to even higher levels above nominal, although the duration is much shorter, usually < 100 µs.

Secondly, the operating details of the high voltage equipment are important in evaluating its susceptibility to SEB. For example, in the case of certain types of DC-DC converters, the voltage across the MOSFET is not continuous. The MOSFET cycles between off and on states, and the voltage across the MOSFET during the off state is higher than during the on state due to an inductive voltage associated with the mechanism that allows the magnetic energy to be discharged [11]. The highest voltage across the MOSFET is during the off state, but its magnitude depends on several operational parameters of the converter (e.g., V_{in}, V_{out} and output current). Thus, a true evaluation of the SEB susceptibility should take into consideration the voltage across the MOSFET throughout the complete duty cycle and set of operating conditions of the converter. Other high voltage components may have similar variations in their operating conditions.

The use of the WNR beam to perform accelerated SEB testing of very high voltage devices [1] has spurred considerable additional testing of the very high voltage devices (> 2 kV) by the microelectronics companies that manufacture these devices. This testing has used the WNR facility as well as other sources of neutrons. The other neutron sources include the quasi mono-energetic neutron beam created by a proton beam on a lithium target (e.g., at the Svedberg Laboratory in Sweden) or high elevation research stations (Sphinx Laboratory at Jungfraujoch, Switzerland, 11 300 ft (3,4 km) high). However, the results of such testing are usually considered proprietary and not published, or if a few are published, it is in a little known publications [12], [13]. In addition, for these vendors having ground level applications, their results are often put into the format of a FIT (failure in time) rate, 1 FIT being equal to one failure in 10^9 device hours of operation [1].

The key points are that none of these very high voltage devices are relevant to avionics applications currently and that some vendors treat their SEB data as proprietary. However, the familiarity of these HV electronics vendors with the overall SEB issue from neutrons means that if they also manufacture lower voltage devices, devices that are relevant to avionics applications, they may have SEB data, but this data will often be considered proprietary.

6 Relevant SEB data and applying it to avionics

6.1 SEB data from heavy ion testing is not relevant

It is surprising that when it comes to SEB induced by high-energy protons and neutrons, there are only a limited number of IEEE papers [1], [2], [4] that discuss this subject and present useful data, despite the fact that the first evidence of proton-induced SEB in MOSFETs was documented in a 1988 report [3]. Since the 1988 report, almost all data published concerning SEB in power devices has been based on single event effects testing using heavy ions to simulate the cosmic rays rather than with protons and neutrons. The results of heavy ion testing are not relevant to the situation with high energy neutrons and protons. This heavy ion SEB data could theoretically be used if the SEB cross section induced by the heavy ions was measured, but in most cases this isn't done, only the values of V_{ds} and V_{gs} are presented at which no SEB occurs.

However, even if heavy ion SEB cross sections were known, applying them to avionics applications would be extremely conservative, and would result in highly conservative SEB rates for avionics applications. For example, just looking at the V_{ds} threshold value at which no SEB occurs, in a 500 V device that was tested with both high energy protons and heavy ions, the threshold was 330 V with WNR neutrons and 300 V with heavy ions. In addition, for a 400 V device, the threshold was 280 V with WNR neutrons and 220 V with heavy ions. Thus, the heavy ion results are overly conservative and there is really no substitute for SEB cross sections in high voltage devices measured using a high energy neutron or proton source.

6.2 SEB data from high energy neutron and proton testing

SEB cross section data from tests using high energy neutron and proton with 400 V and 500 V MOSFETs are shown in Figure 1. The data comes from testing by Boeing [1], [4] and Fermilab,