EFFECT OF OXIDE RESISTANCE ON THE CHARACTERIZATION OF INTERFACE TRAP DENSITY IN MOS STRUCTURES

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Abstract—The oxide resistance in a practical MOS capacitor is generally not high enough to be negligible in the evaluation of interface trap density based on the quasi-static capacitance–voltage ($C-V$) curve. The importance of the effects of oxide resistance ranging from 10^{13} to $10^{16} \Omega$ on the $C-V$ curve and the corresponding interface trap density is theoretically shown. To obtain the oxide resistance in MOS structures the newly reported charge-then-decay method is suggested. From the oxide resistance found, one can compare the distribution curves of interface trap density before and after removing the oxide resistance effect. It is found that the results obtained after removing the oxide resistance effect are more consistent than those without removing it. In addition, the removal of the oxide resistance effect for a sample having a hysteresis $C-V$ behavior is also discussed.

1. INTRODUCTION

A quasi-static technique is important in determining the low-frequency capacitance–voltage ($C-V$) curves of MOS capacitors[1]. From the quasi-static $C-V$ curve or the combination of high-frequency and quasi-static $C-V$ curves, one can find the distribution of interface trap density D_{it} [2–5]. It is noted that based on the quasi-static technique, the D_{it} found can be as low as $10^{10} \text{ cm}^{-2} \text{ eV}^{-1}$ [2,4,5]. Since the quasi-static capacitance is interpreted from the measured current of the MOS capacitor on which a ramp voltage is applied, any existence of oxide leakage current should result in a distortion of the $C-V$ curve[6]. It is, of course, erroneous in the D_{it} found from this distorted $C-V$ curve. The presence of oxide leakage current during quasi-static $C-V$ measurement is mainly due to the imperfection of oxide, such as the surface leakage or the bulk oxide defects. It is quite difficult to distinguish the surface and the bulk oxide leakage from the tilt of the quasi-static $C-V$ curve only. Generally, an N_2 purge during $C-V$ measurement can significantly reduce the leakage. This is due to the removal of water contamination on surface by the N_2 purge. But the defect-induced bulk oxide leakage or the unsatisfied bond related to surface leakage still exists more or less in the MOS capacitor. That is to say a practical MOS capacitor should contain a finite oxide resistance R_{ox} . The higher the R_{ox} , the smaller the error of D_{it} found from the quasi-static $C-V$ curve. Unfortunately, it is found in this work that the R_{ox} of a practical MOS capacitor is generally not high enough to be negligible. Therefore, a study of finding the R_{ox} and then to remove the effect of R_{ox} on D_{it} is worthwhile.

The R_{ox} of a MOS capacitor is generally quite large, e.g., greater than $10^{14} \Omega$ in this work. Any attempt to measure it directly is very difficult. This is mainly due to the reason that the measured current across a bulk oxide is generally around the range of fA, which is close to the limitation of any current meter. According to existing literature, a dual-sweep method had been proposed to eliminate the effect the effect of R_{ox} on $C-V$ curves for a sample with a CVD (chemical vapor deposition) deposited oxide[6]. This method is useful for a deposited oxide when the leakage current is large enough to be accurately measured. But for samples having hysteresis $C-V$ behavior, this method is unapplicable[6].

Recently, we proposed a charge-then-decay method to estimate the R_{ox} of a MOS capacitor[7]. Briefly, a MOS capacitor can hold the residual charges left behind the electrode gate (or the substrate) for a long period due to its large RC time constant[8,9]. From the voltage read by an electrometer and the known parameters of capacitance, one can estimate R_{ox} . The advantages of this method are that no direct measurement of current is needed and the slowly decayed voltage can be accurately measured by an electrometer. It can be used to measure an R_{ox} greater than $10^{14} \Omega$ without suffering the limitation of the current measurement meter. Samples with various oxide thicknesses are experimentally examined. The distribution curves of D_{it} with and without removing R_{ox} effects are compared. From this, the importance of the consideration of the R_{ox} effect is discussed. Also, when a sample consists of a hysteresis phenomenon in $C-V$ curves, such as due to ionization irradiation[9], this method is also applicable. This is finally discussed in this work.

2. THEORETICAL

To start with, we give some theoretical examples to show the effect of R_{ox} on quasi-static $C-V$ curves and the apparent D_{it} . When R_{ox} exists in a MOS capacitor, the measured quasi-static capacitance C_{LF} can be written as:

$$C_{LF} = C_{LF}^* + \frac{V_G/R_{ox}}{dV_G/dt}, \tag{1}$$

where C_{LF}^* is the actual quasi-static capacitance, V_G is the gate voltage and dV_G/dt is the sweep rate. The theoretical relationship between C_{LF}^* and V_G is

known[10]. Figure 1 shows the theoretical quasi-static $C-V$ curves of a MOS capacitor with R_{ox} of 0, 1×10^{16} , 1×10^{15} , 1×10^{14} and $5 \times 10^{13} \Omega$, i.e. curve Nos 1, 2, 3, 4 and 5, respectively. The high-frequency capacitance C_{HF} vs V_G curve is also shown for comparison. Note that the high-frequency $C-V$ curve is independent of R_{ox} . The d_{ox} , the substrate concentration N_A , the area and the dV_G/dt of this example are chosen as $400 \text{ \AA}$, $5 \times 10^{15} \text{ cm}^{-3}$, $1.257 \times 10^{-3} \text{ cm}^2$ (i.e. dot area with a diameter of 0.4 mm), and -0.02 V s^{-1} , respectively. As can be seen from this figure, the C_{LF} curves with R_{ox} greater than $10^{15} \Omega$, i.e. curve Nos 1, 2 and 3, are nearly coincidental.

Fig. 1. Theoretical quasi-static and high-frequency $C-V$ curves of a MOS(p) capacitor with oxide resistance R_{ox} as a parameter.

However, for the C_{LF} curves with R_{ox} smaller than $10^{15} \Omega$, i.e. curve Nos 4 and 5, the effect of R_{ox} on $C-V$ curves appears. Except in the accumulation region, the C_{LF} value of curve No. 5 (or 4) is greater than that of curve No. 1, i.e. ideal case, in the depletion region. This should result in a erroneous D_{it} when the C_{LF} curves shown in this figure are analyzed.

Figure 2 shows the calculated distribution curves of D_{it} according to the $C-V$ curves shown in Fig. 1 by the high-low frequency $C-V$ technique. There are apparent D_{it} plots. Clearly, the smaller the R_{ox} , the larger the value of V_G/R_{ox} in eqn (1), and therefore the larger the effect of R_{ox} on D_{it} . Figures 3a-c show the theoretical relationship curves of midgap interface trap density $D_{it(mg)}$ vs R_{ox} with dV_G/dt , N_A and d_{ox} , respectively, as parameters. In Fig. 3a, it is observed that $D_{it(mg)}$ is strongly dependent on dV_G/dt . As can be seen from eqn (1), the smaller the dV_G/dt , the larger the effect of R_{ox} on C_{LF} . So, dV_G/dt is important in determining the D_{it} when R_{ox} exists. In Fig. 3b, it is observed that the larger the N_A the smaller the effect of R_{ox} on $D_{it(mg)}$. This is due to the reason that a large N_A introduces a high energy difference between the Fermi level E_F and the intrinsic Fermi level E_i in thermal equilibrium. Therefore, a large surface potential ψ_s is needed for the MOS capacitor to enter the situation that the surface E_i is crossing E_F , i.e., the condition of finding the $D_{it(mg)}$. For a clear description, the relationship between V_G , the work function difference between metal and substrate ϕ_{ms} , the oxide voltage drop V_{ox} and the ψ_s can be written as[11]:

$$V_G = \phi_{ms} + V_{ox} + \psi_s. \tag{2}$$

Generally, ϕ_{ms} is negative for a MOS capacitor with an Al-metal gate and a p -type Si substrate[11]. In finding $D_{it(mg)}$, a positive ψ_s is needed for a MOS(p) capacitor. So, an increased ψ_s introduced by the large N_A as described above should result in a small negative V_G , and therefore a small effect of R_{ox} on C_{LF} as can be seen from eqn (1). In Fig. 3c, it is observed that the larger the d_{ox} , the smaller the effect of R_{ox} on

Fig. 3. Theoretical dependence of midgap interface trap density $D_{it(mg)}$ on oxide resistance R_{ox} with: (a) sweep rate dV_G/dt ; (b) substrate concentration N_A ; and (c) oxide thickness d_{ox} as parameters.

$D_{it(mg)}$. It is noted that the V_{ox} in eqn (2) can be written as[11]:

$$V_{ox} = \frac{Q_s}{C_{ox}}, \tag{3}$$

where Q_s is the total charges in the semiconductor and C_{ox} is the oxide capacitance. Note that Q_s is a function of ψ_s . Under a certain N_A , the values of ϕ_{ms} , ψ_s and $Q_s(\psi_s)$ needed to find $D_{it(mg)}$ are independent of d_{ox} . So, a large d_{ox} introduces a small C_{ox} and therefore a large V_{ox} (positive) according to eqn (3). Consequently, the value of negative V_G will become small and the effect of R_{ox} on $D_{it(mg)}$ will decrease as described above. However, the dependence of $D_{it(mg)}$ on d_{ox} is small as can be seen from Fig. 3c.

3. EXPERIMENTAL AND DISCUSSION

p -Type (100) Si wafers with a resistivity of $7 \Omega \text{ cm}^{-1}$ were used as substrates of MOS capacitors. After standard cleaning, the wafers were dry-oxidized at a temperature of 1000°C for various times. The d_{ox} 's of samples used in this work are 204 and $350 \text{ \AA}$. Aluminum was then evaporated on the oxides. On the back side of the wafers, Al was also evaporated after the oxides were etched away. Finally, the samples were postmetallization annealed in N_2 at 400°C for about 10 min. In the following

Fig. 2. Theoretical distribution curves of interface trap density D_{it} vs energy $E_t - E_i$ considering the effect of oxide resistance R_{ox} .

experiments, we will show the effect of R_{ox} on D_{it} first, then discuss the application of the charge-then-decay method to a sample having a hysteresis $C-V$ behavior.

3.1. Removal of the effect of R_{ox} on D_{it}

In this experiment, a sample with a d_{ox} of 204 Å was used. Figure 4 shows the quasi-static and the high-frequency $C-V$ curves of this sample. The sample was tested with an N_2 purge during the $C-V$ measurement. Curve Nos 1, 2 and 3 as shown in this figure are obtained with dV_G/dt of -0.002 , -0.005 and -0.01 V s $^{-1}$, respectively. Clearly, the slowest dV_G/dt , i.e. -0.002 V s $^{-1}$, causes the largest C_{LF} in the depletion region, i.e. curve No. 1. This is consistent with the dependence of C_{LF} on dV_G/dt as indicated in eqn (1). Therefore, it is believed that a finite R_{ox} exists in this sample.

To find R_{ox} , the newly-reported charge-then-decay method was used[7-9]. An electrometer (Keithley 617) with a very high input impedance is needed. The schematic diagram of the charge-then-decay measurement system is shown in Fig. 5a. There are three parts, i.e. an electrometer, a MOS device and a probe system included in this measurement system. A charging voltage V_c is supplied via a switch S_1 for the initial voltage of the system. The V_c used in this work is -4.044 V. For simplicity, the equivalent circuit of the system is given and is shown in Fig. 5b. The R_M (C_M), R_{ox} (C_{ox}) and R_s (C_s) represent the resistance (capacitance)

of the meter, the device and the system, respectively.

When switches S_2 and S_3 are opened, the V_G read by the electrometer decays according to the RC time constant of the meter, i.e. $R_M C_M$, only. The voltage decay behavior of the meter is shown by curve No. 1 in Fig. 6. Clearly, curve No. 1 decays quite slowly. From the V_G read at a decay time t_D of 200 s, one can obtain an approximate RC time constant according to the following equation:

$$V_G(t_D) = V_c \exp(-t_D/RC). \quad (4)$$

In this work, it is found that the RC time constant of the meter is 1,328,233 s. Similarly, the voltage decay behavior of the system including the meter is obtained by closing switch S_2 and is shown by curve No. 2 in Fig. 6. It is observed that curve No. 2 decays faster than curve No. 1. This is mainly due to the reason that R_s is much smaller than R_M . The RC time constant found from curve No. 2 according to eqn (4) is 20,925 s. Finally, the voltage decay behavior of the device including the meter and the system is obtained by closing both switches S_2 and S_3 and is shown by curve No. 3 in Fig. 6. It is observed that curve No. 3 decays slower than curve No. 2. This is due to the significant increase of capacitance when C_{ox} is added although the total resistance is reduced. The RC time constant found from curve No. 3 according to eqn (4) is 42,925 s.

Note that in the voltage range of V_G discussed in Fig. 6, the MOS(p) device is biased in the accumulation region as can be seen from Fig. 4. Therefore, it is reasonable to assume that the device capacitance is C_{ox} . It is noted that the C_{ox} is 213 pF in this work. Besides, the C_s with a value of 4 pF can be obtained by a separate capacitance measurement. Since the RC time constant of curve No. 1 is much greater than that of curve No. 2 or curve No. 3, the effect of R_M can be neglected in comparison with R_s or R_{ox} . From the measured RC time constant as mentioned above and the known C_{ox} and C_s , one can obtain the R_s and R_{ox} easily based on the equivalent circuit shown in Fig. 5b. The R_s and R_{ox} found are 5.2×10^{15} and $2.1 \times 10^{14} \Omega$, respectively. It is believed that the R_{ox} of an oxide may be dependent on the voltage. Based on the technique proposed in this work, the voltage-dependent R_{ox} can be obtained by suitably choosing the t_D which corresponds to a certain voltage of interest. It is of course very tedious to find all the R_{ox} within the $C-V$ sweep range. However, since the values of R_{ox} within a certain voltage range should be of the same order of magnitude for a good insulator, it is believed that, for simplicity, a R_{ox} found from a certain choice of t_D is informative enough for the discussion of the effect of R_{ox} on D_{it} .

Figure 7 shows the distribution curves of D_{it} vs energy E_t-E_i obtained from the $C-V$ curves shown in Fig. 4 with and without removing the effect of R_{ox} . As discussed earlier in this work, an existence of R_{ox}

Fig. 4. Experimental quasi-static and high-frequency $C-V$ curves of a MOS(p) capacitor with sweep rate dV_G/dt as a parameter.

Fig. 5. (a) Schematic diagram of the charge-then-decay measurement system. (b) The equivalent circuit of the measurement system shown in (a).

should result in an error in the D_{it} obtained from the measured quasi-static $C-V$ curves. So, the initial distribution curves of D_{it} obtained from the $C-V$ curves with a dV_G/dt of -0.002 , -0.005 and -0.01 V s^{-1} , i.e. curve Nos 1, 2 and 3, respectively, are different from each other. The smaller the dV_G/dt , e.g. -0.002 V s^{-1} , the larger the D_{it} found, e.g. curve No. 1. This is expectable according to eqn (1) when R_{ox} exists. If the effect of R_{ox} is removed according to eqn (1), the D_{it} data should be decreased. The refund distribution curves of D_{it} after removing the effect of R_{ox} for curve Nos 1, 2 and 3 are presented by curve Nos 1', 2' and 3', respectively, in this figure. As can

be seen from this figure, the curve Nos 1', 2' and 3' are nearly coincidental in the midgap energy, i.e. $E_t - E_i = 0 \text{ eV}$. The consistency of the D_{it} found from three different sweep rates indicates that the R_{ox} found is quite true. It is believed that the D_{it} after removing the R_{ox} effect is more reliable than that before removing.

3.2. Sample having a hysteresis $C-V$ behavior

It is known that the dual-sweep method is not applicable to a sample having a hysteresis $C-V$

Fig. 6. Voltage decay behavior of the measured gate voltage V_G vs decay time t_D for three different combinations of meter, system and device.

Fig. 7. Distribution curves of interface trap density D_{it} vs energy $E_t - E_i$ obtained from the $C-V$ curves shown in Fig. 4 with and without removing the effect of oxide resistance R_{ox} .

Fig. 8. (a) Quasi-static and high-frequency $C-V$ curves of a ^{60}Co irradiated MOS(p) capacitor. There are hysteresis phenomena existing in the $C-V$ curves. (b) Voltage decay behavior of the sample tested from two sweep directions, i.e. from accumulation and inversion. (c) Distribution curves of D_{it} before and after removing the R_{ox} effect for both sweep directions.

phenomenon[6]. However, the hysteresis $C-V$ phenomenon may often occur in some studies, such as irradiation[9]. In this experiment, a sample with a d_{ox} of 350 Å is used. The sample is irradiated by ^{60}Co with a total dose of 1 Mrad. The C_{LF} and C_{HF} curves after irradiation are shown in Fig. 8a. Clearly, many

slow trap states are created near the SiO_2/Si interface due to irradiation since the $C-V$ curves appear as hysteresis phenomena. Now, the dual-sweep method is of no use in the elimination of the R_{ox} effect on D_{it} . Based on the charge-then-decay method, the voltage decay behavior obtained from the two cases, i.e. decay from accumulation and decay from inversion, are shown in Fig. 8b. The R_{ox} s found are 3.17×10^{14} and $2.85 \times 10^{14} \Omega$ as indicated in Fig. 8b. These are quite consistent. The distribution curves of D_{it} before and after removing the R_{ox} effects for both sweep directions are shown in Fig. 8c. Clearly, the distribution curves of D_{it} after removing the R_{ox} effect are nearly independent of sweep direction. It is therefore believed that these are more reliable than those before removal.

4. CONCLUSIONS

The effect of R_{ox} on the determination of D_{it} is important. From the dependence of the quasi-static $C-V$ curve on dV_G/dt , one knows that a finite value of R_{ox} exists in a MOS capacitor. The charge-then-decay method is useful in finding R_{ox} . After removing the effect of R_{ox} on quasi-static $C-V$ curves, reliable distribution curves of D_{it} are obtainable.

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