Impact of Deep P-Well Structure on Single Event Latchup in Bulk CMOS

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***Abstract*—The effect of a deep p-well structure on radiation-induced single event latchup is studied through three-dimensional numerical simulations. Our simulation results show that the deep p-well structure effectively prevents single event latchup even in the case that well taps are significantly far from the source region of a CMOS device. We demonstrate that the deep p-well structure creates an additional conduction path for holes and suppresses the potential perturbation in a p-well.**

I. Introduction

Radiation induced latchup, which is called single event latchup (SEL), is one of the serious concerns in the field of semiconductor device reliability. SEL can not be completely avoided because parasitic bipolar transistors (BJTs) are inherent in bulk CMOS structures as illustrated in Fig. 1, where two BJTs are electrically connected each other such that the collector of one BJT connects to the base of the other BJT [1]. When this positive feedback circuit becomes active by some triggers, the circuit runs into low impedance and high current states, i.e., latchup. In ground applications, terrestrial high-energy neutrons can be the trigger of SEL because secondary ions produced by nuclear reactions induce excess carriers and perturb well potential [2].

For the purpose of the prevention of SEL occurrence, many techniques have been investigated in terms of both process and design approaches, such as SOI technologies, deep n-well (DNW) processes and current limit circuits [3], [4]. Our group has recently found that a deep p-well (DPW) process is an effective way to suppress neutron-induced SEL [5], [6]. This DPW approach has several advantages comparing to other techniques. The adoption of the DPW process does not require geometry change and area increase, which are inevitable in the use of SOI processes and current limit circuits, respectively. As for the DNW process, it has been reported that multi-cell upsets increase due to a parasitic bipolar effect [7]. On the other hand, the DPW does not intrinsically activate this effect.

Table I shows the SEL counts observed in our previous experiments [5]. Three types of SRAM arrays with different well structures have been irradiated by high-energy neutrons for 60 minutes. As for the twin-well profile, which is denoted as w/o deep well, SEL have occurred for VDDs of 1.3 and 1.4 V. On the other hand, no SEL has occurred in DNW and DPW structures. This work has experimentally demonstrated that the DPW structure is as effective on SEL prevention as the DNW structure. However, the mechanism of this effect has not been clarified enough. In the present study, we explore the underlying mechanism through three-dimensional TCAD simulations.

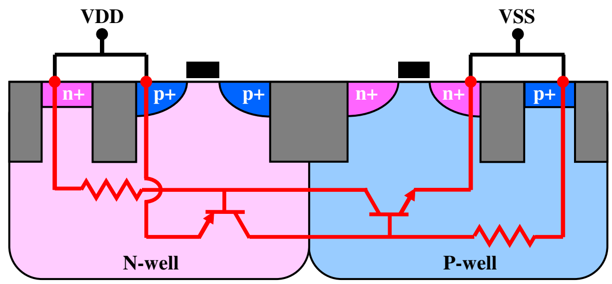

Fig. 1. Cross-sectional image of a bulk CMOS structure with a twin-well process. There are two parasitic BJTs. One is the npn-type BJT consisting of n+ source/p-well/n-well, and another is the pnp-type BJT consisting of p+ source/n-well/p-well. The schematic (red line) depicts an inherent positive feedback circuit consisting of these parasitic BJTs and resistors.

TABLE I. SEL Counts in Sixty Minutes Of Neutron Irradiation [5].

Well	VDD [V]			
Structure	1.0	1.2	1.3	1.4
w/o deep well	0	0	2	7
deep n-well	0	0	0	0
deep p-well	0	0	0	0

II. Simulation Setup

The simulation model consists of an n-well sandwiched between two p-wells as depicted in Fig. 2. Each well has a well tap and a source. Conduction types of the well tap and the source are the same as and opposite to that of the well where they are located, respectively. Each electrode is biased as shown in Fig. 2. In this layout, the source region corresponds to a CMOS device such as a SRAM cell. Well taps have been located far from sources in the model. The distance between these regions is 50 um. This layout is a worse case in terms of SEL tolerance because the potential stabilization by well taps becomes less effective as the well tap distance increases. We have prepared two models with different well structures, one is a typical twin-well and another is a twin-well with a DPW doping. The net doping profiles of these well structures are plotted as a function of depth in Fig. 3, where the right side of the graph is the shallow region of the model. The right and center peaks correspond to the p-well and DPW, respectively. The doping profiles of sources, well taps, n-well, p-well and p-substrate are same in both models.

Nuclear reactions between terrestrial neutrons and constituent atoms of a device produce a variety of secondary ions.

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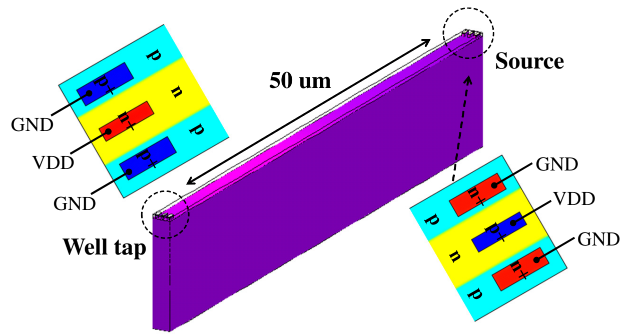

Fig. 2. Simulation model consisting of an n-well sandwiched between two p-wells. Each well has a well tap and a source. The distance between sources and well taps is 50 um. p+ source and n-well tap are biased with VDD and the others are grounded.

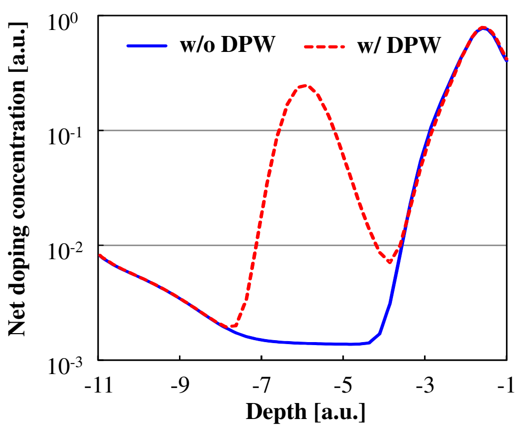

Fig. 3. Net doping profile underneath the n+ source as a function of depth. Solid and broken lines correspond to the model without the DPW (w/o DPW) and the DPW model (w/ DPW), respectively. The right side of the graph is the shallow region of the model. The right and center peaks correspond to the p-well and DPW dopings, respectively.

These ions deposit energy through ionization and generate electron-hole pairs in silicon. This phenomenon is the origin of SEL. The probability of SEL occurrence increases with the amount of electron-hole pairs. In order to estimate the generation rate of the electron-hole pairs, a linear energy transfer (LET), which is defined as an energy deposition per unit length, is calculated using PHITS [8]. Figure 4 shows obtained LET spectra for hydrogen, helium and ions heavier than lithium, indicating that the LET ranges below 4.0 MeV/um. Based on this result, relatively high LETs, 0.5 and 1.0 MeV/um, have been employed as the radiation condition of TCAD simulations. These LETs have been converted to the number of electron-hole pairs by divided by 3.6 eV, which is the energy required to generate an electron-hole pair [9].

In TCAD simulations, the locations of ion tracks have been assumed as shown in Fig. 5. All tracks are parallel to the well stripe and lies in the source region with 1 um length. At each track location, electron-hole pairs described above have been set with Gaussian distribution in the radial direction. Transient calculations for each ion track condition have been carried out using HyENEXSS [10]. Since the probability of SEL occurrence increases with the supply voltage VDD, SEL tolerance can be evaluated with the SEL threshold VDD, which is defined as a minimum VDD required for latchup. To compare SEL tolerance between models with and without the DPW, the SEL threshold VDD has been analyzed in each ion track condition for both models.

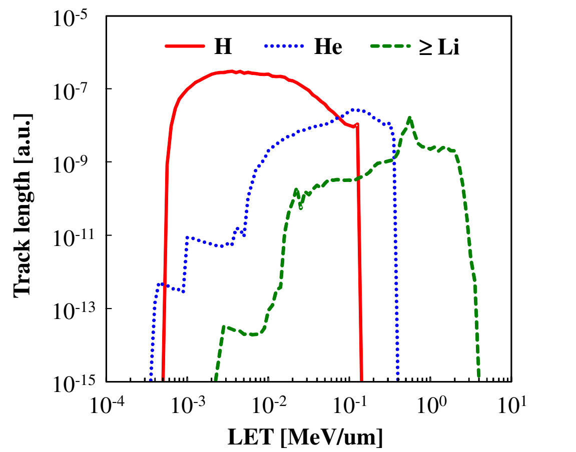

Fig. 4. Calculated LET spectra of secondary ions, hydrogen, helium and ions heavier than lithium, induced by nuclear reactions between terrestrial high-energy neutrons and device constituents including metal layers and package materials. The vertical axis corresponds to the track length of the secondary ion with respective LETs.

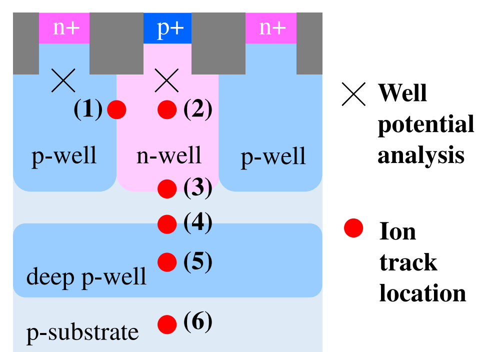

Fig. 5. Cross-sectional locations of ion tracks and well potential analyses.

III. Results and Discussion

Figure 6 shows calculated transient currents of each electrode in the case of ion track (6) with the LET of 1.0 MeV/um, where the ion incidence occurs at 0 s. Figures 6 (a) and (b) correspond to the models without and with the DPW, respectively. In the case of the model without the DPW, abrupt current increases are observed in n+ and p+ sources, indicating SEL occurrence. On the other hand, only a temporary current increase is observed in the case of the model with the DPW. These results demonstrate that the SEL threshold VDD of the DPW model is higher than that of the model without the DPW.

Calculated SEL threshold VDDs are listed in Table II, where a greater than (>) sign represents that the model does not show latchup behavior up to the stated value. These

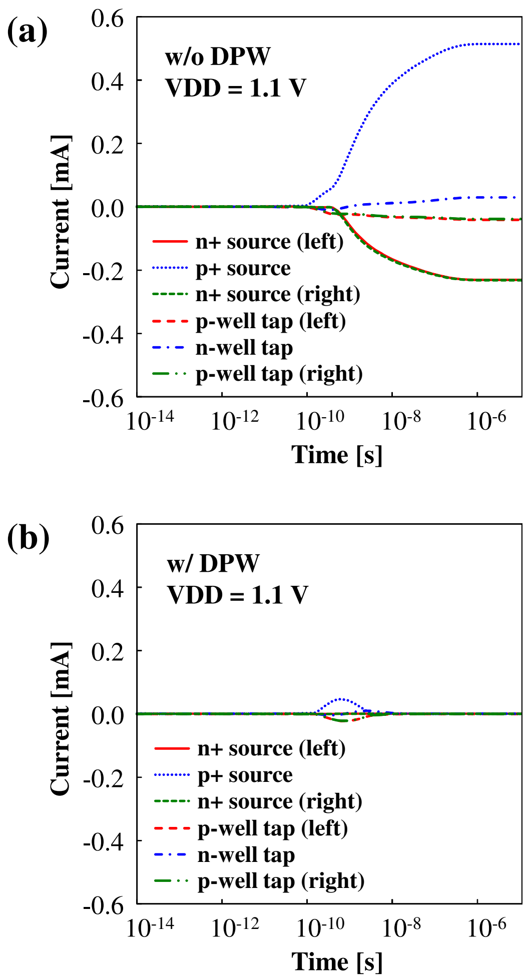

Fig. 6. Transient currents for ion track (6) with LET = 1.0 MeV/um in (a) the model without the DPW (w/o DPW) and (b) the DPW model (w/ DPW). The ion incidence occurs at 0 s. A latchup behavior is observed in the case of (a) w/o DPW. On the other hand, only a temporary current increase is observed in the case of (b) w/ DPW.

calculations are conducted with the voltage step of 0.1 V. The SEL threshold VDDs for the model with the DPW are equal to or greater than that for the model without the DPW. This tendency clearly shows that the DPW structure can prevent SEL occurrence as observed in experiments [5]. As seen in Fig. 5, the ion track location becomes deeper in order from (1) to (6). Therefore, our result also shows that the SEL prevention due to the DPW is effective for charge depositions in the deep region.

In order to elucidate the mechanism of this SEL suppression due to the DPW, the potential perturbations in n- and p-well are analyzed. Well potentials are extracted at points indicated in Fig. 5. The potential perturbations in these points are thought to critically affect the activation of parasitic BJTs because these points are near junctions of the BJTs. Figure 7 shows the time evolution of well potential in the case of the ion track location (6), where the LET and VDD are 1.0 MeV/um and 1.1 V, respectively. These are the same condition as in

TABLE II. SEL THRESHOLD VDD.

Ion track	LET = 0.5 MeV/um		LET = 1.0 MeV/um	
location	w/o DPW	w/ DPW	w/o DPW	w/ DPW
(1)	1.1 V	1.1 V	1.1 V	1.1 V
(2)	1.1 V	1.1 V	1.1 V	1.1 V
(3)	1.1 V	1.2 V	1.1 V	1.1 V
(4)	1.1 V	1.4 V	1.1 V	1.1 V
(5)	1.2 V	$>$ 2.4 V	1.1 V	1.1 V
(6)	1.6 V	$>$ 2.4 V	1.1 V	$>$ 2.4 V

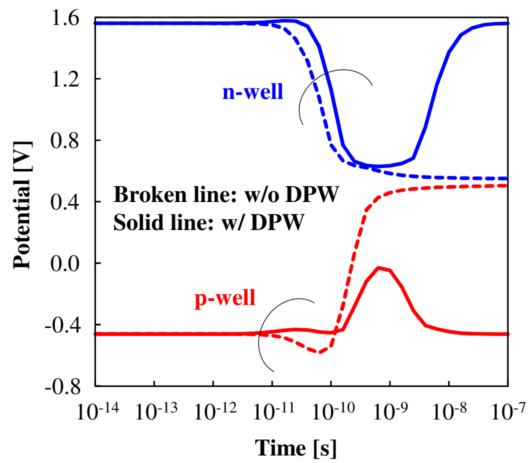

Fig. 7. Time evolutions of n-well and p-well potentials in the case of the ion track (6), where the LET and VDD are 1.0 MeV/um and 1.1 V, respectively. The ion incidence occurs at 0 s. Broken and solid lines correspond to models without and with the DPW.

Fig. 6. As for the model without the DPW, both n-well and p-well potentials fluctuate significantly and asymptotically reach the almost same value. This behavior indicates that two BJTs illustrated in Fig. 1 are activated by deposited electron-hole pairs and the positive feedback sustains, resulting in latchup. As for the model with the DPW, the n-well potential initially exhibits a similar drop as in the case of the model without the DPW. On the other hand, the elevation in the p-well potential is relatively small, leading to the prevention of the positive feedback.

When considering the equivalent circuit depicted in Fig. 1, one of the important factors for the well potential fluctuation is the resistance between the well under the source region and the well tap. As for the p-well, holes flowing through this resistance elevate the p-well potential at the source region. Figure 8 represents the cross-sectional distribution of the hole current under the source region at 1.6×10^{-10} s, where the ion track case, LET and VDD are same as in Figs. 6 and 7. The color scale indicates the magnitude of the hole current flowing from the source region to the well tap region. Figures 8 (a) and (b) correspond to the models without and with the DPW, respectively. In the case of the model without the DPW, holes mainly flow in the shallow region of the p-well. On the other hand, in the case of the DPW model, holes flow not only in the p-well but also in the deeper region, which corresponds to the DPW region. These simulation results suggest that the DPW plays a roll for the reduction of the resistance through

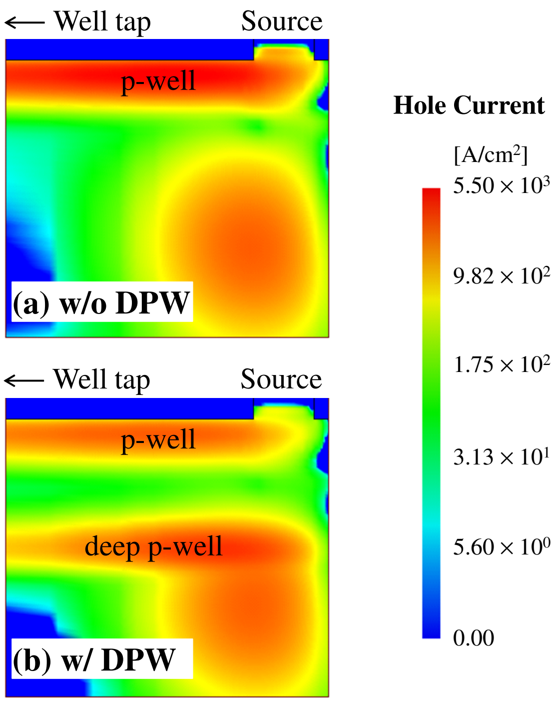

Fig. 8. The cross-sectional distribution of the hole current component along the horizontal direction of the cross section. (a) and (b) are for models without and with the DPW, respectively. Both cross sections represent the center region of the p-well under the source region at 1.6×10^{-10} s. The ion track case is (6), where the LET and VDD are 1.0 MeV/um and 1.1 V, respectively. Red color corresponds to large hole current flowing from the source region to the well tap region.

making an additional conduction path for holes. This prevents the elevation of p-well potential as seen in Fig. 7, leading to the suppression of latchup.

IV. Conclusion

We have investigated the effect of the DPW structure on terrestrial neutron-induced SEL using three-dimensional TCAD simulations. Through the comparison of the SEL threshold VDD between models with and without the DPW, it has been demonstrated that the DPW structure effectively suppresses SEL occurrence even in the case that well taps are significantly far from the source region. This result qualitatively agrees with our previous experiment. Well potential and hole current analyses have indicated that the DPW creates the additional conduction path for holes and reduces the resistance between the well under the source region and the p-well tap. We have concluded that the DPW has a role of preventing potential elevation in the p-well, leading to the SEL suppression.

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