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Method for Determination of Charge Density Distribution in Silicon Nitride of MNOS Structures[2])

By

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A method of measuring the charge density distribution in the nitride layer of MNOS structures (metal–nitride–oxide–semiconductor) is described. The method is based on measurements of the flat-band voltage, or alternatively the threshold voltage as functions of the nitride layer thickness. The basic equations describing the charge distribution in the nitride layer of the MNOS structure are derived. A method of measuring the combined charge stored in the oxide and the surface states is given. It is shown that the method presented 1) is insensitive to an accidental surface charge, which can originate after each successive etching of the nitride, 2) may be used with normally-on as well as normally-off MNOS structures, 3) yields measurement results which are fully verifiable. In addition, the weak points of the charge profile measurements in the Si_3N_4 layer of MNOS structures using the method described in a previous paper are indicated.

Es wird eine Methode zur Messung der Ladungsdichteverteilung in der Nitridschicht von MNOS-Strukturen (Metall–Nitrid–Oxid–Halbleiter) angegeben. Die Methode beruht auf Messungen der Flachbandspannung, oder alternativ der Schwellspannung in Abhängigkeit von der Dicke der Nitridschicht. Die Grundgleichungen, die die Ladungsverteilung in der Nitridschicht beschreiben, werden abgeleitet. Eine Methode zur Messung der im Oxid und den Oberflächenzuständen gespeicherten kombinierten Ladung wird ebenfalls angegeben. Es wird gezeigt, daß die dargelegte Methode 1. unempfindlich gegenüber zufälligen Oberflächenladungen ist, die nach jeder aufeinanderfolgenden Ätzung des Nitrids auftreten können, 2. sowohl bei normalerweise „on"- als auch bei normalerweise „off"-MNOS-Strukturen benutzt werden kann und 3. Meßergebnisse liefert, die vollständig korrekt sind. Zusätzlich werden einige schwache Punkte der Ladungsprofilmessungen in der Si_3N_4-Schicht von MNOS-Strukturen nach der in einer früheren Arbeit beschriebenen Methode aufgezeigt.

1. Introduction

The distribution of electrical charge, $\rho_n(x)$, in the Si_3N_4 layer of MNOS transistors is one of the main problems in the theory of operation of MNOS devices. The functional parameters of MNOS semiconductor memory depend on the charge distribution. The charge centroid measurements [5 to 8] do not solve this problem.

Recently, Endo [1] has presented a paper on the method of measurement of the charge density distribution in the Si_3N_4 layer of MNOS transistors. The dependence of channel conductance of a NOS (nitride–oxide–semiconductor) structure with a floating gate, on the Si_3N_4 layer thickness, x, was measured step-by-step, while successive etching of the nitride layer was in progress.

The main disadvantage of Endo's method is its sensitivity to an accidental surface charge on the Si_3N_4 layer, which can originate after each successive etching of the nitride (see Section 2).

Another disadvantage of the method proposed in [1] for measuring the distribution of electrical charge, $\varrho_n(x)$, in the Si_3N_4 layer is the fact that it can only be used for MNOS structures with a normally-on channel. This is a serious limitation, since the method cannot be used to measure the charge distribution in MNOS structures with an arbitrary substrate (n- or p-type), or an arbitrary charge polarity in the Si_3N_4 layer, e.g. n-type substrate and positive charge in the Si_3N_4.

The current paper concentrates on problems relating to the electrical charge distribution measurements in the Si_3N_4 layer, using the method presented in [1]. It is shown that in order to eliminate the influence of the surface charge on the measurements of $\varrho_n(x)$, the measurements should be performed on MNOS structures with a non-floating gate (the gate must be polarized with respect to the MNOS structure substrate using a voltage source). Next, the basic equations describing the charge distribution, $\varrho_n(x)$, in the Si_3N_4 are derived. The derived equations indicate that the charge density, $\varrho_n(x)$, can be obtained by measuring one of two parameters: (i) $V_{FB}(x)$ the flat-band voltage or (ii) $V_T(x)$ the threshold voltage as functions of the silicon nitride thickness of the MNOS structure.

The method of measuring $\varrho_n(x)$, presented in this paper, is immune to an accidental charge on the surface of the Si_3N_4 layer, and may be used with normally-off MNOS structures.

2. The Problems of Determining $\varrho_n(x)$

There are a few weak points in the method [1] of determining the charge distribution in Si_3N_4 using floating gate MNOS transistors (strictly, nitride–oxide–semiconductor structures). The problems related to the use of this method for measuring the charge distribution can be observed in [1].

Endo [1] in his work states that his results are derived with the assumption that source-drain conductance, G_0, of the MNOS transistor (triode region, channel normally-on) without gate electrode is given by the equation

$$G_0 = \frac{W}{L} \mu_n C_i \left(-V_{fb0} - 2\varphi_{Fp} + \frac{Q_{B,0}}{C_i} \right),$$ (1)

where

$$V_{fb0} = -\frac{1}{C_i} \int_0^l \varrho_n(x)\, dx,$$ (2)

$$Q_{B,0} = -\sqrt{2\varepsilon_s q N_A (2\varphi_{Fp})},$$ (3)

where W is the channel width, L the channel length, $Q_{B,0}$ the charge per unit area within the surface depletion region at the onset of strong inversion, l the thickness of the gate insulator, C_i the capacitance of the gate insulator, φ_{Fp} the bulk Fermi potential for p-type semiconductor, N_A the concentration of acceptor impurities, μ_n the electron mobility (see Section 2 in [1]). Paper [1] states that " the differentiation of (1) with respect to gate insulator thickness, l, leads to the relation between the derivative of the conductance with respect to the thickness, l, and the charge density in the insulator as given by the following equation:

$$\frac{dG_0}{dl} = \frac{W}{L} \mu_n \varrho_n(l'').$$ (4)

One ought to note that a) the assumption about the validity of (1) is false and b) (4) does not follow from (1), even though it can be shown that (4) is valid.

The experimental verification of (1) performed by Endo (see Section 4.1 of this work) has a number of weak points. For example, to calculate the drain-source conductance, G_0, of the MNOS structure with aluminium gate the author of [1] used the following formula for the flat-band voltage:

$$V_{\text{FB}} = -\varphi_{\text{ms}} - \frac{1}{C_1} \int\limits_0^l \frac{l-x}{l}\, \varrho(x)\, dx ,\tag{5}$$

where φ_{ms} is the metal–semiconductor work function difference. Formula (5) is not correct since it does not take into account the charge in the oxide, $\varrho_{\text{ox}}(x)$, different values of dielectric constants of the oxide and nitride, or the surface state charge Q_{ss}. The charge Q_{ox} (8 a), because of its localization relative to the gate electrode, has a decisive influence on the value of the threshold voltage of the MNOS structure. Therefore, the experimental proof of (1) — carried out by Endo — is meaningless.

The fallacy of (1) can be shown using the following reasoning. When the gate electrode of the transistor in the normally-on state is removed, so that the gate is floating, the conductance, G_0, must be a function only of the charge stored in the insulator. This follows from the Gauss law. But according to (1) the value of G_0 is a function not only of the gate insulator charge, but also a function of $C_1(l)$, through the factor $2\varphi_{\text{Fp}}$. This of course cannot be the case, since it would imply that deposition of an additional Si_3N_4 layer with no electrical charge would change the value of G_0, a fact which could not be explained physically, since it would contradict the Gauss law.

Furthermore, (4) cannot be obtained as a result of differentiating (1) with respect to the gate insulator thickness, l, because G_0 is a function not only of V_{FbO} (equation (2)) but also of $C_1(l)$.

The correct form of the equation determining the small-signal source-drain conductance of the transistor without gate electrode can be derived subject to the following assumptions:

(i) The measuring signal is so small that it does not upset the state of thermodynamic equilibrium.

(ii) The charge in the insulator is uniformly distributed in the yz plane.

(iii) The condition of electrical neutrality is satisfied,

$$Q_{\text{ins}} + Q_s = 0 .\tag{6}$$

(iv) The semiconductor is non-degenerate.

(v) The impurities in the semiconductor are ionized at room temperature.

(vi) The channel of the structure is formed in the form of an inverse layer, semiconductor surface potential, $\varphi_s \geq 2\varphi_{\text{Fp}}$ (the subthreshold region of the transistor is not considered, the basic current in the channel is the drift current).

Using assumptions (i) to (vi), for the structure shown in Fig. 1, the following expression for the conductance G_0 [3, 4] can be written:

$$G_0 = -\frac{W}{L}\, \mu_{\text{n}}\, [Q_s - Q_{\text{B,o}}] ,\tag{7}$$

where $Q_{\text{B,o}}$ is given by (3), Q_s is the charge in the semiconductor, and $|Q_s - Q_{\text{B,o}}|$ is the charge density per unit area due to mobile carriers in the inversion layer. Using
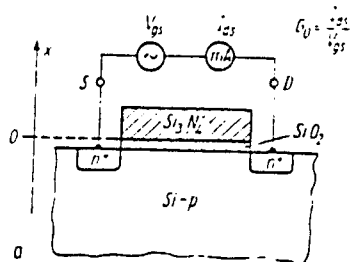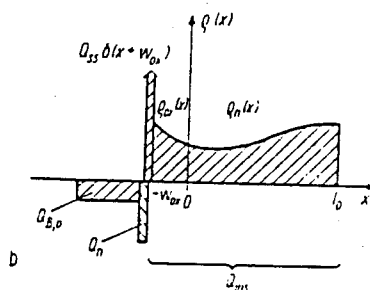
Fig. 1. Illustration of the method with floating gate [1].
a) Measurement circuit. b) Charge distribution in the nitride-oxide-semiconductor structure; normally-on state. c) Band bending in the semiconductor

the Gauss law (see Fig. 1 b),

$$Q_s = -\left[Q_{ox} + \int_0^l \varrho_n(x)\, dx\right] \tag{8}$$

and

$$Q_{ox} = \int_{-w_{ox}}^0 [Q_{ss}\delta(x + w_{ox}) + \varrho_{ox}(x)]\, dx$$

$$= Q_{ss} + \int_{-w_{ox}}^0 \varrho_{ox}(x)\, dx \tag{8a}$$

(w_{ox} is the oxide layer thickness). Combining (7) and (8),

$$G_0 = \frac{W}{L}\,\mu_n \left[\int_0^l \varrho_n(x)\, dx + Q_{ox} - \sqrt{2\varepsilon_s q N_A(2q\,_{Fp})}\right]; \tag{9}$$

of course (9) is valid only if

$$\int_0^l \varrho_n(x)\, dx + Q_{ox} \geqq \sqrt{2\varepsilon_s q N_A(2q\,_{Fp})}, \tag{10}$$

i.e. when the magnitude of the charge stored in the insulator (oxide — nitride), Q_{ins}, is sufficient to induce a strong inversion state in the semiconductor.

True, the differentiation of (9) with respect to the nitride thickness, l, leads to the relation between the derivative of the conductance with respect to the thickness l and the charge density in the nitride as given by (4),

$$\frac{dG_0}{dl} = \frac{W}{L}\,\mu_n\varrho_n(l). \tag{11}$$

However, (11) does not follow from (1) as was stated in [1]. In addition, using the derived equation (9) the following weak points of the method presented in [1] can be singled out:

a) The method of determining the charge distribution in the nitride using floating gate has the property that the value of the measured conductance, G_0, for two dif-

ferent charge profiles, $\varrho_1(x)$ and $\varrho_2(x)$, is the same if the following relation holds:

$$\int_{-w_{ox}}^{l} \varrho_1(x)\,dx = \int_{-w_{ox}}^{l} \varrho_2(x)\,dx\,. \tag{12}$$

This means that the value of G_0 is a function of the "global" charge trapped in the gate isolator ($SiO_2 + Si_3N_4$). In particular it means that the charge of any plane $x \in [-w_{ox}, l]$ or on the Si_3N_4 surface ($x = l$) has the same influence on the value of the conductance G_0. Thus, the method with a floating gate [1] is sensitive to an accidental charge on the Si_3N_4 surface, which can originate after each step of etching of the nitride.

b) A serious defect of Endo's method [1] is the fact that it can only be applied to MNOS structures with a normally-on channel, and even then with a certain restriction. The restriction concerns the change of the operating region of the transistor caused by successive etching of the Si_3N_4 layer. During this process the insulator charge $\left(= \left|\int_0^l \varrho_n(x)\,dx\right| \right)$ decreases because of the decrease in l. This means that for $l \to 0$ assumption (vi) and condition (10) may not be satisfied. If relation (10) does not hold, neither do equations (9) and (11). In this case the calculation of the charge distribution in Si_3N_4 using (11) involves a considerable error. Physically, condition (10) means that during the measurements of G_0 a strong inversion must occur on the surface of the semiconductor for every value of l. Only then the change of the insulator charge, caused by the etching away of a part of the Si_3N_4 layer, causes an identical change of the inverse layer charge, $|\Delta Q_n| = |\Delta Q_{ins}|$ [2 to 4]. If relation (10) is not satisfied, then the change of Q_n (Q_n charge due to electrons in the inversion layer) is smaller than the change that caused it, namely $Q_{nitride}$, that is, $|\Delta Q_n| < |\Delta Q_{nitride}|$ [2, 4]. Then G_0 is a nonlinear function $\int_0^l \varrho_n(x)\,dx$ [2], and the charge distribution $\varrho_n(x)$ cannot be calculated using (11). Therefore, for large l relation (10) is not a sufficient condition for assuring the validity of (9) and (11) through the entire range of the measured conductances $G_0(x)$; $x \in [0, l]$. In addition, on the basis of the measuring procedure described in [1] it is impossible to say whether relation (10) holds or not, especially for $l \to 0$. To solve this problem, the following values must be known (see relation (10)): $Q_{ss} + \int_{-w_{ox}}^{l} \varrho_{ox}(x)\,dx$ (equation (8a)) and Q_{acc} (Q_{acc} accidental charge on nitride surface) (see Section 4.2). These values cannot be measured using Endo's method.

3. The Method with a Non-Floating Gate. Derivation of Basic Equations

The method of measuring the electric charge distribution in the Si_3N_4 layer of an MNOS structure, presented in this paper, is based on measurements of the basic functional parameters of the MNOS structure, namely the flat-band voltage and the threshold voltage, as functions of the nitride layer thickness. In an instrumental sense, the method depends on successive etchings of the Si_3N_4 layer, and the measurements of the flat-band voltage or alternatively the threshold voltage of the MNOS structures. Of course, during these measurements the MNOS gate is conducting, and polarized with respect to the substrate with an applied voltage, i.e. it is non-floating. This method, as well as Endo's method [1], is based upon the following assumption: the etching of the Si_3N_4 and the measurement of $V_{FB}(x)$ or $V_T(x)$ do not disturb the insulator charge distribution, i.e. during the measurements Q_{ss}, $\varrho_{ox}(x)$, and $\varrho_n(x)$ do not change.

To determine the charge density distribution $\varrho_n(x)$ in the Si_3N_4 layer of the MNOS structure, knowing the flat-band voltage $V_{FB}(x)$ or the threshold voltage $V_T(x)$ as functions of x, it is necessary to solve a first-kind Volterra integral equation.

3.1 Determining $\varrho_n(x)$ on the basis of $V_{FB}(x)$ measurements

Let us consider the flat-band voltage, $V_{FB}(x)$, of an MNOS structure as a function of nitride layer thickness x (see equation (A17)),

$$V_{FB}(x) = \varphi_{ms} - \frac{1}{\varepsilon_n}\left\{ \int_0^x (x - \xi)\,\varrho_n(\xi)\,d\xi + \int_{-w_{ox}}^0 (x - \gamma\xi)\varrho_{ox}(\xi)\,d\xi + (x + \gamma\omega_{ox})Q_{ss}\right\}.$$

$$(13)$$

Equation (13) can be rewritten in the form

$$\int_0^x (x - \xi)\,\varrho_n(\xi)\,d\xi = f_{FB}(x),$$

$$(14)$$

where

$$f_{FB}(x) = \varepsilon_n\varphi_{ms} - \varepsilon_n V_{FB}(x) - \int_{-w_{ox}}^0 (x - \gamma\xi)\,\varrho_{ox}(\xi)\,d\xi - (x + \gamma w_{ox})Q_{ss},$$

$$(15)$$

$\varepsilon_n, \varepsilon_{ox}, \varepsilon_s$ absolute permittivity of Si_3N_4, SiO_2, and semiconductor, respectively, and $\gamma = \varepsilon_n/\varepsilon_{ox}$. Let us assume that $f_{FB}(x)$ is a function having a continuous second derivative. Moreover, the function (15) has to satisfy the condition

$$f_{FB}(0) = 0$$

$$(16)$$

which is neccessary to obtain the solution of (14). Substituting $x = 0$ into (15) we can see that condition (16) is satisfied. We should observe that $-\varepsilon_n V_{FB}(0) = -\varepsilon_n V_{FB}^{MOS}$ and $\varepsilon_n\varphi_{ms} + \gamma \int_{-w_{ox}}^0 \xi\varrho_{ox}(\xi)\,d\xi - \gamma w_{ox}Q_{ss} = \varepsilon_n V_{FB}^{MOS}$ (see A15).

Equation (14) can be solved by differentiating it twice. The first differentiation of (14) yields

$$\int_0^x \varrho_n(\xi)\,d\xi = f'_{FB}(x)$$

$$(17)$$

or explicitly

$$\int_0^x \varrho_n(\xi)\,d\xi = -\varepsilon_n V'_{FB}(x) - \int_{-w_{ox}}^0 \varrho_{ox}(\xi)\,d\xi - Q_{ss}.$$

$$(17a)$$

To obtain the final solution of (14), the differentiation must be carried out once again,

$$\varrho_n(x) = -\varepsilon_n V''_{FB}(x).$$

$$(18)$$

This equation means that the charge density distribution in the silicon nitride of an MNOS structure can be obtained by a double differentiation of the measured flat-band voltage as a function of the nitride thickness.

Having obtained the measurement results as a function of the nitride layer thickness, it is easy to calculate the combined charge of the surface states and the oxide $\left(\int_{-w_{ox}}^0 \varrho_{ox}(\xi)\,d\xi + Q_{ss}\right)$. For $x = 0$ the left side of (17a) is equal to zero, and therefore on

the basis of this equation we may write

$$- \varepsilon_n V'_{FB}(0) = \int\limits_{-w_{ox}}^{0} \varrho_{ox}(\xi)\, d\xi + Q_{ss}. \tag{19}$$

Therefore, the value of the first derivative of the flat-band voltage at the point $x = 0$ determines unambiguously, through (19), the combined charge of the oxide and the surface states.

3.2 Determining $\varrho_n(x)$ on the basis of $V_T(x)$ measurements

The charge distribution in the Si_3N_4 layer of the MNOS transistor can also be determined by measuring the threshold voltage of the MNOS transistor as a function of the thickness of the nitride layer. To accomplish this goal an equation analogous to that in Section 3.1 must be solved.

The threshold voltage of an MNOS transistor (enhancement mode) is given by [3, 4]

$$V_T(x) = V_{FB}(x) + 2\varphi_F \pm \frac{\sqrt{4\varepsilon_s q N \varphi_F}}{\varepsilon_n}(x + \gamma w_{ox}) \tag{20}$$

(here and in the following equations + for n-type and − for p-type channel) φ_F bulk Fermi potential, q magnitude of electronic charge). Taking into account (13) we can write

$$V_T(x) = \varphi_{ms} - \frac{1}{\varepsilon_n}\left\{ \int\limits_0^x (x - \xi)\, \varrho_n(\xi)\, d\xi + \int\limits_{-w_{ox}}^0 (x - \gamma\xi)\, \varrho_{ox}(\xi)\, d\xi + \right.$$
$$\left. + (x + \gamma w_{ox}) Q_{ss} \right\} + 2\varphi_F \pm \frac{\sqrt{4\varepsilon_s q N \varphi_F}}{\varepsilon_n}(x + \gamma w_{ox}). \tag{21}$$

Equation (21) can be rewritten in the form

$$\int\limits_0^x (x - \xi)\, \varrho_n(\xi)\, d\xi = \varepsilon_n \varphi_{ms} - \varepsilon_n V_T(x) - \int\limits_{-w_{ox}}^0 (x - \gamma\xi)\, \varrho_{ox}(\xi)\, d\xi -$$
$$- (x + \gamma w_{ox}) Q_{ss} + 2\varepsilon_n \varphi_F \pm \sqrt{4\varepsilon_s q N \varphi_F}(x + \gamma w_{ox}). \tag{22}$$

For $x = 0$ the right side of (22) is equal to zero. This is because $-\varepsilon_n V^{MOS}_T(0) = -\varepsilon_n V^{MOS}_T$ and

$$\varepsilon_n V^{MOS}_T = \varepsilon_n \varphi_{ms} + \gamma \int\limits_{-w_{ox}}^0 \xi \varrho_{ox}(\xi)\, d\xi - \gamma w_{ox} Q_{ss} + 2\varepsilon_n \varphi_F \pm \gamma w_{ox} \sqrt{4\varepsilon_s q N \varphi_F}.$$

Therefore, the neccessary condition for the existence of a solution to (22) is satisfied.
Differentiating (22) we get

$$\int\limits_0^x \varrho_n(\xi)\, d\xi = -\varepsilon_n V_T(x) - \int\limits_{-w_{ox}}^0 \varrho_{ox}(\xi)\, d\xi - Q_{ss} \pm \sqrt{4\varepsilon_s q N \varphi_F}. \tag{23}$$

Differentiating (23) we obtain an expression which determines the charge profile in the nitride layer of the MNOS transistor,

$$\varrho_n(x) = -\varepsilon_n V''_T(x). \tag{24}$$

Thus, $\varrho_n(x)$ can be obtained by a double differentiation of the measured threshold voltage as a function of the Si_3N_4 layer thickness of the MNOS transistor.

An analysis of (23) for $x = 0$ yields the following expression for the combined charge of the surface states and of the oxide,

$$Q_{ss} + \int_{-w_{ox}}^{0} \varrho_{ox}(\xi)\, d\xi = -\varepsilon_n V_T'(0) \pm |\overline{4\varepsilon_s q N}|\, \varphi_F .$$ (25)

4. Discussion

4.1 Determining the charge profile in the Si_3N_4 layer of the MNOS structure

To determine the charge distribution $\varrho_n(x)$ according to (18) or (24) one should differentiate the flat-band or threshold voltage versus nitride thickness data obtained by etching, twice. The error arising from the double differentiation of experimental data will be minimum if the approximation of experimental data by an appropriate analytical function is carried out first, and then followed by a double differentiation of this function.

The method of measuring the charge distribution in the nitride layer of MNOS structures described in this paper, overcomes the defects and limitations of Endo's method. The method may be applied to MNOS structures with an arbitrary type of substrate (n or p) and an arbitrary charge polarity stored in the Si_3N_4 (normally-on or normally-off state).

4.2 Insensitivity of the method to an accidental surface charge

In contrast to Endo's method, the method presented in the current paper is insensitive to an accidental surface charge which may originate after each etching of the Si_3N_4 layer of the MNOS structure. This property is due to the fact that neither the flat-band voltage $V_{FB}(x)$ nor the threshold voltage $V_T(x)$ depend on the charge stored on the interface Si_3N_4 — gate electrode. To show that this is indeed the case, it is sufficient to calculate the flat-band voltage for the two cases shown in Fig. 2.

For the case shown in Fig. 2a, the flat-band voltage is (equation (13))

$$V_{FB,a} = \varphi_{ms} - \frac{1}{\varepsilon_n} \left\{ \int_0^l (l - \xi)\, [\varrho_n(\xi) + Q_{acc}\, \delta(\xi - l)]\, d\xi + \right.$$

$$\left. + \int_{-w_{ox}}^{0} (l - \gamma\xi)\, \varrho_{ox}(\xi)\, d\xi + (l + \gamma w_{ox})\, Q_{ss} \right\} .$$ (26)
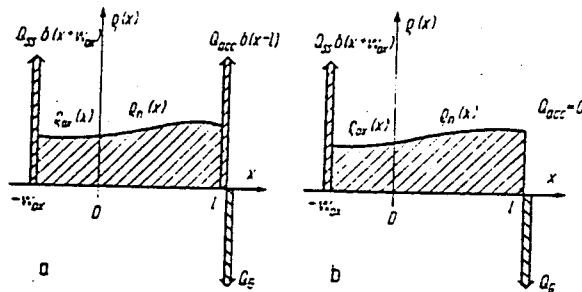

Fig. 2. Illustration of the charge distribution in MNOS structure under flat-band conditions. a) $Q_{acc} \neq 0$; b) $Q_{acc} = 0$. Q_G charge per unit area on the gate electrode

On the other hand, for the case shown in Fig. 2b V_{FB} is given by

$$V_{FB,b} = \varphi_{ms} - \frac{1}{\varepsilon_n} \left\{ \int_0^l (l-\xi)\, \varrho(\xi)\, d\xi + \int_{-w_{ox}}^0 (l-\gamma\xi)\, \varrho_{ox}(\xi)\, d\xi + (l+\gamma w_{ox})\, Q_{ss} \right\}.$$

$$(27)$$

Taking into account the fact that $\int_0^l (l-\xi)\, Q_{acc}\, \delta(\xi - l)\, d\xi = 0$ we may write $V_{FB,a} =$
$= V_{FB,b}$. Thus, the method with a non-floating gate is insensitive to an accidental charge on the Si_3N_4 surface, which can originate after each step of the successive etching of the nitride.

4.3 Determination of the total charge of the oxide

The combined charge of the oxide $Q_{ox} = Q_{ss} + \int_{-w_{ox}}^0 \varrho_{ox}(\xi)\, d\xi$ can be determined in a simple way using (19) or (25). To do this, the value of the first derivative at $x = 0$ of the flat-band voltage or the threshold voltage must be calculated, and substituted into the above-mentioned equations. The ability to measure the charge Q_{ox} is a valuable property of the measuring method presented here. This method allows us to answer the question how the charge Q_{ox} depends on the total charge injected into the insulator of the MNOS structure.

4.4 Verification of the basic assumptions

The basic condition for the validity of the results obtained with this method is the assumption that the Si_3N_4 layer etching processes and the flat-band voltage or threshold voltage measurements do not disturb the charge distribution in the insulator, i.e. during the measurements the values of Q_{ss}, $\varrho_{ox}(x)$, and $\varrho_n(x)$ do not change.

To see how well this assumption is met, the obtained results should be verified. To do this, the flat-band voltage should be calculated using (13) and then compared to the measured value. Of course, the verification should be performed for the entire range of the nitride layer thickness $x \in [0, l_0]$ where l_0 is the initial thickness of the Si_3N_4 layer. The sum, which appears in (13) ($x = l_0$),

$$\int_{-w_{ox}}^0 (l_0-\gamma\xi)\, \varrho_{ox}(\xi)\, d\xi + (l_0+\gamma w_{ox})\, Q_{ss},$$

may be calculated approximately.

For typical MNOS structures the following relation holds: $l_0 \gg \gamma w_{ox}$. Therefore, ignoring γw_{ox} versus l_0 and noting that $\xi \in [-w_{ox}, 0]$, we may write

$$\int_{-w_{ox}}^0 (l_0-\gamma\xi)\, \varrho_{ox}(\xi)\, d\xi + (l_0+\gamma w_{ox})\, Q_{ss} \approx l_0 \left[\int_{-w_{ox}}^0 \varrho_{ox}(\xi)\, d\xi + Q_{ss} \right] = l_0 Q_{ox}.$$

$$(28)$$

Taking into account (13) and (28) we may write the following expression describing the flat-band voltage:

$$V_{FB}(l_0) \approx \varphi_{ms} - \frac{1}{\varepsilon_n} \left\{ \int_0^{l_0} (l_0-\xi)\, \varrho_n(\xi)\, d\xi + l_0 Q_{ox} \right\}.$$

$$(29)$$

If the charge profile is being determined on the basis of threshold voltage measurements $V_T(x)$, then in the verification of the experimental data the following ap-

proximate formula may be used (see (21) and (28)):

$$V_T(l_0) \approx q_{ms} - \frac{1}{\varepsilon_n} \left\{ \int_0^{l_0} (l_0 - \xi) \, \varrho_n(\xi) \, d\xi + l_0 Q_{ox} \right\} +$$

$$+ 2\varphi_F \pm \frac{\sqrt{4\varepsilon_s q N \varphi_F}}{\varepsilon_n} (l_0 + \gamma w_{ox}) . \tag{30}$$

Thus the method of measuring the charge distribution in the nitride layer of MNOS structures presented in this paper is fully verifiable.

Appendix

Determination of the flat-band voltage of MNOS structures

For the flat-band state, the surface potential as well as the semiconductor charge are equal to zero. To achieve this state in a real MNOS structure, one must polarize the gate with a voltage V_{FB}, which will compensate the effect of work function difference, insulator charges and states of semiconductor surface. Thus

$$V_{FB} = q_{ms} + V_n(l) , \tag{A1}$$

where $V_n(l) = f[\varrho(x), Q_{ss}]$ is the voltage which compensates the influence of the insulator charge and the surface states on the state of the semiconductor surface. We assume that the surface state charge is localized in the $x = -w_{ox}$ plane and its surface density is Q_{ss}, i.e. $\int_{-w_{ox}-0}^{-w_{ox}+0} Q_{ss} \delta(x + w_{ox}) \, dx = Q_{ss}$ ($\delta(x)$ Dirac function).

To determine the voltage $V_n(l)$ one must solve the Poisson equation in the SiO_2 and Si_3N_4 regions (see Fig. 2),

$$\frac{d^2 V_{ox}(x)}{dx^2} = -\frac{\varrho_{ox}(x) + Q_{ss}\delta(x + w_{ox})}{\varepsilon_{ox}} ; \quad -w_{ox} \leqq x \leqq 0 , \tag{A2}$$

$$\frac{d^2 V_n(x)}{dx^2} = -\frac{\varrho_n(x)}{\varepsilon_n} ; \quad 0 \leqq x \leqq l , \tag{A3}$$

together with the following boundary conditions:

$$V_{ox}(-w_{ox}) = 0 , \tag{A4}$$

$$\frac{dV_{ox}(-w_{ox})}{dx} = 0 \tag{A5}$$

and

$$V_{ox}(0) = V_n(0) , \tag{A6}$$

$$\varepsilon_{ox} \frac{dV_{ox}(0)}{dx} = \varepsilon_n \frac{dV_n(0)}{dx} \tag{A7}$$

(V_{ox} is the oxide voltage distribution). After the first integration of (A2) and (A3) we obtain

$$\frac{dV_{ox}(x)}{dx} = -\frac{1}{\varepsilon_{ox}} \left\{ \int_{-w_{ox}}^{x} \varrho_{ox}(x) \, dx + \int_{-w_{ox}}^{x} Q_{ss} \delta(x + w_{ox}) \, dx \right\} + \frac{dV_{ox}(-w_{ox})}{dx} , \tag{A8}$$

$$\frac{dV_n(x)}{dx} = -\frac{1}{\varepsilon_n} \int_0^x \varrho_n(x) \, dx + \frac{dV_n(0)}{dx} , \tag{A9}$$

and after performing the second integration we get

$$V_{ox}(x) =$$

$$= -\frac{1}{\varepsilon_{ox}} \int\limits_{-w_{ox}}^{x} \int\limits_{-w_{ox}}^{x} \varrho_{ox}(x)\ dx\ dx - \frac{Q_{ss}}{\varepsilon_{ox}} \int\limits_{-w_{ox}}^{x} dx + \frac{dV_{ox}(-w_{ox})}{dx} \int\limits_{-w_{ox}}^{x} dx + V_{ox}(w_{ox}) ,$$

(A10)

$$V_n(x) = -\frac{1}{\varepsilon_n} \int\limits_{0}^{x}\int\limits_{0}^{x} \varrho_n(x)\ dx\ dx + \frac{dV_n(0)}{dx} \int\limits_{0}^{x} dx + V_n(0) .$$

(A11)

Taking into account (A4) and (A5) and the Cauchy formula

$$\int\limits_{x_\bullet}^{x}\int\limits_{x_\bullet}^{x} f(x)\ dx\ dx = \int\limits_{x_\bullet}^{x} f(\xi)\ (x-\xi)\ d\xi ,$$

(A10) and (A11) may be rewritten in the following form:

$$V_{ox}(x) = -\frac{1}{\varepsilon_{ox}} \int\limits_{-w_{ox}}^{x} (x-\xi)\ \varrho_{ox}(\xi)\ d\xi - \frac{(x+w_{ox})\ Q_{ss}}{\varepsilon_{ox}} ,$$

(A12)

$$V_n(x) = -\frac{1}{\varepsilon_n} \int\limits_{0}^{x} (x-\xi)\ \varrho_n(\xi)\ d\xi + x\frac{dV_n(0)}{dx} + V_n(0) .$$

(A13)

For $x = 0$ we get (see (A8) and (A12))

$$\frac{dV_{ox}(0)}{dx} = -\frac{1}{\varepsilon_{ox}} \int\limits_{-w_{ox}}^{0} \varrho_{ox}(\xi)\ d\xi - \frac{Q_{ss}}{\varepsilon_{ox}} ,$$

(A14)

$$V_{ox}(0) = \frac{1}{\varepsilon_{ox}} \int\limits_{-w_{ox}}^{0} \xi\varrho_{ox}(\xi)\ d\xi - \frac{w_{ox}Q_{ss}}{\varepsilon_{ox}} .$$

(A15)

Substituting (A14) and (A15) into (A6) and then into (A13) yields

$$V_n(x) = -\frac{1}{\varepsilon_n} \left\{ \int\limits_{0}^{x} (x-\xi)\ \varrho_n(\xi)\ d\xi + \int\limits_{-w_{ox}}^{0} (x-\gamma\xi)\ \varrho_{ox}(\xi)\ d\xi + (x+\gamma w_{ox})\ Q_{ss} \right\} ,$$

where

(A16)

$$\gamma = \frac{\varepsilon_n}{\varepsilon_{ox}} .$$

Thus, the following equation determines the flat-band voltage of MNOS structures:

$$V_{FB}(l) = \varphi_{ms} - \frac{1}{\varepsilon_n} \left\{ \int\limits_{0}^{l} (l-\xi)\ \varrho_n(\xi)\ d\xi + \int\limits_{-w_{ox}}^{0} (l-\gamma\xi)\ \varrho_{ox}(\xi)\ d\xi + (l+\gamma w_{ox})\ Q_{ss} \right\} .$$

(A17)

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