Microelectronics Reliability xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Review paper

Ensuring the reliability of power electronic devices with regard to terrestrial cosmic radiation

Gerald Soelkner

Infineon Technologies AG, 85579 Neubiberg, Germany

ARTICLE INFO

Article history:
Received 21 June 2015
Received in revised form 7 December 2015
Accepted 11 December 2015
Available online xxxx

Keywords:
Cosmic radiation
Power devices
Reliability
Accelerated testing
IGBT
MOSFET

ABSTRACT

Terrestrial cosmic radiation is a significant factor for the reliability of power electronic devices, for voltage classes that range from about 300 V to beyond 6500 V. As such, cosmic radiation-induced device failure concerns power diodes, MOSFETs and IGBT, irrespective of the base semiconductor material, Silicon, SiC or GaN. Though the basic mechanism of failure varies with device type, failure is invariably initiated by the creation of ionizing spallation fragments following a collision of a high-energy neutron with a substrate nucleus. This paper summarizes the results of device simulations and dedicated experiments to substantiate our knowledge about failure mechanisms. It will discuss the possibilities of failure rate prediction for different device types and classes. Main focus of this paper is the presentation and discussion of methods for the determination of failure rates by accelerated testing. Results of nucleon irradiation test are compared with storage tests. The effect of bias voltage and temperature, which are the main stressors, is discussed.

Contents

E-mail address: gerald.soelkner@infineon.com.

http://dx.doi.org/10.1016/j.microrel.2015.12.019
0026-2714/© 2015 Published by Elsevier Ltd.

1. Introduction

Cosmic radiation constantly showers our earth with highly energetic particles, mainly protons and light and heavy nuclei. In rare events, particle energies up to extremely high values up to 10^{20} eV have been observed [1]. Since the 1960s, as first satellites were put into orbit, adverse effects of radiation on electronic devices, specifically also power MOSFETs came into focus. Power diodes and MOSFETs had to be hardened against ionizing radiation and irradiation with light and heavy nuclei. A considerable amount of scientific work was dedicated to this problem and a number of test standards were established, e.g. JESD89a [2] and others. A plethora of scientific papers exists on this topic.

Particles of the primary cosmic radiation (Primary CR), made up of energetic nuclear fragments, rarely penetrate our protecting atmosphere to reach the ground. Rather, they enter into collisions with air molecules to give rise to cascades of secondary particles. This terrestrial cosmic radiation (Terrestrial CR), which reaches the ground, is made up of electrons, myons and nucleons. Of the latter, 90% are neutrons that may attain energies of more than 1 GeV. The terrestrial radiation environment is described in full detail in [3]. Most notably, the "spallation" energy spectrum of neutrons of the Terrestrial CR, Fig. 1, also includes neutrons of very high energies, even beyond 100 MeV. The neutron intensity is also function of altitude, increasing from sea level to about 15 km by almost a factor of 1000 and then falling off again (Fig. 2). This increase in neutron flux with altitude is important for the application of power devices, as it will, among other factors, determine the failure rate of power systems which are deployed at high altitudes. Other dependencies, such as on latitude or on solar cycle vary the terrestrial neutron flux by less than a factor of two and are, therefore, not of primary interest.

The question arises, why, from the many secondary particles that constitute the Terrestrial CR, neutrons should be the component that could lead to failure of power electronic devices. Firstly, the underlying mechanism requires a significant deposition of charge in the semiconductor substrate of several fC/μm, in terms of the familiar notion of Linear Energy Transfer (LET). It is not possible to obtain this amount of ionization by stopping of electrons, myons or photons, or even by stopping of protons or pions in the semiconductor via the electromagnetic interaction. A nuclear reaction is required to produce this amount of charge. As neutrons are the most penetrating, the most likely reaction will be a neutron — nucleus collision that gives rise to spallation fragments within or near the semiconductor substrate of a device. Still,

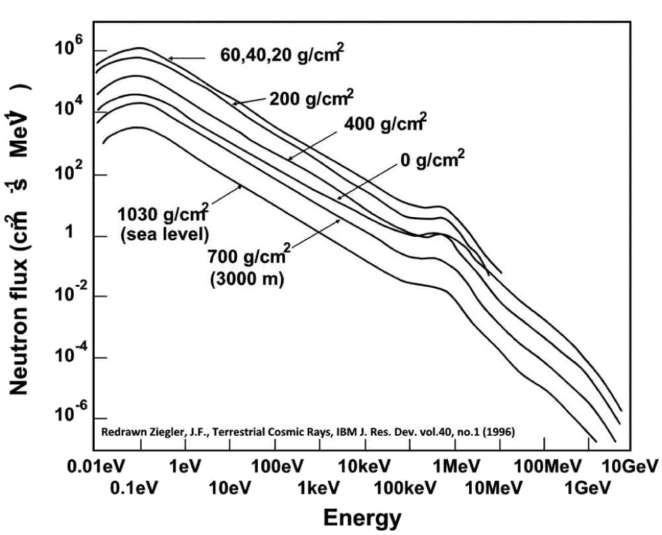

Fig. 1. Neutron flux versus energy with altitude, given as weight of air column g/cm2, as a parameter [3]. The curve marked 1030 g/cm2 is for sea-level neutrons.

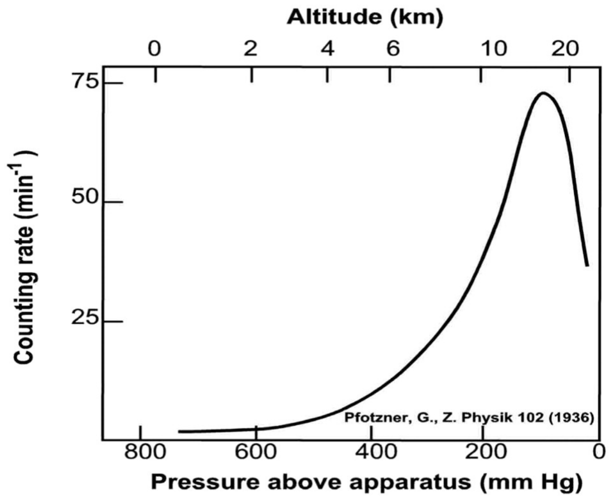

Fig. 2. Cosmic ray intensity versus altitude of G. Pfotzner 1936, see reference in [3]. The intensity peaks at 15 km of altitude with a 1000-fold intensity increase over sea-level.

more exotic ways of localized charge generation do exist, such as myon capture or pion reactions [3].

Secondly, the good agreement between nucleon irradiation testing and the results from storage tests (within the natural terrestrial cosmic radiation environment), which will be presented below, gives a very strong indication that nucleons, and, as protons may be well shielded, high-energy neutrons are the particles that we are concerned with as far as the reliability of power semiconductor devices and systems is the issue. Evidently, it is impossible to shield power devices from high-energy neutrons with a few exceptions where power systems are operated under ground or protected by massive concrete walls [4].

Having identified the radiation component to which power devices are vulnerable, models to describe the details of the mechanism that leads to device failure have to be developed. Failure due to terrestrial CR have been observed for all types of power devices, such as diodes and MOSFETs [5–13], IGBTs [14,15] and GTOs [16], with a wide range of operational voltages.

Recently also, devices based on other semiconductor substrate materials than silicon, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN) either became commercially available or will be available in the very near future. Nucleon-induced failure has been observed for SiC devices [17,18].

Apart from charge deposition via a neutron induced nuclear spallation which, unequivocally, can be regarded as the initial event that will eventually lead to device failure, the details of the charge, electrical field, current and temperature evolution within a device are tightly connected with the details of the device structure. It is therefore unlikely that a unique model will cover all aspects of power device failure. Furthermore, any device simulation will run into difficulties as soon as the underlying models break down, e.g., because temperature limits are exceeded. A simulation until destructive device failure, i.e. until melting temperatures of semiconductor and metallization are reached, is rarely realistic and, at least, will require additional criteria as to what point a device has actually "failed".

Evidently, a working simulation model for cosmic radiation induced failure would, in principle, also allow the prediction of failure rates and may be applied for the improvement of device designs in terms of radiation hardness. As will be shown in the next sections, failure rate prediction is, at the present stage and in general, still impractical or limited to specific cases. On the other hand, device simulations may be applied in a comparative way, i.e. to yield quantitative measures to assess whether a specific design change will increase radiation hardness.

Device failure rates with regard to terrestrial cosmic radiation can up to now only be obtained by device testing. Evidently, a perfect test that

Please cite this article as: G. Soelkner, Ensuring the reliability of power electronic devices with regard to terrestrial cosmic radiation, Microelectronics Reliability (2015), http://dx.doi.org/10.1016/j.microrel.2015.12.019