Turn-on and turn-off voltages of an avalanche p–n junction*

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Abstract: Characteristics of the turn-on and turn-off voltage of avalanche p–n junctions were demonstrated and studied. As opposed to existing reports, the differences between the turn-on and turn-off voltage cannot be neglected when the size of the p–n junction is in the order of microns. The difference increases inversely with the area of a junction, exerting significant influences on characterizing some parameters of devices composed of small avalanche junctions. Theoretical analyses show that the mechanism for the difference lies in the increase effect of the threshold multiplication factor at the turn-on voltage of a junction when the area of a junction decreases. Moreover, the "breakdown voltage" in the formula of the avalanche asymptotic current is, in essence, the avalanche turn-off voltage, and consequently, the traditional expression of the avalanche asymptotic current and the gain of a Geiger mode avalanche photodiode were modified.

Key words: Geiger mode avalanche photodiode; p–n junction; turn-on voltage; turn-off voltage

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1. Introduction

Early in the 1950s, it was discovered that a silicon p–n junction exhibited random "on-off" conducting characteristics biased above a certain threshold voltage, referred to as the junction turn-on voltage or afterwards as the breakdown voltage[1, 2]. Random electrical pulses can be observed across the signal resistor in series with the junction. The "on-off" frequency or pulse rate is extremely sensitive to the visible light, and very weak exposure can cause a drastic increase of the "on-off" frequency[2, 3]. This phenomenon was regarded to be caused by the carrier avalanche effect together with junction resistance and the effect of fluctuation to zero-multiplied carriers[4] and has become the basic operating principle of Geiger mode single photon avalanche detectors[5]. The duration of the conducting state also increases dramatically with a slight increase in the reverse bias. The p–n junction stays in the conductive state and the conducting current is limited by the junction resistance and external series resistance. Contrastingly, the conductive junction turns off if the bias across the junction reaches a smaller threshold voltage (referred to as the turn-off voltage in Ref. [6]). Generally, the junction turn-on voltage is merely about hundreds of millivolts (< 500 mV) larger than the turn-off voltage[6]. Accordingly, the difference between the turn-on voltage and the turn-off voltage is often neglected when characterizing the detector performance and for practical applications[5, 7], since both the turn-on voltage and the turn-off voltage are called the breakdown voltage without distinction.

Recent experiments, however, have shown that the turn-on voltage ($V_{\text{turn-on}}$) and turn-off voltage (V_{off}) of a small p–n junction are quite different. Ignoring the difference will cause incorrect characterization of the device parameters and affect the practical applications of the device. In this study, experiments were conducted to gain an insight into mechanisms in order to account for large differences between $V_{\text{turn-on}}$ and V_{off} for small p–n junctions and, furthermore, theoretical analyses were made to accurately determine the important parameters of a device.

2. Principle and experiments

Two strategies were proposed to confirm that the turn-on and turn-off voltages of a small p–n junction are quite different. The first strategy is to measure the current–voltage (I–V) characteristic curve of a p–n junction without a quenching resistor. Two bias scans were made in opposite directions. A bias scan in a direction from small to large was employed to determine the $V_{\text{turn-on}}$ of the p–n junction, while the opposite bias scan was implemented to determine the V_{off} of the p–n junction. The second strategy is to measure the curve of the multiplication factor (M) versus the bias voltage to infer the difference between the turn-on and the turn-off voltage of a p–n junction. For a conducting junction, M reduces with a decrease in the bias voltage across the junction, V. The avalanche process will be terminated by the fluctuation effects of zero-multiplied carriers when M is 2–5[6], and the conducting junction will be turned off[4]. Thus, one can obtain the turn-off voltage of the junction by measuring the M–V curve. M was obtained by the following method[8].

First, by scanning the curve of the dark current I_{d} versus V of the device. Then, by scanning the curve of the photocurrent, I_{ph}, versus V. The total current should be carefully controlled

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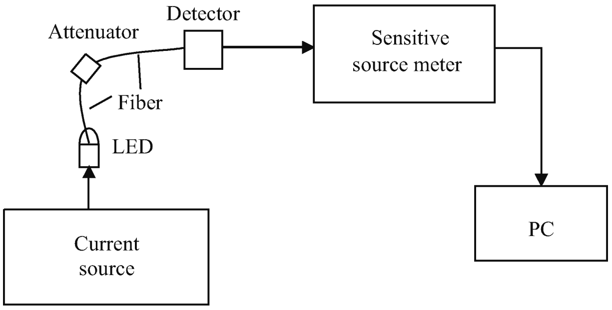

Fig. 1. Schematic set up for multiplication factor measurements. The source meter is a kind of instrument which can provide a bias voltage as well as a measurement of the current in the circuit. The auxiliary is omitted in this block diagram.

to make sure that it is slightly larger than the dark current in order to avoid the influence of the photon accumulation effect on the veracity of M[9] (the measured photocurrent was only 30% of the dark current in this experiment in accordance with Ref. [9]). Under these conditions, the characteristic curve of the total current I_{total} versus the voltage was scanned until the bias voltage was several volts higher than the turn-on voltage ($V_{\text{turn-on}}$) and, hence, the photocurrent (I_{ph}) equals $I_{\text{total}}(V)$–$I_{\text{d}}(V)$. Taking the photocurrent as the non-multiplied photocurrent (I_{ph0}) when it almost did not vary with the increasing bias voltage ($\ll V_{\text{turn-on}}$)[8], then the multiplication factor of the device can be expressed as

$$\begin{aligned} M(V) &= I_{\text{ph}}(V)\big/I_{\text{ph0}} \\ &= \frac{I_{\text{total}}(V) - I_{\text{d}}(V)}{I_{\text{total0}} - I_{\text{d0}}}, \end{aligned} \tag{1}$$

where I_{total0} and I_{d0} are the non-multiplied total current and the non-multiplied dark current, respectively. In order to avoid the influence of temperature on the I–V curve of the device, the devices were stewed for several minutes before next bias scan.

The schematic set up for multiplication factor measurements is shown in Fig. 1. The current was measured by a sensitive Source Meter (Keithley 237), the detector was illuminated by a red LED with a center wavelength at 650 nm. The LED was driven by a current source (Model 120CS, Lake Shore Inc.) and the light from the LED was coupled to the detector through a fiber and a fiber attenuator. In order to decrease the slope of the M–V curve to easily read the voltages at a certain M, we chose a single photon avalanche photodiode (SPAD) with integrated passive bulk quenching resistor (fabricated at the NDL Lab, China), with a square size of 10 μm.

The avalanche pulses of the SPAD were amplified by a high-speed amplifier (40 dB gain, 2 GHz bandwidth, 50 Ω input impedance, HSA-Y-2-40, FEMTO Inc.), and then observed on the oscilloscope (TDS1012, Tektronix Inc.). The quenching resistance (R_{Q}) of SPAD can be estimated by measuring the slope of the reverse I–V characteristics when the bias is much larger than the breakdown voltage[10]. Because the internal resistance in the junction is much smaller than the quenching resistance, it can be neglected[3, 4].

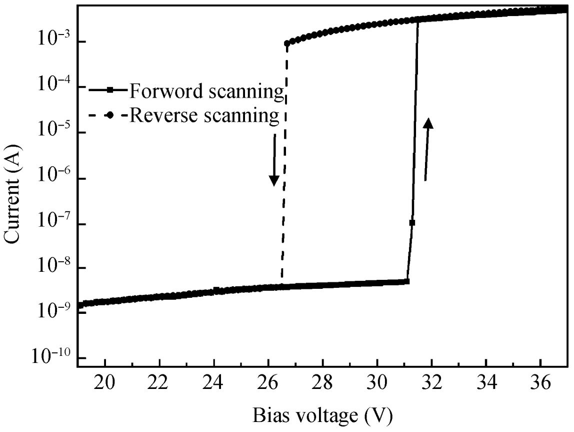

Fig. 2. Current–voltage characteristics of a p–n junction with a diameter of 10 μm in a semilog coordinate. The solid line represents the bias scanning in a direction of small to large while the dashed line represents the bias scanning in a direction of large to small. The curve was measured by a sensitive Source Meter (Keithley 237) at room temperature. The device was placed in a light tight box. Two bias scans were performed in opposite directions. The solid line represents the bias scan from small to large, while the dashed line represents the opposite bias scan and the arrow in the figure represents the scanning direction.

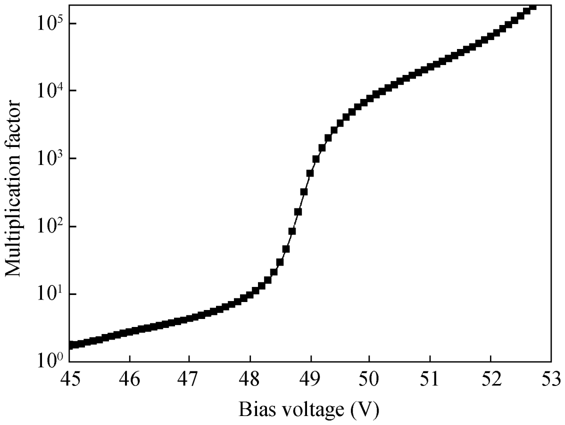

Fig. 3. Dependence of the multiplication factor (M) on the reverse bias of the bulk quenching resistor single photon avalanche photodiode (SPAD). The experimental setup is shown in Fig. 1. The values of M were calculated by Eq. (1).

3. The differences between the turn-on and turn-off voltages of p–n junctions with different areas

Figure 2 shows the current–voltage characteristics of a plane junction with a square size of 10 μm without a quenching resistor. The solid line represents a bias scanning direction of small to large while the dashed line represents a bias scanning direction of large to small. It is evident from Fig. 2 that the turn-on and turn-off voltages of the junction are about 31 V and 26.5 V, respectively. The difference is about 4.5 V, which is much larger than that of Ref. [6] (only a few hundred millivolts).

The curve of the multiplication factor versus the reverse bias of the passive quenching SPAD is shown in Fig. 3. A sharp

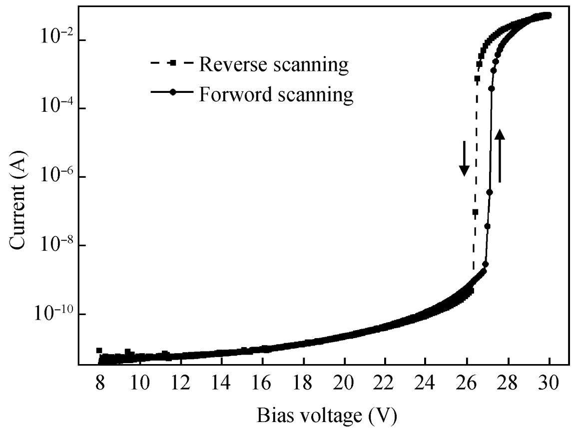

Fig. 4. Current–voltage characteristics of a p–n junction with a diameter of 1 mm in semilog coordinate on the same chip with the one shown in Fig. 2. The solid line represents the bias scanning in a direction from small to large, while the dashed line represents the opposite bias scan. The test method is the same as the one used in Fig. 2.

increase of M can be seen at about 49 V, indicating that the turn-on voltage of the SPAD is about 49 V. We can also see from Fig. 3 that the voltage is from 45.7 to 47.5 V when M is between 2 and 5, thus, the avalanche turn-off voltage should be between 45.7 V and 47.5 V according to Ref. [6]. Therefore, a conservative estimate of the difference between $V_{\text{turn-on}}$ and V_{off} of the SPAD is at least 1.5 V. Furthermore, one can see that M increases slowly when the bias voltage is smaller than $V_{\text{turn-on}}$, where the avalanche diode operates in "linear mode". When the bias is larger than $V_{\text{turn-on}}$, M has an approximately parabolic relationship with the increasing bias[11].

However, for a junction with a larger area (1 mm^2), the difference between $V_{\text{turn-on}}$ and V_{off} is smaller. Figure 4 displays the I–V characteristics of a p–n junction with a square size of 1mm on the same chip as the one shown in Fig. 2. It can be clearly seen that the difference is only about 500 mV, which is basically consistent with the results in Ref. [6]. The difference becomes significant when the area of a junction is smaller than 1 mm^2 by two orders of magnitude.

4. An explanation of the large difference between $V_{\text{turn-on}}$ and V_{off} for a small junction

As we know, the avalanche current equals the product of M and the initial bulk current which is composed of the generation current and the diffusion current[12]. The initial bulk current can be expressed as

$$I_0 = J_0 S = e v_{\text{s}}(n_0 + p_0)S, \tag{2}$$

where J_0 is the initial current density, S is the area of a junction, v_{s} is the saturation velocity of free carriers, which is about 10^7 cm/s in silicon, n_0 and p_0 are the initial carrier concentrations in the depletion region for electrons and holes, respectively, and e is the electron charge. Thus, the avalanche current I_{a} across the junction is

$$I_{\text{a}} = I_0 M = e v_{\text{s}} M(n_0 + p_0)S. \tag{3}$$

On the other hand, an avalanche threshold current (I_{q}) exists in a p–n junction, the junction is in a conducting state if the triggered avalanche transient current (I_{a}) resulted from initial carriers surpasses I_{q}[3, 4, 6]. The avalanche threshold current has been well studied in the TRAPATT-diode theory[13]. If we choose the critical condition and let I_{a} equal to I_{q}, that is,

$$I_{\text{a}} = eMv_{\text{s}}(n_0 + p_0)S = I_{\text{q}}. \tag{4}$$

Thus

$$M(V_{\text{turn-on}}) = \frac{I_{\text{q}}}{e v_{\text{s}}(n_0 + p_0)S}, \tag{5}$$

where $M(V_{\text{turn-on}})$ is the threshold multiplication factor at the turn-on voltage of the junction ($V_{\text{turn-on}}$). As I_{q} is a constant at a given junction and operating condition[6, 14], it can be inferred from Eq. (5) that $M(V_{\text{turn-on}})$ becomes larger as the area of the junction, S, decreases. Furthermore, M has one-to-one correspondence with the voltage across the junction, thus $V_{\text{turn-on}}$ becomes larger when S decreases. In the case of a conducting junction, there are abundant carriers in the depletion region because of impact ionization and, consequently, only a very small M is needed to maintain the conducting state of the junction. At the turn-off voltage, M almost does not change for junctions with same doping profile but of different sizes[6], thus, the turn-off voltage of the junction (V_{off}) remains unchanged, approximately. As a result, the difference between $V_{\text{turn-on}}$ and V_{off} of a junction becomes larger when the area of the junction becomes smaller. The large difference between $V_{\text{turn-on}}$ and V_{off} for a small junction is caused by the increased effect of the $M(V_{\text{turn-on}})$ when the area of a junction decreases.

5. Modifications to the formulas of the asymptotic avalanche current and Geiger discharge gain

For a breakdown p–n junction, the steady conducting current (also called the asymptotic avalanche current) is given by the following classical expression[3, 4]

$$\begin{aligned} I_{\text{f}} &= (V - V_0)/(R_{\text{Q}} + R_{\text{d}}) \\ &\approx (V - V_0)/R_{\text{Q}}, \end{aligned} \tag{6}$$

where V is the external bias voltage, R_{Q} is the external series resistance (quenching resistor), R_{d} is the internal resistance of a p–n junction, which is usually much smaller than R_{Q}, so it can be ignored. V_0 is the breakdown voltage. However, experiments revealed that the difference between $V_{\text{turn-on}}$ and V_{off} was quite different. Thus, it is necessary to focus on whether V_0 is the avalanche junction turn-on voltage ($V_{\text{turn-on}}$) or the turn-off voltage (V_{off}).

Figure 5 shows the oscilloscope capture of the amplified avalanche pulses of the same SPAD with a bias of 53.5 V (or 4.5 V above the junction turn-on voltage). The "flat-topped" shaped avalanche pulse and the normal shaped avalanche pulse can be seen in the same capture. The avalanche asymptotic current can be derived from the amplitude of the "flat-topped" shaped avalanche pulse[3]. One can see that the pulse amplitude of the "flat-topped" pulse on the left side of Fig. 5 is about 150 mV, while the quenching resistance measured by the method mentioned in section 2 is 209 kΩ, and the avalanche

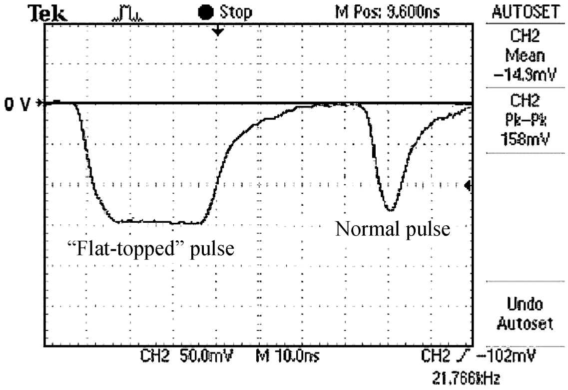

Fig. 5. Capture of random conducting and turn-off avalanche pulses of the same SPAD on the oscilloscope (OSC) with a bias of 53.5 V (or 4.5 V above the junction turn-on voltage). The original avalanche pulses of the SPAD were amplified by the fast amplifier (HSA-Y-2-40, FEMTO Inc.). The device was placed in a light tight box and tested at room temperature. The "flat-topped" shaped avalanche pulse and the normal shaped avalanche pulse can be seen in the same capture.

asymptotic current is about 30 μA, by dividing the amplitude of the flat-topped pulse by the signal resistance and the gain of the amplifier (i.e.: 150 mV/(50 $\Omega \times 100$) = 30 μA). Whereas, the turn-on voltage of the SPAD is about 49 V as aforementioned, if V_0 in Eq. (6) is the turn-on voltage of the SPAD, the I_f is derived to be about 21 μA, which is significantly different when compared to the experimental result (30 μA). On the other hand, if V_0 is the turn-off voltage (V_off) of the SPAD (i.e.: 45.7–47.5 V), the I_f is derived to be between 28.7–37.3 μA. The calculated value of I_f covers the experimental result (30 μA) and the calculated current range is more close to 30 μA. Since the multiplication factor is in an approximate range when the avalanche process turns-off[6], V_off cannot be determined accurately. Accordingly, the view that V_0 should refer to V_off rather than $V_\text{turn-on}$ is reasonable.

Furthermore, as can be seen from Eq. (6), the current I_f varies linearly with the bias voltage, V_0 can easily be extracted by plotting a curve of experimentally measured I_f versus V. Figure 6 shows the I–V curve of the same SPAD used in Fig. 3. It is clear that the extrapolated voltage of the current curve after turning on is about 49 V, which is in accordance with the V_off shown in Fig. 3, instead of being obviously smaller than V_off. Therefore, in practice V_0 is V_off.

Hence, Equation (6) should be modified as

$$I_\text{f} \approx (V - V_\text{off})/R_\text{Q}. \tag{7}$$

The Geiger discharge gain of the avalanche photodiode can be expressed as[4]:

$$\text{Gain} \approx I_\text{f} R_\text{Q}(C_\text{j} + C_\text{s})/e, \tag{8}$$

where C_j and C_s are the junction capacitance and stray capacitance of a junction, respectively. As Equation (8) contains I_f, it can be expressed as

$$\begin{aligned}\text{Gain} &\approx I_\text{f} R_\text{Q}(C_\text{j} + C_\text{s})/e \\ &= (V - V_\text{off})(C_\text{j} + C_\text{s})/e.\end{aligned} \tag{9}$$

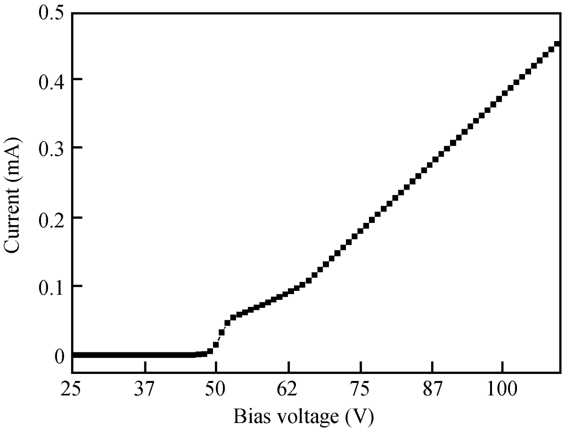

Fig. 6. Current–voltage characteristics of the same SPAD in linear coordinate. The experimental setup is the same as the one used in Figs. 2 and 4.

From Eq. (9) one can infer that the Gain is approximately proportional to the bias voltage if the change of C_j and C_s is ignored with varying bias when the bias voltage (V) is larger than V_off. This conclusion is in accordance with experimental results in Refs. [10, 11, 15]. One can also infer from Eq. (9) that the voltage extrapolated from the Gain curve of a junction almost equals V_off, instead of the avalanche turn-on voltage ($V_\text{turn-on}$), providing an explanation for the fact that the "breakdown voltage" extrapolated from the gain curve versus the over-voltage of the SPADs is always smaller than $V_\text{turn-on}$ as mentioned in Refs. [10, 15]. In addition, if one calculates the Gain by Eq. (9), the veracity is better than the previous one[10].

One can also see that there are two strange inflections in the I–V curve in Fig. 6, which may be caused by the influence of the space charge region effect[3, 8] and the quenching resistor. The mechanisms governing the shape of avalanche pulses have not been clearly understood yet. This aspect warrants further investigation and will be discussed elsewhere.

6. Conclusion

Larger differences between the turn-on and turn-off voltage for small avalanche junctions were confirmed by experiments. This difference increases with the decrease of junction areas and cannot be ignored for small avalanche junctions. The difference has a fundamental influence on characterizing parameters of devices composed of small avalanche junctions. The so-called "breakdown voltage" in the avalanche asymptotic current formula is the avalanche turn-off voltage, instead of the real breakdown voltage. As a result, the traditional avalanche asymptotic current formula and Geiger discharge gain of avalanche photodiode were amended. The mechanism for this difference is the increased effect of the threshold multiplication factor at the turn-on voltage of a junction when the area of a junction decreases.

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