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# Silicon charge detector for the CREAM experiment

I.H. Park[a,*], N.H. Park[a], S.W. Nam[a], H.S. Ahn[b], P. Allison[c], M.G. Bagliesi[d], S.J. Baek[a], J.J. Beatty[c], G. Bigongiari[d], P. Boyle[e], J.T. Childers[f], N.B. Conkin[g], S. Coutu[g], M.A. DuVernois[f], O. Ganel[b], J.H. Han[a], H.J. Hyun[a], J.A. Jeon[a], K.C. Kim[b], M.H. Lee[b], L. Lutz[b], P. Maestro[d], A. Malinine[b], P.S. Marrocchesi[d], S. Minnick[h], S.I. Mognet[g], S. Nutter[i], J.H. Park[a], E.S. Seo[b], R. Sina[b], S. Swordy[e], S. Wakely[e], J. Wu[b], J. Yang[a], Y.S. Yoon[b], R. Zei[d], S.Y. Zinn[b]

[a] *Department of Physics, Ewha Womans University, Seoul 120-750, Korea*
[b] *Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA*
[c] *Department of Physics, Ohio State University, Columbus, OH 43210, USA*
[d] *Department of Physics, University of Siena and INFN, Via Roma 56, 53100 Siena, Italy*
[e] *Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[f] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*
[g] *Department of Physics, Penn State University, University Park, PA 16802, USA*
[h] *Department of Physics, Kent State University Tuscarawas, New Philadelphia, OH 44663, USA*
[i] *Department of Physics and Geology, Northern Kentucky University, Highland Heights, KY 41099, USA*

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**Abstract**

The Cosmic Ray Energetics And Mass (CREAM) payload had its first successful flight in December 2004 from McMurdo Station, Antarctica as a Long Duration Balloon mission. Its aim is to explore the supernova acceleration limit of cosmic rays, the relativistic gas of protons, electrons and heavy nuclei arriving at Earth from outside of the solar system. The instrument is equipped with several systems to measure charge and energy spectra for $Z = 1-26$ nuclei over the energy range $10^{11}$–$10^{15}$ eV. The Silicon Charge Detector (SCD) is a precision device to measure the charge of incident cosmic rays. The design, construction, integration and preliminary performance of the SCD are detailed in this paper.


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## 1. Overview of the CREAM experiment

The aim of the CREAM experiment is to understand the source and acceleration mechanisms of high energy cosmic ray particles by observing energy spectral features from $10^{12}$ to $10^{15}$ eV and abundance changes that might be related to the supernova acceleration limit [1].

The first flight was made successfully in Antarctica in December 2004, carried by a Long Duration Balloon. Flying at the edge of space, between 38 and 40 km in altitude, the CREAM balloon broke the flight record for duration and distance. It flew for nearly 42 days, making three orbits around the South Pole.

The CREAM employs a suite of particle detectors to determine the charge and energy of cosmic rays. Energy is measured by two independent detectors: a sampling tungsten/scintillator calorimeter and a transition radiation detector with a Cherenkov Detector (CD). Both detectors

*Corresponding author.
*E-mail address:* ipark@ewha.ac.kr (I.H. Park).

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also provide the track of an incident particle. The charge of primary cosmic rays up to $Z = 26$ is determined independently by a Timing Charge Detector, CD, and a pixellated Silicon Charge Detector [2].

## 2. Design of the Silicon Charge Detector

One of the important requirements in the design of the Silicon Charge Detector was to minimize the effects of backscattered particles generated by interaction of the incident cosmic particle in the carbon target and showers produced in the calorimeter. Silicon was chosen because it allows fine segmentation as well as precision measurement of charge. With the appropriate segmentation, backscatter is expected to cause charge mis-identification of about 2–3% of low-$Z$ particles near $10^{15}$ eV incident energy, and significantly lower for lower energies and higher charge.

The SCD was designed to have a modular structure such that it consists of 26 ladders, each holding seven silicon sensor modules with an associated analog readout electronics board. Sensors can be detached from the ladder at anytime for repairs, and ladders from the support structure frame as well. Each sensor was divided into a $4 \times 4$ array of pixels with an active area of $15.5 \times 13.7\,\text{mm}^2$. The sensors are slightly tilted and overlap each other in both lateral directions, providing full coverage in a single layer, with a $779 \times 795\,\text{mm}^2$ overall area. The size of the SCD including the ladders, the mechanical support structure, and the 2.0 mm thick electromagnetic (EM) shielding cover, is $818.4 \times 818.3 \times 21.6\,\text{mm}^3$. The weight of the SCD is 14 kg. The total number of electronics channels is 2912. The total power consumed for the readout and control electronics is about 50 W.

## 3. Principle of operation for the charge measurement

The silicon sensors are PIN diodes with a sharp p–n junction in semiconductors. When ionizing particles penetrate a sensor with reverse biased voltage applied, the high energy particles produce electron–hole pairs in depleted region. These sensors are used to measure the charge of incident cosmic particles in terms of a pulse of electric current.

Most relativistic particles like cosmic rays have mean energy loss rates in silicon equal to the minimum. The minimum value of the energy loss in matter, $\mathrm{d}E/\mathrm{d}x$, is almost the same for all particles of the same charge. Thus, the energy loss in any given material is dependent only on the charge and velocity of the particle. A cosmic ray particle penetrates the sensor with nearly constant velocity $v = 0.99c$, producing uniform electron–hole density along its path. Since $\mathrm{d}E/\mathrm{d}x$ increase as $Z^2$, where Ze is the charge of the incident cosmic ray, $\mathrm{d}E/\mathrm{d}x$ at a given kinetic energy is a sensitive measure of $Z$. Therefore one can determine the atomic number of particles by measuring the energy deposited in silicon.

## 4. Fabrication of silicon sensors

The silicon sensors were fabricated from 5 inch diameter silicon wafers. The wafers are 380 μm thick with a RMS variation of 15 μm. The thickness variation within wafers is less than 3.5 μm. The wafer substrate is phosphorus-doped with a resistivity greater than 5000 Ω cm. Each sensor is divided into a $4 \times 4$ array of $2.12\,\text{cm}^2$ pixels. The silicon sensors are DC type PIN diodes with a p–n junction in an $n^-$ type silicon substrate (Fig. 1).

The lightly doped $n^-$ type Si wafer is chemically cleaned and oxidized by heating it in an oxygen atmosphere at around 900 °C. A large fraction of the outer surface is covered with $SiO_2$ of thickness 9000 Å. The back side of the wafer is transformed into an $n^+$ junction by diffusing $n^-$ type impurities such as phosphorus. With the diffusion process, the surface layer becomes heavily doped, so that the depletion layer extends mainly into the $p^-$ side. At the first photolithographic step, the junction layer is covered by a thin layer of photo-resist material, which is then illuminated through a mask in such a way that after development and chemical etching the $SiO_2$ is removed in the diode area.

The remaining $SiO_2$ acts as a mask for the implantation of boron, so that the diode is only formed in the uncovered

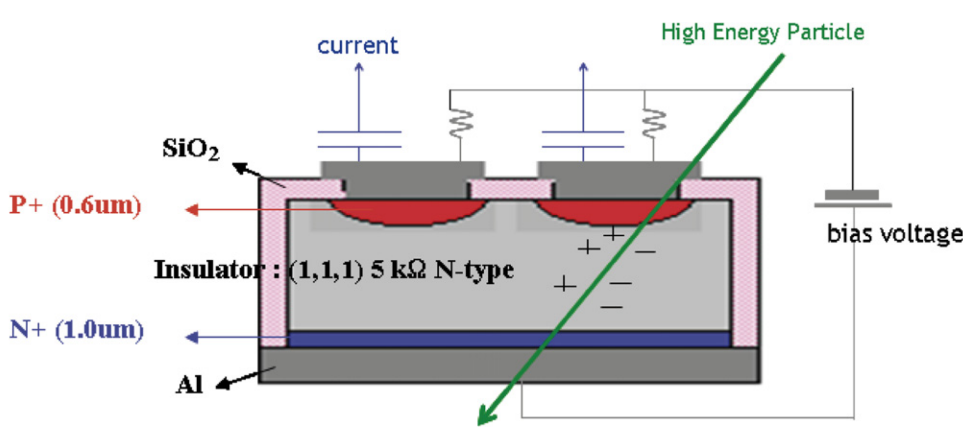


Fig. 1. The structure of silicon PIN diode and its operation as a charge sensor.

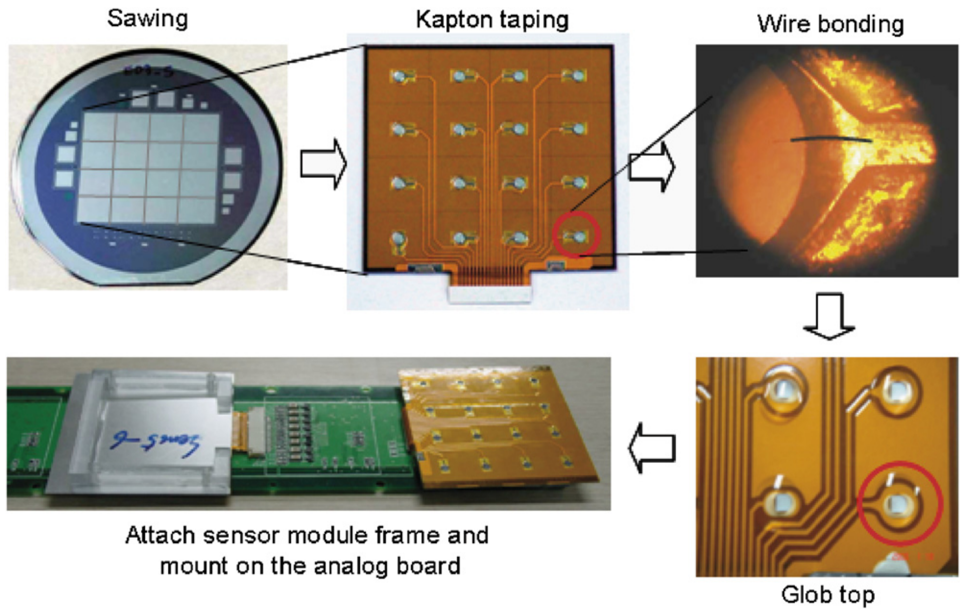


Fig. 2. Packing process of a sensor module.

region. Implantation of arsenic over the entire front-side is followed by an annealing step to produce a $p^+$ junction in order to repair damage to the crystal and to get the implanted atoms properly built into the lattice. Aluminization by evaporation on both surfaces provides the ohmic back contact and the top aluminum layer brings it into final shape, so that radiation does not penetrate through aluminum before reaching the sensitive space-charge region. After aluminum contacts are deposited, the whole surface is passivated with silicon dioxide. Heating the device in a partial hydrogen atmosphere (hydrogen annealing) enables hydrogen to diffuse through the oxide towards the interface, leading to a saturation of the dangling bonds and a reduction of the flat-band voltage.

## 5. Tests of silicon sensors

Although a reverse-biased diode is ideally nonconducting, a small fluctuating current nevertheless flows through semiconductor junctions when voltage is applied. This current appears as noise at the detector output and sets a limit on the smallest signal pulse height which can be observed. The finished sensors were tested for full depletion on the wafer with probe stations, and the capacitance and leakage current were measured [3]. The SCD includes only sensors satisfying the requirement that a leakage current measured per pixel be lower than $8\,\mathrm{nA/cm^2}$ at 100 volts.

The sensors were further checked with $^{90}$Sr $\beta$ source normally incident on the detector by measuring the signal-to-noise ratio at full depletion voltage. About 80% of the fabricated sensors passed our leakage current, capacitance and S/N ratio requirements.

## 6. Assembly of a sensor module

After the silicon sensors were fabricated, they were made into sensor modules. A fabricated sensor wafer was sawed into a 16 pixels sensor. Electrical contacts for reading signals from the pixels were made by attaching a Kapton tape of FPCB (Flexible Printed Circuit Board) onto the sensor. Sixteen analog signals from each sensor run to frontend analog readout board via these Kapton cables. Wire wedge bonding was used to connect each sensor pixel to its Kapton cable. The wire bonding was then protected and preserved by applying glue.

The back side ($n^+$) of the silicon sensor was attached to the sensor module frame using double sided adhesive tape and DP100 epoxy to prevent the sensors from possible slippage resulting from temperature fluctuation. The sensor module frame is made of poly-carbonate which is thermally robust up to 70 °C. The module frame provides a thermal separation between the sensor and the frontend electronics board. The module frame has a tapered shape to allow adjacent sensors to overlap, as shown in Figs. 2 and 5. These sensor modules can be easily mounted and dismounted for repairs to a ladder of the analog electronics board using screws. These post-fabrication steps are shown in Fig. 2.

## 7. Readout electronics

The readout electronics consists of three parts: analog, digital and auxiliary electronics. Fig. 3 shows the architecture of the SCD readout electronics.

The analog electronics system is composed of 26 analog boards, each of which includes seven CR1.4 readout chips. Each chip is connected to a silicon sensor via Cu wires on

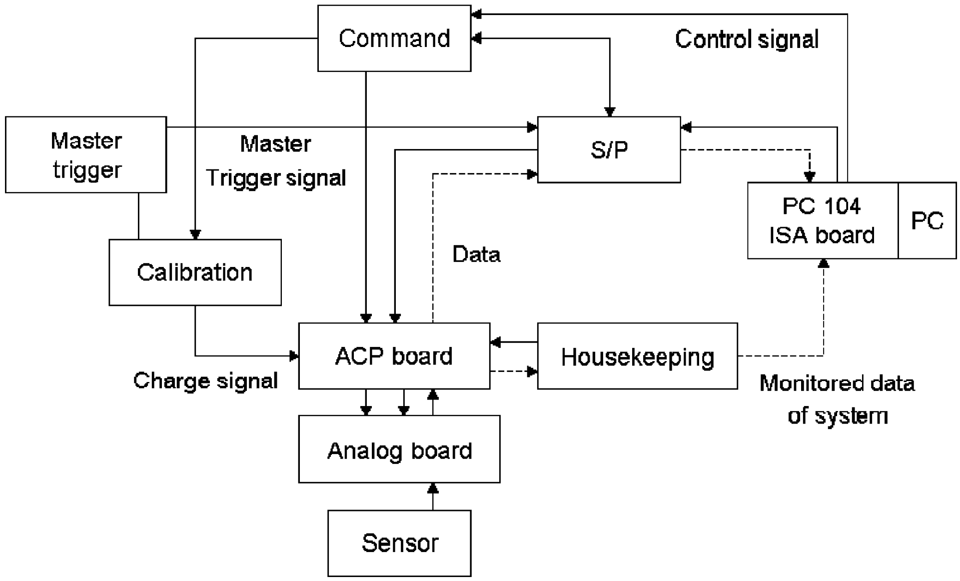


Fig. 3. Schematic overview of the SCD readout.

FPCB. CR1.4 chips are custom VLSI developed originally for large arrays of silicon detectors such as the ATIC and the Pamela experiments. The dynamic range is sufficient to measure charges from H to Ni, even at large incidence angles, when produced at 380 μm thick silicon sensors. The CR1.4 accepts 16 charge signals from a sensor, integrates each charge pulse to hold it as a series of DC levels. Each channel has a charge sensitive amplifier (CSA) followed by a shaping amplifier (SA) and a track and hold (T/H) circuit. The conversion gain is 125 μV/fC. Due to the low gain of CSA, the SA provides an additional amplification as well as appropriate pulse shaping. The outputs of the T/H are multiplexed to a common output buffer, at the prompting of an external trigger. There is a built-in calibration circuit that uses CMOS switches to generate charge pulses from an external DC level that are delivered to the CSA inputs. The CR1.4 chip has an intrinsic noise which increases with detector capacitance at a rate of 8 electrons/pF. Without capacitance added to the input, the measured noise is 3,560 electrons. The capacitance of a silicon pixel is 30 pF, while stray capacitance including bonding is estimated to be about 100 pF, therefore the noise is approximately 5000 electrons, equivalent to 0.8 mV at the CR1.4.

Two large digital electronics boards were placed on both sides of the detector. These boards digitize the analog inputs from the analog boards, transmit controls of the T/H and the multiplexer in response to the trigger from the CREAM data acquisition system, and distribute low voltage power (±5 V) to the analog boards and bias voltage (100 V) to the silicon sensors. It has six layers of PCB structure and connects to the sparsification board via 100-pin twisted and paired cables. A/D conversion was accomplished by 200 ksps, 16 bit MAX1133 ADC chips which accept input signals of ±4.096 V. One LSB (Least Significant Bit) is 0.125 mV and accuracy is ±1.5 LSB corresponding to ±0.1875 mV. The operating range of MAX1133 is between −40 °C and 85 °C, which is suitable for the flight environment. Anti-fuse type ACTEL FPGAs, 42MX16 and 42MX24, were used for logic design in the digital electronics. The anti-fuse type was selected to reduce single-event-upset vulnerability in space. The bias voltage of silicon sensors was delivered to the analog boards via coaxial cables from EMCO Q01-12 DC-to-DC converters in the digital electronics board. EMCO converts 12 V supplied from the CREAM main power supplier to 100 V. Its ultra-miniature size, light weight, low power consumption, and wide temperature range operation are ideal for balloon experiments. The output ripple was measured as low as 0.05%, but was nevertheless further reduced with the addition of external capacitors. The precision low voltage was supplied by various kinds of low drop output regulators. Integration of all the analog and digital boards is shown in Fig. 4.

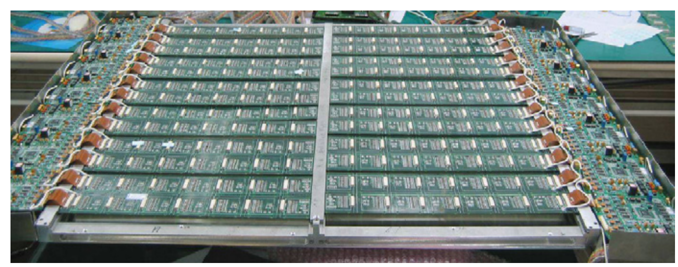

Fig. 4. Assembly of the SCD readout electronics.

The CREAM common auxiliary electronics systems include data sparsification, calibration, control and housekeeping boards. The sparsification board provides data reduction before transmitting to the ground via Telemetry and Data Relay Satellite System (TDRSS). The bandwidth of data transmission is limited to 50 kbps for all channels of the CREAM instrument. The calibration board was designed to inject a known charge to each of 2912 analog electronics channels to analyze its responses. Calibration runs, with input charge created between 0 DAC and 16,000 DAC units, were made every 5 minutes during the flight. The data showed a good linearity. The gain of the CR1.4, as measured by the slope of the linearity graph, was found to be 2. Environmental information, including monitored values of voltages, currents, powers and temperature of the ladders, were collected with low speed sampling A/D converters in the housekeeping board.

## 8. Mechanical support structure and assembly of the SCD

One of the important factors in the design of the mechanical support structure was to maximize the active detection area, while minimizing the dead space between sensors. The support structure is made of a single piece aluminum with a thickness of 2 mm. It was designed to protect all silicon sensors against a possible impact of 10*g* at the time of landing or launch.

As a building block, each ladder was assembled with an analog electronics board and seven sensor modules, each of which holds a silicon sensor, using screws. To improve thermal conduction, aluminum plates under each analog board were added by making a contact to CR1.4 using thermally conductive epoxy DOW Corning 3-6652.

Twenty-six assembled ladders were mounted on the aluminum support structure with screws. The support structure was then mounted on top of the CREAM carbon target. Two digital electronics boxes were located on both sides of the support structure. Finally, the SCD was covered by a thin aluminum shield which reduces EM interference as well as protects the silicon sensors from shocks. Fig. 5 shows a schematic diagram of the support structure, the photo of an assembled ladder, and the photo of a part of the sensors assembled on the support structure. It shows that the silicon sensors are partially overlapping to completely cover the active area.

## 9. Tests, integration and first flight of the SCD

The SCD was tested at CERN H2 beam line with fragments of Indium beams in 2003 [3] and 2004. The silicon sensors demonstrated excellent charge identification. The charge separation resolution was 0.097 for He, better than design value of 0.2 charge units.

The SCD was delivered to the University of Maryland for integration. Thermal and vacuum testing of the CREAM instrument was carried out at NASA-GSFC. Full integration of the instrument with the NASA supplied support systems, and final hang tests were conducted at NASA-WFF. Maintaining the payload within its operating temperature range during the flight is challenging, since at 4 Torr, convection is negligible. The SCD thermal design thus included 28 copper thermal straps, each about 3 mm thick and 51 mm wide. These straps were further painted black to add radiative thermal coupling. The SCD box itself as well as the readout boxes were also painted black for the same reason. Environmental tests were carried out between $-10^{\circ}$ and $40^{\circ}$C in temperature and at 4 Torr in pressure.

After passing all the tests, the CREAM instrument was shipped to Antarctica in November 2004. CREAM was launched in December 16, 2004 and flew for 42 days by breaking the world record of balloon duration.

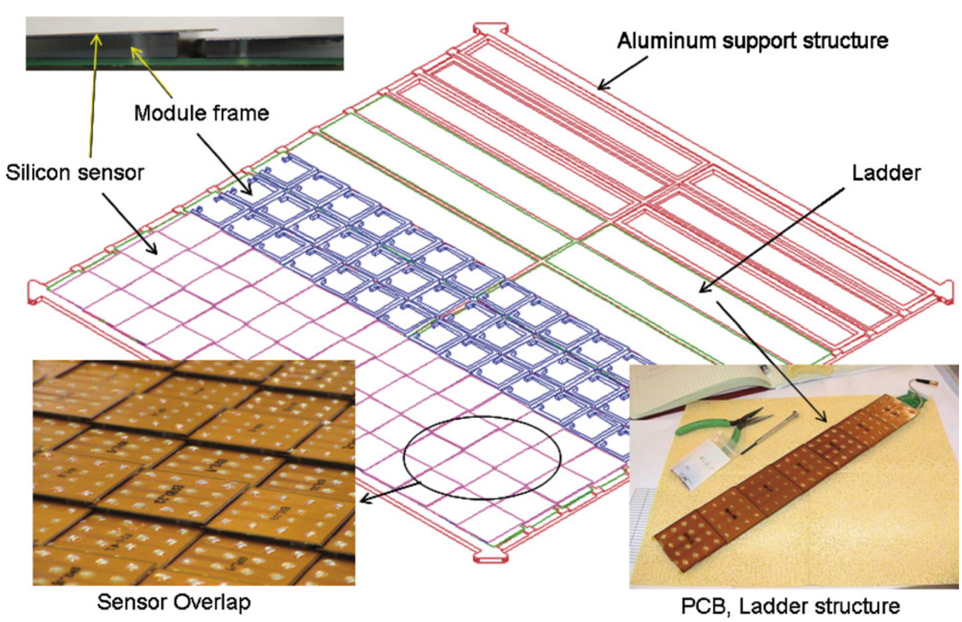


Fig. 5. Schematic drawing of the mechanical support structure. It shows the layer of silicon sensors, sensor module frames, and ladders on the aluminum frame. The bottom left picture shows that the silicon sensors are partially overlapping to completely cover the active area. The bottom right picture shows an assembled ladder.

The housekeeping data showed that the detector temperature fluctuated as the payload altitude changed, but remained within the operational limits. Pedestal values were measured every 5 minutes for all channels, allowing offline corrections for variations caused by temperature changes. Dead or noisy channels, 3.7% of all channels, were masked as part of the data sparsification in flight. The performance of the SCD during this flight is described elsewhere [4].

## 10. Conclusion

The PIN diode silicon sensor was built for precise elemental charge measurements of incident high energy cosmic particles. The performance of sensors were tested in terms of leakage currents. Most of the sensors (over 80% out of 500 total) showed leakage currents below $8\,\mathrm{nA/cm^2}$. The SCD was built with 182 good silicon sensors, and was flown successfully in Antarctica for measurement of elemental charge of high energy cosmic rays.

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## References

[1] S.P. Swordy, et al., Astropart. Phys. 18 (2) (2002) 129.
[2] E.S. Seo, et al., Adv. Space Res. 30 (5) (2002) 1263.
[3] I.H. Park, et al., Nucl. Instr. and Meth. A 535 (2004) 158.
[4] N.H. Park, et al., J. Korean Phys. Soc. 49 (2) (2006) 815.