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Test beam evaluation of newly developed n-in-p planar pixel sensors for use in a high radiation environment

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ABSTRACT

Radiation-tolerant n-in-p planar pixel sensors have been under development in cooperation with Hamamatsu Photonics K.K. (HPK). This is geared towards applications in high-radiation environments, such as for the future Inner Tracker (ITk) placed in the innermost part of the ATLAS detector in the high luminosity LHC (HL-LHC) experiment. Prototypes of those sensors have been produced, irradiated, and evaluated over the last few years. In the previous studies, it was reported that significant drops in the detection efficiency were observed after irradiation, especially under bias structures. The bias structures are made up of poly-Si or Al bias rails and poly-Si bias resistors. The structure is implemented on the sensors to allow quality checks to be performed before the bump-bonding process, and to ensure that charge generated in floating pixels due to non-contacting or missing bump-bonds is dumped in a

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Bulk damage
Surface damage
Bias structure

controlled way in order to avoid noise. To minimize the efficiency drop, several new pixel structures have been designed with bias rails and bias resistors relocated. Several test beams have been carried out to evaluate the drops in the detection efficiency of the new sensor structures after irradiation. Newly developed sensor modules were irradiated with proton-beams at the Cyclotron and Radio-Isotope Center (CYRIC) in Tohoku University to see the effect of sensor-bulk damage and surface charge-up. An irradiation with γ-rays was also carried out at Takasaki Advanced Radiation Research Center, with the goal of decoupling the effect of surface charge-up from that of bulk damage. Those irradiated sensors have been evaluated with particle beams at DESY and CERN. Comparison between different sensor structures confirmed significant improvements in minimizing efficiency loss under the bias structures after irradiation. The results from γ-irradiation also enabled cross-checking the results of a semiconductor technology simulation program (TCAD).

1. Introduction

A new pixel sensor has been developed by Hamamatsu Photonics K.K. (HPK) [1] in collaboration with the ATLAS Japan Silicon Group [2–4]. R&D for this pixel sensor is geared towards applications in High Energy Physics experiments, such as for the future Inner Trackers (ITk) of the ATLAS detector in the high luminosity LHC (HL-LHC) experiment [5]. Since the pixel detectors have been developed with the aim of tracking short-lived charged particles, they are usually installed in the inner-most part of particle detectors. Thus, they are required to have high radiation-tolerance, such as $1.0 \times 10^{16}\, n_{eq}/cm^2$ for the inner layers, and $1.7 \times 10^{15}\, n_{eq}/cm^2$ for the outer layers of ITk in HL-LHC for instance [5]. In order to achieve this requirement, new pixel detectors have adopted n-in-p type silicon structure. It was reported that both n-in-p and n-in-n type sensors were able to collect sufficient amount of charge after being irradiated to lifetime fluence expected at the HL-LHC experiment [6,7], but n-in-p sensors have a number of advantages in HEP applications:

- They do not undergo type-inversion when receiving non-ionizing bulk damage, while n-in-n type sensors do [8].
- Since the p–n junction is formed on the electrode side and the depletion zone grows from this side, charge collection is possible even without full depletion [1].
- Since the collected charge carriers are electrons, faster read-out is possible than for the p-in-n sensors. Moreover, electrons are less affected by trapping than holes [8].
- Lithography is needed on only one side, thereby lowering the manufacturing cost. This feature is vital for the application to the areas larger than 1–2 m^2 [8].

A schematic of the old-prototype sensor structure is shown in Fig. 1. Each pixel electrode is separated by inter-pixel p-stop implants. The typical size of the pixel cells is $250 \times 50\, \mu m^2$. Sensors are connected to the FE-I4 read-out chips [9] via bump-bonding. The size of pixels on the FE-I4 is also $250 \times 50\, \mu m^2$. Each pixel electrode is connected to virtual ground provided by the pre-amplifier when bump-bonded onto the FE-I4. SnAg or In (Ni/In) solder is used for bump-bonding. Sensors have bias structures on their surface with which I-V measurement can be done before the bump-bonding process. This prevents faulty sensors from being bump-bonded on the FE-I4s, and makes it possible to increase the overall module yield. Bias rails were also grounded and connected to each pixels via poly-Si resistors as shown in Fig. 2.

In a previous study [4], we investigated the hit and the charge collection efficiency of HPK sensors and demonstrated that both hit and charge-collection efficiency sharply dropped under the bias rail structures after irradiation with protons. The peak efficiency drop $(1 - \text{efficiency})$ observed was about 55% [4]. This result suggested some possible explanations for the drop in efficiency:

- Signal electrons can be drawn towards and captured in the inter-pixel region, since the surface of such region may be positively charged by the ionizing dose.
- Since the bias rail, which is connected to ground level, is just above the inter-pixel region, the electric potential in the inter-pixel region gets closer to the ground level. This further helps the electrons to be captured in the inter-pixel region. Thus, the

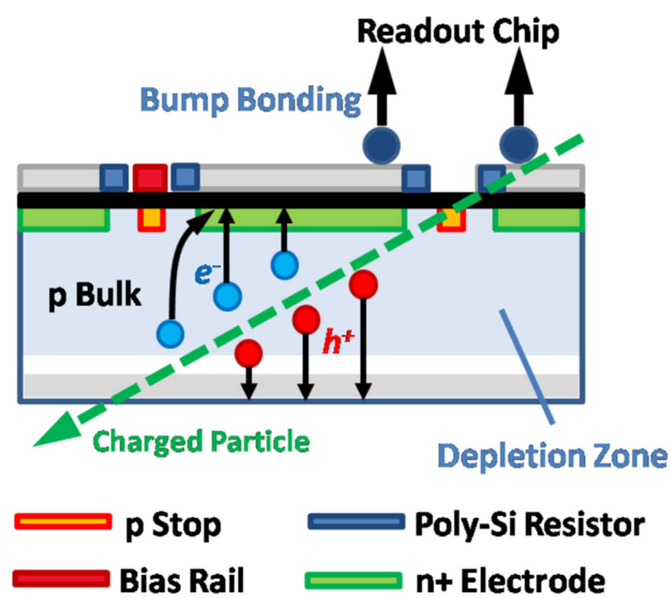

Fig. 1. A schematic of an n-in-p planar pixel sensor profile. (Old-prototype design).

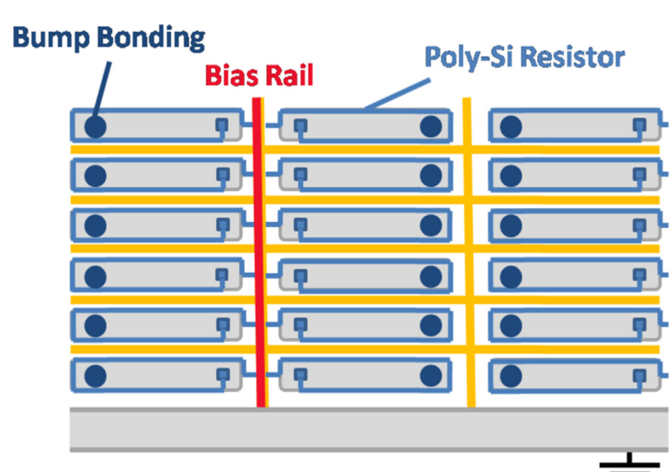

Fig. 2. A schematic view of an n-in-p planar pixel sensor from the electrode side. (Old-prototype design).