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Determination of breakdown voltage of In$_{0.53}$Ga$_{0.47}$As/InP single photon avalanche diodes

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Received June 5, 2010; accepted August 20, 2010; posted online January 1, 2011

We examine the saturation of relative current gain of In$_{0.53}$Ga$_{0.47}$As/InP single photon avalanche diodes (SPADs) operated in Geiger mode. The punch-through voltage and breakdown voltage of the SPADs can be measured using a simple and accurate method. The analysis method is temperature-independent and can be applied to most SPADs.

OCIS codes: 040.1345, 040.3060, 040.5160, 040.5570.

doi: 10.3788/COL201109.010402.

Some avalanche photodiodes (APDs) that are reverse biased beyond breakdown voltage and are operated in Geiger mode may achieve single photon detection$^{[1-10]}$. These APDs are also known as Geiger mode avalanche photodiodes or single photon avalanche diodes (SPADs)$^{[3]}$. Breakdown voltage $V_B$, an important parameter for APDs applied in both linear mode and Geiger mode, is theoretically defined as the voltage threshold above which the gain is infinite. When experimentally determining the breakdown voltage, other approximate definitions are used, typically defining $V_B$ as the reverse bias voltage 1) when the dark current $I_{dark}$ reaches 100 $\mu$A$^{[3,4]}$; 2) when the multiplication factor (or mean gain) $G_m$ reaches 100$^{[5]}$; and 3) when the output pulses exceed 100 mV (0.5 mV at the device)$^{[6]}$. These definitions are good approximations but will meet their limitations when the APD is used as a SPAD. SPADs require that $V_B$ be more accurately determined. When adopting Definition 1, the critical value of the dark current should be revalued for different APDs at different temperatures. Current-voltage ($I$-$V$) characteristics vary significantly for different SPADs. Moreover, the dark current decreases with temperature when it reaches the breakdown value $I_B$. With Definition 2, $G_m$ is difficult to measure accurately near breakdown, especially for thin structures, because $G_m$ further increases with the voltage in such structures$^{[7]}$. This definition will lead to underestimation of the breakdown voltage. The output of the SPADs is affected by many factors, including material, device structure, and operating conditions. Therefore, if the amplitude of the output pulse is monitored as the evidence of breakdown in Definition 3, the critical value also has to be revalued. In this letter, we demonstrate that the breakdown voltage can be correctly determined by analyzing the $I$-$V$ curves which have been extended to a voltage higher than its breakdown value by using a passive quench circuit.

The avalanche breakdown of a SPAD, which can be initiated by both photocarriers and dark carriers, is a complicated process, but can be simplified to a few steps$^{[11]}$. The SPAD is reverse biased above $V_B$. An initial carrier (or electron-hole pair) triggers the impact ionization. The density of the free carriers rises swiftly around the injected point. The avalanche then increasingly spreads by transverse diffusion of the free carriers (in shallow junctions)$^{[11]}$ or by reabsorption of the photons emitted from hot carrier relaxations (in reach-through structures)$^{[12]}$. The avalanche current rises accordingly until it reaches the value at which the quenching occurs.

For an explication of the analysis above, we built an extensively adopted $I$-$V$ characterizing system, using a passive quench circuit. A schematic diagram of the experimental setup and its equivalent circuit are shown in Fig. 1. The device investigated was an 80-$\mu$m-diameter separate absorption charge multiplication (SACM) In$_{0.53}$Ga$_{0.47}$As/InP APD of type C30645 from EG&G, which was proven suitable for use as a SPAD. The total dark current was 10 nA when $G_m$ was 10 at a temperature of 300 K. It was dry-air-sealed in a chamber cooled down by Peltier effect. The avalanche current quenched itself by developing a voltage drop on a ballast resistor of 200 k$\Omega$. The mean current was measured by an amperemeter. $V_{DC}$ is the bias supply voltage, $R_L$ is the quenching resistance, $R_F$ is the diode impedance which is the series of ohmic resistance and space charge.

![Fig. 1. (a) Schematic diagram of the experimental setup and (b) its equivalent circuit.](image-url)
resistance, \( C_d \) and \( C_s \) are the diode capacitance and the capacitance of anode to ground, respectively. The value of \( R_d \) is around 1 kΩ.

The triggering of the avalanche corresponds to closing the switch in the equivalent circuit, as shown in Fig. 1(b). During the quenching, the transient voltage on the diode \( V_d(t) \) is given as

\[
V_d(t) = \frac{R_d}{R_d + R_L} (V_{DC} - V_B) \exp\left(-\frac{t}{RC}\right)
+ \frac{R_d R_L}{R_d + R_L} \left(\frac{V_{DC}}{R_L} + \frac{V_B}{R_d}\right),
\]

where \( R \) is \( R_d \) and \( R_L \) in parallel, and \( C \) is the sum of \( C_d \) and \( C_s \).

\[
R = \frac{R_d R_L}{R_d + R_L},
\]

\[
C = C_d + C_s,
\]

\[
V_d(t) \text{ exponentially falls toward the steady-state value of } V_i:
\]

\[
V_i = \frac{R_d R_L}{R_d + R_L} \left(\frac{V_{DC}}{R_L} + \frac{V_B}{R_d}\right) = V_B + R_d I_t,
\]

where

\[
I_t = \frac{V_{DC} - V_B}{R_d + R_L}
\]

is the steady state value of the current. The deduced formulas of Eqs. (4) and (5) are consistent with those in other references.[13]

A measured curve similar to the curves published in one of our results,[5], including punch-through and breakdown, is shown in Fig. 2. The output of a pigtailed distributed feedback (DFB) diode laser of 1550-nm wavelength was attenuated to −45 dBm and used as input signal. The device was cooled down to −25 °C during measurement. As shown in Fig. 2, the photocurrent \( I_p \) starts to increase at \( V_{DC} = 25 \) V, while the dark current-voltage curve still remains unchanged near this voltage. \( I_p \) as well as the dark current \( I_d \) increases sharply at the voltage near 50 V, and the slope reduces when \( V_{DC} \) exceeds 51.8 V. The punch-through voltage for this APD is 30 V, but this cannot be indicated clearly in the figure.

To learn more about the data from the experiment, we plotted the relative current gain \( G_r \) which is defined as

\[
G_r = 1 + \frac{R_d}{dI_o/dV}
\]

versus \( V_{DC} \) in Fig. 3, where \( I_o \) is the output current (dark current or photocurrent). The constant 1 is arbitrarily chosen just to avoid zero in the logarithmic plot. As shown in the figure, there is a sudden jump of \( G_r \) for \( I_p \) from 1 at a voltage of 30 V, clearly indicating the punch-through. At the voltage above the punch-through value, photocarriers created within the absorption layer can be swept into the multiplication layer by the nonzero electric field. \( G_r \) for \( I_d \) is approximately 1 when \( V_{DC} \) is below 50 V, as well as \( G_r \) for \( I_r \) before punch-through. \( G_r = 1 \) means that there is no avalanche multiplication. \( G_r \) begins to saturate and no longer rises with \( V_{DC} \) when it reaches 51.8 V. In this letter, \( V_B \) is defined as the voltage when \( G_r \) is saturated at a constant other than 1. Therefore, \( V_B \) is 51.8 V for the APD used in the experiment at −25 °C.

The next step of our investigation is to explain the saturation effect and the definition of \( V_B \). The current measured by the amperemeter is neither the instantaneous current nor the steady-state current, but the ensemble average value. It is equal to the total charge of the response pulse accumulated in unit time.

Avalanche quenching corresponds to opening the switch in the equivalent circuit of Fig. 1(b). The voltage of the device APD can be easily obtained from the differential equation for the equivalent circuit and can be

Fig. 2. \( I-V \) curve for dark current and photocurrent of the 80-μm-diameter InGaAs/InP APD at temperature of −25 °C.

Fig. 3. Relative current gain as a function of the voltage on the APD clearly shows the punch-through and breakdown voltage.

Fig. 4. Waveform of avalanche.
The output current $I_o$ can be represented as

$$I_o = \left( V_t - V_B \right) (C_d + C_s) N \quad \frac{}{}$$

where $N$ is the average avalanche rate in unit time, and $t_t$ is the time needed for $V_d$ to recover to $V_t$ from $V_B$. In our experiment, $t_t = 0.2858T_R$, resulting in an $I_o$ value of 0.8698$f$. The value of $V_t$ predicted by Eqs. (7) and (10) agrees with that monitored by the oscilloscope. Both $t_t$ and $T_R$ are independent of $V_{DC}$, but $I_t$ is a linear function of $V_{DC}$, therefore $I_o$ has a linear dependence on $V_{DC}$, $G_e$ is saturated at a voltage above breakdown according to Eq. (10).

The waveform of the avalanche is shown in Fig. 4. A direct current (DC) voltage of 51.7 V superposing the 0.8-V gate voltage is applied on the APD. The excess voltage is 0.7 V, corresponding to $I_t$ of about $3.5 \mu A$, while the measured $I_o$ is 4.1 $\mu A$. As shown in the figure, $t_t$ is about 0.1 $\mu s$, while $T_R$ is 0.4 $\mu s$. Both $V_t$ (51.9 V and alternating current (AC) portion about 160 mV) and $I_o$ agree with the values predicted by Eqs. (7) and (10).

In Fig. 5, the dark count probability per gate and the detection efficiency are plotted as functions of the excess voltage. Gate pulses of 5 ns full-width at half-maximum (FWHM) are applied to the APD after combining with a DC bias of 51.3 V at a temperature of 228 K.

In conclusion, we examine the saturation of the relative current gain. The punch-through voltage and breakdown voltage of SPADs can be measured using a simple and accurate method. The analysis used in this letter is temperature-independent and can be applied to most SPADs.

This work was supported by the National Basic Research Program (973 Program) of China (Nos. G20010339302 and 007CB307001) and the Guangdong Key Technologies R&D Program (No. 2007B010400009).

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