Harmful Proton Radiation Damage and Induced Bit Error Effects on the Performance of Avalanche Photodiode Devices

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Abstract*— This paper has been tested the radiation dependent characteristics of the avalanche photodiodes. Raising the current density however, is not really indicative of lifetime since it is more likely a situation to be avoided than one that simulates normal lifetime degradation. The reliability of semiconductor detectors is very dependent on the degradation modes. This paper has presented the main irradiation effects, i.e., the multiplication gain, minority carrier life time, impact ionization, illumination and radiation damage coefficient. By comparing neutrons, protons and gamma radiation effects, we will apply the model on the two different Silicon avalanche photodiode structures. 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 (SNR) are also investigated. The objective was to analyze the effect depletion region volume, 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. An optical receiver must also be appropriate for the laser wavelength being used. As well as we have taken into account the effects of excess noise on the device performance, and upgrading signal to noise ratio and then to decrease the bit error rated that has a bad effect on the device performance and operating efficiency.

***Keywords*— Optoelectronic Devices, Radiation Damage, Signal to Noise Ratio, Bit Error Rate and Excess Noise**

I. INTRODUCTION

Photonic systems based on optical fibers, such as optical fiber sensors and data transfer systems, are ideally suited for applications where high bandwidth, immunity from electromagnetic interference, low power consumption, and low weight is recommended [1]. In many of these applications a fiber optic communication system is likely to be placed in a nuclear environment such as in the medical radiology, astronomy, nuclear physics and nuclear safeguarding. However, in several fiber optic communication systems, the avalanche photodiode (APD) is preferred to the p-i-n photodetector [l], since it provides high quantum efficiency, high frequency response, low noise, and a higher current gain than a p-i-n diode due to the avalanche multiplication phenomenon. The internal gain mechanism can improve signal to noise ratio, so the coupling of the APD with scintillators provides the high resolution detection of the high-energy particles and gamma-ray [2-5]. Also, Si avalanche photodiodes are among the most sensitive photodetectors for visible and near infrared wavelengths [6], [7].

Hence, it is important to study the effects of nuclear radiation on the performance of these 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 [8]. But ionization damage are 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 APDs used either gamma rays, electrons, protons or neutrons as the radiation sources [13]–[18]. Gamma irradiation primarily produces, ionization defects such as broken bonds, and Proton radiation has the two types of defects on APD's, 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 [20]. Neutrons cause only displacement damages. One may estimate the displacement damage due to protons by scaling the neutron radiation damage [21].

The former creates trapped charges in the insulation layers and changes the surface state at the interface between the semiconductor crystal and the insulating layer. Ionization damage is the major concern for surface devices like MOSFET's. APD's are junction devices and are much less sensitive to ionization damages. Although ionization damage can cause significant increase in the APD surface leakage current due to the increase of surface states, its contribution to the total output noise is often negligible compared to the bulk leakage current. Displacement damage (DD) effectively adds defect sites to the semiconductor crystal, resulting in a rise in the bulk dark current and excess noise factor of APDs fabricated in Si [22, 23] and InGaAs-InP [24, 25]. Besides an increase in dark current, which obviously reduces photocurrent as defects act as electron or hole trapping centers for the photogenerated pairs, also increases the Noise Equivalent Power by increasing shot noise, DD can also alter the effective doping level structure by either donor removal and/or acceptor compensation [26], both of which can alter the quantum efficiency and gain. For example, previous reports by Osborne et al. [27] and Baccaro et al. [28] found neutron irradiation to levels of around 10^{13} n/cm resulted in gain degradation. Likewise, simulations by Pilicer et al. [29] indicate an alteration in the effective doping level with neutron fluence will eventually lead to some marginal degradation in gain, although little change was predicted for the wavelength dependence of the quantum efficiency. In some instances, radiation damage also leads to a reduction in the breakdown bias as observed in some Si [16, 30, 31] and InGaAs devices [24, 25, 32]. Indeed some authors have indicated that damage can even result in catastrophic failure [22, 33] via a mechanism which depends on the reliability of the near surface region. As shown in Fig. 1, the basic APD structure. APDs use a reverse bias applied to a p-n junction. They operate in a fully depleted mode; the reverse bias creates a depletion region in the diode that extends from the junction through the absorption region where photons are absorbed. Absorbed photons create electron-hole pairs in the depletion region. Carriers are swept via drift toward a very high field region near the junction called the avalanche (multiplication) region. Here, carriers create additional e-h pairs through impact ionization, starting the chain reaction of avalanche multiplication (the internal gain mechanism of APDs). Dark current in APDs has two components: surface currents which are unaffected by gain, and bulk leakage current which passes through the avalanche region and is therefore gain multiplied. A common approach to controlling surface current is the incorporation of one or more guard rings [1].

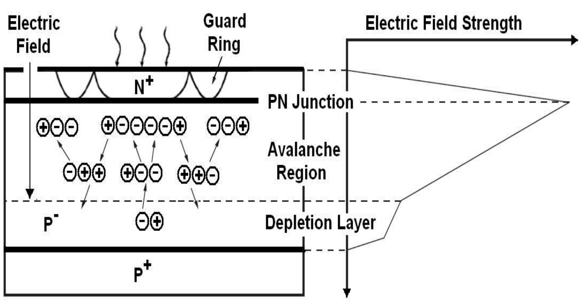

Fig. 1. Schematic of the avalanche process in an APD.

Many improvements were made in fabrication technology for photodiodes and APDs during the last 30 years, including the use of heterojunctions, which provide a way to adjust the bandgap 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 [8, 21]. 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 Non-Ionizing 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 cm for protons is given by [34]:

$$Dose\ (rad\ (SI)) = LET \times Fluence \times 1.6\times10^{-8}\ rad\ (SI).g/MeV \quad (1)$$

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.

In 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.

II. 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 [35, 36]:

$$\frac{\Delta I_{Dark}}{V_V} = \frac{qN_{eff}}{2K_m}\phi \quad (2)$$

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, is related to the displacement damage coefficient for minority carrier lifetime τ_r which is given by [28]:

$$1/\tau_r = 1/\tau_0 + K_r\phi \quad (3)$$

Where τ_0 denotes the pre-irradiation minority carrier lifetime. Also, 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 [6, 26]:

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

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 calculated in ref [19].

In order to analyze the response time of irradiated photodiode, assume a modulated photon flux density as:

$$\varphi = \varphi_0 \exp(j\omega t)\ photons\ /(s.cm^2) \quad (5)$$

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]:

$$\left|\frac{I_{photo}}{aq\varphi_0}\right| = \sqrt{\frac{Sin^2\left(\frac{\omega t_{dr}}{2}\right)}{\left(\frac{\omega t_{dr}}{2}\right)^2}\left(1-\frac{\omega\varepsilon(|V|+V_{bi})}{W(\omega t_{dr})^2}\right)+\left(\frac{\omega\varepsilon(|V|+V_{bi})}{W}\right)^2} \quad (6)$$

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:

$$t_{df} = \frac{\ell^2}{2D} \quad (7)$$

Where D and ℓ are the diffusion constant and the undepleted thickness, 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 the following [6, 37]:

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

Where ε is the absolute silicon dielectric constant and $V_{bi} \approx 0.6$ Volt 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:

$$D = \frac{L_p^2}{\tau_r} \quad (9)$$

The radiation induced change in diffusion length can be expressed as the following [38]:

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

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:

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

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.

$$t_r = \sqrt{t_{dr}^2 + t_{df}^2 + t_{RC}^2} \quad (12)$$

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

$$I_{Dark} = I_{ds} + MI_{db} \quad (13)$$

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: 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, it is usually described by the formula [1]:

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

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]:

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

Where E_g is the band gab energy of silicon, the value of E_g is depend on radiation fluence [19]. Under particles radiation, the Eq. 15 is modified to [39]:

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

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, but 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:

$$\frac{1}{M}\frac{dM}{d\phi} = \frac{1}{M}\frac{\partial M}{\partial V_b}\frac{\partial V_b}{\partial \phi} + \frac{1}{M}\frac{\partial M}{\partial n}\frac{\partial n}{\partial \phi} = -M\left(\frac{V}{V_b}\right)^n\left[\frac{n}{V_b}\frac{\partial V_b}{\partial \phi} + \frac{\partial n}{\partial \phi}Ln\left(\frac{V}{V_b}\right)\right] \quad (17)$$

The excess noise factor F depends on the type of primary injection (electron, hole or mixed injection) and ionization rates. The excess noise factor is given by [22, 25]:

$$F(M) = M\left[1 - (1-K)\left(\frac{M-1}{M}\right)^2\right] \quad (18)$$

From experimental observations it has been found that, in general, the excess noise factor can be approximated by:

$$F(M) = M^x \quad (19)$$

Where K is the effective ionization rate ratio, the parameter x take on values of 0 for PIN photodiode and 0.3 for Si, 0.7 for InGaAs avalanche photodiode.

The responsivity, *S*, of a Avalanche Photodiode can be expressed as:

$$S = \frac{I_{photo}}{P_0} = \frac{q\eta}{h\upsilon} \quad (20)$$

Where the quantum efficiency, η, can be given by:

$$\eta = \frac{I_{photo}/q}{P_0(1-r)/h\nu} \quad (21)$$

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:

$$S/N = \frac{0.5m^2 I_{photo}^2}{2qFB(I_{photo} + I_{Dark}) + \frac{4K_B TBF_n}{R_L M^2}} \quad (22)$$

Where $B \approx 0.35/t_r$ is bandwidth, t_r is rise time. The term ($4K_B TBF_n/R_L$) is the total noise associated with amplifier, it is referred to 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:

$$M_{opt} = \left[\frac{4K_B TF_n}{xq(I_{photo} + I_{Dark})R_L}\right]^{\frac{1}{x+2}} \quad (23)$$

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

$$BER = \frac{1}{2}\left[1 - erf(0.345\,S/N)\right] \quad (24)$$

III. RESULTS AND PERFORMANCE ANALYSIS

In the present work, we have deeply investigated the harmful proton irradiation fluences and its effects on the avalanche photodiode devices performance characteristics and based on the suggested operating parameters al listed below for both models under study.

Table 1: Proposed operating parameters for APD device.

Operating parameter	Symbol	Value
Radiation fluence	φ	$1x10^{11}$ p/cm^2–$5x10^{12}$ p/cm^{-2}
Thermal activation energy	E	0.4 eV–1.0 eV
The amplifier noise figure	F_n	2dB
n coefficient	n	0.2 – 0.3
Boltzman's constant	K_B	$1.38x10^{-23}$ 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	280 K–340 K
Initial output power	P_0	0.1 mWatt–0.497 mWatt
The absorption coefficient	*A*	10^3 cm^{-1}–10^4 cm^{-1}
Depletion region voltage	V	1 Volt–10 Volt
Effective ionization rate	K	0.015–0.035
Electron charge	Q	$1.6x10^{-19}$ J/eV
Initial carrier life time	T_0	2 nsec–10 nsec
Angular frequency at current gain	*Ω*	10^8 Hz

Table 2: APDs Characteristics.

Parameter	APD Structure	
	Perkin Elmer (IR-enhanced) (deep)	Advanced photonix (shallow)
Depth (μm)	130	25
Volume (cm^3)	$6.5X10^{-5}$	$1.3X10^{-5}$
Carrier concentration (cm^{-3})	$4X10^{12}$	$4X10^{13}$
Resistivity (Ωcm^{-1})	3400	300
Operation Voltage (M=100)	400	200
Break down voltage	421V	210 V
Quantum efficiency	80% (λ=900nm), 40% (λ=1060nm)	70%(λ=800nm)
Active area diameter (mm)	0.8	0.9
Operation wavelength (nm)	800-1064	800
Pre-irradiation dark current (nA)	40	2
Rise time (nsec)	≈ 2	≈ 2

Based on the model equations analysis, assumed set of the operating parameters as listed in Tables (1, 2), and the set of the series of Figs. (2-12), the following facts are assured as the following results:

i) As shown in Fig. 2 has assured that as fluence of radiation increases, this leads to decrease in avalanche device gain for both Perkin Elemer and advanced Photonix models. As well as breakdown voltage increases, this 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.

ii) Fig. 3 has demonstrated that as fluence of radiation increases, this leads to increase in coefficient n for both device models under study. Moreover Perkin Elemer model has presented lower coefficient n than advanced Photonix model.

iii) As shown in Fig. 4 has proved that as fluence of radiation increases, these results in decreasing of excess noise factor for both Perkin Elemer and advanced Photonix models. Perkin Elemer model has presented higher excess noise factor than advanced Photonix model under the same fluence of radiation.

iv) Fig. 5 has indicated that as fluence of radiation increases, this leads to increase in effective ionization rate ratio for both device models under study. As well as Perkin Elemer model has presented lower effective ionization rate ratio than advanced Photonix model.

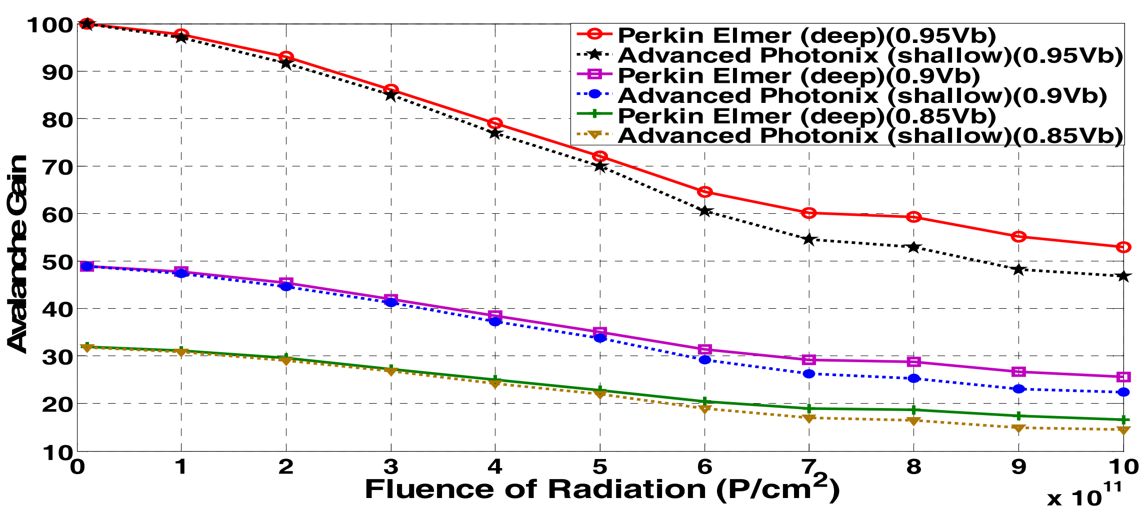

Fig. 2. Variations of avalanche gain against fluence of radiation at the assumed set of parameters.

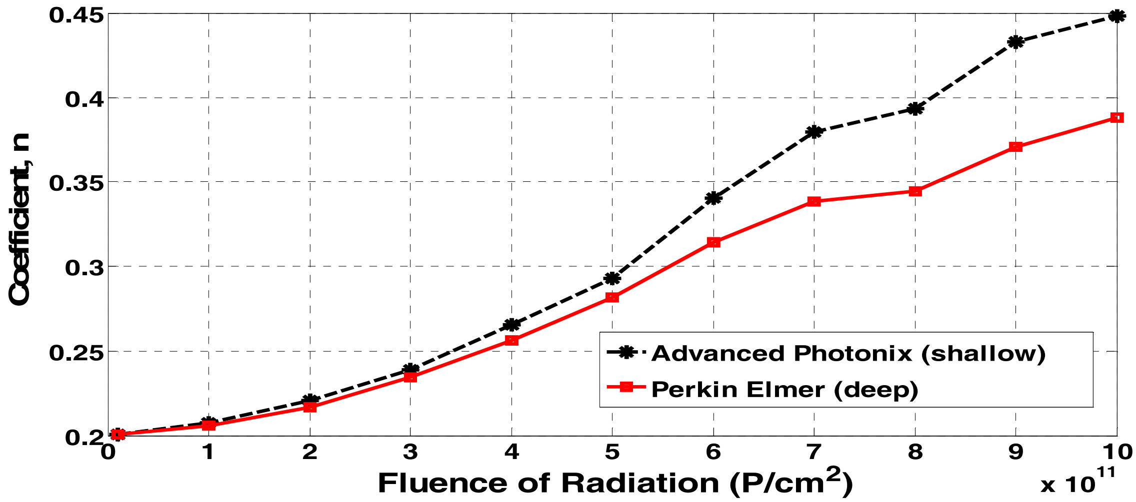

Fig. 3. Variations of the coefficient, n against fluence of radiation at the assumed set of parameters.

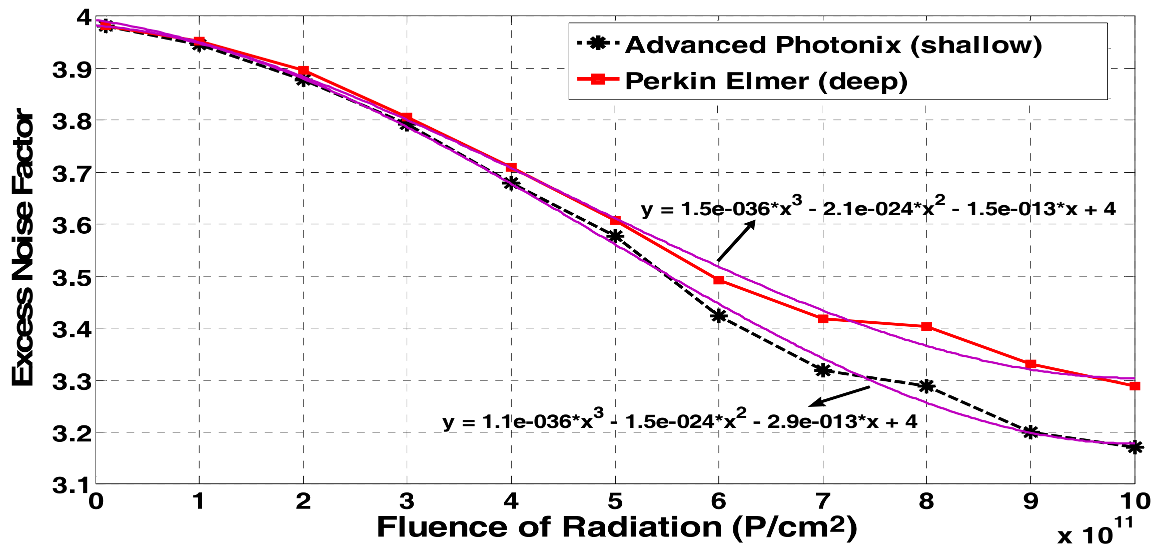

Fig. 4. Variations of the excess noise factor against fluence of radiation at the assumed set of parameters.

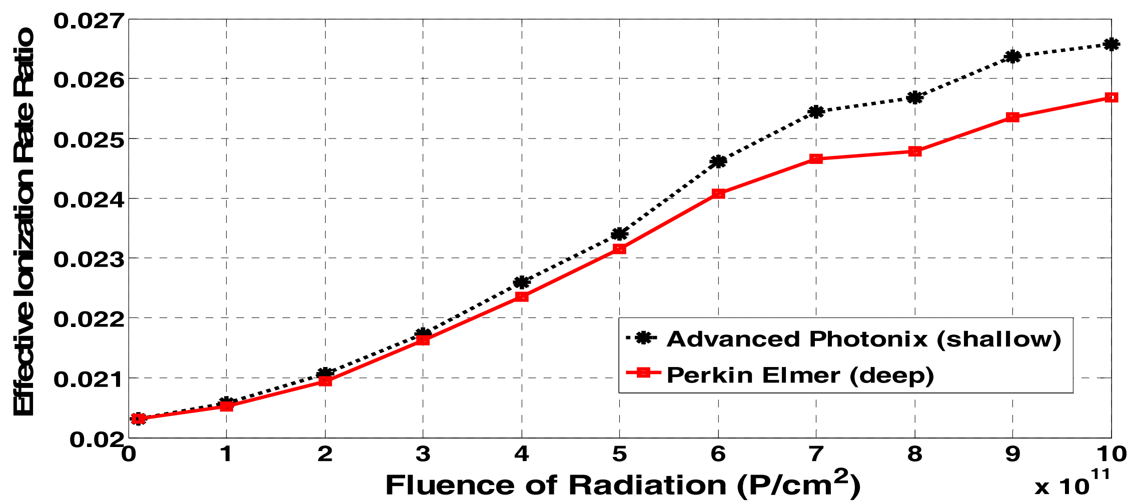

Fig. 5. Variations of the effective ionization rate ratio against fluence of radiation at the assumed set of parameters.

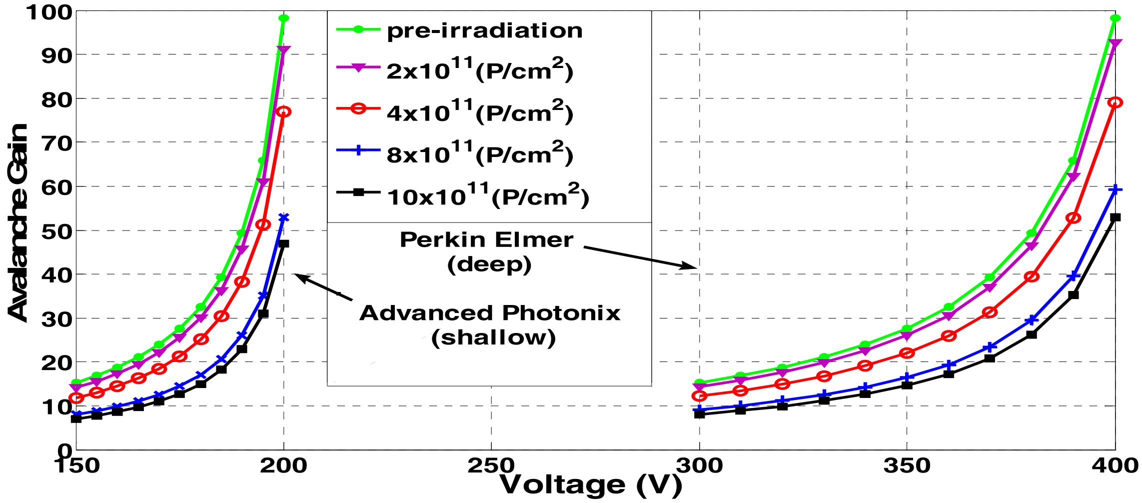

Fig. 6. Variations of the avalanche device gain against applied voltage at the assumed set of parameters.

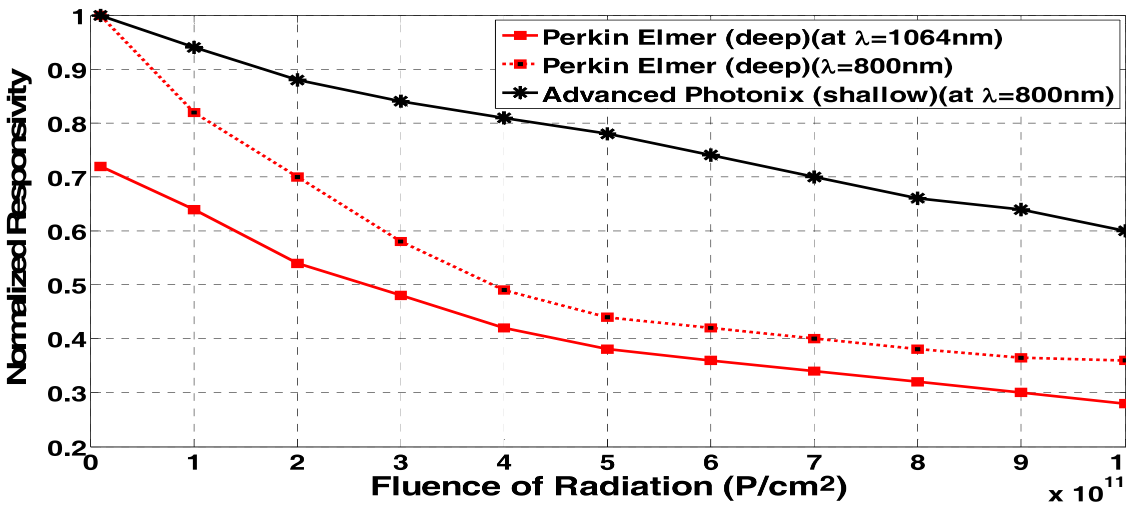

Fig. 7. Variations of the normalized responsivity against fluence of radiation at the assumed set of parameters.

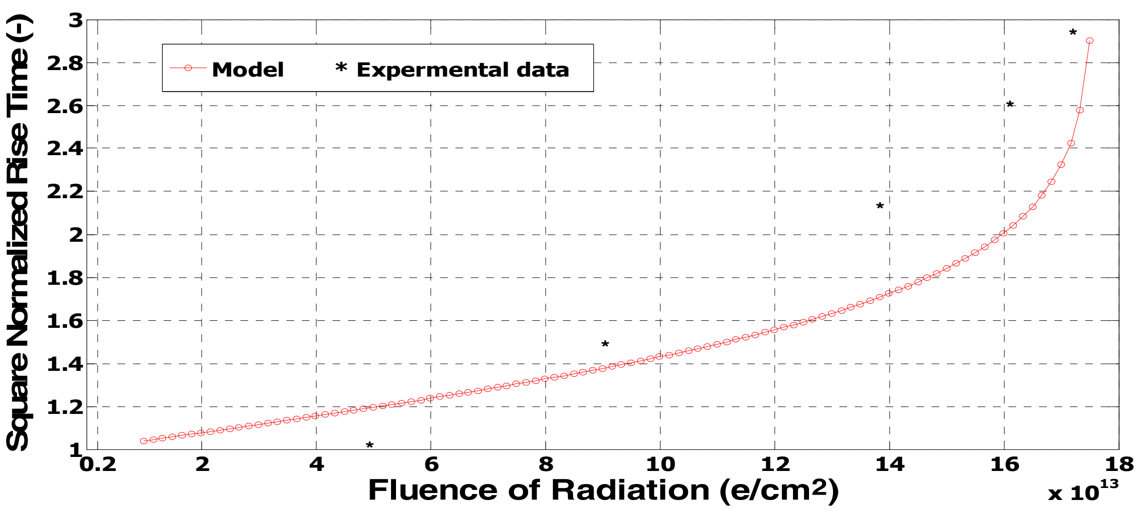

Fig. 8. Variations of the square normalized rise time against fluence of radiation at the assumed set of parameters.

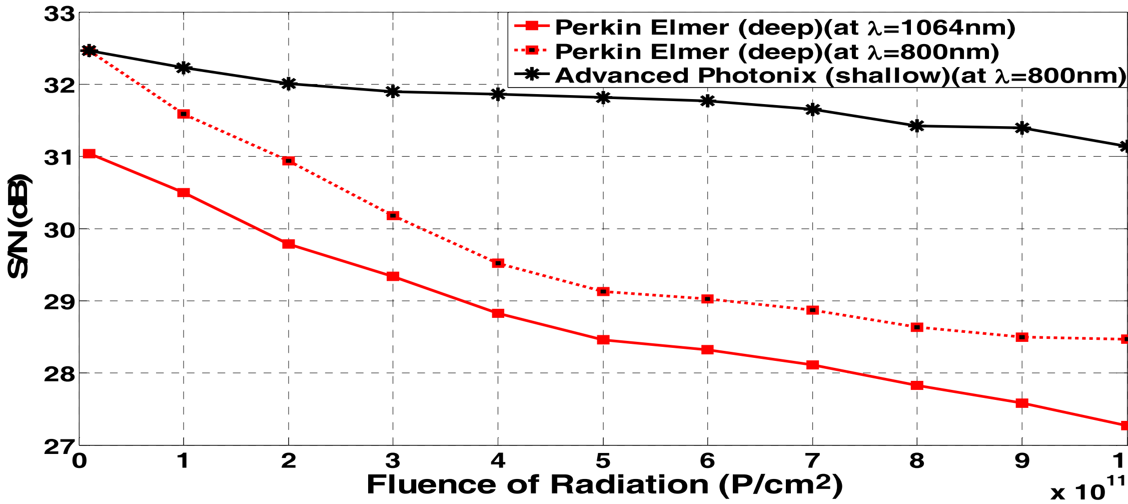

Fig. 9. Variations of the signal to noise ratio against fluence of radiation at the assumed set of parameters.

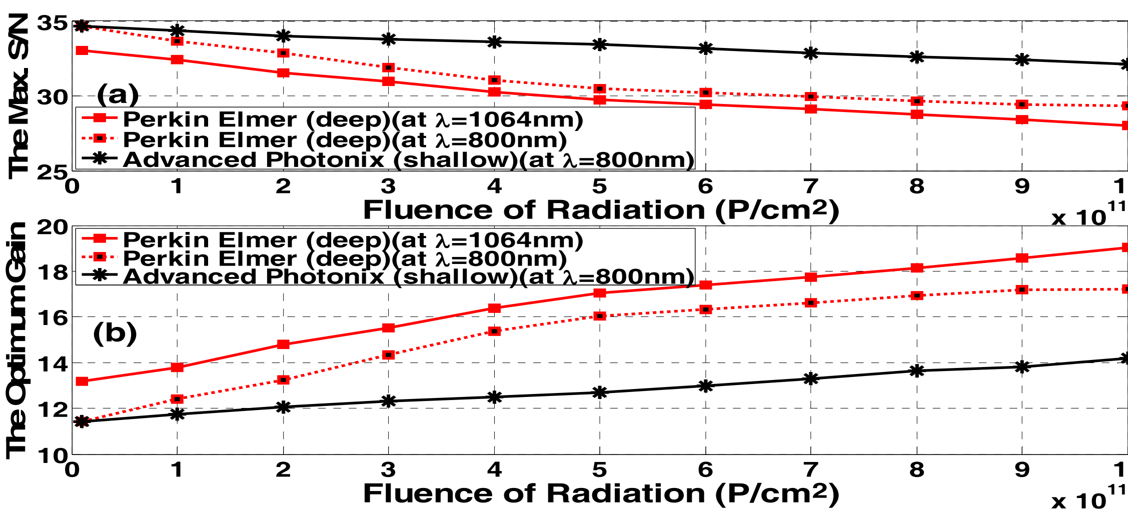

Fig. 10. Variations of both maximum signal to noise ratio and optimum gain against fluence of radiation at the assumed set of parameters.

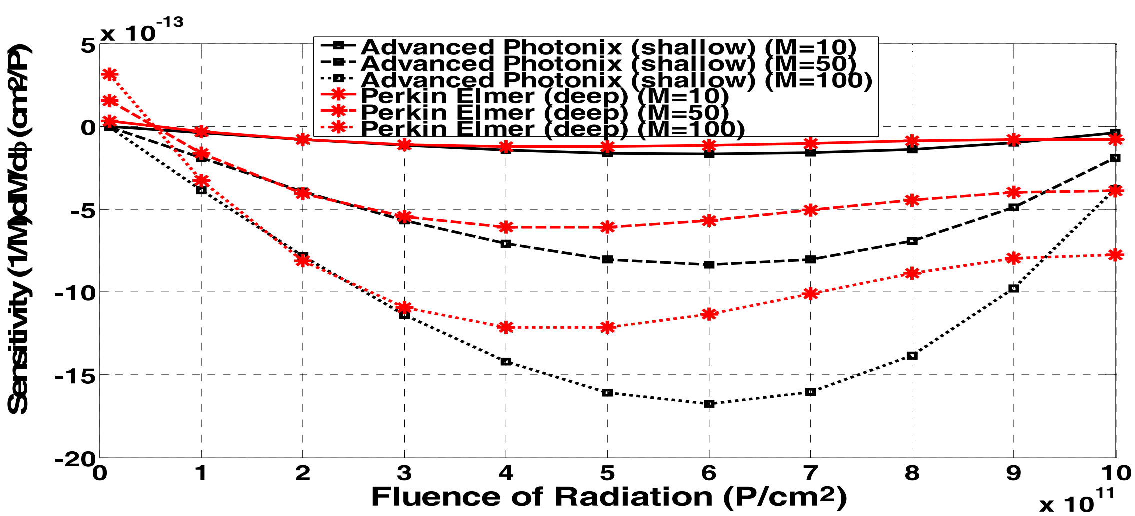

Fig. 11. Variations of the device irradiation sensitivity against fluence of radiation at the assumed set of parameters.

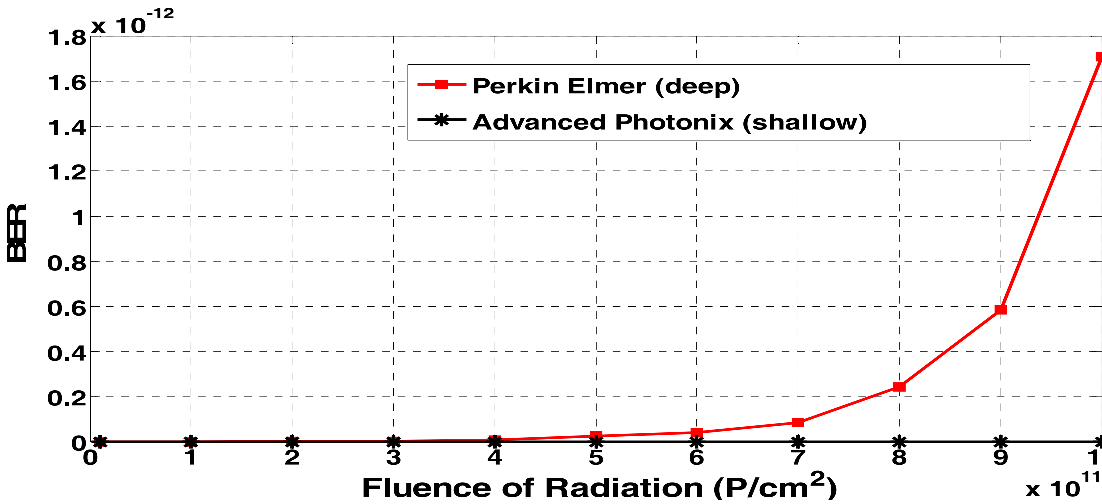

Fig. 12. Variations of the device irradiation BER against fluence of radiation at the assumed set of parameters.

v) As shown in Fig. 6 has assured that applied voltage increases, this results in increasing of avalanche device gain for both Perkin Elemer and advanced Photonix models. But as irradiation fluences increase, this leads to decrease in avalanche device gain for both device models under study.

vi) Fig. 7 has demonstrated that as fluence of radiation increases, these results in decreasing of normalized responsivity 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.

vii) As shown in Fig. 8 has indicated that as fluence of radiation increases, these results in increasing of square normalized rise time for both models under study in both experimental and analytical results.

viii) Fig. 9 has proved that as fluence of radiation increases, these results in decreasing of signal to noise ratio 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.

ix) As shown in Fig. 10 has demonstrated that as fluence of radiation increases, this results in decreasing of maximum signal to noise ratio 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. As well as fluence of radiation increases, this results in increasing of optimum gain for both studying models. Advanced Photonix model has presented lower optimum gain than Perkin Elemer model under the same operating optical signal wavelength.

x) Fig. 11 has indicated that as fluence of radiation increases, this results in decreasing of irradiation sensitivity for both studying models. Perkin Elemer model has presented higher irradiation sensitivity than advanced Photonix model under the same device multiplication factor. As well as multiplication gain factor increases, this leads to decrease in irradiation sensitivity for both studying models. But as high proton irradiation fluences increase, this results in increasing of irradiation sensitivity for models under study.

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

IV. CONCLUSIONS

In a summary, we have investigated 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, this results in the decreased of both avalanche device gain and excess noise factor. Moreover it is evident that the increase proton irradiation fluence, this leads to the increased of both coefficient n and effective ionization rate ratio. As well as the increased applied voltage, this results in the increased avalanche device gain for both studying models. It is indicated that the increased proton irradiation fluence, this results in the decreased of both normalized responsivity and signal to noise ratio at the same operating optical signal wavelength. It is also found that the harmful effects of increasing proton irradiation fluences on the increasing of pulse rise time in our analytical results and with comparing its values with experimental results. It is also theoretically found that the increased proton irradiation fluences, this leads to the decreased of maximum signal to noise ratio and the increased of optimum gain for both models under study. Finally it is evident that the increased fluence of proton radiation, this results in the decreased of irradiation sensitivity for both studying models. As well as the increased multiplication factor, this leads to the decreased in irradiation sensitivity for both models under study. But as the high increased proton irradiation fluences, this results in the increased of irradiation sensitivity 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 compared to Perkin Elemer under the proton irradiation fluences.

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