Linear-mode characters of near-infrared wavelength InGaAs APDs for optical communication

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ABSTRACT
Recent developments in three-dimension imaging, quantum cryptography, and time-resolved spectroscopy have stimulated interest in Linear-Mode and Geiger-Mode detecting avalanche photodiodes operating in the short wavelength. A linear-mode detector based on an InGaAs avalanche photodiode (APD) has been investigated for use at near infrared communication wavelengths. In the experiments of this paper, sine gate signals coupled with DC biased voltage were applied to two APDs with the same semiconductor material and structure for detecting the pulse light signal. As the avalanche signals were mixed with sine wave background, a transformer-based method was applied to eliminate the background noise and improve the detection sensitivity of light induced signal. In order to test the maximum detection sensitivity, the sine pulse was delayed by a delay module before being applied to laser source, thus the pulse light signal and the sine pulse coupled to the detector were synchronized. From the performance tests, the frequency response from 10MHz to 100MHz is tested and the suitable range of biased voltage was acquired. Detection sensitivity and photoelectric gain were investigated in detail at 1.55um infrared wavelengths. In a word, the linear-mode APD working in gate-mode and mutual-differencing method can be widely used in optical communication such as Non-line-of-sight communication, free space communication, fiber communication, deep space communication, and satellite optical network communication.

Key words: InGaAs APD, linear-mode, gate-mode, infrared wavelengths, optical communication

1. Introduction
Avalanche diodes (APDs) are frequently researched and developed over the past two decades. As the key components, they are widely used in satellite laser ranging, fiber communication, deep-space laser communication\cite{1}, ultra-low light imaging\cite{2, 3}. In some applications such as quantum cryptography, quantum key distribution (QKD)\cite{4}, time-resolved photo counting\cite{2}, even a single photon should be detected. In APDs, a macro current signal is triggered by the weak optical signal due to the internal avalanche mechanism. When an APD is biased above breakdown voltage, it is able to detect a single photon, so it is called single photon avalanche diodes (SPADs). A SPAD behaves similar to a flip-flop, and a self-sustained avalanche phenomenon happens. With an infinite photoelectric gain, a SPAD can’t identify the number of the photons that inject to it at a time, thus it works at a counting mode, which is called Geiger-mode\cite{5}. While an APD is biased slightly below breakdown voltage, it acts as an amplifier that transfers a photon signal to a current signal linearly. Such a mode is called linear-mode\cite{6}. Before it is biased, APDs should be optimized in the aspect of semiconductor material and structures.

In the recent years, with the great development of near-infrared wavelength detection, an alloy of III-V compounds such as InAs, GaAs, InP, GaP are utilized to design APDs\cite{1, 7}. The electrical and optical properties of a semiconductor depend on its energy bandgap and whether the bandgap is "direct" or "indirect". A single photon must have enough...
energy to trigger an electron-hold pair, which is related to the energy badgap. The bandgap of the four kinds of III-V semiconductors is 0.33eV, 1.43eV, 1.29eV and 2.25eV, and the corresponding cutoff wavelength is 3.75um, 0.87um, 0.96um and 0.55um respectively. By mixing two or more of the binary compounds, the properties of the resulting ternary and quaternary semiconductors can be tuned to intermediate values. InGaAs is one kind of mixed III-V compounds, and it’s generally described as In$_x$Ga$_{1-x}$As, in which $x$ is the proportion of InAs. Besides, the substrate of a semiconductor material is very important because the lattice must be mutually matched to avoid mechanical stress, which would severely degrade the properties of the material. For lots of reasons, the most convenient substrate for In$_x$Ga$_{1-x}$As is InP. High quality InP substrates are available with diameters as large as 100 mm. In$_x$Ga$_{1-x}$As with 53% InAs is often called "standard InGaAs" without bothering to note the values of "$x$" or "$1-x$" because it has the same lattice constant as InP and therefore the combination leads to very high quality thin films$^8$. Such a standard InGaAs is called InGaAs/InP. It has a long cutoff wavelength of 1.68um, and it is the optimum wavelength band for detecting the optical communication wavelength such as 1.33um, 1.55um.

By now, the APDs for the near-infrared wavelength detection are all based on InGaAs/InP, due to its high quantum efficiency and low dark noise. In these APDs, a structure called separate absorption and multiplication(SAM) is applied$^9$, as Figure 1 shows. The goal of this structure is to provide sufficiently high electric field in the InP multiplier to achieve avalanche gain by impact ionization while maintaining sufficiently low electric field in the InGaAs absorber so that tunneling effects are suppressed in this layer. The use of a charge – or field control – layer between the absorber and multiplier regions of the structure provides flexibility in controlling the internal electric field profile of the device$^9$. Additional InGaAsP grading layers are often employed to minimize hole trapping effects that arise from the valence band discontinuity that exists at abrupt InGaAs/InP heterointerfaces. However, the specific structure of APDs varies with working mode. A Geiger-mode APD has an optical active area of fiber-coupled 25um, a thinner absorption layer to weaken dark noise caused by tunneling effects, and a thicker multiplication layer, more than 1um generally, so that the avalanche probability and photoelectric gain is adequacy to detect a single photo$^9$. While the linear-mode APDs has a lager optical area of 200um, a thinner absorption layer and a thinner multiplication layer less than 0.5um, in order to achieve a high gain-bandwidth product. The design rule of high gain-bandwidth product keeps the trace of optical

![Figure 1 Separate absorption and multiplication(SAM) structure of InGaAs/InP APD](http://spiedigitallibrary.org/)

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communication. The transmission rate of today’s optical communication system is up to GHz, so an efficient receiver with high response speed is demanded. Thus from this perspective, the linear-mode APDs achieve a wide bandwidth in the cost of lower photoelectric gain. Nevertheless, the optical communication in the harsh environment or long distance, such as non-line-of-sight communication and deep space communication, require high photoelectric gain and response speed simultaneously.

There are three possible routes to acquire higher gain while retaining wide bandwidth: (i) explore new material or technology to realize photoelectric transform; (ii) continue to optimize the InGaAs structure; (iii) improve the driver circuits and signal processing methods\[10\]. III-V compounds are the best material for near-infrared wavelength detection by now, and the potential is far from being explored sufficiently. It’s a time-consuming and inefficient job to find new photoelectric material\[9\]. Considering the trade between detection efficiency and dark noise, and the trade between sensitivity and gain-bandwidth product, it is a tough route to improve the InGaAs structure. The techniques of high frequency electronic circuits and signal processing have developed substantially in the recent years. Therefore, improving the APDs’ driver circuits and signal processing methods seems to be efficient to reach our target.

In this paper, a mutual-differencing method is applied to linear-mode APDs, and the photoelectric properties is investigated in detail. Sine gate signals are coupled with DC biased voltage is imposed to two APDs that are made from the same semiconductor material and have the same structures. One of the two APDs is used to detect photon signals, and the other is shaded. In such a scheme, the sine gate acts as sampling signals. As the avalanche signals are buried in sine background noise, a transformer-based method is applied to eliminate the background noise and improve the signal-to-noise ratio of light induced signal. First, the proper DC biased voltage value is tested as the frequency response changes with DC biased voltage, therefore, the APDs are apt to work in a stable state. As the detection sensitivity and photoelectric gain vary with DC biased voltage and sine gate frequency, the relationship between them is researched.

The remainder of this paper is organized as follows. In Section 2, we introduce some relevant techniques, and explain why the gate-mode and mutual-differencing method is chosen in the experiments. Section 3 is devoted to illustrate the experiment platform and deliver the performance tests. Linear-mode APDs’ characters are discussed in Section 4, and Section 5 is the acknowledgement.

2. Relevant techniques

In the traditional application, linear-mode APDs are free running, and detect photon signals passively. However, the response speed is limited by the APDs’ gain-bandwidth product in this mode\[11, 12\]. Recently, a gate signal is applied to Geiger-mode APDs to achieve higher quantum detection efficiency and lower dark count rate. The gate acts as a positive sampling signal and determine the SPAD’s counting rate. Under the control of gate signals, the magnitude of avalanche are limited to very slow and the avalanche can be quenched positively as soon as possible. As the photoelectric gain increased with the DC biased voltage, in the period of high level in a single gate, the amplitude of avalanche signals is higher, while in the period of low level the avalanche is weaker. Hence it is possible to discriminate the avalanche signal and transform it to digital pulse by comparing it with a threshold voltage. Therefore, we attempt to apply a gate signal to a linear-mode APD, to realize positive and high speed sampling.

Before the signal is discriminated, the background noise resulting from the gate signals and the parasitic capacitor of the APD should be suppressed. If the rectangle pulse is used as the gate, the background noise is serial spikes, whose amplitude is much higher than the avalanche signals. With the gate frequency increasing, the rectangle pulse can’t work very well\[13\]. First, a pulse with a higher frequency requires a faster transition time, several ps generally. It’s very
challenging to get a fast transition time while retaining a high-amplitude pulse. Second, the spikes waveform is too complicated to be suppressed completely, especially when the gate frequency is up to GHz. Therefore, the rectangle pulse is replaced by sine waveform in high-speed photon detection. Sine waveform has many advantages. First, it can be obtained more conveniently due to its commonly existence in the RF and microwave technologies. Second, thanks to sine wave gate’s single frequency, the response of an APD is simpler so that it is easier to be suppressed\cite{14,15}. However, the background noise is still the most bothering obstacle in the way of extracting avalanche signals.

Many methods are used to issue the trouble of background. In the research of Zhang J’s group, band elimination filter with the sine wave frequency as the center frequency is used to eliminate background noise\cite{15}. Whereas it requires very complicated signal processing technology, we’ll discuss differencing method here, including self-differencing and mutual-differencing method. The Cambridge Research Laboratory used self-differencing method to subtract the spikes as Figure 2(left) shows\cite{7}. In this method, the signals from APD is delayed a gate clock period and subtracted with the original signals. As the spikes exist in every gate while the avalanche signal is random, self-differencing can suppress spikes and extrude avalanche signals. However, it may leads to a loss of detection efficiency, at least 50\% due to the probability of two avalanche signals in the two successive gate clock. And it requires that the gate frequency and the delay module are matched and keep stable all the time. Figure 2(right) shows the mutual-differencing applied to high speed photon detection. The advantage of mutual-differencing method is splendid\cite{16}. In a mutual-differencing mode, the single photon detector’s sampling frequency can be improved and adjusted without changing the hardware. If the characters of the two APD that are used in mutual-differencing method are approximate enough, the background noise can be suppressed as completely as you can. Therefore, two APDs made from the same material and technique, and from the same batch are better.

![Figure 2 Self-differencing(left) and Mutual-differencing method(right)](image)

In consideration of above-mentioned reasons, in this paper, gate-mode and mutual-differencing method are applied to the two linear-mode APDs, and the linear-mode characters are illustrated, expecting to improve the transmission rate and receiver’s sensitivity in the current near-infrared optical communication system. The packaged dual-APDs are on the way, and a better result is expected later.

3. Performance Test of linear-mode APDs

An experiment platform for linear-mode APD is setup, in which mutual-differencing method is applied as Figure 3
shows. In the scheme, APD1 detects photon signals while APD2 is shaded. Consequently, the signal from APD1 is avalanche signal mixed with background noise, while APD2’s response is just background noise. The two signals enter to power combinatory through coaxial cable with the same length and the background noise is suppressed in the output of the power combinatory. That’s the essence of mutual-differencing. Sine wave generator provides the gate signals, which is divided into two uniform signals by power splitter. The one coupled with DC biased voltage is applied to APDs while the other acts as the trigger signal of the pulse-laser generator. The delay module is used to ensure that the gate and the laser pulse act on the APD simultaneously so that the maximum sensitivity can be measured. The 1.55um infrared light signal was generated by a short-pulse laser source, and it was coupled to the detector by 1.55um fibers. An optical attenuator was used to adjust the laser power. 50 ohm resistances are used to meet the impedance-matching principle.

Figure 3 Linear-mode APD test platform with mutual-differencing method

3.1 Appropriate DC biased voltage test

As the APD’s frequency response varies with the DC bias, an appropriate DC voltage range must be tested. By doing this, we intend to achieve two goals: (i) keeping the APD’s response to the gate signal stable; (ii) achieve a high signal-to-noise ratio. In the test, sine waveform frequency is 10MHz to 100MHz, and the peak-peak amplitude is set to be 4.00V. The ratio of the waveform amplitudes on the point B and A in Figure3 is regarded as the APD’s frequency response. The results are shown in Figure 4. Figure 4(a) and (b) are APD1’s and APD2’s response respectively. As we see, between 20V and 40V, the two APDs’ responses vary with DC bias, and can’t match with each other. Whereas the DC voltage is higher than 65V, the electric field in APD’s multiplication layer is so intense that the gate signals trigger intrinsical avalanche in every gate without photo injection. Therefore, it is hard to discriminate avalanche signals from dark current. While from 40V to 60V, the APD’s response is definite and stable. In the mutual-differencing system, a signal with high SNR in the output can be acquired even the DC biased voltage drift. Hence, a DC biased voltage between 40V and 65V seems to be appropriate, and the following experiments are performed under the DC biased voltage between 40V and 65V.
Figure 4 APDs’ response to the sine gate signal (a) APD1’s response; (b) APD2’s response

3.2 Photoelectric gain and dark current vs DC biased voltage in DC-mode

As a photoelectric transformer, the linear-mode APD’s photoelectric gain is an important character. Generally, the DC biased voltage is the key factor that effects APD’s gain. The relationship between DC bias and gain is shown in Figure 5. And we compare it with a typical APD that can work in Geiger-mode from Amplification Technologies (Figure 7). In Figure 5, the left side of the line is linear-mode area, and the characters of the two kinds of APDs are the same. While on the right side of the line, the photoelectric gain of the APD under test increases rapidly, but it is still five order of magnitude lower than the typical APD. Therefore, the APD under test can’t detect a single photo even when the DC bias is higher than 70V. In order to find the reason, the structure of the APD is investigated. The linear-mode APD’s parameters of absorption layer are same to the typical APD, while the doping level is 20% lower. The carriers trapped by the potential well when avalanche happens are fewer. This character results in a higher response speed which is good for photo signals receiving in optical communication system\(^{[11]}\).

In Figure 6, the dark current increases linearly with DC bias getting higher on the right side of the line. On the left side of the line, there is almost no dark current, which is less than 3nA. In our experiments, it is found that the dark current is stable in DC-mode, while in gate-mode, intrinsical avalanches are definitely be triggered as described in Section 3.1. The following experiments are performed to test the characters of APD in gate-mode.
According to the theories illustrated in Section 1, the APD’s sensitivity varies with DC bias and gate frequency in gate-mode. In the range of 40V to 65V DC bias and 20MHz to 100MHz gate frequency, we adjust the delay module to make the gate signals and laser pulse affecting APD simultaneously so that the maximum sensitivity is tested. As Figure 8 shows, the detection sensitivity increases as the DC bias getting higher. It is obvious that higher DC bias results in a higher electric field in the multiplication layer and more electro-hold pairs are triggered. In Figure 9, the increment of gate frequency causes the sharp decrement of sensitivity. That’s because the activity of electro-holds pairs is depressed while the efficient gate width gets narrow as gate frequency getting higher. Interestingly, the response of APD is linear to the number of photos. It gives the best explanation of linear-mode. Actually, the slopes of these curves indicate the APD’s photoelectric gain, and it is investigated in Section 3.4.
3.4 Photoelectric gain vs DC biased voltage and gate frequency in gate-mode

The ratio of electros to photos is regarded as the photoelectric gain of APD. The number of electros triggered in an avalanche is proportional to the laminal area of an avalanche signal and the time-axis as Figure 10 shows. Finally, Figure 11 and Figure 12 are acquired. As we see, the photoelectric gain increases with DC bias getting higher and gate frequency getting lower, but the changes are not significant. The test result can be referred to evaluate the communication distance if the APD is used in an optical communication system.
4, Final discussion

In this paper, the characters of a linear-mode APD is investigated. Gate-mode is applied to linear-mode APD and mutual-differencing method is used to suppress background noise and acquire avalanche signals. The detection sensitivity and photoelectric gain increases with the DC biased voltage increasing and with gate frequency decreasing. In the scheme mentioned in the paper, the gate signal acts as sampling signals. The gate signal can control the avalanche intensity and can quench it positively, therefore, it is expected that an APD working in gate-mode may achieve higher transmission rate in the near-infrared optical communication than the APD working in free-running mode. However, limited by the current experiment condition, the tests are performed under 100MHz. The performance result illustrate the feasibility of the design proposal in some way. If the two APDs used in such a scheme are packaged as a single cell, the differencing signal will achieve a higher SNR and the avalanche signals are easier to be acquired. The gate frequency, that’s sampling frequency, may be improved consequently. The characters of the linear-mode APD and the performances of the tests show that it is possible to increase the response speed of linear-mode APD by using gate mode and mutual-differencing method. If such a scheme is used in the near-infrared wavelength communication, the transmission rate is expected to be improved greatly.

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