The First measurements on SiPMs with Bulk Integrated Quench Resistors

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Abstract

High ohmic polysilicon which is used as quench resistor in conventional Silicon photomultipliers (SiPMs) turns out to be an absorber for light and is one of the most cost and yield driving technological issues. The silicon photomultiplier is becoming a very good candidate for the replacement of conventional photomultiplier tubes and thus the development of these devices is very striking. We have proposed a new detector concept which has the quench resistor integrated into the silicon bulk avoiding polysilicon resistors. The quenching mechanism has been demonstrated in a proof of principle production performed in house. The first prototypes have been fabricated (second production run) and allowed testing of the device performance. The results from the first measurements will be presented. Based on these results the inherent advantages and drawbacks compared to standard SiPMs will be discussed.

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1. Introduction

Recent advances in the development of Silicon Photomultipliers (SiPMs, MPPCs etc.)[1][2] opened new fields of their applications in which they are placed in inferior position compared to conventional photomultiplier tubes [3][4][5]. Still there is a significant room for further improvements. Namely a higher photon detection efficiency (PDE) would be required for low light level applications like Cherenkov light cameras in Gamma ray astroparticle physics experiments [6], radiation tolerance should be improved for the high energy physics applications [5] and the cost of these devices should be significantly reduced for the high surface coverage experiments [7][8]. A possible approach to address these issues is the bulk integrated quench resistor based SiPMs - SiMPl approach [9]. In this paper first the SiMPl concept will be reviewed and details on the prototype production will be given. Thereafter the results from the first measurements of the produced devices will be presented.

2. The SiMPl concept

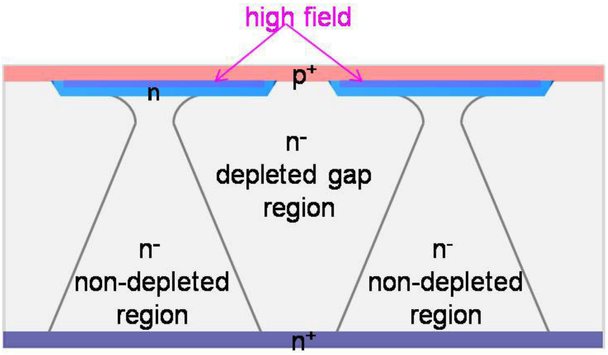

Figure 1: Schematic cross section of two neighboring cells.

SiMPl (Silicon Multipixel light-detector) is an avalanche diode array with bulk integrated quench resistors intended for single photon detection. The two non structured implants: p$^+$ implanted cathode and highly n-doped backplane form the base of the device (Fig. 1). The avalanche region is defined via a deeply n implanted high field region (Anode region). Quench resistors are then formed in the silicon bulk as vertical resistors which are laterally defined by depletion regions (gap regions) extending from the cathode into the bulk. Within the avalanche region the depletion region stops in the deeply n implanted high field region so that these insulating regions are formed only at the edges of the sub pixels. Since the p$^+$ cathode is common to all sub pixels and is not structured there is no need for contacts and metal lines within the matrix. A coupling capacitance in parallel to the quench resistor, necessary for a fast readout, is formed automatically between the internal anodes and a common highly n-doped backplane. A global cathode contact to be connected to a readout amplifier can be placed somewhere at the edge of the matrix. The proper adjustment of the quench

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Email address: `ninkovic@mppmu.mpg.de` (Jelena Ninković resistors requires a relatively high ohmic bulk with a thickness of about 20μm to 100μm depending on sub pixel size. Simulation results which demonstrated the feasibility of the presented concept can be found in [9][10].

The main advantage of this concept comes from the omittance of polysilicon. The production process is cost effectively simplified and the entrance window is free of any conduction lines and therefore the fill factor is limited by means of the cross talk suppression only. The light entrance window is topologically flat and can be easily adapted to specific wavelength ranges by anti-reflective coatings. Therefore SiMPl detectors should have higher PDE compared to conventional SiPMs. The presence of inherent diffusion barrier against minorities in the bulk (the anode implant) leads to the reduced cross talk effect. SiMPl detector has the potential to be radiation harder compared to standard SiPMs since there is no depleted Si-SiO$_2$ interface in SiMPl matrix as the non structured p$^+$ cathode implantation underlays this sensitive region completely. The highly doped surface within the array is formed without edges and therefore there are no lateral high field regions. This gives the ideal situation concerning the radiation induced surface damage whereas the bulk damage is on the same level as for the conventional SiPMs.

The only two disadvantages are the need for specific material for every application and the longer recovery times of pixels. The former one is easily manageable with modern wafer bonding[11] or epitaxial growing. For most of the applications longer recovery time is also no issue.

3. Prototype production

Big pixel size was chosen for the prototype production. SOI (Silicon on Isolator) wafer with n-doped sensor wafer of 70 μm was selected as a bulk material. The processing included in total 5 masks steps. Processing was done combining in house and processing at external partners. Figure 2 shows photograph of one of the processed wafers. Arrays of different size with the same pitch-gap combination are placed on a chip of a size 6x6 mm^2.

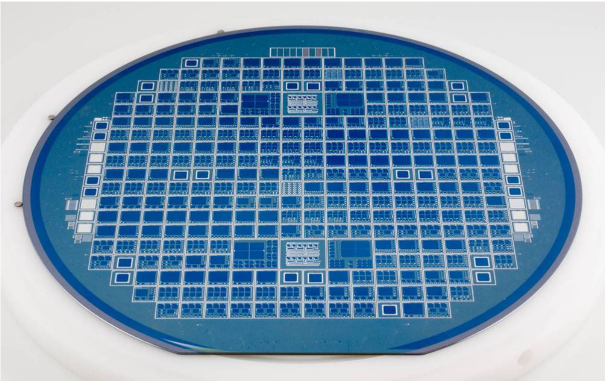

Figure 2: Photograph of one of the produced 6” wafers.

In order to study the sensitivity of device performance to parameter deviations and to allow a fine tuning of the simulation tools the prototype production was made with high number of geometrical variations (pitch/gap), ranging from 100-150 μm for pitch and 10-20 μm gap size.

Wafer	Mean (cm^{-3})	σ (cm^{-3})
1	2.87·10^{+12}	3.8·10^{+10}
2	2.87·10^{+12}	3.4·10^{+10}
3	2.64·10^{+12}	5.7·10^{+10}
4	2.64·10^{+12}	3.1·10^{+10}

Table 1: The mean value and the standard deviation of bulk doping of the sensor wafer measured on 10 diodes homogenously distributed over the wafer surface for 4 processed wafers (CV measurement).

4. Results

Testing of the produced devices started on the wafer level via static measurements on a probe station (Suess PA150 combined with a Keithley 4200 semiconductor parameter system) and was followed up with dynamic measurements of mounted devices.

4.1. *Static measurements*

Since the homogeneity of the bulk doping of the sensor wafer is one of the most critical parameters of the presented concept, dedicated test diodes which allow accurate measurements of it where distributed on the wafer surface. High homogeneity was measured and the results are summarized in the table 1. It was measured by means of the Capacitance-Voltage (CV) measurement on test diodes without the high field implantation. Static current-voltage (IV) measurements of the SiMPl arrays allowed study of the homogeneity of the break down voltage and leakage currents. Figure 3 illustrates measured high homogeneity

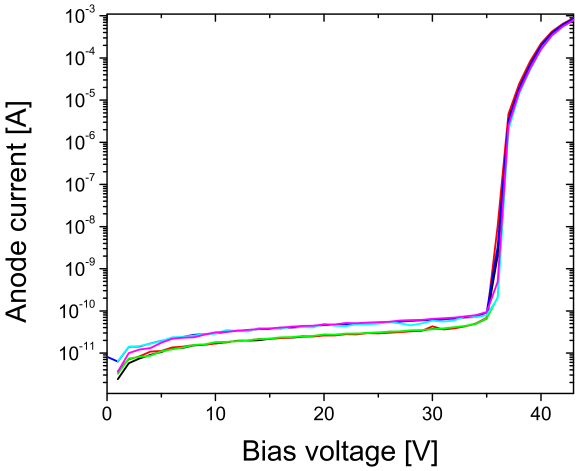

Figure 3: High homogeneity of the breakdown voltages and leakage currents measured on six identical arrays placed over more than a 5 mm distance. Current voltage characteristic was recorded with a 1 MΩ resistor connected in series.

over several millimeters that satisfies requirements for a bigger sensor area device. Emission microscope (PHEMOS1000) was used to localize the high field regions by means of detection of emitted light during the avalanche process. An illustrative example is shown in figure 4 where the overlayed pattern and emission images are shown for the array of 100 cells with a 135 μm pitch and a 17 μm gap size.

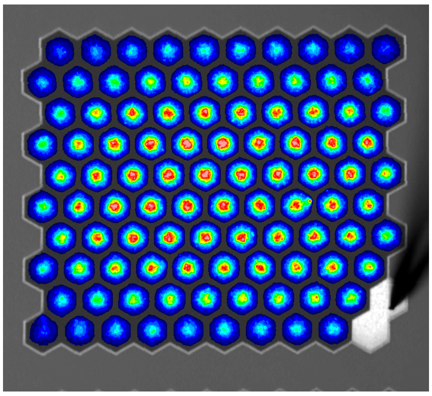

Figure 4: Photoemission micrograph overlayed onto the pattern image for the 100 cell array (135 μm pitch and a 17 μm gap size) operated at 5V overbias.

4.2. Dynamic measurements

After dicing dynamical tests were performed on the bonded structures. A simple read-out board with voltage amplifier (8ASM from Mini Circuit) was designed for the this purpose. Only the thermally generated signals were studied in this paper. The first functionality test was done feeding the signal from the board directly into an oscilloscope (LeCroy wave runner 64i) in order to check the signal shape and therefore the quenching mechanism (figure 5). This simple proof of principle test was followed by the real detector performance test by performing a pulse height measurement on detected signals and storing the extracted information into the histograms (see figure 6). Complete separation of photoelectron peaks in the spectrum indicates uniform gain distribution within the cells of the array. High linearity of the gain of produced devices is shown in figure 7 where the fitted Gauss mean values of detected photoelectron (pe) peaks is plotted as a function of overbias voltage. Unfortunately, due to the non optimal process sequence higher leakage currents ($\sim 2\,\mathrm{nA/cm^2}$) are measured in the devices and therefore they can not be used at room temperatures and moderate cooling is necessary (Dark rate of $\sim 10\,\mathrm{MHz/mm^2}$ at 4V overbias at room temperature). For the rate measurements an Agilent counter 53131A was connected directly after the amplifier board. The behavior of dark rate as a function of overbias at a fixed temperature was studied and the result for one of the studied devices is shown in figure 8. Small resistor value limits the maximal overbias to about 4V for the shown device. After this value the quenching condition is not fulfilled any more.

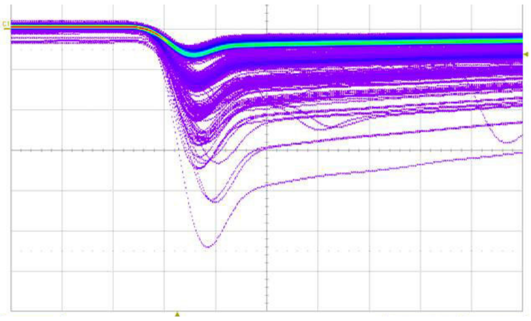

Figure 5: Pulses as recorded with the oscilloscope with 20 mV/div in y axis and 10 ns/div in x-axis.

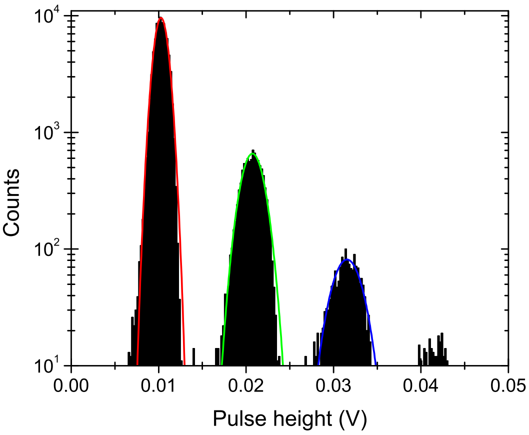

Figure 6: Spectrum of a 100 cells array with 135 μm pitch and 16 μm gap recorded at -20°C biased at ~2V overbias voltage (triggered at 1/2 first photoelectron pulse height.

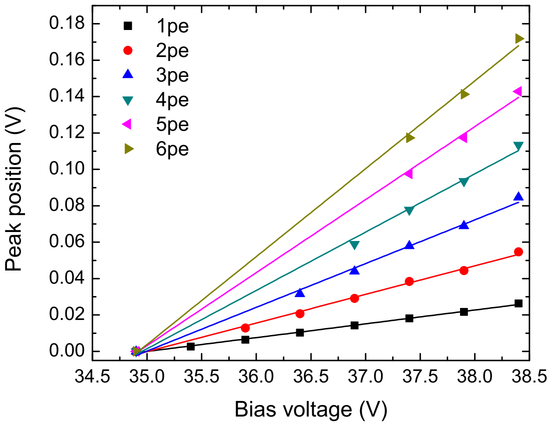

Figure 7: Linearity of the gain as a function of overbias for the 10x10 array with 135 μm pitch and 16 μm gap recorded at -20°C. Linear fits connect points which correspond to the same photoelectron peaks.

The major difference of our concept compared to the conventional polysilicon devices, when using them at different temperatures, is the change of the resistor value with temperature. The polysilicon resistor increases the resistance when cooled whereas the vertical bulk resistor is behaving in the opposite

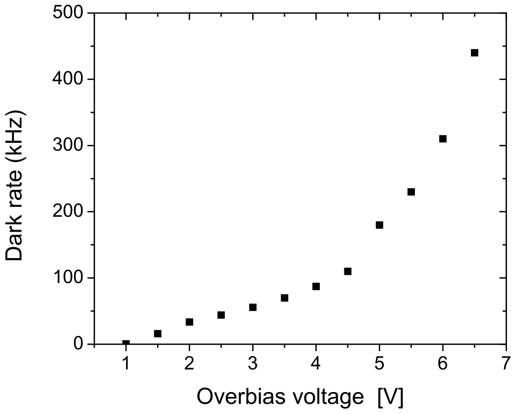

Figure 8: Dark rate behavior as a function of applied overbias measured at -45C for the array of 100 cells of a 135 μm pitch and a 13 μm gap size.

way. The resistance value can be calculated measuring the recovery time of the pulses and assuming the capacitance of a plate capacitor for the high field region. Obtained values for the two significantly different devices are shown in figure 9. This example illustrates relatively wide range of the resistance values that can be obtained in our approach.

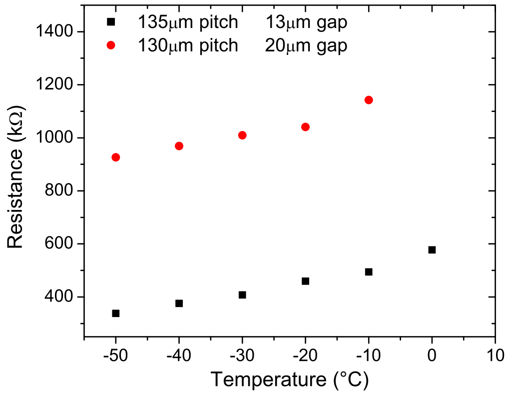

Figure 9: Change of the resistance with temperature. The resistance of vertical bulk resistors was calculated, as explained in the text, for two devices shown with different symbols.

Figure 10 shows the change of the inverse resistance value, that is proportional to the mobility of the charge carriers, as a function of temperature. Fitted curve shows nice agreement to the theoretical $\sim T^{-2.4}$ dependence[12] of the change of the mobility of the electrons in silicon with temperature and therefore confirms the functionality of the vertical bulk resistors in SiMPl detectors.

5. Summary

SiMPl is a new detector concept that promises improved characteristics compared to conventional silicon photomultipliers together with simplification of production technology and therefore more fault tolerant and cost effective mass production. Prototyping phase was performed in the Max Planck Institute Semiconductor Laboratory. Measurement on the first bonded structures demonstrated the quenching mechanism and showed very promising results. Higher leakage current prevents usage of these devices at room temperature for which the resistor values were optimized in the design. Still, overbias voltage of up to ~ 4V are possible. Further characterization of the device performance is ongoing. In parallel optimization of the process sequence is planned and the improved characteristics are expected in the next iteration.

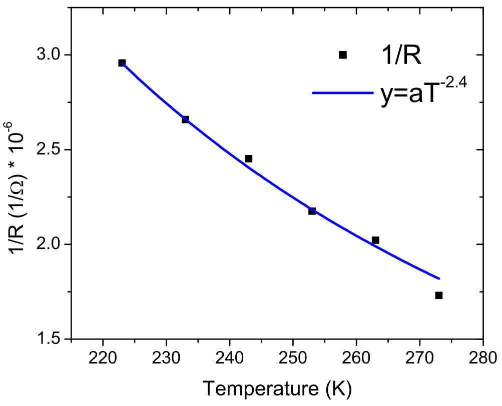

Figure 10: Measured data for the inverse resistance of vertical bulk resistors as a function of temperature. The fit $1/R=aT^{-2.4}$[12] gives nice agreement of the measured data to the change of the mobility of electrons in the silicon bulk.

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