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On the efficiency of photon emission during electrical breakdown in silicon

A. Nepomuk Otte [a,b,*]

[a] Santa Cruz Institute for Particle Physics, University of California, 1156 High Street, Santa Cruz, CA 95060, USA
[b] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

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ABSTRACT

This paper presents a study of photons that are emitted during electrical breakdown in p–n silicon diodes. The method that was developed for this study uses the optical-crosstalk effect that is observed in Geigermode-APD (G-APD) photon detectors. The outcome of this study is twofold: firstly, mainly photons with energies between 1.15 and 1.4 eV contribute to the optical crosstalk in G-APDs used in this study. This observation is explained by the strong energy dependence of the absorption length of photons in silicon. Secondly, the intensity with which photons with energies between 1.15 and 1.4 eV are emitted during a breakdown is 3×10^{-5} photons per charge carrier in the breakdown region. The uncertainty of the intensity is estimated to be a factor of two. For this study a simulation package *Si*liconphotomultiplier *Si*mulator (*SiSi*) was developed, which can be used to address various other questions that arise in the application of G-APDs.

1. Introduction

The Geigermode-APD (G-APD)[1] has emerged as a promising novel photon detector for a number of potential applications ranging from medical imaging to demanding experiments in high-energy and astroparticle physics. The G-APD is a matrix of small avalanche photo diodes (hereafter called cells) with a packing density of typically 100 up to a few 1000 cells per square millimetre. Each cell autonomously operates in Geiger mode but the outputs of all cells are connected to a common readout. The G-APD has a number of specific features such as excellent single photoelectron resolution, logarithmic compression, a strong voltage dependence of the PDE, and optical crosstalk (OC), to name some of them. For a review of the G-APD, see e.g. Refs. [1,2].

One feature, optical crosstalk, is often a nuisance in many applications. The effect originates from photons that are emitted during the breakdown of a G-APD cell. If such a photon is absorbed in a cell that is different from the one from which it was emitted, a breakdown can be initiated in that cell. The probability that another cell is fired by OC depends on the layout of the G-APD, the operation parameters, and on the characteristics of the photon emission. In the extreme case, OC can cause a catastrophic cascade, which triggers all cells of a G-APD at once.

It is long since known that photons are emitted in the process of avalanches in semiconductors [3]. However, it is not clear what is the dominating emission mechanism of these photons (see e.g. Refs. [4–6]). The lack of clarity is partly caused by the significant systematic uncertainties of the measurements. This is, for example, reflected by the discrepancies in the measured emission spectra (see e.g. Refs. [7,8]).

In this paper, I present a method that characterizes the photons that cause OC in a $1\times1\,\mathrm{mm}^2$ large G-APD that was produced by MEPhI/Pulsar. The method determines (a) the energies of the photons that cause OC and (b) the efficiency with which these photons are emitted during the breakdown of a cell.

In Section 2, I describe the G-APD model that I used for this study. The method and the results of this study are presented in Section 3. This paper concludes with a discussion in Section 4.

2. The model

This study was done with a G-APD model that, hereafter, is called the *Si*liconphotomultiplier *Si*mulator, *SiSi*. The relevant processes, which needed to be simulated by *SiSi* are

- emission of photons during breakdown,
- ray tracing and absorption of photons,
- diffusion and drift of charges.

2.1. Layout of the simulated G-APD

Depending on the characteristics of the G-APD that one wants to study with a simulation, the description of the layout

* Corresponding author at: Santa Cruz Institute for Particle Physics, University of California, 1156 High Street, Santa Cruz, CA 95060, USA. Tel.: +1 831 459 4870; fax: +1 831 459 5777.
E-mail address: nepomuk.otte@gmail.com

[1] Other commonly used notations are SiPM, MPPC, DPPD, and so on.

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of the G-APD can be as simple as a Boolean array where each cell of the G-APD corresponds to one element of the array—which is, for example, sufficient to understand the basic responses of a G-APD to short (a few nanoseconds long) flashes of light. However, for the present study, it is necessary that the G-APD be simulated in all three dimensions, such that the propagation of photons and charges within the device can be adequately reproduced.

For a correct description of the behaviour of charge carriers and photons within the G-APD under study, the device that is used in this study is divided in *SiSi* into two regions in the vertical direction (cf. Fig. 1). The below given numbers refer to the design and are used in the simulation. The thicker and lower of the two regions is the p^{++}-doped bulk. The bulk is a low resistivity, non-depleted, and 390 μm thick silicon wafer. The region on top of the bulk is an epitaxial p-doped layer that is 2.5 μm thick. While the bulk is featureless and non-depleted, the epitaxial layer is mostly depleted and is subdivided into several regions, for example, the avalanche regions (n-on-p avalanche photo diodes of $21 \times 21\,\mu m^2$ in diameter), a very thin, non-depleted layer below the surface and additional dead regions between cells (42 μm pitch between cells).

2.1.1. Simulation of the emission and propagation of photons within the G-APD

In the simulation, it is assumed that the number of photons emitted in a breakdown is linearly correlated with the amount of charge that flows through the avalanche region, i.e. proportional to the gain of the G-APD. It is further assumed that the energy distribution of the photons can be described by a Planck distribution. The photon emission is thus parameterized by (a) the efficiency of photon emission per charge in the avalanche region and (b) the temperature of the Planck distribution. It is, moreover, assumed that the photons are emitted uniformly within the avalanche region and no preference is given to the direction of emission.

Once emitted, each photon is ray-traced in *SiSi* until the photon either leaves the G-APD or is absorbed. For the energy dependent absorption length, the data published in Ref. [9] are used in the simulation.

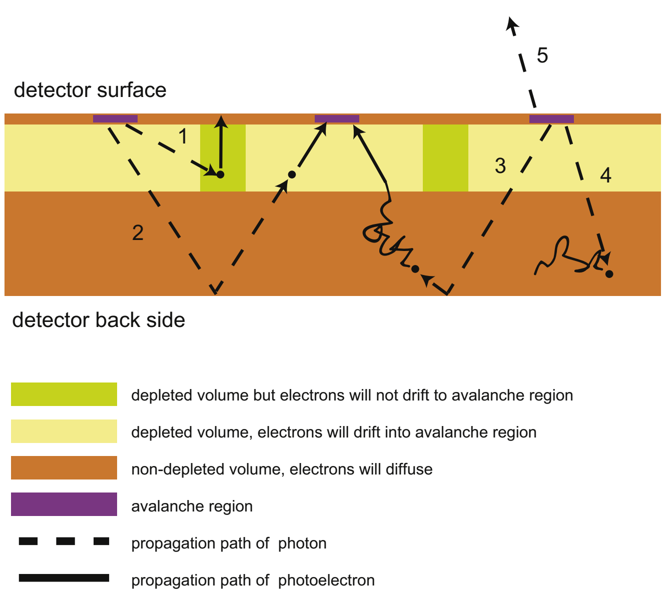

Fig. 1. Cross-section (not to scale) of the layout of the G-APD that is simulated with *SiSi*. Indicated in the figure are five different simulated cases of individual photons emitted in avalanches: 1. Absorption of a photon in depleted volume but neither the generated hole nor the electron drifts into the avalanche region (only one of the charge carriers, the electron, is shown). 2. Reflection of a photon from the surface of the detector and subsequent absorption of the photon in the depleted volume. The electron or hole drifts into the avalanche region and possibly initiates a breakdown of that cell. 3. Absorption of a photon in the non-depleted bulk. The minority charge carrier diffuses into the depleted epitaxial layer, drifts from there into the avalanche region of the cell and possibly initiates the breakdown of that cell. 4. Absorption of a photon in the non-depleted bulk and recombination of the minority charge carrier in the bulk. 5. Escape of a photon through the surface of the detector.

2.1.2. Simulation of drift and diffusion of charges

In the event of a photon being emitted in an avalanche and being absorbed in a depleted region of the epitaxial layer, for example cases 1 and 2 in Fig. 1, the created hole and electron experience a drift field that possibly guides one of them into the avalanche region where a breakdown can be initiated—case 2 in the figure. Note that Fig. 1 only shows the drift path of the charge carrier that drifts into the direction of the avalanche region. Whether this is the hole or the electron depends on the structure of the device, n-on-p in this case, and on whether the photon is absorbed in between the surface of the device and the avalanche region or below the avalanche region.

If a photon is absorbed in a non-depleted region, for example, in the bulk, the created minority charge carrier does not experience a drift field and, therefore, performs a random walk until the charge carrier either enters a depleted region (case 3 in Fig. 1) or recombines with a majority charge carrier (case 4). The period of time until the minority charge carrier recombines depends on the doping concentration of the bulk. In the device that was used in this study, the doping concentration of the p^{++}-bulk is $5 \times 10^{18}\,cm^3$ [10]. For such a doping level, typical recombination times of minority charge carriers are about 100 ns (e.g. Ref. [11], and references therein). During that period, the minority charge carrier typically diffuses a few tens of micrometres. If the minority charge carrier diffuses into the depleted region, it has the chance to drift into the closest avalanche region.

The simulation of a random walk is a time-intensive process, which is why a faster computational diffusion process is implemented in *SiSi*. Note that as long as recombination times are above 30 ns, the results do not depend on the actual value of the recombination time because additional breakdowns in the simulation and the measurement were only recorded within a period of time of 18 ns after the breakdown of the first cell.

3. Results

3.1. Measurement of optical crosstalk

For this study, the OC in the G-APD under study is quantified by recording noise events. A sample of noise events overlaid on top of each other is shown in Fig. 2. For the majority of the events, only the cell triggered by the noise event is observed. With lower probability, events are recorded where additional cells fire at the same time or somewhat delayed. These additional cells are fired by OC-photons. For this particular G-APD, the probability to fire at least one additional cell due to OC-photons is more than 30%. This is much higher than the probability that an additional cell is fired by uncorrelated noise, which is $<1\%$ if an additional noise event takes place within 10 ns after the first one.

Fig. 3 shows the frequency at which a given number of cells of the G-APD fires within a period of 18 ns. This is the so-called optical-crosstalk probability-distribution function (OC-distribution) and is a characteristic function of the G-APD.

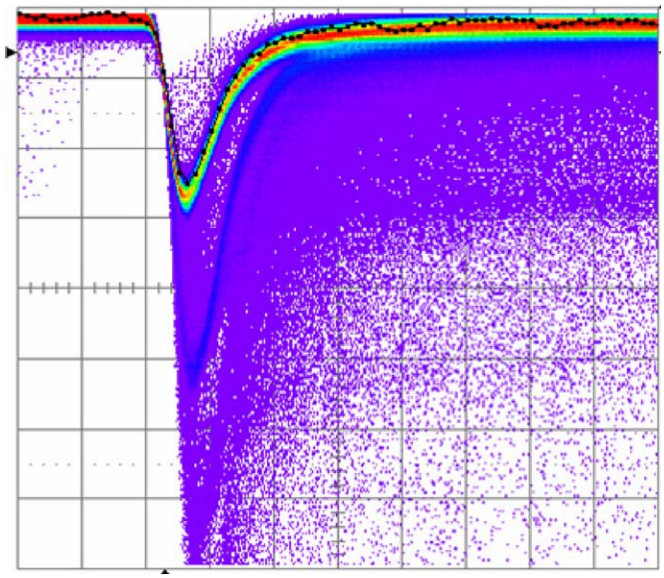

Fig. 2. An oscilloscope screen shot of many traces overlaid on top of each other (2 ns division in time and 2 mV in amplitude). The traces are from noise events of the studied G-APD. Most of the time, a signal corresponding to one fired cell is observed. With lower probability (indicated by the lower intensity in the figure), a signal of 2, 3 or even more simultaneous and delayed fired cells is observed. These are events in which additional cells have fired because of optical crosstalk.

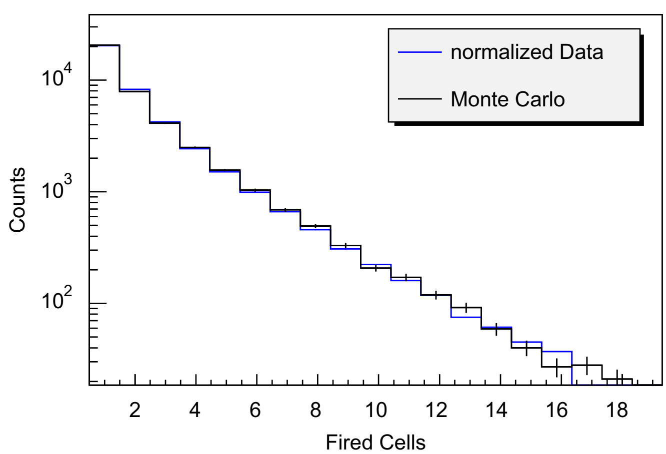

Fig. 3. Crosstalk distribution; measured (blue) and simulated (black) optical crosstalk probability distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Simulation of optical crosstalk

The OC-distribution is simulated by picking cells of the G-APD at random, generating a breakdown in the cell and each time recording the number of cells that are fired in addition to the randomly picked one by photons emitted during the breakdown. Fig. 4 shows two such simulated events where 7 and 10 additional cells, respectively, are fired by OC-photons. Both times the additional cells are not all fired by OC-photons from the first fired (primary) cell. This is indicated in the displayed events by the generation of a fired cell. Only the cells labelled as generation 1 were fired by OC-photons emitted in the primary cell. Cells labelled as generation 2 are fired by OC-photons from cells of the first generation and so on. Note that the depicted events are rare events that occur with a probability of about 1% (cf. Fig. 3).

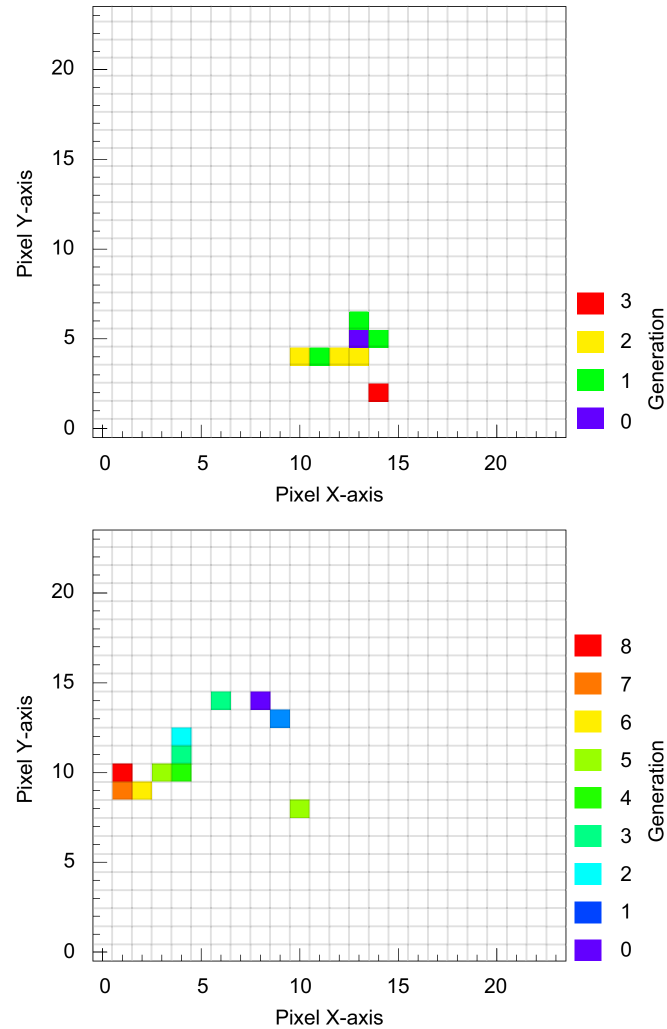

Fig. 4. Two simulated events where additional cells are fired due to crosstalk.

Fig. 3 also shows, in addition to the measured OC-distribution, a simulated distribution that was obtained in the described way above of randomly picking and firing a cell of the G-APD. Good agreement between both distributions is obtained after adjusting the two parameters, intensity and temperature, in the simulation that determine the energy spectrum of the emitted photons (see Section 2.1.1).

Note that, by setting the recombination time of the minority carriers in the bulk to zero, it can be determined that about 30% of the crosstalk in the studied G-APD is generated by minority carriers which diffuse out of the bulk.

3.3. Characteristics of optical-crosstalk photons

The good agreement of the simulated OC-distribution with the measurement to describe the photon emission during breakdown is not unique for one set of parameters. Equally good agreement is obtained for any a priori chosen temperature of the Planck spectrum and a posteriori adjusted efficiency of the photon emission [12]. The level of agreement between the simulation and the measurement, therefore, does not depend on the shape of the simulated emission spectrum but only on the intensity of the emission.

The observed lack of dependence on the shape of the emission spectrum indicates that only photons with energies in a very

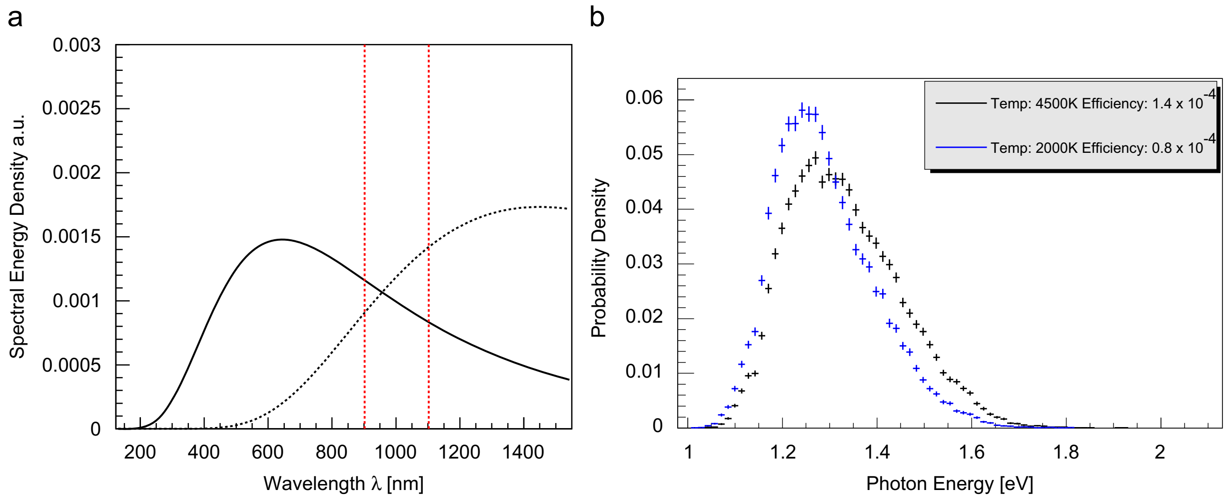

Fig. 5. The left panel shows two simulated emission spectra of photons during the breakdown of a cell; Planck spectra with a temperature of 4500 K (solid line) and 2000 K (dashed line), respectively. In both simulation the measured OC-distribution is reproduced. The dashed vertical lines mark the range of photon energies between 1.15 and 1.4 eV, where most of the OC causing photons is found. The right panel shows corresponding simulated energy distributions of photons that caused the breakdown of an additional cell. (a) Simulated photon-emission spectra and (b) energy distributions of photons that have fired an additional cell.

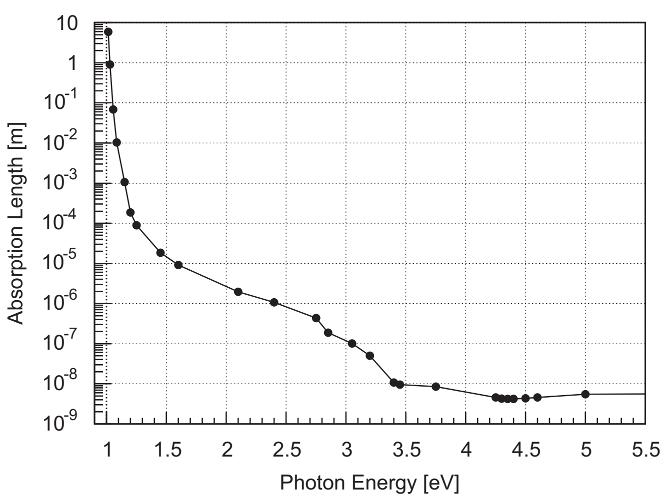

Fig. 6. Absorption length of light in silicon. Data from Ref. [9].

narrow range are responsible for optical crosstalk. This is confirmed if one investigates the energy distributions of the photons which have caused the breakdown of an additional cell and different sets of parameters for the photon emission which result in good agreement with the measured OC-distributions.

Fig. 5(a) shows two different emission spectra for which the simulated OC-distributions agree with the measurement. The corresponding energy distributions of the photons that have triggered additional cells to fire are shown in Fig. 5(b). Despite the very different emission spectra, the energy distributions are very similar. Moreover, with a full width at half maximum of 0.3 eV, the energy distributions are very narrow.

The reason for the narrow energy distribution is the strong energy dependence of the absorption length of light in silicon (cf. Fig. 6), which together with the geometry of the G-APD acts like an 'energy filter'. Photons with energies above 1.4 eV have absorption lengths of less than 10 μm and are likely to be absorbed within the same cell from which they are emitted. Photons with energies below 1.15 eV have absorption lengths above 1 mm and are likely not to be absorbed within the G-APD at all.

Because of the narrow energy distribution, the average intensity of the emitted photons in the energy range between 1.15 and 1.4 eV during a breakdown is determined but the spectrum is not (cf. range between the vertical lines in Fig. 5(a)). For different simulated emission spectra which reproduce the measured OC-distribution, an average intensity between 1.15 and 1.4 eV of 3×10^{-5} emitted photons per charge carrier in the breakdown is obtained. The result is uncertain by a factor of two, mainly because of uncertainties in the geometry of the G-APD.

4. Discussion

In this paper, I present a method that uses the optical-crosstalk effect of a G-APD to characterize some aspects of the emission of photons during breakdown in silicon. By reproducing the optical-crosstalk distribution of a G-APD produced by MEPhI/Pulsar in a Monte-Carlo simulation, I could determine the following characteristics of photons that cause OC in the studied G-APD:

- Mainly photons with energies between 1.15 and 1.4 eV cause additional cells to fire.
- The reason for the narrow, about 0.4 eV wide, energy distribution of the optical crosstalk producing photons can be attributed to the strong energy dependence of the absorption length of light in silicon and the geometry of the G-APD.
- In the energy range between 1.15 and 1.4 eV, the intensity of the photon emission during breakdown is 3×10^{-5} photons per charge carrier in the breakdown region. The intensity is uncertain by a factor of two, mainly because of remaining uncertainties in the layout of the device. Within these uncertainties the measurement agrees with Ref. [8].
- For the given design ~30% of the crosstalk arises from minority charge carriers that diffuse out of the bulk.

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