THRESHOLD VOLTAGE STABILIZATION IN

N-CHANNEL IMPLANTED ENHANCEMENT DEVICES

There is a gate-oxide thickness (or implant energy) for implanted devices which is self-compensating for oxide thickness variations. That is, an oxide on the thick side will reduce the implanted charge at implanting enough to offset the greater effect on V_T in the finished device that the charge causes due to the thicker oxide. That is, for an N-channel device, where

$$V_T = -\Phi_{\mu S} - \frac{Q_{SS}}{C_0} + \frac{Q_B}{C_0} + 2\phi$$

$$= \frac{Q_B - Q_{SS}}{C_0} - \Phi_{\mu S} + 2\phi$$

$$= \frac{Q_I + Q_{ST} - Q_{SS}}{C_0} - \Phi_{\mu S} + 2\phi$$

where Q_I = implanted charge and Q_{ST} = charge from starting material.

Finally,

$$V_T = \frac{Q_I + Q_{ST} - Q_{SS}}{\kappa_0 \varepsilon_0} x_0 - \Phi_{\mu S} + 2\phi$$

We require that

$$\frac{dV_T}{dx_0} = \frac{dQ_I}{dx_0} \frac{x_0}{\kappa_0 \varepsilon_0} + \frac{Q_I + Q_{ST} - Q_{SS}}{\kappa_0 \varepsilon_0} = 0$$

or

$$\frac{1}{\kappa_0 \varepsilon_0} \frac{dQ_I}{dx_0} = - \frac{Q_I + Q_{ST} - Q_{SS}}{\kappa_0 \varepsilon_0 x_0}$$

or

$$x_0 \frac{dQ_I}{dx_0} = - (Q_I + Q_{ST} - Q_{SS})$$

$$x_0 \frac{dN_I}{dx_0} = - (N_I + N_{ST} - N_{SS})$$

$$\frac{dN_I}{N_I + N_{SS} - N_{SS}} = - \frac{dx_0}{x_0}$$

Then

$$\frac{dN_I}{N_I} \frac{N_I}{N_I + N_{ST} - N_{SS}} = - \frac{dx_0}{x_0}$$

$$\frac{dN_I}{N_I} = - \frac{dx_0}{x_0} \left[\frac{N_I + N_{ST} - N_{SS}}{N_I} \right]$$

If the gate oxide at the time of implant is thicker than the final value x_0 by some increment ε, then for some given range $\overline{R}_p$ the center of the distribution is below the silicon surface by some multiple k_1 of the standard deviation σ_0 in accordance with (see Figure 1)

$$\overline{R}_p = x_0 + \varepsilon + k_1 \sigma_0$$

from which

$$x_0 = \overline{R}_p - \varepsilon - k_1 \sigma_0$$

If the oxide thickness x_0 changes,only the parameter k_1 in this equation changes since both the range and the standard deviation for the implant are fixed by the implant energy. Thus

$$dx_0 = -\sigma_0 dk_1$$

so that

$$\frac{dx_0}{x_0} = \frac{-\sigma_0 dk_1}{x_0}$$

and

$$\frac{dN_I}{N_I} = \frac{\sigma_0 dk_1}{x_0}\left[\frac{N_I + N_{ST} - N_{SS}}{N_I}\right]$$

But the implanted charge N_I is related to the cumulative normal distribution $F(k_1)$ by

$$N_I = k_2 F(k_1)$$

and

$$dN_I = k_2 dF(k_1)$$

so that

$$\frac{k_2 dF(k_1)}{k_2 F(k_1)} = \frac{\sigma_0 dk_1}{x_0}\left[\frac{N_I + N_{ST} - N_{SS}}{N_I}\right]$$

from which

$$\frac{1}{F(k_1)}\frac{dF(k_1)}{dk_1} = \frac{\sigma_0}{x_0}\left(\frac{N_I + N_{ST} - N_{SS}}{N_I}\right)$$

However, the normal distribution $f(k_1)$ is related to the cumulative normal distribution by

$$f(k_1) = \frac{dF(k_1)}{dk_1}$$

so that

$$\frac{f(k_1)}{F(k_0)} = \frac{\sigma_0}{x_0}\left(\frac{N_I + N_{ST} - N_{SS}}{N_I}\right)$$

However, for a boron implant

$$\sigma_0 = 0.11\sqrt{\bar{R}_p} \qquad \text{(both in } \mu\text{)}$$

so that σ_0 can be found from

$$\left(\frac{\sigma_0}{0.11}\right)^2 = x_0 + \varepsilon + k_1\sigma_0$$

to be

$$\sigma_0 = \frac{0.11}{2}\left[k_1 + \sqrt{k_1{}^2 + \frac{4(x_0 + \varepsilon)}{0.11^2}}\right]$$

We are then looking for a solution of

$$\frac{f(k_1)}{F(k_1)} = \frac{1}{x_0}\left[\frac{N_I + N_{ST} - N_{SS}}{N_I}\right]\frac{0.11^2}{2}\left[k_1 + \sqrt{k_1{}^2 + \frac{4(x_0 + \varepsilon)}{0.11^2}}\right]$$

for a value of k_1 which, in turn, determines σ_0 and $\overline{R}_p$. The left-hand member of this equation is a monotonically decreasing function of k_1, as shown in Figure 2, while the right-hand member is a monotonically increasing function of k_1: in order for a solution to exist, the right-hand member must have a value at $k_1 = 0$ which is less than the value of the left-hand member at $k_1 = 0$. Therefore we must have

$$\frac{0.11\sqrt{x_0 + \varepsilon}}{x_0}\left[\frac{N_I + N_{ST} - N_{SS}}{N_I}\right] < 0.7978$$

Thus there is some minimum oxide thickness below which the stabilization cannot be achieved: this limit exists because the fall-off at the skirt of the normal distribution is not steep enough to permit a large enough percentage change in implanted charge to accommodate the percentage change in oxide thickness that an even relatively small change in thickness represents as the center value of the oxide thickness approaches zero. To illustrate the graphical solution for typical values, for

$$N_I + N_{ST} = 2.1 \times 10^{11}$$

$$N_I = 1.83 \times 10^{11}$$

$$N_{SS} = 0.3 \times 10^{11}$$

$$x_0 = 0.105\ \mu$$

$$\varepsilon = 0.015\ \mu$$

$$\frac{N_I + N_{ST} - N_{SS}}{N_I} = \frac{2.1 - 0.3}{1.83} \approx 1.0$$

$$\frac{f(k_1)}{F(k\ )} = \frac{\overline{0.11}^2}{2 \times 0.105}\left[k_1 + \sqrt{k_1{}^2 + \frac{4(.12)}{0.11^2}} \right]$$

$$= .0576\ [k_1 + \sqrt{k_1{}^2 + 39.67}]$$

Values for the right-hand member are plotted in Figure 2 against a standard equation for the left-hand member. At the intersection

$$k_1 = 0.725$$

$$\frac{f(k_1)}{F(k_1)} = 0.407$$

so that

$$\sigma_0 = 0.04274\ \mu$$

and

$$\overline{R}_p = 0.1509\ \mu$$

This leads to the requirement that an acceleration of 45 keV has to be used.

As a more convenient, though approximate solution,

$$\sigma_0 = \frac{\overline{0.11}^2}{2}\left[k_1 + \sqrt{k_1{}^2 + \frac{4}{0.11^2}(x_0 + \varepsilon)} \right]$$

$$= \frac{\overline{0.11}^2}{2}\ \ k_1 + \frac{2}{.11}\sqrt{x_0 + \varepsilon}\sqrt{1 + \frac{\overline{0.11}^2 k_1{}^2}{4(x_0 + \varepsilon)}}$$

$$\simeq \frac{\overline{0.11}^2}{2}\left[k_1 + \frac{2}{.11}\sqrt{x_0 + \varepsilon}\left(1 + \frac{\overline{0.11}^2 k_1{}^2}{8(x_0 + \varepsilon)} \right) \right]$$

Then, noting that for typical values of

$$x_0 + \varepsilon \simeq 0.105 + 0.015\ \mu$$

$$= 0.12\ \mu$$

so that

$$\frac{\overline{0.11}^2 k_1^{\,2}}{8(.12)} = 0.0126\ k_1^{\,2}$$

if we restrict $k_1^{\,2} \leq 1$.

Then,

$$0.0126\ k_1^{\,2} \leq 0.0126$$

Thus, within a 1% error,

$$\sigma_0 \simeq \frac{\overline{0.11}^2}{2}\ k_1 + 0.11\sqrt{x_0 + \varepsilon}$$

$$= 0.0065\ k_1 + 0.11\sqrt{x_0 + \varepsilon} \qquad [\mu]$$

Then, if we approximate

$$\frac{f(k_1)}{F(k_1)} = 0.725 - 0.439\ k_1$$

over the range $0.5 < k_1 < 1.0$, as shown in Figure 2, we can obtain an approximate solution

$$0.725 - 0.439\ k_1 = \frac{0.00605\ k_1 + 0.11\sqrt{x_0 + \varepsilon}}{x_0} \times \left[\frac{N_I + N_{ST} - N_{SS}}{N_I}\right]$$

from which

$$k_1 = \frac{0.725 - \dfrac{0.11\sqrt{x_0 + \varepsilon}}{x_0}\left[\dfrac{N_I + N_{ST} - N_{SS}}{N_I}\right]}{0.439 + \dfrac{0.00605}{x_0}\left[\dfrac{N_S + N_{ST} - N_{SS}}{N_I}\right]}$$

Substituting in

$$\sigma_0 = 0.00605\ k_1 + 0.11\sqrt{x_0 + \varepsilon}$$

(boron implant enhancement only)

$$\sigma_0 = \frac{0.004386 + 0.04829\sqrt{x_0 + \varepsilon}}{0.439 + \dfrac{0.00605}{x_0}\left[\dfrac{N_I + N_{ST} - N_{SS}}{N_I}\right]} \qquad [\mu]$$

Computing a solution for the constants used previously in the graphical solution,

$$\sigma_0 = 0.0425\ \mu$$

A test should be made for the approximate solution that

$$0.5 < k_1 < 1.0$$

If k_1 falls outside this range, the graphical solution should be used.

CAUTION:

If the preceding design is incorporated into an N-channel enhancement mode device where a depletion mode device is subsequently implanted onto the same wafer, the variability of the depletion mode device may be adversely affected. This will be discussed in a future memo.

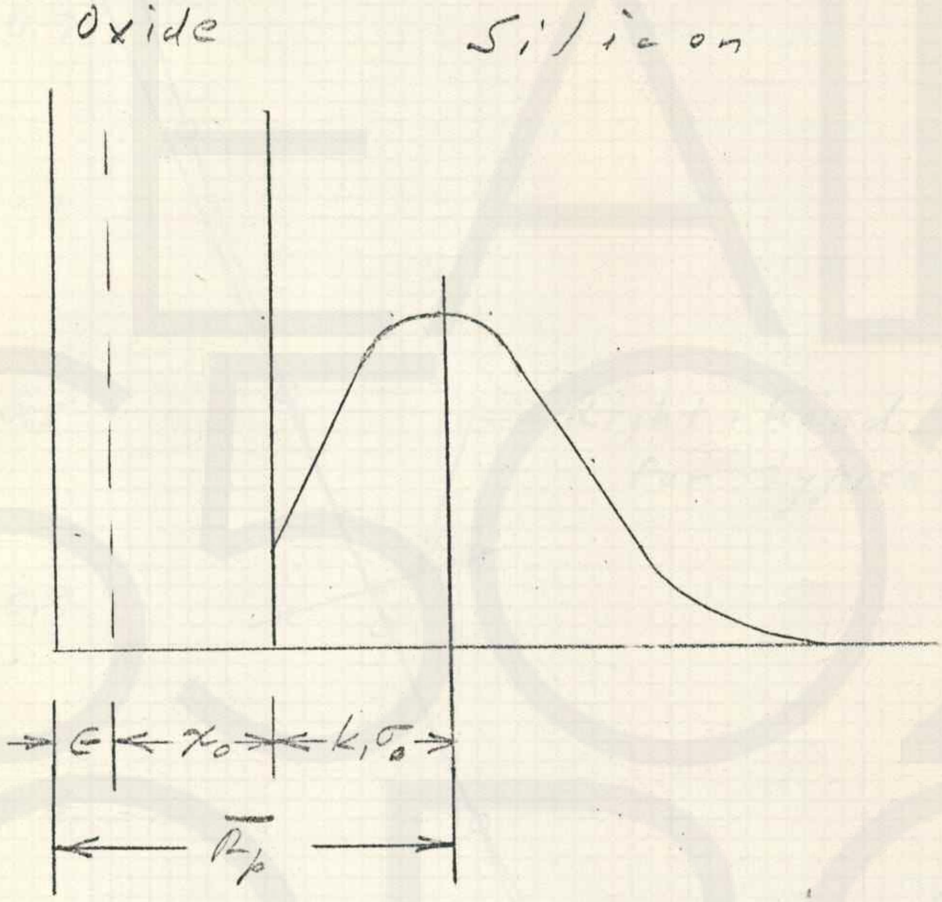

Figure 1

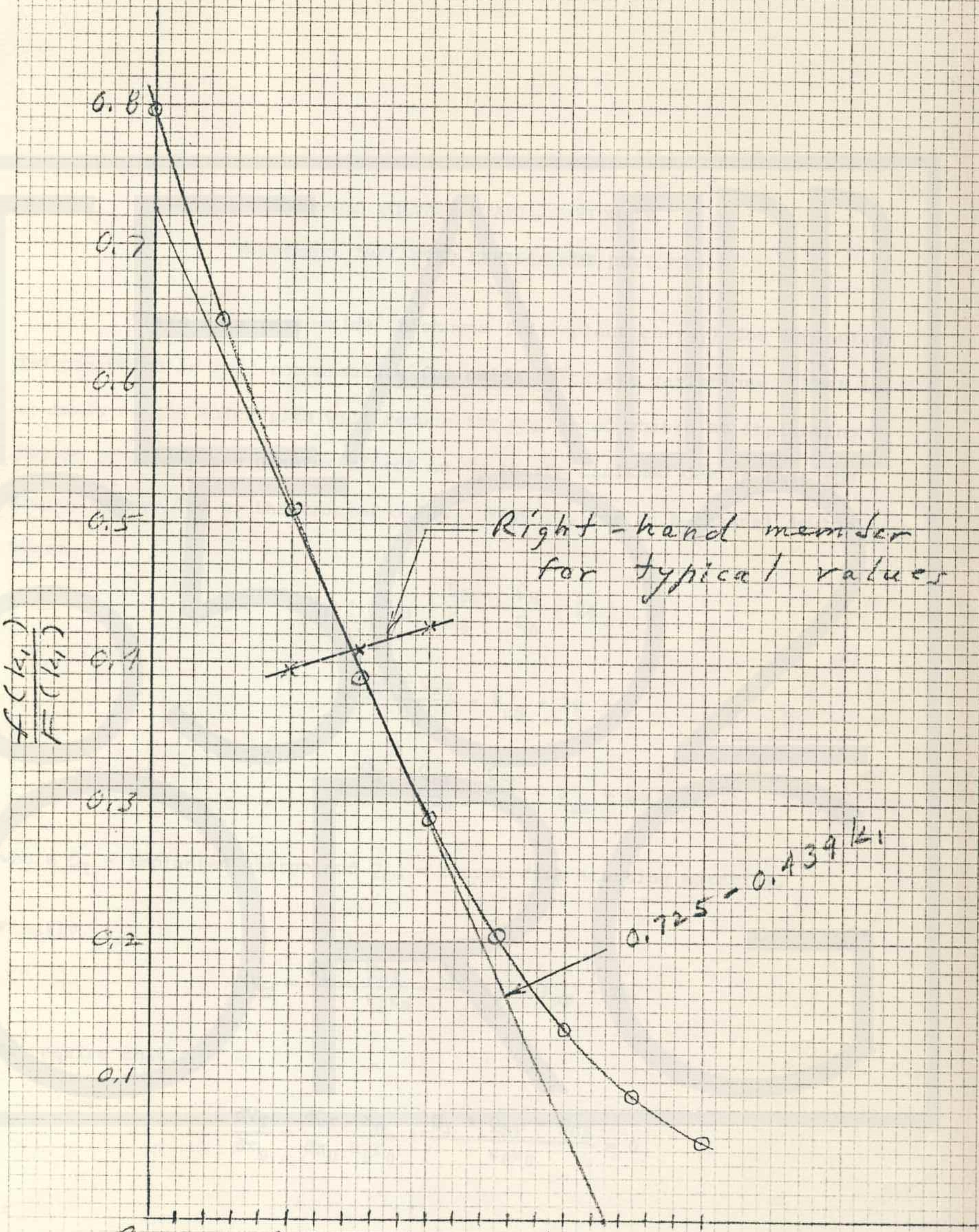

Figure =

BRUNING 40-8500 10x10 TO THE INCH
MADE IN U. S. A.