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CDF Run II silicon vertex detector annealing study

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ABSTRACT

Between Run II commissioning in early 2001 and the end of operations in September 2011, the Tevatron collider delivered 12 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV to the Collider Detector at Fermilab (CDF). During that time, the CDF silicon vertex detector was subject to radiation doses of up to 12 Mrad. After the end of operations, the silicon detector was annealed for 24 days at 18 °C. In this paper, we present a measurement of the change in the bias currents for a subset of sensors during the annealing period. We also introduce a novel method for monitoring the depletion voltage throughout the annealing period. The observed bias current evolution can be characterized by a falling exponential term with time constant $\tau_I = 17.88 \pm 0.36(\text{stat.}) \pm 0.25$ (syst.) days. We observe an average decrease of $(27 \pm 3)\%$ in the depletion voltage, whose evolution can similarly be described by an exponential time constant of $\tau_V = 6.21 \pm 0.21$ days. These results are consistent with the Hamburg model within the measurement uncertainties.

1. Introduction

In high-energy physics (HEP) experiments, silicon sensors serve a crucial role in the detection of charged particle positions, momenta, and to some extent, dE/dX information. Due to their typically close location to the collision point of hadron colliders, silicon sensors often incur intense radiation damage due to the numerous particles from collisions that traverse them. The macroscopic effects of radiation damage on silicon sensors in HEP detectors have been extensively studied. The leakage currents increase linearly with radiation dose, and for n-bulk sensors, the depletion voltage V_{dep} initially decreases until the sensor appears to undergo type inversion at which point V_{dep} then increases with radiation dose. These macroscopic changes have been linked to the formation of crystal defects when atoms are displaced from their lattice positions after collisions with particles from the radiation field.

The process of annealing is the opposite effect, where increasing the temperature of the silicon sensor allows the displaced atoms to settle back into vacant lattice positions, eliminating the local crystal defect, and at least partially recovering some of the initial behavior of the silicon sensor as it was before irradiation. Annealing, which is strongly temperature dependent, has been studied with test sensors, where the irradiation phase and the annealing phase can be isolated from each other by strict temperature controls. Such temperature control enables the construction of silicon-behavior models which can closely approximate ideal silicon sensor behavior. The most popular of them is the Hamburg model [1,2] whose verification and that of other models is ongoing.

Because annealing can prolong the life of a HEP silicon detector, understanding how the macroscopic quantities such as leakage current and depletion voltage change with time for different temperatures is of great interest to the HEP silicon detector community. Test bench studies are usually done at warm (40–80 °C) temperatures to maximize the annealing effect in the available time, while annealing of HEP detectors is more practical at room temperature.

This paper describes the annealing studies that were performed with the silicon detector system at the CDF experiment at Fermi National Accelerator Laboratory. The silicon sensors were exposed to 0.4–12 Mrad of radiation over the course of 10 years, and dedicated annealing studies were performed after the end of Tevatron Run II. This *in situ* measurement of annealing with an operating HEP detector required a new method for monitoring the depletion voltage of the sensors. We discuss some annealing theory in Section 2 and the detector in Section 3. The measurement and monitoring procedures are detailed in Section 4. The analysis of the current changes and depletion voltages is given in Sections 5 and 6, respectively, and the results and conclusions follow in the remaining sections.

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2. Silicon annealing

The behavior of a silicon detector can be characterized by several quantities. For this study, we consider the leakage current, and the depletion voltage V_{dep}, which for an unirradiated sensor is defined as the minimum bias voltage applied to the sensor that can deplete it of free charge carriers. As the silicon sensors are irradiated, the behavior of these quantities changes. The leakage current increases in a manner linearly proportional to the fluence:

$$\Delta I = \alpha \Phi_{eq} V \tag{1}$$

where α is the current related damage rate, Φ_{eq} is the fluence, and V is the volume of the sensor. ΔI is the increase in leakage current from its original value I_0. The magnitude of α is temperature-dependent and on the order of 10^{-17} A/cm.

During annealing, the leakage current is observed to decrease and the rate of this decrease strongly depends on temperature, based on studies performed in the temperature range 0–60 °C. The decrease of the leakage current is often parameterized according to the Hamburg model, which suggests a leakage-current evolution according to the formula:

$$\Delta I(t) = \Delta I(t_0) \sum_i b_i \exp\left(-\frac{t}{\tau_i}\right). \tag{2}$$

In this expression, t_0 represents the start time of annealing and the sum is over different types of crystal defects, each of which has a temperature-dependent characteristic time constant τ_i and an amplitude b_i, subject to the constraint $\sum_i b_i = 1$. Table 1 shows characteristic values for the constants b_i and τ_i for the annealing temperature of 18 °C, and also 11 °C and -5 °C, which are the nominal operating temperatures of the SVX and L00 CDF silicon subdetectors, respectively (see Section 3). Note that the weights b_i are not temperature dependent, but the time constants τ_i scale according to the Arrhenius equation.

Fig. 1 shows the expected leakage current behavior during annealing for annealing temperatures of 15, 18 and 21 °C. As can be seen, the leakage current is at its maximum immediately after warming, and then decreases due to the annealing behavior as described in Eq. (2). The shaded region in Fig. 1 corresponds to the period when CDF annealing data were recorded. As the time constants of the individual terms in Eq. (2) span several orders of magnitude, the measurements presented are sensitive to only a subset of the parameters in Eq. (2). A more appropriate parameterization is thus

$$\Delta I(t) = A_I \exp\left(-\frac{t}{\tau_I}\right) + B_I, \tag{3}$$

where A_I and B_I are empirical constants, and τ_I is a time constant associated with annealing; it is calculated to be 17.6 days, as discussed in Section 8.1.

The change in the depletion voltage V_{dep} during annealing occurs in a more complicated fashion. According to the Hamburg model, as the sensor is irradiated with an accumulated fluence Φ_{eq}, V_{dep} changes proportionally to any adjustments in the effective doping concentration:

$$\Delta N_{\text{eff}} = N_A(\Phi_{eq}, t) + N_C(\Phi_{eq}) + N_Y(\Phi_{eq}, t) \tag{4}$$

where t is the annealing time, and N_A, N_C and N_Y represent contributions from short-term annealing, a stable damage component independent of annealing time, and reverse-annealing, respectively. As we are primarily interested in the time-dependence of annealing, N_c merely serves as an overall offset, and so we do not specify its explicit form. The short-term and reverse annealing components are given by

$$N_A(t) = N_A \exp\left(-\frac{t}{\tau_A}\right), \quad \text{and} \tag{5}$$

$$N_Y(t) = \begin{cases} N_Y(1 - \exp(-k_{1Y} t)) & \text{for first-order process} \\ N_Y\left(1 - \dfrac{1}{1 + k_{2Y} N_Y t}\right) & \text{for second-order process} \end{cases}. \tag{6}$$

where the dependencies on the fluence Φ_{eq} have been absorbed by the constants N_A and N_Y. An explanation of the definitions and differences of first- and second-order processes can be found in Ref. [1].

At room temperature, reverse-annealing has a time scale on the order of 500 days [1], for which both first- and second-order processes can be approximated for this analysis by a term linear in annealing time: $N_Y(t) \approx N_Y t/\tau_Y$, where τ_Y is the 500-day time constant. We therefore expect the depletion voltage V_{dep} to follow

$$V_{\text{dep}} = V_A \exp\left(-\frac{t}{\tau_V}\right) + V_C + V_Y\left(\frac{t}{\tau_Y}\right) \tag{7}$$

where V_A and V_C represent offsets, and V_Y is the constant associated with reverse-annealing. The short-term annealing time constant τ_V is expected to be $3.6^{+2.2}_{-1.3}$ days, based on parameters given in Ref. [1], and scaling to 18 °C using the Arrhenius equation. Note that the value of this time constant is expected to be much less than that of Eq. (3).

To illustrate the temperature dependence on the predicted annealing behavior of V_{dep}, we plot the Hamburg-model prediction assuming annealing temperatures of 15, 18, and 21 °C, shown in the top plot of Fig. 2. For these predictions, we use values of V_A, V_C and V_Y based on estimates made specifically for the L00 narrow

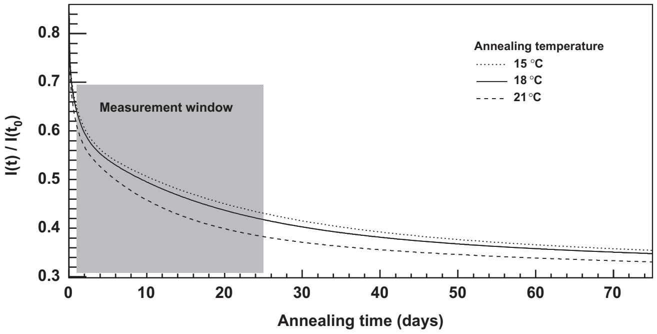

Fig. 1. Expected behavior of the bias current during annealing for various temperatures, based on constants in Refs. [1,2]. The shaded region corresponds to the period when annealing data was recorded for this study.

Table 1
Characteristic values assumed for b_i and τ_i in Eq. (2), based on details found in Refs. [1,2]. The time constants have been scaled to various temperatures using the Arrhenius equation.

Term i	1	2	3	4	5	6
τ_i at 18 °C (days)	1.68×10^{-2}	1.12×10^{-1}	1.02	13.9	83.7	∞
τ_i at 11 °C (days)	4.99×10^{-2}	3.32×10^{-1}	3.05	41.4	249	∞
τ_i at -5 °C (days)	7.46×10^{-1}	4.97	45.5	619	3 720	∞
b_i	0.156	0.116	0.131	0.201	0.093	0.303