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Abstract. This paper discusses the radiation dependent characteristics of avalanche photodiodes (APDs). The reliability, of semiconductor detectors, is very dependent on the degradation modes. In this study, we present the main irradiation effects such as the multiplication gain, minority carrier life time, illumination, and radiation damage coefficient. Protons radiation effects, on the model of two different silicon avalanche photodiode structures, has been investigated. The results demonstrate that the model can accurately calculate the internal parameters of the APDs and produce data that can be directly compared with measurements. The fluence effects of 51 MeV proton irradiation, on the photosensitivity and signal to noise ratio, are also investigated. The objective was to analyze the effect depletion region volume and carrier concentration, of the i-region of APDs, on radiation hardness. Moreover, we have investigated, deeply, some of the degradation performance and capabilities of typical APDs, currently used in many communication and sensing systems, over wide range of the affecting parameters. APDs are used in systems that require coherent, and often single mode, light such as high data rate communications and sensing applications. APDs are an attractive receiver choice for low signal applications because their internal gain mechanism can improve signal to noise ratio. Additionally, we have taken into account the harmful effects of proton radiation on the device performance such as signal to noise ratio, bit error rate, gain, sensitivity, device responsivity and operating efficiency. [DOI: 10.1117/1.OE.52.1.014003]

Subject terms: excess noise; silicon avalanche photodiodes; signal to noise ratio; bit error rate; radiation damage; sensing systems and irradiation effects.

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1 Introduction

It is important to study the effects of nuclear radiation on the performance of optoelectronic devices. The study of nuclear radiation effects, on semiconductors, shows that two types of defects are introduced. They are ionization damage and displacement damage. Both ionization defects and displacement damage could lead to permanent damage of the semiconductor material.[1–8] Ionization damage is mostly transient and, usually, causes little permanent damage to the photodiode performance for total doses below 10^5 rad (Si).[9–12] Previous studies, of radiation damages of avalanche photodiodes (APDs), used either gamma rays, electrons, protons, or neutrons as the radiation sources.[13–18] Irradiation primarily produces ionization defects such as broken bonds. Proton radiation has the two types of defects on APD's which include ionization and primarily displacement damage such as vacancies and interstitials.[19] Gamma rays were believed to cause the same amount of ionization damage as protons of the same dose but very little displacement damage.[19,20] Neutrons cause only displacement damages.

Many improvements were made in fabrication technology, for photodiodes and APDs. during the last 30 years including the use of hetero junctions which provide a way to adjust the band gap by varying material composition along with much more efficient carrier injection. The evolution of optoelectronic materials and fabrication methods is the most important factor in interpreting older data because all of the older work was done on part technologies that are so different from those in use today. In addition to the technology evolution issue, the technical points, listed below, are also important when interpreting older work. Comparison of damage from different irradiation types: Most early radiation damage studies were done with only one irradiation type (gamma, electrons, protons, or neutrons), providing no direct comparison of damage between different types of radiation.[21–24] This, along with the developmental nature of most of the devices in earlier studies, makes it very difficult to compare older results with more contemporary work. Changes in device design and structure occurred very rapidly. It is often possible to adjust the earlier data using the more modern interpretation of displacement damage with the nonionizing energy loss (NIEL) concept. Dark current, in devices biased during irradiation, indicates degradation is more severe than predicted by (NIEL). Note the relationship between the dose in energy deposited per unit volume and the fluence in particles per centimeter for protons is given by Ref. 25

$$\mathrm{Dose}[\mathrm{rad(SI)}] = \mathrm{LET} \times \mathrm{Fluence} \times 1.6 \times 10^{-8}\,\mathrm{rad(SI).g/MeV}, \tag{1}$$

where LET is the linear energy transfer coefficient in silicon and they are equal to 0.0578, 0.0239, and 0.0180 MeV cm/mg for 5.1, 16.2, and 23.4 MeV protons, respectively.

The present study addresses the need to develop an understanding of the types of structures and material systems that exhibit tolerance to radiation degradation and the need to gain confidence in our test methods and models for applying laboratory studies to calculate the anticipated device response in a given gamma and proton environment. We focus on photodiode and APD technologies that are commonly found in commercially available devices since they are the most practical option for nuclear applications designers.

2 APD Device Modeling Analysis

For avalanche detectors, radiation induced changes, in dark current, are important to quantify because dark current changes are an important component of such figures of merit as avalanche gain and signal to noise ratio. The dark current changes per unit depletion region volume, V_V of irradiated Si avalanche photodiode have been expressed as:[26,27]

$$\frac{\Delta I_{\text{Dark}}}{V_V} = \frac{qN_{\text{eff}}}{2K_m}\phi, \tag{2}$$

where q is the electronic charge, N_{eff} is the effective carrier concentration, and φ is the radiation fluence. The damage coefficient, for the material type in the depletion region K_m, and K_r, is related to the displacement damage coefficient for minority carrier lifetime τ_r which is given by Ref. 28:

$$1/\tau_r = 1/\tau_0 + K_r\phi, \tag{3}$$

where τ_0 denotes the preirradiation minority carrier lifetime. In addition, defects generated during irradiation cause changes in the effective substrate doping concentration and consequently in the depletion voltage, V. The two microscopic mechanisms, related to the N_{eff} variation, are the donor removal (in n-type silicon) and the deep acceptor level generation which are macroscopically modeled as a function of the radiation particle fluence, φ by Ref. 29:

$$N_{\text{eff}}(\phi) = N_0 \exp(-c_1\phi) - c_2\phi, \tag{4}$$

where N_0 is the donor concentration before irradiation, c_1 is the donor removal coefficient, and c_2 is the acceptor introduction rate. c and β are constant that are calculated in Ref. 19. In order to analyze the response time of irradiated photodiode, assume a modulated photon flux density as:

$$\varphi = \varphi_0 \exp(j\omega t)\text{photons}/(s.\text{cm}^2). \tag{5}$$

To fall on photodiode, where ω is the sinusoidal modulation frequency, the total photocurrent density through the depletion region generated by this photon flux can be shown to be:[1]

$$\left|\frac{I_{\text{photo}}}{aq\varphi_0}\right| = \sqrt{\frac{\sin^2\left(\frac{\omega t_{dr}}{2}\right)}{\left(\frac{\omega t_{dr}}{2}\right)^2}\left[1-\frac{\omega\varepsilon(|V|+V_{bi})}{W(\omega t_{dr})^2}\right] + \left[\frac{\omega\varepsilon(|V|+V_{bi})}{W}\right]^2}, \tag{6}$$

where a is the photodiode area and t_{dr} is the transit drift time of carriers through the depletion region. The time for diffusion of carriers from the undepleted region to the depleted region is given by:

$$t_{df} = \frac{\ell^2}{2D}, \tag{7}$$

where D and ℓ are the diffusion constant and the undepleted thickness, respectively, which changes with the changing of the depletion layer width W, since $\ell = W_0 - W$, W_0 is the substrate thickness. The depletion width W can be expressed as follows:[6,30]

$$W = \sqrt{\frac{2\varepsilon(|V|+V_{bi})}{qN_{\text{eff}}}}, \tag{8}$$

where ε is the absolute silicon dielectric constant and $V_{bi} \approx 0.6$ V is the junction built-in potential. The diffusion current arises from the regions within a diffusion length of the minority carriers next to the junction:

$$D = \frac{L_p^2}{\tau_r}. \tag{9}$$

The radiation induced change in diffusion length can be expressed as the following:[31]

$$L_p = \left(\frac{1}{\alpha}\right)\frac{1-e^{\alpha W}\left(1-\frac{I_{\text{photo}}}{aq\varphi_0}\right)}{e^{\alpha W}\left(1-\frac{I_{\text{photo}}}{aq\varphi_0}\right)}, \tag{10}$$

where α is the absorption coefficient of silicon. Value of α is depend on radiation fluence.[19] The time constant t_{RC} of the photodiode with a load resistance R_L is given by:

$$t_{RC} = 2.2(R_S + R_L)C, \tag{11}$$

where C is the capacitance of photodiode, R_s is the series resistance of photodiode. Finally, for fully depleted photodiodes, the rise time t_r and fall time are the same.

$$t_r = \sqrt{t_{dr}^2 + t_{df}^2 + t_{RC}^2}. \tag{12}$$

The total dark current (I_{Dark}) in Eq. (2) is related to the bulk and surface dark current as:

$$I_{\text{Dark}} = I_{ds} + MI_{db}. \tag{13}$$

The fact that slight increase in total dark current was observed with gamma irradiation confirms that the increase after proton irradiation is primary due to bulk dark current I_{db}, however, the surface dark current, I_{ds}, is the dominant at gamma irradiated field. The gain, of an APD, can be easily measured by continuous light method which consists of the dark current and the current under continuous illumination are recorded for each fluence value. The gain is then calculated as the current amplification, with respect to a reference bias, where no amplification is assumed. The gain, as a function of bias voltage at different radiation fluence, is usually described by the formula[1]

$$M(\phi, V) = \frac{1}{1 - \left(\frac{V}{V_b(\phi)}\right)^{n(\phi)}}, \tag{14}$$

where V_b is the breakdown voltage and the exponent n is a constant depending on the semiconductor material doping profile. Both V_b and n depend on the radiation fluence. An approximate universal expression of the breakdown voltage, for all semiconductors studied, can be given as follows:[1]

$$V_b \approx a_1 \left(\frac{E_g}{1.1\mathrm{eV}}\right)^{1.5} \left(\frac{N_{\mathrm{eff}}}{10^{16}\ \mathrm{cm}^{-3}}\right)^{-0.75}, \tag{15}$$

where E_g is the band gab energy of silicon and the value of E_g is dependent on radiation fluence.[19] Under particles radiation, Eq. 15 is modified to:[31]

$$V_b = a_2 \left(\frac{d^3}{\sigma\phi}\right)^{\frac{a_3}{3}}. \tag{16}$$

The constants a_1, a_2, a_3 will depend heavily on parameters such as dopant gradation, contact architecture, and initial defect density. Equation 16 should apply to both biased and unbiased irradiation, however, the constants will change to accommodate the different average defect distance, d and the cross-section for defect generation in the active region, σ. We can obtain the radiation sensitivity (coefficient) of gain as:[22–25]

$$\begin{aligned}\frac{1}{M}\frac{dM}{d\phi} &= \frac{1}{M}\frac{\partial M}{\partial V_b}\frac{\partial V_b}{\partial \phi} + \frac{1}{M}\frac{\partial M}{\partial n}\frac{\partial n}{\partial \phi} \\ &= -M\left(\frac{V}{V_b}\right)^n \left[\frac{n}{V_b}\frac{\partial V_b}{\partial \phi} + \frac{\partial n}{\partial \phi} Ln\left(\frac{V}{V_b}\right)\right]. \end{aligned} \tag{17}$$

The responsivity, S, of avalanche photodiode can be expressed as the following formula:

$$S = \frac{I_{\mathrm{photo}}}{P_0} = \frac{q\eta}{h\upsilon}, \tag{18}$$

where the quantum efficiency, η, can be given by the following expression:

$$\eta = \frac{I_{\mathrm{photo}}/q}{P_0(1-r)/h\nu}. \tag{19}$$

The multiplication mechanism, in the avalanche region, multiplies the background current, signal current and dark current. For the modulated signal with modulated index m and average power density P_o, the signal-to-noise power ratio of the APD can be obtained as:

$$S/N = \frac{0.5 m^2 I_{\mathrm{photo}}^2}{2qFB(I_{\mathrm{photo}} + I_{\mathrm{Dark}}) + \frac{4K_B T B F_n}{R_L M^2}}, \tag{20}$$

where $B \approx 0.35/t_r$ is bandwidth, t_r is rise time. The term $(4K_B T B F_n / R_L)$ is the total noise associated with amplifier and is referred to as the thermal noise of load resistor R_L by the amplifier noise figure F_n. The optimum value, of multiplication gain for the maximum signal-to-noise ratio, can be obtained by setting the first derivative of S/N ratio with gain to zero. This yields:

$$M_{\mathrm{opt}} = \left[\frac{4K_B T F_n}{xq(I_{\mathrm{photo}} + I_{\mathrm{Dark}})R_L}\right]^{\frac{1}{x+2}}. \tag{21}$$

In digital optical communication, the bit error rate (BER) for the APD can be written as:

$$\mathrm{BER} = \frac{1}{2}[1 - \mathrm{erf}(0.345 S/N)]. \tag{22}$$

3 Simulation Results and Performance Analysis

In the present work, the device modeling has been deeply investigated under the harmful proton irradiation fluences and its effects on the avalanche photodiode devices performance characteristics were based on the suggested operating parameters. The results are all listed below for both models under study.

Table 1 Proposed operating parameters for APD device.[3,5,8,13]

Operating parameter	Symbol	Value
Radiation fluence	φ	$1\times10^{11} - 5\times10^{12}$ p/cm^{-2}
Thermal activation energy	E	0.4–1.0 eV
The amplifier noise figure	F_n	2 dB
n Coefficient	n	0.2–0.3
Boltzman's constant	K_B	1.38×10^{-23} J/K
Acceptor introduction rate	B	0.0205 – 0.0248 cm^{-1}
Donor removal coefficient	C	0.0008 – 0.002 cm^{-1}
Absolute temperature	T	340 K
Initial output power	P_0	0.1–0.497 mW
The absorption coefficient	A	$10^3 - 10^4$ cm^{-1}
Depletion region voltage	V	1–10 Volt
Effective ionization rate	K	0.015–0.035
Electron charge	Q	1.6×10^{-19} J/eV
Initial carrier life time	T_0	2–10 ns
Angular frequency at current gain	Ω	10^8 Hz

Based on the model equations analysis, assumed set of the operating parameters as listed in Tables 1 and 2, and the set of the series of Figs. 1–7, the following facts are assured as the following results:

i. As shown in Fig. 1, the model has assured that as fluence of radiation increases. This leads to decrease in avalanche device gain for both Perkin Elemer and advanced Photonix models. This also leads to increases in breakdown voltage which results in increasing of avalanche device gain for both Perkin Elemer and advanced Photonix models. Perkin Elemer model has presented higher avalanche device gain than advanced Photonix model, under the same breakdown voltage effect.

Table 2 APDs characteristics.[3,8,13,15,23]

Parameter	APD structure Perkin Elmer (IR-enhanced) (deep)	Advanced photonix (shallow)
Depth (μm)	130	25
Volume (cm^3)	6.5×10^{-5}	1.3×10^{-5}
Carrier concentration (cm^{-3})	4×10^{12}	4×10^{13}
Resistivity (Ω cm^{-1})	3400	300
Operation voltage ($M = 100$)	400	200
Break down voltage	421 V	210 V
Quantum efficiency	80% ($\lambda = 900$ nm), 40% ($\lambda = 1060$ nm)	70% ($\lambda = 800$ nm)
Active area diameter (mm)	0.8	0.9
Operation wavelength (nm)	800–1064	800
Preirradiation dark current (nA)	40	2
Rise time (ns)	≈2	≈2

ii. As shown in Fig. 2, the model has assured that as applied voltage increases which results in increasing of avalanche device gain for both Perkin Elemer and advanced Photonix models. However, as irradiation fluences increase, this leads to decrease in avalanche device gain for both device models under study.

iii. Figure 3 has demonstrated that as fluence of radiation increases, a decrease of normalized responsivity is seen for both Perkin Elemer and advanced Photonix models. Perkin Elemer model has presented lower normalized responsivity than advanced Photonix model, under the same operating optical signal wavelength.

iv. Figure 4 has proven that as fluence of radiation increases, a decrease of signal to noise ratio is seen for both Perkin Elemer and advanced Photonix models. Perkin Elemer model has presented lower signal to noise ratio than advanced Photonix model, under the same operating optical signal wavelength.

v. As shown in Fig. 5, the model has demonstrated that as fluence of radiation increases, a deacrease of maximum signal to noise ratio is seen for both Perkin Elemer and advanced Photonix models. Advanced Photonix model has presented higher maximum signal to noise ratio than Perkin Elemer model, under the same operating optical signal wavelength. In addition, as fluence of radiation increases, an increase of optimum gain for both studying models is seen. Advanced Photonix model has presented lower optimum gain han Perkin Elemer model, under the same operating optical signal wavelength.

vi. Figure 6 has indicated that as fluence of radiation increases, a decrease of irradiation sensitivity is seen for both studying models. Perkin Elemer model has presented higher irradiation sensitivity than advanced Photonix model, under the same device multiplication factor. In addition, as multiplication gain factor increases, a decrease in irradiation sensitivity is seen for both studying models. However, as high proton irradiation fluences increase, an increase of irradiation sensitivity is seen for models under study.

vii. Despite that radiation has a bad effect on SNR of all structures, Fig. 7 shows that the smallest thickness will be the greatest degree of hardness for radiation as advanced Photonix structure has no significant value of BER until 10^{12} proton radiation fluence.

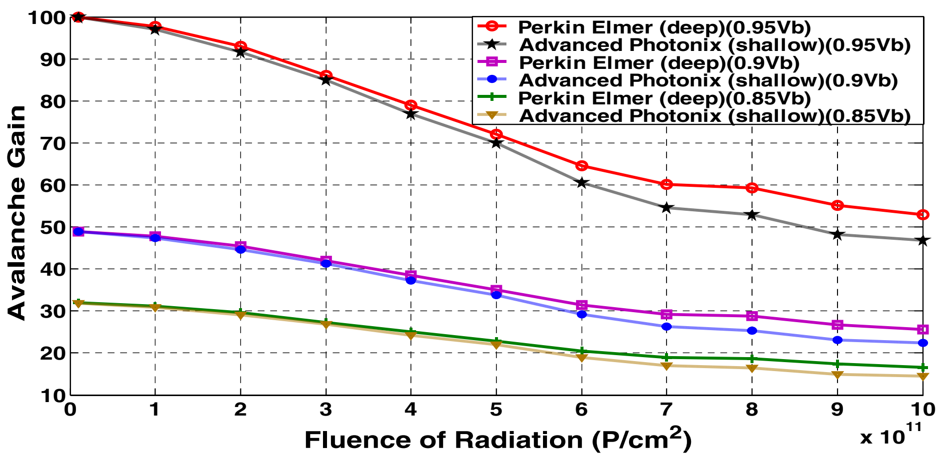

Fig. 1 Variations of avalanche gain against fluence of radiation at the assumed set of parameters.

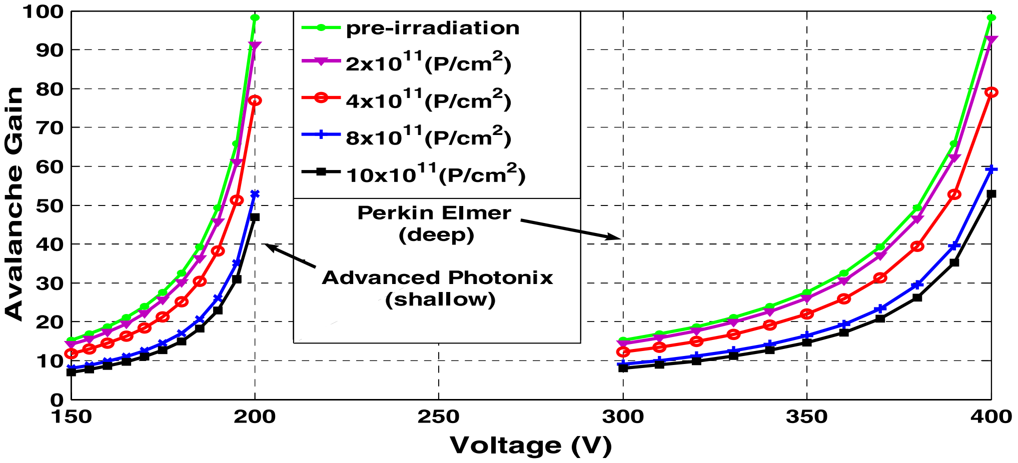

Fig. 2 Variations of avalanche device gain against applied voltage at the assumed set of parameters.

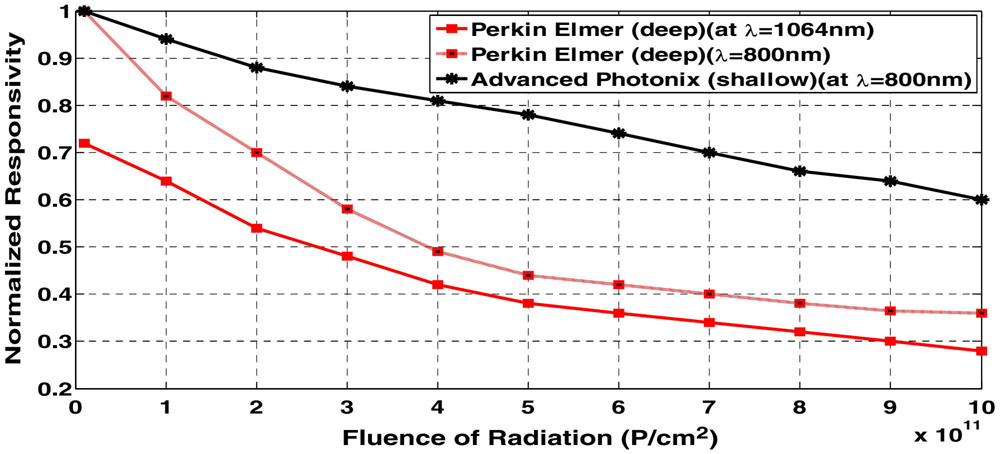

Fig. 3 Variations of normalized responsivity versus fluence of radiation at the assumed set of parameters.

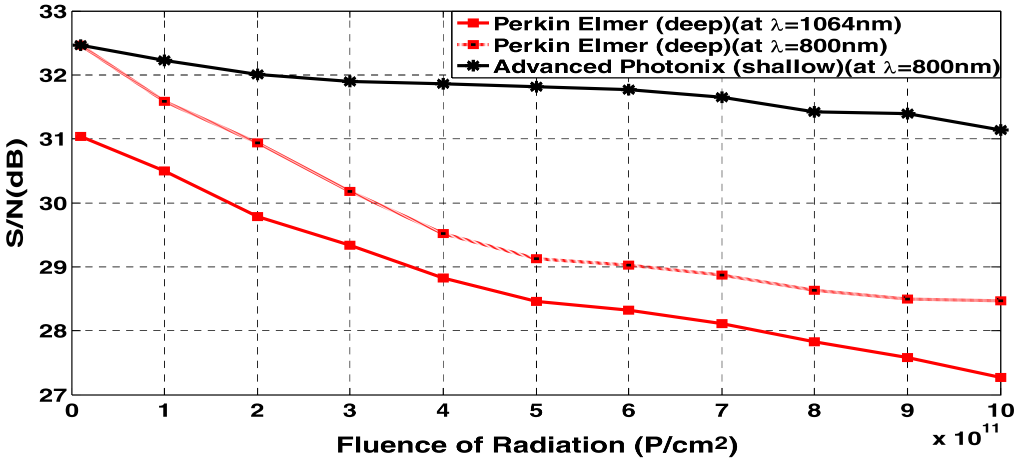

Fig. 4 Variations of the signal to noise ratio against fluence of radiation at the assumed set of parameters.

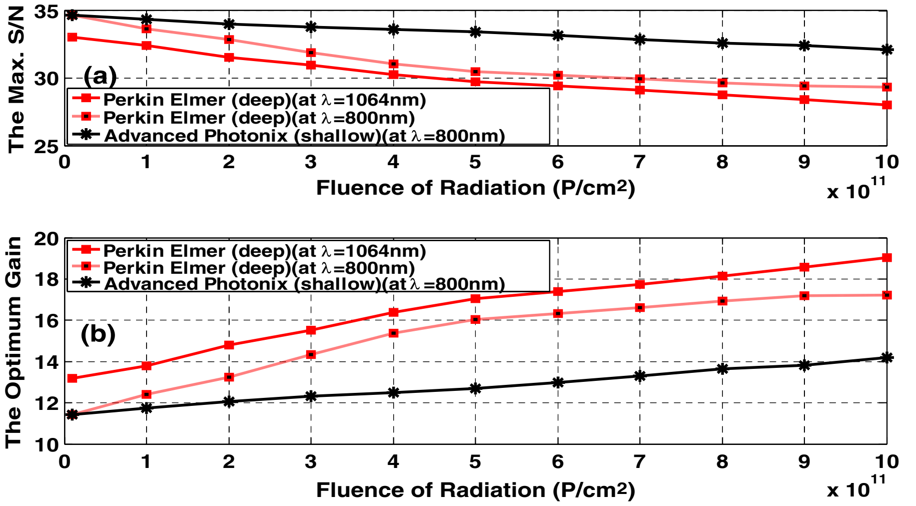

Fig. 5 Variations of both maximum signal to noise ratio and optimum gain against fluence of radiation at the assumed set of parameters.

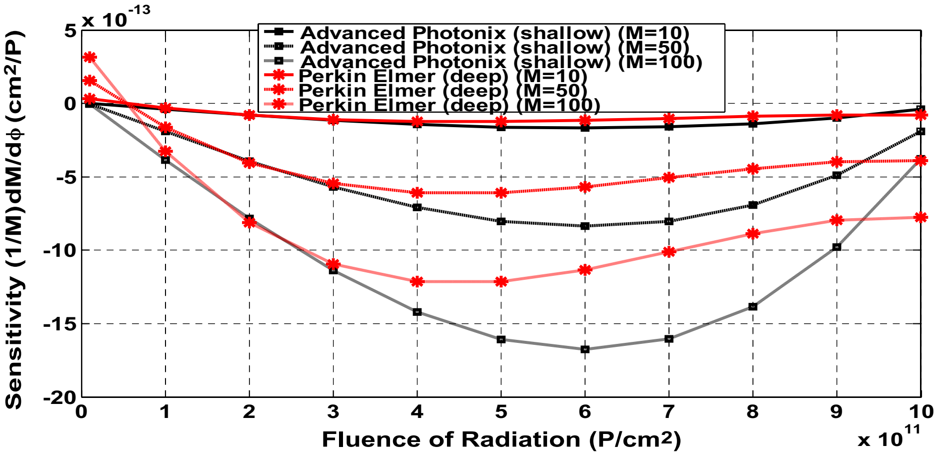

Fig. 6 Variations of the device irradiation sensitivity against fluence of radiation at the assumed set of parameters.

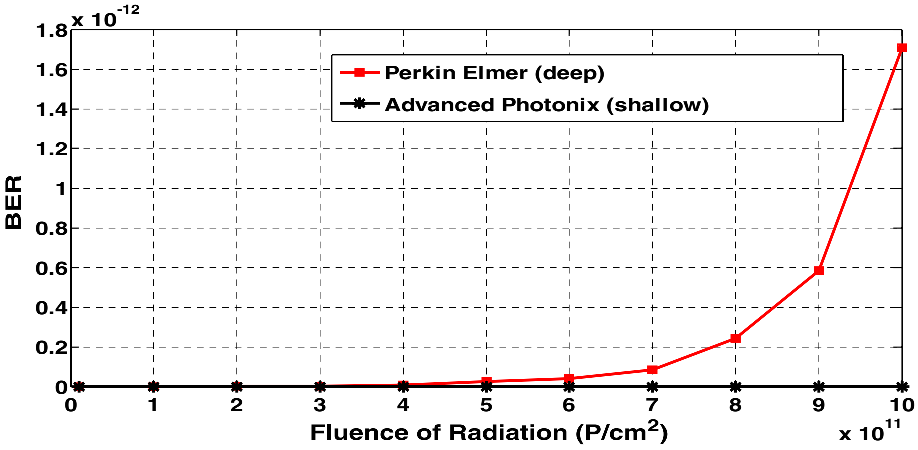

Fig. 7 Variations of the device irradiation BER against fluence of radiation at the assumed set of parameters.

4 Conclusions

In summary, the model has been investigated for the harmful proton irradiation effects on the avalanche device characteristics for both mentioned models under study. It is, theoretically, found that the increased fluence of proton irradiation results in the decrease of both avalanche device gain and excess noise factor. Moreover, it is evident that the increased proton irradiation fluence leads to the increase of both coefficient n and effective ionization rate ratio. In addition, as the applied voltage is increase, an increase in avalanche device gain is seen for both studying models. It is indicated that the increased proton irradiation fluence results in the decrease of both normalized responsivity and signal to noise ratio at the same operating optical signal wavelength. It is also, theoretically, found that the increased proton irradiation fluences leads to the decrease of maximum signal to noise ratio and the increase of optimum gain for both models under study. Finally, it is evident that the increased fluence of proton radiation results in the decrease of irradiation sensitivity for both studying models. In addition, an increase in multiplication factor leads to the decrease in irradiation sensitivity for both models under study. However, as the high increased proton irradiation fluences, an increase of irradiation sensitivity is seen for models under study. Perkin Elemer model has presented higher irradiation sensitivity than advanced Photonix model, under the same device multiplication gain factor. From the mentioned results, the advanced Photonix model has presented high device performance characteristics in comparison to Perkin Elemer under the proton irradiation fluences. We have concluded that there is a strong interest in the use of APDs as space-borne data receivers. APDs are an attractive receiver choice for low signal applications because their internal gain mechanism can improve signal to noise ratio. An optical receiver must also be appropriate for the laser wavelength being used. The near infrared is the preferred wavelength regime for deep space optical communications largely due to the wavelengths of available laser technologies that meet the optical power requirements of a deep space optical link. InGaAs APD (Hamamatsu) and Ge APD (Judson) structures with experimental studies show low device operation performance characteristics in comparison to our suggested APD structures, under the same operating conditions, in the near infrared regions and under high proton irradiation doses.[3,5]

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