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CHARACTERIZATION OF SHALLOW ION-IMPLANTATIONS IN VLSI DEVICES WITH GATED DIODE STRUCTURES

by

Chen-Chung Chao

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December 8, 1982

Date

Professor in Charge

Chairman of Department

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TABLE OF CONTENTS

	PAGE
Title Page	i
Certificate of Approval	ii
Acknowledgements	iii
Table of Contents	iv
List of Tables	v
List of Figures	vi
Abstract	1
Chapter	
1. Introduction	2
2. Theory	4
3. Experiment	10
4. Results and discussions	13
5. Conclusions	29
Appendix A	30
Appendix B	37
Appendix C	45
References	46
Vita	47

LIST OF TABLES

Table Page

1. The parameters extracted from N-X curves by using non-linear least squares method. 25

2. The parameters extracted from N-X curves with corrections and from SUPREM. 27

LIST OF FIGURES

Figure Page

1. MOS structure. 4
2. Cross-section of the gated diode structure. 10
3. Experimental setup and data acquistion system. 11
4. 10 KHz C-V curves with different V_{SB}. 13
5. Equivalent circuit of the gated diode in different regions. 14
6. N-X curves with $V_{SB} = -1$ V 16
7. N-X curves with $V_{SB} = -1.5$ V 17
8. N-X curves with $V_{SB} = -3$ V 18
9. N-X curves with $V_{SB} = -4$ V 19
10. N-X curves with different Vsb. 21
11. Curves before and after using non-linear least square method. 22
12. Curves before and after using Kennedy's correction. 23
13. Results from SUPREM 26
14. ω/λ and g_2 vs. g_1, cf equation (A-27), (A-28) and (A-11). 36

ABSTRACT

The impurity profile, including the corrections near the semiconductor surface and junction, of a shallow ion-implanted layer has been characterized by C-V data obtained on a gated-diode structure with a microcomputer-controlled measurement system.

CHAPTER 1

INTRODUCTION

The knowledge of the doping profiles of a shallow ion-implanted layer is very important, especially in impurity profile related operating characteristics like the threshold voltage adjustment and punch-through control in VLSI device studies.

Traditionally, the doping profile has been obtained with the depletion approximation and C-V measurements; however, this is an approximation since the majority carriers distribution in the vicinity of the junction must be considered according to Kennedy and O'Brien [1]. In addition, the impurity profile near the semiconductor surface is influenced by accumulation of majority carriers as described by Ziegler, Klausmann, and Kar [2]. Brief reviews of the above theories will be given in chapter 2.

The microcomputer-based, automatic data-acquition and analysis system will be outlined in chapter 3.

In chapter 4, the C-V curves and the corresponding equivalent circuit models of the various regions will be qualitatively described. The N-X curves of the shallow ion-implanted gated diode including the corrections near the semiconductor surface and near the junction will be discussed. The parameters like the the surface concentration, the peak concentration, the range of the ion implanation, the junction depth and substrate doping concentration extracted from the corrected N-X curves will be compared to the parameters from the Computer-Aided-Design program SUPREM.

The conclusions will be listed in chapter 5.

CHAPTER 2

THEORY

2.1 C-V profiling from Depletion Approximation

The differential capacitance in the depletion region of the C-V characteristics can be used to extract the impurity profile of the semiconductor devices. It can be derived as follows:

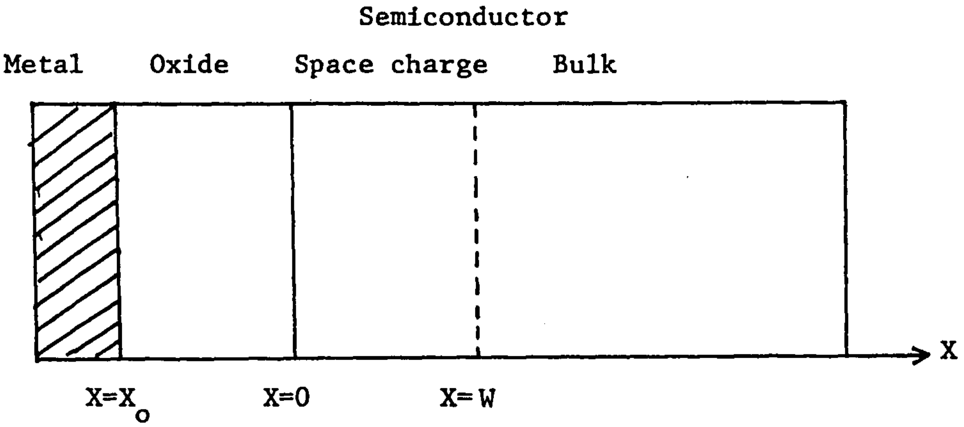


Figure 1. MOS structure

For an MOS structure in depletion shown in Figure 1., the gate charge dQ_G must equal the change in the space charge dQ_{SC} by Gauss' law, with the assumption of no net charge stored in the oxide. Thus

$$dQ_G = - dQ_{SC} \tag{2.1}$$

and

$$dQ_G = qN(W)dW \tag{2.2}$$

where dQ_{SC} space charge change is due enirely to the complete uncovering of additional ionized dopants, q is the charge of an electron, N(W) is the dopant density (atoms/(cm**3)) at a distance W from the oxide-semiconductor interface.

$$dQ = C\, dV_{GB} \tag{2.3}$$

Equating (2.1) and (2.2), we obtain the variation of the gate-to-bulk voltage.

$$dV_{GB} = -\, qN(W)\, \frac{dW}{C} \tag{2.4}$$

where C represents the series sum of the oxide capacitance Co and depletion capacitance C_{SC}.

$$\frac{1}{C} = \frac{1}{C_o} + \frac{1}{C_{SC}} \tag{2.5}$$

Co = ε_o/X_o and C_{SC} + ε_s/W , where ε_o the dielectric constant of the oxide, X_o the oxide thickness, ε_s the dielectric constant of the semiconductor and W the depletion width.

Now
$$dW = \varepsilon_s\, d(\frac{1}{C_{SC}}) = \varepsilon_s\, d(\frac{1}{C}) \tag{2.6}$$

So that

$$\begin{aligned} dV_{GB} &= -qN(W)\varepsilon_s (\frac{1}{C}) d(\frac{1}{C}) \\ &= \frac{\varepsilon_s qN(W)}{2}\, d(\frac{1}{C^2}) \end{aligned} \tag{2.7}$$

therefore,
$$N(W) = \frac{2}{\varepsilon_s q}[\frac{d(\frac{1}{C^2})}{dV_{GB}}]^{-1} = \frac{2C_o^2}{\varepsilon_s q}[\frac{d(\frac{C_o}{C})^2}{dV_{GB}}]^{-1} \tag{2.8}$$

From (2.5)

$$\frac{1}{C_{SC}} = \frac{1}{C} - \frac{1}{C_o} = \frac{W}{\varepsilon_s}$$

$$W = \frac{\varepsilon_s}{C_o}\left(\frac{C_o}{C} - 1\right)$$

$$= \frac{\varepsilon_s X_o}{\varepsilon_o}\left(\frac{C_o}{C} - 1\right) \qquad (2.3)$$

Equations (2.8) and (2.9) are the basis for the dopant determination from C-V measurement on an MOS structure.

2.2 Impurity profile correction near the junction

Kennedy et al. [1] found that the impurity profile inferred from the differential capacitance of the semiconductor junction is not that of the impurity atom distribution but, instead, that of the majority carrier distribution. So we can relate the apparent impurity profile (majority profile) and the true impurity distribution with the following analysis:

Assume the measured differential capacitance C of the test junction and the majority carrier distribution n(X) in N-type semiconductor.

It is

$$n(X) = -\frac{2C_o^2}{\varepsilon_s q}\left[\frac{d\left(\frac{C_o}{C}\right)^2}{dV_{GB}}\right]^{-1} \qquad (2.10)$$

where X is the test junction space charge layer width at the applied biasing voltage V_{GB}.

The electric current within this material due to both drift and diffusion of majority carriers is given by

$$J_n = q\ D_n \frac{dn}{dx} - q\ M_n n \frac{dx}{dx} \qquad (2.11)$$

When Jn = O, we have to maintain an electric field containing the local variations of electron density.

$$(x) = - \frac{dx}{dx} = - \frac{kT}{q}\left(\frac{1}{n(X)}\ \frac{dn(X)}{dx}\right) \qquad (2.12)$$

Assuming extrinsic semiconductor material (neglect the contribution from minority carrier density) , we have from Poisson's equation.

$$\frac{d}{dx} = \frac{q}{\varepsilon_s}\ [N(X) - n(X)] \qquad (2.13)$$

where N(X) is the impurity atom distribution.

By combining (2.12) and (2.13), we obtain

$$- \frac{kT}{q}\frac{d}{dx}\left(\frac{1}{n(X)}\ \frac{dn(X)}{dx}\right) = \frac{q}{\varepsilon_s}\ [N(X)-n(X)] \qquad (2.14)$$

and therefore

$$N(X) = n(X)\ - \left(\frac{kT}{q}\right)\left(\frac{\varepsilon_s}{q}\right)\ \frac{d}{dx}\ \left[\frac{1}{n(X)}\ \frac{dn(X)}{dx}\right] \qquad (2.15)$$

Equation (2.14) rigorously relates the desired impurity atom distribution N(X) to the majority carrier distribution n(X).

2.3 Impurity profile correction near the semiconductor surface

Equations (2.8) and (2.9) are based on the assumption that the charge in the space charge region is solely due to the ionized dopants. The depletion approximation is only valid for the depletion region where $W \geq 2\lambda$, W is measured from the semiconductor surface, and λ is the extrinsic Debye Length [3] given as

$$\lambda_D = \sqrt{\frac{2kT\varepsilon_s}{q^2 N(W)}} \qquad (2.16)$$

k is Boltzmann's constant, and T the absolute temperature.

Ziegler et al. [2] have developed a method to determine the doping profile of the semiconductor right up to the surface. The corrected doping density becomes

$$N(W) = \frac{2C_o^2}{q\varepsilon_s}\left[\frac{d(\frac{C_o}{C})^2}{dV_{GB}}\right]^{-1} g_2(\frac{W}{\lambda_D}) \qquad (2.17)$$

$$W = \frac{{}_{s}X_o}{\varepsilon_o}(\frac{C_o}{C} - 1)[1 - g(\frac{W}{\lambda_D})] \qquad (2.18)$$

where

$$g_2(\frac{W}{\lambda_D}) = (1 - \frac{2(\frac{W}{\lambda_D})^2 g(\frac{W}{\lambda_D})}{1 - g^2(\frac{W}{\lambda_D})})\frac{1}{1-g(\frac{W}{\lambda_D})} \qquad (2.19)$$

$$(\frac{W}{\lambda_D})^2 = g(\frac{W}{\lambda_D}) - \ln(g(\frac{W}{\lambda_D})) - 1 \qquad (2.20$$

The procedures for calcuating the doping profile is summarized as follows:

1. Measure $g_1(\frac{W}{\lambda_D})$ from C-V data

$$g_1(\frac{W}{\lambda_D}) = \frac{kT}{q} \frac{1}{(\frac{C_o}{C} - 1)^2} \frac{d}{dV_{GB}} (\frac{C_o}{C})^2 \qquad (2.21)$$

$$= \frac{1 - g(\frac{W}{\lambda_D})}{(\frac{W}{\lambda_D})^2} \frac{2g(\frac{W}{\lambda_D})}{1-g(\frac{W}{\lambda_D})} \qquad (2.22)$$

2. Calculate $\frac{W}{\lambda_D}$ and g by solving equations (2.20) and (2.21)

3. Compute g_2 , where g_2 can be obtained from g_1 and g .

where

$$g_2(\frac{W}{\lambda_D}) = \frac{g_1}{2g+(1-g)g_1} \qquad (2.23)$$

4. Finally, N(W) and W are determined from equations (2.17) and (2.18)

$$N(W) = \frac{2C_o^2}{q\varepsilon_s} \left[\frac{d(\frac{C_o}{C})^2}{dV_{GB}}\right]^{-1} g_2(\frac{W}{\lambda_D})$$

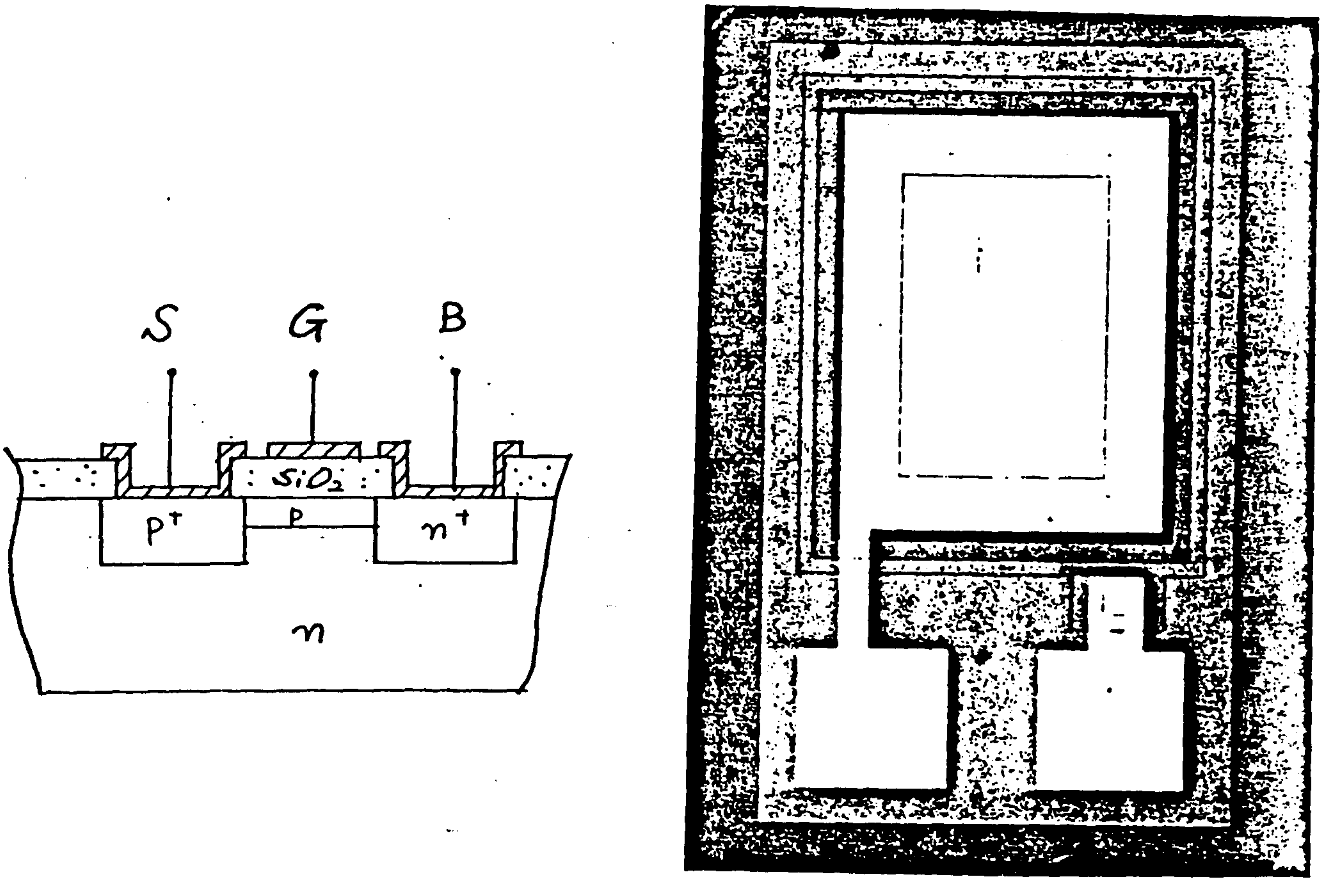
$$W = \frac{\varepsilon_s X_o}{\varepsilon_o} (\frac{C_o}{C} - 1) [1 - g(\frac{W}{\lambda_D})]$$

A detailed derivations of Ziegler's Theory will be shown in Appendix A.

CHAPTER 3

EXPERIMENT

The simplified cross section and photomicrograph of the gated diode structure is shown in Figure 2.



Simplified cross section

Photomicrograph

Figure 2. Cross-section of the gated diode structure

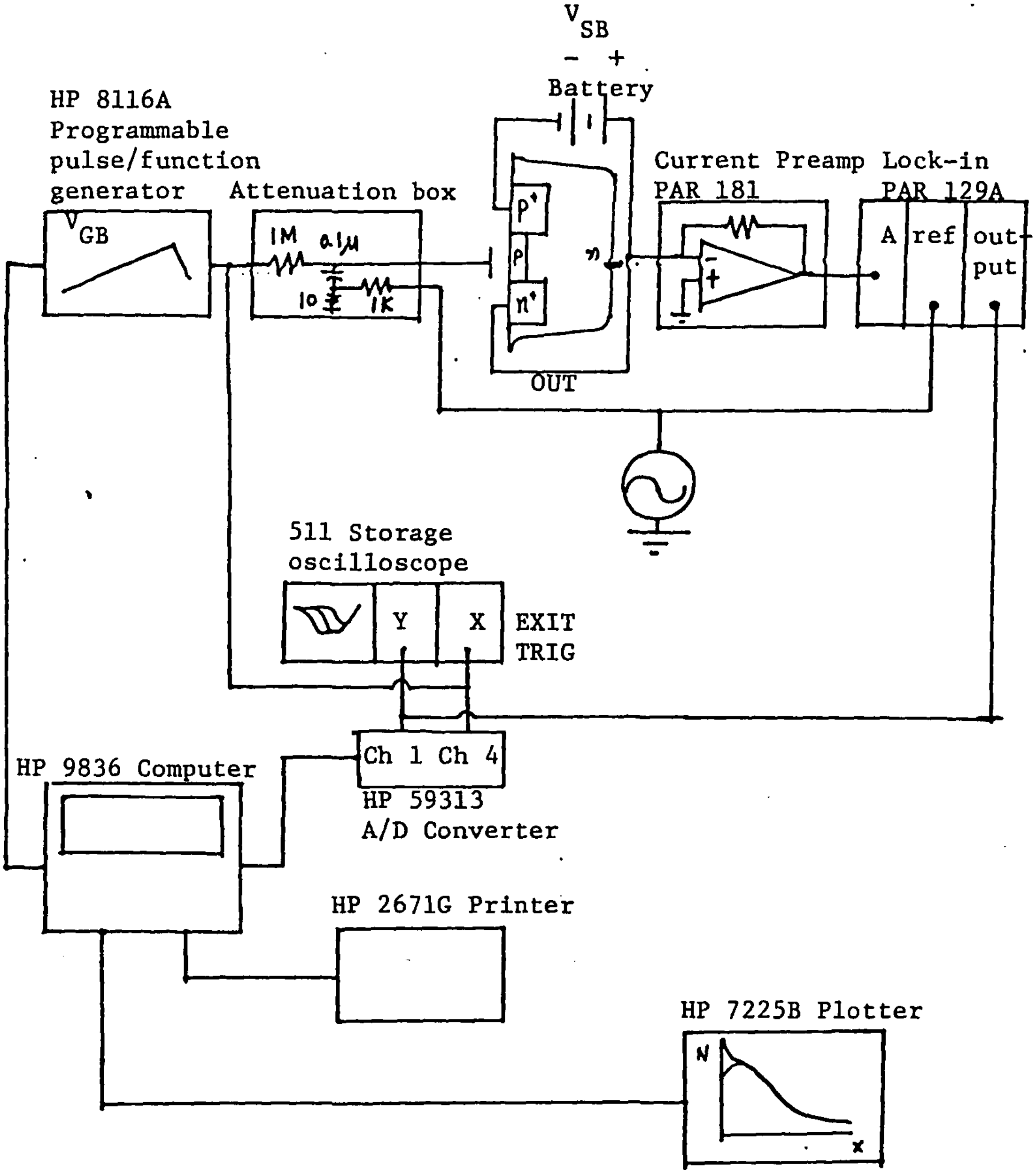


Figure 3. Experimental setup and data acquisition system.

Figure 3. is the experimental C-V setup and automatic measurement system diagram. The substrate of the gated diode (bulk) is connected to The inverting input of The current preamplifier. The gate terminal (gate) receives a ramped d-c voltage provided by HP 8116A progammable pulse/function generator and a small a-c signal. V_{SB} is supplied from battery in order to avoid the noise coming from the power lines. The output of the current preamplifier is proportional to the current through the gated diode, which consists of in-phase component due to conductance of the device and a quadruature-phase component due to capacitance. The output of quarduature-phase compenent of the lock-in amplifier is proportional to the capacitance of the gated diode. The bias voltage and the output of the lock-in amplifier can be applied to the horizontal and the vertical input of HP 511 storage oscilloscope (as a monitor device) and HP 59313 A/D converter (for data conversion use). A HP 9836 microcomputer is connected with a HP 59313 and a HP 8116A for instruments control, measurements, data collection and analysis.

All the computer programs developed for HP 9836 will be shown in Appendix B.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 C-V curve

Figure 4 is a set of C-V plots of a buried channel p-channel gated diode with different V_{SB}.

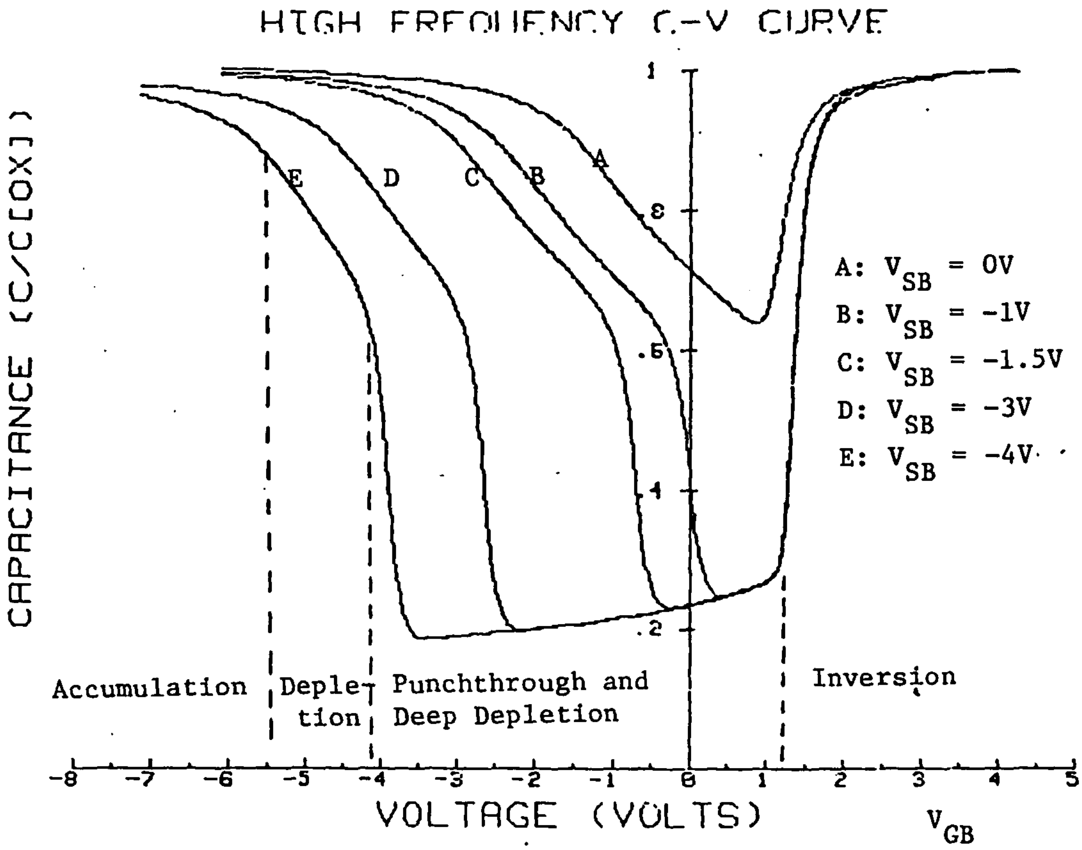
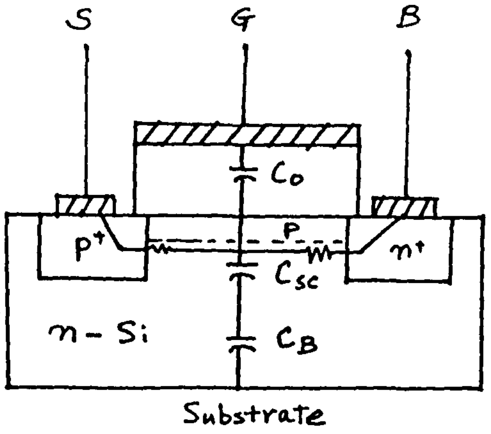
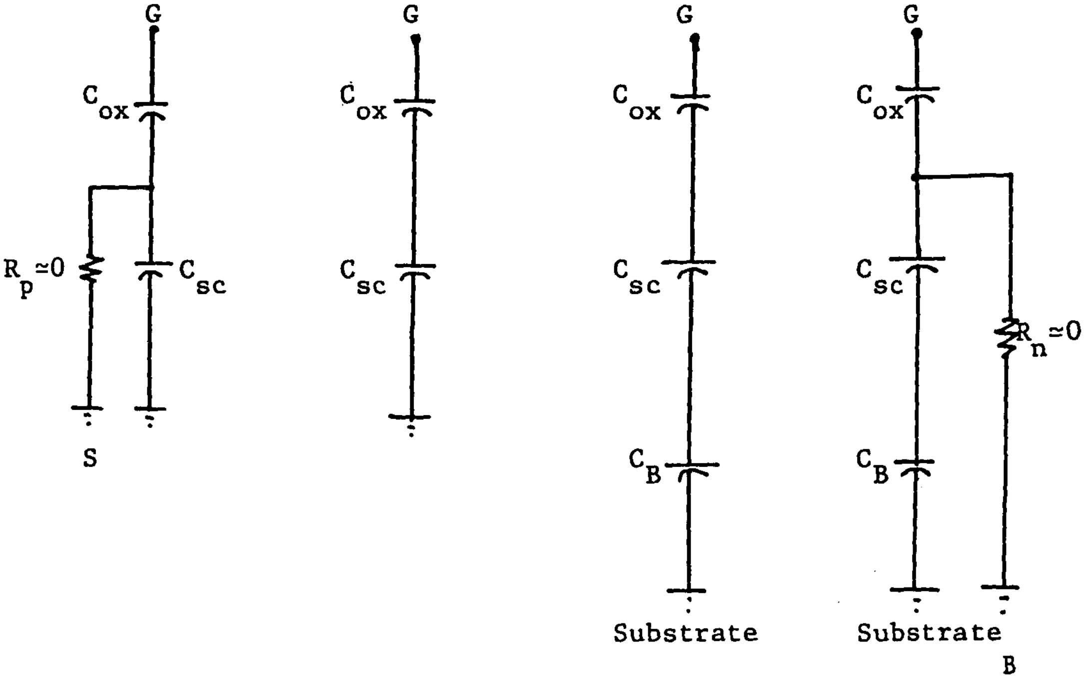


Figure 4. 10 KHz C-V curves with different V_{SB}.





Accumulation — 5A

Depletion — 5B

Punch-through and Deep Depletion — 5C

Inversion — 5D

Figure 5. Equivalent circuit of the gated diode in different region.

A qualitative discussion of the various regions and the equivalent circuit model has been shown in Figure 5.

4.1.1 Accumulation [Figure 5A]

It can be characterized by the accumulation of majority carriers. There is a conductive path between the surface and the source (P+) . The equivalent capactance is just the oxide capacitance.

4.1.2 Depletion [Figure 5B]

Holes are collected by P+ region and electrons are collected by the N+ region under this condition. There is no conductive path at surface either N+ or P+ regions, and the depleted P implant near the surface behaves as the space charge capacitance. The equivalent capacitance will be the series sum of the oxide capacitance and space charge capacitance.

4.1.3 Punch-through and Deep depletion [Figure 5C]

It can be characterized by complete depletion of the implant of all mobile carriers, leaving only space charge there, the depletion regions near the surface and the bulk p-n junction to be touched together. Besides the depletion capacitance and oxide capacitance, the bulk substrate capacitance has to be taken into account.

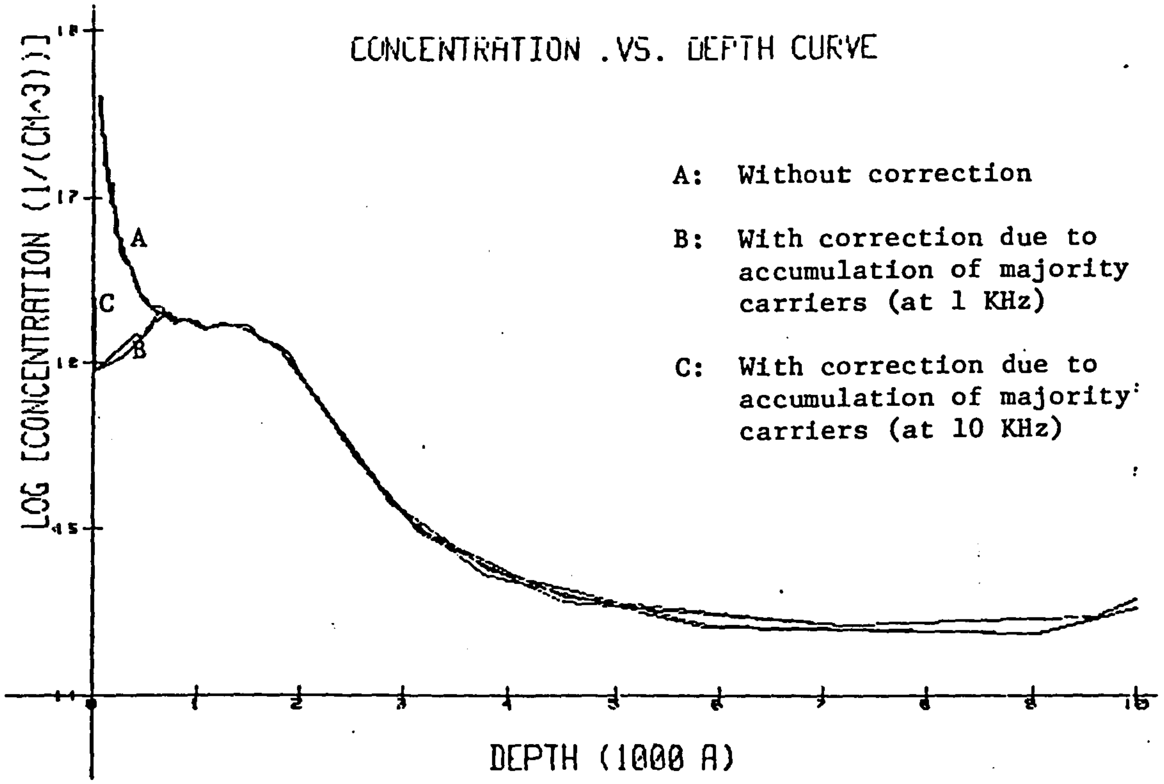


Figure 6. N-X curves with V_{SB} = 1 V.

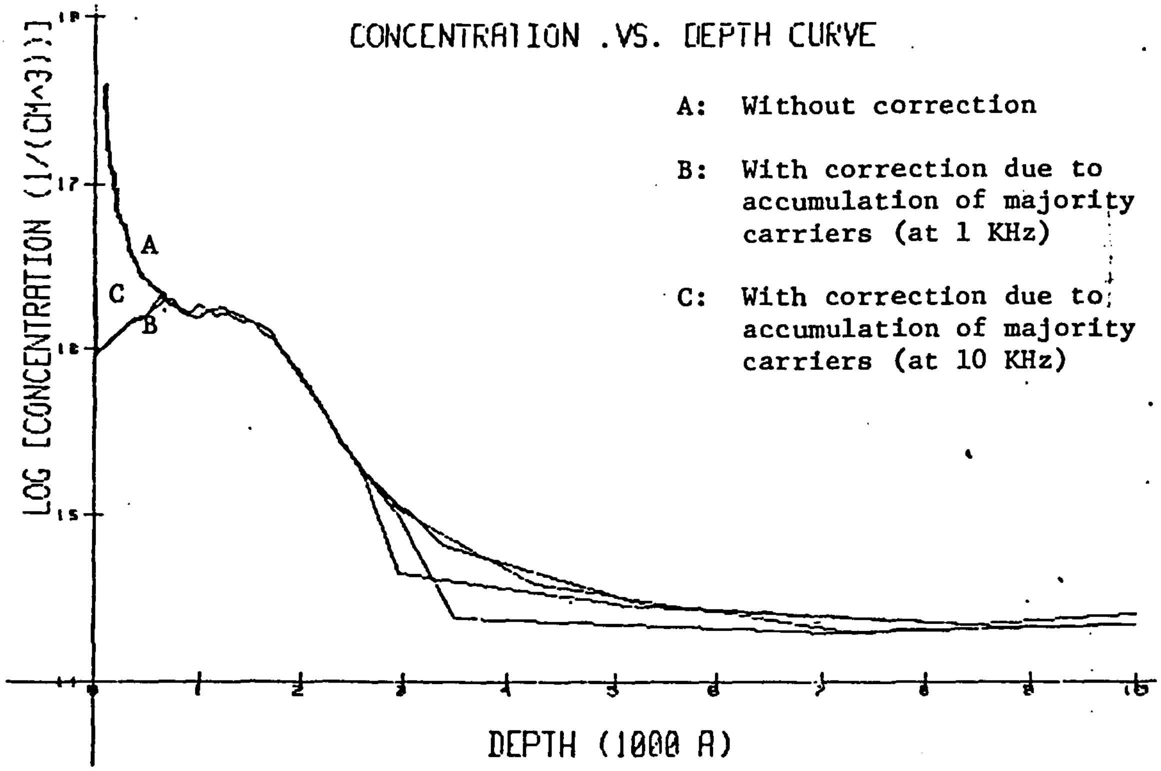


Figure 7. N-X curves with V_{SB} = 1.5 V.

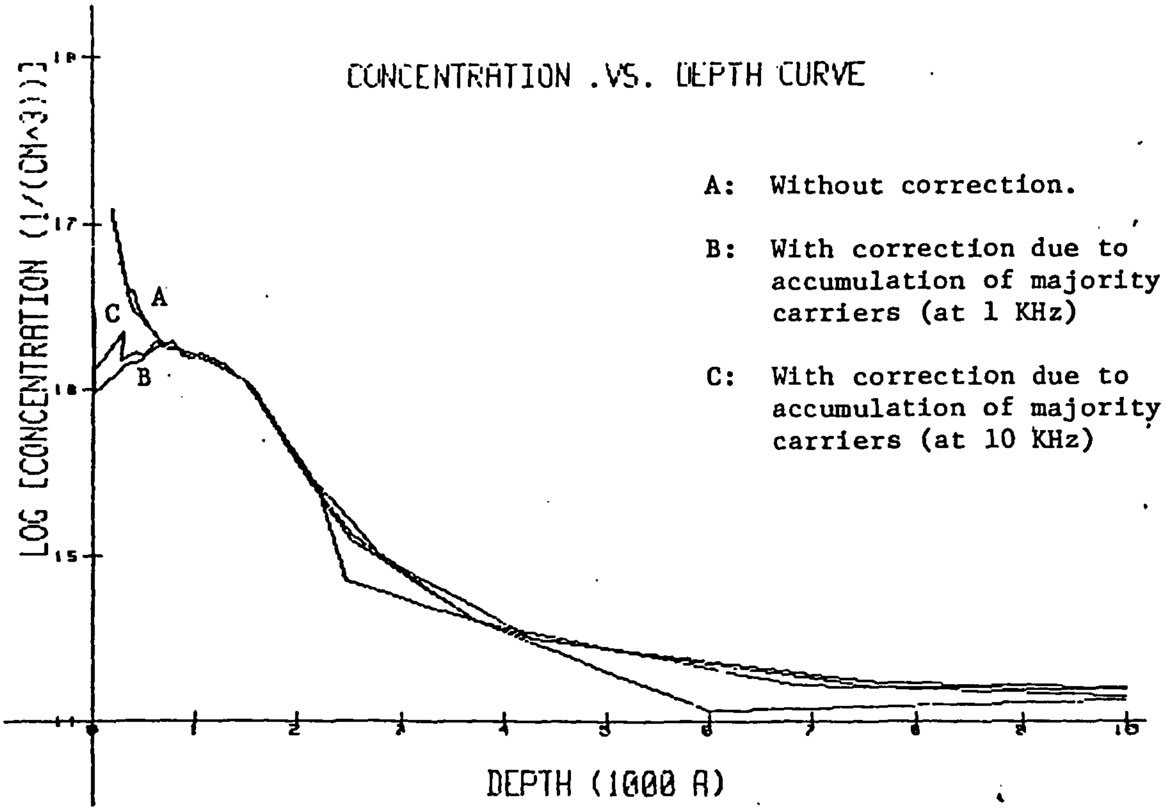


Figure 8. N-X curves with Vsb = 3 V.

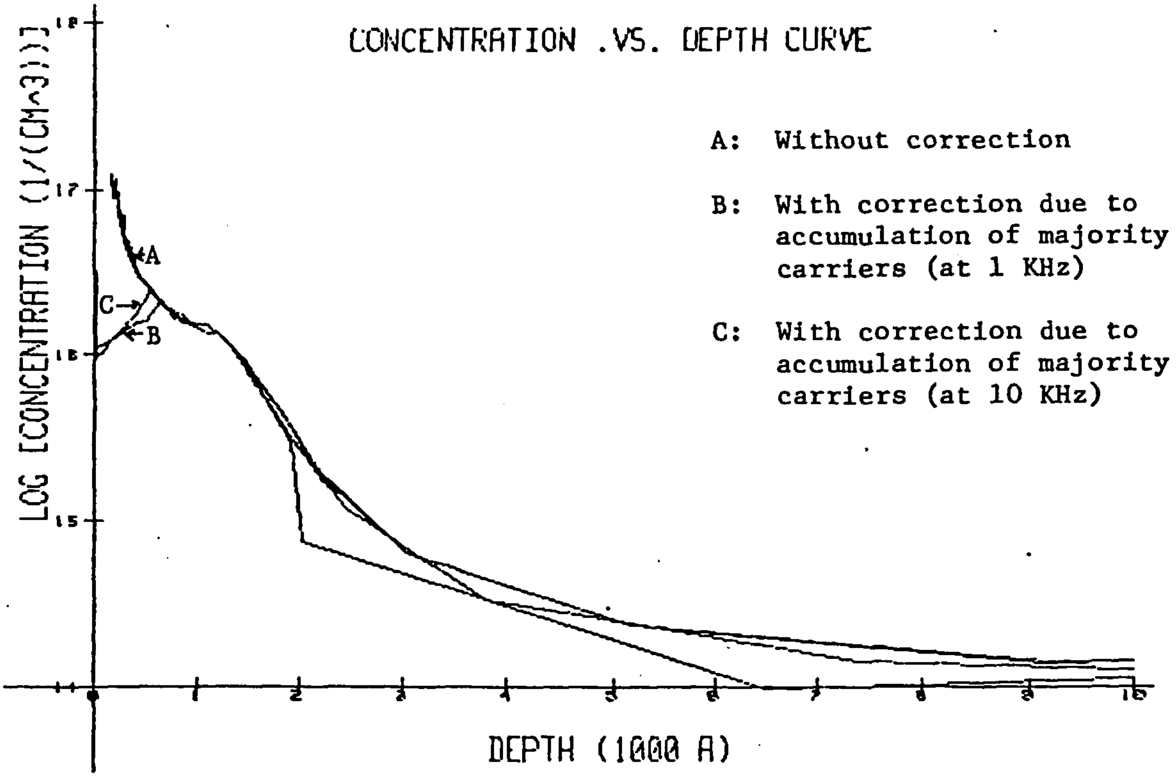


Figure 9. N-X curves with Vsb = 4 V.

4.1.4 Inversion [Figure 5D]

For enough positive voltage applied on the gate, electrons from the N+ (bulk) will be attracted to the surface to invert it to N-type. This also produces a conductive path between the semiconductor and the N+ region. Only the oxide capacitance contributes to the total capacitance.

4.2 N-X curve

By utilizing the equations (2.8) , (2.9) ,(2.17) , (2.18), the impurity profiles with and without correction near the semiconductor surface for various freqencies and source-to-bulk biases are shown from Figure 6 to Figure 9. For example, the impurity profile directly coming from C-V based on Depletion Approximation is shown in curve A of Figure 6. Curve B and curve C represent the impurity profiles obtained with correction near the semiconductor surface based on Ziegler's model at 1 KHz and 10 KHz, respectively.

From Figure 6 to Figure 9, In Figures 7, 8, and 9, there are clear deviations away from the uncorrected impurity profile around 3000 Å. It is due to the effect of $W < 2\lambda$ and the nature of the correction performed with Ziegler's technique. Tracing back the Ziegler's theory, we have found it based on uniform doping assumption and extended to the slow-varying doping distribution. Thus, it is easily understood that such problems will take place in ion-implantation profiles near the junction. For Figure 10. different impurity profiles represent that the depletion widths are changing with different V_{SB}.

The non-linear least squares method has been employed to

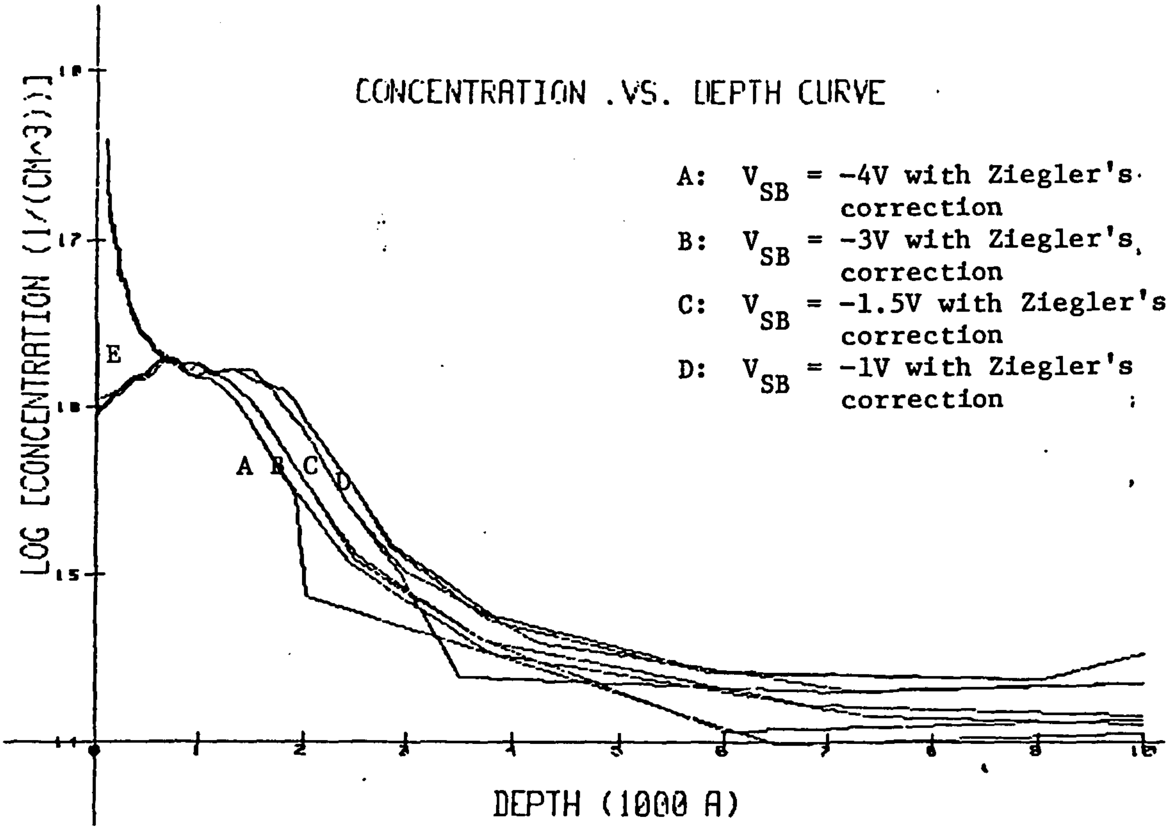


Figure 10. N-X curves with different Vsb.

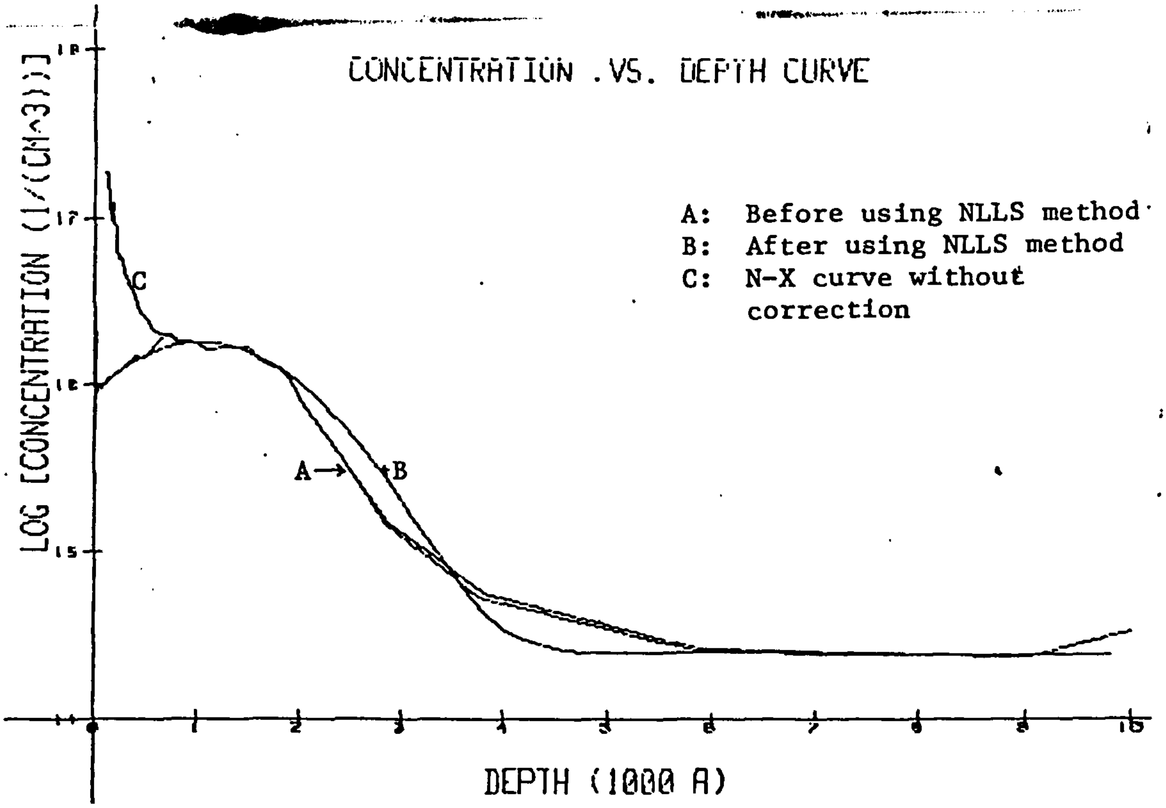


Figure 11. Curves before and after using non-least square method.

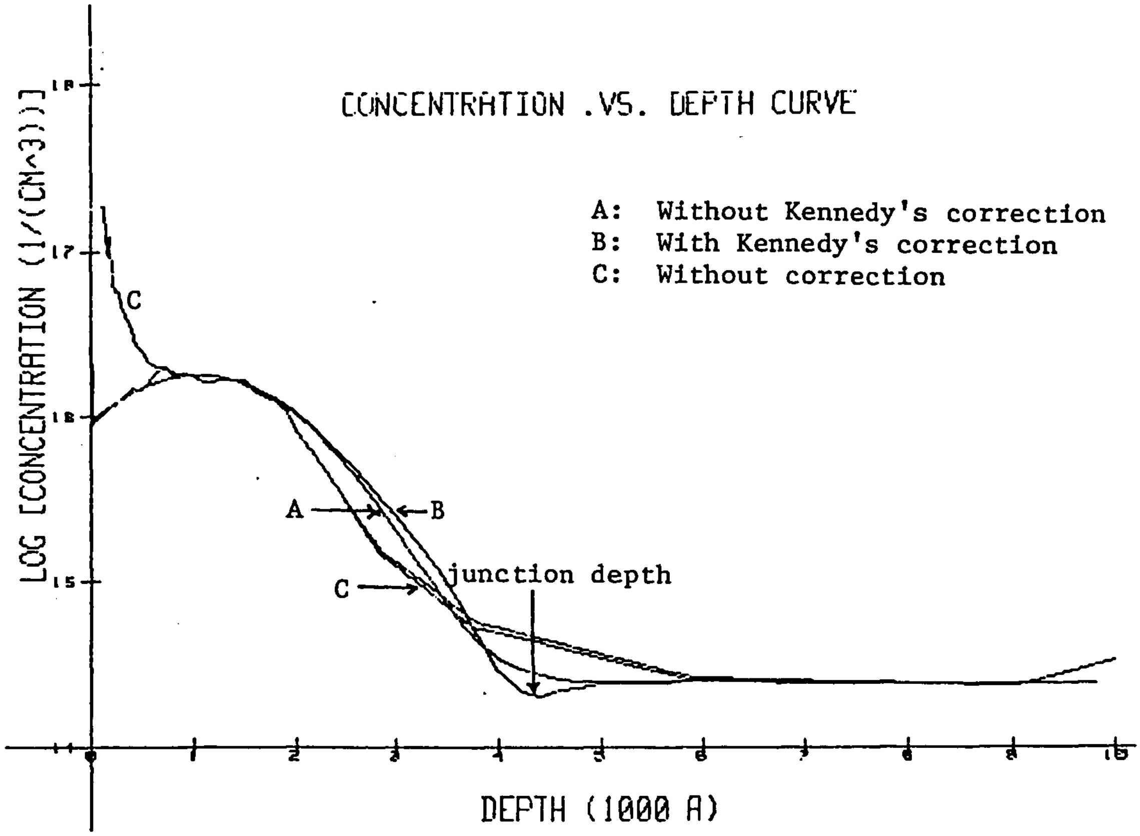


Figure 12. Curves before and after using Kennedy's correction.

extract parameters for ion-implantation profiles of the form

$$N(X) = N_o e^{-\alpha(X-X_o)^2} + N_1 e^{-\beta X} - N_B \qquad (4.1)$$

, where N_o is the peak concentration, X_o represents the range of the ion-implantation (Rp) and β is the channeling factor, N_B is the substrate doping.

The parameters with various biases has been listed on TABLE 1. Figure 11 shows the impurity profile before and after using non-linear least squares curve fitting technique. It clearly tells us that the peak concentration of the ion implantation can be accurately determined from this method within the tolerance of error [3]. It is still difficult to determine the substrate doping concentration from Figure 10, because the artifical tails obtained from C-V measurement is dependent on the biases V_{SB} [4]. The substrate doping determined from equation (4.1) from various N-X curves is around 2.E14 1/(cm**3).

Figure 12 shows the Kennedy's correction near the semiconductor junction by employing a non-linear least squares method to " curve fit ." We can roughly determine the junction depth by examining the N-X curve after correction.

TABLE 1. The parameters extracted from N-X by using non-linear least square method.

	NX1K10	NX10K10	NX1K15	NX10K15
N_0	1.80E16	1.78E16	1.79E16	1.76E16
α	66.83	71.27	69.47	69.68
X_0	0.1142	0.1137	0.1062	0.1036
N_1	4.5E14	4.7E14	4.0E14	4.5E14
β	0.01	0.01	0.01	0.01
N_B	2.E14	2.E14	2.E14	2.E14

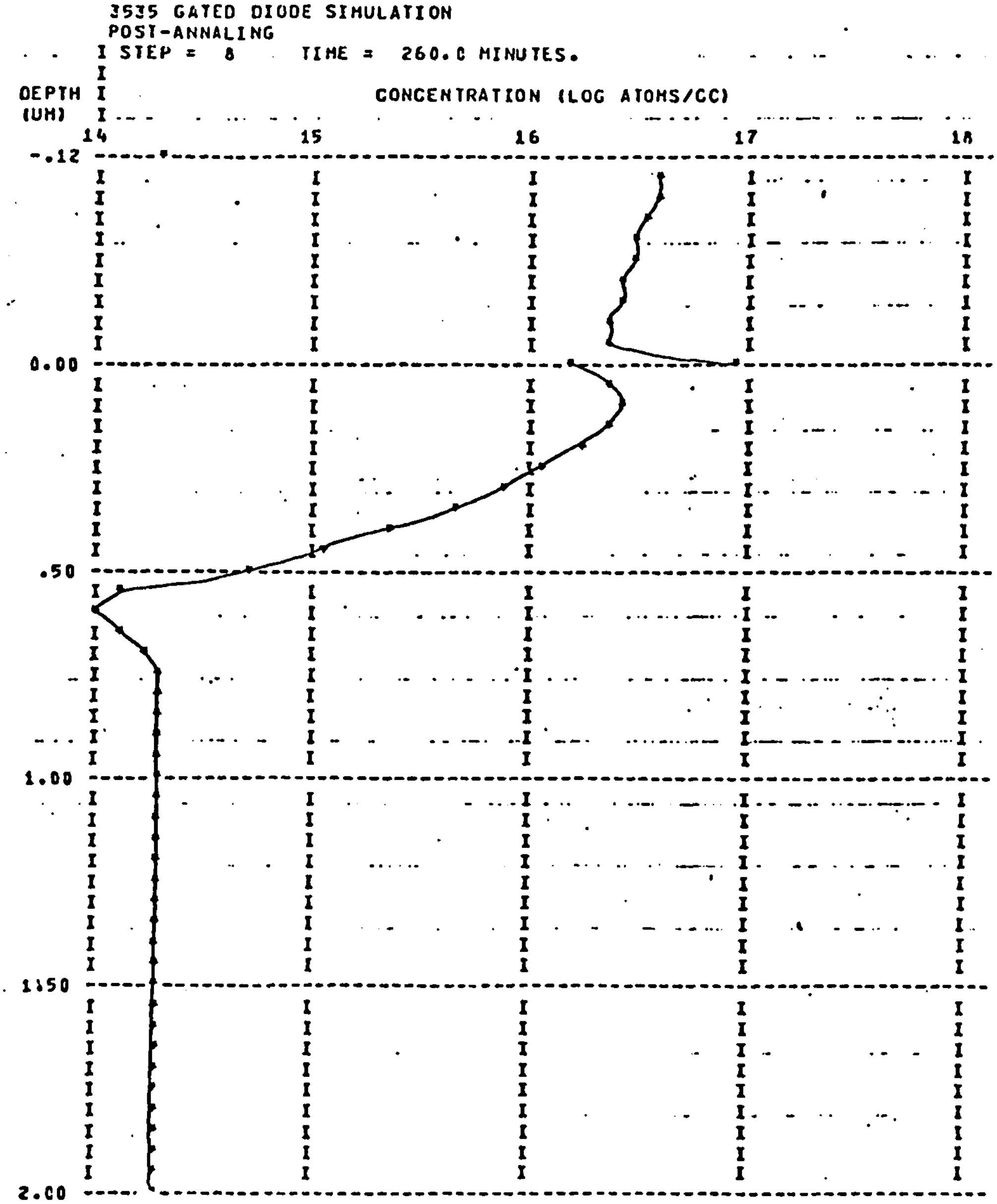


Figure 13. Results from SUPREM.

TABLE 2. The parameters extracted from N-X with corrections and from SUPREM.

	NX1K10	SUPREM	SUPREM
N_o	1.80E16	2.33E16	2.51E16
X_o	0.1142	0.1050	0.1050
N_B	2.E14	2.E15	2.E14
N_s	0.99E16	1.34E16	1.50E16
X_j	0.4300	0.4206	0.5811

4.3 Simulation results from SUPREM

Now, we can compare the impurity profiles from C-V with corrections to the impurity profiles from SUPREM, which is a complete process simulation program for modeling semiconductor devices.

The fabrication sequences for the gated diode will be shown in Appendix C. The impurity profile from SUPREM will be shown in Figure 13.

From TABLE 2, which consists of the parameters extracted from SUPREM and parameters from the non-linear least squares technique, we conclude that the parameters like the surface concentration, the peak concentration, the range of the ion implantation, and the junction depth, can be determined within the tolerance of error from both sources.

CHAPTER 5

CONCLUSIONS

Summar[illegible] leads to [illegible] following conclusions:

1. A lot of time spent on the data collection and analysis has been saved after the establishment of an automatic data acquistion system and the development of the related parameters extration computer software.

2. Some parameters extracted from corrected impurity profiles like the surface concentration, the peak concentration, the range of the ion implantation and the junction depth are comparable to the parameters obtained from SUPREM.

3. From the definition of the Debye Length, we understand it is a function of temperature. Thus, by decreasing the measurement temperature, we might obtain a more accurate doping profile close to the semiconductor surface.

4. A more accurate doping profile with taking the interface- state effects into account can be obtianed from the comparsion of the high-frequency and the low-frequency measurements [5].

Appendix A

The Derivations of Ziegler's Theory [2]

Since $C_{sc} = -\frac{dQ_{sc}}{d\psi_s} = -[\frac{dQ_{sc}}{dw}]\cdot[\frac{dw}{d\psi_s}]$, we shall first obtain $\frac{dQ_{sc}}{dw}$, and then $\frac{d\psi_s}{dw}$ in terms of N(w) or w.

From the depletion approximation, w is the width of the depletion layer defined by the equation:

$$Q_{sc} = \int_0^\infty \rho_{sc}(x,w)dx = \pm q \int_0^w N(x)dx. \qquad \text{(A-1)}$$

where Q_{sc} is the space charge per unit area, x the distance from the semiconductor surface, and $_{sc}(x,w)$ the space charge density. (+ for n-type semiconductor and - for p-type).

Differentiation of equation (4) with respect to w leads to:

$$\frac{dQ_{sc}(w)}{dw} = \int_0^\infty \frac{\partial \rho_{sc}(x,w)}{\partial w} dx = \pm qN(w) \qquad \text{(A-2)}$$

Here N(w) means the doping density N at the distance X = w.

To obtain $\frac{d\psi_s}{dw}$, we begin with Poisson's equation

$$\frac{\partial^2\psi(x,w)}{\partial x^2} = -\frac{\rho_{sc}(x,w)}{\varepsilon_s} \qquad \text{(A-3)}$$

Integrating (A-3) twice, we get

$$\psi_s(w) = -\frac{1}{\varepsilon_s}\int_\infty^0 \{\int_\infty^x \rho_{sc}(x,w)dx\}dx$$

which when differentiated with respect to w gives

$$\frac{d\psi_s(w)}{dw} = -\frac{1}{\varepsilon_s}\int_{\infty}^{o}\{\int_{\infty}^{x}\frac{\partial\rho_{sc}(x,w)}{\partial x}\,dx\}\,dx \qquad \text{(A-4)}$$

Substitution of the integration variable x by x/λ and use the relation

$$\rho_{sc}(x,w) = q[N(x) - n(x,w)] \qquad \text{(A-5)}$$

where n(x,w) is the electron concentration, in equation (7) leads to:

$$\frac{d\psi_s(w)}{(w)} = \frac{q\lambda^2}{\varepsilon_s}\int_{\infty}^{o}\{\int_{\infty}^{x/x}\frac{\partial n(x,w)}{\partial w}\,d(\frac{x}{\lambda})\}\,d(\frac{x}{\lambda}) \qquad \text{(A-6)}$$

First, we shall derive a relation for $\frac{\partial n(x,w)}{\partial w}$ in terms of N, w/λ and x/λ for uniform doping case.

For a constant doping density, equation (A-3) yields in case of $\psi_s \leq 0$, i.e. $Q_{sc} \geq 0$,

$$-\varepsilon_x = \frac{\partial\psi}{\partial x} = \frac{2kT}{q\lambda}[\exp(\frac{q\psi}{kT}) - \frac{q\psi}{kT} - 1]^{1/2} \qquad \text{(A-7)}$$

Substitution of z into (A-7)

$$z = \frac{n}{n_o} = \exp(\frac{q\psi}{kT}) \qquad \text{(A-8)}$$

and subsequent integration results in

$$\int_{\frac{n}{n_s}}^{\frac{n}{n_o}}\frac{dz}{z\sqrt{z-\ln z-1}} = 2\,\frac{x}{\lambda} \qquad \text{(A-9)}$$

where n_o is the electron concentration in bulk semiconductor and n_s is the electron concentration at semiconductor surface and

$$\lambda = \left(\frac{2kT\varepsilon_s}{q^2 N}\right)^{\frac{1}{2}} \tag{A-10}$$

From the relation $Q_{sc} = \varepsilon_s \left(\frac{\partial\psi}{\partial x}\right)\Big|_{\psi=\psi_s}$ and $Q_{sc} = qNW$, cf. equations (A-1), (A-10), (A-7) and (A-8). We obtain the following relationship between W and n_s:

$$\begin{aligned} \frac{W}{\lambda} &= \left(\frac{n_s}{n_o} - \ln \frac{n_s}{n_o} - 1\right)^{\frac{1}{2}} \\ &= (g - \ln g - 1)^{\frac{1}{2}} \end{aligned} \tag{A-11}$$

where $\frac{n_s}{n_o}$ is limited to $0 \leq g\left(\frac{n_s}{n_o}\right) \leq 1$

To obtain $\frac{\partial n(x,w)}{\partial w}$, we start from Poisson's equation (A-3) and differentiate it with respect to w:

$$\begin{aligned} \frac{\partial^2}{\partial x^2}\left(\frac{\partial\psi}{\partial w}\right) &= -\frac{1}{\varepsilon_s}\left(\frac{\partial\rho_{sc}}{\partial w}\right) \\ &= \frac{q}{\varepsilon_s}\frac{\partial n}{\partial w} \end{aligned}$$

From equation (A-8), we have:

$$\frac{\partial\psi}{\partial w} = \frac{kT}{q}\frac{\left(\frac{\partial n}{\partial w}\right)}{n}$$

Then we obtain:

$$\frac{\partial^2}{\partial x^2}\left(\frac{\left(\frac{\partial n}{\partial w}\right)}{n}\right) = \frac{q^2}{kT\varepsilon_s}\left(\frac{\partial n}{\partial w}\right) \tag{A-12}$$

Since equation (A-12) is a self-adjoint differential equation, it is clear that $y_1(x,w) = \frac{\partial n}{\partial x}(x,w)$ is one solution of equation (A-12). Assume the second solution of equation (A-12).

$$y_2(x,w) = y_1(x,w)U(x) \tag{A-13}$$

Substituting (A-13) into equation (A-12), we will obtain

$$U''(x) + \{ \frac{2n'' - \frac{2n'^2}{n}}{n'} \} U'(x) = 0 \tag{A-14}$$

Assume $u'(x) = v(x)$, equations (A-14) becomes

$$v'(x) = \{ \frac{2n'' - \frac{2n'^2}{n}}{n'} \} v(x) = 0 \tag{A-15}$$

The solution of (A-15) is $v(x) = \frac{n}{n'} = \frac{n}{(\frac{\partial n}{\partial x})}$

so $U(x) = \int_o^x v(x)dx = \int_o^x \frac{n}{(\frac{\partial n}{\partial x})} dx$

The general solution of equation (A-12) is

$y(x) = C_1 y_1(x) + C_2 y_2(x)$

Therefore

$$\frac{\partial n}{\partial w} = C_1 \frac{\partial n}{\partial x} + C_2 \frac{\partial n}{\partial x} \int_o^x \frac{n}{(\frac{\partial n}{\partial x})} dx \tag{A-16}$$

Determination of C_1 and C_2 can be obtained from the following boundary conditions:

$$\lim_{n \to \infty} \frac{\partial n(x,w)}{\partial w} = 0 \tag{A-17}$$

and $$\int_o^\infty \frac{\partial n(x,w)}{\partial w} dx = n_o \tag{A-18}$$

Using the relation $\frac{\partial n}{\partial x} = \frac{\partial n}{\partial \psi}, \frac{\partial \psi}{\partial x}$ and equations (A-7) and (A-8), we obtain

$$\frac{\frac{\partial n(x,w)}{\partial x}}{\frac{n_o}{\lambda}} = 2\,\frac{n}{n_o}\left(\frac{n}{n_o} - \ln\frac{n}{n_o} - 1\right)^{\frac{1}{2}} \qquad \text{(A-19)}$$

Therefore, from equation (A-17), we find that $C_2 = 0$ and consequently $\frac{\partial n(x,w)}{\partial w}$ has the form of $C_1 \frac{\partial n(x,w)}{\partial x}$ only. From equation (A-18) and $N = n_o$, we finally get the solution:

$$\begin{aligned} \frac{\partial n(x,w)}{\partial w} &= \frac{N}{\lambda}\, f\left(\frac{x}{\lambda}, \frac{w}{\lambda}\right) \\ &= \frac{N}{\lambda}\left(- \frac{\frac{\partial n}{\partial x}}{1 - \frac{n_s}{n_o} \cdot \frac{n_o}{\lambda}}\right) \end{aligned} \qquad \text{(A-20)}$$

Equation (A-6) will become

$$\begin{aligned} \frac{d\psi_s(w)}{w} &= - \frac{qNw}{\varepsilon_s}\, \frac{1}{1 - \left(\frac{n_s}{n_o}\right)} \\ &= - \frac{qNW}{\varepsilon_s}\, \frac{1}{1 - g\left(\frac{W}{\lambda}\right)} \end{aligned} \qquad \text{(A-21)}$$

Let us now consider the non-uniform doping density $N(x)$.

$$\frac{\partial n(x,w)}{\partial w} = \frac{N(w)}{\lambda}\, f\left(\frac{x}{\lambda}, \frac{w}{\lambda}\right)$$

Substitution of the above equation in equation (A-6) and use of equation (A-21) result in:

$$\frac{d\psi_s}{dw} = -\frac{qN(w)}{\varepsilon_s}\frac{w}{1-g(\frac{w}{\lambda})} \tag{A-22}$$

which when combined with equation (A-2) produce the desired relation for C_{sc}.

$$C_{sc} = \frac{\varepsilon_s}{w}[1-g(\frac{w}{\lambda})] \tag{A-23}$$

Equations (A-11), (A-22) and (A-23) and the relation $\frac{d}{d\psi_s}(\frac{1}{C_{sc}^2}) = \frac{d}{dw}(\frac{1}{C_{sc}^2})\frac{dw}{d\psi_s}$ lead to:

$$\frac{d}{d\psi_s}(\frac{1}{C_{sc}^2}) = -\frac{1}{\varepsilon_s qN(w)}\{\frac{1}{1-g(\frac{w}{\lambda})} - 2\frac{w^2}{\lambda^2}\frac{g(\frac{w}{\lambda})}{[1-g(\frac{w}{\lambda})]^3}\} \tag{A-24}$$

from which, and equations (A-10) and (A-23), we finally obtain:

$$g_1(\frac{w}{\lambda}) = \pm\frac{kT}{q_2}C_{sc}^2\frac{d}{d\psi_s}(\frac{1}{C_{sc}^2}) \tag{A-25}$$

$$N(w) = \pm\frac{2}{\varepsilon_s q}\frac{d}{d\psi_s}(\frac{1}{C_{sc}^2})^{-1}\cdot g_2(\frac{w}{\lambda}) \tag{A-26}$$

The functions g_1 and g_2 are given by

$$g_1(\frac{w}{\lambda}) = -\frac{2g(\frac{w}{\lambda})}{1-g(\frac{w}{\lambda})} + \frac{1-g(\frac{w}{\lambda})}{\frac{w^2}{\lambda^2}} \tag{A-27}$$

$$g_2(\frac{w}{\lambda}) = \frac{1}{1-g(\frac{w}{\lambda})}\{1 - 2\frac{w^2}{2}\frac{g(\frac{w}{\lambda})}{(1-g(\frac{w}{\lambda}))^3}\} \tag{A-28}$$

Graphs of g_2 vs g_1 and w/λ vs g_1 will be shown in Figure 14.

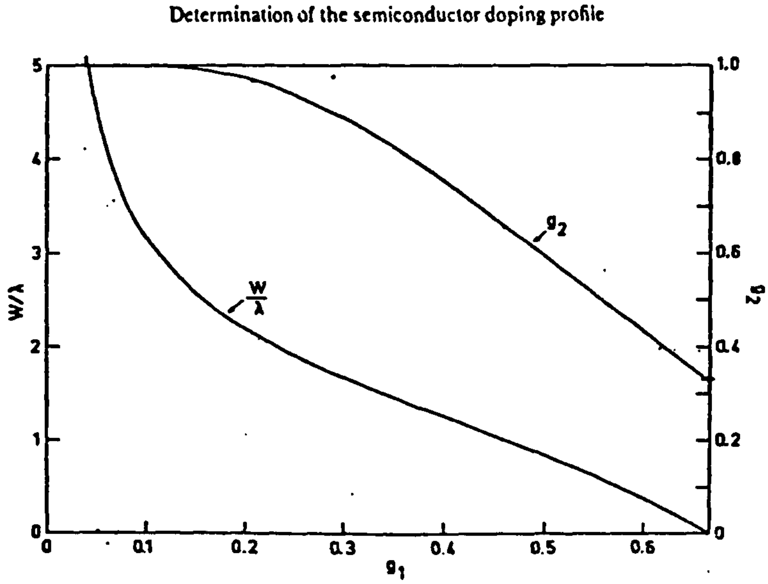
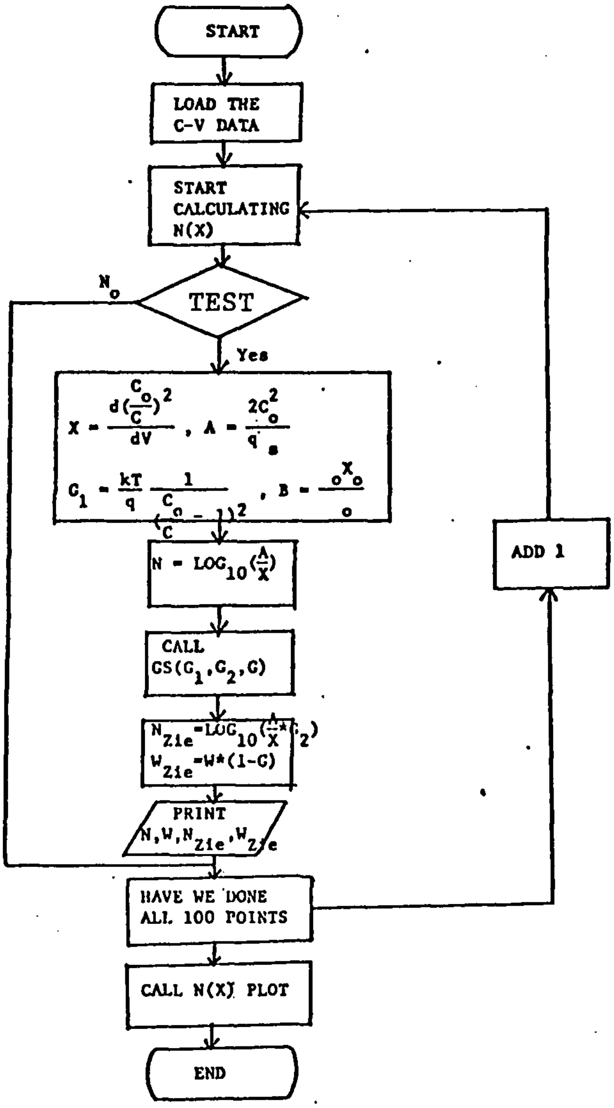


Figure 14. W/λ and g_1 vs. g_2 , of equation (A-27) , (A-28) and (A-11). [2]

Appendix B-1-1

Flowchart for Calculating and Plotting N(X) with Ziegler's Correction from C-V Data



Appendix [illegible]

```
[illegible] !**************************************************************
20      !       THIS PROGRAM CALCULATES AND PLOTS N(X) WITH ZIEGLER'S
30      !         CORRECTION FROM C-V DATA
40      !**************************************************************
50      DIM C(200),V(1000),Cn(1000),Ct(1000),W(1000),Cct(100),Cw(100),Cnt(100),Cn
(100),Ck(1000),Occt(1000),Ocw(1000),Ocnt(1000),Ocnw(1000)
60      COM /G1/ G1
70      DIM Notes$[30],Gendate$[11],Doping_type$[1],Sanple_code$[10],Data_file$[1
],File_specifier$[30],Answer$[1]
80      INTEGER High_volt,Points
90      REAL Bias_volt(1000),Capacitance(1000),Conductance(1000)
100     REAL Cap_const,Cond_const,Capac_oxide,Meas_freq
110     REAL Dev_area,V_source_bulk,Temperature
120     INPUT "ENTER DATA FILENAME:",Data_file$
130     INPUT "SPECIFY LEFT OR RIGHT HAND DRIVE",Answer$
140     IF Answer$="L" THEN
150         File_specifier$=Data_file$&":INTERNAL,4,1"
160     ELSE
170         File_specifier$=Data_file$&":INTERNAL,4,0"
180     END IF
190     !
200     !    LOAD THE C-V DATA FILE
210     !
220     ASSIGN @Path1 TO File_specifier$;FORMAT OFF
230     ENTER @Path1;Notes$
240     ENTER @Path1;Gendate$,Doping_type$
250     ENTER @Path1;High_volt,Points
260     ENTER @Path1;Bias_volt(*),Capacitance(*),Conductance(*)
270     ENTER @Path1;Tempertaure
280     ASSIGN @Path1 TO *
290       FOR J=1 TO 1000 STEP 20
300         PRINT J,Bias_volt(J),Capacitance(J)
310       NEXT J
320     PRINT "ENTER COX"
330     INPUT Cox
340     !
350     !       FLIP C-V DATA W.R.T. V
360     !
370       FOR J=1 TO 1000
380         V(1001-J)=-Bias_volt(J)
390         Cn(1001-J)=Capacitance(J)/Cox
400       NEXT J
410     Q=1.6E-19
420     Aks=11.7
430     Eo=8.86E-14
440     Ako=3.9
450     Ak=8.62E-5*Q
460     T=300
470     Akt=Ak*T
430     Vt=Akt/Q
490     Xo=1.25E-5
500     Co=Ako*Eo/Xo
510     A=2*(Co*Co)/(Q*Aks*Eo)
520     B=Aks*Xo/Ako
530     PRINT "ENTER JMAX"
540     INPUT Jmax
550     PRINT "ENTER JSTEP"
560     INPUT Jstep
570     !
580     !       START CALCULATING N(X)
```

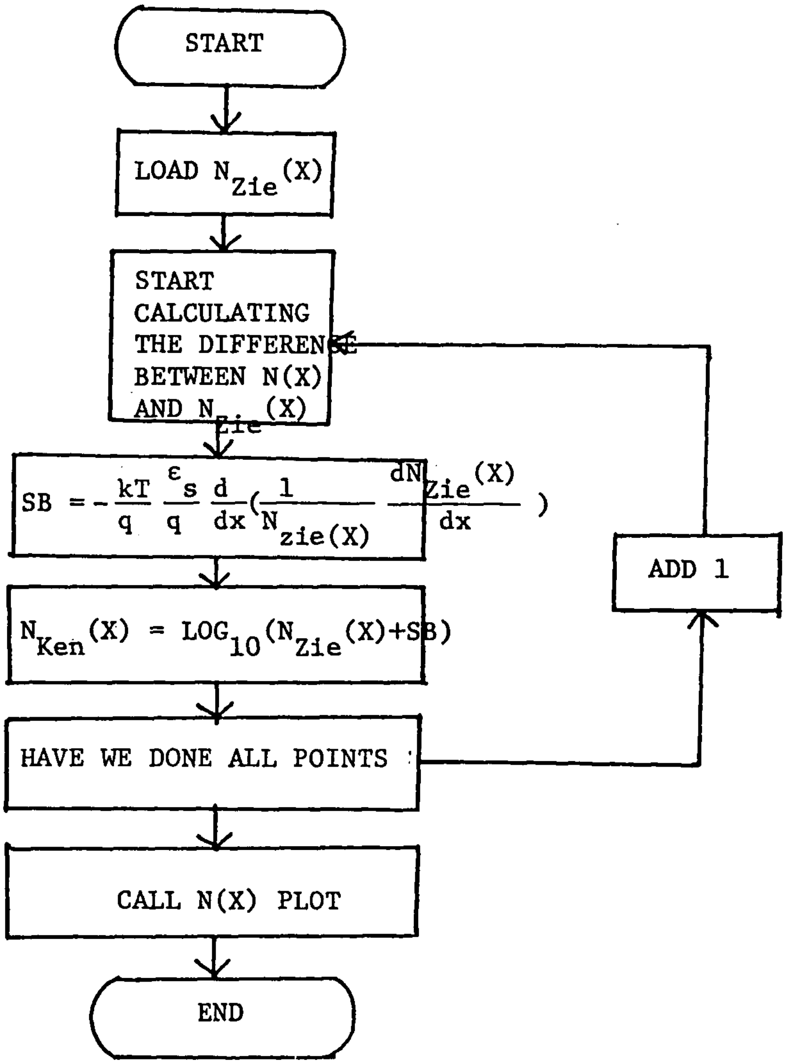
```
590    !
600    FOR J=99 TO Jmax STEP Jstep
610        IF (Cn(J+Jstep)-Cn(J-Jstep))<0 THEN GOTO 950
620      X=(1/(Cn(J+Jstep)*Cn(J+Jstep))-1/(Cn(J-Jstep)*Cn(J-Jstep)))/(V(J+Jstep)-
V(J-Jstep))
630      G1=Vt/((1/Cn(J)-1)^2)*X
640      Ca=A/X
650      !
660      !     N(X) WITHOUT CORRECTION
670      !
680      Ocnt(J)=LGT(A/X)
690      Ocnw(J)=B*(1/Cn(J)-1)*1.E+8
700      !
710      !     COMPARISION BETWEEN X AND 2*LD(LD2)
720      !
730      Ld2=2*SQR(2*Vt*Aks*Eo/(Q*Ca))*1.E+8
740        IF (Ocnw(J))=Ld2) THEN GOTO 930
750          PRINT J,X,Ocnw(J),Ld2
760      !
770      !  CALL CORRECTION TERMS
780      !
790      CALL Gs(G11,G2,G)
800          PRINT J,X,G1,G11,G2,G
810        IF (G2<=.33) THEN GOTO 900
820      !
830      !      N(X) WITH ZIEGLER'S CORRECTION
840      !
850      Ct(J)=A*G2/X
860      W(J)=B*(1/Cn(J)-1)*(1-G)
870      Occt(J)=LGT(Ct(J))
880      Ocw(J)=1.E+8*W(J)
890      GOTO 950
900      Ocw(J)=1.E+8*B*(1/Cn(J)-1)*(1-G)
910      Occt(J)=LGT(A*.33/X)
920      GOTO 950
930      Occt(J)=Ocnt(J)
940      Ocw(J)=Ocnw(J)
950    NEXT J
960    FOR J=499 TO Jmax STEP Jstep
970      PRINT J,Occt(J),Ocw(J),Ocnt(J),Ocnw(J)
980    NEXT J
990    !
1000   !  REDUCE DATA BY FACTOR JSTEP
1010   !
1020   FOR J=99 TO Jmax STEP Jstep
1030     Y=INT((J+1)/Jstep)
1040     Cct(Y)=Occt(J)
1050     Cw(Y)=Ocw(J)
1060     Cnt(Y)=Ocnt(J)
1070     Cnw(Y)=Ocnw(J)
1080   NEXT J
1090   FOR I=1 TO 100
1100     PRINT I,Cct(I),Cw(I),Cnt(I),Cnw(I)
1110   NEXT I
1120   !
1130   !  PLOT N(X) WITH AND WITHOUT CORRECTION
1140   !
1150   CALL Nvsx(0,1.E+4,Nb,300,Cct(*),Cw(*),100)
1160   CALL Nvsx(0,1.E+4,Nb,300,Cnt(*),Cnw(*),100)
1170   !
1180   !   SAVE N(X) DATA
```

```
1190  !
1200  PRINT "TYPE Y IF YOU WANT TO STORE THIS DATA"
1210  PRINT "TYPE N OTHERWISE"
1220  INPUT M$
1230  IF M$="N" THEN 1300
1240  PRINT "ENTER FILE NAME OF THE IMPURITY PROFILE"
1250  INPUT N$
1260  CREATE BDAT N$,1,3300
1270  ASSIGN @Path2 TO N$;FORMAT OFF
1280  OUTPUT @Path2;Cct(*),Cw(*),Cnt(*),Cnw(*)
1290  ASSIGN @Path2 TO *
1300  END
1310  !**************************************************************************
1320  !       SUBROUTINE FOR PLOTTING N(X) CURVE
1330  !**************************************************************************
1340  SUB Nvsx(Xmin,Xmax,Nb,Temp,Concentration(*),Depth(*),Points)
1350  !
1360  !   Plotting subroutine for N(X) CURVE
1370  !
1380  !   Initialization
1390  DEG
1400  WINDOW Xmin-850,Xmax+200,13.5,18.5
1410  CSIZE 5,.4
1420  LORG 6
1430  !
1440  !   Title of graph
1450  !
1460  MOVE (Xmax+Xmin)/2,18
1470  LABEL "CONCENTRATION .VS. DEPTH CURVE"
1480  !
1490  !    Label axes
1500  !
1510  LORG 4
1520  MOVE (Xmax+Xmin)/2,13.5
1530  LABEL "DEPTH (1000 A)"
1540  LDIR 90
1550  LORG 6
1560  MOVE Xmin-750,16.5
1570  LABEL "LOG [CONCENTRATION (1/(CM^3))]"
1580  !
1590  !   Number axes
1600  !
1610  LDIR 0
1620  CSIZE 2,.8
1630  LORG 6
1640  FOR I=Xmin TO Xmax STEP 1000
1650     MOVE I,14
1660     LABEL I/1000
1670  NEXT I
1680  !
1690  LORG 8
1700  FOR I=14 TO 18 STEP 1
1710     MOVE 0,I
1720     LABEL I
1730  NEXT I
1740  Loux=9.E+39
1750  FOR I=1 TO Points
1760      IF Depth(I)<Loux AND Depth(I)>0 THEN
1770         Loux=Depth(I)
1780      END IF
1790  NEXT I
```

```
1800  !
1810  !    Draw axes and plot data points
1820  !
1830  AXES 1000,1,0,14,1,1
1840  CLIP Xmin,Xmax,13,18
1850  FOR I=1 TO Points
1860     IF Depth(I)=0 AND Concentration(I)=0 THEN GOTO 1880
1870     PLOT Depth(I),Concentration(I),+1
1880  NEXT I
1890  CLIP OFF
1900  SUBEND
1910  !*******************************************************************
1920  !       SUBROUTINE FOR CALCULATING CORRECTION TERMS G1,G2 AND G
1930  !*******************************************************************
1940  SUB Gs(G11,G2,G)
1950  COM /G1/ G1
1960  Dg=.001
1970  G=.001
1980  FOR I=1 TO 1000
1990  IF G=1 THEN GOTO 2180
2000  IF G<=0 THEN GOTO 2180
2010  !
2020  !      USE NEWTON-RAPHSON METHOD TO SOLVE G
2030  !
2040  F=(1-G)/(G-LOG(G)-1+.001)-2*G/(1-G)-G1
2050  Fp=(-1+1/G+LOG(G))/((G-LOG(G)-1+.001)^2)-2/((1-G)^2)
2060  Newg=G-F/Fp
2070  IF ABS(G-Newg)<1.E-2 THEN GOTO 2090
2080  GOTO 2170
2090  G=Newg
2100  G11=G1
2110  IF G11>=.7 THEN GOTO 2190
2120  !
2130  !     CALCULATE G2
2140  !
2150  G2=ABS(G1/(2*G+(1-G)*G1))
2160  GOTO 2190
2170  G=G+Dg
2180  NEXT I
2190  SUBEND
```

Appendix B-2-1

Flowchart for Calculating and Plotting N(X) with Kennedy's Correction



Appendix B-2

```
10     !*****************************************************************
20     !       THIS PROGRAM CALCULATES AND PLOTS N(X) WITH KENNEDY'S
30     !         CORRECTION NEAR THE JUNCTION
40     !*****************************************************************
50     DIM Cct(200),Cw(200),Cnt(200),Cnw(200),A(100),Y(100),B(100),T(100),S(100)
60     REAL Beta(10)
70     !
80     !   LOAD N(X) DADA FILE
90     !
100    PRINT "ENTER FILE NAME OF THE IMPURITY PROFILE"
110    INPUT X$
120    ASSIGN @Path1 TO X$;FORMAT OFF
130    ENTER @Path1;Temp,Area,Vsb,Cct(*),Cw(*),Cnt(*),Cnw(*)
140    ASSIGN @Path1 TO *
150    !
160    !   ENTER PARATERS EXTRACTED FROM NON-LINEAR LEAST SOUARE METHOD
170    !
180    PRINT "ENTER # OF PARAMETERS"
190    INPUT K
200    PRINT "ENTER PARMETERS SEQUENTIALY"
210      FOR J=1 TO K
220        INPUT Beta(J)
230      NEXT J
240    Dx=.02
250    X=0
260    FOR I=1 TO 50
270      A(I)=X
280      Z1=Beta(1)*EXP(-Beta(2)*((X-Beta(3))^2))
290      Z2=Beta(4)*EXP(-Beta(5)*X)
300      Z3=Beta(6)
310      !
320      !  DEFINE FUNCTION FOR PLOT USE
330      !
340      Z=Z1+Z2-Z3
350      !
360      !  TAKE THE DIFFERENCE BETWEEN N(X) AND n(X)
370      !
380      Zx=(Z*(Z1/Beta(1)*(1-Beta(2)*((X-Beta(3))^2))+(Beta(5)^2)*Z2)-(Beta(2)
X-Beta(3))*Z1+Beta(5)*Z2)*(Beta(2)*Z1+Beta(5)*Z2))/(Z^2)
390      Zc=(8.62E-5*1.6E-19*300*8.86E-14)/((1.6E-19)^2)
400      Dz=Zc*Zx*1.E+8
410      Sa=-(((2*Beta(2)*(X-Beta(3))*Z1+Beta(5)*Z2)/Z)^2)+(Z1*(-2*Beta(2)+2*(B
a(2)^2)*((X-Beta(3))^2))+(Beta(5)^2)*Z2)/Z
420      Sb=-Zc*Sa*1.E+8
430      S(I)=LGT(ABS(Z+Sb))
440      T(I)=LGT(ABS(Z-Dz))
450      Y(I)=LGT(ABS(Z))
460      B(I)=A(I)*1.E+4
470      PRINT B(I),Y(I),S(I),Sb
480      X=X+Dx
490    NEXT I
500    PAUSE
510    !
520    !  PLOT N(X) CURVES WITH AND WITHOUT KENNEDY'S CORRECTION
530    !
540    CALL Nvsx(0,1.E+4,Nb,300,Cct(*),Cw(*),200)
550    CALL Nvsx(0,1.E+4,Nb,300,Cnt(*),Cnw(*),200)
560    CALL Nvsx(0,1.E+4,Nb,300,Y(*),B(*),50)
570    CALL Nvsx(0,1.E+4,Nb,300,S(*),B(*),50)
580    END
590    !*****************************************************************
```

```
600    !     SUBROUTINE FOR PLOTTING N(X) CURVE
610    !****************************************************************************
620    SUB Nvsx(Xmin,Xmax,Nb,Temp,Concentration(*),Depth(*),Points)
630    !
640    !    Plotting subroutine for N(X) CURVE
650    !
660    !    Initialization
670    DEG
680    WINDOW Xmin-850,Xmax+200,13.5,18.5
690    CSIZE 5,.4
700    LORG 6
710    !
720    !    Title of graph
730    !
740    MOVE (Xmax+Xmin)/2,18
750    LABEL "CONCENTRATION .VS. DEPTH CURVE"
760    !
770    !     Label axes
780    !
790    LORG 4
800    MOVE (Xmax+Xmin)/2,13.5
810    LABEL "DEPTH (1000 A)"
820    LDIR 90
830    LORG 6
840    MOVE Xmin-780,16.5
850    LABEL "LOG [CONCENTRATION (1/(CM^3))]"
860    !
870    !    Number axes
880    !
890    LDIR 0
900    CSIZE 2,.8
910    LORG 6
920    FOR I=Xmin TO Xmax STEP 1000
930       MOVE I,14
940       LABEL I/1000
950    NEXT I
960    !
970    LORG 8
980    FOR I=14 TO 18 STEP 1
990       MOVE 0,I
1000      LABEL I
1010   NEXT I
1020   Lowx=9.E+39
1030   FOR I=1 TO Points
1040        IF Depth(I)<Lowx AND Depth(I)>0 THEN
1050           Lowx=Depth(I)
1060        END IF
1070   NEXT I
1080   !
1090   !    Draw axes and plot data points
1100   !
1110   AXES 1000,1,0,14,1,1
1120   CLIP Xmin,Xmax,13,18
1130   FOR I=1 TO Points
1140      IF Depth(I)=0 AND Concentration(I)=0 THEN GOTO 1160
1150      PLOT Depth(I),Concentration(I),+1
1160   NEXT I
1170   CLIP OFF
1180   SUBEND
```

APPENDIX C

```
*** STANFORD UNIVERSITY PROCESS ENGINEERING MODELS PROGRAM ***

                      *** VERSION 0-03 ***

 1....TITL 3535 GATED DIODE SIMULATION
 2....GRID DYSI=0.005, DPTH=0.6, YMAX=2.5
 3....SUBS ORNT=100, ELEM=-, CONC=2.E14
 4....PLOT TOTL=Y, CMIN=14, NDEC=4, WIND=2
 5....PRINT TOTL=Y, HEAD=Y
 6....COMM GROWING IMPLANT OXIDE
 7....MODEL NAME=SPM1
 8....STEP TYPE=DEPO, TIME=1, GRTE=0.076
 9....COMM P-LAYER IMPLANT
10....STEP TYPE=IMPL, ELEM=B, DOSE=1.25E12, AKEV=40, MODL=SPM1
11....PLOT TOTL=Y
12....STEP TYPE=DEPO, TIME=20, GRTE=0.05
13....STEP TYPE=OXID, TEMP=1050, TIME=30,  MODL=NITO, MODL=SPM1
14....COMM STRIPING OXIDE
15....STEP TYPE=ETCH, TEMP=25
16....COMM GROWING GATE OXIDE
17....STEP TYPE=OXID, TEMP=900, TIME=60, MODL=WETO, MODL=SPM1
18....STEP TYPE=OXID, TEMP=900, TIME=15, MODL=NITO, MODL=SPM1
19....PLOT TOTL=Y
20....COMM POST-ANNALING
21....STEP TYPE=OXIDE, TEMP=900, TIME=260, MODL=NITO, MODL=SPM1
22....PLOT TOTL=Y
23....END
```

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VITA

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