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APPLICATION OF LINEAR RESPONSE THEORY TO RADIATION EFFECTS IN MICROELECTRONIC INTEGRATED CIRCUITS (SHORT-TERM ANNEALING AND REBOUND EFFECT)

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This report is concerned with a theoretical study of the radiation response of MOS devices and ICs. This topic has been a field of strong interest since such devices were found to be sensitive to ionizing radiation. During the past two decades, many experiments have been performed in this area, however, no comprehensive theory has been proposed to explain these phenomena. Ten years ago, an attempt was made to apply linear response theory in the work of Derbenwick and Sander.[1] Actually, in this work, a convolution integral was introduced, but a foundation based on linear response theory was not presented. The name itself (linear response theory) appeared nearly ten years later, in the work of Oldham.[2]

In our opinion, this linear response theory can describe a very broad area of radiation response phenomena in MOS devices. Such a theory is extremely important as the very first phenomenological approach in this field. However, the way it has been presented in these two works[1,2] did not provide an understanding or enable one to properly apply it to existing experimental data.

In our previous report, a sound foundation for the application of linear response theory to radiation effects in integrated circuits was presented for the first time. In that report, a more general expression was derived:

$$\delta V(t) = \dot{D}\int_0^{t_r} R(t-\tau)\,d\tau. \tag{1}$$

This equation describes both short- and long-term annealing as well as simultaneous irradiation and annealing.

In this report, we will be concerned with the application of the general expression of Eq.(1) to cases of specific interest, specifically, two problems: 1. the case of short-term annealing and 2. the rebound effect.

For the case of short-term annealing, that is, $\delta t \equiv t-t_r < t_r$, it is necessary to find some simple analytical expressions which will be applicable to existing experimental data.[1-5] For this purpose, we first rewrite Eq.(1) in the following form:

$$\delta V(t) = \dot{D}\int_{t-t_r}^{t} R(\tau)\,d\tau. \tag{1a}$$

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For our purpose, it is convenient to break Eq.(1a) into three intervals:

$$\delta V(t) = \dot{D}\int_0^{t_r} R(\tau)d\tau + \dot{D}\int_{t_r}^{t} R(\tau)d\tau - \dot{D}\int_0^{t-t_r} R(\tau)d\tau. \qquad (2)$$

In this expression, the first is independent of time and is proportional to the total dose. In particular, for the ln(t) model, one has

$$\delta V(t_r) = D_{(tot)}[A(1+D_o/D_{tot}) \ln(1+D_{tot}/D_o)-(A+C)]. \qquad (3)$$

The time dependence comes in through the second and third integrals on the right-hand side of Eq.(2), which describes the pure annealing. For a small time interval, $\delta t \equiv t_r - t$, after the exposure time t_r, the second integral can be calculated to any order of magnitude in $\delta t/t_r$, namely

$$\dot{D}\int_{t_r}^{t} R(\tau)d\tau = \dot{D}\delta t\ R(t_r) = 1/2\dot{D}(\delta t^2)R'(t_r) +$$

$$+1/3\ \dot{D}(\delta t)^3R''(t_r) + \ldots =$$

$$= D_{tot}(\delta t/t_r)[R(t_r) + 1/2(\delta t/t_r)t_rR'(t_r) +$$

$$1/3(\delta t/t_r)^2t_r^2R''(t_r)]. \qquad (4)$$

In particular, for the ln(t) model, the first-, second- and third-order terms are given as follows:

$$\delta_1 V(t) = D_{tot}(\delta t/t_r)[A\ln(1+D_{tot}/D_o)-C]$$

$$\delta_2 V(t) = (A/2)D_{tot}^2(\delta t/t_r)^2(D_o+D_{tot})^{-1}$$

$$\delta_3 V(t) = -(A/3)D_{tot}^3(\delta t/t_r)^3(D_o+D_{tot})^{-2}$$

For the case in which $D_{tot} \gg D_o$ ($t_r \gg t_o$), these expressions can be simplified:

$$\delta_1 V(t) = D_{tot}(\delta t/t_r)[A\ln(D_{tot}/D_o)-C] \qquad (5)$$

$$\delta_2 V(t) = (A/2)D_{tot}(\delta t/t_r)^2 \qquad (6)$$

$$\delta_3 V(t) = -(A/3)D_{tot}(\delta t/t_r)^3. \qquad (7)$$

Directly integrating the third term of Eq.(2), we now obtain

$$\dot{D}\delta t[A\ln(\delta t/t_o)-(A+C)],$$

which can also be expressed as

$$D_{tot}(\delta t/t_r)[A\ln(\delta t/t_o)-(A+C)]. \tag{8}$$

In this integration, we have assumed $t_o \ll \delta t$.

Adding Eqs.(5) and (8), we obtain a complete first-order term:

$$\delta_1 V(t) = AD_{tot}(\delta t/t_r)[\ln(D_{tot}/D_o)-1]. \tag{9}$$

Eq.(9), together with Eqs.(6) and (7), are very important for the interpretation of short-term annealing. This part of the annealing curve has so far not been described analytically, although a wealth of experimental data exists[1-4]. In particular, the constant A and its temperature dependence in the case of thermal annealing can be determined experimentally. Also, the temperature dependence of A and t_o can be separated.

The application of linear response theory has so far not been justified to the study of the rebound effect. The ln(t) dependence for the response function has been accepted for the description of the annealing behavior of radiation-induced positive oxide charge. The application of a single response function to the data of Danchenko et al.[5] appears to be feasible. We shall explain this unexpected phenomenon below:

We present the response function, R(t), as the sum of <u>two</u> response functions:

$$R(t) = A_h\ln(1+t/t_h)-C_h - A_e\ln(1+t/t_e)+C_e \tag{10}$$

For time $t \gg t_e$, t_h,

$$\begin{aligned} R(t) \approx\ & A_h\ln(t/t_o)+A_h\ln(t_o/t_h)-C_h \\ & -A_e\ln(t/t_o)-A_e\ln(t_o/t_e)+C_e, \end{aligned} \tag{11}$$

or

$$R(t)=A\ln(t/t_o)-C! \tag{12}$$

Here we have one single response function, where

$$A=A_h-A_e \quad \text{and}$$

$$C=C_h-C_e-A_h\ln(t_o/t_h)+A_e\ln(t_o/t_e). \tag{13}$$

Here T_o can be any chosen unit of time. The most natural choice is

$$t_o=(T_e t_h)^{1/2},$$

then,

$$C=C_h-C_e-(A/2)\ln(t_e/t_h). \tag{14}$$

<u>Conclusion</u>

Linear response theory has been applied in the field of radiation effects in integrated circuits, specifically to short-term annealing and the rebound effect. Application to short-term annealing was made possible by Eq.(1), which was derived in the previous report. A simple analytical expression for short-term annealing has thus been obtained, which simplifies analysis of the existing experimental data and suggests new experimental studies and, for the first time, the response function for the rebound effect has been derived. We have thus shown that the correct application of linear response theory provides a very powerful method for the analysis of radiation effects in integrated circuits.

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