

Fabrication and Characterization of Large Silicon Micro-Resistor Array

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Abstract— Silicon Photo-Multiplier is a state of the art photo-detector, capable of detecting extremely low light flux with high gain ($\sim 10^5$) and high resolution. The SiPM consists of a large array of Avalanche Photo Diodes (APDs), connected to a common bias grid through individual series resistors and biased in ‘Geiger’ mode. The series resistor acts as quenching mechanism, which stops the avalanche produced in an APD due to incidence of photon(s). Thus, the quenching resistor is an integral component to the device operation. We have fabricated a large array of silicon micro-resistors to be later integrated with SiPM. Amorphous silicon thin films were grown with Hot Wire CVD instrument at lower substrate temperatures of about 300 °C. In-situ boron doped films of thickness 100 -200 nm were grown and patterned to create large array of micro-resistors. Statistical analysis of the resistance obtained from individual resistor testing was observed to be about 7% at 1-sigma level across the array of the resistors. Variation of the resistance across rows of the resistor array was comparatively lower to be $\sim 5\%$. A systematic variation in the resistance was observed in particular direction of the array and thus could be attributed to the variation in the thickness of the deposited film. This article describes, characterization of in-situ doped silicon thin films obtained using HWCVD process as well as fabrication, characterization and analysis of the large silicon micro-resistor array.

Keywords—Silicon Photo-Multiplier, Hot Wire CVD, quenching resistor

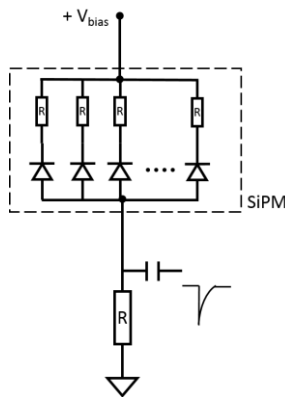


Fig. 1. Schematic Representation of Silicon Photo-Multiplier (SiPM).

I. INTRODUCTION

Silicon based resistors are integral part of many sensors and on-chip circuits. Typically such resistors are integrated with main sensor device and last stage of fabrication and thus are required to be fabricated at lower temperatures to minimize thermal budget of overall device. Silicon Photo-Multiplier (SiPM) is one such state of the art photo-detector device capable of detecting extremely low light flux with high resolution [1, 2]. The SiPM is a large array of avalanche photo diodes (APDs) all connected in parallel and biased above their breakdown voltage (Geiger mode) for high gain operation. When properly biased, if a photon(s) hits the active area of the device, it produces an electron-hole pair which gets swept across the junction of the APD by high electric field. Due to high electric field carriers get accelerated and gain high energy, subsequently imparting it to other carriers, thus forming an avalanche. To bring back the device to operational mode this avalanche has to be quenched which is achieved with a series resistor as shown in Fig 1.

Thus, the quenching resistor is a vital component to the SiPM. Typical size of the resistor is $50 \mu\text{m} \times 10 \mu\text{m}$. Since SiPM typically has few thousand APDs (pixels) and the response of the device is summation of individual pixel response. The uniformity of the quenching resistance is of prime importance for SiPM, as variation of the resistance may cause change in RC time constant of the individual diodes during recovery time, leading to poor timing response of the device.

We have explored fabrication of array of such silicon micro-resistors to be integrated with SiPM. Large number of these resistors were characterized using I-V measurements and uniformity of the resistance across the array was judged. To achieve low thermal budget to grow poly-silicon films, Hot Wire CVD (HWCVD) instrument was used. The HWCVD provides facility of growing in-situ boron doped silicon films at moderate temperatures of 300 °C - 400 °C.

II. FABRICATION OF SILICON MICRO-RESISTOR ARRAY

A test structure was fabricated with HWCVD deposited in-situ boron doped a-Si films at substrate temperatures of about 300 °C [3]. Layer stack of the test structure is shown in Fig 2. Highly resistive silicon wafer substrate was first deposited with thick SiO_2 layer for electrical isolation of the substrate. This was used

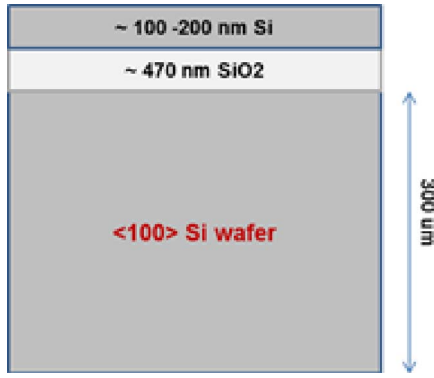


Fig. 2. Layer stack-up of the test structure. A thick layer of SiO₂ was used to isolate the substrate from resistor array.

as a base substrate to grow Si thin films using HWCVD.

A. Growth and characterization of the Si thin film

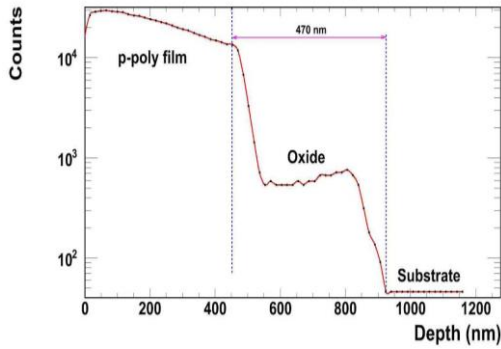


Fig. 3. Results from Secondary Ion Mass Spectroscopy (SIMS) measurements of a-Si film grown using HWCVD with layer stack as shown in Fig. 2.

As described earlier, HWCVD was used to grow a-Si films with in-situ boron doping. B₂H₆ was used to introduce boron doping (p) into the a-Si film growth process using Silane (SiH₄). Growth parameters such as SiH₄ and B₂H₆ gas flow was optimized to get desired resistivity of the resulting film. Typically films with 100-200 nm thickness were grown. Resistivity of the film was measured using four-probe sheet resistance measurement. Films were also characterized using powder XRD measurement to estimate the crystallinity of the film and Secondary Ion Mass Spectroscopy (SIMS) to establish doping uniformity of the film across the depth. Fig 3 shows the results from the SIMS measurements. SIMS measurements indicate relative doping across the depth of the sample. SIMS measurements indicate the doping of boron in the film to be fairly uniform along its thickness.

B. Process for fabrication of the resistors

Once the film was optimized and characterized, resistor arrays were patterned with photo-lithography and Reactive Ion Etching (RIE) system. Size of the individual resistor was 10 μm

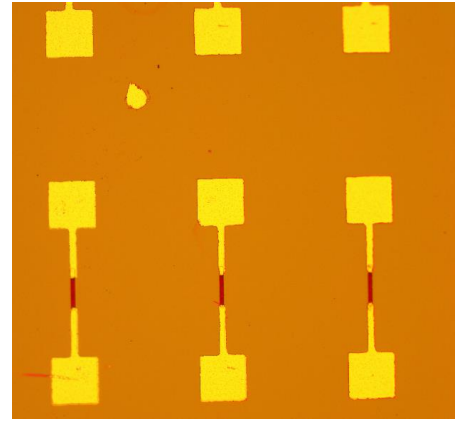


Fig. 4. Microscopic image of part of the fabricated resistor array. Contact pads were provided for characterization using probes.

x 50 μm and complete array was spread across large area of about 5 mm x 5 mm. A thin layer of about 50 nm was deposited for passivation onto the sample. Contacts windows were etched into the SiO₂ thin film for aluminum contacts. Aluminum was deposited with RF sputtering and patterned using wet etching agent. Final sample was subjected to Rapid Thermal Annealing (RTA) cycle optimized at 500 °C for 60 seconds. Annealing step was performed in Ar + N₂ ambient environment. Microscope photograph of the final sample is shown in Fig 4. Large number of these resistors were characterized with I-V measurements using probe station before and after final annealing cycle. Characterization procedure and results are described in the next section.

III. CHARACTERIZATION AND RESULTS

Fabricated resistors were subjected to I-V characterization and rigorous analysis of the measurements was done to estimate uniformity of the resistance across the sample. Uniformity of 7% was achieved at 1-sigma level. I-V characteristics of the resistors were recorded by using Keithley source meter. Measurements were done before and after final annealing cycle.

Fig 5 (a) and (b) shows the I-V characteristics of a resistor, before and after annealing cycle, respectively. Annealing cycle removes the Schottky barrier formed at the Al-Si contact and thus significant reduction in the resistance is observed. About 100 resistors were measured before annealing. Analysis was performed to estimate nature and source of non-uniformity in the resistance.

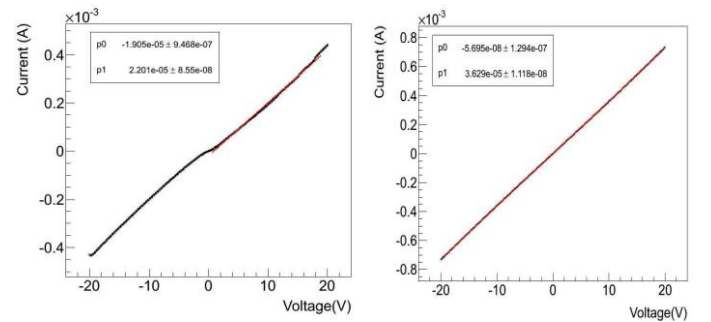


Fig. 5. IV Characteristic of a resistor a) before annealing and b) after annealing.

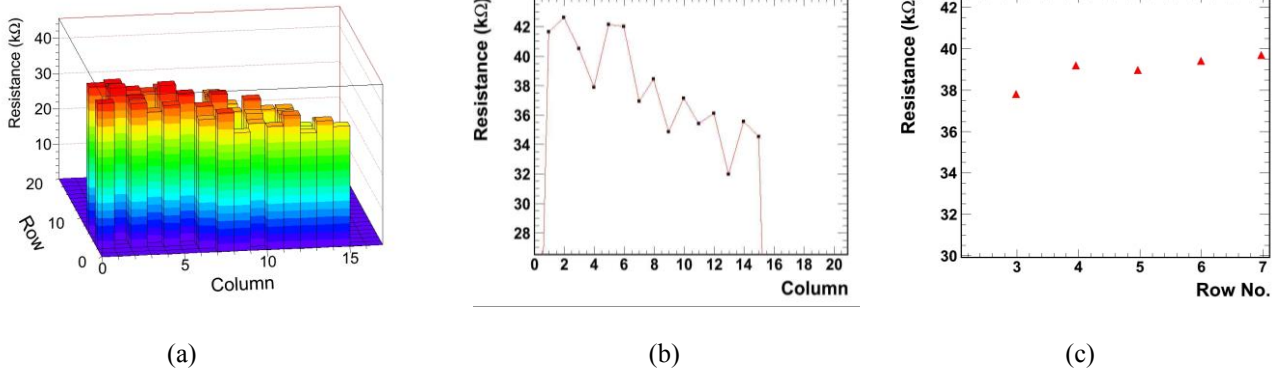


Fig. 6. a) 2-D bar graph showing variation of the resistance across the array, distributed as rows and columns. b) Average resistance of each column as function of column number. This indicates systematic variation in the resistance across the columns. c) Average resistance of rows plotted for respective rows. This shows comparatively lower variation in the direction of columns.

Fig 6 (a) shows the visualization of the resistance across the sample. Systematic variation of the resistance can be seen from one end of the array to another. Further, average of the resistance of each column was calculated and plotted as a function of the column number. Fig 6 (b) shows clear trend in resistance variation. This indicates non-uniformity of the resistance due to variation of the film thickness, which can be improved by optimizing the deposition conditions further. Fig 6 (c) shows the average resistance of rows for each row. Fig 7 shows the histogram of the resistance measured at different parts of the array after annealing. The variation of about 7% has been seen. The variation of the resistance across the column was seen to be lower ($\sim 5\%$).

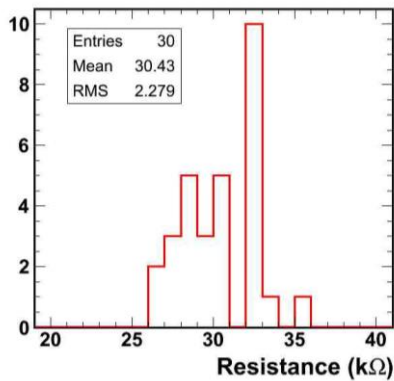


Fig. 7. Histogram of resistance measured from different parts of the array after annealing process. Variation of about 7% is observed at 1-sigma level.

IV. CONCLUSION

Quenching resistor is an integral component of the large area pixel detectors like SiPM. The uniformity of these resistors is of prime importance for SiPM as variation of the resistance may cause change in RC time constant of the individual diodes during recovery time, leading to poor timing response of the device.

We have fabricated a large array of silicon micro-resistors to be later integrated with SiPM. Amorphous silicon thin films were grown with HWCVD instrument at lower substrate

temperatures of about 300 $^{\circ}\text{C}$. In-situ boron doped films of thickness 100 -200 nm were grown. Films were later patterned, passivated and aluminum contacts were made using optical lithography. Fabricated resistors were thoroughly characterized using individual I-V measurements. Detailed analysis of the recorded I-V data was carried out by fitting the measured I-V data with first order polynomial and recording fit parameters for each of the tested resistors. Statistical analysis of the resistance obtained from fit parameters indicate variation of about 7% at 1-sigma level across the array of the resistors. Variation of the resistance across rows of the resistor array was comparatively lower to be $\sim 5\%$. The systematic variation was mainly observed across the rows of the array as indicated in Fig 6 (c) and thus could be attributed to the variation in the thickness of the deposited film.

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