Low noise optical receiver using Si APD

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ABSTRACT

Time of flight laser range finding, scanning video imaging and deep space communications are three applications requiring very low noise optical receivers in order to achieve detection of fast and weak optical signal. Avalanche photodiode is the detector of choice for its high quantum efficiency, compact size and reduced electronics complexity. Optimal operating condition in terms of gain and temperature is the key to maximize the signal to noise ratio.

This paper describes the model and the measured performance of a hybrid optical receiver using a TE cooled Silicon Avalanche Photodiode. Receiver performance in terms of responsivity and NEP will be presented as a function of temperature, signal power and APD Gain. A NEP of only 5fW/sqrt(Hz) has been obtained with a bandwidth of 200MHz in linear mode at a wavelength of 1060nm.

Keywords: Photodiode, Avalanche Photodiode, Signal to noise ratio, Noise equivalent power, Optical receiver, transimpedance amplifier, Silicon APD

1. INTRODUCTION

Silicon Avalanche photodiodes (Si APD) are the preferred optical detectors for applications where the wavelength lies between 400nm and 1100nm and where high speed and low optical power detection is required. The avalanche multiplication of the photo-generated carriers is responsible for the signal-to-noise ratio improvement when compared to a simple PN or PIN detector. BER or probability of detection in communication systems [1], maximum range and range resolution for Laser range finder or NEP in scanning video imager [2] can be improved by using APD.

APD gain is the parameter that one has to choose in order to maximize system performance. The gain maximizing signal-to-ratio (SNR) or noise equivalent power (NEP) depends on system parameters; mainly background and signal optical power, operating temperature and operating wavelength and on the optical receiver itself; i.e. the transimpedance amplifier and APD characteristics.

This paper will present measurements of the characteristics of an APD and a transimpedance amplifier which will be used to build a model of the optical receiver. Measurement methods presented here are simple but accurate enough to highlight key characteristics. SNR and NEP will be simulated in typical operating conditions. Special care will be held to temperature which has strong impact on semiconductor devices.

A LLAM-1060-R8BH [7] from Excelitas will be used to demonstrate the validity of the model of the optical receiver. The LLAM module uses a long wavelength enhanced APD (C30954 from Excelitas [8]) mounted on a thermo electric cooler (TEC) allowing a precise control of the temperature of the APD. The C30954 is suitable for detection of visible light as well as NIR (up to 1100nm) which is ideal to highlight general APD characteristics.

We will first look at the characteristics of the APD in terms of gain-voltage relationship, spectral response and noise. Model of these parameters in temperature will be explained. Next, the transimpedance amplifier frequency response and noise will be model. Finally, simulations will be used to highlight optimal operating point of the APD in typical operating conditions.
2. SILICON APD

The gain obtained by avalanche multiplication of the carriers is unique to APDs. This gain mechanism helps improve SNR in many applications but it comes at the price of increased complexity of operation when compared to a simple PN or PIN detector. The structure of the APD includes an absorption region similar to a PIN detector but a thin section of the structure allows multiplication of the carriers.

There are different APD structures commercially available. The structure of the C30954 is a rear entry reach-through which offers the best available combination of high speed, low noise and capacitance, and extended IR response. Figure 1 shows the structure.

![Rear entry "reach-through" structure](image)

Fig. 1. Rear entry "reach-through" structure. Photons are absorbed in the absorption region. Electrons will drift to the gain region where the electric field is such that impact ionization occurs.

The photons pass through the thin front contact (p⁺ region) to be mainly absorbed in the absorption region (π) where electron-hole pairs are generated. Electrons drift in direction of the cathode going through the multiplication region where the electric field is high enough to allow impact ionization. Holes go in the opposite direction and are collected at the anode (p⁻ side). As such, mostly electrons will be injected in the multiplication region. Maximizing the ratio of electrons to holes injected in the multiplying region reduces the noise generated in the APD due to the higher ionization coefficient of electron [3].

The gain is defined as the average multiplication for all carriers generated in the diode. It is function of the electric field and ionization rates of electrons and hole. Above “reach-through” the electric field is proportional to the bias voltage applied to the APD. Gain is possible for bias voltage above “reach-through” voltage; i.e. when the junction is fully depleted. The ionization rates mainly vary with electric field and temperature [5].

This short introduction to the “reach-through” structure highlighted three parameters having an impact on the characteristics of the APD: ratio of electron to hole injected in the multiplication region, dependence of the gain on the electric field, and dependence of the gain with the temperature. We will show how this translated on the APD characteristics.

2.1 Gain and bias voltage

The gain will be defined here as the ratio of the current measured a given bias voltage to the current measured at 50V. The 50V is somehow arbitrary. It must be low enough to avoid multiplication, which means it must be below reachthrough voltage but high enough to have a small electric field sweeping out the carriers from the APD. Light is applied in the center of the active area with a beam radius of approximately 1/3 of the active area. Light outside of the active should be avoided for accurate measurement. The dark current present when no signal impinges the APD must be subtracted from the measurement for proper gain calculation.

Applying a known amount of light (in the order of 0.1nW - 1nW) is used to measure the unity gain responsivity defined as the current per watt of optical signal at 50V. We will use this definition throughout this paper.

Figure 2 shows the C30954 gain as a function of the bias voltage for different temperature.
The gain is equal to 1 until “reach-through” at about 100V. Above that voltage the junction is fully depleted and multiplication of the carriers occurs. The gain increases as the bias voltage is raised and eventually reaches infinity at the breakdown voltage.

The gain voltage curve can be accurately modeled by equation 1 for bias voltage above reach-through and is showed by the dotted lines in figure 2.

\[
M = \frac{K}{(V_{bd} - V_{op})^n}
\]

(1)

The breakdown voltage at 25 ºC (Vbd@25ºC) best fit value is 436V and the model parameters, for 900nm, are K = 14000 and n=1.19. Note that breakdown voltage is unique to each APD while K and n are typical to the structure. An interesting feature of the gain is that it can be maintain constant by keeping a constant voltage difference between the breakdown voltages and the operating voltage which gives an easy way of setting the gain if the breakdown voltage is known. In this case, gain is 100 at 61V below breakdown voltage.

The breakdown voltage varies with temperature because of the dependence of holes and electrons ionization rates with temperature [5]. The breakdown voltage variation with temperature is approximately linear which allows one to define a breakdown voltage temperature coefficient (\(\Delta V_{bd}\)). In this case, \(\Delta V_{bd}\) is 2.7V/ºC. This coefficient may vary from one APD to the other.

Figure 2 also shows the measured gain curves at 1060nm. The gain is smaller for the same bias voltage at 1060nm compared to 900nm. This is due to the absorption of long wavelength occurring across the full thickness of the APD. Photons absorbed below the multiplication region will inject holes which have a lower gain than electrons. The gain mainly come from electrons multiplication but also holes. Shorter wavelengths are absorbed in the absorption region so the gain is due to electrons only. The gain curve model of equation 1 is still valid at 1060nm but K must be changed to 11000 to get a good fit.

2.2 Spectral response

An important characteristic of a system is the operating wavelength. The choice of the most appropriate APD for the application starts by choosing the APD which will give the highest unity gain responsivity (or, stated differently, highest quantum efficiency defined as the number of electron-hole pairs per photon) at the operating wavelength.
The spectral response of a Si APD will depend on its structure like thickness of the absorption region, anti-reflection coating on the entry side of the light and effective thickness of the front contact. The main factor impacting spectral response is the thickness of the APD plus the absorption coefficient of Silicon. Absorption coefficient ($\alpha$) is a strong function of wavelength [4] for Silicon ($1/\alpha=1.66\mu$m@600nm, 23$\mu$m@900nm and 633$\mu$m@1064nm). Thick devices are preferred for long wavelength since it maximizes the number of photons absorbed and thin front contact at preferred for short wavelength. Silicon absorption coefficient varies with temperature as well which means the quantum efficiency will also vary with temperature. Figure 3 shows the measured spectral response of the C30954 APD which is optimized to detect long wavelength.

![Fig. 3. Spectral response curves. Unity gain responsivity for long wavelength varies significantly with temperature due to the strong dependence of the absorption coefficient with temperature.](image)

Responsivity for wavelength between 600nm and 1000nm stays fairly constant with temperature in the case of the C30954 APD. A small improvement of the responsivity at low temperature is generally expected for this structure due to the lower absorption coefficient of Silicon at low temperature allowing photons to go through the front contact with less absorption [5]. However, the measures showed here do not concur. It might be due to the limited accuracy of the test setup used to get these curves.

Variation of responsivity for wavelength above 1$\mu$m is easily observed. Figure 4 shows measured responsivity at 1060nm at different temperature.
Fig. 4. Unity Gain responsivity at 1060nm from -20°C to +90°C for the C30954 APD. Unity gain responsivity temperature coefficient is 0.002A/W/°C.

The linear fit on figure 4 is in reasonable agreement with the measures leading to a unity gain responsivity temperature coefficient of 0.002A/W/°C at 1060nm.

2.3 Noise

Si APD noise current \(i_{\text{APD}}\) is well modeled with the McIntyre equation [3] given by equation 3.

\[
i_{\text{APD}} = \sqrt{2q(I_{\text{DS}} + (I_{\text{DB}} + I_{\text{pd}})M^2F)}
\]

\[
F = k_{\text{eff}}M + (1 - k_{\text{eff}})^2 - \frac{1}{M}
\]

Where \(I_{\text{DS}}\) is the surface dark current, \(I_{\text{DB}}\) is the bulk dark current, \(I_{\text{pd}}\) is the photo current at gain of 1, \(k_{\text{eff}}\) is the effective ionization ratio, \(F\) is the excess noise factor, \(M\) is the gain and \(q\) is the electronic charge.

The noise current is the sum of the shot noise from the bulk dark current \((2qI_{\text{DS}}\) in equation 3) plus the noise generated by the avalanche multiplication \((2qIM^2F)\). The excess noise factor is function of the gain and the effective ionization ratio.

The effective ionization ratio cannot be measured directly but by injecting a known amount of light and measuring the noise current one can use equations 3 and 4 to extract \(k_{\text{eff}}\). The signal current must be much higher than the bulk dark current. Figure 5 shows the measurement made at 900nm and 1047nm.

The effective ionization ratio is around 0.017 at 900nm which is a typical value for rear entry reach-through structure. A model using \(k_{\text{eff}}=0.022\) and 0.012 is showed to highlight the precision of the fit. \(k_{\text{eff}}\) measured at 1047nm is around 0.027 due to the absorption of photons not only in the absorption region of the APD but also in and after the multiplication region. Photons absorbed in these regions will inject holes in the multiplication region which translates in higher noise.

The ionization coefficient calculated at 3 different temperatures at 1060nm is showed in figure 6. \(k_{\text{eff}}\) of 0.030 was used to fit the data. The photocurrent at gain of 1 was 0.4nA at 70degC, 0.4nA at 40degC and 0.3nA at 25degC. The results show that at 1060nm the effective ionization coefficient can be considered constant from 25degC to 70degC.
Fig. 5. Effective ionization ratio fit. A fit of the McIntyre model is used to extract $k_{\text{eff}}$ by measuring the illuminated noise current. $k_{\text{eff}}$ is higher for long wavelength due to the injection of holes and electrons in the multiplication region. $k_{\text{eff}} = 0.017$ at 900nm and 0.027 at 1047nm.

Fig. 6. Illuminated current noise measured as a function of gain at 25 ºC, 40 ºC and 70 ºC. The model used a $k_{\text{eff}}$ of 0.03 at all temperatures and a unity gain photocurrent of 0.44nA at 70degC, 0.44nA at 40degC and 0.31nA at 25degC. $k_{\text{eff}}$ can be considered constant inside this temperature range at 1060nm.

The surface dark current is not multiplied in the multiplication region so its impact is often negligible compared the bulk dark current. However, the surface dark current varies in temperature as showed in figure 7. The variation of surface dark current with temperature follows the Arrhenius equation with activation energy ($E_a$) of 0.7eV (equation 4). The impact of surface dark current at high temperature must be taken into account.

$$I(t) = I_0 e^\frac{-E_a}{kT_{\text{ref}}} \left(\frac{1}{T_{\text{ref}}} - \frac{1}{T}\right)$$

(4)

Dark current, measured at a gain around 100, is showed in the figure 7 with the fit of equation 4. The surface dark current at 25°C is 50nA.
The bulk dark current is the most difficult parameter to measure for this APD. In fact, the value of the bulk dark is low and it cannot be measured directly. Again, we will use the McIntyre model in absence of light and measure the noise as a function of the gain. A fit of the McIntyre model by adjusting the bulk dark current is the easiest method and it is presented in figure 8.

The bulk dark current will vary in temperature following the Arrhenius equation with activation energy equal to half the bandgap of Si, i.e. around 0.55eV [5].

Modeling the APD with the voltage-gain curve, the unity gain responsivity and the noise is sufficient to simulate the APD in most operating conditions. The model developed here is only valid for bias voltage above reach-through which is typically where it is used. Other characteristics like capacitance, saturation, rise and fall time and gain uniformity are not included in the model presented here and they are considered constant here.

The APD is generally connected to a transimpedance amplifier to form an optical receiver; the front end of an optical system. The optical receiver defines the signal-to-noise ratio of the system assuming the rest of the electronic is well designed. As such, transimpedance amplifier must also be modeled in order to predict front end performance.
3. TRANSIMPEDEANCE AMPLIFIER

The transimpedance amplifier must be designed by taking into account the APD capacitance. In fact, as opposed to voltage amplifier which can often be considered independent from the device connected to it, transimpedance amplifier will see their characteristics changing with the detector connected to it.

The typical model of the transimpedance amplifier is showed in figure 9.

![Fig. 9. Optical receiver. The photodiode is modeled by a current source, $I_{pd}$. Equivalent input capacitance is the sum of the photodiode and the amplifier capacitance. The feedback resistance, $R_f$, sets the transimpedance value at low frequency. The voltage amplifier gain is $-A_v$.](image)

The frequency response of the optical receiver showed in figure 9 is easily found to be:

$$V_o = -\frac{R_f}{1 + j\omega R_f C} \frac{I_{pd}}{A_v}$$  \hspace{1cm} (5)

The bandwidth of the receiver can be calculated from equation 5:

$$f_c = \frac{1}{2\pi \frac{R_f}{A_v C}}$$  \hspace{1cm} (6)

Equation 5 highlights the important point of the receiver. To get high bandwidth, low feedback resistance and capacitance is required as well as high voltage gain. Getting high voltage gain at high frequency is rather difficult so high frequency receivers tend to have low feedback resistance.

The voltage gain is considered as constant over frequency which is not usually the case. A $1^{st}$ order system could be used to represent the voltage gain more accurately leading to a $2^{nd}$ order system instead of a $1^{st}$ order system as given by equation 5.

The noise model of the optical receiver is showed in the next figure.

![Fig. 10. Optical receiver noise model. The 4 noise sources are APD, thermal noise from feedback resistance, equivalent noise current and noise voltage from the amplifier.](image)

Total input equivalent current noise is the sum of the thermal noise from the feedback resistor, shot noise from any leakage current at the input of the amplifier, APD noise plus the equivalent noise current from the voltage noise of the amplifier.
\[ i_{\text{receiver}}^2 = i_{\text{APD}}^2 + 2q_i \frac{V_o C}{\text{AMP}} + \frac{4kT}{R_f} \text{Hz} \]

APD noise, shot noise from input leakage current and thermal noise from the feedback resistance are all constant with frequency. The voltage noise from the amplifier generates a current noise increasing with frequency. Voltage noise is typically dominant at high frequency.

The average noise of the receiver within a given bandwidth is obtained by integrating equation 7 over the bandwidth of the system and dividing by the bandwidth.

The frequency response and noise voltage at the output of the LLAMD-1060-R8BH was measured at different temperature to validate the model.

3.1 Measured performance

Figure 11 shows measured frequency response and noise voltage at the output of the LLAM-1060-R8BH. The frequency response is measured by applying light on the APD in order to generate a noise at least 10 times the noise of the receiver in the dark. The output voltage noise represents the frequency response of the receiver since the APD noise is considered white across the bandwidth of the receiver.

The units in the middle figures are in nV/\sqrt{Hz}. Note that the output impedance of the transimpedance amplifier is around 50ohm and the input impedance of the spectral analyzer is also 50ohm. Input noise current is calculated by multiplying the measured noise voltage by 2 divided by the transimpedance value at the frequency. Transimpedance is 12kohm for low frequencies. Model parameters are: \( V_n = 0.52nV/\sqrt{Hz} \), \( i_{\text{AMP}} = 0A \) at 25ºC and -40 ºC but 2µA at +70ºC to take into account the APD dark current.

Fig. 11. LLAM-1060-R8BH frequency response and noise measured at -40ºC, +23ºC and +70ºC. The first column is the measured frequency response, the middle column is the noise voltage at the output of the receiver and the right hand
The bandwidth changes a bit at 70°C indicating a variation of some transistors characteristics. However, the noise model is acceptable at all temperature. The noise current can be integrated over the bandwidth of the receiver to get an average input noise current. In this case, the average noise current is about 1.9 pA/√Hz. Because of the voltage noise, systems with lower bandwidth will have lower average noise current. For example, if we integrate over 180 MHz, we get 1.7 pA/√Hz.

The model will vary from one unit to the other because of the active components used in the transimpedance amplifier. In fact, discrete components have in general large tolerances on their characteristics which cause variation in the noise model of the transimpedance amplifier.

4. SIMULATION

Based on the model developed in the previous pages we will now look at simple examples to highlight how the gain and temperature of the APD can be used to optimize the SNR and NEP.

The noise equivalent power (NEP) is defined as the equivalent optical power generating a signal equal to the noise. It is simply the equivalent input noise current of the optical receiver divided by the responsivity of the APD (M time Resposivity @ M=1) or by the output noise voltage of the receiver divided by the receiver responsivity (in V/W). The NEP is a useful specification since in application like time of flight laser range finder or communication, this condition occurs while waiting for the return pulse or, in digital modulation, while the received bit is a 0. The NEP sets the lowest threshold possible to decide whether an optical pulse is detected or not [9].

Figure 12 shows the measured NEP at 1060nm of a LLAMD1060DR8BH. The TEC was used to change the temperature of the APD. The bandwidth is 185 MHz and the average noise current was 1.7 pA/√ (Hz). The APD was modeled using our model developed previously.

![NEP as a function of the gain for the LLAM-1060-R8BH measured at 1060nm. A NEP of 5fW/√Hz is measured at gain of ~1200 at 23°C. The total noise equivalent noise power is ~68pW for 185MHz bandwidth. APD bulk dark current is around 1fA.](image)

The model calculations correlate reasonably will with measured values. Note that the APD bulk dark current was extremely low on this particular APD: even at gain of 2000 at room temperature the noise from the APD is still lower than the noise of the amplifier which means that it is in the range of 1fA. This is not usually the case.

Figure 13 shows the simulated NEP of the LLAM-1060-R8BH previously characterized but using a bulk dark current of 0.8pA.

![Simulated NEP of the LLAM-1060-R8BH using a bulk dark current of 0.8pA.](image)
Figure 13 shows that at low gain heating up the APD improves NEP but at high gain, it is no longer the case. The bulk dark current increases following an exponential law with temperature whereas the responsivity varies linearly. Minimum NEP occurs at higher gain for low temperature operation.

The last simulation presented will be SNR. It is calculated using equation 8.

\[
\text{SNR} = \frac{M \cdot R \cdot P}{\sqrt{I_{\text{receiver}}^2 \cdot B_w}}
\]

Where \( R_0 \) is the unity gain responsivity, \( P_{\text{opt}} \) is the optical power, \( I_{\text{receiver}} \) is calculated using equation 4 and \( B_w \) is the bandwidth of the receiver. Figure 14 shows the SNR for a signal power of 1nW (left) and 10pW (right) at 0°C, 40°C and 70°C. A bulk dark current of 0.8pA was used to show its impact.

Increasing the temperature of the APD helps improving the SNR when the bulk dark current is negligible in front of the primary photocurrent. However, under low light level condition, bulk dark current will also play an important role in determining SNR as clearly showed on the right end side of figure 14.
5. CONCLUSION

The measured performance and the model of an optical receiver have been presented. The model includes the gain-voltage characteristics, the spectral response curve and the noise of the APD. The noise model of the APD fits well with the McIntyre theory under illuminated condition. The transimpedance amplifier noise model includes the shot noise from leakage current, thermal noise from feedback resistance and a voltage noise source. Low frequency noise is dominated by the thermal noise whereas high frequency noise comes from the voltage noise. Special attention was taken on the temperature behavior of these characteristics.

The model was used to predict variation of NEP and SNR as a function of the APD gain and temperature. NEP and SNR both depend on amplifier noise, optical power, temperature and bulk dark current of the APD. There is not a single optimum gain or temperature that will maximize the SNR of NEP at all time thus the model developed here can be used to find this point knowing system parameters.

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