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Characterization of linear-mode avalanche photodiodes in standard CMOS

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Abstract

Linear-mode Avalanche PhotoDiodes (APDs) can be fabricated in standard CMOS processes for obtaining high multiplication gains that allow to determine the number of incident photons with great precision. This idea can be exploited in several application domains, such as image sensors, optical communications and quantum information. In this work, we present a linear-mode APD fabricated in a 0.35 µm CMOS process and report its noise characterization and gain.

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Keywords: Avalanche photodiode; CMOS; dark current; gain; linear-mode.

1. Introduction

The Avalanche PhotoDiode (APD) technology offers ideal properties for photon sensing applications, such as high sensitivity, good energy resolution and fast response. Recent efforts in the field have been mostly dedicated to the development of Geiger-mode APDs, also known as Single-Photon Avalanche PhotoDiodes (SPADs), especially after demonstrating the feasibility of monolithically integrating these detectors in standard CMOS processes [1, 2]. In spite of this, linear-mode APDs offer additional valuable qualities, such as the ability to determine the number of incident photons by simply analyzing the current amplitude from the detector, in addition to low noise levels even at room temperature [3, 4]. Although several linear-mode APDs are presently available, most of them are manufactured by means of cost consuming dedicated processes with poor reliability, require high bias voltages to operate (typically

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between 100-200 V) and also present relatively low multiplication gains [5]. In this contribution, we introduce a linear-mode APD fabricated in a commercial CMOS process for obtaining high multiplication gains.

2. Device and set-up characteristics

The present linear-mode APD was manufactured in the High-Voltage AustriaMicroSystems (HV-AMS) 0.35 µm CMOS process. No process modifications were applied during the fabrication of the chip through a Multi-Project Wafer (MPW) service by Europractice. The multiplication region of the photodetector consists of a p^+/deep n-tub junction on a p-substrate and presents an active area of 20 µm x 100 µm. The junction is surrounded by a low doped deep p-tub implantation to achieve a planar multiplication region and hence prevent the premature edge breakdown. Moreover, the corners of the sensor are round shaped to avoid the apparition of electric field peaks. The layout of the device, together with its schematic cross-section, is depicted in Fig. 1. To operate the APD in linear-mode, the deep n-tub implantation or cathode is biased slightly below the breakdown voltage of the junction. The photocurrent is measured at the p^+ implantation or anode by connecting this electrode to a readout board. The diagram of the experimental set-up is schematically depicted in Fig. 2.

The readout board includes an amplification system and a microcontroller. The amplification system comprises two gain stages. The first one is based on a TransImpedance Amplifier (TIA) built using an operational amplifier (model LPC662 by Texas Instruments) and a feedback resistance with an appropriate value, whilst the second one consists of the same operational amplifier in inverting configuration. The microcontroller (model PIC32MX795 by Microchip) performs the digitization and following transmission to a computer of the generated data. To provide amplification of the APD current due to a broad range of optical powers, several feedback resistances extending between 1 kΩ and 10 MΩ have been used to achieve a programmable gain in the TIA. Owing to the TΩ input resistance of the operational amplifier, no APD current is leaked into the instrumentation used for the experimental characterization. To convert the negative voltage at the output of the first gain stage into positive, the inverting operational amplifier has a constant gain of -1. Then, the resultant value can be easily digitized by the succeeding Analog to Digital Converter (ADC). The generated data is transmitted by serial communication to a computer. A software self-developed in Matlab is used to receive and store the experimental data, in addition to control the power source (model N6705A by Agilent Technologies) by means of an Ethernet cable. To show the potential of this technology, the linear-mode APD was illuminated with an 880 nm LED (model SFH 485 by Siemens) at several optical powers. The experimental set-up was placed inside a black box to avoid any uncontrolled light sources.

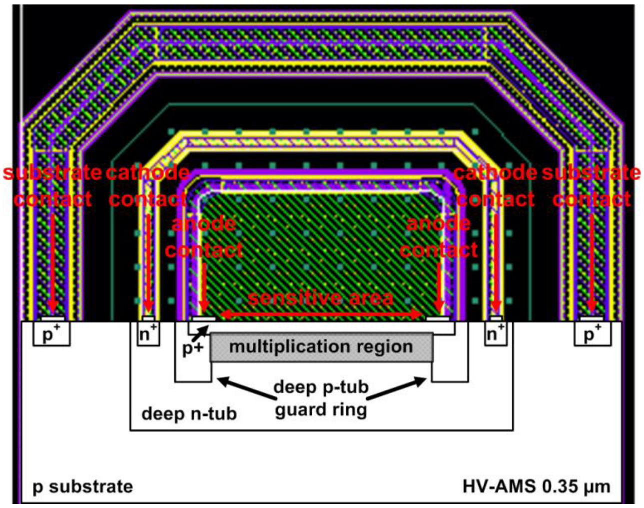

Fig. 1. Layout and schematic cross-sectional views of the linear-mode APD in the HV-AMS 0.35 µm CMOS process.

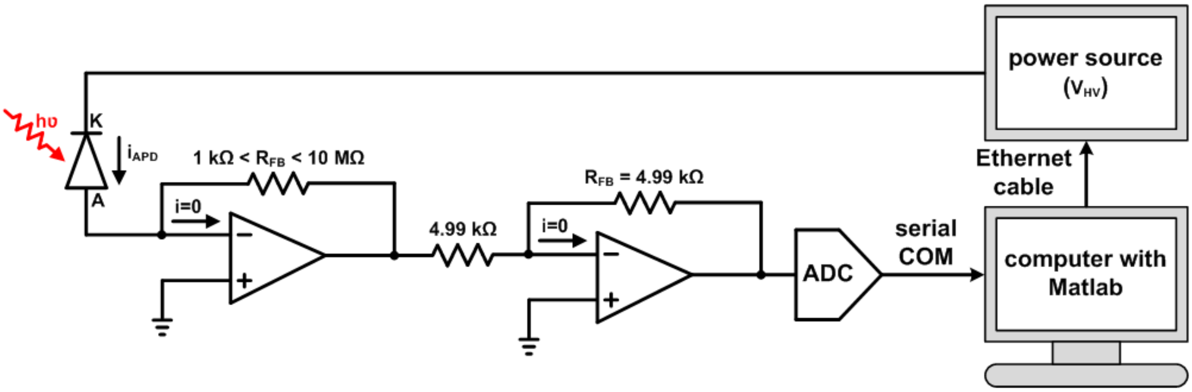

Fig. 2. Schematic diagram of the experimental set-up used to characterize the linear-mode APD.

3. Experimental measurements and discussion

Using the experimental set-up described above, the dark current and multiplication gain (M) of the device were characterized at different sensor polarizations. All measurements were conducted at room temperature. The reverse current-voltage curve measured in darkness is shown in Fig. 3, together with the multiplication gain. The breakdown voltage of the sensor is 18.72 V. The dark current is 1.2 nA for M = 12 and 2.9 nA for M = 21. Normalizing the latter by the area of the APD, a dark current density of 1450 nA/mm^2 is obtained. This value is around 200 times higher than the one reported in [6], which is also measured with an APD in a standard CMOS technology and at the same gain. The difference can be attributed to variations in the fabrication process of the devices. At 18.70 V, which is slightly below the breakdown of the junction, the multiplication gain of our device presents a maximum value of approximately 1700. This result outperforms the values available in the literature for linear-mode APDs fabricated in silicon [6]. The photocurrent generated by the linear-mode APD was also investigated as a function of the optical density (see Fig. 4), showing excellent linearity.

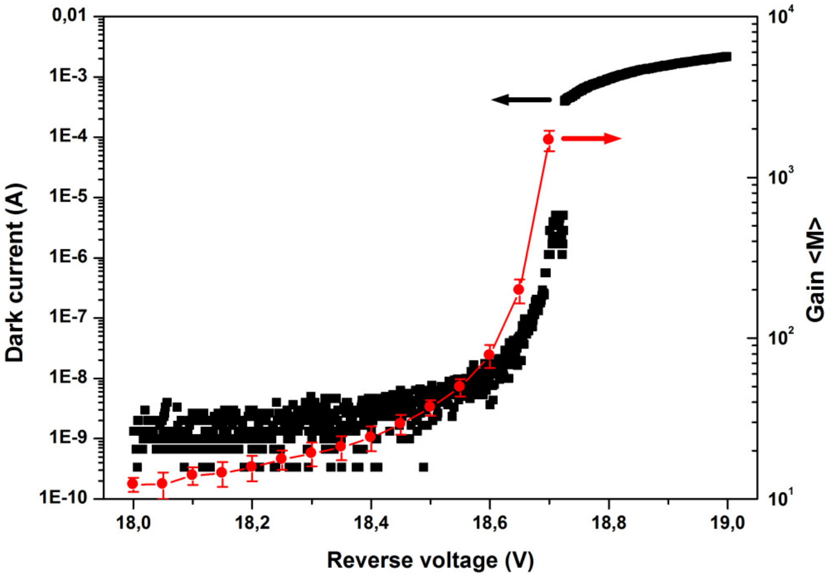

Fig. 3. Measured dark current and multiplication gain as a function of the reverse high voltage.

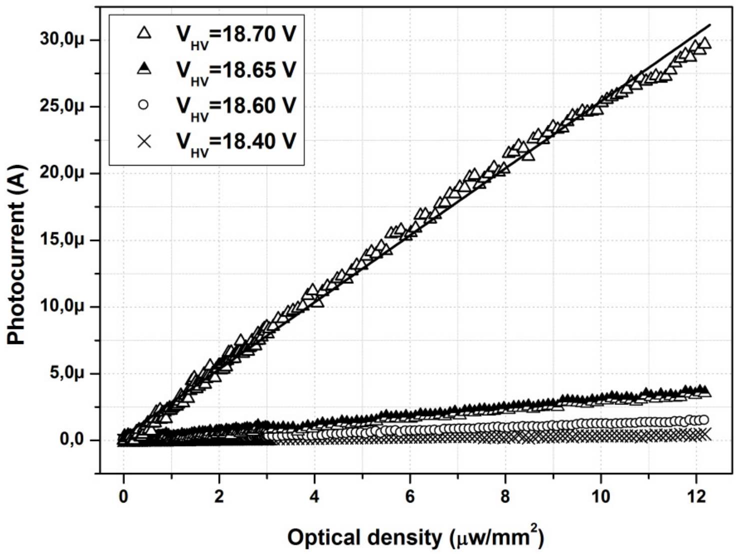

Fig. 4. Generated current due to absorbed photons as a function of the optical density and for different reverse high voltages (V_{HV}).

4. Conclusion

A linear-mode APD fabricated in a conventional 0.35 µm CMOS process has been reported and characterized. To detect the dark and photocurrent generated by the sensor, whose values range between the nanoampere and miliampere order, a special readout board with two gain stages has been used. The experimental characterization shows high multiplication gains and excellent linearity between the incident optical power and the generated photocurrent. These promising results indicate that linear-mode APDs fabricated in standard CMOS processes can be used for effectively counting the number of incident photons in many applications, such as image sensors, optical communications and quantum information.

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