A LOW FREQUENCY C-V MEASUREMENT TECHNIQUE AND ANALYSIS FOR SURFACE STATE DENSITY DETERMINATION

by

Gregg R. Myers
5th Year Microelectronics Student
Rochester Institute of Technology

ABSTRACT

A flexible low frequency measurement system was set up for providing high quality low frequency C-V curves suitable for analysis and a method is described to analyze the low frequency C-V response for surface state density calculations. This method was used to calculate surface densities over a large portion of the band gap for several MOS capacitors.

INTRODUCTION

The response of a MOS capacitor to high and low frequency AC signals superimposed over an applied DC voltage is well documented. Several different techniques including the use of a "lock-in" amplifier and the use of a quasi-static technique have been used to obtain reliable low frequency C-V graphs suitable for analysis [1][2]. The low frequency response is generally more difficult to obtain than the high frequency response. This is due to the fact that most MOS capacitors have such a slow minority carrier generation rate that probing frequencies of around 10 Hz or lower are needed to yield a true low-frequency C-V response. If the probing frequency is not low enough, the experimenter instead sees a C-V response which lies somewhere between the true high frequency and the true low frequency response.

Kuhn has obtained good results for low-frequency C-V curves using the "quasi-static" technique. This technique employs a slowly varying linear voltage ramp and an electrometer. This technique is termed "quasi-static" because there is no superimposed AC signal applied to the gate of the MOS device, only a slowly varying DC voltage. A typical low frequency C-V measurement system might resemble the system shown below:

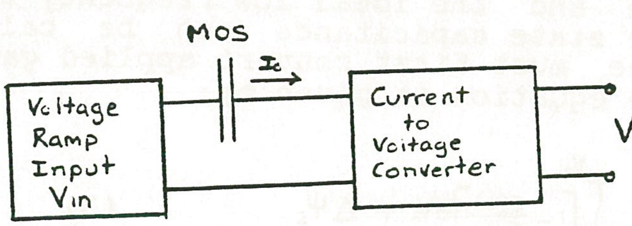

Figure 1

Typical Low Frequency C-V Measurement System

In this system the linear ramp to the MOS capacitor causes a current, Io, equal to C*(dv/dt) to be introduced at the input of an amplifier. The amplifier is configured as a current to voltage converter and causes a voltage, Vo, to be introduced at the output of the circuit and is given by:

$$Vo = K*Io \qquad (1)$$

where K is a constant related to the amplification factor of the amplifier. Unfortunately, most MOS capacitors have capacitances on the order of a hundred picofarads or less and therefore the output voltage needs to be amplified considerably to obtain a reasonable output signal for Vo. This requires an amplifier with a high input impedance which is capable of operating with an extremely low bias current. Instead, an electrometer can be substituted for the amplifier such as the Keithley 600A. This particular amplifier has an input impedance of greater than 10E15 ohms and is capable of measuring current to 10E-12 Amps.

Once an accurate method for measuring the low frequency C-V response is available, several useful parameters can be extracted from the results. For example, Castagne [1] has shown that the interstitial trap density for a MOS capacitor in the energy range from accumulation to the onset of inversion is given by the equation:

$$D_{it} = \frac{C_{LF} C_{ox}}{C_{ox} - C_{LF}} - \frac{C_{HF} C_{ox}}{C_{ox} - C_{HF}} \qquad (2)$$

Where Cox is the oxide capacitance, Clf is the measured low frequency capacitance, and Chf is the measured high frequency capacitance. The problem with this technique is that the surface state density can only be calculated over a very small portion of the energy gap. A better technique allows for the comparison of the actual measured low frequency C-V response to the ideal low frequency C-V response. This technique is derived from the following model which is valid for any MOS device maintained in thermal equilibrium:

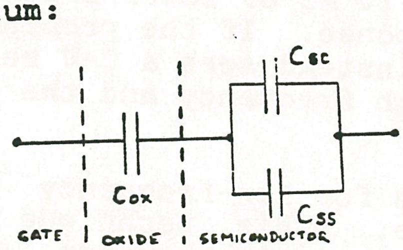

Figure 2

Model Of MOS Device Maintained In Thermal Equilibrium

In this model Cox refers to the oxide capacitance, while Csc is the ideal low frequency capacitance and Css is the capacitance introduced by the surface states. It is therefore evident that if the oxide capacitance and the ideal low frequency capacitance is known, then the surface state capacitance can be calculated. In order to do this one must first convert applied gate voltage to surface potential. The equation is given by:

$$\psi_s = \int_{V_{acc}}^{V_a} \left[1 - \frac{C(V_a)}{C_{ox}}\right] dV_a + \Delta\psi_s \qquad (3)$$

The constant, $\Delta\Psi_s$, is determined by plotting capacitance Vs surface potential for both measured and ideal low frequency C-V responses. The constant is equal to the difference that the measured plot of capacitance vs surface potential needs to be shifted (in terms of surface potential) to agree with the ideal curve in strong accumulation and inversion. Now the actual surface state capacitance as a function of surface potential can be calculated by:

$$N_{SS}(\Psi_s) = \frac{C_{MEASURED}(\Psi_s) - C_{IDEAL}(\Psi_s)}{q} \quad (4)$$

In order to use this method for obtaining the surface state density, it is necessary to know the ideal low-frequency C-V response. Several computer programs are available for this calculation thereby simplifying the technique somewhat.

This report analyzes some low frequency C-V measurements made at RIT and shows how the aforementioned equations can be used to calculate the surface state density for MOS capacitors.

EXPERIMENTAL

The following experimental set-up was used to obtain low frequency C-V plots to be used for analysis:

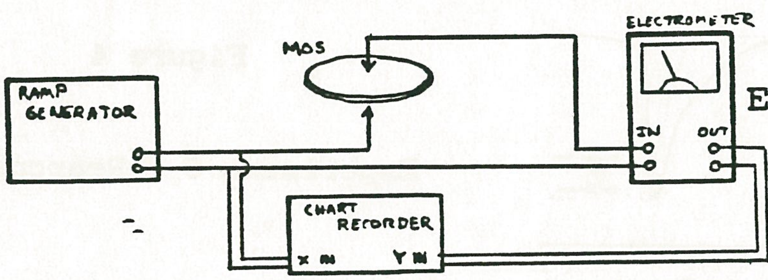

Figure 3

Experimental Low Frequency C-V Measurement System

Shielded coaxial cable was used for all connections. The ramp generator was taken from a high frequency C-V measurement system currently in use at RIT. Some initial tests of the circuit with discrete capacitors indicate that there is some added capacitance in the system which makes the measured current on the electrometer larger than what is should be. To compensate for this error, the oxide capacitance, Cox, is measured with a commercial capacitance meter and the actual measured results obtained from the electrometer are set to this value. Thus a 'conversion factor' between measured current on the electrometer and actual capacitance is determined.

Low frequency C-V curves should also be measured with a light shield over the device under test. The implications of not using a shield will be discussed in the RESULTS section. This is <u>very important</u> if the measured C-V response is to be used for surface state density determination. The chassis ground connections on the chart recorder should be disconnected from the common inputs for the X and Y terminals on the recorder. The reason for this is that oscillations are somehow set up within the measurement system, probably due to feedback imposed by unwanted 'ground loops'. Disconnecting the chassis ground from the chart recorder leaves the chassis of the

recorder electrically "floating" and appears to correct the problem. If this step is not done, a pulsing output appears on the electrometer and C-V measurements are impossible to obtain. Leaving the chart recorder "floating" may be a source of added stray capacitance which should be taken into consideration when evaluating the resulting low frequency C-V response.

The capacitors used for obtaining the C-V responses in this experiment were fabricated at RIT by Gary Heinenkamp. All capacitors measured here were fabricated on <111> P-type silicon and had a gate area of approximately $1X10^6$ square micrometers. The capacitors are intentionally very large in order to make the output current, Io, larger since the larger currents are easier to measure using the available equipment.

RESULTS/DISCUSSION

Several low-frequency C-V responses were obtained using the set-up in Figure 2. An interesting side effect of measuring the low frequency C-V curves is the effect of ambient room lighting on the results. The effect on the C-V response is shown below:

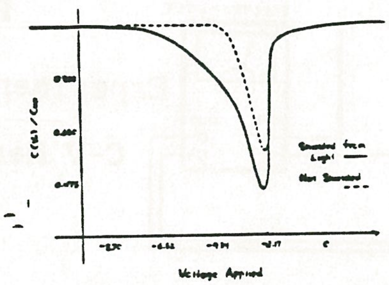

Figure 4

Experiment C-V Response

The difference between the two curves is related to the electron-hole pair generation in the semiconductor caused by ambient room light. Obviously one should shield the MOS capacitor from all light in order to obtain accurate results for surface state densities.

In order to obtain the surface state density for the MOS device, it is first necessary to relate the applied gate voltage to surface potential for both the ideal and the measured low frequency C-V curves. This is easily done by utilizing equation and employing a graphical technique. The graphical technique is shown below:

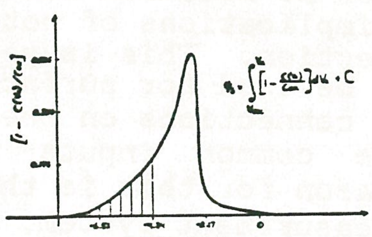

Figure 5

Graphical Technique For Determining Surface Potential As A Function of Applied Voltage

If the measured C-V results are entered into a computer then

numerical integration techniques could be utilized instead. The ideal low frequency capacitance, Csc, can now be determined as a function of surface potential by utilizing equation . A plot of capacitance vs surface potential for the measured and ideal responses is shown below:

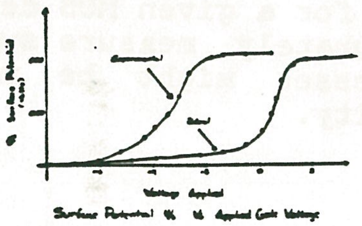

Figure 6

Calculated Surface Potential

Vs Applied Voltage

Now the surface potential can be determined since the difference between the ideal curve and the measured curve (in capacitance) is 1/q times the surface state density. A plot of surface state density vs surface potential calculated from the above results is shown below:

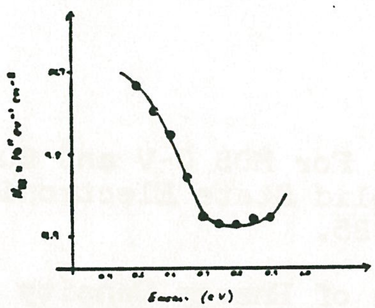

Figure 7

Surface Density Vs Energy

The results of the measured low frequency C-V response are dependent on how accurately the true capacitance of the MOS device can be determined from the measured current flowing through the device. As previously mentioned, the system used in this experiment had some stray capacitance inheritant to the leads connecting up the various components of the system and the fact that the chart recorder was left electrically "floating". Since the the oxide capacitance of the measured low frequency C-V response was set to the value obtained using a commercial capacitance meter the results are also dependent upon the accuracy of that piece of equipment. Discrete capacitors were measured using the commercial meter and the measured values fell within the 10 percent tolerence values given to the capacitors by the manufacturer. The results for the surface density calculations are at least comprable to that obtained by Kuhn in his paper [1] and (since no other method was currently available to compare the results obtained here) are accepted as being accurate.

CONCLUSIONS

The low frequency measurement system described in this report is much more flexible and provides better results than the existing low frequency C-V measurement technique currently in use at RIT. It has also been shown that the low frequency C-V response can be utilized to determine the surface state density for a given MOS device. The implications of being able to accurately measure surface state density are that MOS fabrication processes might be modified in order to reduce the surface state density.

ACKNOWLEDGEMENTS

Thanks to Mike Jackson for his help explaining the determination of surface state densities; to Dr. Lynn Fuller for his help in explaining the workings of the present low frequency measurement system and modification of the Keithley 600A electrometer for use with the chart recorder; to Dale Webb for helping supply the ideal low frequency C-V response for comparison with the measured response.

REFERENCES

[1] Kuhn, M. "A Quasi-Staic Technique For MOS C-V and Surface State Measurements". Solid State Electronics. Vol 13, 1970. Pp. 873-885.

[2] Singh and Simmons. "Determination of Energy Density Distribution And Capture Cross-Section of Interface States in the Metal-Nitride-Oxide-Semiconductor (MNOS) Structure". Solid State Electronics. Vol 25, No. 3, 1982. Pp. 219-226.

[3] Webb, Dale. Senior Research Project, 1987.