Microelectronics Reliability xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Microelectronics Reliability

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

The influence of microwave pulse width on the thermal burnout effect of a PIN diode limiting-amplifying system

Shipeng Yi, Zhengwei Du *

State Key Laboratory on Microwave and Digital Communications, Tsinghua National Laboratory for Information Science and Technology, Department of Electronic Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 21 March 2017
Received in revised form 12 June 2017
Accepted 12 June 2017
Available online xxxx

Keywords:
Absorption efficiency factor
Burnout effect
PIN diode limiting-amplifying system
Pulse width

ABSTRACT

This paper analyzes the influence of the microwave pulse width on the thermal burnout effect of a PIN diode limiting-amplifying system. Based on theoretical analyses and simulation, the relationship of the burnout effect on a PIN diode limiter and a PIN diode limiting-amplifying system is obtained first. By adopting an absorption efficiency factor, the theoretical model of the relationship between the microwave pulse width and the burnout power threshold for the PIN diode limiting-amplifying system is obtained. The proposed theoretical formulas can be determined by using at least two sets of simulation or measurement results to fit the constant coefficients, which can greatly reduce the simulation or experimental costs. The results obtained by the theoretical formulas are in good agreement with the numerical simulation results obtained by our self-designed device–circuit joint simulator, which verifies the correction of the theoretical analyses and modeling. The available microwave pulse width range for the proposed theoretical formulas is from 10 ns to 10 μs. In consideration of the potential threat of microwave pulses, the system-level study results obtained in this paper will be helpful for the design of the radio frequency receivers.

1. Introduction

In the past few years, growing attention has been paid to the threat posed by microwave pulses on communication systems, especially their radio frequency (RF) receivers. The received microwave pulses may interfere, degrade or even damage the RF receivers. As well known, the typical structure of an RF receiver front end includes an antenna, a PIN diode limiting-amplifying system, a band-pass filter, a mixer, a local oscillator and an intermediate frequency amplifier (IFA), as shown in Fig. 1. The PIN diode limiting-amplifying system consists of a PIN diode limiter and a low noise amplifier (LNA). As the key component of an RF receiver, the PIN diode limiting-amplifying system plays an important role in primarily amplifying signals and protecting the post-stage circuits. However, microwave pulses will directly affect the PIN diode limiting-amplifying system after they enter the antenna of an RF receiver, high power microwave pulses may damage the PIN diode limiting-amplifying system and further cause the whole RF receiver failed [1].

According to the intensity, the effects of microwave pulses on semiconductor devices can be classified into three types: temporary upsets, permanent upsets, and permanent damages [2]. Microwave pulses may cause semiconductor devices temporary upsets at low energy fluence, permanent upsets at intermediate energy fluence and permanent damages at high energy fluence. Because the permanent damage is the most severe effect in the three types, it is paid more attention in the study of microwave pulse effects on semiconductor devices. Both electrical damage and thermal damage can cause a semiconductor device permanent damage. For example, a metal-oxide-semiconductor field-effect transistor (MOSFET) with an oxide layer at the electrodes can be permanently damaged by oxide punch through or junction burnout, which is electrical damage and thermal damage, respectively. While for some semiconductor devices like the PIN diodes and the pseudomorphic high electron mobility transistors (PHEMTs), thermal damage is the reason for their permanent damage. Junction burnout, metallization burnout and thermal second breakdown, which are the thermal damages, are three common permanent damage mechanisms for the semiconductor elements like the PIN diodes and the PHEMTs [2–4]. Therefore, the permanent damages of the PIN diode limiting-amplifying system with semiconductors like PIN diodes and PHEMTs can be regarded as a thermal burnout effect.

For injected pulses of several milliseconds or longer, semiconductor devices may be permanently damaged by impurities transfer and the maximum temperature in the semiconductor devices is usually about 500–600 K. However, the typical pulse width of microwave pulses is from several nanoseconds to several microseconds limited by the manufacturing technology of microwave sources [1]. Thus, impurities transfer is not the reason for the permanent damage of microwave pulses because the pulse width of microwave pulses is not long enough

* Corresponding author.
E-mail address: zwdu@tsinghua.edu.cn (Z. Du).

http://dx.doi.org/10.1016/j.microrel.2017.06.025
0026-2714/© 2017 Elsevier Ltd. All rights reserved.

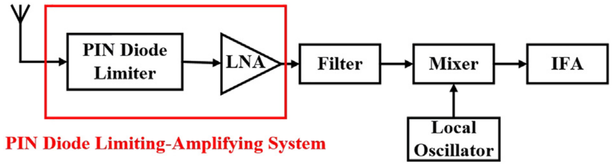

Fig. 1. The typical structure of an RF receiver front end.

for impurities to transfer. Therefore, the fusion of the semiconductor materials which may damage the channels or the fusion of the electrodes is the main cause of the burnout effect by microwave pulses and the maximum temperature in a semiconductor device reaching the melting point of the specific semiconductor material or the electrodes can be regarded as the criterion of the occurrence of a burnout phenomenon [5]. So, compared to the permanent damage by longer pulses, the permanent damage by microwave pulses usually needs higher power and higher temperature.

The microwave pulse burnout effects on some semiconductor devices have been studied. However, previous studies usually focus on a single RF module like a PIN diode limiter and an LNA. The experimental and theoretical study of microwave pulse burnout effect on a PIN diode starts in the 1960s [6]. Some studies of microwave pulse burnout effects on an LNA are carried out in recent years [7–12]. Furthermore, the theoretical formulas of the relationship between the microwave pulse parameters and the damage power thresholds for a single PIN diode and transistor are obtained in [7].

Although there are a few studies about the microwave pulse burnout effects on circuits with multiple semiconductor elements like a monolithic microwave integrated circuit (MMIC) [13], the studies are still limited to a single RF module. Studies about a subsystem or system in an RF receiver are quite limited. Gao et al. [14–15] and Chvala et al. [16] studied the realization and optimization of electrostatic discharge protection structures to avoid being burnt out. Nilsson and Jonsson have carried out experiments to study the burnout effect of microwave pulses on a limiting-amplifying system [17]. To the best of our knowledge, there is no available publication about the theoretical analysis of the microwave pulse burnout effect on a PIN diode limiting-amplifying system which includes both of the two RF modules. Compared to the study on a single RF module, the study on an RF subsystem or system will be more efficient and accurate for analyzing the thermal burnout effect of a whole RF receiver. Therefore, the burnout effect analysis of microwave pulses on a PIN diode limiting-amplifying system is of great significance.

The pulse width and power are the main key parameters of sinusoidal microwave pulses, which directly relate to the accumulated energy of the injected microwave pulses and the dissipated energy in the semiconductor devices. Because the burnout mechanisms of microwave pulses on both a single PIN diode limiter and a single LNA have been studied, the purpose of this paper is mainly focused on finding the relationship between the microwave pulse width and the burnout power threshold of the PIN diode limiting-amplifying system theoretically. The main study methods in this paper are theoretical analyses and numerical simulations. The adopted simulation program in this paper is our self-designed device–circuit joint simulator for its good convergence property and suitability under the condition that an intense electric field is injected into a semiconductor device which commercial technology computer aided design software usually lacks [7,9,12,18]. The simulator includes a circuit solver and a device solver. The circuit solver is similar to the PSpice software and the device solver can show the transient state in the semiconductor device by solving the semiconductor equations and the heat conduction equation based on the finite-difference time-domain (FDTD) method. The circuit solver and the device solver are combined by a time domain coupling algorithm. The correction of our device–circuit joint simulator has been verified by comparing with the simulation results obtained by other commercial software (including Sentaurus and Medici) and measuring results in many cases [7,9,12,18].

The rest of this paper is organized as follows. In Section 2, the structure of the studied PIN diode limiting-amplifying system is introduced. In Section 3, the burnout device is determined by theoretical analyses and simulation verification. In Section 4, the relationship between the microwave pulse width and the burnout power threshold is studied by theoretical analyses and modeling. Numerical simulations are also carried out to verify the correction of the theoretical model. Finally, a conclusion is presented in Section 5.

2. Structure of the studied PIN diode limiting-amplifying system

As mentioned above, a PIN diode limiting-amplifying system consists of a PIN diode limiter and an LNA. Therefore, the basic structure and working mechanism of the studied PIN diode limiter and the studied LNA are presented in this section.

2.1. PIN diode limiter

Because the external microwave pulses can affect an electronic system, a PIN diode limiter is usually added in the front stage of an LNA for protection [19]. The basic working mechanism of a PIN diode limiter is based on the conductivity modulation effect. When the amplitude of an injected microwave pulse is relatively large, the PIN diode limiter will work and limit the amplitude of the injected microwave pulse. The typical type of PIN diode limiters is a limiter with a single or double PIN diodes. In this paper, a single PIN diode limiter, whose structure is shown in Fig. 2, is chosen as the first part of the PIN diode limiting-amplifying system in the study. The single PIN diode limiter consists of a PIN diode and a parallel inductance. The parallel inductance in this study is 20 nH and the PIN diode is model CLA4602 made by Skyworks [20]. The structure and dimensions of model CLA4602 PIN diode whose material is Silicon (Si) are shown in Fig. 3. The PIN diode consists of a cuboid bulk and three cylindrical layers named P, I and N layer, respectively. The thickness of the I layer and the anode radius are 1 μm and 15 μm, respectively.

2.2. LNA

The main function of an LNA is to primarily amplify the signals received by an RF receiver. An LNA usually consists of a core semiconductor device, an input matching circuit, an output matching circuit and a DC bias circuit. PHEMTs are widely used in communication and radar systems for their low noise, high gain and high cut-off frequency properties. Therefore, model ATF-36163 GaAs PHEMT made by Avago Technologies [21] with the gate length of 0.2 μm and the gate width of 200 μm is chosen as the core semiconductor device in the studied LNA. The sectional device structure and dimensions of model ATF-36163 GaAs PHEMT is shown in Fig. 4.

Using this PHEMT, an LNA is designed with the Advanced Design System (ADS) software from Keysight Technologies [22]. The schematic diagram of the studied LNA is shown in Fig. 5. This LNA works at the

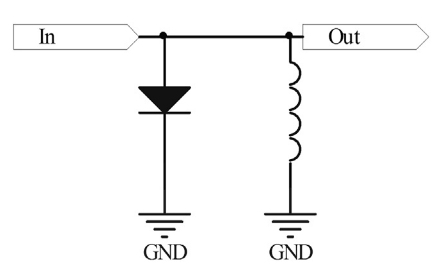

Fig. 2. Structure of the studied single diode limiter.

Please cite this article as: S. Yi, Z. Du, The influence of microwave pulse width on the thermal burnout effect of a PIN diode limiting-amplifying system, Microelectronics Reliability (2017), http://dx.doi.org/10.1016/j.microrel.2017.06.025