Cosmic radiation effect on silicon photonic Mach-Zehnder Modulator

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Abstract: We evaluated the radiation effects of cosmic rays on silicon Mach-Zehnder Modulator loaded on International Space Station. Permanent changes of refractive index (10^{-3}) and carrier lifetime reduction have been observed after 6 months' radiation. © 2022 The Author(s)

1. Introduction

Silicon photonics (SiPh) is a promising technology for future communications. Owing the advantages of CMOS compatible, low cost, low loss and high speed, demands are increasing for the high-speed communications among earth, International Space Station (ISS) and low earth orbit (LEO) [1]. Harsh environment in space contains cosmic rays (e.g. alpha, gamma rays) that may have adverse influence on semiconductor photonics device performances [1,2]. It is, therefore, important to understand the impact of these radiation effects and verify the operation robustness and reliability of silicon Photonics Integrated Circuits (PIC) in order to develop proper risks mitigation strategies for incorporating them in future space-borne instruments. Previous works by various groups have demonstrated the radiation effect of alpha or gamma rays on passive or active devices in the laboratory environment [3-4]. Ionizing radiation (e.g. X, alpha, gamma rays) could induce traps and trap charges between silicon and oxide interface [4]. High energy particles such as gamma rays may introduce defects and displacement damage to reduce carrier lifetime [2,3]. Most of these studies only focused on transient response of the opto-electronic devices. While to the authors' knowledge, there is a lack of complete study on how high energy particles can affect the device performance in a long-term in-space environment. Therefore, it is our program goal to perform long-term, in-space tests of our foundry fabricated PICs containing Mach-Zehnder modulator (MZM) on the ISS. After 6 months and about 180 million miles' flights, optical and opto-electronic responses were measured and compared with the pre-flight results. Permanent changes of effective index and carrier lifetime reduction have been observed. Our work paves the way for potentially deploying PICs for future spaceborne applications.

2. Results

To verify the radiation hardness under cosmic rays and operation reliability in universe environment, foundry fabricated SiPh MZM was mounted on the RAM side (forward of the Space Station) for 6 months' flight (Fig. 1(a-b)). The MZM consists of two arms with a 42 μm length difference. P and N doping levels are designed as 6e17 cm^{-3} while P++ and N++ are heavily doped as 1e20 cm^{-3} to form the ohmic contact (Fig. 1(c)) [5]. Effective *p-n* junction length is about 5 mm. Optical spectra of MZM were measured before and after radiation exposure (pre and post flight) for comparison and analysis (Fig. 1(d)). Transmission spectra model is used to fit the data and extract parameters [6]. One example data of MZM is shown in Fig. 1(d). After flight, spectra have obvious shift, and the Extinction Ratio (ER) has decreased. At least eight devices' transmission spectra were measured before and after flight for a statistical demonstration. Changes of real and imaginary part of effective index were extracted from the measured MZM transmission spectra in Fig. 1(e-f). Real part of effective index changed around 10^{-3}, up to $2.5*10^{-3}$. Considering the thermo-optic coefficient of silicon ($1.8*10^{-4}$ K^{-1}), temperature fluctuation (3°C) in measurement environment induced silicon effective index change is set as the error bar in the real part of effective index (Fig. 1(e)). Imaginary part of effective index changed around 10^{-3}, which leads to the obvious reduction (nearly 10dB) of Extinction Ratio for MZM (Fig. 1(d,f)).

Electrical and electric-optical responses (DC bias and high speed) were also tested and compared after exposure. For the I-V curve, dark saturation current increased from 10^{-11} to 10^{-9} after flight (Fig. 2(a)). For voltage 0.5~1V, calculated ideality factor increased from 1.57 to 1.84 after flight. Series resistance varied from 7.08 to 13.28 ohm after radiation. Under reverse bias, the spectra shift of MZM under the same bias was close to the pre-flight results (Fig. 2(b)). For the high-speed test, a Vector Network Analyzer (VNA) was connected to one GSG port of the device through a bias tee and RF probe. For another GSG port of the same device (Fig. 1(b)), RF probe with 50-ohm terminator was applied on the GSG pads to reduce reflection. Reflection coefficient S11 was obtained by measuring the VNA. Optical spectrum method was used to characterize the high speed EO response for the device before and after exposure. We measured at least 3 pre- and post-flight devices. All three devices have shown very close S11 which indicated the RC constant didn't change appreciably after exposure. For high speed EO response, all three devices have shown extended 3dB bandwidth after exposure. High speed response was determined by RC constant, carrier transit time (mobility dependent) and carrier lifetime. As the RC constant didn't change too much (S11 dependent) and the mobility didn't degrade too much [7], the carrier lifetime would increase after exposure [2,3].

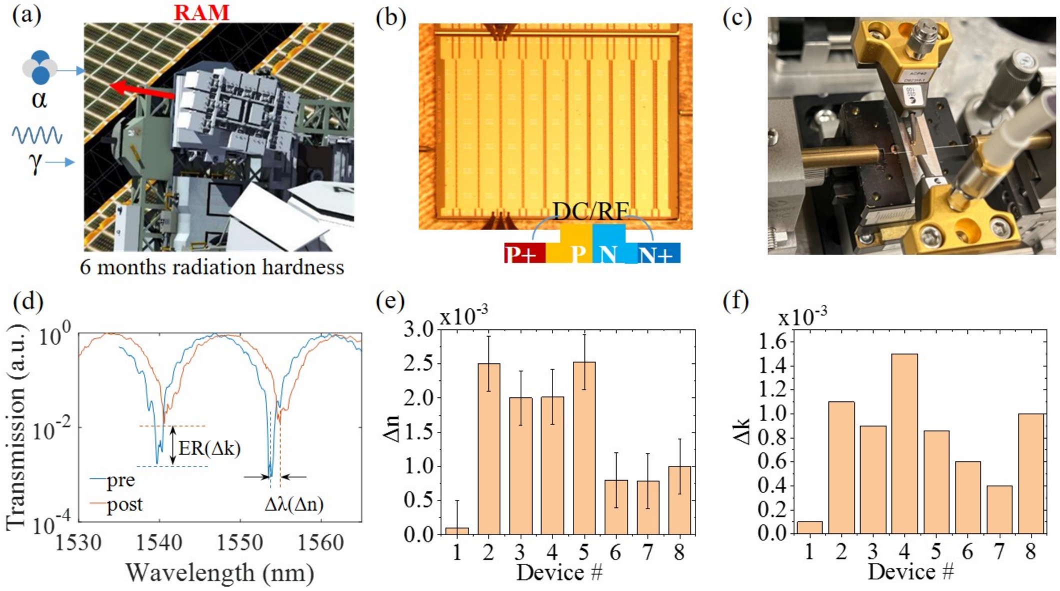

Fig. 1. (a) Radiation environment. (b) Device image and (c) setup of the MZM modulator. (d) Representative transmission spectra for pre and post flight devices. (e) Extracted real part and (f) imaginary part of effective index change of 8 MZMs post flight.

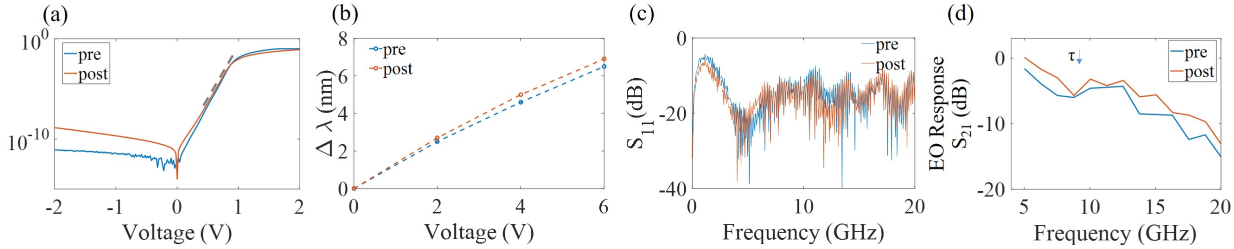

Fig. 2. (a) measured I-V curves of *p-n* junction. (b) Spectra shift of MZM under reverse bias (0~-6V). (c) S11. (d) High-speed EO response (S21) of pre (blue) and post (red) flight MZM.

3. Summary

In this work, we tested and compared the silicon Mach-Zehnder modulator before and after in-space radiation exposure. Measured results show minor permanent changes in real and imaginary part of effective index around 10^{-3} and carrier lifetime reduction. Most of devices can work normally without obvious degradation. Our work paves the fundamental step for future in-space applications of silicon photonic devices and PICs.

3. References

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