Oxide Charges Densities Determination Using Charge-Pumping Technique With BTS in MOS Structures

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Abstract: - A New electrical method, using charge-pumping (CP) technique under bias thermal stress (BTS), has been described in this paper. This technique is based on the charge-pumping measurement which in turn used to extract the flat-band voltage before and after an applied bias voltage at high temperature. The obtained flat band voltage shift, that is due to redistribution of the mobile ionic charges, or to generation of the oxide trapped charge or both, may be used to determine their densities.

Key-Words: - Oxide charges, charge pumping technique, bias thermal stress technique, flat-band voltage, oxide charge, mobile ionic charge density, oxide trapped charge density.

1 Introduction

A major breakthrough in semiconductor processing occurred in the early 1960, with the development of the silicon planar process that was described first by Hoerni [1]. However, attempts at MOSFET fabrication were blocked by charge migration problems, which led to deterioration of their electrical characteristics. In the period 1963-1964, various charges associated with the thermally oxidized silicon structure were observed to cause serious yield and reliability problems. Subsequently, a number of investigations concerning oxide charges were started in various laboratories and many have continued to the present time. During that period, it has been generally established that four general types of charges are associated with the MOS system [1-3]. The four general types of charges are interface-trapped charge, fixed oxide charge, oxide-trapped charge and mobile ionic charge. Initially, most of the studies were devoted to the processing parameters so that their adverse effects on device properties could be minimized. More recently, efforts have been focused on a quantitative understanding of the densities, cross sections, and the nature of the oxide charges and traps so that ultimate device performance might be achieved. With further process refinements, the first reliable and reproducible discrete MOSFET's and simple integrated circuits (IC's) were produced on commercial basis in that period.

The serious problem of instability is caused in the devices by one type of oxide charges such as mobile oxide charge which is commonly quantified by using a MOS capacitor and by measuring the flat-band voltage shift (ΔV_{FB}) that is due to an applied bias-temperature stress (BTS). The mobile oxide charge is not related to the structure of the Si-SiO2 system. It is just due to impurity ions introduced during or after processing. This means that in principle mobile oxide charge can be avoided if care is taken to prevent these impurities from reaching the device (during or after processing).

Back in 1965 the shift in the flat-band voltage was attributed by Snow et al [4] to the motion of alkali ions in SiO2. At that time one knew from conductivity studies that the alkali atoms are so abundant every where that their ions could easily be introduced and incorporated in layers of oxide grown on silicon.

A few decades ago the amount of contamination was so high that a stable device could not be manufactured and thus the other types of charges could not be investigated. Nowadays these contamination problems have been greatly reduced by using guttering and very "clean" processing techniques. In laboratories it is somehow believed that mobile oxide charge no longer plays an important role in the observed instabilities of semiconductor devices and that mobile ions in SiO2 are only of historical importance. This contention has been now disproved and the importance of the study of mobile ions in the oxides has again been revived. It is, because, not only the initial mobile ion contamination but also the activation of the already existing neutral sodium of the device during the subsequent processing stages which can cause serious problems in device performance.

Even in samples containing initially very low concentrations of oxide charges such as mobile ions and oxide trapped charge, these charges can be enhanced

under the influence of exposure of ions, X-rays, and laser beams to the SiO2 layer. As these types of beams play an increasingly important role in the present and future processes, instability due to the resulting mobile Na+ ions and oxide trapped charges may be anticipated.
There are many techniques that are commonly used to study the nature and the properties of oxide charges in MOS structure as well as to measure their densities [1-8] such as A-High Frequency MOS C-V measurement [2-5], Conductance method, and Thermally Stimulated Ionic Current (TSIC) method [9-12]. However, a few of them have been standardized due to their draw backs. In this work a new methods have recently been developed that may be used to measure the densities of the oxide charges using the charge-pumping technique [13, 14].
In this new method a Charge-pumping current measurement is investigated before and after bias thermal stress (BTS). The produced charge-pumping current curves can be used to extract the flat-band voltage shifts that may be due to redistribution of the oxide charges such as mobile ions and to recombination of oxide trapped charges. These curves and shifts can be used to determine the density of mobile ions as well as the trapped charges. But, this is can be done only if the effect of the two types of oxide charges can be separated. Since the trapped charge will contribute in producing the charge pumping current peak then, the pumping charge technique may be used to obtain the trapped oxide charge density change.

2 Oxide Charges Defects

The Si-SiO2 system is formed when a layer of silicon dioxide (SiO2) is either grown thermally or deposited by chemical vapor deposition (CVD) processes on a silicon substrate. In either case, a thin SiOx layer is formed at the interface between the two materials. In the Si-SiO2 system, defects are induced either in manufacturing processes or by high-field effects such as hot-carrier injection.

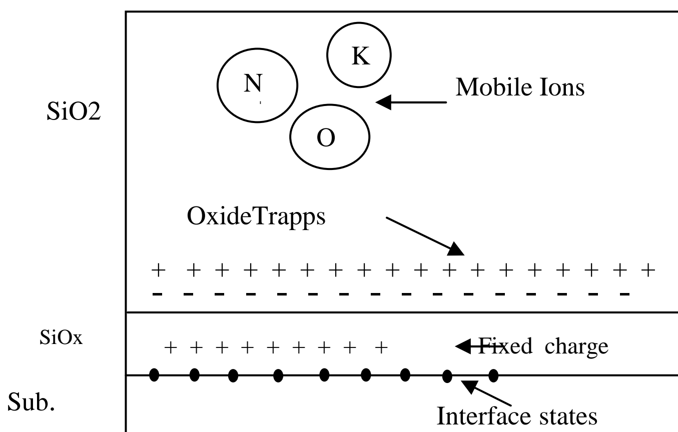

Fig.1. Locations of charges in the MOS oxide.

Early studies of the MOS devices show that the threshold voltage Vt and the flat band voltage Vfb could strongly be affected by these charges. The understanding of the origin and nature of these charges is very important if they are to be controlled or minimized during device processing [1-3]. The net result of the presence of any charge in the oxide is to induce a charge of opposite polarity in the underlying silicon.
The amount of charge induced will be inversely proportional to the distance of the charge from the silicon surface. Thus, an oxide charge residing in the oxide very near the Si-SiO2 interface will reflect all of its charge in the silicon, while an oxide charge near the oxide outer surface will cause little or no effect in the silicon. The oxide charge is measured in terms of the net charge per unit area at the silicon surface. Most oxide charge quantifications can be made using the capacitance voltage (C-V) method. This method is simple and rapid [1,2] and in most cases provides a quantitative or at least a semi-quantitative measure of the surface charge. The oxide charges can be classified into four types as proposed by a committee of scientists' [1,3] in 1980. These types of defects in the Si-SiO2 system are the fixed oxide-charge Qf, the mobile ionic charge Qm, the interface-trapped charge Qit, and the oxide-trapped charge Qot. Figure 1 illustrates the defects and their location in the Si-SiO2 system. Only two types of oxide charges such as oxide trapped charge and mobile ions and have been studied in this work along with the methods that allow measuring their density.
Oxide trapped charges (Qot) may be positive or negative due to holes or electrons trapped in the bulk of the oxide, similar to interface trapped charges with the only difference that they exist in the bulk [15]. Trapping may be resulted from any phenomenon which either create or inject carriers in the bulk of the oxide such as ionizing radiation (including X-ray, gamma ray, low and high-energy electron irradiation) or avalanche injection. Like the interface-trapped charges, a low temperature (300° C) could eliminate the oxide-trapped charges induced by radiation, anneal in an inert ambient. Either the oxide trapped charge distribution or the total trapped charge and its centroid can be quantitatively determined in the oxide by using the most common methods such as etch-off C-V method or photo I-V method [1]. The former method can be investigated by etching off the oxide thickness and measuring either the number of traps in etched-off oxide or the number of traps remaining in the oxide by C-V technique. The latter method is used by DiMaria et al [15] to determine the total oxide trapped charge and the charge centroid. Przewlocki [16] also used this method to determine the trapped charge density and distribution.

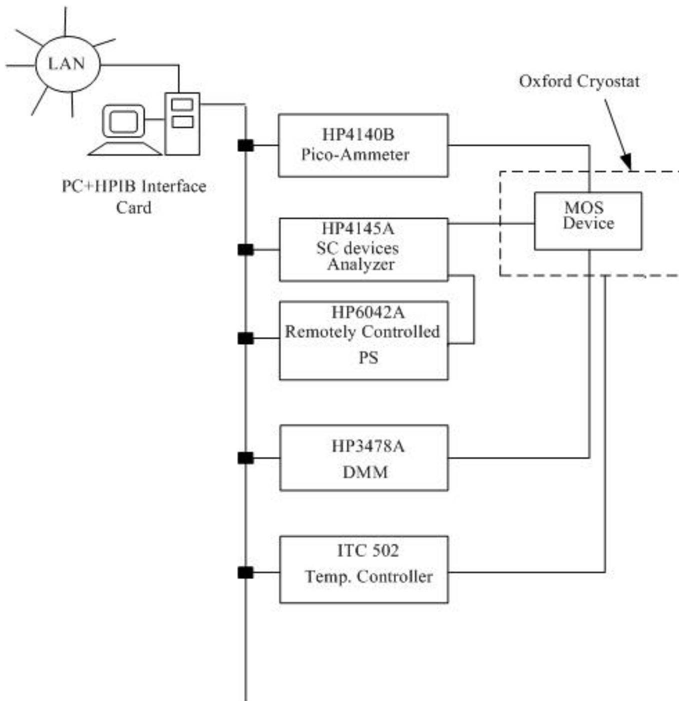

Fig.2 Experimental set up for charge pumping current And CV measurement with BTS.

A mobile ionic charge in thermal oxides were the first charge to be extensively investigated since further studies in the SiO2 system could not be carried out until the mobile ion level was minimized. The mobile ionic charge is due to ionic impurities such as Li+, Na+, K+, and possibly H+. This charge can easily move from one edge to the other of the oxide layer under thermal-electrical stressing, and the resulting movement of charge can result on an unwanted instability and a change in the electrical device parameters [1,3]. The full study of the effect of mobile ionic charge and how to determine its density are discussed in details in the next chapters. The effect of ionic drift that is caused by electric field can be effectively minimized in a number of ways. The most commonly employed approach is to eliminate, through the use of ultra-clean processing techniques, as much ions to contamination in the oxide as possible. For example, great care must be taken to keep the quartz walls of the furnace in which the oxide is grown virtually sodium free. Krieglar et al [1] have reported that a mixture of hydrogen chloride gas and dry oxygen is extremely effective for the "cleaning " of quartz furnace tubes. They also found that the addition of a small percentage of hydrogen chloride or chlorine to the oxidizing atmosphere significantly improved the electrical stability of SiO2 films grown in the presence of dry oxygen.

3 Experimental Setup

The characterization tools used to investigate all the techniques mentioned in the previous section are shown in Fig.2. These measuring instruments are arranged and controlled by PC in such a way that measured data and needed parameters are extracted with high resolution. Therefore, automated operation from measurement to analysis is necessary. This can be achieved by using instruments that can be remotely controlled by computer. The IEEE bus (also known as, HPIB, GPIB or ASCII bus) which is used as an interface bus for the Hewlett Packard instruments, is one of the most popular data buses used in the industry and laboratories. It is a carefully defined instrumentation interfacing means that simplifies the integration of measuring instruments and a calculator or computer into a system [17].

4 Charge Pumping Technique with BTS

The simplified experimental set up for measuring the charge-pumping current is illustrated in Fig.3 [13, 14]. A gate voltage signal of amplitude such that it can sweep the energy level from the deep accumulation to the deep inversion is applied to a MOSFET as shown in Fig.3. The drain and source are tied together and connected to a dc reverse-biasing voltage. A dc Pico-ammeter (HP4140B) is connected to a substrate to measure the resulting charge pumping current. Experimental measurements have been carried out on a number of encapsulated wafers in 64-pin PGA package with oxide thickness 40 and 12 nm respectively. The charge pumping current of the given MOS device is first measured before applying any stress. Then the MOS structure is heated to a certain temperature up to 100°C and held for a period up to 15 min, which is long enough to ensure that all the available ions at a given temperature drift completely across the oxide. At the same time a positive gate bias of 5 V is applied which is enough to produce an oxide field greater than 2 MV/cm. After holding the MOS device at elevated temperature and high electric field for the required period, it is cooled back to room temperature so that no further redistribution of oxide charges takes place during the second charge-pumping current measurement. The flat band voltage shift between the charge-pumping current curve before and after bias-temperature stress is partially due to the mobile ion concentration drifted at a given

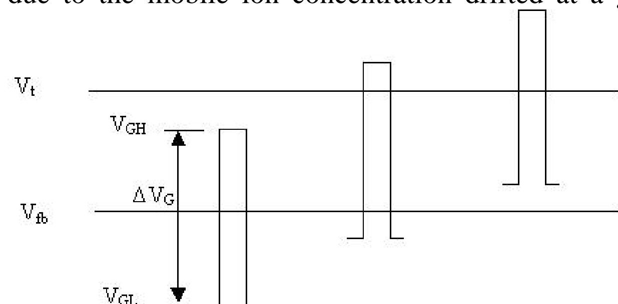

Fig.3 illustration of the base level method on a nMOSFET.

temperature. The flat-band voltage shift may be used to determine the mobile ion concentration within the oxide layer in MOS device.

4.1 Theoretical Background

When a MOSFET transistor is pulsed into inversion, the surface region becomes deeply depleted and electrons will flow from the source and drain regions into the channel where some of them will be captured by the surface states. When the gate pulse is deriving the surface states back into accumulation, the mobile charges drift back to the source and drain under the influence of the reverse bias, but the oxide charges trapped in the surface states will recombine with the majority carriers from the substrate. The oxide trapped charge Qot that will recombine is given by [18]:

$$Q_{ot} = A_g .q.\int D_{ot}(E)dE \quad (1)$$

Where Ag is the area of the channel of the MOSFET (cm^2) and $D_{ot}(E)$ is the oxide trapped charge density at energy E.

When applying repetitive pulses to the gate with frequency f, varying the pulse base level from inversion to accumulation keeping the amplitude of the pulse constant, the oxide charge Qot will give rise to a current

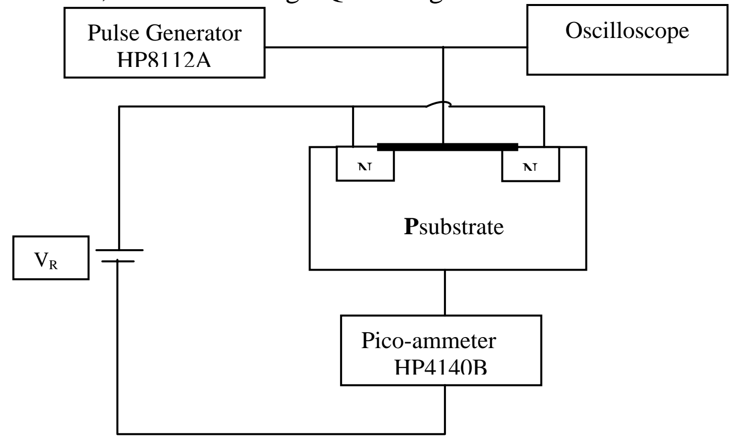

Fig.4 Simplified Experimental set-up for charge

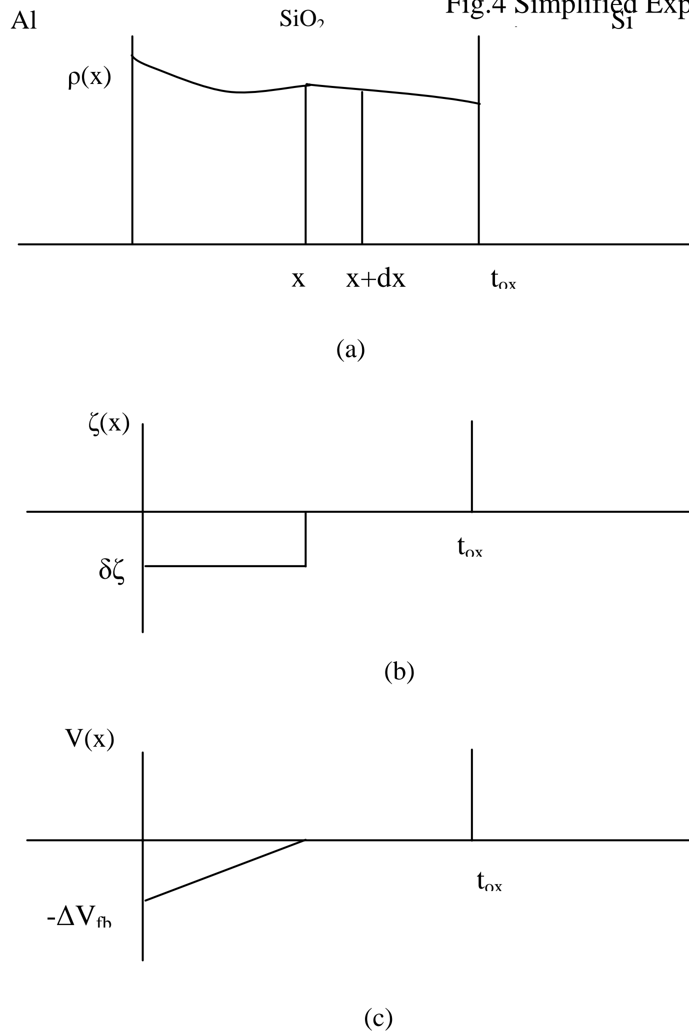

Fig.5 Distribution of (a) charge, (b) field and (c) potential within the oxide of MOS structure.

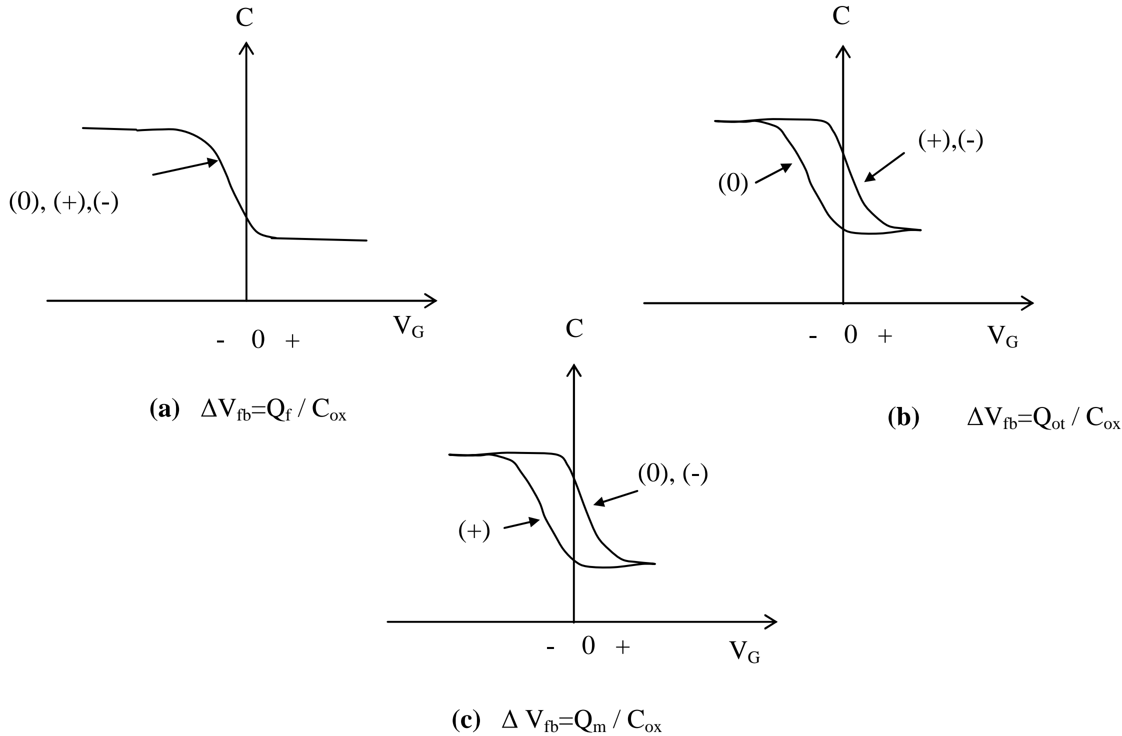

Fig. 6 Diagram illustration of ionic charge effect separation through the use of BTS method. (0) the initial CV curve, (+) after positive bias stress, (-) after negative bias stress.

in the substrate. This current can be written as:

$$I_{cp} = f.Q_{ot} \tag{2}$$

By measuring this substrate current, an estimate of the mean capture cross-section, threshold voltage and the interface-state density over the energy range swept by the gate pulse can be obtained. Furthermore, the charge-pumping current Icp that undergoes an abrupt increase from zero to its maximum value after a certain position of the gate pulse base level can be used to determine the flat-band voltage. It has generally been found that the value of the base voltage corresponding to the half of maximum current Icpm/2, in the Icp-Vg curve is the flat-band voltage [19].

5 The Oxide Charges Effects Separation

Whether they are due to mobile ions or to other types of oxide charge are distributed unevenly in the bulk, that is their density ρ(x) varies with distance (and also with time in case of time-dependent stress). To study the influence of a charge distribution on the properties of the MOS structure, at first, the effect of only those charges which are located in a layer between x and x+dx is calculated. The origin of the x-axis is taken at the metal-oxide interface as shown in Fig.5.

The previous work found that flat-band voltage shift is due to the change in the redistribution of mobile ionic charges and recombination of trapped charges under the bias-temperature stress. However, the oxide fixed charge distribution does not change under this treatment [3].

In a second step, the effect of the various layers from zero to tox is added. Using Gauss`s law, the electric field in the oxide ζ_{ox} exhibits a discontinuity $\delta\zeta_{ox}$ when crossing this charge layer. This discontinuity is given by

$$\delta\zeta_{ox} = \frac{\rho(x)dx}{\varepsilon_o \varepsilon_{ox}} \tag{3}$$

For ensuring flat band condition in the silicon, ζ_{ox} must be zero on the right hand side of the discontinuity. Thus the profile of the electric field should be such as shown in Fig.5 and the corresponding gate voltage that ensures flat band conditions is given by:

$$\delta V_{fb4} = \frac{-\rho(x)xdx}{\varepsilon_o \varepsilon_{ox}} \tag{4}$$

Using a classical result of electrostatics, namely the superposition theorem, the effects of all layers comprised between zero and tox are added and the gate voltage Vfb, which is necessary to ensure a flat-band condition at the Si-SiO2 interface, is found to be

$$\Delta V_{fb} = -\int_0^{t_{ox}} \frac{\rho(x)xdx}{\varepsilon_o \varepsilon_{ox}} \tag{5}$$

Where $\rho(x)$ is the volume-density of charge within the oxide, tox the oxide thickness, εo the permittivity of the free space, εox the relative permittivity of oxide and the distance x is measured from the metal-oxide interface.

The effect of each charge layer depends on its distance from the oxide-silicon interface as can be seen in Eq.(5). A layer has no effect if it is located at the metal-oxide

interface and has a maximum effect if it is located at the oxide-silicon interface. If the charge contained in the oxide is due to mobile ions and oxide traps Q_m, a change in the distribution, caused by an applied stress (temperature + electric field), gives rise to a new value of the flat-band voltage Vfb. This effect can be used to obtain the density of mobile ions.

5.1 Conventional Technique (C-V with BTS)

This method is carried out by measuring the shifts in the flat-band voltage Vfb under the influence of the BTS. A more reliable estimate of Vfb is obtained from the portion of high frequency C-V curve corresponding to the depletion.

In the case of a real structure, the shift in the flat-band voltage is due to the sum of the effects of oxide charges and the work function difference. This section presents how to distinguish between flat-band voltage shift due to mobile ionic charge and those due to the other types of oxide charge. Considering an experiment where the only oxide charge is oxide fixed charge (Qf), the initial high frequency C-V curve is labeled (o) in Fig.6a. After heating at 180°C during a half hour with a positive gate bias (with respect to substrate) producing an electric field of a few million volts per centimeter across the oxide, and cooling back to room temperature, the curve labeled (+) in Fig.6a is obtained. Repeating the bias-temperature stress with negative bias yields curve (-) in Fig.6a. Figure 6a shows that no shift in the C-V curve is produced. Therefore the oxide fixed charge distribution does not change under this treatment. Repeating this bias temperature stress experiment with oxide trapped charge (Qot) that anneals out at low temperature, curves (o), (+), and (-) in Fig.6b show that the oxide trapped charge density is changed. Gate bias polarity has no effect. Therefore, it is most likely that the oxide trapped charge centers are immobile. Finally, Fig.6c shows the results of repeating this experiment on an oxide contaminated by mobile ionic charge (Qm). Initially Vfb is low, and after positive bias stress it increases. With negative bias stress, Vfb returns to its original value. These results are attributed to mobile ion movement that alters the flat-band voltage.

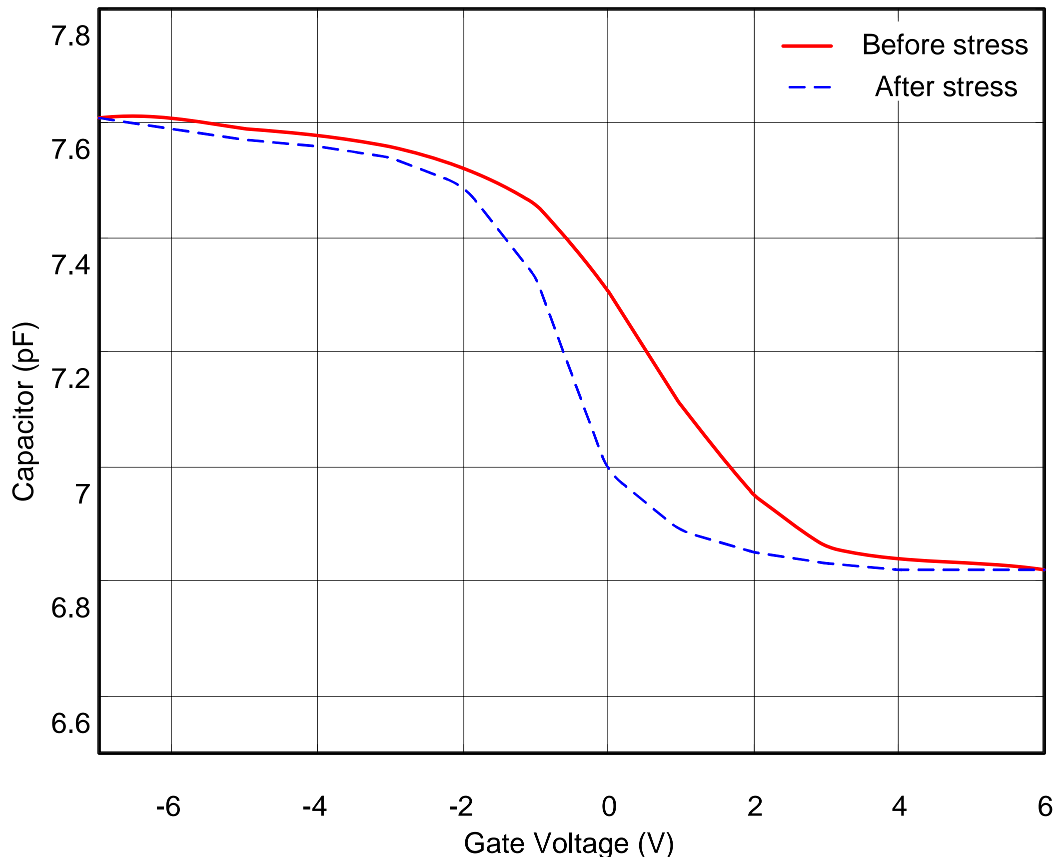

Fig.7 HF capacitance-gate voltage curve of nMOSFET.

Table 1. Values of the flat-band voltage shifts, trapped charge density and mobile ion density for different types of MOS devices.

Devices	ΔV_{fb} using CP (mV)	ΔV_{fb} using CV (mV)	ΔI_{cp} (nA)	Qm 10^{12} (cm^{-2})	Qot 10^{10} (cm^{-2})
pMOSFET	50	45	0.8	4.44	0.11
nMOSFET	62	50	0.4	4.75	0.14

5.2 Recent Developed Technique (CP with BTS)

Since the charges contained in the oxide such as mobile ions or oxide traps, a change in their densities after an excitation (temperature, photons) causes also a shift in the flat band voltage but in opposite polarity. This effect may be separated through the use of a change in the maximum charge pumping current ΔIcp. After applying bias thermal stress to MOS device, the induced charge that is due to the mobile ions or to oxide traps can be considered as a charge sheet located at the oxide-silicon interface. Under this specific situation, expression (5) becomes

$$\Delta V_{fb} = \frac{(Q_m - \Delta Q_{ot})}{C_{ox}} \quad (6)$$

where the change in the trapped charge ΔQ_{ot} can be calculated from Eq.(2) as follows

$$\Delta Q_{ot} = \frac{\Delta I_{cp}}{f} \quad (7)$$

The substitution of Eq.(7) into Eq.(6) gives the total amount of mobile charges [20]

$$Q_m = \Delta V_{fb} C_{ox} + \frac{\Delta I_{cp}}{f} \quad (8)$$

From the measurement of the change in the maximum charge pumping current and the shift of the flat band voltage, the amount of mobile ions can be obtained.

6 Experimental Results and Discussion

The produced flat band voltage shifts by BTS stress were measured by both charge pumping CP and high frequency capacitance voltage CV technique as shown in figures 7-10. These shifts that are due to total effect of the oxide charges that consist of a contribution of the mobile charge drift and a contribution of trapped charges effect. In the CP curves as shown in Figs 8 and 10, It can be noted that there is a shift in the flat band voltage and a change in the CP current peak magnitude. These phenomena can be used to determine the oxide trapped charge density and the amount of mobile ions. However, The separation of mobile ion density from the traps density cannot be investigated in the case of HFCV technique. Through the use of the obtained curves of different MOSFET's and Eq.(8), the mobile ions density can be determined as given in Table.1. Besides, this table shows values of the flat-band shift voltage shifts ΔV_{fb} for different devices as obtained by the CP method as well as by the CV method.

7 Conclusion

The obtained results by using the present method are quite reliable and are not affected by an error in the measurement of V_{fb} which may be caused by the traps level density at Si-SiO2 interface. It is so because in charge pumping technique, any change in the oxide trap level density can be measured by current and its effect can be subtracted from the measurement of V_{fb} shift that is due to BTS. It may be noted that as the bias-temperature treatment causes small changes in interface trap level density, the maximum CP current before and after bias-temperature drift changes little bit. It may also be noted that the shift in flat band voltage has a lower value when the same amount of ions is present in a thinner oxide. For current IC fabrication processes, a flat-band shift of 50 mV is acceptable which in a technology using an oxide thickness less than 10 nm corresponds to an ionic density of about 10^{10} ions.cm-2 [19,21].

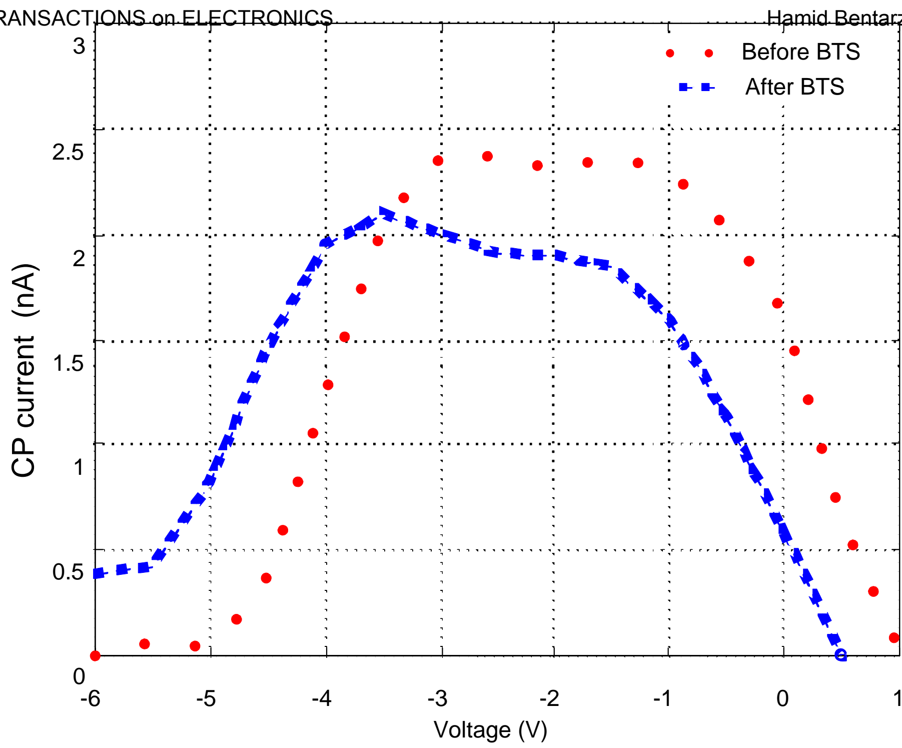

Fig.8 Charge pumping current as function of the gate bias voltage for nMOSFET.

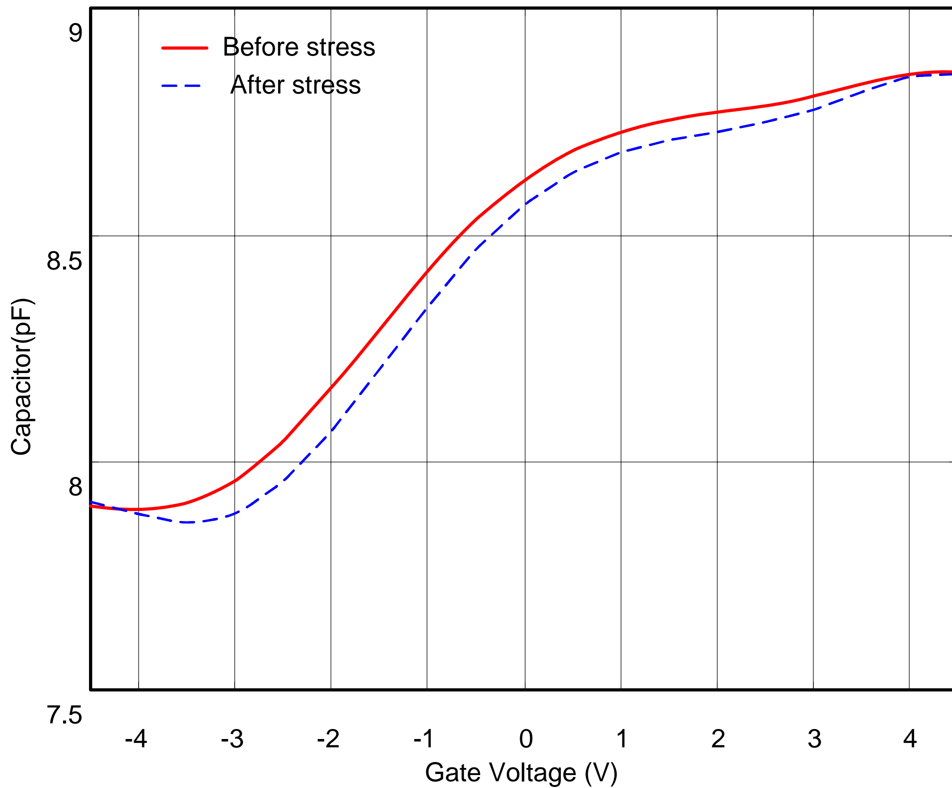

Fig.9 HF capacitance as function of gate bias voltage for p-MOSFET

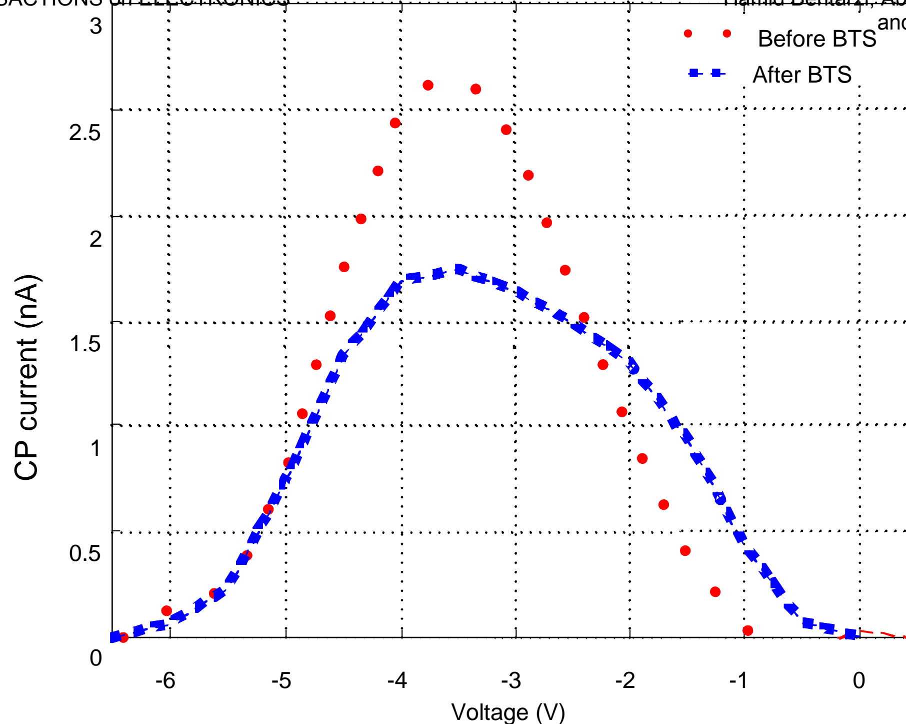

Fig.10 Charge pumping current as function of the gate bias voltage for pMOSFET.

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