SLAC-PUB-10910

The BaBar Silicon Vertex Tracker: Performance and Radiation Damage Studies [1]

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Preprint submitted to Elsevier Science *24 November 2003*

Work supported in part by the Department of Energy Contract DE-AC02-76SF00515
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94025
Presented at the6th International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors,
9/29/2003 - 10/1/2003, Florence, Italy

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Abstract

The BaBar Silicon Vertex Tracker is a five layers, double sided AC-coupled silicon microstrip detector operating on the PEP-II storage ring at the Stanford Linear Accelerator Center. The performance of the SVT after 4 years of running is described. Results from radiation hardness tests are presented and the implications of the absorbed radiation dose on the SVT lifetime are discussed.

1 Introduction: the BaBar experiment

The primary goal of the BaBar experiment (1; 2) is the measurement of the time-dependent CP violation in the B_d meson system and the overconstraint of the elements of the Unitarity Triangle, in order to improve the knowledge of the weak interactions and to test the consistency of the Standard Model. The BaBar detector operates on the PEP-II e^+e^- storage ring at the Stanford Linear Accelerator Center. The electron beam of 9.0 GeV collides head-on with the positron beam of 3.1 GeV at a center-of-mass energy of 10.58 GeV, the mass of the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ decays exclusively to $B^0\bar{B}^0$ and B^+B^- pairs, providing an ideal environment for the study of the weak interactions in the $B_{d,u}$ system.

2 Design and Performance of the BaBar Silicon Vertex Tracker

The Silicon Vertex Tracker (SVT) (3; 4) is the core of the BaBar tracking system, also constituted by the drift chamber (DCH) and operating in a 1.5 T magnetic field. The SVT has been designed to reconstruct B vertices with a

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[1] Presented by Matteo Rama at the 6^{th} International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors (Firenze, Italy, September 29 - October 1, 2003)

precision better than 80 μm along the direction of the boost of the center of mass, and to provide precise and high-efficiency reconstruction of charged particle trajectories. In particular, it must provide complete stand-alone tracking for those low-momentum ($p_T < 120$ MeV/c) charged particles that cannot be measured with sufficient precision by the drift chamber. This feature is important due to the considerable number of low-momentum particles produced from the B decays in the BaBar experiment. Additional constraints are imposed by the interaction region in which SVT is allocated. The forward angular coverage is limited, by the presence of the B1 permanent magnet, to a polar angle of 20°; in the backward direction, the SVT sensitive area extends down to 150°.

All the requirements discussed so far have concurred in the choice of the detector design. The SVT is constituted by five layers of double-sided, AC-coupled silicon microstrip sensors, with the strips on the opposite sides of each sensor orthogonally oriented. The silicon sensors and the associated readout electronics are assembled into mechanical units called modules that, from the electrical point of view, are divided into two independent half-modules. The three inner, barrel-shaped layers are placed between 3.2 and 5.4 cm from the IP and are formed by 6 straight modules; the two outer layers are placed between 9.1 and 14.4 cm from the IP and are composed of 16 and 18 arch-shaped modules: the peculiar arch design was chosen to increase the crossing angle for charged particle near the edges of acceptance, while minimizing the amount of silicon required to cover the solid angle. The silicon sensors forming the modules are 300 μm thick, with a readout strip pitch ranging from 50 to 210 μm depending on the layer and the readout coordinate (z or ϕ).

The core of the SVT front-end electronics is a custom readout chip produced with the 0.8 μm Honeywell CMOS process, the AToM (A Time-over-threshold Machine) (5), capable of simultaneous acquisition, digitization and readout of 128 channels. The set of AToM chips and associated electronics that serve a side of a half-module is called readout section (ROS). After the installation of the SVT in 1999, a total of 9 ROSs out of 208 were damaged and not used in the data acquisition. However, during the 2002 PEP-II/BaBar shut-down it was possible to access the SVT and 5 ROSs were recovered, so that only 4 sections are not read-out at present. It is worthwile noting that no ROS is not operational due to radiation damage so far.

All the design performance goals of the SVT have been reached. The single hit efficiency is typically about 97%, and it has been substantially unchanged since the beginning of the BaBar data taking in 1999. The single hit resolution, shown in figure 1, varies as a function of the SVT layer and the incidence angle of the charged particle on the silicon sensors. For particles crossing the silicon sensors perpendicularly with a momentum greater than 1 GeV/c, the hit resolution ranges within 10-15 μm in the three inner layers, and within 30-40 μm in the two outer layers. The SVT provides particle identification information through the measurement of dE/dx. It provides a separation greater than 2σ between kaons and pions up to a momentum of 0.5 GeV/c and between kaons and protons up to a momentum of 1.0 GeV/c.

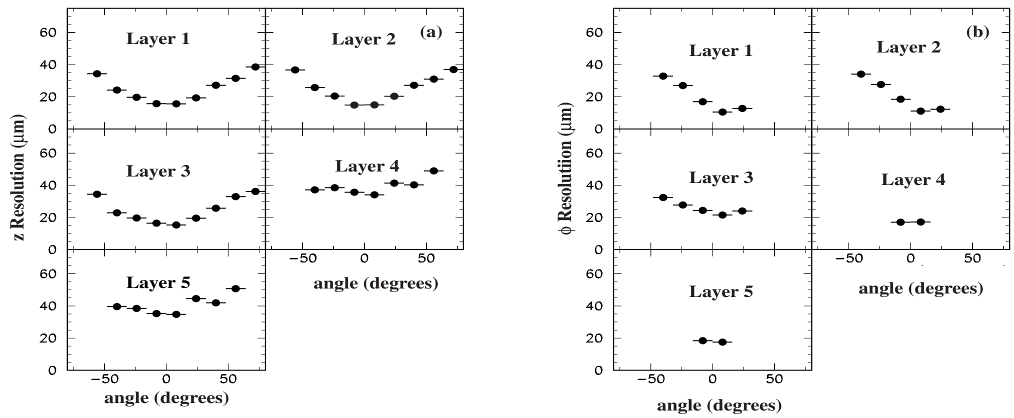

Fig. 1. SVT hit resolution in the a) z and b) ϕ coordinate as a function of the incident angle of the track.

3 Radiation Damage Studies

When the BaBar experiment was designed, the instantaneous luminosity goal of the PEP-II e^+e^- collider was $\mathcal{L} = 3.0 \times 10^{33}$ cm^{-2}s^{-1}, corresponding to a nominal total integrated luminosity of 30 fb^{-1} per year. Based on these numbers, the SVT was designed for an absorbed dose rate of 2 Mrad over a time period of 10 years. PEP-II has reached instantaneous luminosity peaks of beyond 6×10^{33} cm^{-2}s^{-1} and the radiation level in the interaction region is higher than it was expected. The absorbed radiation dose is particularly high for the inner layers in the horizontal plane, the plane where the electron and positron beams lie before colliding. Recent calculations based on beam currents extrapolations indicate that the absorbed dose in these layers will be up to 5 Mrad by the year 2005.

A Radiation and Monitoring protection system protects the SVT from the radiation. The system is composed of 12 reverse-biased PIN diodes placed between the beam pipe and the inner SVT layer. Six diodes are installed in the forward direction (the e^- direction) and six in the backward. Each diode has an active area of 1×1 cm^2 $\times$ 300 μm. The 12 PIN diodes are used both for monitoring and for protection. The instantaneous dose on each diode is monitored by measuring the diode current after the subtraction of the pedestal

current, that depends on the temperature and the total absorbed dose. The total absorbed dose is derived by integrating the instantaneous dose.
A *fast* and a *low* abort system are installed. The fast abort system protects SVT from sudden radiation spikes by ordering the dump of the $e^{\pm}$ beams within a time of about 500 μs. The slow abort system dumps the beams if the radiation level keeps higher than a pre-defined threshold for several minutes.
Silicon PIN-diodes have worked well so far, but they are starting suffering from radiation damage. The leakage currents of the diodes in the horizontal plane range within 1-2 μA, while the typical signals when the beams are stable are of the order of 10-30 nA. The leakage current is expected to grow up to 7-8 μA by 2005, making it more and more difficult to measure the radiation dose accurately. Good candidates for the replacement of the PIN-diodes are the diamond sensors, for several reasons: their sensitivity is comparable to the PIN-diodes' one, they are very radiation hard, have a very low leakage current (of the order of a few pA) and the radiation signals are fast enough to be used in the fast abort system. However, to replace the diodes it is necessary to open the SVT and move the inner layers. This operation takes several weeks and it is planned to be done during the 5 months downtime starting in Summer 2005.

Since it is of crucial importance to evaluate the impact of the absorbed radiation on the SVT lifetime, several studies have been performed or are currently in progress to understand the effect on both the front-end electronics and on the silicon sensors.

The ATOM chips connected to an half-module equal to the ones installed on the real SVT were irradiated using a ^{60}Co source in the laboratories of SLAC and LBL (6). The chips were powered and running during the irradiation, to simulate the working conditions of the chips of the SVT. The degradation of the gain and the increase of the noise was measured as a function of the irradiated dose. It was observed a decrease of gain of 3%/Mrad and an increase of noise of about $15-20\%$/Mrad. Figure 2 shows the gain of one of the irradiated chips as a function of the absorbed dose. No digital failures were observed up to an absorbed dose of 5 Mrad. These results are consistent with what has been observed on the chips of the real SVT, where a gain decrease of about 5%/Mrad and a noise increase of $15-20\%$/Mrad has been measured. The degradation of the performance of the AToM chips represents the main contribution to the decrease of the signal to noise ratio (S/N) due to radiation damage. The noise level is expected to double after an absorbed dose of 5 Mrad, with a decrease of S/N down to the range 10-15.

To investigate the changes of the silicon sensors properties as a function of the irradiated dose, the silicon sensors were irradiated using a 0.9 GeV electron beam from the LINAC of the Elettra synchrotron in Trieste (7). It was found

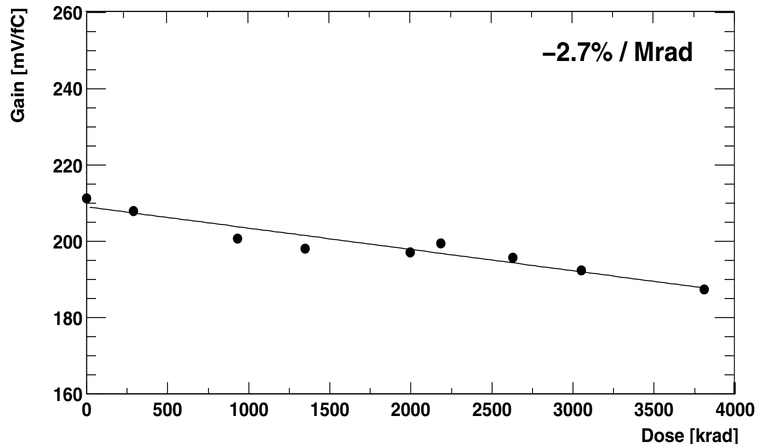

Fig. 2. Gain of an irradiated AToM chip as a function of the absorbed dose.

an increase of the leakage current of 2 μA/Mrad/cm^2 (T=23 ^oC). The variation of the depletion voltage as a function of the absorbed dose was measured from the distribution of the $1/C^2$ vs. V diode characteristic after different absorbed doses, as shown in figure 3. Based on this study, the bulk-type inversion is expected around an absorbed dose of 3 Mrad. After the bulk-type inversion occured, no significant increase of the current contribution from edge zone of the detectors was observed, and the bias voltage at which the adjacent strips on the n-side are isolated decreased. These results suggest that the SVT microstrip sensors are still usable after bulk-type inversion. The increase of the leakage current versus the absorbed dose measured at Elettra has been compared with what is seen on the real SVT. Using the I-V measurements performed since the installation of the SVT in 1999 and evaluating the absorbed dose from the PIN-diodes, the increase of the leakage current is found to be about 2 μA/Mrad/cm^2 (T=23^o). The main uncertainty affecting this result derives from the estimate of the scale factor to obtain the SVT wafers absorbed dose from the nearby PIN diode dose; the result is consistent with what was found in the irradiation tests at Elettra. The noise contribution due to the increase of the leakage current is at least a factor 2 smaller than the noise from the AToM chip.

The effect of high energy electron radiation on the charge collection efficiency (CCE) of a microstrip detector identical to those used in the inner layer of the SVT has been investigated. A SVT half-module with the front-end electronic connected has been irradiated with a 0.9 GeV electron beam at Elettra. The irradiation was not uniform, to simulate the conditions encountered in the BaBar interaction region by the modules intersecting the horizontal plane. The CCE was measured by illuminating the silicon surface with a 1060 nm LED. The 500 μm spot diamater light source allows to produce a detailed CCE map of the silicon sensors. Preliminary results show a CCE reduction of $\sim 6\%$ after an absorbed dose of 5.5 Mrad.

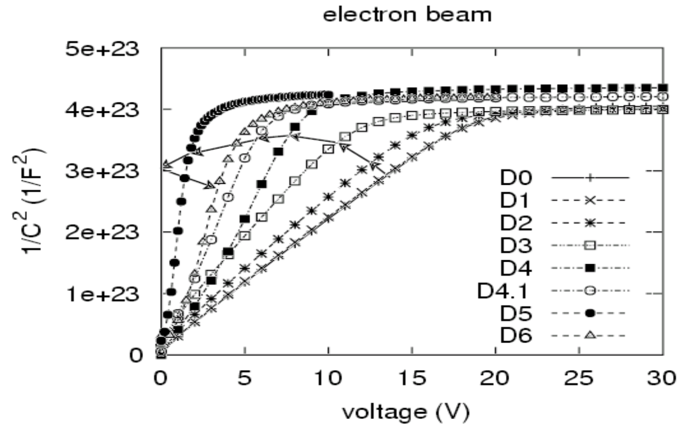

Fig. 3. Capacitance-voltage diode characteristic for different absorbed doses. The dose increases from D0 (0 Mrad) to D6 (3.9 Mrad). The type-inversion occurred between D5 and D6.

4 Conclusions

The BaBar Silicon Vertex Tracker is working well, the physics performance meet the design expectaction and only 4 read-out sections out of 208 are not read-out at present. The rate of the absorbed radiation dose is significantly higher than originally foreseen, and it is thus crucial to understand the implications on the SVT performance. Several studies, performed or currently in progress, seem to indicate that the SVT will work fine up to absorbed doses of 5 Mrad. According to the present estimates, this limit won't be reached before Summer 2005, when the most irradiated modules will be replaced.

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