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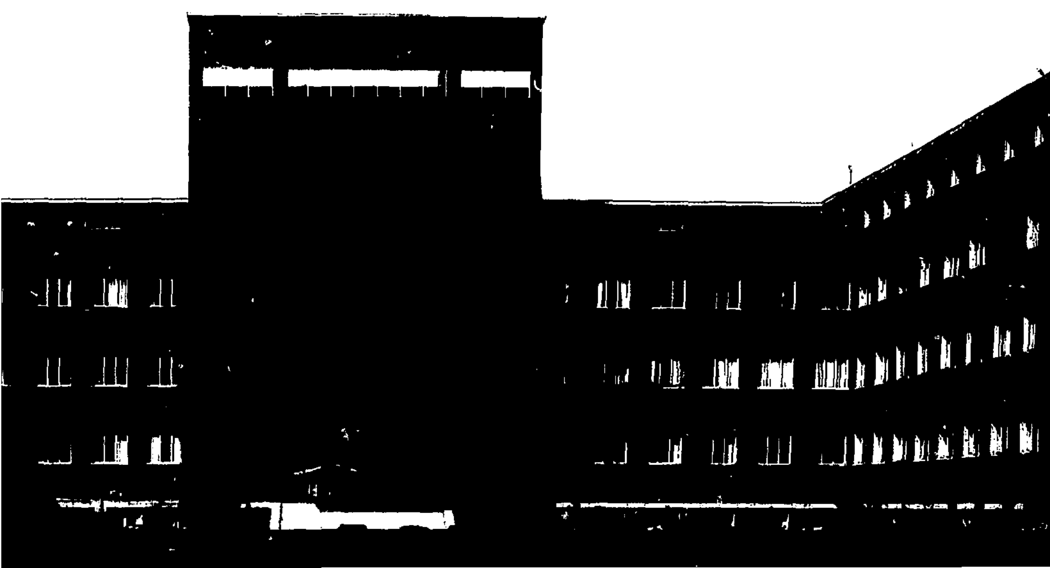

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ABSTRACT

A new automated quasi-static C-V measurement technique for MOS capacitors is developed. This technique uses an integrating electrometer to measure the charge accumulated on a MOS capacitor in response of a small applied voltage step. Making use of the internal data storage system of a commercial electrometer and a personal computer, the charge Q on the MOS capacitor is measured as a function of time t and stored. The capacitance is then obtained by analyzing this Q-t data set. A Si MOS sample is measured and analyzed in terms of interface charges as an example. Advantages over a commercial quasi-static meter which uses similar measurement technique are presented. It is also shown that this technique is potentially capable of measuring both high and low frequency C-V curves simultaneously.

I. INTRODUCTION

Capacitance-Voltage (C-V) measurement techniques are widely used for evaluation and characterization of Metal-Oxide-Semiconductor (MOS) structures in Si electronic device technology. The power of the C-V technique comes from the fact that many properties of the insulating oxide layer, the silicon substrate and their interface can be determined easily and accurately. For example, a single high frequency C-V measurement may reveal type and concentration of dopants in the Si substrate, the thickness and the charge content of the oxide layer, the type and the concentration of interface states. Among these, interface states play an important role both in the operation of devices and in the interpretation of C-V measurement data itself. Therefore, measurement of interface states has been one of the most important tasks in MOS technology. The accuracy in extracting the density of states by utilizing one single high frequency C-V measurement depends on the assumptions made about the Si substrate and about the measurement itself and in many cases, these assumptions may not be valid. Common practice for eliminating the error sources is to combine a high frequency C-V curve with a low frequency one[1]. This method enables us to determine the related parameters experimentally and thus removes the need for theoretical assumptions.

With 'low frequency' it is meant that both minority carriers and interface states 'follow' the signal of the measurement. In most cases, frequencies below 1 Hz may be needed for a true low frequency measurement. At such low frequencies, C-V techniques employing admittance bridges or lock-in amplifiers suffer from noise because very small a-c displacement currents must be measured. A method developed by Kuhn[2] and known as voltage ramp method has been widely used for low frequency measurements. This technique, like the above mentioned ones, measures very low displacement currents and has similar problems. An alternative and perhaps the best way for obtaining the low frequency C-V curve is to measure the charge accumulated on the MOS capacitor for various values of the gate bias. This technique, as first suggested by Ziegler and Klausman[3] and later extended by Brews and Nicollian[4], makes it possible to reach close to DC conditions i.e., practically zero measurement frequency, without significant noise problems. This charge measurement technique was further improved and modified to develope a commercial low frequency C-V meter (Keithley 595). This instrument, as explained by Mego[5], uses a feedback charge measurement circuit to measure the displacement charge corresponding to a small voltage step, reducing several error sources. A comparison of this meter with another one (HF 4140B) has recently been published by Sadwick[6]. Since the frequency of the low frequency measurements is not absolute zero in most cases, these methods are often called quasi-static C-V measurements.

During the study of electrical properties of Ge-implanted Si[7] we developed an automated technique for quasi-static C-V measurements. The measurement concept of this method is similar to that used by the Keithley 595 quasi-static C-V meter. The major advantage of our technique is that it employs many measurement points unlike the three point measurement technique of Keithley 595. It offers more flexibility and control over measurement parameters. This is particularly useful when samples with unusual characteristics will be measured. In this work, we present the details of this technique. As an example, a Si MOS capacitor is measured and analyzed in terms of interface states. It is also shown that this method can in principle measure high and low frequency curves simultaneously. For this and other purposes further improvements are proposed.

II. EXPERIMENTAL SETUP AND MEASUREMENT PROCEDURE

The basic circuit for measuring a quasi-static C-V curve is shown in fig.1. A Keithley 617 electrometer in coulomb mode measures the charge on the MOS capacitor for a voltage applied by a Keithley 230 voltage

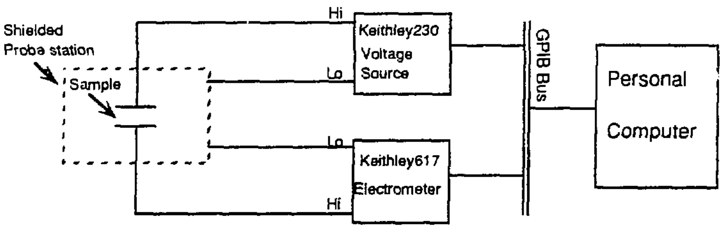
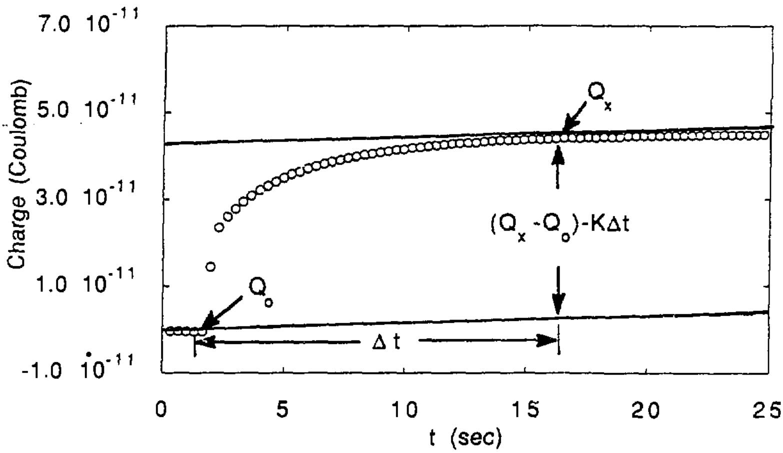
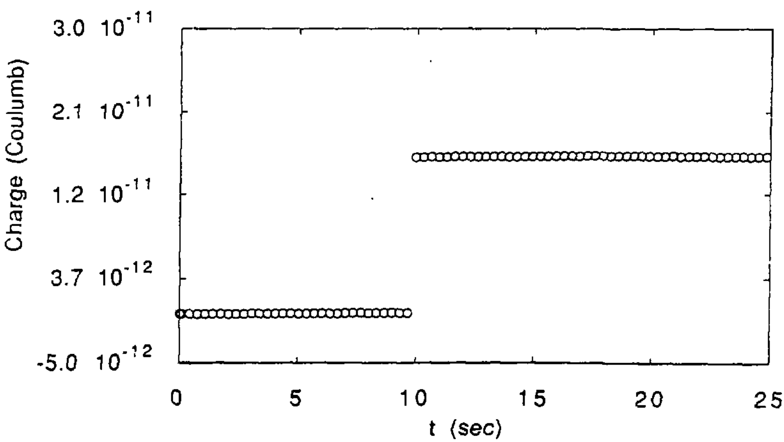


Fig. 1 Block diagram for quasi-static C-V measurements

source. In coulomb mode, the electrometer's input is connected to an integrator. Since the input of this integrator is at virtual ground, the full voltage applied by the voltage source drops over the MOS capacitor. This circuitry is similar to the Keithley 595 quasi-static meter where a voltage source and an integrator are combined in a single meter to take charge measurements at three different times. Both the electrometer and the voltage source are connected to a GPIB bus system so that they can be controlled by a personal computer. A measurement cycle is as follows: The bias of interest is applied to the sample for sufficiently long time to allow the sample to reach equilibrium. This time should be determined experimentally. It may vary from a few miliseconds in the accumulation regime to several minutes in the inversion regime of a C-V curve. The input of the electrometer is zeroed for a while after the sample has reached the equilibrium. By this operation, the capacitor of the integrator at the electrometer input is discharged. Finally, a small step voltage, ΔV(0.1 V in this work), is applied while the charge(Q) on the capacitor is measured as a function of time(t).



(a)



(b)

Fig.2 Q-t curves of a Si MOS capacitor in a) inversion b) accumulation

The internal data storage system of the electrometer is used to take and store 100 measurements . Two measured Q-t curves for a Si MOS sample at inversion and at accumulation are shown in fig.2 a and fig.2 b, respectively. The time interval between two data points is 330 msec. This value is the lower limit that the electrometer can provide for this type of measurement. It is seen that the rise time of the curve shown in fig.2 a is much longer than that of fig.2 b because of the large difference between response times of minority carriers in inversion and the majority carriers in accumulation. Nevertheless, the equilibrium is reached within the period of the measurements (which is about 30 sec) for both cases. Capacitance of the sample may be obtained from these curves by dividing ΔQ measured after the sample has reached the equilibrium by ΔV. In order to eliminate the effect of noise, we calculate the capacitance by fitting a line to the last part of the Q-t curve and use the following equation

$$C = \frac{(Q_x - Q_0) - K \cdot \Delta t}{\Delta V}$$

where Q_0 is the charge measured just before the step voltage ΔV is applied (ΔV is applied after some data points have been measured, Q_0 corresponds to the 4th point of the data set shown in fig.2 a), Q_x is the charge measured after the voltage is applied and equilibrium is reached (90th point in each data set is used), K is the slope of the curve fitted at the point where Q_x is measured and Δt is the time interval between t of Q_0 and the t of Q_x. This calculation procedure is schematically shown in fig.2. The measurement of a Q-t curve in *one single* measurement cycle has some advantages and potential applications : A plot of Q-t curve reveal whether the sample has reached the equilibrium which is an important point for the accuracy of the measurement. The noise and other error sources can be recognized from a Q-t curve as, for example, deviation from the exponential behavior. The correction to the measured data is made by fitting a line to the Q-t curve not by using only two points of it, as is shown in fig.2 a. This further reduces the errors due to fluctuations in the Q-t curve. As will be discussed in the next section, a high frequency capacitance can be in principle obtained from a Q-t curve. Another advantage of this method is that one has full control over the parameters like step voltage, measurement time, waiting times for equilibrium etc. This may especially be desirable when unusual samples like the Ge-implanted ones are being measured[7].

The number of measurements in a single Q-t curve is limited to 100 by the internal storage system of the electrometer. Similarly, the minimum time interval between two measurements is limited by the conversion time of the electrometer which is 330 msec. These limitations can be eliminated by using an A/D converter card in a personal computer instead of internal data storage system of the electrometer. In this case, analog output of the electrometer or a separate integrator can be used. The minimum time interval can then be pulled down to microseconds and the total number of measurement can be chosen freely.

III. AN EXAMPLE : Si MOS CAPACITOR

In fig.3 a quasi-static C-V curve measured by using the technique explained above together with a high frequency curve measured by a PAR 410 C-V Plotter is displayed. The sample used for these measurements is a MOS capacitor fabricated on n-type Si by using a pyrogenic oxidation technique. As seen from this figure, the shape and the position of the low frequency curve are as expected: in accumulation and inversion regions the low frequency capacitance is equal to the oxide capacitance; in the depletion region it roughly follows the high frequency one until the inversion regime is reached or the effects of interface states become significant. The small differences between high frequency and quasi-static curves in the accumulation regime may be attributed to the effect of series resistance of the substrate or the back side ohmic contacts.

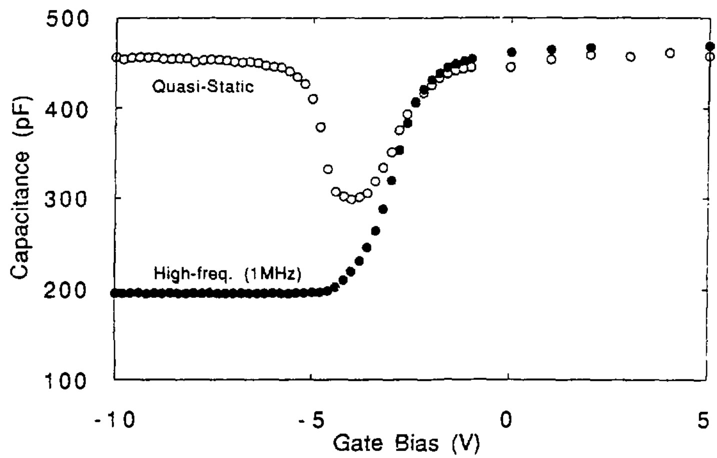


Fig.3 High and low frequency curves of a SiMOS capacitor

To be complete, we performed a calculation for the density of interface states by using low and high frequency curves shown in fig.3. The method used here is the most accurate capacitance method for this type of calculations[1]. The interface state density as a function of position in the band gap is shown in fig.4. A state density below

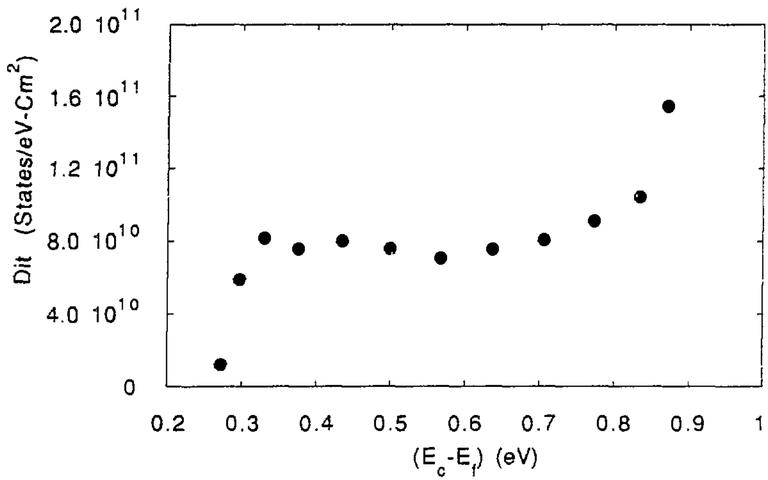


Fig.4 Density of interface states as a function of position in the bandgap of Si.

1×10^{11} (eV^{-1}-cm^{-2}) is usually considered to be acceptable for device production. Therefore, one may conclude that the oxide grown in this experiment has good enough quality for device productions.

It is useful to measure the high and low frequency capacitance simultaneously in order to calculate the density of interface states and dopant concentration accurately. There exist no instrumentation and method performing such a simultaneous measurement by using one single circuitry and one measurement cycle. This seems to be possible by analyzing the nonequilibrium portion of a Q-t curve. A high frequency C-V curve is obtained when minority carriers and interface states can not follow the applied gate signal. Assuming that the rise time of the step voltage applied at time t_0 is infinitely small, there will always be a small time interval in which the minority carrier response may be assumed to be negligible while the majority carriers are in equilibrium with the applied voltage. If the charge accumulated on the MOS capacitor could be measured in this time interval, the associated capacitance found by dividing it by ΔV will be a high frequency one. Unfortunately, the minimum time interval provided by the electrometer is 330 msec which is too long to demonstrate this possibility. With a fast A/D card one may obtain the required time intervals for this application. However, although we can not obtain a high frequency curve with 330 msec time interval, it is possible to obtain one which lies between high and low frequency regimes. Fig.5 shows several ΔQ/ΔV calculated from data points 4 and 7, 4 and 8, 4 and 60 of a Q-t curve of fig.2 b and the high frequency curve obtained by another instrument.

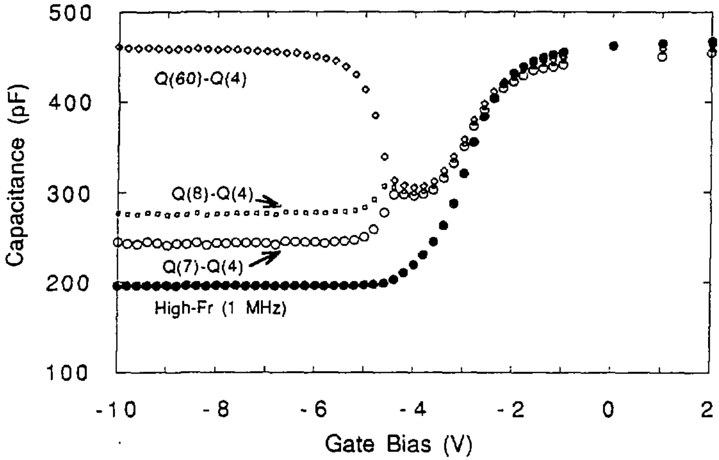


Fig. 5 C-V curves obtained from the nonequilibrium part of the Q-t data. High and low frequency curves are also shown.

The time interval between pt.4 and pt.7 is about 1 sec which is not short enough for a high frequency one and not long enough for a low frequency one. Therefore, the C-V curve obtained from points 4 and 7 lies between the low frequency curve (of points 4 and 60) and the high frequency one.

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