Electrical effects of transient neutron irradiation of silicon devices

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Abstract

The key effects of combined transient neutron and ionizing radiation on silicon diodes and bipolar junctions transistors are described. The results show that interstitial defect reactions dominate the annealing effects in the first stage of annealing for certain devices. Furthermore, the results show that oxide trapped charge can influence the effects of bulk silicon displacement damage for particular devices.
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1. Introduction

Neutron and ionizing irradiation of bipolar transistors generally causes damage to these devices [1]. Neutron irradiation generates defects by displacing silicon atoms. For each displacement collision, a pair of defects is created, the interstitial atom and the vacancy left behind. These defects reduce transistor gain by increasing the recombination rate of electrons and holes thereby increasing the base current of these devices. After the radiation ceases, these defects undergo reactions that produce composite defects that are less effective at carrier recombination. Ionizing radiation, which occurs during neutron irradiation, also damages these devices, primarily by releasing electrons and holes in the ever-present silicon dioxide in these devices [2]. This process leads to trapped positive charge in the oxide, and it also produces interface traps, often by releasing hydrogen from sites in the oxide. Furthermore, the electric field caused by the trapped charge affects the recombination rate.

A primary motivation for these calculations is the need to understand the expected phenomena from radiation sources that produce varying degrees of atomic displacement effects compared with ionization effects. For example, ion implantation can be used to mimic neutron irradiation but it will be accompanied by larger ionization effects. For this reason, in the simulations to be described, the ionization effects are comparable with the atomic displacement effects.

In this article, we discuss continuum simulations of the temporal evolution of these phenomena, and these simulations rely on information from atomistic simulations of defects in silicon and silicon dioxide. For the displacement defects, density-functional theory (DFT) calculations are used to obtain the energy levels of the defects, primarily interstitials and vacancies. The continuum simulations also use information from DFT and kinetic Monte Carlo atomistic simulations of athermal migration of interstitials driven by carrier injection. Finally, these continuum simulations are used to describe the transient electrical effects of these devices during and after irradiation.

The simulations are used to illustrate some of the consequences of the combined phenomena but they are not used to understand specific data in this report. In these continuum simulations, the sequence of events are described by focusing on three specific phenomena. The first is the response of a diode to combined transient neutron and

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ionizing radiation. The second is the phenomena in the silicon dioxide portion of this diode. The third is a discussion of the effect of the trapped charge in the oxide on the neutron displacement damage in a diode. In each of these simulations, the radiation dose rates and pulse durations are given values that should be representative of actual values expected if this simulation capability were used for comparisons with experimental data.

2. Simulations

The calculations are performed with REOS (radiation effects in oxides and semiconductors), software developed to solve for the radiation effects response of the silicon semiconductor and its oxide [3]. In these simulations, kinetic equations are solved to obtain the time-dependent effects of ionizing radiation [3–6]. These equations include contributions from the drift–diffusion transport of the mobile species such as electrons, holes, interstitials, vacancies, hydrogen and other atomic species [3,6]. The equations also include contributions from the reactions governing the release of protons and neutral hydrogen from source sites and the reactions of these hydrogen atoms with the silicon dangling bonds at the interface [3,6]. The effects of the electric field are included in these calculations [3–5]. This field includes contributions from the gate bias, the space-charge of all the charged species and the band-bending in the silicon substrate. All the simulations to be discussed are done using REOS.

The simulations to be described focus on the electrical behavior of a uniformly doped silicon diode. This diode consists of a 10-μm thick p-doped region doped with 10^{15} cm^{-3} boron acceptors, and a 10-μm thick n-doped region doped with 10^{17} cm^{-3} phosphorus donors. For these one-dimensional simulations, the electrical phenomena are controlled by the more lightly doped region, the p-doped portion. For the two-dimensional simulations including oxide effects, a 1-μm thick portion of this structure is covered by a 1-μm thick layer of silicon dioxide. In agreement with typical samples, a large concentration of interstitial oxygen impurities is also assumed; to be specific, $[O] = 10^{18}$ cm^{-3}. The initial interstitials and vacancies are allowed to react with each other, with the boron acceptors and with the oxygen impurities. All defects known to create energy levels within the silicon bandgap are allowed to capture and release electrons and holes. The defect reactions are assumed to be diffusion-limited, and the reaction rates are therefore defined in terms of diffusion coefficients and the capture radius for each reaction. The carrier capture and emission reaction rates are obtained from literature values for energy levels and approximations for capture cross-sections. For comparison with the electrical measurements of recombination rates, the interstitials and vacancies are allowed to react with dopants and impurities while electrons and holes were injected.

Numerous simulations were done to explore the defect reactions that control early-time recombination rate annealing. Based on insight gathered from these test calculations, the essence of the early-time annealing can be understood by considering the reactions of interstitials and vacancies with dopants and impurities. Such reactions are more important than direct recombination of interstitials and vacancies unless the irradiation dose is extremely large or one is considering phenomena within a highly defective disordered region.

2.1. Transient annealing

To be specific, this report discusses the few defect reactions that are likely to be important to understand the early-time annealing. The primary reactions are those that remove the main defects, interstitials and vacancies. In the simulations to be described, the following two reactions are the primary reactions:

$$O_i + V \rightarrow O_v$$

and

$$B_s + I \rightarrow B_i.$$
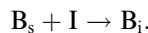
In the first reaction, a vacancy V reacts with interstitial oxygen O_i to create an oxygen–vacancy pair O_v; in the second reaction, an interstitial I reacts with substitutional boron B to create interstitial boron B_i.

When possible, the reaction coefficients are obtained from experimental data. In some cases, no information is available and thus the information was obtained by simple approximations to the atomistic phenomena. In particular, the reaction coefficients for the reactions involving vacancies was obtained by simulating experiments that involved measuring the ESR signal before and after a series of thermal annealing steps [7].

The properties of interstitials are not well known. Similar to vacancies, they are thought to have several charge states in the silicon bandgap. However, these assignments are based on calculations because electrical properties of interstitials have never been measured directly. It is assumed that these defect migrate rapidly and react with other defects.

The rapid migration of interstitials at low temperatures has led to the hypothesis that they migrate via an athermal mechanism driven by sequential recombination of electrons and holes [8,9]. The athermal diffusion occurs because the minimum energy site depends on the charge state of the interstitial, and the hopping of the interstitial from site to site causes diffusive motion [9]. Following the initial proposal, several electronic structure calculations have been undertaken to understand the atomistic details [10–14]. These calculations for interstitials in silicon have concluded that the diffusion involves jumps between the hexagonal and tetrahedral interstitial sites. Some calculations have concluded that the jumps involve the $m = 0$, 1 and 2 charge states but most recent calculations conclude that the jumps involve the $m = 0$ and 1 charge states.

In our implementation of the Recombination Enhanced Diffusion (RED) mechanism, we developed a simplified