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Full Length Research Paper

Performance Response Characteristics of Avalanche Photodiodes (APDs) Under High Thermal and Protons Irradiation Environments

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This paper has been examined the high temperature irradiation variations testing in order to be used to determine avalanche photodiode lifetime, even though APD failure mechanisms are more sensitive to increases in current density. As a measured parameter of degradation, the current density is of great significance when searching for failure modes in APD. 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 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 photon-starved (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.

Keywords: Proton radiation damage, Optical functional device, High temperature environments and Radiation effects.

INTRODUCTION

In several fiber optic communication systems, the avalanche photodiode (APD) is preferred to the p-i-n photodetector (Sze, 2007: (Squillante., et al 1986), 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 (Moszynski., et al 1999), (Christopher., et al 2007). Also, Silicon avalanche photodiodes are among the most sensitive photodetectors for visible and near infrared wavelengths (Chistokhin., et al 2009: (Andrea ., et al 2003: (Arbat., et al 2010) . 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 (Geoffrey ., et al 1993). But ionization damage are mostly transient and usually causes little permanent damage to the photodiode performance for total doses below $l0^5$ rad (Si) [(Shinobu ., et al 2006: (Cappelletti1., et al 2006 : Cappelletti., et al 2008 : Kwang ., et al 2008). Previous studies of radiation damages of APDs used either gamma rays, electrons, protons or neutrons as the radiation sources (Swanson., et al 1987: Dai.,et al 1996: Grahl., et al 2003: Ikagawa., et al 2005: Pulvirenti., et al 2008: Ogasawara., et al 2010) . Gamma rays were believed to cause the same amount of ionization damage as protons of the same dose but very little displacement damage (Antunovic., et al 2005). Neutrons cause only displacement damages. One may estimate the displacement damage due to protons by scaling the neutron radiation damage (Xiaoli Sun and Henri Dautet, 2001: Antunovic., et al 2005: Ruzin., et al 1999). 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 [(Pilicer., et al 2005), (Gedam., et al 1991) and InGaAs-InP (Laird., et al 2005), (Jamie ., et al 2003). 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 (Lindstrom., et al 2006), both of which can alter the quantum efficiency and gain. For example, previous reports by Osborne et al. (Baccaro., et al 1999) and Baccaro et al. (Osborne., et al 2000) found neutron irradiation to levels of around 10^{13} n/cm resulted in gain degradation (Ercan and Tapan, 2007). In some instances, radiation damage also leads to a reduction in the breakdown bias as observed in some Si [(Ikagawa., et al 2005), (Jamie ., et al 2006), (Jamie ., et al 2006) and InGaAs devices [(Laird., et al 2005), (Jamie ., et al 2003), (Becker, 2004). Indeed some authors have indicated that damage can even result in catastrophic failure (Pilicer., et al 2005), (Ingram., 2010) via a mechanism which depends on the reliability of the near surface region.

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 [(Geoffrey., et al 1993), (Ruzin., et al 1999). 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 (Xiaoli ., et al 1997):

$$Dose\ (rad\ (SI)) = LET \times Fluence \times 1.6 \times 10^{-8}\ rad\ (SI).g\ /\ MeV \qquad (1)$$

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. APD technologies that are commonly found in commercially available devices since they are the most practical option for nuclear applications designers.

In the present study, we have 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 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.

APD DEVICE MODELING ANALYSIS

The dark current, I_{Dark}, for a device having depletion depth W, active area A and the effective carrier concentration, N_{eff} under high temperature irradiation T and the radiation fluence Φ is given by (Srour., et al 2000):

$$I_{Dark} = \frac{qAW(T,\phi)N_{eff}(T,\phi)}{2\tau_r(T,\phi)} \qquad (2)$$

Where τ_r is the minority carrier lifetime after irradiation and it is given by (Osborne., et al 2000):

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

Where τ_0 denotes the pre-irradiation minority carrier lifetime and K_r is the damage coefficient for τ_r.
For silicon detectors, changes in dark current per unit depletion region volume have been expressed as (Becker., et al 2003):

$$\frac{\Delta I_{Dark}}{V_V} = \frac{qN_{eff}}{2K_m}\phi \qquad (4)$$

where V_V is the depletion region volume, and Km is the damage coefficient for the material type in the depletion region. A simple model of the annealing can be constructed if we assume that the radiation-induced defects anneal according to a first-order mechanism (Srour., et al 2000), at a given absolute high temperature irradiation T, K_m can be related to an activation energy E by the Arrhenius formula:

$$K_m(T) = K_m(0)\exp(E / K_B T) \tag{5}$$

Where K_B, is Boltzmann's constant.

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]:

$$N_{eff}(\varphi) = N_0 \exp(-c\,\phi) - \beta\,\phi \tag{6}$$

Where N_0 is the donor concentration before irradiation, c is the donor removal coefficient, and β is the acceptor introduction rate. By increasing φ, N_{eff} decreases. The depletion width W can be expressed as the following (Andrea ., et al 2003), (McPherson, 2005):

$$W = \sqrt{\frac{2\varepsilon(|V| + V_{bi})}{qN_{eff}}} \tag{7}$$

Where q is the electronic charge, ε is the absolute silicon dielectric constant and $V_{bi} \approx 0.6$ Volt is the junction built-in potential. In order to analyze the response time of irradiated PIN photodiode, assume a modulated photon flux density as:

$$\varphi = \varphi_0 \exp(j\omega t)\ \ photons\ /(s.cm^2) \tag{8}$$

To fall on photodiode, where ω is the sinusoidal modulation frequency. The total current density through the depletion region generated by this photon flux can be shown to be (Sze, 2007):

$$J_{photo} = \left(\frac{j\omega\varepsilon(|V| + V_{bi})}{W} + q\varphi_0 \frac{1 - e^{-j\omega t_{dr}}}{j\omega t_{dr}}\right) e^{j\omega t} \tag{9}$$

$$\left|\frac{I_{photo}}{aq\varphi_0}\right| = \sqrt{\frac{Sin^2\left(\frac{\omega\, t_{dr}}{2}\right)}{\left(\frac{\omega\, t_{dr}}{2}\right)^2}\left(1 - \frac{\omega\varepsilon(|V| + V_{bi})}{W(\omega\, t_{dr})^2}\right) + \left(\frac{\omega\varepsilon(|V| + V_{bi})}{W}\right)^2} \tag{10}$$

Where a is the photodiode area, ε is the material permittivity 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:

$$t_{df} = \frac{\ell^2}{2D} \tag{11}$$

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 diffusion current arises from the regions within a diffusion length of the minority carriers next to the junction:

$$D = \frac{L_p^2}{\tau_r} \tag{12}$$

The irradiation induce diffusion length change can be expressed as the following (Abd El-Naser ., 2009):

$$L_p = \left(\frac{1}{\alpha}\right) \frac{1 - e^{\alpha W}\left(1 - \frac{I_{photo}}{aq\,\varphi_0}\right)}{e^{\alpha W}\left(1 - \frac{I_{photo}}{aq\,\varphi_0}\right)} \tag{13}$$

Where α is the absorption coefficient. The time constant t_{RC} of the photodiode with a load resistance R_L is given by:

$$t_{RC} = 2.2(R_S + R_L)C \tag{14}$$

Where C is the capacitance of photodiode, R_s is the series resistance of photodiode and it is given by:

$$R_S = \frac{\rho(W_0 - W)}{A} + contact\quad resistore \tag{15}$$

Where ρ is resistivety of the substrate. Finally, for fully depleted photodiodes the rise time t_r and fall time are generally the same.

$$t_r = \sqrt{t_{dr}^2 + t_{df}^2 + t_{RC}^2} \tag{16}$$

Radiation induced changes in dark current are important to quantify, because dark current changes are an important component of such figures of merit as signal to noise ratio and noise equivalent power (NEP). The total spectral noise current of an unilluminated APD is given by:

$$I_n = \sqrt{2q(I_{ds} + I_{db} M^2 F) B} \tag{17}$$

Where I_{ds} is the unmultiplied surface dark current, I_{db} is the gain-multiplied bulk dark current, M is the gain, F is the excess noise factor, and B is the noise bandwidth [1]. Total dark current (I_{Dark}) is related to the parameters in (2) by:

$$I_{Dark} = I_{ds} + MI_{db} \tag{18}$$

$$MI_{db} \approx I_{Dark}\ gamma - I_{Dark}\ protons \approx I_{Dark}\ neutrons \tag{19}$$

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. The gain is then calculated as the current amplification with respect to a reference bias, where no amplification is assumed:

$$M(\phi, V_r) = \frac{I_{Photo}(\phi, V_r) - I_{Dark}(\phi, V_r)}{I_{Photo}(0, V_r) - I_{Dark}(0, V_r)} \tag{20}$$

The gain as a function of bias voltage at different radiation fluence, it is usually described by the formula:

$$M(V) = \frac{1}{1 - \left(\frac{V}{V_b}\right)^n} \tag{21}$$

Where V_b is the breakdown voltage and n is a coefficient to be determined experimentally. Both V_b and n depend on the fluence.

$$\frac{1}{M}\frac{dM}{d\phi} = \frac{1}{M}\frac{\partial M}{\partial V_b}\frac{\partial V_b}{\partial \phi} + \frac{1}{M}\frac{\partial M}{\partial n}\frac{\partial n}{\partial \phi} = -M\left(\frac{V}{V_b}\right)^n \left[\frac{n}{V_b}\frac{\partial V_b}{\partial \phi} + Ln\left(\frac{V}{V_b}\right)\frac{\partial n}{\partial \phi}\right] \tag{22}$$

Table 1. Proposed operating parameters for our suggested APD device.

Operating parameter	Symbol	Value
Radiation dose or fluence	Φ	$3x10^{14}$ p/cm^2–$5x10^{15}$ p/cm^{-2}
Thermal activation energy	E	0.4 eV–1.0 eV
The amplifier noise figure	F_n	2 dB
n coefficient	n	1–2
Boltzman's constant	K_B	$1.38x10^{-23}$ J/K
Donor concentration before irradiation	N_0	10^{17} cm^{-3}–10^{20} cm^{-3}
Acceptor introduction rate	B	0.0205–0.0248 cm^{-1}
Donor removal coefficient	C	0.0008–0.002 cm^{-1}
Ambient temperature	T	280 K–340 K
Initial output power	P_0	0.1 mWatt–0.497 mWatt
The absorption coefficient	α	10^3 cm^{-1}–10^4 cm^{-1}
Initial multiplication gain	M	20-150
Depletion region voltage	V	1 Volt–10 Volt
Bias voltage	V_{bias}	50–400 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
Optical Signal wavelength	λ	0.65-1-1.3 μm
Quantum efficiency	η	75%–90%

In the present analysis, we assume the optical signal power to be intensity modulated at a sinusoidal modulation frequency ω such that yields:

$$P(t) = P_o(1 + m\ \exp(j\omega t)) \quad (23)$$

Where P_o is the average optical power signal density and m, the index of modulation. The frequency dependent multiplication gain has been computed from (Jamie ., et al 2006), (Jamie ., et al 2006):

$$M(\omega) = \frac{M}{\sqrt{1+\omega(Mt_{Rc}+t_{td})^2}} \quad (24)$$

Where t_r is the intrinsic response time and M, the multiplication gain. For the APD structure, 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 (Pilicer., et al 2005), (Jamie ., et al 2003):

$$F(M) = MK + \left[2 - \frac{1}{M}\right](1-K) \quad \text{(25-a)}$$

$$F(M) = M\left[1-(1-K)\left(\frac{M-1}{M}\right)^2\right] \quad \text{(25-b)}$$

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

$$F(M) = M^x \quad (26)$$

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

$$\eta = \frac{I_{photo}\ /\ q}{P_0(1-r)/h\nu} \quad (27)$$

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

$$S/N = \frac{0.5m^2 I_{photo}^2}{2qMFB(I_{photo}+I_{Dark}) + \dfrac{4K_B TBF_n}{R_L M^2}} \quad (28)$$

Where B ≈ $0.35/t_r$ is bandwidth and t_r is rise time. The term ($4K_BTBF_n/R_L$) 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:

$$M^3 q(I_{photo}+I_{Dark})R_L\left[1+\left(\frac{M^2-1}{M}\right)\left(K+\frac{\partial K}{\partial \phi}\frac{\partial \phi}{\partial M}-1\right)\right]-4kT=0 \quad (29)$$

Doing so for a sinusoidally modulated signal, with m=1 and F approximated by M^x, yields:

$$M^{x+2} = \frac{2qI_{Dark}+4K_BT/R_L}{xq(I_{photo}+I_{Dark})} \quad (30)$$

The noise equivalent power (NEP) of the APD which corresponds to the rms value of the incident optical power required to produce unity signal-to-noise ratio in a 1 Hz bandwidth has been computed from

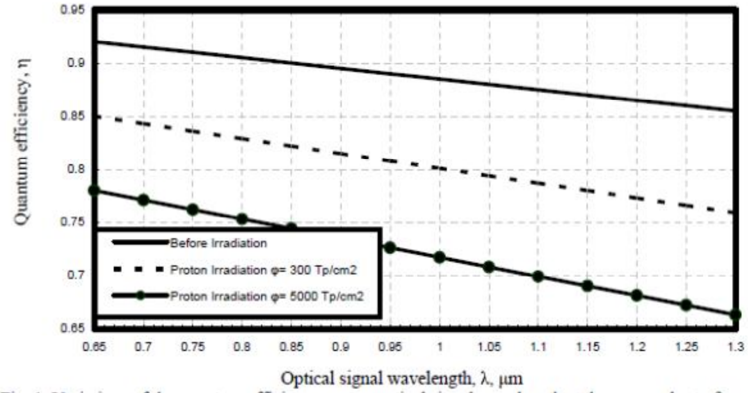


Fig. 1. Variations of the quantum efficiency versus optical signal wavelength at the assumed set of parameters.

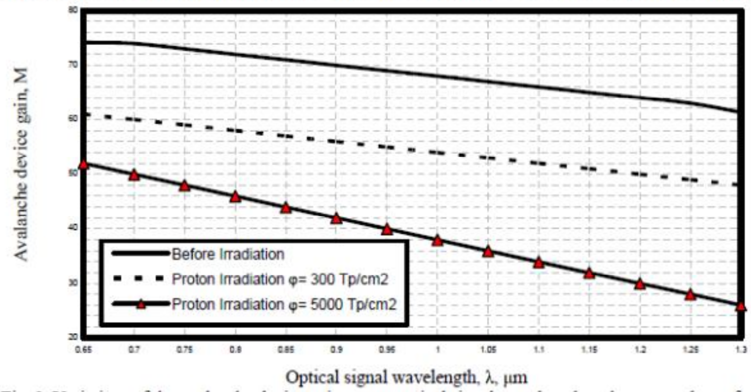


Fig. 2. Variations of the avalanche device gain versus optical signal wavelength at the assumed set of parameter

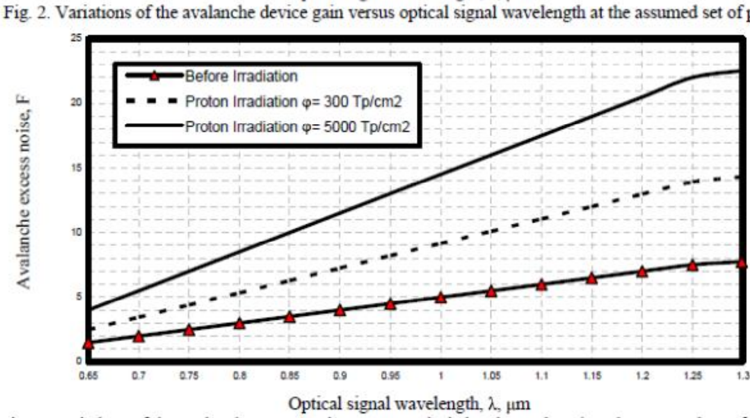


Fig. 3. Variations of the avalanche excess noise versus optical signal wavelength at the assumed set of parameter

$$NEP=\frac{\sqrt{2}h\nu}{\eta}\left[\frac{qR_L M^3(I_{Photo}+I_{Dark})\left(1-(1-K)\left(\frac{M-1}{M}\right)^2\right)+2KT}{q^2R_L M^4\left(1-(1-K)\left(\frac{M-1}{M}\right)\right)^2}\right]^{0.5} \qquad (31)$$

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

$$BER=\frac{1}{2}erfc\left[\frac{\left(\frac{q\eta\mu P_{opt}AM}{h\nu}\right)^2 R_L}{4\sqrt{2}\left(2qR_L M^3(I_{Photo}+I_{Dark})B\left(1-(1-K)\left(\frac{M-1}{M}\right)^2\right)+4KTB\right)}\right] \qquad (32)$$

SIMULATION RESULTS AND DISCUSSIONS

We have investigated deeply avalanche photodiodes as a media of optical detectors under thermal irradiated fields under the assumed set of the operating parameters listed in Table 1.

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

i) As shown in Figs. (1, 2) have assured that as both optical signal wavelength and proton irradiation

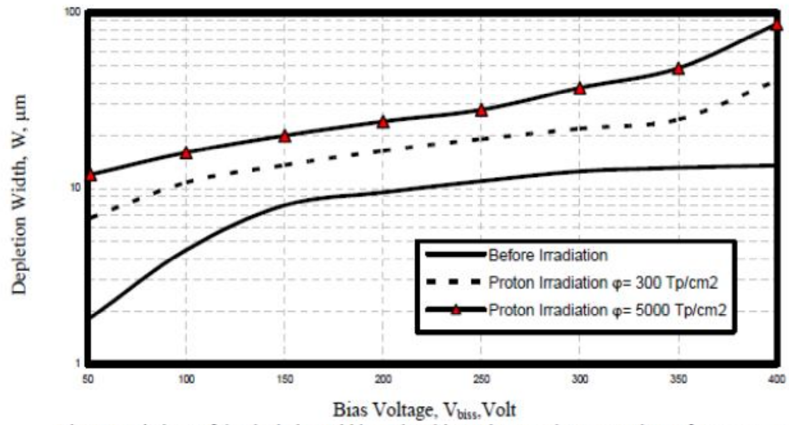


Fig. 4. Variations of the depletion width against bias voltage at the assumed set of parameters.

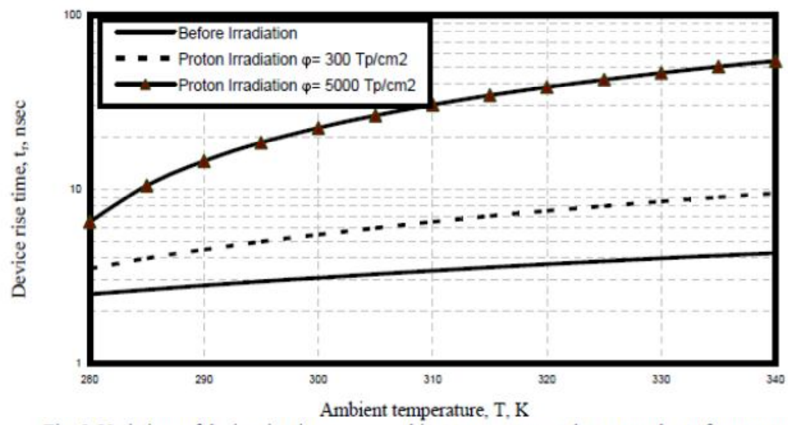


Fig. 5. Variations of device rise time versus ambient temperature at the assumed set of parameters.

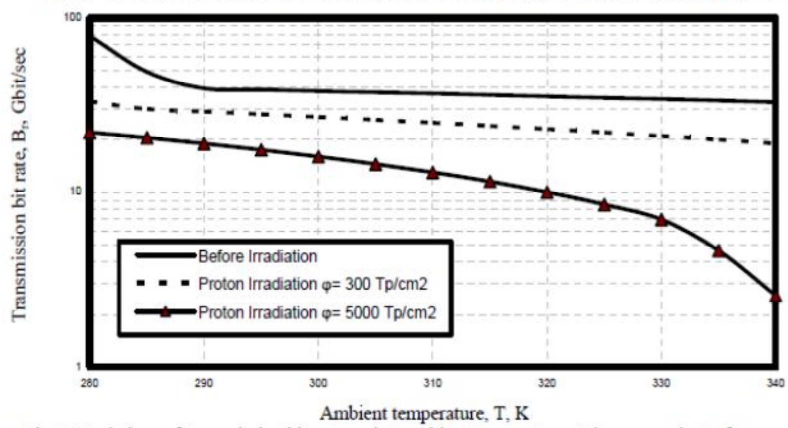


Fig. 6. Variations of transmission bit rate against ambient temperature at the assumed set of parameters.

fluences increase, this leads to decrease in both device gain and quantum efficiency.

ii) Fig. 3 has demonstrated that as both optical signal wavelength and proton irradiation fluences increase, this results in increasing of excess noise to the devic Fig. 4 has proved that as both bias voltage and proton irradiation fluences increase, this leads to increase in depletion width in the junction devices area.

iii) As shown in Fig. 5 has indicated that as both ambient temperature and proton irradiation fluences increase, this results in increasing of rise time of the device pulse.

iv) As shown in Figs. (6, 7) have indicated that as both ambient temperature and proton irradiation fluences increase, this results in decreasing of both signal to noise ratio and transmission bit rates.

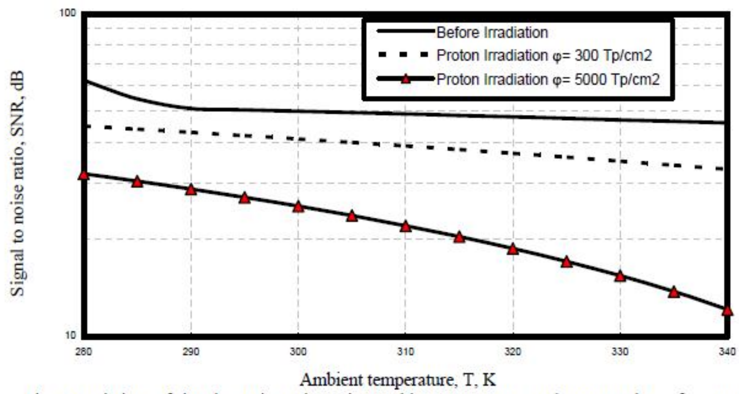


Fig. 7. Variations of signal to noise ratio against ambient temperature at the assumed set of parameters.

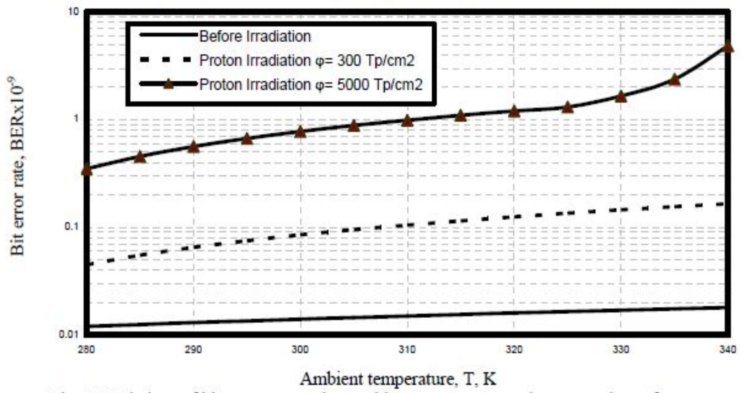


Fig. 8. Variations of bit error rate against ambient temperature at the assumed set of parameters.

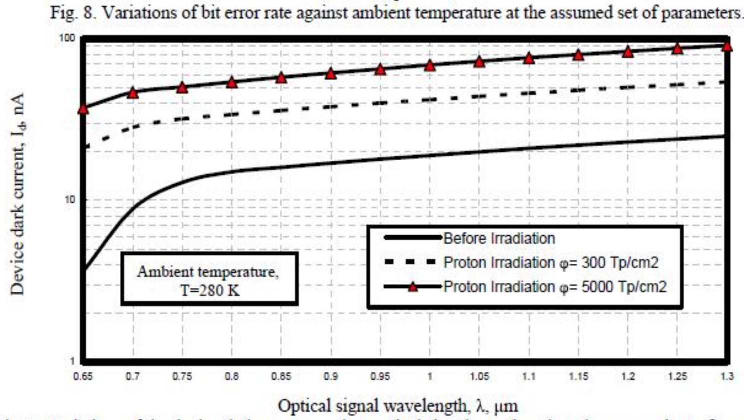


Fig. 9. Variations of the device dark current against optical signal wavelength at the assumed set of parameters.

v) As shown in Fig. 8 has proved that as both ambient temperature and proton irradiation fluences increase, this results in increasing of bit error rate at the receiving side.

vi) Figs. (9-11) have assured that as ambient temperature, optical signal wavelength, and proton irradiation fluences increase, this leads to increase of device dark current.

vii) As shown in Fig. 12 has demonstrated that as both ambient temperature, and proton irradiation fluences increase, this leads to increase of noise equivalent power of the avalanche photodiode device.

CONCLUSIONS

In a summary, We have been developed the transmission performance characteristics of avalanche photodiode devices under higher temperature effects and within proton irradiation fluences environments. It is theoretically found that the increased operating optical signal wavelength and proton irradiation fluences, this results in the increased excess noise and the decreased device quantum efficiency and device gain. As well as the increased ambient temperature and proton irradiation fluences, this leads to the decreased of both signal to

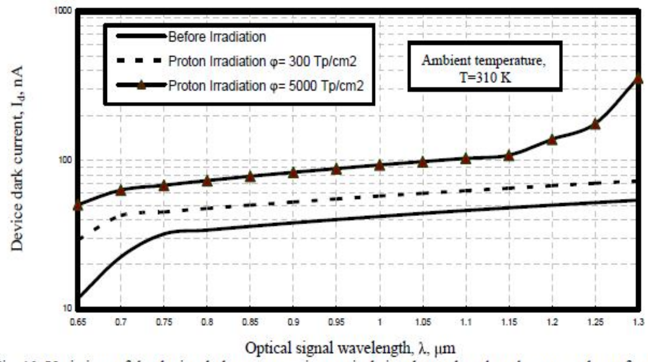


Fig. 10. Variations of the device dark current against optical signal wavelength at the assumed set of parameters.

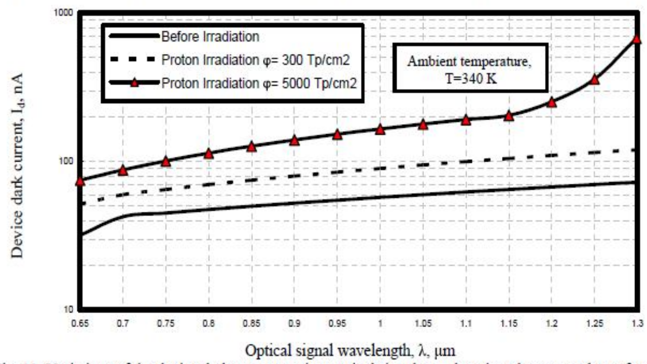
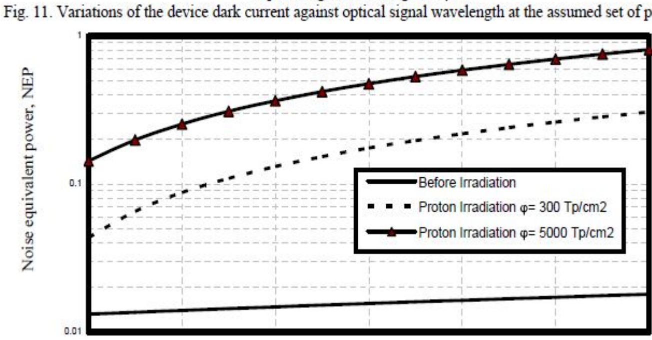


Fig. 11. Variations of the device dark current against optical signal wavelength at the assumed set of parameters.



noise ratio and transmission bit rates, and the increased of both bit error rate and pulse rise time. It is evident that the increased ambient temperature, operating optical signal wavelength, and proton irradiation fluences, this results in the increased of both dark current and noise equivalent power.

REFERENCES

A. Arbat, A. Comerma, J. Trenado, D. Gascon, A. Vila, L. Garrido and A. Dieguez, “Comparison between technologies for APDs fabrication in particle Detectors,” Proc. Eurosensors XXIV, pp. 677–680, 5-8 Sep. 2010.

Abd El-Naser A. Mohamed, Mohamed M, El-Halawany, Hazem M, El-Hageen (2009): “Electro-optical characteristics of PIN photodiode under high thermal irradiated fields,” J. Optoelectronics and Advanced Materials, 11(11): 1704–1712, Nov. 2009.

Andrea C, Dario B, Riccardo R, Alexander K, Jeff W, Alexei L, Gianfranco DB, Manuel L, Maurizio B, Carlos M, Miguel U, Nicola Z (2003), “Radiation Hardness of Silicon Detectors for High-Energy Physics Applications,” IEEE Transactions on Nuclear Science,50(4): 1121-1128, Aug. 2003.

Antunovic Z, Britvich I, Deiters K, Godinovic N, Ingram Q, Kuznetsov A, Musienko Y, Puljak I, Renker D, Reucroft S, Rusack R, Sakhelashvili T, Singovski A, Soric I, Sain J (2005). “Radiation hard avalanche photodiodes for the CMS detector,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Vol. 537: 379-382, 2005.

Baccaro S, Bateman JE, Cavallari F, Da Ponte V, Deiters K, Denes P, Diemoz M, Kirn T, Lintern AL, Longo E (1999). “Radiation damage effect on avalanche photodiodes,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 426: 206-211, 1999.

Becker HN (2004). “Dark Current Degradation of Near Infrared Avalanche Photodiodes from Proton Irradiation,” IEEE Transactions on Nuclear Science, 2004.

Becker HN, Miyahira TF, Johnston AH (2003). “The influence of structural characteristics on the response of silicon avalanche photodiodes to proton irradiation,” Nuclear Science, IEEE Transactions on, Vol. 50, pp. 1974-1981, 2003.

Cappelletti MA, C´edola1 AP, Peltzer EL. Blanc´a Y (2008) “Simulation of silicon PIN photodiodes for use in space-radiation environments," Semicond. Sci. Technol., 23(2): 7-13, 2008.

Cappelletti1 MA, Urcola1 U, Peltzer EL, Blanc Y (2006). "Radiation-damaged simulation PIN photodiodes," Semicond. Sci. Technol., 21: 346 351, 2006.

Chistokhin IB, Pchelyakov OP, Tishkovsky EG, Obodnikov VI, Maksimov VV, Ivanov AA, Pinzhenirrr EI. Gramsch E (2009). "Silicon Avalanche Diodes for Direct Detection of Nuclear Particles," 10 th International Conference and Seminar EDM 2009, SEC. V, pp. 359-362, Jul. 2009.

Christopher JS, Michael RS, William GL, Frank LA, James FChristian (2007). "CMOS-based avalanche photodiodes for direct particle detection," Nuclear Instruments and Methods in Physics Research A 579: 94–98, 2007.

Dai M, Buchinger E, Lee JKP, Dautet H (1996). "Time Resolved Annealing Studies of Single Neutron Irradiated Avalanche Photodiodes," IEEE Transactions on Nuclear Science, 43(6): 2595-2600, Dec. 1996.

Ercan P, Ilhan T (2007). "Signal fluctuation in neutron-irradiated silicon Avalanche Photodiodes," Nuclear Instruments and Methods in Physics Research A 573, pp. 291-293, 2007.

Gedam SG, Singh A, Banerjee PK, Mitra SS (1991) "Effects of Neutron Irradiation on Current Gain and Noise in Silicon Avalanche Photodiodes," IEEE Transactions on Nuclear Science, 38(5): 1013-1017, Oct. 1991

Geoffrey P. Summers, Edward A Burke, Philip Shapiro, Scott R. Messenger and Robert J. Walters, "Damage Correlation in semiconductors Exposed to Gamma, Electron and Proton Radiation," IEEE Trans. On Nuclear Science, Vol. 40, No. 6, pp. 1372-1379, Dec. 1993.

Grahl J, Kronquist I, Rusack R, Singovski A, Kuznetsov A, Musienko Y, Reucroft S, Swain J, Deiters K, Ingram Q, Renker D, Sakhelashvili T (2003). "Radiation hard avalanche photodiodes for CMS ECAL," Nuclear Instruments and Methods in Physics Research A 504, pp. 44–47, 2003.

Ikagawa T, Kataoka J, Yatsu Y, Saito T, Kuramoto Y, Kawai K, Kokubun M, Kamae T, Ishikawa Y, Kawabata N (2005). "Study of large area Hamamatsu avalanche photodiode in a g-ray scintillation detector," Nuclear Instruments and Methods in Physics Research A 538, pp. 640–650, 2005.

Ingram Q, Deiters K, Renker D, Sakhelashvili T, Kuznetsov A, Musienkoy Y, Swain J, Reucroft S, Kronqvist I, Rusack R, Singovski A, Vikas P, Antunovic Z, Godinovic N, Soric I (2010). "Avalanche Photodiodes for the CMS Electromagnetic Calorimeter," International Europhysics Conference on HEP, pp. 1-5, 2010.

Jamie S. Laird, Toshio H, Shinobu O, Hidenori O, Tomihiro K (2003). "Heavy-Ion Induced Single-Event Transients in High-Speed InP-InGaAs Avalanche Photodiodes," IEEE Transactions on Nuclear Science, 50(6): 2225-2232, Dec. 2003.

Jamie SL, Shinobu O, Toshio H, Heidi B, Allan J, Hisayoshi I (2006). "Effects of Gamma and Heavy Ion Damage on the Impulse Response and Pulsed Gain of a Low Breakdown Voltage Si Avalanche Photodiode," IEEE Transactions on Nuclear Science, 53(6): 3786-3793

Jamie SL, Shinobu O, Toshio H, Heidi B, Allan J, Hisayoshi I (2006). "Effects of Displacement Damage on the Time-Resolved Gain and Bandwidth of a Low Breakdown Voltage Si Avalanche Photodiode," IEEE Transaction on Nuclear Science and Space Radiation Effects Conference, (NSREC), pp. 1-9, 17-21 July, 2006.

Kwang HK, Young SK, Jung SK (2008). "Signal and noise performance of large-area PIN photodiodes and charge-sensitive preamplifiers for gamma radiography," Nuclear Instruments and Methods in Physics Research A 591, pp. 63–66, 2008.

Laird JS, Hirao T, Onoda S, Yamakawa T, Wakasa T, Abe H, Ohyama H, Kamiya T (2005). "Non-linear charge collection mechanisms in high-speed communication avalanche photodiodes," Nucl. Instrum. Meth. Phys. Res. A, Vol. 541: 228–235, 2005.

Lindstrom G, Fretwurst E, Honniger F, Kramberger G, Moller-Ivens M, Pintilie I, Schramm A (2006). "Radiation tolerance of epitaxial silicon detectors at very large proton fluences," Nuclear Instruments and Methods in Physics Research A 556, pp. 451–458, 2006.

McPherson M (2005). "Infrared photoconduction in radiationdamaged silicon diodes," J. Opt. A: Pure Appl. Opt. 7, pp. S325 S330, 2005.

Moszynski M, Kapusta M, Zalipska J, Balcerzyk M, Wolski D, Szawlowski M, Klamra W (1999). "Low Energy y-rays Scintillation Detection with Large Area Avalanche Photodiodes," IEEE Transactions on Nuclear Science, 46(4): 880-885, Aug. 1999.

Ogasawara S, Livi E, Grotheer, McComas DJ (2010). "Thin dead-layer avalanche photodiodes enable low-energy ion Measurements," Nucl. Inst. and Meth A, 614, pp. 271-277, 2010.

Osborne MD, Hobson PR, Watts JS (2000). "Numerical simulation of neutron radiation effects in avalanche photodiodes," IEEE Transactions on Electron Devices, Vol. 47: 529-536, 2000.

Pilicer E, Kocak F, Tapan I (2005). "Excess noise factor of neutron-irradiated silicon avalanche photodiodes," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 552: 146-151, 2005.

Pulvirenti A, Riggi F, Vernet R, Awes TC, Muller H, Tupikin N, Badala A, Blanco F, LaRocca P, Librizzi F, Pappalardo GS (2008)."Characterization of avalanche photodiodes (APDs) for the electromagnetic calorimeter in the ALICE experiment," Nuclear Instruments and Methods in Physics Research A 596, pp. 122-125, 2008.

Ruzin A, Casse G, Glaser M, Zanet A, Lemeilleur F, Watts S (1999). "Comparison of Radiation Damage in Silicon Induced by Proton and Neutron Irradiation," IEEE Transactions on Nuclear Science, Vol. 46(5): 1310-1313, Oct. 1999.

Shinobu Onoda, Toshio Hirao, Hisayoshi Itoh and Tsuyoshi Okamoto (2006). "Evaluation of Transient Current in Si PIN photodiode Induced by High-Energy Charged Particles," Proc. Sch. Eng. Sch. Inf. Sci. Tokai Univ. 31, pp. 1-4, 2006.

Squillante MR, Farrell R, Lund JC, Sinclair F, Entine G, Keller KR (1986). "Avalanche Diode Low Energy X-Ray and Nuclear Particle Detector," IEEE Transactions on Nuclear Science, 33(1): 336-339, Feb. 1986.

Srour JR, Fellow, Lo DH (2000). "Universal Damage Factor for Radiation-Induced Dark Current in Silicon Devices," IEEE Transaction on Nuclear Science, 47(6): 2451- 2459, Dec. 2000

Swanson EA, Arnau ER, Walther FG (1987). "Measurements of natural radiation effects in a low noise avalanche photodiode," IEEE Trans. Nucl. Sci., Vol. NS-34, pp. 1658–1661, Dec. 1987.

Sze SM (2007). Physics of Semiconductor Devices, John Wiley and Sons, 3rd Ed, USA, 2007.

Xiaoli S, Henri D (2001). "Proton Radiation Damage of Si APD Single Photon Counters," Radiation Effects Data Workshop

pp. 146–150, 2001.
Xiaoli S, Member, IEEE, Daniel R, Henri D, James B, Abshire, Senior Member, “Measurement of Proton Radiation Damage to Si Avalanche Photodiodes,” IEEE Transactions on Electron Devices, Vol. 44(12): 2160-2166, Dec. 1997