

SOME PHYSICAL CONSIDERATIONS ON THE
N CHANNEL SILICON GATE DEPLETION LOAD

"0 1 9" P R O C E S S

FOREWORD

The following analysis on the 019 process is not meant to be a rigorous treatment of detailed physics of semiconductor devices, but rather is meant to be a practically oriented approach of applying recognized theory to the 019 process. Hopefully it will be of use to the process engineer in analyzing electrical considerations affected by his process decisions and to the design engineer in analyzing process considerations that will affect his electrical parameters.

Due to the amount of items covered in a relatively short period of time by myself, there may be errors not caught--either typographical or theoretical. If so, please let me know so I can make the necessary changes, if deemed appropriate.

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A T T A C H M E N T S

1. Article on HCl usage in oxide growth.
2. Selections from Grove.
3. Selections from Crawford.
4. Implantation Information:

Plot of Range and Scattering
"Ion Implant Profile Calculations"
"Effect of Gate Oxide Thickness Variations on
Implanted Enhancement and Depletion Devices"

5. Depletion Device Operation - Edwards and Marr.
6. "019" Run Sheet

TABLE 4.1 IMPORTANT PROPERTIES OF GERMANIUM, SILICON, GALLIUM ARSENIDE, AND OF SILICON DIOXIDE AT 27°C.

	Ge	Si	GaAs	SiO ₂
Atomic or molecular weight	72.60	28.09	144.63	60.08
Atoms or molecules/cm ³	4.42 × 10 ²²	5.00 × 10 ²²	2.21 × 10 ²²	2.3 × 10 ²²
Crystal structure	Diamond, 8 atoms/unit cell	Diamond, 8 atoms/unit cell	Zinc-blende, 8 atoms/unit cell	Random network of SiO ₄ tetrahedra, 50% covalent, 50% ionic bonding
Lattice constant (Å)	5.66	5.43	5.65	...
Density, ρ (g/cm ³)	5.32	2.33	5.32	2.27
Energy gap (ev)	0.67	1.11	1.40	~8
Effective density of states conduction band N _c (cm ⁻³) valence band N _v (cm ⁻³)	1.04 × 10 ¹⁹ 6.0 × 10 ¹⁸	2.8 × 10 ¹⁹ 1.04 × 10 ¹⁹	4.7 × 10 ¹⁷ 7.0 × 10 ¹⁸	...
Intrinsic carrier concentration n _i (cm ⁻³)	2.4 × 10 ¹³	1.45 × 10 ¹⁰	~9 × 10 ⁶	...

Lattice (intrinsic) mobilities (cm ² /v sec) electrons holes	3900 1900	1350 480	8600 250	Insulator; $\rho > 10^{10} \Omega\text{-cm}$ at 300°K.
Dielectric constant	16.3	11.7	12	3.9
Breakdown field (v/ μ)	~8	~30	~35	~600
Melting point (°C)	937	1415	1238	~1700
Vapor pressure (Torr)	10 ⁻⁷ at 880°C 10 ⁻⁹ at 750°C	10 ⁻⁶ at 1250°C 10 ⁻⁷ at 1050°C	1 at 1050°C 100 at 1220°C	10 ⁻³ at 1450°C 10 ⁻¹ at 1700°C
Specific heat, C_p (Joule/g°C)	0.31	0.7	0.35	1.0
Thermal conductivity, k_{th} (watt/cm°C)	0.6	1.5	0.81	0.014
Thermal diffusivity $\kappa = \frac{k_{th}}{\rho C_p}$ ($\frac{\text{cm}^2}{\text{sec}}$)	0.36	0.9	0.44	0.006
Linear coefficient of thermal expansion $\frac{\Delta L}{L \Delta T}$ ($^{\circ}\text{C}$)	5.8 × 10 ⁻⁶	2.5 × 10 ⁻⁶	5.9 × 10 ⁻⁶	0.5 × 10 ⁻⁶

STEP 1 - INITIAL OXIDATION

TEMPERATURE: 1050°C, O₂ + HCl
 CYCLE: 5' O₂
 40' O₂
 5' O₂

From Grove p. 27, $x_o^2 + Ax_o = B(t + \tau)$

where

$$A = 2D \left(\frac{1}{r_s} + \frac{1}{h} \right), B = \frac{2DC^*}{N_i}, \tau = \frac{x_i^2 + Ax_i}{B}$$

where

x_i is the time zero starting thickness.

For large times $\tau \gg A^2/4B$, the parabolic relation applies: $x_o^2 = Bt$

$$B = \frac{x_o^2}{t} = \frac{(1000 \text{ \AA})^2}{50 \text{ min}} = \frac{(1000 \text{ \AA})^2}{50 \text{ min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{1 \text{ cm}}{10^8 \text{ \AA}} \times \frac{1 \text{ cm}}{10^8 \text{ \AA}} = \frac{10^6 \text{ cm}^2}{10^{16} \text{ hr}} \times \frac{60}{50}$$

$$B = 1.2 \times 10^{-10} \text{ cm}^2/\text{hr} = 10^6/50 \text{ \AA}^2/\text{min} = 1.2 \times 10^{-2} \mu^2/\text{hr}$$

This corresponds to an activation energy, E_a , of $\sim 1.24 \text{ eV}$, where $B \propto e^{-E_a/KT}$ per Grove.

This matches well with Grove's graph, p. 29 (0^2).

Attached: Grove p.p. 27, 28, 29

Article on HCl effect on oxidation:

Primary advantages of HCl:

1. Chlorine ties up sodium at oxide interface.
2. Reduces Q_{ss} by order of magnitude compared to standard oxide growth
3. Eliminate μ reduction of minority carries normally encountered during standard oxidation.

STEP 2 - "BORON IMPLANT - FIELD"

DOSE = 8×10^{11} , ENERGY = 35KeV, FSA = 2×10^{-6}

SETTING = 61.07.

SETTING: $i = \text{current} = \frac{Q}{\tau} = d q e A$

*-dose
-ion charge
-electronic e
-area*

$A = 2.2'' \times 67.25''$ (continuous mode)

SETTING = $\frac{d q A e}{\text{FSA}} = \frac{\text{Dose} \times 1.6 \times 10^{-19} \text{ Coul} \times 2.2 \times 67.25 \times (2.54)^2}{2 \times 10^{-6} \text{ cm}^2}$

= Dose $\times 763.61 \times 10^{-13}$

= Dose $\times 7.6361 \times 10^{-11}$

The setting is the dose in units of 10^{11} ions/cm² times 7.6361

Therefore, for a dose of 8×10^{11} , the setting should be:

$7.6361 \times 8 = \underline{\underline{61.09}}$

I² PROFILE: \bar{x} @ 35 KeV: 1175 Å

σ @ 35 KeV: 375 Å

From the normal distribution $f_n(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2\sigma^2}(x-\mu)^2}$

The peak is related to the dose by

$f_n(x)|_{\mu=\text{center}} = \frac{1}{\sigma\sqrt{2\pi}}$; $C_{p0} = \frac{Q}{\sigma\sqrt{2\pi}} = .3989 \frac{Q}{\sigma} \approx .4 \frac{Q}{\sigma}$

For FIELD I²: $C_{p0} = .4 \frac{Q}{\sigma} = \frac{.4 \times 8 \times 10^{11} \text{ ions/cm}^2}{375 \times 10^{-8} \text{ cm}} = \frac{3.2 \times 10^{11}}{375 \times 10^{-8}} \frac{\text{ions}}{\text{cm}^3}$

$C_{p0} = \frac{3200 \times 10^{16}}{375} = 8.53 \times 10^{16}$

$$N(x) = C_{p0} \exp \left[-\frac{1}{2\sigma^2} (x-\mu)^2 \right]$$

<u>@ $x = \mu \pm \sigma$, $C_{p0} \exp(-1/2)$</u>	= .61 Cpo	± 375 Å
<u>@ $x = \mu \pm 1.5\sigma$, $C_{p0} \exp(-1.12)$</u>	= .32 Cpo	± 562.5
<u>@ $x = \mu \pm 2\sigma$, $C_{p0} \exp(-2)$</u>	= .14 Cpo	± 150.0
<u>@ $x = \mu \pm 3\sigma$, $C_{p0} \exp(-4.5)$</u>	= .01 Cpo	± 1125.00
<u>@ $x = \mu \pm .5\sigma$, $C_{p0} \exp(-1/8)$</u>	= .88 Cpo	± 187.5
<u>@ $x = \mu \pm .25\sigma$, $C_{p0} \exp(-1/32)$</u>	= .97 Cpo	± 93.75

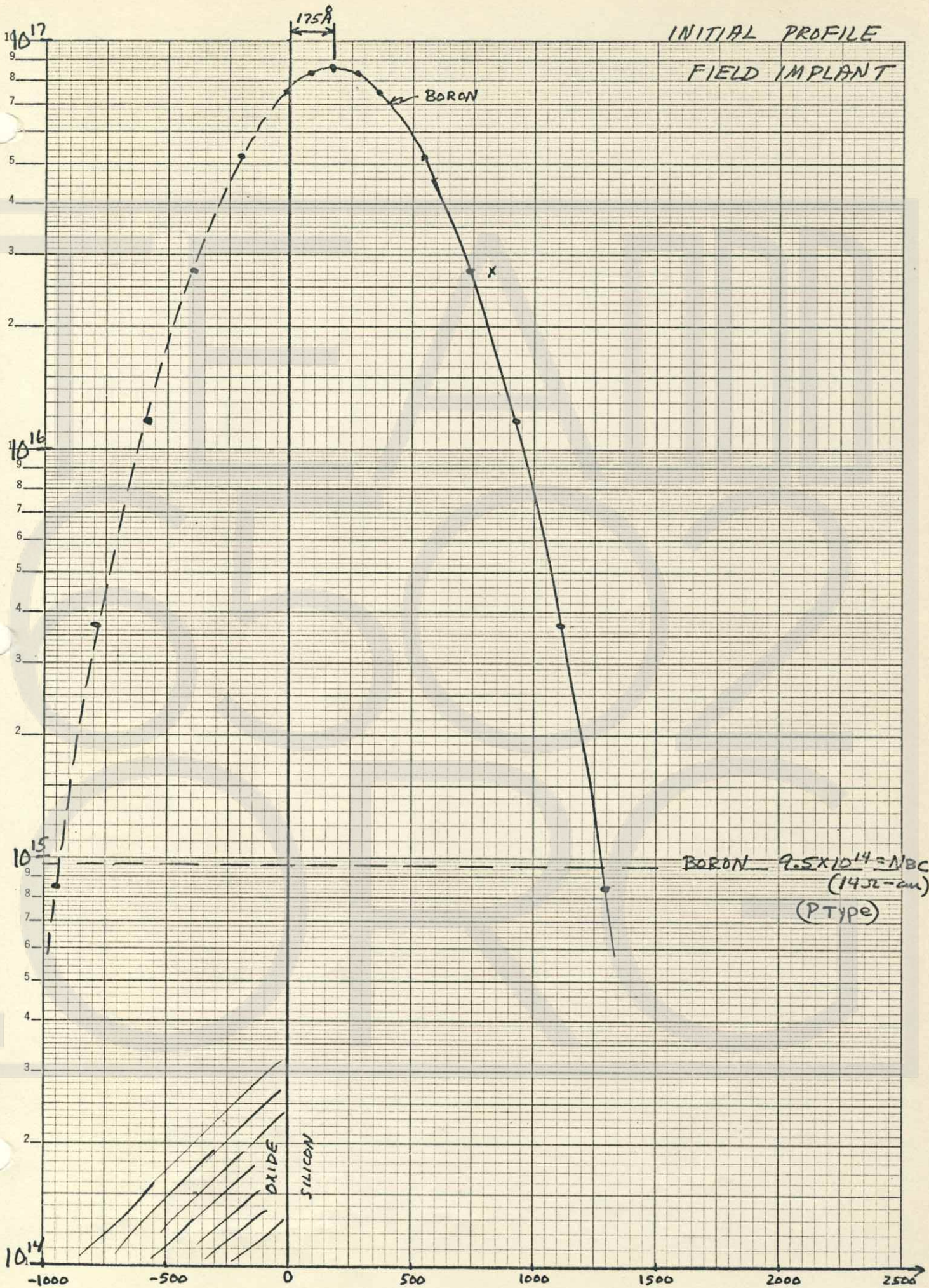
Point of distribution relative to μ Å	$\sigma = 375$ Å Point of distribution relative to μ Å	Cpo @ +175 Å Relative to interface Å	% of Cpo	Cpo = 8.53×10^{16} Actual Cpn
.25 σ	± 93.75	81.25, 268.75	.97 Cpo	8.27E16
.50 σ	± 187.50	-12.5, 362.50	.88 Cpo	7.51E16
1.00 σ	± 375.00	-200, 550.0	.61 Cpo	5.20E16
1.50 σ	± 562.50	-387.5, 727.5	.32 Cpo	2.73E16
2.00 σ	± 750.00	-575, 925.0	.14 Cpo	1.19E16
2.50 σ	± 937.5	-762.5, 1112.5	.04 Cpo	3.7E15
3.00 σ	± 1125.00	-950, 1300	.01 Cpo	8.53E14

$$N_{BC} (14 \mu\text{-cm}) = 9.5 \times 10^{14} / \text{cm}^3$$

ATTACHED: Appendix from Paivinen's article on I²

K&E SEMI-LOGARITHMIC 46 5490
 3 CYCLES X 70 DIVISIONS
 MADE IN U.S.A.
 KEUFFEL & ESSER CO.

INITIAL PROFILE
 FIELD IMPLANT



STEP 4, 7 - PYRO

Oxides of 6-7K Å are grown via the decomposition of silane in the reactor.



STEP 6, 9 - DENSIFICATION--FIELD I² ANALYSIS

TOTAL TIME: 70' @ 950°C O₂+HCl
 ↑ (2@ 30' O₂+HCl + 5' N₂)

$$\sqrt{D}_{\text{BORON, 950}^\circ\text{C}} = 3.7 \times 10^{-2} = .037 \mu/\text{hr}^{1/2}$$

$$\sqrt{D}_{\text{BORON, 1000}^\circ\text{C}} = .08 \mu/\text{hr}^{1/2}$$

$$\frac{\sigma_0^2}{2(Dt)_0} = 1 ; Dt_0 = \frac{\sigma_0^2}{2}$$

$$Dt_1 = Dt_0 + Dt_\Delta$$

and

$$C_{p_1} = C_{p_0} \sqrt{\frac{Dt_0}{Dt_1}}$$

≠

$$\sigma_1 = \sigma_0 \sqrt{\frac{Dt_1}{Dt_0}}$$

See attachment on Implant Analysis.

$$C_{p0} = 8.53 \times 10^{16}$$

$$Dt_0 = \frac{\sigma_0^2}{2} = \frac{(375 \text{ \AA})^2}{2} = \frac{(3.75 \times 10^{-2})^2 \mu^2}{2} = 7.03 \times 10^{-4} \mu^2$$

$$Dt_{\Delta} = (0.37)^2 \frac{\mu^2}{\text{hr}} \times \frac{70}{60} \text{ hr} = 15.97 \times 10^{-4} \mu^2$$

$$Dt_1 = 23 \times 10^{-4} \mu^2 = Dt_0 + Dt_{\Delta}$$

$$\sqrt{\frac{Dt_1}{Dt_0}} = \sqrt{\frac{23 \times 10^{-4}}{7.03 \times 10^{-4}}} = 1.81$$

$$C_{p1} = \frac{8.53 \times 10^{16}}{1.81} = 4.71 \times 10^{16}$$

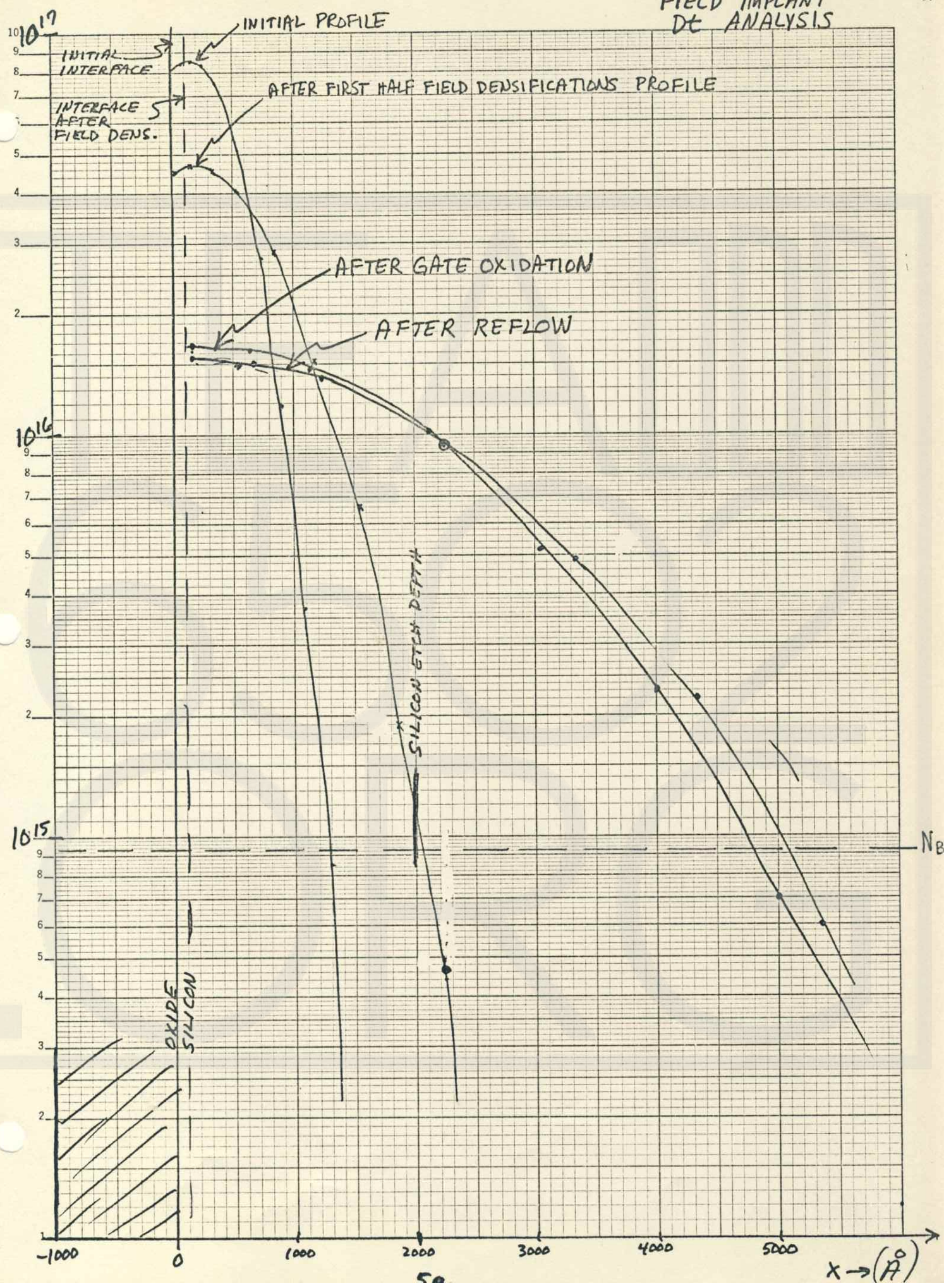
$$\sigma_1 = \sigma_0 \sqrt{\frac{Dt_1}{Dt_0}} = 375 \text{ \AA} \times 1.81 = 679 \text{ \AA}$$

AFTER DENSIFICATIONS: $C_{p1} = 4.71 \times 10^{16}$

$$\sigma_1 = 679 \text{ \AA}$$

$N\sigma$	\AA	$C_{p0} = + 175$ from interface	% of C_{p0}	$C_{p1} = 4.71 \times 10^{16}$ C_{pn}
.25	170	5,345	.97	4.57
.50	340	-,515	.88	4.14
1.00	680	-,855	.61	2.87
1.50	1020	-,1195	.32	1.51
2.00	1360	-,1535	.14	.66
2.50	1700	-,1875	.04	.19
3.00	2040	-,2215	.01	.05

FIELD IMPLANT DE ANALYSIS



KE SEMI-LOGARITHMIC 46 5490
3 CYCLES X 70 DIVISIONS
MADE IN U.S.A.
KEUFFEL & ESSER CO.

FIELD IMPLANT FINAL ANALYSIS

Gate Anneal	40'	- 950°C	} $\sqrt{D_{BORON}} = .037$	$t = 78'$
Phos Pre-Dep	33'	- 950°C		$Dt_{\Delta} = 17.8E-4$
Furnace Dry	5'	- 950°C		
Reflow	20'	- 1000°C	} $\sqrt{D_{BORON}} = .060$	$t = 20'$ $Dt_{\Delta} = 12E-4$

$\sum_{1.2} Dt_{ox} = 29.8E-4$

$Dt_0 = \frac{\sigma_0^2}{2} = \frac{(1931 \text{ \AA})^2}{2} = \frac{(19.31 \times 10^{-2})^2}{2} \mu^2 = 186.44E-4 \mu^2$

$Dt_i = Dt_0 + Dt_{\Delta} = 216.2E-4 \mu^2$

$\sqrt{\frac{Dt_i}{Dt_0}} = \sqrt{\frac{216.2}{186.4}} = 1.08$

$Cp_1 = \frac{Cp_0}{1.08} = \frac{1.66 \times 10^{16}}{1.08} = 1.54E16$

$\sigma_1 = 1931 \times 1.08 = 2085.5 \text{ \AA}$

(Note: See pages 8 & 9 for derivation of Cp and σ after gate oxidation.)

$N\sigma$	$\sigma_1 = 2086$ Å	175 Å from interface	% of Cp ,	$Cp_1 = 1.54 \times 10^{16}$ Cp_n
.25	521	696	.97	1.49×10^{16}
.50	1043	1218	.88	1.38
1.00	2086	2261	.61	.94
1.50	3129	3304	.32	.49
2.00	4162	4337	.14	.22
2.50	5201	5376	.04	.06
3.00	6242	6417	.01	.02

Movement of oxide - Si interface during densifications:

Using Groves graph, p. 29 where we know we are relatively close on the graph, the constant B for 950°C is $\sim 7.5E-3 \mu^2/\text{hr}$.
(O₂)

Since t densification = 70',

$$(\Delta X_0)^2 = Bt = 7.5E-3 \frac{\mu^2}{\text{hr}} \times \frac{70}{60} \text{ hr} = 8.75E-3 \mu^2$$

$$(\Delta X_0)^2 = 87.5E-4 \mu^2; \Delta X_0 = 9.35E-2 \mu$$

$$\Delta X_0 = .0935 \mu = 935 \text{ \AA}$$

This assumes no initial oxide growth.

This is unrealistic since we are speaking of O₂ diffusing thru first 6 - 7K, then 12 - 14K of pyro before it reaches the interface. Very little oxide will be formed during the densifications--certainly not the 935 Å calculated above.

Now consider the case of an existing initial oxide.

Use the linear rate constant of Grove, p. 30 to find B/A then knowing B, solve for A.

Use 9000 Å as an average (1st pass - 6K; 2nd pass - 12K)

$$\tau = \frac{(.9 \mu)^2 + .9 \mu B}{.0075} = \frac{X_i^2 + AX_i}{B}; \frac{B}{A} = .03 \text{ (p. 30, Grove)}$$

$$\tau = \frac{.81 + .9 \times .0075}{.0075} = 109$$

$$X_0^2 = B(t + \tau) = .0075(1 + 109) = .83 \mu^2$$

$$X_0 = .9110 \mu = 9110 \text{ \AA}$$

$$9110 \text{ \AA} - 9000 \text{ \AA} = 110 \text{ \AA}$$

This represents a ΔX_0 of $\sim 110 \text{ \AA}$.

Therefore, it would be reasonable to expect we would not grow more than 125 Å during the subsequent field densifications.

NOTE: A 2000 Å silicon etch clears out nearly all of the boron from the field implant per the page 5a graph.

STEP 15 - GATE OXIDATION 5-40-5 1050°C O₂ + HCl

5' - O₂
 40' - O₂ + HCl
 5' - O₂

 50' - O₂

Using "B" from Initial Oxidation (since temperatures are the same),

$$X_0^2 = Bt = 1.2 \times 10^{-2} \frac{\mu^2}{hr} \times \frac{50}{60} hr = 1.0 \times 10^{-2}$$

$$X_0 = 1000 \text{ \AA} \text{ (as expected)} - \text{Lot 019-H max} \sim 1020 \text{ \AA}$$

Note: A 5-42-5 time would yield:

$$X_0^2 = Bt = 1.2 \times 10^{-2} \times \frac{52}{60}; (1020 \text{ \AA} = X_0 \sim 1050 \text{ \AA})$$

Movement of Field Implant:

$$C_{p0} = 4.71 \times 10^{16}$$

$$\sigma_0 = 680 \text{ \AA}$$

$$\sqrt{D}_{\text{BORON}, 1050} = 1.4 \times 10^{-1} \mu/hr^{1/2} = .14 \mu/hr^{1/2}$$

$$D = .0196 \mu/hr; D t_{\Delta} = .0196 \times \frac{50}{60} = .0163$$

$$D t_0 = \sigma_0^2 / 2 = (6.8 \times 10^{-2})^2 \mu^2 / 2 = 23.12 \times 10^{-4} \mu^2$$

$$D t_1 = D t_0 + D t_{\Delta} = (23.13 + 163) E-4 \mu^2 = 186 E-4 \mu^2$$

$$\sqrt{\frac{D t_1}{D t_0}} = \sqrt{\frac{186 E-4}{23.1 E-4}} = 2.84$$