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Correlating percent in-package hydrogen to hydrogen concentration in oxide after ionizing radiation exposure

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Abstract – Radiation-induced interface trap buildup is a strong function of hydrogen content in the semiconductor materials, which is quantitatively mapped to percent of hydrogen in the semiconductor packaging using a combination of experimental and simulation-base approaches.

Keywords – TCAD, MOS capacitors, Total Ionizing Dose, Hydrogen concentration, Nitride, Interface traps, Hydrogen passivation, ELDRS.

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I. INTRODUCTION

Linear bipolar circuits such as comparators, operational amplifiers and voltage regulators exhibit a high sensitivity to total ionizing dose (TID) as well as enhanced low dose rate sensitivity (ELDRS) [1]. Numerous studies have presented experimental data on and models of the physical mechanisms for TID and ELDRS effects in linear bipolar circuits and bipolar junction transistors (BJTs) [2-8].

TID and low dose rate sensitivity are strongly dependent on the buildup of traps at bipolar base oxide-semiconductor interface (N_{IT}). And the rate of N_{IT} generation depends on several factors such as base oxide thickness, internal electrical fields, final passivation materials, and pre-irradiation elevated temperature stress [9-11]. It was also experimentally demonstrated that ELDRS in BJTs is strongly related to hydrogen content in the gas ambient inside hermetically sealed part packaging. [12-16]. This suggests a correlation between a relatively observable quantity, i.e., H_2 in gas, that indirectly impacts defect buildup with hydrogen in the base oxide, which is difficult to quantify but can be mapped directly to N_{IT} through well-developed models [3-8]. In their 2007 paper, Chen *et al.* presented a simple analytical model that related the volume percent of H_2 in ambient gas to hydrogen content in the base oxide [16]. However, this correlation was not examined in detail nor experimentally quantified.

In this work, metal-oxide-semiconductor (MOS) capacitors were fabricated and irradiated with different hydrogen concentrations in a controlled gas ambient. Radiation-induced N_{IT} were extracted experimentally from capacitance-voltage (C-V) data at various dose steps and H_2 gas concentrations. At the same dose steps, simulations were performed to map varying base oxide hydrogen concentrations to corresponding N_{IT} densities [8]. The experimental data were then compared to a simulated data set. This comparison allows for empirical validation and verification of Chen's analytical model relating percentage of hydrogen in gas to hydrogen concentration in the base oxide.

II. EXPERIMENTAL DETAILS

A. Test structure design

Fig. 1 illustrate a cross-section of the MOS capacitors used in this study. The SiO_2 layer is deposited on a p-type silicon. Aluminum is used for both gate and substrate electrodes. The gate electrode area is 500umx500um. The oxide thickness of the insulator regions is equal to 100nm.

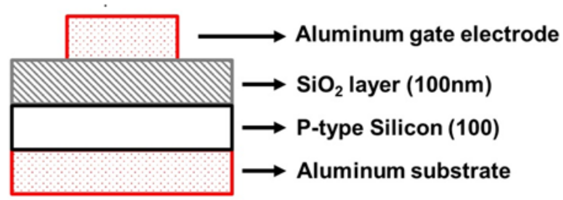


Fig. 1. Representational cross-sections of metal-oxide-semiconductor (MOS) capacitor used in this study.

B. Test structure fabrication

The capacitors were fabricated at Arizona State University (ASU) in cleanroom. At first, dry oxidation on a (100) orientation p-type wafer was performed to grow the SiO_2 layer. Electron beam evaporation was used for the aluminum gate electrode deposition. The gate electrode was deposited on the backside of the wafer to form the ohmic p-silicon substrate contact. To reduce defect density at the Si/SiO_2 interface, rapid thermal annealing (RTA) at 380°C for 2 mins was performed in the forming gas environment.

C. Experimental setup

Radiation testing was performed at ASU using a Co^{60} gamma-ray source to explore the effects of the in-package hydrogen gas content on the total dose response of the capacitors. All capacitors were exposed at a dose rate of 4.25 rad [Si]/sec. Capacitors were irradiated at room temperature with all pins shorted together during irradiation (i.e., biased in thermal equilibrium). A glass chamber flange was used to perform the irradiations in hydrogen atmosphere (Fig. 2). Several %Hydrogen concentrations were used in this study: 1%, 10%, and 100%. These concentrations are determined by the partial pressure measured inside the glass chamber. Two devices were irradiated for each hydrogen concentration. Before radiation exposure, the capacitors were soaked in the gas chamber for 48 hours to ensure complete saturation of the hydrogen into capacitor materials. A deep vacuum was performed before pumping the pure hydrogen gas into the chamber. After reaching each targeted dose, devices were removed from the chamber and high frequency (1 MHz) C-V measurements were performed using an Agilent 4284A LCR meter. Electrical characterization was performed immediately after radiation exposure at room temperature and in open air.

Fig. 2. Glass chamber flange used for soaking and radiation testing of samples under hydrogen environment [16].

III. EXPERIMENTAL RESULTS

Figs. 3- 5 show the measured C-V plots on the capacitors for different percentage of hydrogen in the package. Each curve represents the average of two irradiated capacitors.

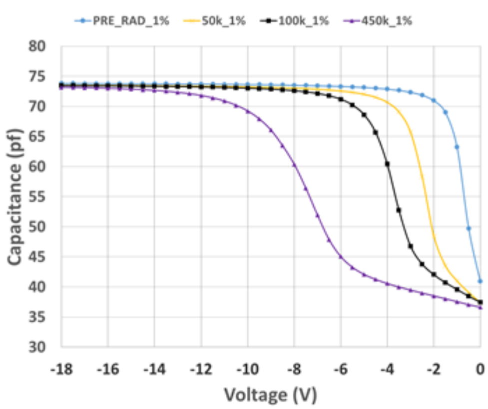


Fig. 3. C-V measurement of the MOS-Capacitor irradiated under a hydrogen environment: 1%.

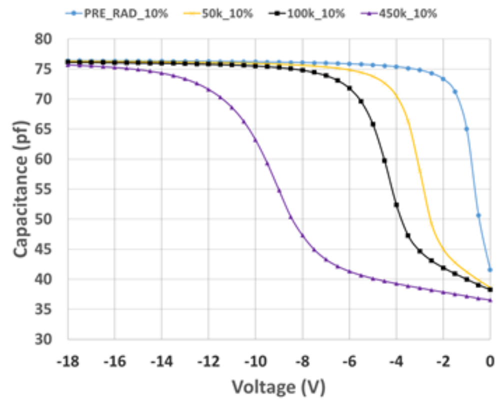


Fig. 4. C-V measurement of the MOS-Capacitor irradiated under a hydrogen environment: 10%.

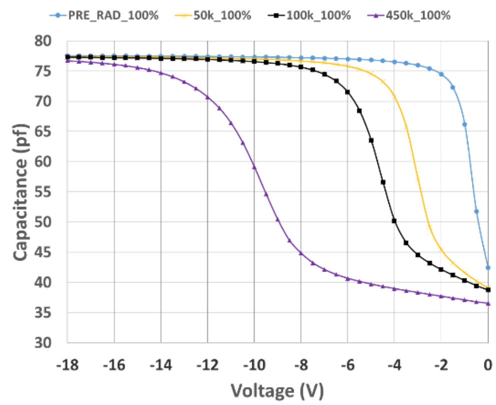


Fig. 5. C-V measurement of the MOS-Capacitor irradiated under a hydrogen environment: 100%.

In Figs. 3- 5 a clear shift in the slope of the C-V curve related to dose and hydrogen concentration can be observed. This shift is used to extract the change in N_{IT} [17]. Fig. 6 plots the extracted change in N_{IT} for different irradiation levels and %Hydrogen in the gas ambient.

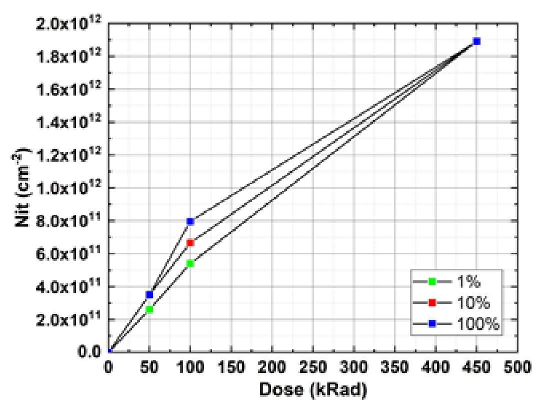


Fig. 6. Change in N_{IT} of the capacitor irradiated under hydrogen atmosphere.

IV. SIMULATION MODEL

Simulated N_{IT} defects were calculated using a python model in development by H. P. Hjalmarson at Sandia National Laboratories. A primary driving equation of this model is

$$\frac{du}{dt} = f(u,D,t) \ , \qquad (1)$$

where u represents a vector that describes destiny of a species in a computational grid as a function of position r and time t [8, 18]. D represents ionizing dose as a function of position and time. It is assumed that all species, except interface traps, eventually reach a steady state between competing reactions. With these steady-state populations,

$$\frac{du}{dt} = 0 \quad , \qquad (2)$$

This allows for reduced order modeling to be used throughout the model [18]. Eqs. 1 and 2 combined with only interface trap densities changing gives the equation:

$$\frac{d[N_{IT}(r,t)]}{dt} = f(u, g,t) \ , \qquad (3)$$

The reactions and species include electrons, holes, excitons, oxygen vacancies, interface traps, hydrogen release, and hydrogen depassivation [8]. The model can simulate the production of interface traps as a function of hydrogen concentration, dose rate, total dose, temperature, and more.

V. RESULTS AND DISCUSSION

The model described above is used to calculate N_{IT} as a function of total dose and hydrogen concentration in in the bipolar base oxide. The total dose was set to 50krad(Si), 100krad(Si), and 450krad(Si). The hydrogen concentration in the oxide was set to a range of 10^{12} cm^{-3} to 10^{18} cm^{-3}. All other parameters (dose, dose rate, oxide thickness, temperature, and bias) were set to be the same as in the experiment so that a meaningful comparison can be made. To establish a quantitative relationship between the percentage hydrogen in the semiconductor packaging to the concentration of hydrogen in the oxide, we assumed the model developed by Chen *et al* [16],

$$N_{H_2,ox} = K_{H_{2,ox}} P_{H,2} \qquad (4)$$

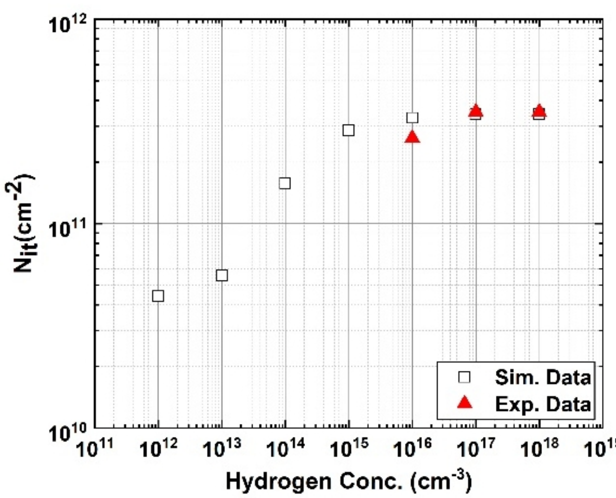
where $N_{H_2,ox}$ is the base oxide hydrogen concentration, $K_{H_{2,ox}}$ is the solubility of hydrogen in the oxide and $P_{H,2}$ is the partial pressure of H_2 computed from volume percentage in the ambient. The relation between the hydrogen percent to partial pressure is presented in [16]. Using the above equation, we get an assumed correlation between the percent of hydrogen in the package gas ambient and the hydrogen concentration in the bipolar base oxide (see Table 1).

Table I

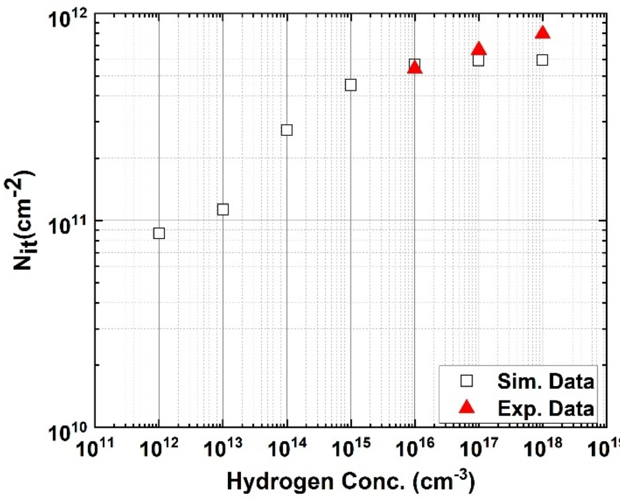
%Hydrogen to hydrogen concentration in oxide (cm^{-3})

Percent H_2 in gas (%)	H_2 partial pressure (torr)	Hydrogen conc. in oxide (cm^{-3})
1	7.35	10^{16}
10	73.5	10^{17}
100	735	10^{18}

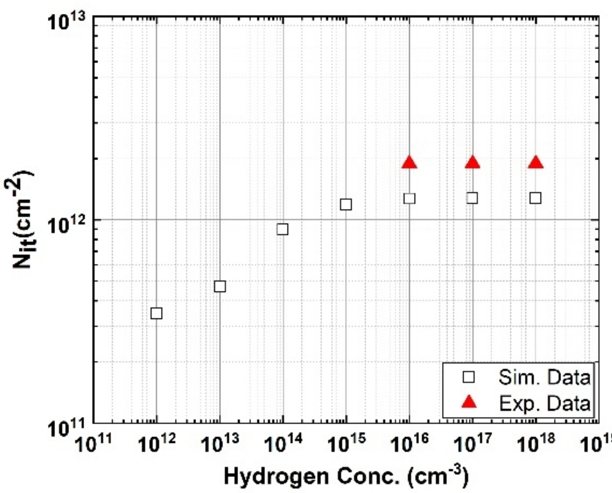
Using Eq. (4) with a solubility factor $K_{H_{2,ox}}$ = 1.36x10^{15} cm ^{3}/torr, the accuracy of Chen's model can be evaluated. Fig. 7 (a)–(c) show the simulated and experimental data plotted as function of hydrogen concentration in the base oxide for different dose levels. The results shown in Fig. 7 show that the experimental values reasonably match with the simulated data at higher values of hydrogen concentrations (i.e., between 10^{16} cm^{-3} to 10^{18} cm^{-3}).



(a)



(b)



(c)

Fig. 7. Comparing the simulated and experimental Nit vs different hydrogen concentrations at the oxide interface to different irradiation levels (a).50kRad (b).100kRad (c).450kRad.

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