Experimental characterization improving the design of InGaAs/InP APD for single photon detection

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The passively quenched operation of avalanche photodiode (APD) has been used to characterizing InGaAs/InP APD including punch through voltage, avalanche voltage and break down voltage that are all important in the design of APD for single photon detection. The punch through voltage at certain doping level can be related to the thickness of the InP multiplication layer and the thickness of the un-intentionally doped n-type InP layer can be adjusted in according to the experimental data. The analysis indicates that the punch through voltage should be close to the breakdown voltage that can be realized by adjusting the thickness of InP multiplication layer.

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There has been increased needs for single photon detection especially in quantum optics and quantum cryptography applications in the communication wavelengths of 1310–1550 nm. There have been very few suitable detectors existed in the near infrared region. Some studies on Germanium avalanche photodiode for photon counting have been reported[1,2], however, these germanium avalanche diodes have to operate at temperature of 77 K and the detection efficiency is very low. Although there has reported about efficient single-photon counting at 1550 nm by means of frequency up-conversion[3], it suffers from strong background counts, more power consumption, and not convenient for practical applications. In a quantum key distribution system, we need not only to count the number of single photons, but also the state of the photon. The quantum key distribution system operates in one-bit-per-photon scheme and the bit error rate is used as the discrimination of the safety for the transmission system. There has not much choice for the single-photon avalanche diode (SPAD) in the communication wavelengths between 1300 and 1600 nm. Therefore the study on the avalanche photodiode for photon counting in recent year has concentrated on the InGaAs/InP APD, especially on the separate absorption, grading, and multiplication (SAGM) InGaAs/InP avalanche photodiode (APD)[4−6]. These APDs have to operate under reverse-bias at a higher voltage than its breakdown voltage or so called in Geiger mode to exploit its extreme sensitivity. The self-sustained avalanche current after breakdown should be quenched immediately to ensure a safety operation. Geiger mode has been efficiently realized in gated-mode in which the APD is reverse-bias to a voltage just below the breakdown voltage and an electric pulse is superimposed on the DC bias voltage so that the voltage on the APD increases instantaneously to cause avalanche breakdown. A quench circuit is needed to cut off the avalanche current and then recover to its original bias level to prepare the next detection[7,8]. Therefore various kinds of quenching circuits have been developed for the use of the commercial available avalanche diodes[9].The quantum bit error rate (QBER) in the gated mode detection are from thermal noise and after pulses which are the multiplication of the released carriers trapped in the depletion layer during avalanche process. A comprehensive characterization of a number of commercially available APDs will lead to an effective performance of gated-mode operation[10]. Although there has reported the design of InGaAs/InP avalanche photodiode for single photon detection, the analysis is based on the commercial available devices[11]. All the commercial available APDs are not designed especially for single photon detection. They are designed for conventional optical communication and for work below breakdown. They should be carefully studied and characterized in choosing for single photon detection. It has already been found that the photon-counting performance of these devices varies significantly, for example, the variation of several volts of breakdown voltage is usual. Only a few of these devices can be used for single photon detection.

Here we report the improvement of the design of InGaAs/InP APD for single photon detection based on the experimental characterization which are usually only for good choice and the best opperation of the commercial available APDs. The passive quench circuit has been used to characterize the APD and probe the performance of APD operated at much higher excess bias voltage without thermal constraints impact on the APD[12]. The measured I-V characteristics of a commercial available APD clearly indicate punch through voltage, avalanche voltage, and the breakdown voltage. All the measured data are parameters that structure material related with and can be used to improve the design of InGaAs/InP APD for single photon detection.

In the experiment, the passive quench circuit uses a current limiting resistor of 200 kΩ. The APD device is dry air-sealed in a chamber cooled down by Peltier effect. One of these I-V curves measured at temperature of -25 °C is shown in Fig. 1 for an APD of type C30645 from EG&G. The data provided by the manufactory are active diameter of 80 μm, breakdown voltage of 60 V, the quantum efficiency of 0.85 at 1310 nm, and total dark current of 10 nA at M=10. The output of a pigtailed DFB diode laser of 1550 nm wavelength was attenuated to −45 dBm and used as input signal of the APD which switched on to measure photon-current-voltage curve, and switched off to measure dark-current-voltage curve. It is clear from the measurement that there has a step of increase on the photon current-voltage curve appeared at about of 27.5 V, while the dark-current-voltage curve still keep unchanged near this voltage. This results are as same as the reported measurement of I-V curves[11] except that we extend the applied voltage to excess the breakdown to show the saturation effect. Here we distinguish the breakdown from avalanche. The breakdown is at the voltage where the gain factor M_e begins to drop down and saturation appears while avalanche is at the voltage where the current increases quickly, the gain factor $M_e \geq 1$ and increases with the bias. In according to the manufactory the voltage dependence of the gain, for gains above 4, is given approximately by a empirical formula:

$$M_e = 50/(V_b - V_a) \tag{1}$$

where V_b is the breakdown voltage, V_a is the applied voltage. The breakdown appears when $V_a = V_b$, that is $M_e \to \infty$. However, the experimental feature of the breakdown is that the multiplication factor drops and the current increases linearly when applied voltage to over breakdown so that the APD perform such as a pure resistor. The gain is not directly measurable quantity. However, the punch through, avalanche, and breakdown can be easily indicated on the I-V curve as shown in Fig. 1. The photon current increases slowly with the increase of bias voltage after punch through. The avalanche appeared at different places for different origins: The avalanche induced by photon carriers started at about 48 V while the thermal carriers induced avalanche started at about −51.5 V. This can be explained as high probability of the photon induced carriers at the interface of InP/InGaAs since the photon absorption begins in the InGaAs side of the InGaAs/InP interface. The reason that dark carries do not initiate avalanche can only be explained as these dark carriers do not pass through the multiplication layer since the avalanche process does not distinguish carriers from different origins. The dark carriers that have main contribution to the dark current are from leakage. The Breakdown appeared at almost the same voltage of 55 V. Above the breakdown, both the dark current and the photon current increase slowly down with the bias voltage increases and saturated to same value that is limited by the circuit resistance.

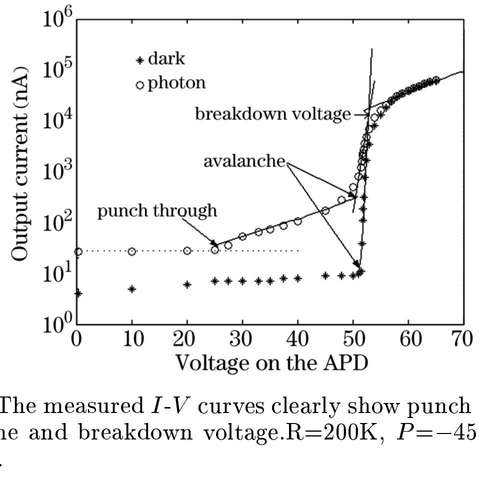

Fig. 1. The measured I-V curves clearly show punch through, avalanche and breakdown voltage.R=200K, P=−45 dBm at −25 °C.

The breakdown voltage which is important for single photon detection are technically defined in different ways[8,13,14]. The breakdown voltage is not a designed value. However, the excess voltage has been defined for practical applications,

$$V_e = V_a - V_b. \tag{2}$$

In the gated mode operation, we need a constant bias $V_c < V_b$ and a gate pulse with amplitude of V_p. V_p is usually limited to several volts for convenient electronics. These requirements rise to an appeal for improving the design of the APD itself. The designed data are the doping density, composition, and the thickness of the epilayers and its structure. The goal is to adjust the punch through, avalanche, and breakdown voltages. The punch through voltage is directly related to the thickness of the multiplication layer of InP.

A schematic of the electric field profile of a SAGM together with its microstructure and corresponding band diagram is shown in Fig. 2. It is clear that for the device to possess high quantum efficiency the electric field at the hetero-interface between the quaternary and the InGaAs should be nonzero, i.e,. the depletion layer must punch through into the absorption layer. In the p$^+$n junction the depletion extends to the n-InP side with low n-type doping. The width of the depletion under reversed bias increases with the external applied voltage that can penetrate in the absorbing layer. The inner build field increases exponentially with the extend of the depletion layer if the p$^+$n junction was made by inner diffusing technique that is the usual case as shown in the Fig. 2.

The photon-current-voltage curve measured in the experiment indicates that the APD has no response until the external reverse bias rises to about 27.5 V. The photon current increases slowly with increasing the bias and the avalanche start at about 48 V. The avalanche initiated by the dark carriers at about −51.5 V,where the S/N ratio is about 20 dB. It is reasonable to increase the thickness of the n-InP multiplication layer so that

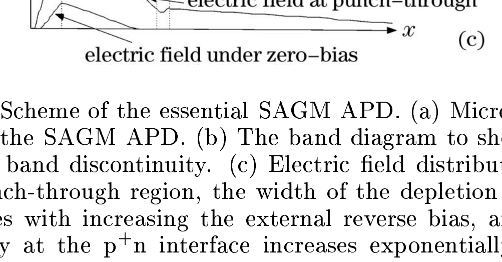

Fig. 2. Scheme of the essential SAGM APD. (a) Microstructure of the SAGM APD. (b) The band diagram to show the valence band discontinuity. (c) Electric field distribution at the punch-through region, the width of the depletion region increases with increasing the external reverse bias, and the intensity at the p$^+$n interface increases exponentially with increasing the width of the depletion region.

the punch through voltage reaches a voltage of −51.5 V where the probability of single photon absorption is high. Once the avalanche started by the photo-carrier it will dominate the whole avalanche process until breakdown. The punch through voltage and it corresponding width of the depletion region can only be estimated theoretically because they depend on the carrier distribution which is depends on the material growth and not be easily controlled. The experimental method introduced here can easily measure the punch through voltage which can be used to improve the design of APD.

It is essential that the dark counts should be very low when the bias is near and below the punch through voltage. The amplitude of the gate pulse can decrease if the punch through voltage increases further but not over the dark avalanche voltage. The designed structure is for the avalanche photodiode initiated by the hole produced in the absorption layer. The experimental data has shown that the dark current-voltage curve did not indicate clearly the punch through. The avalanche initiated by the carriers in thermal origin from the absorption layer at voltage higher than that the avalanche induced by photo-generated carriers. When the punch through voltage reaches avalanche voltage, the photon carrier induced avalanche will build up faster and is possible to use an electric pulse with less than 5 V to reach breakdown.

Therefore the thickness of the InP layer should be increased so that can have a higher punch through voltage for single photon detection. It is evident that the excess voltage will be easily optimized in the practical application.

The thickness of the absorption layer InGaAs in the conventional design for APD is about the range of 3 to 4 μm in consideration of full absorption of the input photons. As in the measured curve, the dark current increased much faster than the photo-current after avalanche. The excess voltage has limited value. The thickness of the absorption layer of InGaAs may be considered to be less than 1 μm which can be decided from the detection efficiency of single photon and the dark counts, which determine the quantum error bit rate.

The experimental data from passive quench operation could be used to improve the design of InGaAs/InP APD. The punch through voltage, avalanche voltage and breakdown voltage can be related to structure parameters such as the thickness of the multiplication layer and absorption layer in combining with theoretical analysis, the experimental data are helpful for the manufactory to develop better avalanche photodiode for single photon detection.

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