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Beam test performance of a pixelated silicon array for the charge identification of cosmic rays

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A B S T R A C T

A large area silicon array for the next generation of space-based experiments has been designed to determine, via multiple dE/dx measurements, the electric charge of cosmic radiation. The instrument can achieve an excellent charge discrimination, thus allowing to assess the elemental composition of charged cosmic rays at relativistic energies. Pairs of silicon sensors segmented into pixels were tested with a beam of fully ionized nuclei from boron to nickel ($Z=28$) with a kinetic energy of ~ 1 GeV/amu, at the Fragment Separator (FRS) of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt. The response of the sensors to different nuclear species was accurately characterized. The results of the beam test clearly show that a double-layered silicon array can achieve single-element separation with a resolution close to 0.2 electron charge units, in the whole interval of atomic number Z under test.

1. Introduction

The identification of cosmic nuclei, via a precise measurement of their charge Z, is a mandatory requirement for the next generation of space experiments, designed to push to higher energies the currently available data from direct measurements of the energy spectra and abundances of individual chemical species in the flux of cosmic rays (CR). Earlier experiments could resolve only groups of elements or, in a few cases, achieve single-element discrimination over a limited charge range, by combining the response of scintillation and Cherenkov counters.

Silicon sensors can provide an excellent charge separation by taking advantage of the Z^2 dependence of the saturated specific ionization (dE/dx) for relativistic particles on the Fermi plateau. Pixelated silicon arrays have been successfully used in the balloon missions ATIC [1] and CREAM [2–4], providing single-element discrimination. With a single layered array, the former achieved charge resolutions of about 0.25–0.35 electron charge units (e) for elements between C and Si, while the latter improved to 0.2–0.23e with two layers of pixels. Lower resolutions close to 0.4–0.5e were obtained for heavier elements up to Fe [5,6].

Charge detectors can be significantly affected by the back-scattered shower particles emerging from the instrument mass placed below the array (as for instance, from the high-Z absorbers in the calorimeter section), that may induce fake charge identification by releasing additional amounts of energy that add up to the primary particle ionization signal. The choice of a pixel segmentation reduces the probability that the back-scattered particles cross the same pixel as the primary charged particle and allows to identify and eliminate the hits not associated with the incident particle track. Pixelated sensors also offer the advantage of an easier pattern recognition task, as compared with silicon strip devices that are affected by ambiguities in the pairing of coordinates measured on orthogonal planes.

In order to extend the energy reach of the previous instruments in the region of the spectrum above hundreds of GeV/amu, a large sensitive area is needed to collect an adequate number of cosmic-ray nuclei to populate the higher energy bins of the distribution. The associated front-end (FE) electronics is required to have low noise (as needed for the identification of $Z=1$ particles with a signal-to-noise ratio larger than 5) and a large dynamic range – of the order of 10^3 minimum ionizing particles – to be able to measure the ionization produced in silicon by nuclei up to Fe and above, free from saturation effects.

The present paper summarizes the main results obtained with the R&D program MATRIX – funded in Italy by the Istituto Nazionale di Fisica Nucleare (INFN) – to develop the building blocks of large area Si arrays [7–9], including the associated front-end electronics [10] and readout.

The aim of the beam test was to characterize the response of the sensors, in terms of linearity and resolution, over a wide interval of the atomic number Z. Earlier tests with atmospheric muons and particle beams [8,11] showed that the instrument could achieve a signal-to-noise ratio close to 7 for $Z=1$ ultra-relativistic particles with a detection efficiency $>99\%$.

2. An array of silicon pixel sensors

The sensors described in this paper were developed on an n-type FZ high resistivity wafer (phosphorous doped, resistivity ≥ 10 kΩ cm,

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⟨100⟩ crystal lattice orientation). A high resistivity is required to operate the detector at a low bias voltage (less than 100 V).

Sensors with square pixels of 1.28 cm^2 sensitive area were manufactured by SINTEF (Norway), according to the custom design concept shown in Fig. 1. The 8×8 array of p^+ implanted pixels (with a 90 μm inter-pixel gap) is surrounded by 13 p^+ implanted guard-rings on one side, while the common ohmic contact is on the opposite side. Each pixel has 5 bonding-pad openings for the signal readout. The first guard-ring has also a bonding-pad opening to allow for the possibility to bias the guard-rings, whenever needed (normally it is left floating, as long as the guard-ring current remains lower than 0.5 μA). The design included a grid of 20×20 contact holes ($\phi = 100$ μm) between the p^+ and metal layer, to reduce the junction spiking probability. The main parameters of the sensors are summarized in Table 1.

The leakage current, capacitance and full depletion voltage of individual pixels were measured. Fig. 2(a) and (b) present a few typical results from the measurements.

The leakage current is the reverse current of the pn-junctions. It generates a background noise due to the thermally excited minority carriers, present in the depleted region and drifting toward the electrodes under the influence of the local electric field. It depends on various factors, such as temperature, humidity and sensor aging. The leakage current gives a first and simple estimation of the quality of the sensors.

The leakage current between the backplane and each pixel was measured as a function of the reverse bias voltage ($I-V$ curve) as shown in Fig. 2(a). The bias voltage was increased up to 150 V in steps of 0.2 V. The measurements were made at room temperature, typically around 25 °C, with a relative humidity below 30%. The leakage current was found to be less than 1 nA for a single pixel at the full depletion voltage. The breakdown voltage of the sensors exceeds 150 V.

The bulk capacitance is the capacitance to the backplane. It is proportional to the reciprocal of the square root of the bias voltage applied to the sensor until the full depletion is reached and it assumes a constant value in the over-depleted regime. The bulk capacitance was measured as a function of the reverse bias voltage in order to determine the full depletion voltage. This information is very important for the module assembly, as the sensors have to be matched in depletion voltage when they are mounted on the same ladder. The capacitance measurements were performed on all the pixels using a Keithley 6487 unit as a voltage source and an Agilent 4263B LCR meter between the bias line and the backplane. The CV curves were measured at a frequency of 1 kHz and an amplitude of 1 V. Fig. 2(b) shows a typical curve of $1/C^2$ as a function of the bias voltage. The full depletion is close to 30 V.

The overall capacitance of a pixel is $\sim$26 pF at full depletion. As the detectors are manufactured from 500 μm thick wafers with a specific resistivity in the range from 10 to 30 kΩ cm, the expected depletion voltage is in the range from 30 to 90 V. However, the bulk resistivity increases during the gettering process steps, whereby about 95% of the thickness is depleted below 10 V, slowly reaching the full depletion and saturating over 30 V [11].

Table 2 shows the acceptance criteria for “Class A” sensors. If one of the pixels has a high leakage current (5 nA $< I_{Leak} <$ 200 nA at 100 V), the sensor is classified as “Class B”, while it falls into “Class C” if there are two pixels with a high leakage current. For space applications, only “Class A” sensors are selected.

2.1. Front-end electronics

Each pair of Si sensors – the building block of the array – is readout by a dedicated front-end board (VAB) hosting four front-end Application Specific Integrated Circuits (ASIC) – of the VA family (VA32-HDR14) – for a total of 128 readout channels. The VAB board [10] implements a sequencer for the readout of four FE

Table 1
Main parameters of the silicon pixel sensors.

Wafer size	6 in.
Nominal thickness	(500 ± 10) μm
Bulk material	n-type (phosphorus) float zone
Surface treatment	Double side polished
Wafer resistivity	10–30 kΩ cm
Crystal orientation	⟨100⟩
Number of pixels	64
Sensor size	95 mm × 95 mm
Number of guard-rings	13
Active area	90.64 mm × 90.64 mm
Pixel pitch	11.33 mm
p^+ Implant pixel size	11.24 mm × 11.24 mm
p^+ Implant (Inter pixel gap)	90 μm
p^+ Implant	Boron
n^+ Ohmic contact implant	Phosphorus
Contact hole	$\phi = 100$ μm
Number of contact holes	20 × 20
Passivation	SiO_2/Si_3N_4

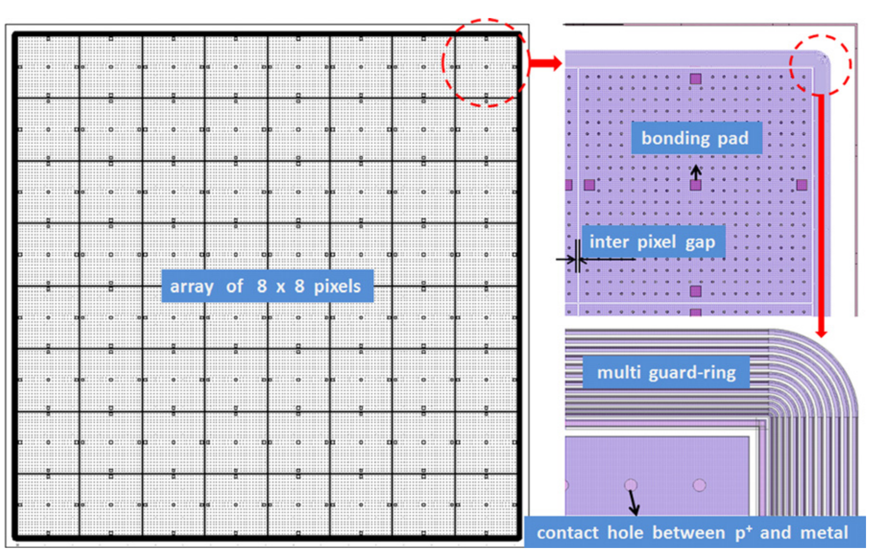

Fig. 1. Schematic layout of the pixel structure and guard-ring (top view) of the silicon sensors under test.