A SINGLE-FREQUENCY APPROXIMATION FOR INTERFACE-STATE DENSITY DETERMINATION

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Abstract—Fast interface state densities in the Si-SiO₂ system can be determined by measurements of the MIS capacitor admittance. Traditional detailed analysis require elaborate frequency dependent techniques. The more commonly used approximation techniques are difficult to interpret for interface state densities less than $1 \times 10^{11} \text{ eV}^{-1} \text{ cm}^{-2}$. We present here a new single frequency technique as an approximation method which provides quantitative criteria on the quality of such interfaces. The data required are a single high frequency capacitance vs voltage measurement and a corresponding conductance vs voltage measurement. The validity of this technique is best demonstrated in a three-dimensional plot of conductance, frequency and voltage. This also gives added insight into the relationship between the temporal and thermodynamic properties of interface electronic states. Comparison of results using this approximation to more detailed treatments demonstrates the validity of this new method for low surface state density determination in a range from $7 \times 10^9 \text{ eV}^{-1} \text{ cm}^{-2}$ to $8 \times 10^{11} \text{ eV}^{-1} \text{ cm}^{-2}$.

INTRODUCTION

Surface states on crystalline solids have attracted much theoretical and experimental attention. The metal-insulator-semiconductor (MIS) capacitor is the most useful tool for studying such states in the semiconductorinsulator interface. This is particularly true for characterizing semiconductor devices in the microelectronics industry.

The MIS structure was first proposed as a voltage variable capacitor in 1959 by Moll[1], and was first employed in the study of interface characteristics by Terman[2] and by Lebovec and Slobodskoy[3]. Several techniques have been employed to determine interface state density. These include capacitance measurement methods[4–6] and MIS conductance measurements which are the more accurate. A detailed and comprehensive analysis of the conductance method is given by Nicollian and Goetzgergen[7].

To explain experimental data quantitatively for fast interface states one generally must consider the behaviour of free carriers in the presence of traps which are in the vicinity of an interface. MIS conductance is one experimental result which has its origin in interface state trapping free carriers. This conductance behaviour can be derived from analyzing the changes in recombination statistics caused by time dependent changes in Fermi-Dirac statistics.

Considering electrons as majority carriers the Shockley-Read recombination statistics [8], applied to surface states, yields the capture rate by traps which are single level in energy. This rate is

$$R_{b} = N_{ss}C_{n} [1 - F(E, t)]n_{s}$$
(1)

and the emission rate is

$$S_n = N_{ss} e_n F(E, t) \tag{2}$$

where N_{ss} is the interface state density (cm^{-2}) , C_n the electron capture probability $(cm^3 - sec^{-1})$; e_n the electron emission constant (sec^{-1}) ; n_s the free electron density at the surface (cm^{-3}) ; and F(E) the Fermi function. Lehovec, Slobodskoy and Spraque[3] considered the Fermi function to be time dependent. This required n_s to be time dependent and hence also the rates. The generated charge per unit area could then be written as

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = q \left[R_n(t) - S_n(t) \right] \tag{3}$$

where q is electronic charge. We note that only if we consider this time dependence to be due to a fluctuating surface potential can we consider eqn (3) to be a current density.

To derive the admittance in a MIS system resulting from this current one considers F(E, t) to be the the sum of d. c. and a. c. parts.

$$F(E, t) = F(E, t)_o + F(E, t).$$
 (4)

Here $F(E, t)_o$ is the Fermi function established by a d.c. bias or quasistatic ramp voltage applied to the interface and F(E, t) is the change due to an a.c. modulation. This leads to an expression for the admittance of single level interface states

$$Y_{ss} = j\omega \frac{q^2 N_{ss} F_o (1 - F_0)}{kT (1 + j\omega F_o / C_n N_{so})}.$$
 (5)

Further analysis leads to the surface state capacitance and conductances, from the denominator

$$\tau = F_0(C_n n_{so})^{-1} = F_O(C_n n_{s0})^{-1} \exp(-q\psi_s/kT)$$
(6)

which in the surface state time constant where ψ_s is the surface potential. By reviewing eqn (6) we can see that trap time constants are expotentially related to surface potential. This leads to the wider spread of conductance data and time constant dispersion that is observed experimentally. An analysis by Nicollian and Goetzbergen[7] considered the spatial fluctuation of sur-

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face thereby leading to a more complete time constant versus surface potential thereby leading to a more complete time constant versus surface potential dispersion effect. They obtained very lengthy functions to account for spread in conductance data plots. The spread in plots arises from, (a) random fluctuations of surface potential for the cases of both random built in charge distributions and charged interface states, and (b) from random distributions of ionized impurity ions. This analysis offers a more reasonable correlation to measured conductance data than previous work by Lebovec. However, it does require many capacitance and conductance vs frequency plots and much analysis time.

Our study centers on the examination of interface states in the silicon-silicon dioxide system using the conductance technique. When one is dealing with many samples or if one requires a particular surface state density then it is advantageous to be able to monitor surface state properties rapidly during processing.

The most accurate calculation of N_{ss} is given by the Nicollian-Goetzberger theory. However, their methods require such extensive data acquisition that it is not applicable in performing some device research. The point of this paper is that our approximation technique is more quantitative and gives results closer to the Nicollian-Goetzberger calculations than other approximation techniques. Other approximation techniques either fail for N_{ss} less than 10^{11} (eV⁻¹ - cm⁻²) or the results are highly subjective leading to large errors. This is due to the fact that these approximations only use capacitance data where N_{ss} has a small effect. On the other hand our approximation in addition utilizes the conductance where N_{ss} has a larger effect. As with other approximation techniques we have compromised time constant dispersion and use single time constant parameters which lead to results of direct relevance to interface state density. The surface potential dependence of the time constant will make a small contribution to the time constant if we are determining the peak N_{ss} for restricted regions of the band gap. These are precisely the conditions encountered during device fabrication. We also suggest here an organizational format for analyzed conductance data. A three dimensional plot of conductance vs frequency and potential is proposed. The contours of both measured conductance and substrate conductance, when compared in this coordinate system, bear added insight into the overall behaviour of electronic states at an interface. The details of the method and its comparison to the Nicollian-Goetzberger approach are presented in conjunction with the experimental results.

2. EXPERIMENTAL

Experiments were conducted on silicon die mounted in microelectronics device packages. Monsanto, Czolchralski grown silicon wafers of $\langle 100 \rangle$ crystal orientation were used. Impurity concentration in the silicon were 0.8×10^{15} cm⁻³- 1.5×10^{15} cm⁻³ of phosphorous and $4 \times$ 10^{14} cm⁻³- 7×10^{14} cm⁻³ of boron for *n*- and *p*-type samples respectively. Initially the *n*- and *p*-type silicon wafers, 2 in. in dia. and about 400 μ m thick, were thermally oxidized in a steam atmosphere. This oxide layer was etched back to bare silicon with hydrofloric acid and a second oxide, 1600 Å, was grown in a hydrogen chloride atmosphere. This procedure was used to rid the surface of unwanted impurities and defects.

A thin conducting film was vacuum deposited on one surface. Several conducting materials were used for comparison. No material dependent effect was noted. The field plate pattern was etched into the thin film conductor layers with photolithographic and photoresisting techniques. The oxide was removed from the backside of the wafers. The pattern consists of 500 μ m \times 500 μ m squares for capacitance voltage analysis. Individual die $4 \text{ mm} \times$ 4 mm were then scribed and mounted. Mounting was accomplished with silver epoxy for the back contact in device packages. Electrical connection was made with 1 mil aluminum wire from each field plate to a convenient package lead. The finished package represented a single system on which many experiments could be conducted. All of the samples were stored in a dry environment throughout the course of these experiments.

Capacitance and equivalent parallel conductance was measured on those MIS capacitor samples. The standard technique of phase sensitive detection was used as the method of measuring these parameters. Figure 1 shows a



Fig. 1. Instrumental block diagram.

typical experiment block diagram of the system used. Precautions were taken to limit phase shifts and series resistance effects by using low input and output impedances on either side of the sample capacitor. Particular care was taken in applying the modulation signal to the sample since signal amplitude and harmonic distortion are detrimental to narrow band measurement accuracy. In this experiment the Princeton Applied Research Model 110 Low Distortion Oscillator having less than 0.01% total harmonic distortion, was used. With this modulation technique, a.c. capitance is measured. For example

$$dQ/dV = C + V(dC/dV)$$
(7)

must be evaluated for this experiment. By restricting the modulated semi-conductor surface potential to be less than kT/q ($kT/q\delta25.9$ mV) the depletion width edge in the semiconductor remains within the bounds of thermal smearing. Hence, the depletion edge will vary within a region of one Debye length. The result of this restriction leads to $dC/dV \approx 0$ in eqn (7). In this way the depletion region is not overwhelmingly modulated and the non-linear effects of the capacitor are not a contributing term to the measured signal.

In a current sensing measurement of this type, the test sample should be the major or current controlling impedance in the measurement. Therefore a low impedance termination is necessary for accurate results. The Princeton Applied Research Model 181 Current Sensitive Preamplifier, operated in the lower sensitivity settings, was used here.

MIS capacitors are field effect devices. Their capacitance and conductance parameters can vary with respect to semiconductor surface potential. With this in mind a specially constructed voltage ramp generator was used to bias the field plate. The circuit shown in Fig. 2 produces ripple free, linear ramps at voltage rates from less than 1 mV/sec-500 mV/sec. The ramp can be initiated, stopped, and reversed anywhere between positive and negative 50 V.

Expressions for conductance and capacitance result from a Taylor expansion of the current function for an MIS capacitor. These are

$$i_{\omega} = v_{\omega} \, (\sin \, \omega t) G \text{ at } v_0 \tag{8}$$

for conductance and

$$i_{\omega} = v_{\omega} (\cos \omega t) C \text{ at } v_0 \tag{9}$$

for capacitance. The current i_{ω} is measured by the 1815 preamp, v_{ω} is the sinusoidal voltage applied to the field plate, and, V_o is the quasistatic ramp voltage also applied to the capacitor field plate.

The Princeton Applied Research Model 124A Lock-In Amplifier was used for signal sensing at the output of the PAR 181 amplifier. With a Hewlett-Packard chart recorder energized by the ramp as the abscissa and the lock-in amplifier output as the ordinate, capacitance-



Fig. 2. Voltage ramp generator. Schematic of the ramp generator used is shown. The circuit employs wide range op-amps with negative capacitive feedback to produce linear ramp voltage or pulse voltages.

voltage and conductance-voltage data could be acquired under continuous and quasistatic conditions.

3. RESULTS-TRADITIONAL METHODS

Normal methods of data analysis can be time consuming. All of the analysis suggest a basic equivalent circuit which represents the effects in an MIS capacitor. The variables in this circuit are indicated by Nicollian and Goetzberger as in Fig. 3. The substrate impedance can be written as

$$Z_s = Z_m - (j\omega C_{\rm ox})^{-1}.$$
 (10)

From this the substrate admittance is

$$Y_{s} = \frac{G_{m} + j(\omega C_{m} - |Y_{m}|^{2} / \omega C_{\text{ox}})^{2}}{(G_{m} / \omega C_{\text{ox}})^{2} + (1 - C_{m} / C_{\text{ox}})^{2}}.$$
 (11)

The substrate conductance can be determined from measured data.

$$G_{s} = \frac{G_{m}}{(G_{m}/\omega C_{ox})^{2} + (1 - C_{m}/C_{ox})^{2}}.$$
 (12)

To determine an N_{ss} distribution one first usually makes *C-V* and *G-V* plots at several modulation frequencies. From each plot G_s/ω is calculated at a field plate voltage chosen such that the surface is in a condition of depletion. A plot of G_s/ω versus ω is then made which in turn gives rise to N_{ss} . Figure 4 of G_s/ω vs ω for our samples shows a conductance peak from which interface state density can be calculated for a position in the energy bandgap which corresponds to the applied voltage. The peak in G_s/ω with respect to frequency gives rise to the surface state capacitance. We then can find interface state density from

$$N_{ss} = (C_{ss}/qA) \,\mathrm{cm}^{-2} - \mathrm{eV}^{-1} \tag{13}$$

where C_{ss} is surface state capacitance, A is the capacitor area and q is the electronic charge. Several other field plate voltages are then considered, each contributing to a data point for an N_{ss} profile. In the analysis, *n*-type material will provide information on electron traps or states whereas *p*-type material provides the necessary information for hole states. From these data points the



Fig. 3. Metal-Insulator-Semiconductor capacitor effective equivalent circuit. This circuit represents the behaviour of a MIS capacitor. C_{ox} in the oxide capacitance, C_D is the voltage variable depletion capacitance, and C_{ss} - R_{ss} is the voltage and frequency variable interface state branch.



Fig. 4. Normalized equivalent parallel conductance spectrum. This conductance data is calculated from measured data at one bias condition. It is this data which furnishes densities at a particular band gap energy.

profile of N_{ss} through about half the bandgap can be determined for each sample. This is shown in Fig. 5 for some of our samples. This figure shows the full calculation for N_{ss} throughout the bandgap using the Nicollian-Goetzberger conductance spectra technique.

3. RESULTS-APPROXIMATION . METHOD

As a more accurate alternative to other approximation techniques and as the Nicollian-Goetzberger conductance spectra technique requires lenghty analysis we propose, an approximation whereby one can use the more easily obtainable G_m instead of G_s under certain limitations. The substrate admittances can be written in terms of the surface state admittance and depletion capacitance,

$$Y_{ss} = Y_{ss} + j\omega C_D = (Z_s)^{-1}$$
(14)

where

$$Y_{ss} = (R_{ss} + 1/(j\omega C_{ss}))^{-1}$$
(15)



Fig. 5. Interface state density. Profiles of fast interface state density in the band gap of four of our silicon samples as calculated by the Nicollian-Goetzberger technique.

letting $C_{ss} R_{ss} = \tau$ yields

$$Y_s = \frac{\omega^2 C_{ss} \tau}{1 + \omega^2 \tau^2} + j\omega \left(C_D + \frac{C_{ss}}{1 + \omega^2 \tau^2} \right)$$
(16)

so

$$G_{s} = \omega^{2} C_{ss} / (1 + \omega^{2} \tau^{2}).$$
(17)

Differentiating G_s with respect to τ and setting the result equal to zero gives rise to the maximum of G_s where $\omega^2 \tau^2$ equals 1 at that maximum. This then yields

$$G_{s,\max} = \omega C_{ss}/2 \tag{18}$$

To obtain greater insight, we suggest that one can combine the plots of $G_{s}\omega$ vs ω for several voltages even though this is not necessary for our approximation. Figure 6 is a three dimensional representation of conductance versus frequency and vs voltage for one of our samples.

From an analysis of measured data one can find the behaviour of the substrate conductance G_s/ω with frequency at a given surface potential. Experimentally, we generally found that between 10 and 100 kHz this conductance peaks and also varies slowly with respect to frequency. Moreover, in those cases where this is not true it is immediately obvious from the non-diatonic behaviour of the measured conductance data. The behaviour of the substrates conductance (G_s/ω) with respect to the surface potential at a given frequency is also available from the data. It is this frequency phenomenon which leads to a method of approximating the peak in N_{ss} by using G_m instead of G_s for a sample. In this technique a comparison is made between the measured conductance (G_m/ω) and the substrate conductance (G_s/ω) . It can be shown by comparisons of three dimensional representations similar to Fig. 6 that the difference in $G_{s,max}/\omega$ and $G_{m,max}/\omega$ is insignificant under common conditions. In particular the value of τ for the two maximums must be considered. Mathematically, the question is whether $\tau([dG_s/d\tau = 0])$ is the same as $\tau[(dG_m/d\tau) = 0]$. From eqn (10)

$$Z_{M} = Z_{s} + 1/(j\omega C_{\rm ox}). \tag{19}$$

This will yield for measured admittance

$$Y_{m} = \frac{\omega^{2}G_{s}C_{ox}(C_{s} + C_{ox}) + j(\omega C_{ox}G_{s}^{2} + \omega^{2}C_{s}(C_{s} + C_{ox}))}{G_{s}^{2} + \omega^{2}(C_{s} + C_{ox})^{2}}.$$
(20)

Therefore

$$G_m = \frac{\omega^2 G_s C_{\rm ox} (C_s + C_{\rm ox})}{G_s^2 + \omega^2 (C_s + C_{\rm ox})^2}.$$
 (21)

First one must consider the total derivative of G_m with respect to τ .

$$\frac{\mathrm{d}G_m}{\mathrm{d}\tau} = \frac{\partial G_m}{\partial G_s} \frac{\mathrm{d}G_s}{\mathrm{d}\tau} + \frac{\partial G_m}{\partial G_s} \frac{\mathrm{d}C_s}{\mathrm{d}\tau} \tag{22}$$

which is zero when one is at a maximum in measured conductance. From eqn (16) where the first term yields conductance and the second capacitance, we obtain

$$dG_s/d\tau = \omega^2 C_{ss} (1 - \omega^2 \tau^2) (1\phi \omega^2 \tau^2)^{\lambda 2}.$$
 (23)

From eqn (21),

$$\frac{\partial G_m}{\partial G_s} = \frac{\omega^2 C_{\rm ox} (C_s + C_{\rm ox}) [\nu^2 (C_s + C_{\rm ox})^2 - G_s^2]}{[G_s^2 + \omega^2 (C_s + C_{\rm ox})^2]^2} \quad (24)$$
$$dC_s/d\tau = 2\omega^2 \tau C_{ss} (1 + \omega^2 \tau^2)^{\lambda/2} \quad (25)$$



Fig. 6. Measured equivalent parallel conductance. Measured conductance as well as substrate conductance can be presented in this three dimensional format i.e. conductance magnitude vs frequency and field plate voltage.

and

$$\frac{\partial G_m}{\partial C_s} = \frac{\omega^2 G_s C_{\text{ox}} [G_s^2 - \omega^2 (C_s \phi C_{\text{ox}})^2]}{(G_s^2 + \omega^2 (C_s + C_{\text{ox}})^2)^2}$$
(26)

so $(dG_m/d\tau) = 0$ yields

$$(C_s + C_{ox})[\omega^2 \tau^2 - 1] = 2\tau G_s$$
 (27)

which leads to

$$\omega^2 \tau^2 \delta 1 + C_{ss} (C_D + C_{ox})^{-1}.$$
 (28)

Now for $G_{m,\max}$ or $\omega^2 \tau^2 = 1 + C_{ss} (C_d \phi C_{ox})^{-1}$

$$G_{s}\delta \frac{\omega C_{ss} \left(\frac{C_{ss}\phi C_{D}\phi C_{ox}}{C_{D} + C_{ox}}\right)^{1/2}}{\frac{C_{ss}\phi 2C_{D}\phi 2C_{ox}}{C_{D}\phi C_{ox}}}.$$
(29)

Comparing this to $G_{s,\max}\delta\omega C_{ss}/2$

$$\frac{G_s(G_{m,\max})}{G_{s,\max}} = 2 \frac{(C_{ss} + C_D + C_{ox})^{1/2}}{(C_{ss} + 2C_D + 2C_{ox})} (C_D + C_{ox})^{1/2}.$$
(30)

It can easily be seen that the ratio varies as a suppressed function of the reciprocal square root of C_{ss} . This means appreciable changes in C_{ss} cause only nominal changes in the ratio.

Because of the resulting similarities of G_m and C_s , a single C-V, G-V plot can be made at about 20 kHz. The peak in the C-V plot can be used to approximate fast interface density since the expression for N_{ss} can be rewritten as

$$N_{ss} = \frac{2}{eA} \frac{G_{m,\max}/\omega}{\left(\frac{G_{m,\max}}{\omega C_{ox}}\right)^2 + \left(1 - \frac{C_m}{C_{ox}}\right)^2}$$
(31)

This approximation for peak interface state density was calculated for our samples where $G_{m,max}$ now cor-

responds to the maximum in conductance on the G-V plot. Comparisons of one sample to another, indeed, demonstrate the correlation of our approximation measurement to the more detailed analysis method. Our approximation technique for N_{ss} is within about 25-30% of the Nicollian-Goetzberger peak N_{ss} value between flat band and mid gap. Since, N_{ss} is known to change by an order of magnitude or more in the region between flat band and mid gap, Fig. 5, this approximation is reasonable. On the accumulation side of flat band majority carrier effects dominate and can give an indiction of an increasingly high value for N_{ss} . Frequencies into the MHz region are necessary for accurate measurements here.

Hence, for a determination of the peak in a surface state profile one needs only three measured values. These are the maximum in G_m with its corresponding capacitance C_m and the insulator capacitance C_{ox} . The advantage of the approximation is realized from the need of only one C-V G-V plot.

Typical values for some of the important parameters are

$$N_{ss} = 5 \times 10^{10} \text{ eV}^{\lambda 1} \lambda \text{ cm}^{\lambda 2}$$

$$C_{ss}/A = 8 \times 10^{3} \text{ pf/cm}^{2}$$

$$C_{os}/A = 2.5 \times 10^{4} \text{ pf/cm}^{2}$$

$$C_{D}/A = 3.7 \times 10^{4} \text{ pf/cm}^{2}$$

(at the point of the peak)

$$N_{D} = 10^{16} \text{ cm}^{-3}.$$

These data give rise to a determination of the G_s ratio.

$$\frac{G_s(G_{m,\max})}{G_{s,\max}} = 0.998 = 1.$$

Figure 7 shows the variation of this ratio for both C_{ss} and N_{ss} . Here it is seen that N_{ss} is as large as $1 \times 10^{12} \text{ eV}^{-1} - \text{cm}^{-2}$ before as much as a 10% systematic error appears.



Fig. 7. Ratio representation of calculated substrate conductance. Shown is the variation of substrate conductance as calculated from time constant behaviour compared to that when calculated from measured equivalent parallel conductance.

992

4. CONCLUSION

Fast interface state density for the silicon-silicon dioxide system can be determined by several methods. Capacitance and conductance data from MIS capacitors are used for the determination of trap density. An alternative to overwhelming data acquisition and data reduction in the complete analysis is to use an approximation technique. A conductance approximation technique is introduced in this experiment. In the most typical case, the substrate conductance maximizes in the region of 20-50 kHz under conditions of depletion. If the behaviour of measured conductance, as opposed to substrate conductance, is considered with respect to frequency and to surface potential we note that it is similar to that behaviour due to surface states in ths substrate conductance. An approximation technique is revealed from the need of only a single C-V/G-V plot in the frequency range mentioned. One need only determine the maximum value of G_m/ω on the G-V plot and use this value to calculate the approximate maximum density of surface states for a given sample. In terms of comparative analysis this technique can be a valuable tool for judging the quality of semi-conductor interfaces.

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