ON THE ORIGIN OF ELECTROMECHANICAL VIBRATIONS OF MOS STRUCTURES IN MISAWA-MORITANI-NAKAI EFFECT

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In the present paper a theory is proposed that makes it possible to explain the results of measurements of electromechanical vibrations of metal-oxide-semiconductor (MOS) structures, obtained in the Misawa-Moritani-Nakai experiment, without the assumption of the dominant role of the native piezoelectricity and electrostriction of SiO_2 films in the vibrating phenomena. The theory takes into account the electric charge distribution in the whole MOS sample. Provided that Coulomb's and elastic forces only are responsible for the vibrations, an analysis of the bending moment is performed and formulae for the phenomenological "piezoelectric" and "electrostrictive" constants are derived.

К ВОПРОСУ О ПРОИСХОЖДЕНИИ ЭЛЕКТРОМЕХАНИЧЕСКИХ КОЛЕБАНИЙ СТРУКТУР ТИПА МЕТАЛЛ–ДИЭЛЕКТРИК–ПОЛУПРОВОДНИК В ЭФФЕКТЕ МИСАВЫ–МОРИТАНИ–НАКАИ

В работе предложена теория электромеханических колебаний структур типа металл – диэлектрик – полупроводник, с помощью которой удается объяснить результаты измерений эксперимента Мисавы – Моритани – Накаи, не предполагая доминантной роли естественного пьезоэлектричества и электрострукции пленок SiO_2. Данный теоретический подход учитывает распределение электрического заряда во всей системе МДП. Предполагая, что наличие колебаний в пленках обусловлено только кулоновскими и упругими силами, проведен анализ изгибающего момента и выведены формулы для феноменологических «пъезоэлектрических» и «электрострикционных» констант.

I. INTRODUCTION

It is known that a Si MOS sample in the form of a clamped-free beam can perform transverse vibrations the frequency of which is equal to the frequency of an ac modulation voltage superimposed on the applied bias voltage. This elec-

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tromechanical effect was first observed by Misawa et al. [1]. In [2] the authors described a method for detecting the vibrations by means of a laser beam and proposed a simple phenomenological theory of the electromechanical effect. According to their theory, the existence of the electromechanical vibrations is attributed to both the piezoelectric and electrostrictive effect of SiO_2 films. It seems to be questionable, however, to acount for the vibrations simply by the native piezoelectricity and electrostriction of SiO_2 films used in experiments. The reasons for this opinion are as follows. Firstly, the atomic structure of SiO_2 films grown thermally or sputtered on silicon wafers has normally an amorphous and hence isotropic character, as confirmed by many experimentalists. On the other hand, piezoelectricity presupposes anisotropy. These two facts lead to the conclusion that the native piezoelectricity of the SiO_2 films can be neglected. Secondly, electrostriction is a property of all materials, and not only of the oxide films. Thirdly, there always exists an electric-charge distribution in the MOS sample, and the applied electric field gives rise to Coulomb's forces associated with the distribution. In this way, stress fields can be generated not only in the oxide, but also in the semiconductor and on the interfaces between the media in question.

The purpose of this paper is to present the theory, briefly communicated in [3], which takes into account the reasons mentioned above and, consequently, leads to a new interpretation of the results of Misawa et al. In contrast to [2], we assume that the electromechanical vibrations are induced by the effect of Coulomb's forces acting upon electric charges distributed in the whole MOS sample. After calculating the modulation bending moment generated by the alternative electric field and comparing our approach with that proposed in [2], we derive formulae for the coefficients called in [2] as "piezoelectric and electrostrictive constants for SiO_2 film". The theoretical values of these coefficients are compared with experimental data available.

II. BASIC ASSUMPTIONS AND EQUATIONS

Similarly as it was in [2], we consider a clamp-free Si MOS sample of rectangular bimorph type (Fig. 1). Let t_1, $2t_2$, and t_3 be the thicknesses respectively of the SiO_2 film, Si substrate and Al electrode (both the Al electrodes have the same thickness, width and length). When a small ac modulation voltage ΔV_G, superimposed on the bias voltage V_G, is applied to the electrodes, the MOS sample performs vibrations which are described by the well-known equation of motion:

$$\mu \frac{\partial^2 \bar{y}(\bar{x}, t)}{\partial t^2} = -\frac{\partial^2 M(\bar{x}, t)}{\partial^2 \bar{x}^2}. \qquad (1)$$

Here μ is the mass density for unit length, t is time and $M(\bar{x}, t)$ is the total bending moment at a cross section whose centre is located in the point $(\bar{x}, \bar{y}(\bar{x}, t))$.

Generally, $M(\bar{x}, t)$ can be expressed as follows:

$$M(\bar{x}, t) = M_0 - M_v \quad (2)$$

where M_0 is the bending moment due to the stress of the elasticity and M_v is the bending moment due to the stress which is generated by the electric field in the MOS sample. Solving the equation (1) requires to know an explicit form of $M(\bar{x}, t)$. Obviously, $M(\bar{x}, t)$ can be calculated from the stress field in the MOS sample. Therefore, it is necessary to investigate the origin of the stress field in detail. We shall make the following assumptions:

1) For sufficiently low frequencies of the applied electric field, we shall assume the validity of the equation well-known from elastostatics:

$$\operatorname{div} \bar{\bar{\tau}} = f \quad (3)$$

where $\bar{\bar{\tau}}$ is the stress tensor and f is the force density.

2) The force density f is given only by Coulomb's forces acting upon charges distributed in the semiconductor, in the oxide, and on the interfaces.

3) For small amplitudes of the vibrations, we shall assume the validity of Hook's law

$$\bar{\bar{\tau}} = \bar{\bar{c}} \,.\, \bar{\bar{\varepsilon}} \quad (4)$$

where $\bar{\bar{c}}$ is the elastic constant tensor and $\bar{\bar{\varepsilon}}$ is the strain tensor.

4) For simplicity, we shall suppose that all the layers which the MOS sample consists of are homogeneous, apart from the charge distribution. Moreover, the charge density will be supposed to be constant along the equipotential surfaces parallel to the electrodes.

III. CALCULATION OF THE BENDING MOMENT

Let x, y, z be a local rectangular system of coordinates the origin of which is located in the centre of a cross section of the bimorph (see Fig. 1). We define the system in such a way that the x- and the y-axis are parallel with the plane $\bar{x}\bar{y}$, the x-axis being perpendicular to the cross section. The total bending moment can be expressed as follows:

$$M(\bar{x}, t) = -c \int_{-\infty}^{+\infty} \tau_{11} y \, dy \quad (5)$$

where c is the width of the Al electrode on the bimorph and τ_{11} is the stress tensor element which represents a normal stress in the x-direction. According to the relation (4), τ_{11} can be expressed in terms of the other components of stress and strain. For a cubic medium (Si substrate) as well as for an isotropic medium (SiO_2 film), we have

$$\tau_{11} = \frac{1}{s_{11}} \varepsilon_{11} + m(\tau_{22} + \tau_{33}) \quad (6)$$

where m is the Poisson ratio ($m = c_{12}/(c_{11} + c_{12})$) and s_{11} is the reciprocal value of the Young modulus for the medium in question. From equation (3), we can derive the relation

$$\tau_{22} + \tau_{33} = -\int_{-\infty}^{y} f \, dy + \Phi(x, y, z). \quad (7)$$

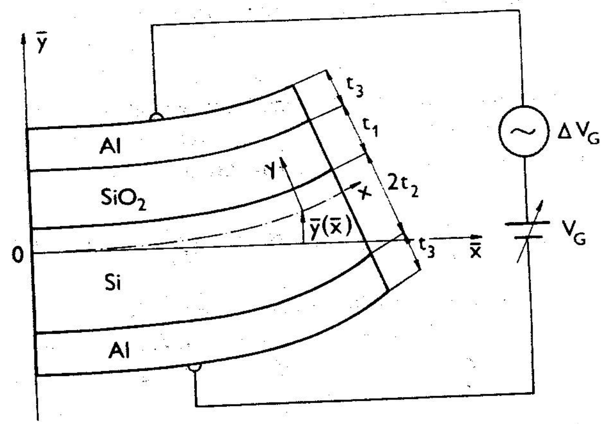

Fig. 1. Schematical illustration of the electromechanical effect.

Here f is the y-component of the force density (the other components are assumed to be negligible) and the function $\Phi(x, y, z)$ is identically equal to zero because for $f \to 0$ we assume the validity of the relation (6) with $\tau_{22} + \tau_{33} = 0$. If we realize that

$$M_0 = -c \int_{-\infty}^{+\infty} s_{11}^{-1} \varepsilon_{11} y \, dy \quad (8)$$

then from relations (2), (5—8), we obtain the formula

$$M_v = -c \int_{-\infty}^{+\infty} \left(ym \int_{-\infty}^{y} f \, dy \right) dy. \quad (9)$$

Now, according to the assumption 2) given in Section II, f can be expressed in terms of the electric field as follows: for the insulator

$$f = \varrho_1 E_1 \quad (10)$$

whilst for the semiconductor

$$f = \epsilon_0 \epsilon_s E_s \frac{\partial E_s}{\partial y}. \quad (11)$$

Inside the Al electrodes, the electric field as well as the force density is zero.

Besides, for the semiconductor-insulator interface lying in the plane $y = a$, we must take into account the force acting upon the interface, with the corresponding force density

$$f = \frac{\epsilon_0}{2}\left[\epsilon_1 E_1^2(a) - \epsilon_s E_s^2(a)\right]\delta(y-a) \qquad (12)$$

and for the other interfaces we must consider force densities given by formulae similar to (12). In relations (10—12), ϵ_1, E_1, $E_1(a)$ and ϵ_s, E_s, $E_s(a)$ are the relative permittivity, the electric field and its boundary value respectively of the insulator and the semiconductor, ϱ is the fixed-charge density in the insulator (we assume that contributions of mobile charges is negligible) and ϵ_0 is the permittivity of vacuum. By using the relations (10—12), formula (9) can be rewritten into the form

$$M_v = -\frac{c\epsilon_0}{2}\left\{m_1\epsilon_1\int_a^b E_1^2 y\,dy + m_s\epsilon_s\int_d^a E_s^2 y\,dy\right\}, \qquad (13)$$

where m_1 and m_s are the Poisson ratios respectively of the insulator and semiconductor, $a = t_2 - t_1/2$, $b = t_2 + t_1/2$, $d = -t_2 - t_1/2$. Formula (13) is valid under the assumption that the total charge of the MOS sample is zero. Integrating by parts and utilizing the Poisson equation $\varrho_1 = \epsilon_0\epsilon_1\partial E_1/\partial y$, we can express the first integral in formula (13) as follows:

$$\int_a^b E_1^2 y\,dy = \frac{1}{2}(b^2-a^2)E_1^2(a) - \frac{E_1(a)}{\epsilon_1\epsilon_0}\int_a^b (y^2-b^2)\varrho_1\,dy + \qquad (14)$$

$$+\frac{1}{(\epsilon_1\epsilon_0)^2}\int_a^b\left[\varrho_1\int_b^y (y^2-b^2)\varrho_1\,dy\right]dy.$$

Similarly, if V_1 is the voltage drop across the insulator, we obtain the relation

$$V_1 = \int_a^b E_1\,dy = (b-a)E_1(a) - \frac{1}{\epsilon_1\epsilon_0}\int_a^b (y-b)\varrho_1\,dy. \qquad (15)$$

The second integral in formula (13) can be expressed in other way. We shall assume that for sufficiently low frequencies, E_s depends on time through the potential φ in the semisonductor only, i.e. $E_s = E_s(\varphi)$. Since $E_s = -\partial\varphi/\partial y$, we have

$$\int_d^a E_s^2 y\,dy = -\int_{\varphi(d)}^{\varphi(a)} E_s(\varphi)\left(a - \int_{\varphi(a)}^{\varphi}\frac{d\varphi'}{E_s(\varphi')}\right)d\varphi. \qquad (16)$$

In the experiment, a small modulation voltage ΔV_G is applied to the electrodes. Consequently, a small modulation voltage drop ΔV_1 appears across the insulator. The corresponding modulation bending moment can be calculated by linearizing the relations (13—16) with respect to ΔV_1. From formulae (14) and (15), we obtain the relation

$$\Delta\left(\int_a^b E_1^2 y\,dy\right) = \frac{\Delta V_1}{b-a}\left[(b+a)V_1 + \frac{1}{\epsilon_0\epsilon_1}\int_a^b (y-b)(a-y)\varrho_1\,dy\right]. \qquad (17)$$

Formula (16) should be linearized with respect to a small change in $\varphi(a)$, denoted by $\Delta\varphi(a)$. Assuming that $\varphi(d)$ does not change in time, from formula (16) we have

$$\Delta\left(\int_d^a E_s^2 y\,dy\right) = -aE_s(a)\,\Delta\varphi(a). \qquad (18)$$

As will be seen below, the right-hand side of formula (18) can be expressed in terms of V_1 and ΔV_1. We shall utilize the boundary condition

$$\epsilon_1 E_1(a) - \epsilon_s E_s(a) = \frac{\eta}{\epsilon_0} \qquad (19)$$

where η is the surface state charge per unit on the semiconductor-insulator interface ($\eta = \eta_{FS} + \eta_{SS}$, where η_{FS} corresponds to "fast" states and η_{SS} to "slow" states). Linearizing the condition (19), we have

$$(C_{SC} + C_{FS})\,\Delta\varphi(a) = -\epsilon_0\epsilon_1\,\Delta E_1(a). \qquad (20)$$

Here $C_{SC} = -\epsilon_0\epsilon_s\left.\frac{\partial E_s}{\partial\varphi}\right|_{\varphi(a)}$ is the capacitance per unit area of the space charge region and $C_{FS} = -\partial\eta_{FS}/\partial\varphi(a)$ is the capacitance per unit area due to the fast surface states. By utilizing the relations (15), (18—20), after some arrangements, we obtain the formula

$$\Delta\left(\int_d^a E_s^2 y\,dy\right) = \frac{a\epsilon_1\Delta V_1}{\epsilon_s(C_{SC}+C_{FS})(b-a)}\left\{\frac{\epsilon_0\epsilon_1 V_1}{b-a} - \left[\eta + \frac{1}{b-a}\int_a^b (b-y)\varrho_1\,dy\right]\right\}. \qquad (21)$$

According to formulae (13), (18) and (21), the modulation bending moment can be expressed as follows:

$$\Delta M_v = -\frac{c\epsilon_0\Delta V_1}{2(b-a)}\left\{m_1\epsilon_1\left[(b+a)V_1 + \frac{(b-a)^3}{\epsilon_0\epsilon_1}\left(\frac{1}{2}\langle\varrho_1\rangle_1 - \frac{1}{3}\langle\varrho_1\rangle_2\right) + \frac{m_s\epsilon_1 a}{C_{SC}+C_{FS}}\left[\frac{\epsilon_0\epsilon_1 V_1}{b-a} - \left(\eta + \frac{b-a}{2}\langle\varrho_1\rangle_1\right)\right]\right]\right\}, \qquad (22)$$

where we have introduced the notation

$$\langle\varrho_1\rangle_n = \frac{n+1}{(b-a)^{n+1}}\int_a^b (b-y)^n\varrho_1\,dy. \qquad (23)$$

In the approach of Misawa et al. [2], ΔM_v is expressed by the relation

$$\Delta M_v = -\frac{c t_1 t_2}{s_{11}}\left(2\gamma_{13}\frac{V_1}{t_1} + d_{31}\right)\frac{\Delta V_1}{t_1}, \tag{24}$$

where the coefficients γ_{13} ("electrostrictive constant") and d_{31} ("piezoelectric constant") are determined from experimental data. By comparing the expressions (22) and (24), with respect to the relations $b-a=t_1$, $b+a=2t_2$, $a=t_2-t_1/2$, we obtain the following formulae:

$$d_{31}=\frac{s_{11}}{2t_2}\left[m_1 t_1^2\left(\frac{1}{2}\langle\varrho_1\rangle_1-\frac{1}{3}\langle\varrho_1\rangle_2\right)-\frac{m_s\epsilon_0\epsilon_1(t_2-t_1/2)}{C_{SC}+C_{FS}}\left(\frac{\eta}{t_1}+\frac{\langle\varrho_1\rangle_1}{2}\right)\right] \tag{25}$$

$$\gamma_{13}=\frac{1}{2}s_{11}\epsilon_0\epsilon_1\left[m_1+\frac{\epsilon_0\epsilon_1 m_s(t_2-t_1/2)}{2t_1t_2(C_{SC}+C_{FS})}\right] \tag{26}$$

IV. NUMERICAL RESULTS AND DISCUSSION

In practically important cases, for example, as it was in [2], the MOS samples are such that $t_1 \ll t_2$. Besides, for samples of good quality, it is reasonable to assume that $\langle\varrho_1\rangle_1 \sim \langle\varrho_1\rangle_2$ and $C_{FS} \ll C_{SC}$. Then, under the flat band conditions ($\varphi \equiv 0$), the formulae (25) and (26) can be simplified as follows (cf. [3]):

$$d_{31}=\frac{s_{11}}{2t_2}\left[m_1 t_1^2\left(\frac{1}{2}\langle\varrho_1\rangle_1-\frac{1}{3}\langle\varrho_1\rangle_2\right)-\frac{\epsilon_1 m_s t_2 L_D}{\sqrt{2}\epsilon_s}\left(\frac{\eta}{t_1}+\frac{1}{2}\langle\varrho_1\rangle_1\right)\right]. \tag{27}$$

$$\gamma_{13}=\frac{1}{2}s_{11}\epsilon_0\epsilon_1\left(m_1+\frac{\epsilon_1 m_s L_D}{2\sqrt{2}\epsilon_s t_1}\right), \tag{28}$$

where L_D is the Debye length for the semiconductor ($L_D=\epsilon_0\epsilon_s\sqrt{2}/C_{SC}(\varphi=0)$). For a semiconductor of a given type (N or P), L_D can be calculated from the well-known formula

$$L_D=\left(\frac{2\epsilon_0\epsilon_s kT}{e^2N}\right)^{1/2} \tag{29}$$

where T is the absolute temperature, N is the concentration of majority carriers in the semiconductor, e is the electronic charge, and k is the Boltzmann constant. The numerical values of γ_{13} were calculated from formulae (28) and (29) for $s_{11}^{-1}=6.6\times10^{-10}$ Nm^{-2}, $\epsilon_1=3.84$, $\epsilon_s=12$, $m_s=0.28$, $m_1=0.2$ and for the values of the other parameters taken from [2] (see Tab. 1). In Table 1 γ_{13}^{exp} and d_{31}^{exp} are the values determined in [2] from experimental measurements. One can see that in the case of the n-Si MOS sample, the theoretical value of γ_{13} lies within the interval of the accuracy of the value of γ_{13}^{exp}. In the case of the p-Si MOS sample, the value of γ_{13} is *somewhat smaller than that of* γ_{13}^{exp}. Calculation of L_D shows that $L_D \sim t_1$ in both cases. Therefore, we may write

Table 1

Parameters of the samples and coefficients characterizing the piezoelectric and electrostrictive effect of the SiO_2 films

$T = 300$ K Sample	N [cm^{-3}]	t_1 [nm]	$2t_2$ [mm]	γ_{13} [10^{19} cm^2 V^{-2}]	γ_{13}^{exp} [10^{19} cm^2 V^{-2}]	d_{31}^{exp} [10^{14} cm V^{-1}]
n-Si MOS	3×10^{14}	230	0.25	6.34	7.6 ± 1.5	9.2 ± 1.9
p-Si MOS	1.5×10^{15}	280	0.2	5.59	11 ± 2	21 ± 4

$$d_{31} \doteq -\frac{s_{11}\epsilon_1 m_s}{2\sqrt{2}\epsilon_s}L_D\left(\frac{\eta}{t_1}+\frac{1}{2}\langle\varrho_1\rangle_1\right). \tag{30}$$

Taking the values of d_{31} from the last column of Table 1 and using the formulae (29) and (30), we obtain the estimate of $\left(\frac{\eta}{t_1}+\frac{1}{2}\langle\varrho_1\rangle_1\right)$. The result is 3.56×10^{16} e/cm^3 for the n-Si MOS sample and 1.82×10^{17} e/cm^3 for the p-Si MOS sample.

As we have seen, the value of the coefficients γ_{13} and d_{31} is determined not only by the oxide, but also by the semiconductor and the semiconductor-oxide interface. From Section III it follows that the results would remain unchanged if we considered the MOS sample without the Al layer on the semiconductor. In other words, an ideal semiconductor-metal contact should not contribute to the generation of the electromechanical vibrations.

Although the agreement between our theory and the experiments seems to be quite good, one should be careful in formulating the conclusions from experimental results. In [2], an Al-sputtered SiO_2—Al—Si sample was also investigated. In this case, the values of γ_{13}^{exp} and d_{31}^{exp} appear to be greater than those following from our theory at the previous values of the constants s_{11}, m_1, and ϵ_1. However, it is obvious that even if the sample was an ideal one, the properties of sputtered SiO_2 may differ from those of thermally grown SiO_2. The accuracy of determining the voltage drop across the insulator should also be taken into account.

Our theory predicts the dependence of the coefficients γ_{13} and d_{31} on the temperature and on the concentration of majority carriers in the semiconductor. This point seems to be crucial for verification of the theory. There is, however, only a small amount of experimental data available at present, which preserves to complete confirming all our theoretical predictions.

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