Experimental study on the depth of electric field punching through into the absorption layer of APD

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Dark-current-voltage curves and photon-current-voltage curves were measured by a passive quenched circuit so that the voltage applied to the avalanche photodiode can be much higher than breakdown voltage in study on the depth of punch through. The photo-current-voltage curve indicated clearly the punch-through voltage while the dark current-voltage curve is insensitive to the punch through. Furthermore, the avalanches initiated by the photo-generated carrier at a voltage lower than that from the thermo-generated carriers and explained based on the different distribution of the carriers.

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There have been increased needs for single photon detection in varies of areas especially in quantum information where the sensitivity should be made possible to detect one bit per photon. The single photon counting techniques in the communication wavelengths are attracted attentions since there has the lowest loss in the fiber communication system, and the wavelength is eye safe. However, there have not detectors especially designed for single photon detection. The best choice from the commercial detectors right now is the separated absorption and multiplication (SAM) InGaAs/InP avalanche photodiode (APD). These APDs have to work at a reverse bias that is higher than its breakdown voltage to probe its highest sensitivity that is so called Geiger mode operation[1]. Several ways including passive quenching, active quenching and gated mode have been used to operate single photon avalanche diode (SPAD)[2]. The gated mode technique has been recognized to be an effective way to realize single photon detection in Geiger mode[3–5] where the APD is reverse-biased 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 trigger avalanche breakdown. A quench circuit is needed to cut off the avalanche current and then recovers to its original bias level to prepare for next detection[6]. Decreasing the dark counts and increasing the detection efficiency are the two major considerations for the SPAD. A simple and easy method to decrease the dark counts is to cool down the devices. However, the breakdown voltage decreases with temperature that means the multiplication factor decreased with temperature. The life time of the trapped carrier during avalanche increases with decreasing temperature to limit the performance of APD since the release of the trapped carriers can trigger so-called after pluses and the after pluses will last a longer time. The practical application requires the SPAD operated at an optimized temperature of above 200 K so that can realized economically with Peltier cooler[7,8]. In fact, Both the detection efficiency η and the dark counts P_{dark} increases (decreases) when the temperature or V_{E} increases (decreases)[9]. And the maximum multiplication factor, the highest detection efficiency and the best signal-to-noise ratio occured at different temperature and bias conditions[10]. For more practical and economical consideration the higher temperature is the better if the dark current can be decreased by device structure improvement and the material growth. Fortunately the recent type of ETX 40 APD operated above –40 °C (233 K) has made it possible to use only a single stage of Peltier cooler for single photon detection[11]. After the operation temperature was optimized in the Peltier cooling range, much attention has been paid to the bias for the gated mode operation. In general, when bias is increased above the breakdown point, photon counting detection sensitivity will increase and will be saturated at specific voltage. Increasing the bias will improve the time resolution of the detector and it saturated at some level. Increasing the bias above breakdown will increase the dark-count rate of the detector, no saturation can be observed[12]. The excess voltage V_{E}, which is defined as the applied voltage V_{A} minus the breakdown voltage V_{B}, has been extensively studied for efficient single photon detection. However, the reported data in the study for the excess voltage were scattered widely because the breakdown voltage itself was not clearly and definitely defined from the technical consideration though the breakdown voltage is theoretically defined as a voltage that triggers self-sustained avalanche current in the APD[2–4,12,13], We report here experimental study on the depth of the electric field at the depletion region punch-through into the absorption layer.

The passive quench circuit which was originally used for single photon detection[1] was used here to measure the I-V characteristic of a commercial available APD. The ballast resistor of 200 kΩ was used in the circuit in consideration of hard thermal constraints avoidance when higher excess bias was used though a resistor of 56 kΩ could ensure good quenching for all overvoltages in photon counting[7]. A pigtailed continuous wave (CW) laser source at 1550 nm wavelength attenuated to −45 dBm was used in the measurement. The photocurrent-voltage curves were measured when the laser was switched on and then switched off to measure the dark-current-voltage curves. The APD was mounted on a two-staged Peltier effect device and dry air sealed in an insulated metal box. The measured results are shown in Fig. 1 for two types of the APD. Figure 1(a) shows the I-V characteristic for C30645E from EG&G measured at temperature of –25 °C. The photon I-V curve shows clearly the punch through, avalanche and the breakdown where the photocurrent begins to saturated while the dark current has no sign for the punch through. The punch through voltage is at 30 V. The avalanche starts at a voltage of 50 V and breakdown at 52.5 V where the photocurrent begins to be saturated. The dark current saturated at a voltage same as that of the photo-current. Figures 1(b)–(d) show the current-voltage characteristics measured at different conditions. Figure 1(a) is for C30645E from EG&G measured at temperature of –25 °C. Figure 1(b) is for C30645E from EG&G measured at temperature of 0 °C where the punch through appeared at 30 V, same as measured at temperature of –25 °C but the avalanche starts at 52 V and breakdown at 55.4 V. Figure 1(c) shows the results for APD of type OF3600B-C2 from Oki, which are 156Mbps APD-preamplifier coaxial module with single mode fiber, measured at temperature of –20.3 °C. The curve shows a punch through at 30 V, start point of avalanche at 37 V, and breakdown at about 56 V where the dark carriers begin to avalanche. Figure 1(d) was measured at temperature of –9.5°C.

The relative current gain which is defined as

$$G_{\rm r} = 1 + {\rm d}I/{\rm d}V \tag{1}$$

can clearly show the saturate effect of the avalanche current. The relative current gain-voltage curve measure for C30645E from EG&G measured at temperature of –25 °C is shown in Fig. 2. The punch through voltage and the saturate effect are more clearly indicated. The avalanche initiated by photo-generated carrier at a voltage lower than that initiated by dark carrier and both of the avalanche have the same breakdown voltage.

The breakdown voltage is featured with triggering a self-sustained avalanche. The other definition is described as that at that bias the multiplication factor goes large infinitely[14]. However, neither the infinite large M_e, nor the self-sustained avalanche can accurately be determined experimentally. Therefore the authors redefined the breakdown voltage in several ways[2,4,7]. Furthermore, the breakdown includes two levels of the voltage. It is breakdown at a voltage quickly and then immediately drops due to the circuit ohm resistance to a voltage which is called as the actual breakdown voltage[2].

The breakdown voltage in this paper is defined as the voltage when the relative gain has become a constant which is the feature of a linear device. The photocurrent depends on the punch through voltage and begins to avalanche at an applied voltage different from that of the dark current. The dark carriers which do not depend on the punch through are explained as they exist outside the multiplication region at that bias[13]. Only the thermal carriers generated in the absorption layer need punch through voltage so that can drift into the multiplication layer to initiate avalanche. We can therefore consider only the dark carrier from the absorption layer the band gap of which is 0.73 eV at room temperature so that may have much thermal carriers.

Part (a) of Fig. 3 is the schematic diagram of the InGaAs/InP SAGM APD, light input from p-InP substrate. The p$^+$n junction is formed from high p-doped InP and un-intentionally n-doped InP, or intrinsic InP with n-doping density of about 10^{14} cm^{-3}. The low doping density allows the electric field at the depletion region to extend deep into the absorption layer and the applied voltage can be higher to increase the multiplication factor. The grating layer with band gap of 1.05 eV has a thickness of about 100 nm. The thickness of the absorption layer with band gap of 0.73 eV is about 2 μm with density of about 10^{15} cm^{-3}. Part (b) is the corresponding band profile under zero bias showing the absorption InGaAs layer sandwiched between n-InP. A potential well

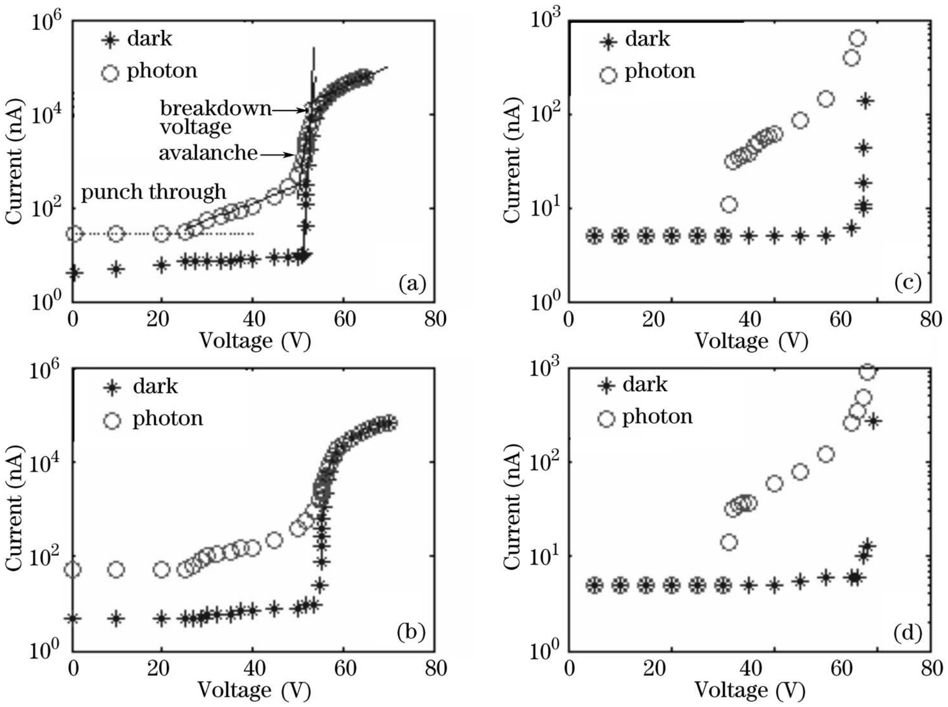

Fig. 1. Photocurrent-voltage characteristic and dark-current-voltage characteristic measured at different temperatures.

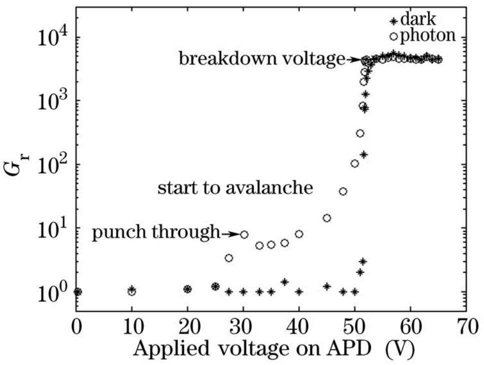

Fig. 2. The relative current gain-voltage characteristic measured for C30645E from EG&G operated at temperature of –25 °C, R = 200 K, and P = –45 dBm.

formed at valence band. Part (c) shows the carrier distribution, the photo-generated carriers follow the exponential attenuation law, while the thermal dark carriers in the potential well have a Gaussian distribution[15].

The dark current is the sum of the un-multiplied I_{du}, mainly due to surface leakage, and the bulk dark current experiencing multiplication I_{dm} multiplied by the gain[16]. The dark current measured at the punch-through voltage is insensitive to the punch through voltage that means $I_{\mathrm{d}} = I_{\mathrm{du}}$. And the measured I-V curves indicate that the dark avalanche started at a voltage much higher than that for the photo-avalanche. This is an experimental demonstration that under the bias the photo-carrier can initiate the avalanche while there are only negligible bulk dark carriers because the multiplication process does not distinguish photo carrier from dark carrier.

The probability of dark carriers existed at the boundary of InGaAs absorption layer is very low. One of the reasons is much recombined centers existed at the interface and the limited thermal carriers have been exhausted by the inner built electric field at the hetro-interface. The other reason is quantum interference of the carrier in the potential well in the valence band. The spatial distribution of quantum particles may be supposed to have a Gaussian form which is the minimum uncertainty wavepacket[15].

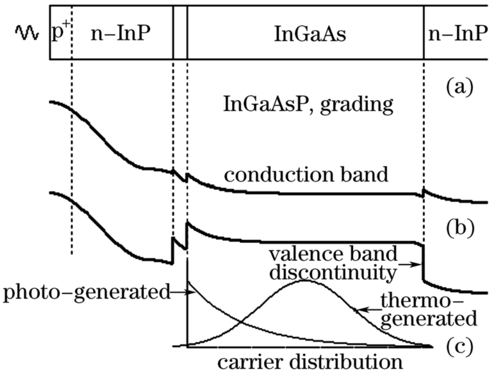

Fig. 3. (a) Schematic diagram of the InGaAs/InP SAGM APD, (b) the corresponding band profile under zero bias, (c) the carrier distribution.

In conclusion, the characteristic of a SPAD can be accurately described with respect to the depth of electric field punch through. The measured I-V curves indicate that the dark current does not sensitive to the punch through and the dark avalanche started at a bias higher than that of the photo-avalanche. This is a demonstration that the leakage, mainly from the surface, has the main contribution to the dark current before dark avalanche. With the depth of electric field punch through into the absorption layer can clearly describe the physics underlay, in comparison with the excess voltage. This phenomenon can be explained based on the carrier distribution.

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