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Effective Funneling Length in Alpha-Particle Induced Soft Errors

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The funneling phenomenon in alpha-particle induced soft errors is investigated using a 3-D device simulator(CADDETH), a simple diffusion model(HSERAM), and experimental results. Effective funneling length(L_F) which is different from Hu's model is proposed as a guideline for submicron memory cell/device design. Effective funneling length was found to strongly depend on memory cell size (size effect) and on the proximity of adjacent cells (proximity effect), as well as on substrate impurity concentration. A critical collected charge for mega-bit DRAM cells can be quantitatively calculated based on these new findings concerning the funneling phenomenon and the proposed simulation method.

1. INTRODUCTION

Among the reliability problems in VLSIs, hard errors such as hot-carrier effects and soft errors such as alpha-particle-induced effects are becoming increasingly more of a problem as device geometories become finer. Unlike hot-carrier effects, however, the susceptibility to soft errors is expected to increase if the power supply voltage is reduced. This seems to impose constraints on the design of VLSIs(Si and GaAs). The soft error rate(SER) in mega-bit memories is strongly influenced by the funneling effect which affects the charge collection process. Furthermore, funneling causes additional reliability problems such as induced-latch-up, source-drain shorts, emitter-collector shorts, and leakage between trench capacitors(1).

Thus, it is necessary to understand the funneling phenomenon and to obtain some guidelines, i.e. effective funneling length(L_F) which can be used in designing submicron cells/devices. This paper investigates the funneling phenomenon using a 3-D device simulator(CADDETH)(2) and a simple diffusion model(HSERAM)(3). The simulation results are compared with the experimental ones. As a result, effective funneling length proposed here is shown to be Hu's model(4) in which hole current flowing in the substrate induces an electric field(funneling field).

2. SER SIMULATION METHOD

Fig. 1 shows a plot of the potential distribution in the substrate due to the funneling effect 10 ps after an alpha-particle (5 MeV) has struck $2 \times 6\ \mathrm{um}^2$ pn junction. Substrate resistivity is $10\,\Omega\mathrm{cm}$. The 3-D device simulation used in this study takes into account the conventional carrier-generation model(5), SHR recombination, Auger recombination, and $Si\text{-}SiO_2$ interface recombination in the soft error simulation.

It should be noted that the electric field outside the depletion layer is notably smaller than

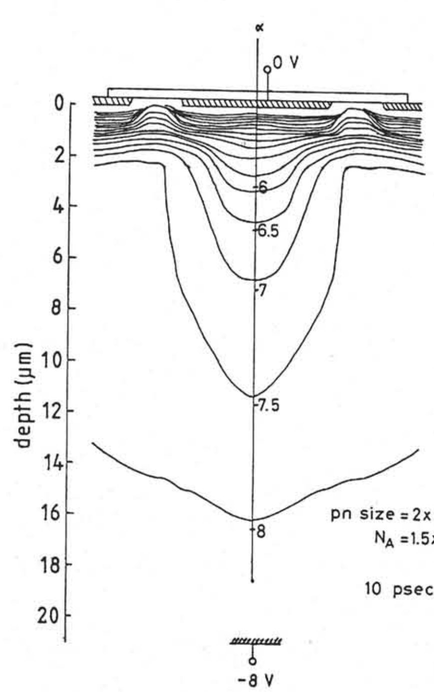

Fig. 1. The potential distribution due to the funneling effect ($\theta = 0$).

that inside the depletion layer, although the potential distortion spreads down along the track into the substrate. The shape of the potential distribution implies that in additional to a drift-like mechanism, there is a diffusion-like mechanism in the charge collection process.

The SER simulation was carried out as follows: First, the total collected charge(Q_T) caused by the single alpha-particle event is calculated by the 3-D simulator taking into account the possible electron-hole interaction. Next, by comaring it with the total charge calculated by the diffusion model:

$$Q_T = Q_{drift}\ (\text{depletion layer} + L_F) + Q_{dif} \quad \ldots\ldots (1),$$

effective funneling length(L_F) can then be determined as shown in Fig. 2. The potential barrier effect in Q_{dif} which exerts a repulsive force against diffusion current is taken into account in the form of:

$$Q_{dif} = R \times Q^0_{dif}, \quad 0 \leq R \leq 1 \quad \ldots\ldots (2).$$

The quantitative calculation of SER requires the statistical treatment. Therefore, an analytical L_F formula which can be used under the various α-particle injection conditions, or at least, an accurate L_F under a critical condition(e.g. 1000 fit) is needed.

3. EFFECTIVE FUNNELING LENGTH(L_F)

According to Hu's model which takes the hole-current-induced electric field into account, the funneling length is given as:

$$L_F = \frac{\mu_n}{\mu_p} W/\cos\theta \quad \ldots\ldots (3),$$

where W is the depletin width.

3.1 Dependence on Substrate Concentration(N_A)

The relation between L_F and substrate impurity concentration(N_A) is shown in Fig. 3 for various pn junction sizes. The following relation can be obtained:

$$L_F \propto (N_A)^{-\alpha} \qquad \alpha \leq 0.5 \quad \ldots\ldots (4).$$

It is found that α is not fixed at 0.5 and is also strongly dependent on pn junction size and the space between junctions. L_F becomes less dependent on N_A as junction size increases.

3.2 Dependence on Junction Size —— Size Effect

Fig. 4 shows the relationship between L_F and pn junction sizes(A) for varius N_A. From the figure,

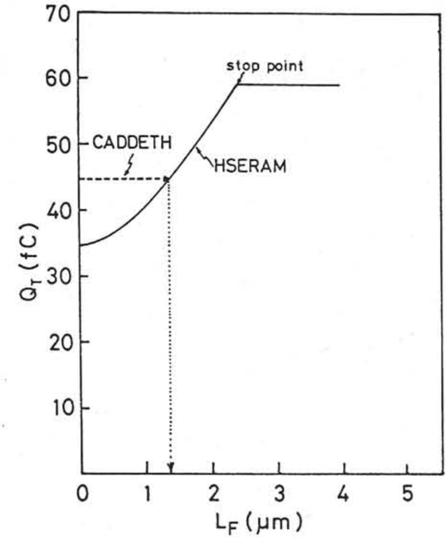

Fig. 2. The L_F determination method.

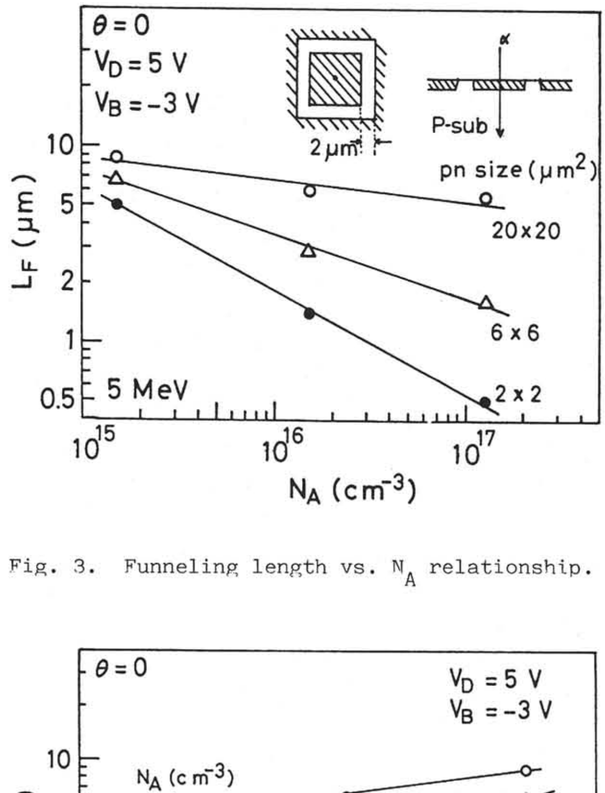

Fig. 3. Funneling length vs. N_A relationship.

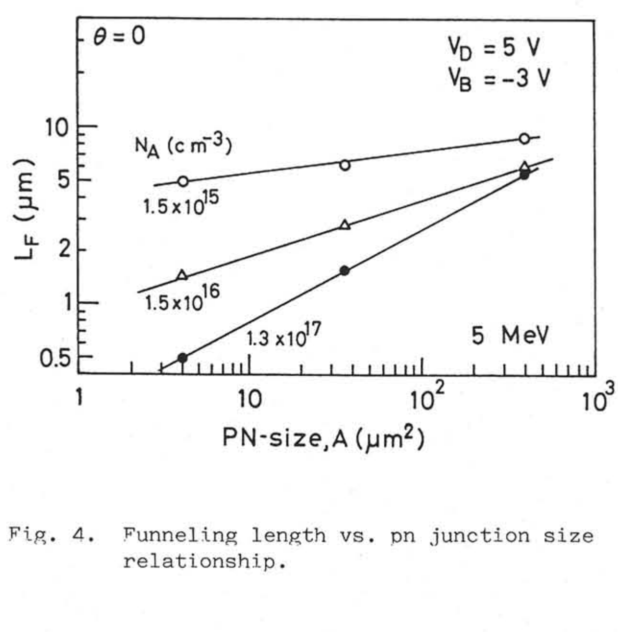

Fig. 4. Funneling length vs. pn junction size relationship.

$$L_F \propto A^{\beta} \qquad \beta \leq 0.5 \qquad \ldots\ldots (5)$$

is obtained. This relation, which is not taken into consideration in Hu's model, is useful for cell/device design.

pn junction dependency can be explained as follows:

1)Depletion layers with a smaller area have a greater ability to recover from the potential distortion, which results in a smaller funneling length.

2)With smaller pn junction size, the potential distortion due to funneling effect extends into the adjacent n^+ regions and some of the carriers generated are then absorbed in adjacent regions.

Fig. 5 shows a comparison of the experimental and calculated results for various junction sizes. Excellent agreement is seen.

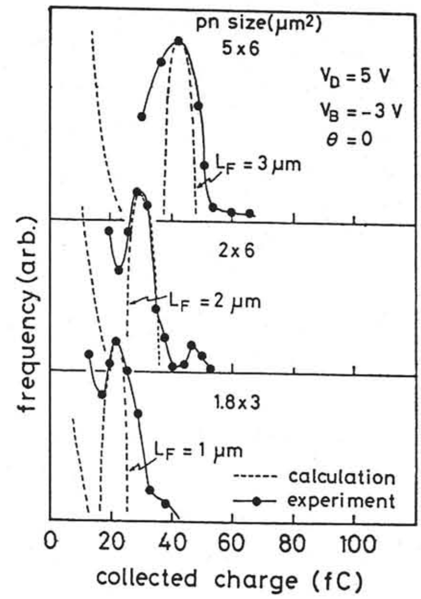

Fig. 5. A comparison between experimental results and calculated results for various pn

3.3 Influence of Adjacent Cells

Fig. 6 shows funneling length and collected charge for an alpha-particle (5 MeV) injected vertically on a 2 x 6 μm^2 pn junction. It is found that as the space (S) between cells becomes less than 2 μm, the L_F and Q_T become smaller. This proximity effect is also an important parameter in cell designs.

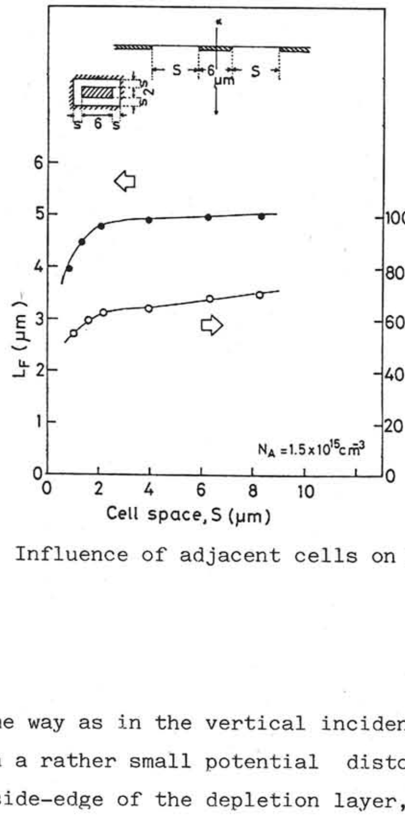

Fig. 6. Influence of adjacent cells on L_F and Q_T.

3.4 L_F at Various Angles of α-Particle Incidence

Non-vertical injection of an α-particle is a condition which must be considered in SER estimation. Fig. 7 shows L_F under the non-vertical incidence condition. Substrate impurity concentration was 1.5×10^{15} cm^{-3}(a) and 1.5×10^{16} cm^{-3}(b). It should be noted that L_F becomes smaller near the n^+ junction edge. Also, non-vertical condition with its longer alpha-particle track in the depletion layer does not results in a longer L_F, although eq. (3) predicts that L_F will increase as θ increases. The edge of L_F obtained from eq. (3) is also shown in Fig. 7. Obviously, there is a significant difference between the model presented here and Hu's model.

The differences can be explained as follows:

1)Under the conditions of non-vertical incidence, the electron-hole pairs generated within the depletion layer do not move along the alpha-particle track; Rather, they move along the electric field within the depletion layer. Therefore, the potential distortion due to the non-vertical incidence spreads vertically down in the same way as in the vertical incidence. This results in a rather small potential distortion near the side-edge of the depletion layer, which leads to a smaller L_F.

2)In addition, non-vertical α-particle incidence also distorts the potential in the adjacent depletion layer. Due to the proximity effect, some of the electron-hole pairs generated along the alpha-particle track are absorbed in the adjacent cell depletion layers, leading to a decreased L_F, as shown in Fig. 8.

3.5 L_F under other conditions

In addition to the above mentioned dependency on L_F, SER also depends on alpha-particle energy, the thickness of passivation layer, the position of the alpha-particle source, and the purity of materials, etc.

4. COCLUSION

These new findings on funneling phenomenon will be impotant guidelines for the design of submicron VLSIs.

1)From eqs. (4) and (5), it can be seen that a kind of scaling law exists which determines the limitation of planar cells, stacked capacitor cells, and trench capacitor cells.

2)L_F does not depend on the alpha-particle track length in the depletion layer. This finding is significant in the determination of SER for trench cells.

3)Although the total collected charge(Q_T) can be estimated by eq. (1), the worst incidence condition has the size effect.

The funneling phenomenon in alpha-particle-induced soft errors was clarified to some extent in this paper. However, a new model is needed which is capable of expalining the temporal behavior of high energy electrons and holes induced by an alpha-particle injection.

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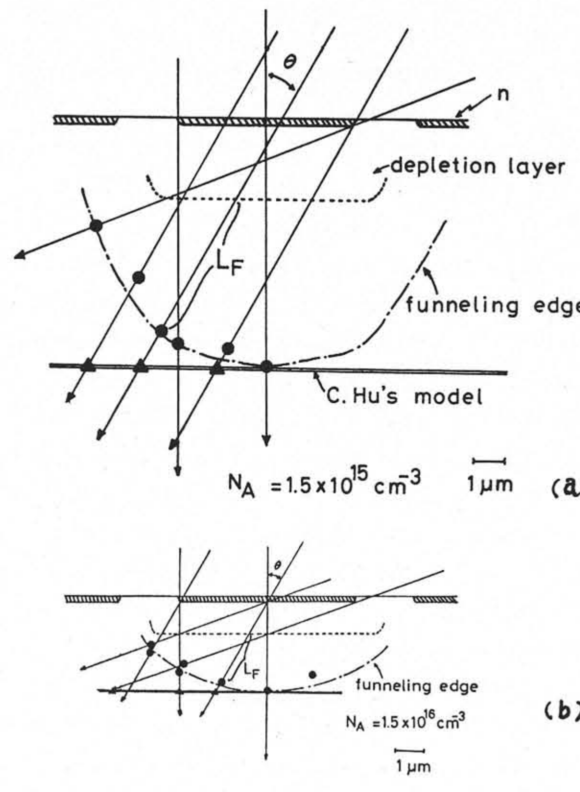

Fig. 7. Effective funneling length under the non-vertical incidende conditions. (a) N_A=1.5 x 10^{15} cm^{-3}, (b) 1.5 x 10^{16} cm^{-3}

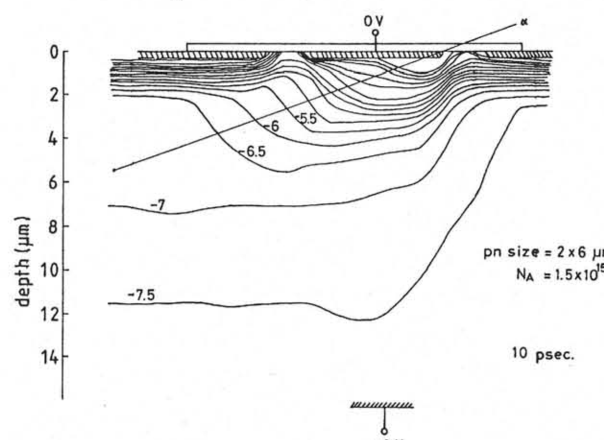

Fig. 8. The potential distortion due to a non-vertical incidence.

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