Recent advances in the detection of optical photons with silicon photodiodes

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Geiger-mode avalanche photodiodes are interesting substitutes for conventional photomultiplier tubes in measurements of fast optical waveforms. In this paper we discuss the physical mechanisms involved in the detector operation and we clarify how these effects set a limit to the achievable timing performance. We show that a proper choice of the electric field profile is mandatory for the design of devices combining high quantum efficiency and timing resolution given by the ultimate transit time limit.

1. Introduction

The extended quantum efficiency of solid-state devices in the near infrared makes high sensitivity semiconductor detectors interesting substitutes for conventional photomultiplier tubes (PMTs). In this perspective, the demonstration of silicon photodiodes with timing performance comparable and even better than that of microchannel-plate PMTs have opened the way to new applications of such devices in fast optical waveform measurements, laser ranging, optical time domain reflectometry, and so forth [1–3].

Essentially, these devices are p–n junctions working as Geiger-Müller counters. In the following we will focus our discussion on the two structures shown in fig. 1 [4,5]. The photodiode is operated biased above the junction breakdown voltage, $V_b$, so that the electric field at the n+p junction is high enough to sustain the avalanche multiplication. However, the diode current is negligible until the first carrier, generated in the junction depletion layer, impact ionizes, thus triggering a diverging avalanche process. A suitable electronic circuit senses the rise of the diode current and quenches the multiplication process by lowering the bias voltage down below $V_b$. If the first carrier is photogenerated, the leading edge of the avalanche pulse is synchronous with the photon arrival time. Finally, after a suitable dead time, the circuit restores the bias up to above $V_b$, and the device is again able to detect another photon [6].

In principle, the measurement of the photon arrival time is affected by jitter, due to both the detector and the electronics. We have developed circuits with time jitter less than 10 ps FWHM (full width at half maximum). However, our experiments showed that the best time resolution ranges from 20 to 350 ps FWHM, depending on the device geometry [1,5]. It follows that the detector itself is the limiting factor for the timing

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Fig. 1. Cross section of the samples used in the experiments: (a) thin junction device, (b) thick junction device (RCA C30902S).
Dimensions are quoted in μm.
performance. Therefore, our efforts have been devoted to gain a deeper insight in the detector operation and in the link between design parameters and achievable time resolution.

In this paper we show that, in spite of the simple device structure, many mechanisms are involved in its operation as a Geiger-mode avalanche photodiode (GM-APD). We clarify how these effects set a limit to the timing performance, and how the detector design can be modified to avoid them.

2. Physical mechanisms affecting the time resolution

The time jitter in GM-APDs is the evidence of randomness in the physical mechanisms involved in the device operation. In the following, we introduce and discuss such mechanisms.

2.1. Photon absorption in the depletion layer

A first contribution to the time jitter comes from the depth of the depletion layer. In fact, the avalanche process starts when the photogenerated pair impact ionizes for the first time. This event occurs with a statistical delay, mainly depending on the distance between the point where the photon is absorbed and the high field region, where impact ionization most likely occurs.

If a monochromatic radiation is considered, the absorption probability is an exponentially decaying curve, with a characteristic length, $L_\alpha$, strongly dependent on the wavelength. If $L_\alpha$ is much longer than the depletion layer thickness, $W$, and the electric field makes the carriers drift at the saturated velocity, $v_s$, almost everywhere in the depleted region, this time jitter will be of the order of $W/v_s = 10 \text{ ps/\mu m}$. It follows that the thinner the depleted region, the better the ultimate time resolution. Unfortunately, other jitter mechanisms do not allow to reach this limit.

2.2. Multiplication buildup

It is well known that the avalanche multiplication is a stochastic process. Even if an ionization mean free path can be defined, the point where a carrier will actually ionize is random. The fluctuations in the number and in the position of ionizing events cause an additional jitter in the delay between the triggering of the avalanche process and the crossing of the current detection threshold. We studied the phenomenon with a Monte Carlo approach. Fig. 2 shows a typical result of the simulation of the avalanche current rise, for the structure of fig. 1a. The photon is absorbed at $t = 0$. The shift in the onset of each current waveform corresponds to the time required to the first photogenerated carrier to reach the high field region and to impact ionize. As long as the average number of carriers in the depletion layer is below about one hundred, the statistical jitter in the history of each carrier affects significantly the following current growth. This is why the current waveform looks very noisy at the beginning. In case of all the carriers fail to ionize, the avalanche gets quenched. When the carrier density is high enough, the statistical fluctuations are averaged and the current follows the dashed exponential rise, in agreement with the theoretical result obtained by solving the time-dependent continuity equation [7]. The corresponding time constant $\tau$ is given by:

$$
\tau = \frac{1}{(V_{th} + V_{th})} \int_0^Z \exp \left( - \int_x^Z (\alpha - \beta) \, dx' \right) \, dx
$$

$$
= \frac{Z \gamma}{V_{th}(1 - \gamma)},
$$

where $v_h$ and $v_e$ are the holes and electrons saturated velocities, respectively; $Z$ is the thickness of the high field region, where the multiplication coefficients for electrons and holes, $\alpha$ and $\beta$, are not negligible; $\gamma$ is a factor 0.6–0.7 in a silicon junction with a low $V_{th}$. Note that the external integral, $I$, in the denominator of eq. (1) can be referred to as the loop gain of the avalanche process (which has a regenerative feedback). As can be inferred from the simulations, the overall jitter in the crossing of a threshold at 1 $\mu A$ or higher is $= 10$ ps FWHM, i.e., much lower than the observed value attained with the fastest device. We concluded that this mechanism is not important in present devices.

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density exponentially rises by avalanche multiplication around the seed point. (iii) Space charge effects locally lower the electric field. (iv) In a few picoseconds the carrier density is so high that the maximum electric field reaches the breakdown value. The multiplication process becomes self-sustaining and the diode current cannot increase further, until the avalanche is triggered in another region. This spread can be assisted by lateral drift and diffusion of free carriers. (v) When the multiplication process occurs over the whole active area, the avalanche current reaches its final steady-state value.

Let us first make some comments on the lateral diffusion. The density of free carriers over the junction area shows a strong gradient at the border between the region where the impact ionization already occurs and the neighboring non-avalanching region. Once a carrier has reached this region by diffusion, it can trigger the avalanche even here. The free carrier density steeply rises and reaches in a few picoseconds its maximum value. The boundary region interested by the density gradient has thus moved, but the gradient is unchanged. Therefore the phenomenon is not a simple diffusion but it is assisted by the avalanche multiplication, which bootstraps the lateral spreading. We estimated that the spreading velocity of such a mechanism is given by

$$v_p = 2\sqrt{D/\tau},$$

where $\tau$, given by eq. (1), depends on the device bias and $D$ is the mean diffusion carrier coefficient. In GM-APDs with high field regions less than 2 $\mu$m thick and biased more than 20% above $V_b$, eq. (2) gives a spreading velocity higher than 10 $\mu$m/ns, in quantitative agreement with the experiments.

At the interface between avalanching and non-avalanching regions, the carriers also experience an electric field which could assist their lateral drift outward the avalanching region. However a first estimate of this contribution shows that it is negligible compared to the diffusion effect.

In order to make it clear how the avalanche spreading impairs the timing performance of the detector, note that avalanches triggered at different positions lead to different current rise times. In fact, the closer the seed point is to the center of the junction area, the faster is the activation of the whole device and thus the rise of the avalanche current. Since the detector circuit senses the photon when the diode current crosses a discriminator threshold, the randomness in the position where the photon impinges leads to a randomness in the crossing time of the threshold. Thus, it is not surprising that the time resolution of these devices increases by reducing the illuminated area on the GM-APD [8].

2.3. Position of photon absorption over the active area

In a GM-APD, the steep growth of the free carrier density causes space charge effects, which lower the junction electric field, thus slowing down the multiplication process. At steady state, the junction electric field has reached everywhere its breakdown value, and a uniform current density flows through the whole device area. Since the avalanche is triggered in a single seed point and, at steady state, the multiplication occurs over the entire junction area, there should be a transverse propagation of the avalanche activation. We have studied this phenomenon both theoretically and experimentally. We found that this spreading is assisted by various mechanisms and that, depending on the device geometry, one or another can dominate [5,6].

Our approach was to study the avalanche spreading by measuring the dependence of the current leading edge on the position where the photon impinges. In shallow junctions, such as the device in fig. 1a, the experimental waveforms of the avalanche build up can be accurately fitted, at different seed positions and bias arrangements, by assuming that the lateral spread of the avalanche occurs with a constant velocity $v_p = kI_f$ (see fig. 3), where $I_f$ is the final steady state current flowing through the junction and $k$ is a constant (3 $\mu$m/ns mA for the device of fig. 1a).

On the basis of these results, we concluded that the multiplication process spreads according to the following physical picture: (i) The avalanche is firstly triggered in a point of the device area. (ii) The free carrier density exponentially rises by avalanche multiplication around the seed point. (iii) Space charge effects locally lower the electric field. (iv) In a few picoseconds the carrier density is so high that the maximum electric field reaches the breakdown value. The multiplication process becomes self-sustaining and the diode current cannot increase further, until the avalanche is triggered in another region. This spread can be assisted by lateral drift and diffusion of free carriers. (v) When the multiplication process occurs over the whole active area, the avalanche current reaches its final steady-state value.
3. Time resolution and device design

We have pointed out that the best timing performance can be achieved in devices where the avalanche spreading is steered by multiplication-assisted diffusion. In this section we give some guidelines on the design of high performance GM-APDs. Usually the depletion layer thickness is determined by the quantum efficiency required at a certain wavelength. Therefore, just to pinpoint some fundamental dependences we refer to a reach-through structures with a 30 μm depletion layer, and we discuss how the device performance is affected by the change of the sensitive area diameter and of the electric field profile.

Let us first consider the device (D#1) of fig. 1b. At 275 V, it is 40 V above the typical Vp of 235 V. The electric field intensity peaks at the n-p junction (3.3 x 10^5 V/cm) and progressively decreases in the p-doped layer, reaching 10^5 V/cm at about 3 μm from the junction. In the almost intrinsic region of the depletion layer, an electric field of 10^4 V/cm makes the carriers drift at saturated velocity. For comparison we also consider a second device (D#2) with a similar doping profile but a high field region only 0.1 μm thick and a Zo of 163 V. Since the two devices have different Zo, we compare their performance at the same relative excess bias (Vp-V)/Vp. For D#2 this requirement leads to an operating voltage of 190 V and a peak electric field of 6 x 10^5 V/cm.

Fig. 5 shows the dependence on the device radius of both diffusion and photon assisted spreading velocities.

Another phenomenon can compete with the lateral diffusion. It is well known that hot carriers in avalanching p-n junctions emit photons even in the visible range. While the physical origin of this radiation is still a debated issue, the emission intensity and spectrum of these secondary photons have been measured. The emission probability was independently estimated by McIntyre [9] and by us in 10^-5 photons with energy higher than the silicon bandgap per carrier crossing the junction. It follows that a hot-carrier related photon, emitted in the avalanching region, can be absorbed in another region of the device area, thus triggering the avalanche even there. Since the probability for a photon to be absorbed in the detector is proportional to the device active volume, this process is likely to dominate the avalanche spreading in APDs with large area and thick depletion layer, as the one shown in fig. 1b (RCA C30902S).

We have studied the spreading process in reach-through photodiodes, both experimentally and with a Monte Carlo simulation. It comes out that photons having an absorption coefficient = 10 cm^-1 are the most effective in spreading the avalanche. In these photodiodes, the avalanche spreads randomly instead of propagating evenly and any dependence of the current rise on the seed point is completely lost. The avalanche signal has a rise time which does not depend on the seed point.

Fig. 4 shows the Monte Carlo simulation of the avalanche pulse in the reach-through device shown in fig. 1b. The current leading-edge and the time jitter obtained from the simulation closely fit the experimental results. The intrinsic randomness of the photon-assisted process leads to a worse timing performance of thick-junction devices. Therefore it is not an academic problem to forecast which mechanism is responsible for the spreading of the avalanche in a GM-APD. The following section focuses on this topic.

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The results were obtained from a computer simulation of the avalanche dynamics. The diffusion velocity was estimated from eq. (1), while the photon assisted contribution was estimated by switching off the diffusion process in the simulation and then computing the resulting ratio between the device radius and the current risetime. As expected, the role of the photon-assisted process increases by increasing the sensitive area diameter; it becomes eventually dominant in D#1 for radii greater than 80 μm. D#2 has a diffusion velocity more than three times larger than D#1. This is a direct consequence of the steeper field profile of D#2. In fact, since the two devices are compared at the same relative excess bias, they have almost the same loop gain of the avalanche process, ∆. It follows from eq. (1) that the thinner high field region of D#2 yields a shorter time constant, τ, and a faster diffusion-assisted spreading (eq. (2)).

These results highlight that, by adopting a suitable steep electric field profile, the diffusion-assisted avalanche spreading can overcome the noisy photon-assisted process even in reach-through APDs with a diameter larger than 100 μm. Therefore, APDs for photon timing applications with large sensitive area and high quantum efficiency should be designed with a steep electric field profile. Note that this criterion is exactly the opposite of the design rule for low-noise APDs operated below Vp, where the peak electric field is kept low in order to minimize the avalanche multiplication noise.

4. Conclusions

The time resolution of current GM-APDs is limited by the mechanisms involved in the spreading of the avalanche over the device area. The best performance is obtained when the detector area is reduced and the steering mechanism is the multiplication-assisted diffusion. We have shown that by a proper design of the electric field profile the latter mechanism can be made dominant. This result open the way to the design of new detectors combining high quantum efficiency and a timing resolution given by the ultimate transit time limit.

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