Dual-Transistor Method to Determine ΔV_{ot} and ΔV_{it} for MOS Devices*

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35-Word Abstract

It is shown how standard ΔVth and mobility measurements made on otherwise identical n- and p-channel transistors can be combined to accurately estimate radiation-induced ΔV_{ot} and ΔV_{it}. Applications of the method are described.

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To understand the radiation response of MOS devices, one must distinguish among effects of oxide-trapped charge and interface-trap buildup and annealing. To this end, radiation-induced threshold-voltage shifts, ΔV_{th}, are often expressed as sums of components due to oxide-trapped charge, ΔV_{ot}, and interface traps, ΔV_{it} [1]. Values of ΔV_{ot} and ΔV_{it} commonly are estimated for MOS transistors via midgap [1,2], subthreshold slope [3,4], mobility [5-7], and/or charge-pumping [4,8] methods. Midgap, slope, and charge-pumping methods depend on accurate low-current measurements. Hence, these techniques are not well-suited for devices with large parasitic leakage. Also, because accurate low-current measurements are difficult to perform at high speed, these methods can be difficult to apply to very rapid measurements after a short radiation pulse. Mobility methods do not require low-current measurements, and so do not face these restrictions. Unfortunately, without an independent measurement of interface-trap density, mobility methods cannot be applied to one transistor to determine ΔV_{ot} and ΔV_{it} unambiguously [6,7].

In this summary a dual-transistor technique to estimate ΔV_{ot} and ΔV_{it} is described. The method is applied to n- and p-channel MOS transistors on the same chip, irradiated under identical conditions. Features of midgap and mobility methods are combined to estimate ΔV_{ot} and ΔV_{it} accurately and unambiguously from ΔV_{th} and mobility measurements, made at currents 2-5 orders of magnitude above those required for typical subthreshold current or charge-pumping analysis [1-4,8], as verified in several cases.

The dual-transistor method requires that otherwise identical n- and p-channel transistors (e.g. on the same wafer, to best match oxide radiation response) be irradiated under the same conditions <u>at the same oxide electric field</u>. With this pre-condition, it is assumed: (i) that ΔV_{ot} is approximately equal for these n- and p-channel transistors; (ii) that interface traps predominantly are charged negatively for n-channel and positively for p-channel devices; (iii) that the postirradiation mobility, μ, is related (approximately) to the preirradiation mobility, μ_o, and the interface-trap buildup, ΔN_{it}, by the Sun-Plummer equation [5], $\mu/\mu_o \approx [1 + \alpha(\Delta N_{it})]^{-1}$, where (iv) α is taken to be the same for n- and p-channel transistors. Assumption (i) is consistent with MOS-capacitor work where ΔV_{ot} was found not to depend on doping type or level [1]; (ii) is similar to, but less restrictive than, the common assumption of interface-trap charge neutrality at midgap [1,2]; and (iii) and (iv) are consistent with extensive data of Sexton and Schwank [7].

With these plausible assumptions, equations can be derived that express ΔV_{ot} and ΔV_{it} in terms of n- and p-channel threshold-voltage shifts, ΔV_{thn} and ΔV_{thp}, and mobility degradation, μ_n/μ_{no} and μ_p/μ_{po}. To do so, ΔV_{thn} and ΔV_{thp} are first parameterized in terms of variables representing ΔV_{ot} and ΔV_{it}:

(1) $\Delta V_{thn} = -H + S_n$ and (2) $\Delta V_{thp} = -H - S_p$.

Here, by (i), $\Delta V_{otn} \approx \Delta V_{otp} = -H$. By (ii), $\Delta V_{itn} = S_n$ and $\Delta V_{itp} = -S_p$, where the new variables H, S_n, and S_p are positive by definition. Because different parts of the bandgap are being sampled [1,4,8], S_n is generally not equal to S_p. From (iii) and (iv), with a further variable change, one may re-write the Sun-Plummer equations to complete a system of 4 equations in 4 unknowns:

(3) $S_n = \beta_n/\alpha^*$ and (4) $S_p = \beta_p/\alpha^*$.

Here $\alpha^* S_n = \alpha\ \Delta N_{itn}$, and $\alpha^* S_p = \alpha\ \Delta N_{itp}$, where α is the usual Sun-Plummer constant [5,7]. Also, $\beta_n = (\mu_{on}/\mu_n) - 1$, and $\beta_p = (\mu_{op}/\mu_p) - 1$, where μ_{on} and μ_{op} are n- and p-channel preirradiation mobilities, and μ_n and μ_p are postirradiation mobilities, respectively.

Equations (1)-(4) can be solved exactly to arrive at the final expressions, in terms of the quantities of interest:

$$\Delta V_{itn} = \frac{\beta_n (\Delta V_{thn} - \Delta V_{thp})}{\beta_n + \beta_p} , \qquad (5)$$

$$\Delta V_{itp} = \frac{-\beta_p (\Delta V_{itn})}{\beta_n} = \frac{-\beta_p (\Delta V_{thn} - \Delta V_{thp})}{\beta_n + \beta_p} , \qquad (6)$$

$$\Delta V_{otn} = \Delta V_{otp} = \frac{\beta_p(\Delta V_{thn}) + \beta_n(\Delta V_{thp})}{\beta_n + \beta_p} , \qquad (7)$$

and

$$\alpha^* = \frac{\beta_p + \beta_n}{\Delta V_{thn} - \Delta V_{thp}} . \qquad (8)$$

Note that the value of the constant α^*, that relates μ to ΔV_{it}, emerges naturally in the solution. Since α^* should be approximately constant (e.g. through a series of irradiations) if Eqs. (3) and (4) are valid, Eq. (8) can be used as a "self-consistency" check of the method.

The dual-transistor method is compared to midgap and subthreshold slope methods below. For the dual-transistor analysis, n- and p-channel transistor threshold voltages and mobilities were measured at ± 5 V drain voltage and ± 16-100 μA channel currents [9]. Subthreshold slope and midgap methods were applied as discussed in Refs. 1 and 3.

To see how the methods compare for cases in which midgap and subthreshold slope techniques are expected to be valid [10], consider the following example. In Fig. 1(a) current-voltage (I-V) characteristics are shown for n-channel transistors with 47-nm oxides as a function of x-ray dose. Values of ΔV_{itn} inferred from these curves with the dual-transistor, midgap, and slope methods are shown in Fig. 1(b). To within the uncertainties of the midgap and slope methods, values of ΔV_{itn} inferred with all three methods agree to within better than ± 10 percent. (Uncertainties in midgap and slope analyses are caused by the slope change that occurs at $I_{DS} \approx 10$ nA at the highest doses in Fig. 1(a), reflected by the error bars in Fig. 1(b)). Similar agreement is observed for ΔV_{otn}, ΔV_{otp}, and ΔV_{itp}. Further, for these data, the value of α^* inferred from dual-transistor analysis [Eq. (8)] is 0.50 ± 0.03, demonstrating self-consistency through the irradiation series. Similar agreement among the methods is also found for irradiation and anneal of two other types of devices, up to 10-times more radiation resistant [11].

Now that the dual-transistor method has been verified in these cases, consider the following example in which the application of midgap and slope methods is questionable because of high leakage currents. In Figs. 2(a) I-V curves and (b) inferred values of ΔV_{itn} are shown as a function of Co-60 dose and elevated-temperature anneal for n-channel transistors with large parasitic leakage. Previous applications of midgap and slope analyses [1,3] have suggested that the 1-2 decades of "straight" I-V curve above the leakage in Fig. 2(a) would allow for reasonable estimates of ΔV_{ot} and ΔV_{it}. Along these lines, midgap and slope values shown in Fig. 2(b) are derived [1,3] from current measurements of 20-100 nA to try to minimize the impact of the leakage. Still, for doses ≥ 50 krad, values of ΔV_{itn} obtained with these methods are up to ≃ 4 times higher than values obtained with the dual-transistor method. After 1-h anneal at 100°C, the parasitic leakage [Fig. 2(a)] is reduced to ≤ 10^{-11} A. Thus, midgap and subthreshold slope methods are expected to be valid through anneal. And, in Fig. 2(b), excellent agreement among all methods is observed through this region. The value of α^* [Eq. (8)] is 1.25 ± 0.11 through irradiation and anneal, once again showing the self-consistency of the dual-transistor analysis. Also, values of ΔV_{itn} obtained via dual-transistor analysis increase linearly with dose [Fig. 2(b)], as expected [12], in contrast to the strong nonlinearity suggested by midgap and slope analyses. Finally, for the corresponding p-channel transistors that did not show high leakage, values of ΔV_{otp} and ΔV_{itp} agree to within better than ± 10 % for all methods. It is concluded that the dual-transistor method can provide much more accurate estimates of ΔV_{ot} and ΔV_{it} than subthreshold current (and charge-pumping) methods for devices with high leakage.

Like single-transistor techniques, the dual-transistor method has limitations. It cannot be applied if otherwise identical n- and p-channel transistors are not available (preferably on the same wafer). No information is given about changes in interface-trap density through the bandgap. Also, the method is difficult to apply at small electric fields, where work function differences between n- and p-channel transistors may not be known accurately enough to permit compensation for the resulting differences in radiation response. However, the dual-transistor method does provide accurate estimates of ΔV_{ot} and ΔV_{it} in cases of great interest, even when large parasitic leakage (e.g. due to parasitic field leakage or high-temperature operation) is present. It is also much easier to apply than subthreshold current or charge-pumping techniques at very short times after a radiation pulse, as shown in detail in the full paper. The dual-transistor method therefore fills important gaps in the characterization of MOS radiation response.

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9. In mobility methods, the "dc-conductance" mobility (Refs. 5-7) is usually measured, instead of the "field-effect" mobility used here. Dual-transistor analysis may also be applied to linear threshold-voltage and/or dc-conductance mobility measurements. Saturation values are shown here to illustrate the (perhaps surprising) degree of accuracy that can be obtained even with simpler high-current measurements.
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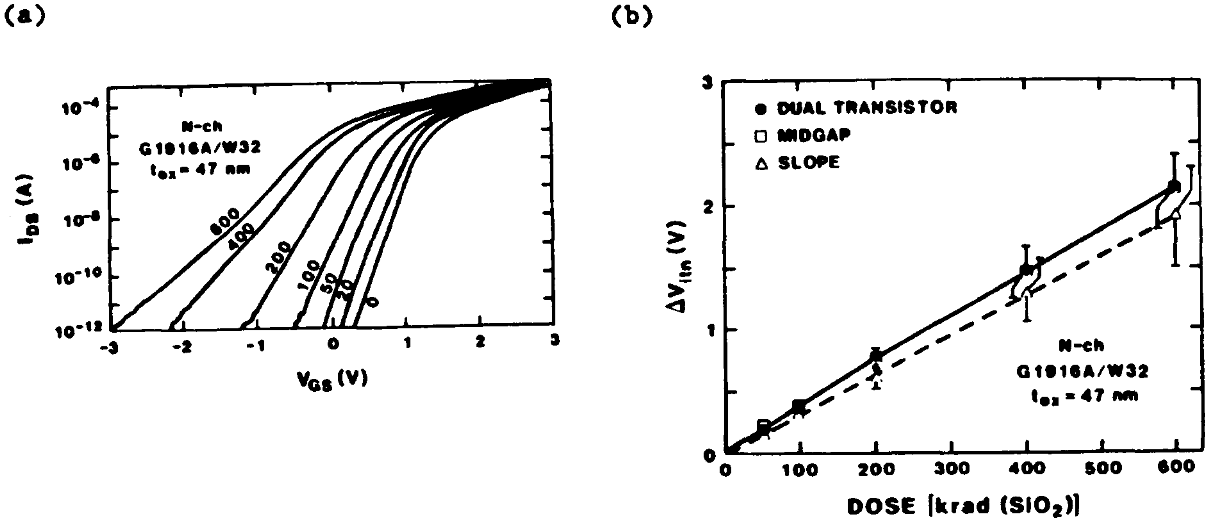
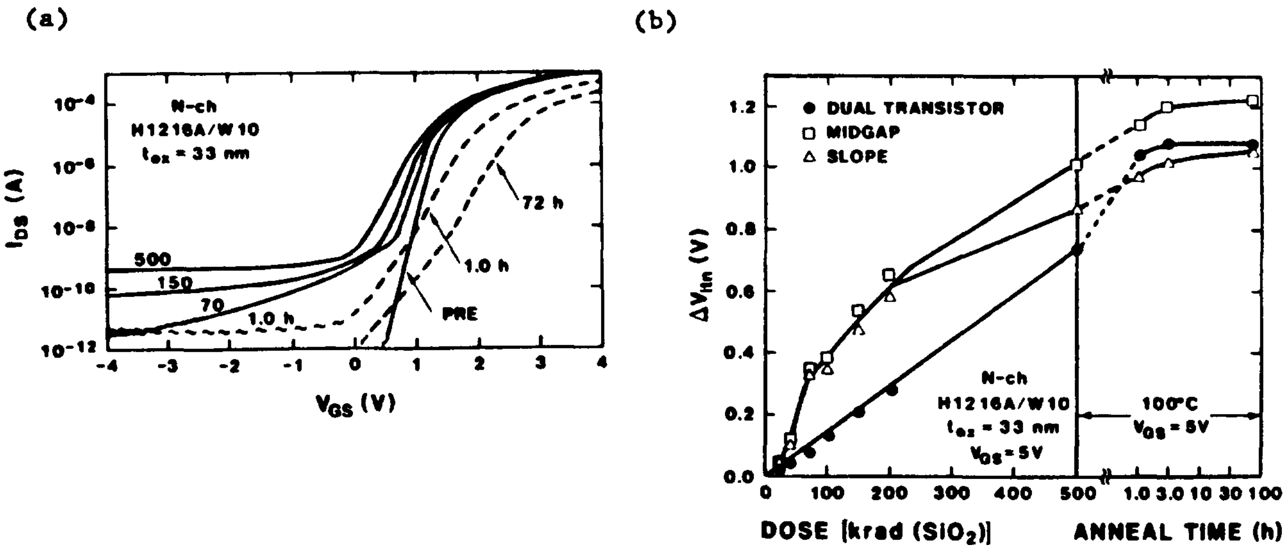


1. (a) Current-voltage traces and (b) inferred values of ΔV_{itn} for 3 x 16 μm transistors with 47-nm oxides. The total x-ray dose received before each trace in (a) is shown in krad(SiO_2). The radiation bias was V_{GS} = +6 V.



2. (a) Representative current-voltage traces and (b) inferred values of ΔV_{itn} for 2 x 16 μm transistors with 33-nm oxides. The Co-60 dose or the annealing time at 100°C is shown in (a) for each trace. The irradiation and anneal bias was V_{GS} = +5 V.