Optik 125 (2014) 5422–5425

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

The influence of space irradiated PIN photodetector on BER in satellite laser communication system

Yun Liu [a,*], Shang-Hong Zhao [a], Sheng-Sheng Yang [b], Yong-Jun Li [a], Ruo-Xin Qiang [a]

[a] School of Information and Navigation, Air Force Engineering University, Xian 710077, China
[b] Cryogenics Technology and Physics Laboratory, Lanzhou Institute of Physics, Lanzhou 730000, China

ARTICLE INFO

Article history:
Received 3 October 2013
Accepted 27 May 2014

Keywords:
Satellite laser communication system
Bit error rate
Space radiation environment
PIN photodetector
Decision threshold

ABSTRACT

By analyzing the radiation dose on PIN photodetectors in space radiation environment, the variation of photocurrent and dark current after radiation is obtained. On the basis, the bit error rate of satellite laser communication based on space radiation dose of PIN photodetectors is established. According to simulation, when radiation dose is about 1.6×10^3 Gy and 7×10^4 Gy, bit error rate reaches 10^{-6} induced by 50 MeV and 10 MeV protons separately; and when radiation dose is within the range of 5×10 Gy–6×10^5 Gy, electrons and gamma-ray irradiation also cause increase in bit error rate to 10^{-6}. The principle of damage dose on bit error rate is investigated, and the influence of decision threshold on bit error rate is further discussed. The result shows that when radiation dose is 1 MGy, if decision threshold is increased from 4.3×10^{-7} A to 5.5×10^{-7} A, bit error rate will decrease about 4 orders of magnitude. Hence, a proper decision threshold can improve system bit error rate efficiently.

1. Introduction

Devices in satellite laser communication system are affected by space ionizing radiation environment, which results in the degradation of on-orbit communication performance. Being the reflection of reliability, BER is an important index in evaluating the radiation impact on satellite laser communication. Different from traditional BER model, BER on-orbit is influenced and restricted by several factors induced by radiation environment, such as the decrease of output power and photocurrent, the increase of dark current and amplifier noise etc. Hence, a proper BER model is needed to evaluate the performance of satellite laser communication in space environment. Since photodetector is an important device of laser receiver, study on its space radiation impact is significant in setting up on-orbit BER model. Successful experimental and analytical studies of radiation impact on photodetector have been down [1–5], while, at the same time, there are only a few researches in defining how radiation impact on photodetector contributes to the on-orbit system BER. Hence, degradation of PIN photodetector irradiated by gamma-ray, 1 MeV and 2 MeV electrons, 1 MeV and 10 MeV protons is analyzed, and on the basis, the on-orbit BER model is given.

2. Space radiation damage model of PIN photodetector

Displacement damage dose and total ionizing dose are the two main radiation effects induced by space radiation to semicon materials. The displacement damage dose introduces defects in semicon materials, which shortens the lifetime of minority charge carriers, while the total ionizing dose makes superfluous electron–hole pairs and causes surface damage. The two damage effects act together and cause the quantum efficiency decrease, surface recombination velocity increase, and generation current increase of PIN photodetector, these finally result in the decrease of photocurrent and increase of dark current.

2.1. Damage mechanism of photocurrent

For PIN photodetector, quantum efficiency reflects the photoelectric conversion ability, thus, it has a direct influence on photocurrent, and is one of the most important parameters of photodetectors. The definition of quantum efficiency, η, is described as

$$\eta = \frac{\text{Output photoinduced carrier number}}{\text{incident photon number}} \times 100\% \quad (1)$$

The quantum efficiency can be farther given by

$$\eta = (1-r) \times \left(1 - \frac{e^{-\alpha W}}{1+\alpha L_p}\right) \quad (2)$$

* Corresponding author.
E-mail address: ikmnji@126.com (Y. Liu).

http://dx.doi.org/10.1016/j.ijleo.2014.06.020
0030-4026/

where r, α, W, and L_p are reflective coefficient, absorption coefficient, depletion width, and minority carrier diffusion length, respectively. Onoda [1] examined the optical spectral response of Si pin photodiodes after gamma and electron irradiation, and explained the effects by modeling the degradation of the minority carrier diffusion length in the base region. The degradation in L_p can be expressed as

$$\frac{1}{L_p} = \sqrt{\left(\frac{1}{L_{p0}}\right)^2 + k_{Lp} \times D} \tag{3}$$

where L_{p0}, k_{lp}, and D are the initial diffusion length, diffusion length damage factor and particle fluency, respectively. According to (2), quantum efficiency is a function of diffusion length, and it decreases with the decreasing of diffusion length. And photocurrent I_p is given by

$$R = \eta \times \frac{q\lambda}{hc} \tag{4}$$

where G is the gain of PIN photodetector, P_r is received power, and response R is expressed as

$$I_p = R \times G \times P_r \tag{5}$$

where λ, q, c, and h are the wavelength, electron charge, velocity of light and Planck constant, respectively. Hence, the damage mechanism of photocurrent is given by formula (2)–(5).

2.2. Damage mechanism of dark current

The dark current of PIN photodetector is made up of three components, diffusion current, generation-recombination current, and surface recombination current. Diffusion current is comparatively smaller than the other two currents, hence, ignoring the diffusion current, dark current of PIN photodetector is considered to be consisted of generation-recombination current and surface recombination current.

The increase in surface recombination current is mainly caused by TID effect. TID effect results in the surface damage of PIN photodetector, thus, it brings interface-states in semiconducting material. Hence, the interface-states increase surface recombination speed, and result in the gain of dark current. Interface-states electronic energy level exist between SiO_2 and Si, since SiO_2/Si area is transition region from oxide to non-oxide, there is a high concentration of weak bond, radiation induced interface-states is process of weak bond's breaking into dangling bond [6]. Induced interface state density N_{ss} is affected by both radiation dose and electric field, their relationship can be expressed as

$$N_{ss}(E, D) = \gamma \times D^{2/3} \exp(\beta E^{1/2}) \tag{6}$$

where E is electric field intensity, D is radiation dose, β and γ are constants. Surface recombination current I_s is a function of surface recombination speed S, sectional area A and intrinsic carrier concentration n_i.

$$I_s = \frac{Aqn_iS}{2} \tag{7}$$

Carriers near interface are trapped by interface-states, so its surface recombination speed is proportional to interface state density ($S \propto N_{ss}$). Hence, surface recombination current is also proportional to interface state density. The relationship of surface recombination current, radiation dose, electric field is achieved according to formula (6) and (7).

Generation-recombination current originates from carrier drift movement. DDD effect introduces lattice defects in the material, these defects bring in additional energy levels within the band gap, which increases the recombination rate of minority carriers and majority carriers, and results in reduced minority carrier lifetime and increased generation-recombination current. Srour [2] gives the universal formula in calculating radiation-induced dark current in silicon devices.

$$I_{gr} = qWD_dK_{\text{dark}} \tag{8}$$

where K_{dark} is universal damage factor, D_d is displacement damage dose. Hence, the dark current of space irradiated PIN photodetector is the sum of surface recombination current and generation-recombination current.

3. On-orbit BER model of satellite laser communication system

For IM/DD working mode, BER of satellite laser communication system is caused by the superimposition of noise voltage and signal voltage, ignoring space radiation effects. $P(1|0)$ represents the error probability that code "0" is misidentified as code "1", and $P(0|1)$ represents the error probability that code "1" is misidentified as code "0". By considering the noise probability density of photodetector as Gaussian distribution, conditional probability density $P(1|0)$ and $P(0|1)$ are expressed as

$$P\left(1\middle|0\right) = \frac{1}{\sigma_0\sqrt{2\pi}} \int_{I_D}^{\infty} \exp\left[-\frac{(I-I_0)^2}{2\sigma_0^2}\right] dI = \frac{1}{2} erfc\left(\frac{I_D - I_0}{\sigma_0\sqrt{2}}\right) \tag{9}$$

$$P\left(0\middle|1\right) = \frac{1}{\sigma_1\sqrt{2\pi}} \int_{-\infty}^{I_D} \exp\left[-\frac{(I-I_1)^2}{2\sigma_1^2}\right] dI = \frac{1}{2} erfc\left(\frac{I_1 - I_D}{\sigma_1\sqrt{2}}\right) \tag{10}$$

where $I_0, I_1, \sigma_0, \sigma_1, I_D$ are average photocurrent of code "0", average photocurrent of code "1", noise power of code "0", noise power of code "1", and decision threshold, respectively. Then, expression of BER is obtained.

$$\text{BER} = \frac{1}{4}\left[erfc\left(\frac{I_D - I_0}{\sqrt{2}\sigma_0}\right) + erfc\left(\frac{I_1 - I_D}{\sqrt{2}\sigma_1}\right)\right] \tag{11}$$

$$I_D = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1} \tag{12}$$

In the radiation conditions, photocurrent decreases and dark current increases, only consider the radiation effects on photodetector, on-orbit BER model of satellite laser communication system is defined as

$$\text{BER} = \frac{1}{4}\left[erfc\left(\frac{I_D - \left(I_0^1 + \Delta I_{\text{dark}}\right)}{\sqrt{2}\sigma_0}\right) + erfc\left(\frac{\left(I_1^1 + \Delta I_{\text{dark}}\right) - I_D}{\sqrt{2}\sigma_1}\right)\right] \tag{13}$$

where ${I_0}^1$ is irradiated average photocurrent of code "0", and ${I_1}^1$ is irradiated average photocurrent of code "1", ΔI_{dark} is dark current increment.

4. Simulation and results

Gamma-ray, 1 MeV electron, 2 MeV electron, 1 MeV proton, 10 MeV proton irradiated PIN photodetector and system BER are simulated.

Fig. 1 shows diffusion length of minority carriers versus radiation dose ranging from 10^2 Gy to 10^7 Gy, as the radiation dose increases, the diffusion length decreased logarithmic linearly. For same radiation dose, the impact of proton is larger than electron and gamma-ray, and for same radiation source, impact varies with the particle energy. Since decrease of diffusion length is the result of both TID effect and DDD effect, when at the same radiation dose, TID