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Radiation Damage Characterization of InGaAsP Laser Diodes for Space Laser Communication

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Abstract: The 1.55 μm InGaAsP multi-quantum-well laser diodes with distributed feedback structures were irradiated by electrons and ^{60}Co-γ rays. The experimental results show the slope efficiency of laser diode is mostly affected by the total ionizing dose produced by charging particles, and the threshold current and the optical power mainly by displacement damage dose. The displacement damage dose methodology was employed to evaluate radiation damage of the laser diodes, and to predict the power degradations of these diodes in space. The calculated results indicate that the optical powers of the diodes will have more serious degradation for medium Earth orbit than for geosynchronous Earth orbit, due to higher fluence density of high energy electrons in GEO orbits.

Key words: optoelectronic; radiation effect; displacement damage; total ionizing dose

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1 Introduction

High speed laser diodes are a key part of current and future free space laser communication, and they are more and more used for space applications, including intra- and inter-satellite communications due to their good features and performances. Consequently, assessing radiation hardness of laser diodes is crucial before integrating them into satellites. The space radiation damage effects have been shown to be responsible for the performance degradations of optoelectronic devices in flight[1−2]. These energetic particles in space degrade the electrical and optical performance of the devices. Therefore, understanding the radiation response of the devices is extremely important for accurate predictions of the expected mission lifetime.

In order to predict the degradation of a laser diode, it is necessary to know how the parameters respond to different electron and proton energies, *i.e.* the energy dependence of the damage coefficients. Once the energy dependence of the damage coefficients is known, the diode performance in space can be predicted for a given radiation environment.

Many research articles show laser diode radiation damages are mainly related to displacement damage[3−6], but the relationship between the damage coefficients and displacement damage dose (D_d) is infrequently given. In this study, the radiation effects of electron and ^{60}Co-γ ray irradiations were investigated on laser diodes made in China to compare the effects of both ionizing dose and displacement damage dose on their optical and electrical properties. Optical power damage coefficients induced by different electron energies has been correlated with D_d, based on the principle of nonionizing energy loss (NIEL). The D_d methodology was employed to predict laser diode response in geosynchronous Earth orbit (GEO) and medium Earth orbit (MEO) space missions. In addition the change of optoelectronic device parameters during irradiation is also one of the most important questions for application of optoelectronic devices in high energy physics experiments where harsh radiation environments produce damage in different materials of these devices. As a result the research can provide reference data for optoelectronic device structure design used in radiation environment and for the radiation-hardness design in Chinese space laser communication systems and in high energy experiments.

2 Experimental details

Devices used in this study are 1.55 μm InGaAsP multi-quantum-well laser diodes with dis-

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tributed feedback structures, fabricated in an InGaAsP/InP semiconductor system. The thickness of $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}_y\mathrm{P}_{1-y}$ multi-quantum-well active region is 255 nm. These devices have a threshold current range from 10.48 to 11.01 mA, and a slope efficiency range from 0.095 to 0.108. The irradiations were performed by the electron accelerator facility and ^{60}Co-γ ray source located at the Lanzhou Institute of Physics. All the devices were short-circuited during exposure. The devices were irradiated at room temperature with 1 and 2-MeV electrons, respectively, up to 10^{16}e/cm^{2}at two fluence rates of 10^{13} and 10^{15}e/cm^2·h, and by ^{60}Co-γ ray up to the total ionization dose (TID) of 5×10^7 rad(Si) at dose rate of 1×10^5 rad(Si)/h. Each time, two samples were placed in the vacuum chamber during irradiation and 22 samples in all were irradiated by ^{60}Co-γ rays, 1- and 2-MeV electrons. A mean value was used to characterize the device degradations. To prevent the pigtail fibers of the diodes from being irradiated by electron and γ ray, a 15-mm-thick lead plate fixture with an opening facing radiation sources was used to minimize the radiation effects on the pigtail fibers.

The devices were immediately characterized after attaining a particular fluence or dose level. All measurements were done at 25 ℃ by placing diodes on a temperature-controlled plate. A Keithley 2 400 was used as power supply, and a JDSU InGaAs optical power meter was used to measure optical power-current curve through the pigtail fibers. The pulse width of the current forcing diodes was set to 100 ms to decrease injection-enhanced annealing effect.

3 Results and discussion

Optical power and threshold current are two of the most important laser diode parameters. The radiation effect of ^{60}Co-γ ray on output power of the laser diode is shown in Fig. 1, where optical power is plotted as a function of forward current in the laser diode before and after irradiation. Note that threshold current is essentially unchanged after irradiation, whereas the slope efficiency, defined as the slope of the output power above the threshold current region, was slightly decreased after irradiation from the initial value of 0.108 to that of 0.096 at a dose of 5×10^7 rad(Si), about 11% degradation. The results proved the investigated quantum-well laser diodes are quite resistant to γ ray irradiation, which is similar to the results of other 1.55 μm diodes irradiated by γ rays [3].

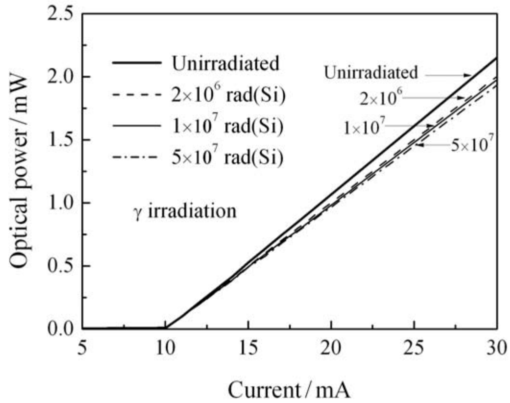

Fig. 1 Radiation effects of ^{60}Co-γ rays on the laser diodes.

Fig. 2 illustrates the radiation effect of 2 MeV electron (1 MeV electron results not shown here) on output power of the laser diode before and after irradiation up to 10^{16}e/cm^2. It is found that the threshold current increase notably at the electron fluence levels above 1×10^{13}e/cm^2, which is attributed to the creation of non-radiative recombination centers in the active region due to radiation induced displacement damages, and therefore resulting in the decrease in non radiative carrier lifetime[7−10]. In addition the slope efficiency was less affected by radiation damage than threshold current but increased sufficiently to affect performance at fluences over 10^{13}e/cm^2. The slope efficiency was decreased from the initial value of 0.098 to that of 0.076 after irradiation at a fluence of 1×10^{16}e/cm^2, about 23% degradation.

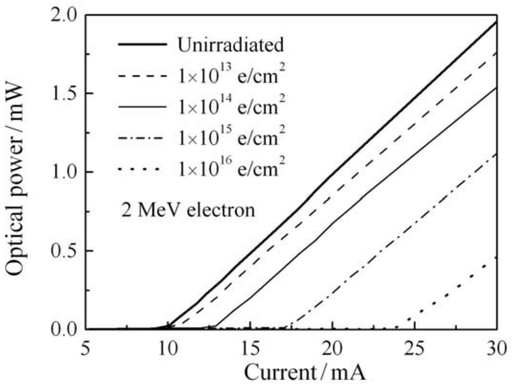

Fig. 2 Radiation effects of 2 MeV electrons on the laser diodes.

It can be found from Figs. 1 and 2 that slope efficiencies could be decreased through ^{60}Co-γ ray irradiation, or electron irradiation, probably indicating there exists a relation between the TID given by ^{60}Co-γ ray and that given by electrons. So the absorbed doses by the whole active region of the laser diodes were calculated for the γ ray and electron irradiation experiments. Considering the difficulty in obtaining the material parameters of the complex stoichiometric active material, an InGaAsP stoichiometric coefficient was employed to simplify the calculation of the absorbed TID, based on the Geant4 radiation transport toolkit. The calculated results were shown in Fig. 3. When the absorbed TID is less than 1×10^7 rad, the degradations of normalized slope efficiency, the ratio of the value after irradiation to the one before irradiation, are consistent with the TID absorbed by the active region of the diodes, whatever given by γ ray or electron. Electron radiation data were not compared with that of ^{60}Co-γ ray above 1×10^8 rad due to the absence of γ ray irradiation data. However there is a large discrepancy over 1×10^8 rad between 1- and 2-MeV electron irradiation results, probably indicating displacement damage begin to play an important role on the degradations of slope efficiencies at higher electron fluencies, a further experiment required to confirm that.

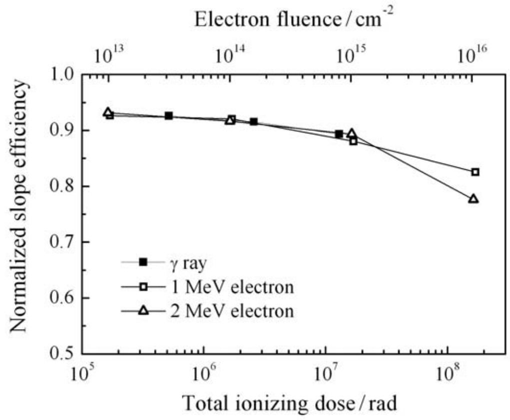

Fig. 3 The relationship between normalized slope efficiency and the total ionizing doses absorbed by the active regions of the diodes.

It can be seen from Figs. 1 and 2 that the degradations of optical powers have a huge difference between the irradiations of ^{60}Co-γ ray and electron above threshold current. The normalized optical power of the laser diodes at a biased current of 30 mA well above threshold current is plotted in Fig. 4 as a function of absorbed TID for ^{60}Co-γ ray and electrons. The optical power decreased from 2.15 mW before irradiation to 1.93 mW after irradiation at a dose of 5×10^7 rad by ^{60}Co-γ ray, a reduction of about 10%, whereas in the case of electron irradiation, a reduction of about 43% can be found at approximately equal absorbed TID. The calculation results show electrons produce far more degradation in laser diodes than γ rays do at an equal TID, indicating the additional degradation can be attributed to displacement damage, which creates defect energy levels in semiconductor material degrading the performance of the laser diode through a reduction in the minority carrier lifetime.

NIEL is defined as the part of the energy, lost per unit length by a particle moving in the material, through nuclear elastic, and nuclear inelastic interactions, thereby producing the initial displacement damage and excited phonons[11]. This displacement damage creates defect energy levels in semiconductors that can act as trapping and recombination centers. The unit of NIEL is typically MeV·cm^2/g.

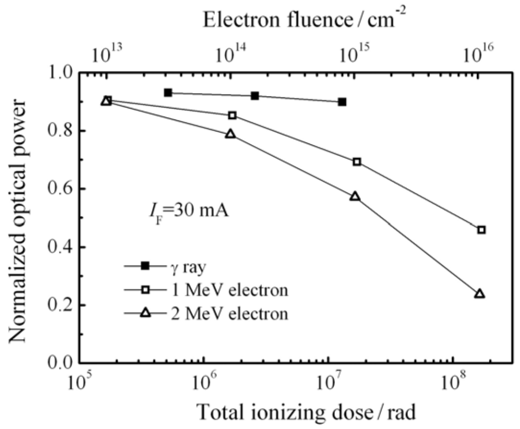

Fig. 4 Normalized optical power of the laser diodes at a biased current of 30 mA as a function of absorbed TID for ^{60}Co-γ ray and electron.

In order to calculate the NIEL of electron in the active material of the laser diodes, again an simple InGaAsP stoichiometric coefficient was employed. The calculated NIELs in InGaAsP material are 3.29×10^{-5} MeV·cm^2/g and 5.31×10^{-5} MeV·cm^2/g for 1 and 2 MeV electron, respectively based on the Geant4 radiation transport toolkit.

The displacement damage dose method can simplify the performance evaluation since that the displacement damage effects on optoelectronic device parameters for different particle energies can be correlated on the basis of D_{d}. The D_{d} can be calculated by multiplying the particle fluence by the appropriate NIEL value for the given irradiating particle energy and target material[12]. However the D_{d} is usually expressed in the form of the effective displacement damage dose, as shown in Eq. (1)

$$D_{\mathrm{deff}}=\Phi(E)S(E)\left[\frac{S(E)}{S(E_{\mathrm{ref}})}\right]^{(n-1)}, \tag{1}$$

where $\Phi(E)$ is the fluence level for electrons, $S(E)$ is the NIEL value for electrons incident on the InGaAsP material, $S(E_{\mathrm{ref}})$ is the NIEL for reference energy electrons, and D_{deff} is the resulting effective displacement damage dose. The reference energy for electron is usually taken as 1 MeV. The exponent n accounts for a nonlinear dependence on NIEL. For any value of n other than unity, the D_{d} represents an effective D_{d} (*i.e.* D_{deff}) for the given particle and reference energy (E_{ref}).

If the normalized maximum power data shown in Fig. 4 are plotted as a function of effective 1 MeV electron D_d given by Eq. (1), and the data will collapse to a single characteristic curve, as shown in Fig. 5. A good linearity between electron D_deff and the parameters of the laser diodes was obtained, indicating the displacement damage dose method can provide the valuable reference for the evaluation of laser diodes radiation damage effects. In order to cause the data to collapse to a single curve, a nonlinear least squares fitting of Eq. (1) is used to determine the best value of n. The best correlation is obtained with $n=2.53$, where E_ref is set to 1 MeV.

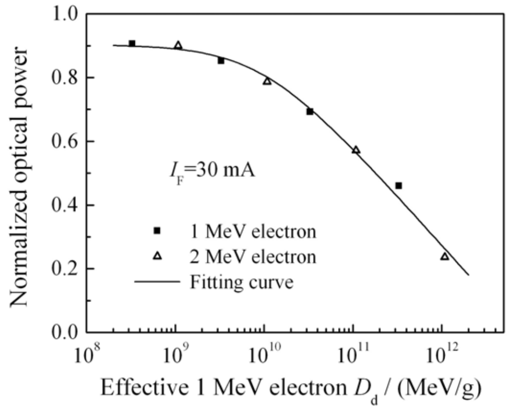

Fig. 5 Normalized optical power as a function of the effective 1 MeV electron D_d. The symbols represent the experimental data and the solid line represents the fitting curve for the cell.

The degradation data by 1 MeV/2 MeV electrons shown in Fig. 5 can be fitted using the semi empirical equation[13]

$$N(E)=1-C\log(1+\frac{D_\mathrm{deff}(E)}{D_\mathrm{x}})\ , \tag{2}$$

where $N(E)$ represents the normalized parameter of interest, $D_\mathrm{deff}(E)$ is the effective dose given by Eq. (1), C and D_x are fitting parameters to be determined. The solid line represents the characteristic curves generated using Eq. (2) for the laser diodes. The fitting parameters are characteristic for this diode structure, and the best correlation is obtained with $C=0.051$ and $D_\mathrm{x}=9.64\times10^9$ MeV/g. The characteristic curve can be used to predict the diode response to irradiation by electrons or even by electron spectrum. However more experimental data are demanded to predict the degradations of these diodes by other particles and energies.

In order to predict the power degradations of the diodes in space missions, the D_deff deposited in active regions of the diodes were calculated for GEO (altitude 35 870 km, inclination 0°) and MEO (altitude 20 000 km, inclination 42.5°) radiation environments. The radiation models of AP8MAX and AE8MAX were employed to simulate the proton and electron spectrum in the GEO and MEO orbits. Taking a simple Al shielding structure of cylinder for example, the total D_deff deposited were calculated as a function of Al thickness according to Eq. (1). The results were shown in Fig. 6. When Al thickness over 1 mm, D_d produced by protons in both orbits can be neglected. So the D_deff data in Fig. 6 come mainly from the contribution of electrons in the GEO and MEO orbits. Using the characteristic curve in Fig. 5, the relationship between the normalized optical power and D_deff can be converted into that between the normalized optical power and the Al thickness.

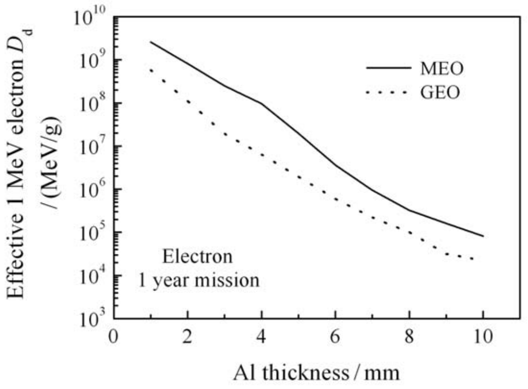

Fig. 6 Effective 1 MeV electron D_d as a function of Al shield thickness in GEO and MEO orbits for a 1-year-minssion.

Taking account of a 5-year-mission lifetime and two time redundant uncertainty of both space radiation environments, MEO radiation environment will deposit about 2.56×10^{10} MeV/g effective displacement dose in the diodes for a 1 mm-thickness Al shielding, thereby resulting in an optical power reduction to ∼ 73% of the initial value in the end of lifetime. The optical power will increase to ∼ 90% of the initial value using a 5 mm-thickness Al shielding. For the cases in GEO orbit, radiation environment will have smaller effects on the diodes than MEO environment does, due to lower fluence density of high energy electrons in GEO orbits. The predicted results for the diode structure still need to be validated through on-orbit data from space flight missions.

4 Conclusion

Displacement damage and total ionizing dose are analyzed to compare the differences of radiation effects on the diodes produced by electrons and ^{60}Co-γ rays. The research results show that slope efficiency of laser diode is mostly affected by the TID produced by charging particles, and threshold current and optical power mainly by displacement damage dose. A correlation can be established between the damage coefficients and D_d. For the space radiation environments of GEO and MEO mainly composed of electrons, the absorbed D_d by the active regions of the diodes is calculated, and a preliminary prediction results are presented about the power degradations of these diodes. The displacement damage dose method may be appropriate for predicting the reliability of the 1.55 μm InGaAsP laser diodes used in laser communication systems under severe radiation environments, including electron-rich and proton-rich orbits.

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用于空间激光通信的InGaAsP激光二极管辐射损伤研究

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摘要： 对1.55 μm波长DFB结构的InGaAsP多量子阱激光二极管开展电子和^{60}Co-γ射线辐照试验。试验结果表明，激光二极管的斜度效率主要受带电粒子沉积的电离总剂量影响，而阈值电流和光功率主要受位移损伤剂量的影响。利用位移损伤剂量方法评价激光二极管的辐射损伤特征，并且预测其在空间辐射环境中的光功率衰退情况。模拟计算结果表明，MEO轨道辐射环境对激光二极管光功率辐射损伤远大于GEO轨道的影响，这主要是由于MEO轨道辐射环境的高能电子通量密度远大于GEO轨道的通量密度。

关键词： 光电器件；辐射效应；位移损伤；总电离剂量

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