Single-Photon Avalanche Diode with Ultrafast Pulse Response Free from Slow Tails

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Abstract—A single-photon avalanche diode (SPAD) with a novel structure is presented here. The slow tail in the pulse response, which plagued the performance of previous ultrahigh-speed SPAD’s, has been eliminated. The pulse response is cleaner and sharper than that of the fastest microchannel-plate photomultipliers (MCP’s), making the new devices almost ideal for photon timing measurements of fast optical waveforms. The typical photon detection efficiencies are 16% at 630 nm and 4% at 850 nm and the timing resolution of the 8-μm devices is 45-ps full width at half maximum (FWHM). Unprecedented performance is demonstrated: just 300 ps after a light pulse, a signal three order of magnitude weaker can be easily measured.

PHOTON counting is the technique of choice in accurate measurements of weak optical signals and fast light pulses, in the nanosecond and picosecond range [1]–[3]. Among commercially available photodetectors only two devices attain single-photon sensitivity: photomultiplier tubes (PMT’s) and avalanche photodiodes (APD’s). A new silicon APD designed for single-photon detection with ideally sharp time response is presented here.

When an APD junction is biased above the breakdown voltage $V_b$ (Geiger mode of operation), it remains in a zero current state for a considerably long time (hundreds of microseconds or even milliseconds), until the first minority carrier is generated and triggers the avalanche process. A current pulse in the millampere range is thus delivered to the external circuit. If the carrier is photogenerated, the pulse leading edge marks very precisely the photon arrival time. The detector time resolution is measured by the full width at half maximum (FWHM) of the statistical distribution of the delays between the photon arrival time and the leading edge of the detector pulse. APD’s specifically designed for timing response of a few tens of picoseconds have been called single-photon avalanche diodes (SPAD’s) [4].

The pulse response of conventional SPAD’s exhibits two components: a peak and a slow tail [5]. The peak arises from carriers photogenerated within the junction depletion layer and collected by the drift process. As a rule of thumb, the thicker the depletion layer, the worse the time resolution [12]. The slow tail arises from carriers photogenerated in the neutral regions surrounding the junction, which reach the depletion layer by diffusion. This tail is a serious drawback in the measurement of optical waveforms, particularly when weak signals must be detected just after stronger peaks (e.g., Rayleigh scattering after a Fresnel reflection in fibers [2]). In principle, deconvolution analysis could be employed for data correction [3]. In practice, this is seldom obtainable with high accuracy.

Fast readthrough APD’s with completely depleted structure (commercially available EGG-RCA C50902S and Silk models) exhibit a single-photon response with almost negligible tail [6]. In these devices the wafer thickness beneath the APD junction is reduced by about 30 μm by etching, thus resulting in a time resolution above 150-ps FWHM in single-photon detection. In order to attain picosecond response, the depletion layer thickness should not exceed a few micrometers. At this level, etching cannot be adopted: a planar device structure must be designed and a different solution has to be found for minimizing the tail. We have already demonstrated that epitaxial SPAD’s can significantly reduce the diffusion effects [7]; in this work, we introduce a new SPAD structure, providing an ultrafast pulse response completely free from slow tailing effects. We first discuss the principle of device operation and then we compare the time response of the new detector with that of previous epitaxial SPAD’s [7] and ultrafast microchannel-plate photomultipliers (MCP’s).

Fig. 1 shows the cross section of the new device structure. The shallow n⁺-p photodiode junction (0.3 μm deep) is fabricated in a 2.6-μm p-epilayer (10 Ω·cm), grown on an n-type substrate (1 Ω·cm). The edge breakdown occurs at 70 V. The avalanching area, with $V_b = 20$ V, is defined by a boron implantation (80 keV, 7·10¹² cm⁻²). Impact ionization occurs in the high-field region, 0.4 μm thick. A p⁺ boron-implanted buried layer (150 keV, 1.3·10¹⁵ cm⁻²) reduces the photodiode series resistance to a few kilohms. In order to get rid of diffusion tails, the buried layer is interrupted beneath the avalanching area, so that the epilayer can be fully depleted here by reverse biasing the substrate. Fig. 2 shows the electron potential energy at the operating bias. Electrons photogenerated in the substrate or in the depletion region of the substrate–epilayer junction cannot reach the avalanching area. Photon absorption in the neutral p⁺ buried layer is avoided by the metal plate of the n⁺ contact, acting as an
Fig. 1. Schematic cross section of the new SPAD detector. The shaded areas depict the depleted layers of the photodiode junction and of the auxiliary substrate–epi-layer junction, in the central region of the device. The metal n+ contact plate acts as optical shield.

Fig. 2. Electron potential energy in the central region of the detector at the operating bias. Both junctions are reverse biased: the cathode is grounded, the anode is at +60 V, and the substrate is at +40 V.

Only carriers photogenerated within the depleted volume of the sensitive junction are collected and trigger the avalanche.

It may be suspected that slow components in the detector response could come from some residual neutral or low-field regions still present in the structure. However, carriers photogenerated in the quasi-neutral n+ surface layer are collected within 20 ps [8]. Those photogenerated in proximity of the “saddle” in the potential distribution (Fig. 2) diffuse out of this small region within 10 ps. Finally, some neutral regions left by misalignments between the n+ contact plate and the p+ buried layer can be depleted by further increasing the reverse bias of the substrate junction.

We fabricated devices with diameters ranging from 8 to 100 μm. Care was taken to minimize the density of defects introduced during the fabrication processes, since they cause local electric field concentrations (microplasmas) and enhance the dark count rate of the detector [4], [6]. After the buried layer implantation, an annealing step of 30 min at 900°C in N₂ assures a full recovery of the crystal damage before the epitaxial growth. An effective gettering action is provided by the isolation step, performed with a heavy phosphorous diffusion around each device. Regarding the shallow n+ layer, the adoption of phosphorous deposition yields the best breakdown uniformity and the lowest defect density. By reducing the phosphorous concentration to $5 \times 10^{19}$ cm$^{-3}$ at the surface, we achieved a dislocation density of $5 \times 10^4$ cm$^{-2}$ [9], which assures a reliable fabrication of defect-free SPAD’s with diameter up to 30 μm. Further technological improvements are required to increase the yield of larger detectors. The typical dark count rate of the 8-μm devices is 100 carriers per second at 10 V above $V_c$ and 10 000 at 40 V above $V_c$.

Note that the device is somewhat similar to an n-p-n bipolar transistor with a high base resistance (6 kΩ for the 8 μm and 1 kΩ for the 100-μm SPAD’s), operated with the two junctions reverse biased. If the substrate–epi-layer junction is not properly reverse biased, the transistor can be turned on as soon as the avalanche is triggered and electron injection from the substrate occurs. In our measurements the active junction was reverse biased at 60 V (40 V above $V_c$) and the transistor was held off by reverse biasing the substrate 20 V with respect to the anode.

The time response of the detectors was measured in a conventional photon-timing setup [1]. An active quenching circuit [10] senses the avalanche pulse from the SPAD cathode. The results fully confirm the absence of slow tails in the response of the new photodiode. Fig. 3 shows a 20-ps pulse of a laser diode, as measured with the new device (marked as A) and with a previous double-epitaxial SPAD (B). The diameter of the active area was 8 μm in both cases. The B device has a continuous neutral p+ buried layer (2 μm thick, 0.3 Ω·cm) [7] also beneath the photosensitive area. Electrons photogenerated in this layer give rise to an exponential tail with 270-ps lifetime. On the contrary, SPAD A is clearly free from this diffusion tail down to, at least, two decades below the peak value, where the symmetrical skirt of the laser waveform prevents further investigation of the detector response. At any rate, just 300 ps after a light pulse, the new device is able to detect a signal three orders of magnitude weaker. The photon detection efficiency was measured as a function of wavelength by using a white lamp and a monochromator. We obtained typical values of 15% at 630 nm and 4% at 850 nm, in agreement with theoretical estimates. Fig. 3 also shows some very weak features on the laser diode waveform: arrow 1 marks a small pulse ($\approx 10^{-3}$ of the peak value) due to the reflection at a lossy optical fiber connector; arrow 2 marks a residual optical oscillation of the laser, likely due to a ringing in the fast driving current signal. The same measurement performed with device B demonstrates how even a small diffusion tail can completely obscure such features.

Fig. 4 compares the new SPAD response with that of an ultrafast MCP (Hamamatsu R2809U), measured with a picosecond dye laser. As far as the tail is concerned, SPAD A has a response clearly sharper than that of the MCP. The peak width is 35-ps FWHM for the MCP and 45-ps FWHM for SPAD A. These values do not represent the ultimate performance achievable with these detectors: [11] reports a value of 22.5-ps FWHM for MCP’s;
reported a record value of 20-ps FWHM with a 5-μm SPAD [4]. We have already demonstrated that the timing performance of SPAD’s can be improved by: 1) shrinking the diameter of the sensitive area, 2) designing a steep electric field profile for the active junction, and 3) increasing the value of the avalanche current [12]. However, electric field profiles optimized for the best timing performance usually lead to a higher carrier generation rate in the active junction. Since the goal of this new photodetector was to demonstrate the tail suppression, we adopted a conservative design for the active junction.

In conclusion, we have devised a novel SPAD detector with a pulse response free from slow tails and even sharper than that of the fastest MCP’s. These results make SPAD’s almost ideal detectors for photon timing measurements of fast optical waveforms. Presently fabricated devices, with 8 μm diameter, achieve a time resolution of 45-ps FWHM.

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REFERENCES