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**NEW METHOD FOR DETERMINING AVALANCHE  
BREAKDOWN VOLTAGE OF SILICON  
PHOTOMULTIPLIERS**

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Новый метод определения напряжения лавинного пробоя кремниевых фотоумножителей

Рассмотрен лавинный пробой и гейгеровский режим работы кремниевого  $p-n$ -перехода. Предложен прецизионный физически мотивированный метод определения напряжения лавинного пробоя кремниевых фотоумножителей (Si ФЭУ). Метод основан на измерении зависимости относительной эффективности регистрации фотона ( $PDE_{отн}$ ) от напряжения смещения при инжекции в зону лавинного размножения  $p-n$ -перехода одного типа носителей (электрона или дырки). Инжекция электрона или дырки из базовых областей полупроводниковой структуры Si ФЭУ осуществляется с помощью коротковолнового или длинноволнового света. При малых перенапряжениях (1–2 В) эффективность регистрации линейно зависит от напряжения смещения, и поэтому экстраполяция  $PDE_{отн}$  до нулевого значения определяет напряжения лавинного пробоя Si ФЭУ с точностью несколько милливольт.

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New Method for Determining Avalanche Breakdown Voltage of Silicon Photomultipliers

The avalanche breakdown and Geiger mode of the silicon  $p-n$  junction is considered. A precise physically motivated method is proposed for determining the avalanche breakdown voltage of silicon photomultipliers (Si PM). The method is based on measuring the dependence of the relative photon detection efficiency ( $PDE_{rel}$ ) on the bias voltage when one type of carriers (electron or hole) is injected into the avalanche multiplication zone of the  $p-n$  junction. The injection of electrons or holes from the base region of the Si PM semiconductor structure is performed using short-wave or long-wave light. At a low overvoltage (1–2 V) the detection efficiency is linearly dependent on the bias voltage; therefore, extrapolation to zero  $PDE_{rel}$  value determines the Si PM avalanche breakdown voltage with an accuracy within a few millivolts.

The investigation has been performed at the Dzheleпов Laboratory of Nuclear Problems, JINR.

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In modern experimental physics, development of new devices shows a clear trend to replace traditional optical detectors by silicon photomultipliers (Si PMs) — a new generation of photodetectors. Si PMs are micropixel silicon avalanche photodiodes operating in the so-called Geiger mode at a bias voltage higher than the breakdown voltage. Therefore, Si PMs have a high internal amplification rate  $\sim 10^6$  at room temperature and can detect weak light fluxes at a level of individual photons counts.

The internal gain in the photodiode can be obtained, in principle, by creating a strong electric field in the depleted region of the  $p-n$  junction, and free charge carriers accelerated in this field could produce impact ionization of the  $p-n$  junction and develop the avalanche multiplication process. The dependence of the gain  $G$  on the reverse bias voltage  $V_b$  of the avalanche photodiode (APD) and different regions of the electric discharge by analogy with the operating modes of the gas counter of nuclear radiation are schematically shown in Fig. 1.

The multiplication process of free carriers in the  $p-n$  junction is characterized by a  $k$ -factor equal to the ratio of the impact ionization coefficients of holes and electrons ( $k = \beta/\alpha$ ). For silicon,  $\alpha > \beta$  for any values of the electric field strength [1, 2]. In the proportional region (i.e., when the output signal is proportional to the intensity of the detected light) avalanche multiplication is mainly due to electrons ( $k \ll 1$ ) and therefore the avalanche is quenched. The

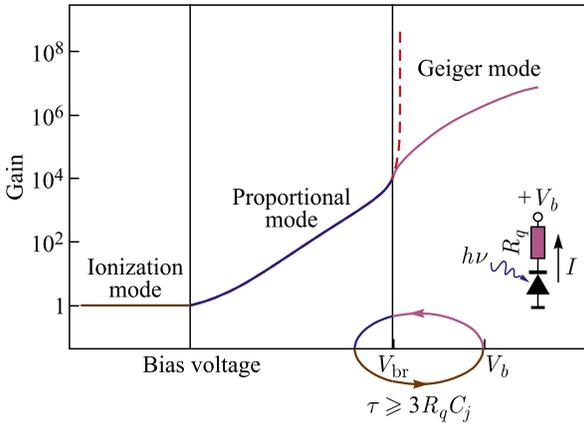


Fig. 1. The schematic representation of the gain versus the reverse bias voltage for an avalanche photodiode

gain of the avalanche photodiode in the proportional mode  $G_e \geq \exp(\alpha W)$ , where  $W$  is the width of the avalanche multiplication zone and reaches  $10^4$  at room temperature [3].

With increasing  $V_b$  the electric field strength in the depletion region of the  $p$ - $n$  junction grows, which leads to an increase in the impact ionization coefficients of electrons and holes, and  $k$ -factor [2]. The avalanche multiplication at a bias voltage higher than a certain threshold value, so-called breakdown  $V_{br}$ , is due to both electrons and holes ( $k \rightarrow 1$ ). At high electric fields ( $E \geq 5 \cdot 10^5$  V/cm), impact ionization of the  $p$ - $n$  junction by holes gives rise to positive internal feedback and, as a consequence, to development of self-sustaining electron-hole avalanche and thermal breakdown of the photodiode  $p$ - $n$  junction [4]. At the bias voltage  $> V_{br}$ , production of one electron-hole pair in the avalanche multiplication region of the  $p$ - $n$  junction is enough to initiate a self-sustaining discharge with a formal gain  $G \rightarrow \infty$ . The probability of triggering the avalanche breakdown by an electron or a hole is given by  $P_{pair} = P_e + P_h - P_e P_h$ , where  $P_e$  and  $P_h$  are the electrons and holes triggering probabilities. It is important to note that when  $V_b = V_{br}$ , the triggering probability is  $P_e = P_h = 0$ .

The discharge can be interrupted by a quenching resistor  $R_q$  connected in the bias circuit in series with a photodiode (Fig. 1), which creates a negative external feedback. To quench the discharge, it is necessary to reduce on the  $p$ - $n$  junction to voltage  $V_{br}$ , i.e., the voltage drop across the resistor during the discharge should be equal to or larger than the so-called overvoltage  $\Delta V = V_b - V_{br}$ . Thus, for quenching the discharge the condition  $R_q I \geq V_b - V_{br}$  should be fulfilled. The electron-hole avalanche stops when  $V_b = V_{br}$ , but the voltage across the photodiode continues to decrease as a result of draining of the accumulated charge carriers from the  $p$ - $n$  junction to the base regions of the APD.

The time of recovery of the  $p$ - $n$  junction potential to its original condition after the avalanche discharge is  $\tau \geq 3R_q C_j$  in accordance with the exponential law of the recharging of the  $p$ - $n$  junction capacitance  $C_j$  through the quenching resistor  $R_q$ . With increasing bias voltage, the recovery time significantly increases as a result of partial discharge of  $C_j$  due to the increase in the dark current, and others [5].

Thus, the APD operation at a bias voltage higher than the breakdown voltage with negative feedback made via the resistor  $R_q$  in the bias circuit in series with the photodiode is called the Geiger mode by analogy with the gas-discharge Geiger-Muller counter. Due to the linear element  $R_q$  connected in the bias circuit, the gain in the Geiger mode is a linear function of the overvoltage  $G_{eh} \sim C_j(V_b - V_{br})$ .

The silicon photomultiplier is a matrix of identical small  $p$ - $n$  junctions (pixels) with quenching resistors connected in parallel on the surface of the common silicon substrate. The typical pixel density is  $10^2$ – $10^4$   $\text{mm}^{-2}$  with a pitch of 10–100  $\mu\text{m}$ .

The pixels are independent photon microcounters working in the digital (Geiger) “yes/no” mode. They generate a standard signal when detecting a single photon, but at the detection flashes of light, when a lot of pixels are simultaneously fired, the output signal on the total load is a sum of standard signals. Thus, the SiPM is in general an analog device capable of measuring the intensity of light with a dynamic range corresponding to the total number of pixels.

The main characteristics of the SiPM (gain, detection efficiency, and others) are determined by the overvoltage  $\Delta V = V_b - V_{br}$ . Therefore, the avalanche breakdown voltage  $V_{br}$  is an important parameter, the determination of which is necessary for detailed studies and application of the SiPM. The spread of  $V_{br}$  allows estimating the influence of different technological factors and processes in the development and production of the SiPM.

Note that  $V_{br}$  increases with temperature. The temperature coefficient of the avalanche breakdown voltage  $V_{br}(T)$  is also an important parameter of SiPM.

There are several methods for determining the breakdown voltage of the SiPM [6–16], which are based on different assumptions and models and therefore have limited accuracy. The new physically motivated precision method for determining  $V_{br}$  is based on measurements of the relative SiPM detection efficiency.

The photon detection efficiency (*PDE*) is the product of the geometrical factor  $\varepsilon$  (ratio of sensitive area to total surface of SiPM), pixel quantum efficiency *QE*, and probability  $P_{tr}$  for triggering avalanche breakdown by the produced free charge carriers:

$$PDE = \varepsilon QE(\lambda) P_{tr}(\lambda, T, \Delta V).$$

The quantum efficiency of the pixel is determined by the probability for production of the charge carriers in the sensitive volume and significantly depends on the wavelength  $\lambda$  of the detected light:

$$QE(\lambda) = [1 - r][\exp(-L_{ep}/\lambda_{ep}(\lambda))][\exp(-L_{SiO_2}/\lambda_{SiO_2}(\lambda))] \times \\ \times [1 - \exp(-L_{Si}/\lambda_{Si}(\lambda))],$$

where  $r$  is the reflection coefficient from the pixel surface,  $L_{ep}$  and  $L_{SiO_2}$  are the thicknesses of the epoxy resin and silicon oxide layers used as protective coatings,  $\lambda_{ep}(\lambda)$  and  $\lambda_{SiO_2}(\lambda)$  are the light absorption lengths in the coatings,  $L_{Si} = W_n + W + W_p$  is the thickness of the sensitive layer (Fig. 2), and  $\lambda_{Si}(\lambda)$  is the light absorption length in silicon.

The avalanche breakdown triggering probability depends on the overvoltage and on the position where the primary electron–hole pair is produced in the sensitive layer of the pixel. Three photogeneration zones of primary electron–hole pairs  $W_n$ ,  $W$ ,  $W_p$  and their typical thickness [17] are shown in Fig. 2. The triggering probability of the electron–hole pair in the avalanche multiplication

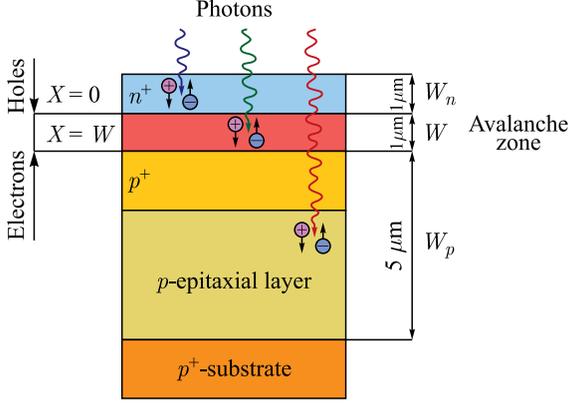


Fig. 2. A simplified schematic view of the pixel structure on the  $p$ -substrate

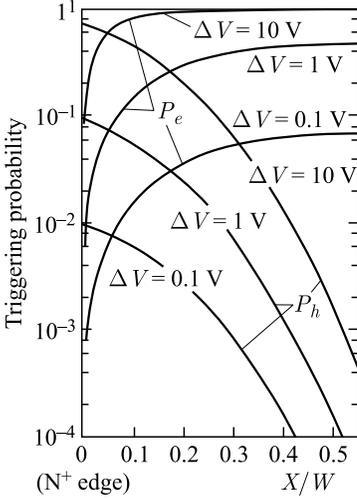


Fig. 3. The triggering probabilities  $P_e(x, \Delta V)$  and  $P_h(x, \Delta V)$  as a function of the positions of the carriers generated in the avalanche multiplication zone with a width  $W$  at several overvoltage values  $\Delta V$  [18]. Coordinates of the zone boundaries  $X = 0$  and  $X = W$  are shown in Fig. 2

zone  $W$  is given by

$$P_{\text{pair}}(x, \Delta V) = P_e(x, \Delta V) + P_h(x, \Delta V) - P_e(x, \Delta V)P_h(x, \Delta V),$$

where  $P_e(x, \Delta V)$  and  $P_h(x, \Delta V)$  are the triggering probabilities for electrons and for holes generated at the point with the coordinate  $x$  at overvoltage  $\Delta V$ . Figure 3 shows the dependence of  $P_e(x, \Delta V)$  and  $P_h(x, \Delta V)$  on the coordinates of the generation of charge carriers in the avalanche multiplication zone calculated by W. G. Oldham et al. [18].

Electrons and holes produced in the zone  $W_p$  drift in the electric field in opposite directions, holes to the  $p$ -base and electrons to the avalanche multipli-

cation zone  $W$ , and thus the latter can trigger an avalanche breakdown. On the contrary, if the photons are absorbed in zone  $W_n$ , an avalanche can be triggered only by holes. The avalanche triggering probability of electrons and holes produced outside multiplication zone  $W$  was calculated and verified experimentally by P. Antognetti, W. G. Oldham (Fig. 4) [19]. The triggering probability of holes is much lower than that of electrons due to the difference between their impact ionization coefficients ( $\alpha > \beta$ ).

As can be seen in Fig. 4, the triggering probabilities of electrons and holes injected into the avalanche multiplication zone of the  $p$ - $n$  junction are linear functions of overvoltage at its low values (1–2 V). The  $PDE$  is proportional to the triggering probability; therefore, it is also a linear function of the overvoltage and consequently of the bias voltage  $V_c$ . Extrapolation of the function  $PDE = PDE(V_c)$  or relative  $PDE_{rel} = PDE_{rel}(V_c)$  to zero values determines the SiPM avalanche breakdown voltage.

Electrons or holes can be injected into the  $W$  avalanche multiplication zone using short-wave or long-wave light. If the SiPM is illuminated by short-wave light with  $\lambda = 400$  nm, it is almost completely absorbed ( $> 99\%$ ) in the layer  $W_n$ , and holes will drift into the zone  $W$ . If the SiPM is illuminated by long-wavelength light with  $\lambda = 1000$  nm, which is weakly absorbed in thin  $W_n$  and  $W$  layers ( $\approx 1\%$ ), it is mainly electrons that will drift from the layer  $W_p$  into the avalanche multiplication zone.

To illustrate the method, we determine the avalanche breakdown voltage for the SiPMs of two types, SSPM-050701GR-TO18 and S60 [20]. Their  $PDE$  is measured by the method of low-intensity light flashes ( $\sim 10$  photons) method [21, 22], when the probability for production of free charge carriers in the sensitive layer of SiPM is low.

A typical LED charge spectrum of the SiPM for low-intensity light pulses is shown in Fig. 5. In accordance with the Poisson distribution  $P(n; \mu) = \mu^n \exp(-\mu)/n!$ , the average number of photogenerated pairs that triggered avalanche breakdown pixels of the SiPM is

$$\mu = -\ln P(0; \mu),$$

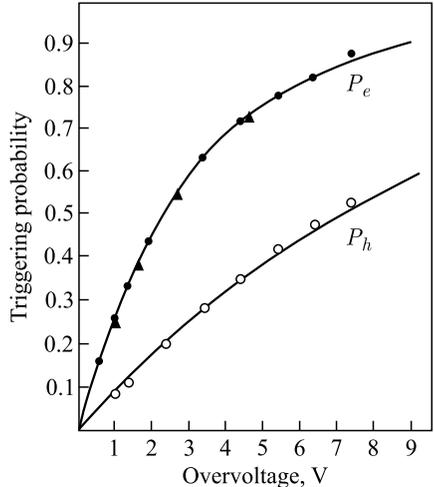


Fig. 4. The avalanche triggering probabilities for electrons  $P_e$  and for holes  $P_h$  as a function of the overvoltage  $\Delta V$  [19]

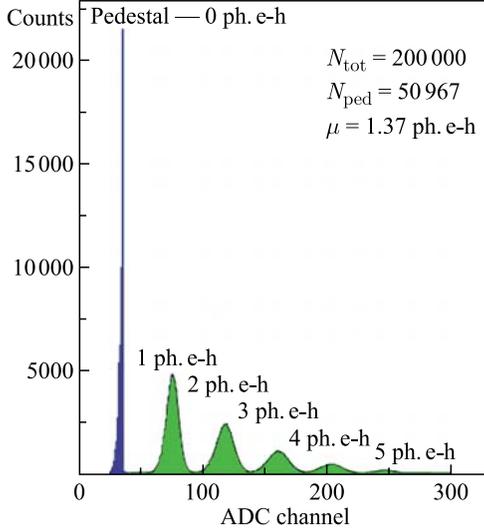


Fig. 5. The S60 SiPM pulse height spectrum for low-intensity light flashes with the mean number of photogenerated electron-hole pairs  $\mu = 1.37$  ph. e-h

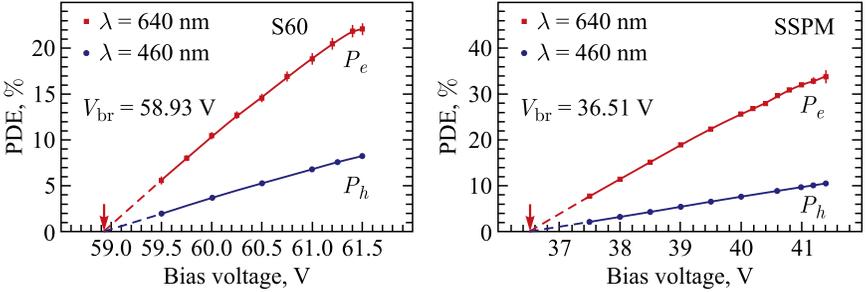


Fig. 6. The photon detection efficiency as a function of the overvoltage for different wavelengths of light for the S60 and SSPM-050701GR-TO18 SiPMs based on  $p$ -substrate

where  $P(0; \mu) = N_{\text{ped}}/N_{\text{tot}}$  is the probability of non-generation of a signal from SiPM,  $N_{\text{ped}}$  is the number of events in the pedestal and  $N_{\text{tot}}$  is the total number of events in the spectrum. The photon detection efficiency was determined from the expression

$$PDE = -\ln(N_{\text{ped}}/N_{\text{tot}})/N_{\text{ph}},$$

where  $N_{\text{ph}}$  is the average number of photons incident on the SiPM. The average number of photons was estimated by the H6780-04 photosensor (Hamamatsu) with the known quantum efficiency using the low-intensity light flash method.

The *PDE* measurement was performed using red ( $\lambda \approx 640$  nm) and blue ( $\lambda \approx 460$  nm) light, when mainly one type of free charge carriers, electrons or holes, are injected into the avalanche multiplication region. The linear extrapolation of the initial part of  $PDE = PDE(V_c)$  dependence to zero values determines the Si PM avalanche breakdown voltage (Fig. 6). The values of breakdown voltage obtained for different wavelengths of light coincide with high accuracy  $\sim 10^{-3}$  V, which confirms the reliability of the proposed method.

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