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Distribution of surface states based on Hill and Coleman conductance technique

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Abstract. Hill-Coleman's single frequency conductance technique for the determination of surface state density has been extended upto 2 kHz. A.c. conductance (G_m) and capacitance (C_m) *versus* gate bias (V_G) curves were obtained at various signal frequencies. Shift of the observed peaks in the G_m *versus* V_G curves for different signal frequencies was utilized for the determination of surface state density at different surface potentials (ψ_s). Determination of surface state density for different ψ_s values was also done by Nicollian-Goetzberger method and the results compared. Results obtained by Hill-Coleman technique compare reasonably well with those obtained by the other method.

Keywords. Metal-oxide-semiconductor structure; a.c. conductance; interface state density; surface state distribution.

1. Introduction

The electrical properties of metal-oxide-semiconductor (MOS) structures are mainly determined by the shallow and deep traps and impurity concentrations in the semiconductor-insulator interface. The characterization of surface states using this structure has been very useful in modern microelectronics device industry.

Various experimental techniques *viz.* conductance technique of Goetzberger and Nicollian (1967), quasistatic technique of Kuhn (1970), Castagne (1968) and Castagne and Vapaille (1971) for measuring the density of interface states and their behaviour are available in literature. Although conductance technique of Nicollian and Goetzberger is known to be the most accurate and comprehensive for studying the semiconductor-insulator interface, some authors prefer quasistatic methods over the Nicollian and Goetzberger technique because the quasistatic method is easy and fast in determining surface state density and its distribution. Further, the quasistatic method is able to explore a larger part of the band gap than the conductance techinique. The analysis of quasistatic data related to fast surface states lying at Si-SiO$_2$ interface is based on the generation of carriers through traps or surface states, whereas the a.c. conductance arises due to capture and emission of carriers through these states. The generation recombination *via* the surface states under steady state is derived from the time-derivative of Fermi-Dirac statistics (Shockley and Read 1952; Lehovec *et al* 1963).

Since the Nicollian-Goetzberger method requires such an extensive data acquisition that it is not easy to analyse the data quickly. Recently a simpler and quick conductance approximation technique has been proposed and used by Hill and

Colemen (1980). According to this approximation, single high frequency capacitance-voltage (C-V) and corresponding conductance-voltage (G-V) plots are required for the estimation of surface state density at the position in the bandgap, where the measured conductance peak appears. The agreement between the values obtained from the exact Nicollian and Goetzberger technique is within 70%. For the system having low density of states say 10^{10} eV^{-1} cm^{-2} or less it provides better agreement (Singh, unpublished).

For the estimation of surface state density by the single frequency approximation method developed by Hill and Coleman, the authors feel that their method is applicable only when the probing signal frequency is higher than 20 kHz. Further, they did not contemplate to use their method for determining the distribution of surface state density in the bandgap region of Si. The present authors show in this paper that this method can be used with lower signal frequencies also say upto 2 kHz. Further, the peaks observed in the measured conductance *vs.* gate bias curves with frequency as parameter were found to be located at different positions of the gate bias for different probing signal frequencies. The present authors have used this behaviour of the curves to find the distribution of surface state density in the band gap of Si although the range of bandgap which could be explored by this method is quite limited. Comparison of the results obtained by N-G method is also presented and shown that the accuracy of the method is within the limits the original authors have claimed.

2. Experimental techniques

2.1 MOS *device preparation*

The MOS capacitors used in the experiments were fabricated on n-type silicon single crystal of $\langle 111 \rangle$ orientation and having doping density 3×10^{15}/cm^3. After mechanical and mechanical-cum-chemical polishing and cleaning with high resistivity deionized water, the wafers were subjected to resistance heated furnace for oxidation. The thickness of the oxide grown was determined by ellipsometric arrangement and checked for its capacitance value in the strong accumulation region. Circular dots of Al were deposited on the oxide using vacuum vapour depositing technique. n^+-diffusion was made on the back side of the wafers after removing the oxide. Al

Table 1. Particulars of Si, oxidation and annealing conditions for various samples.

Sample No.	Doping density (cm^{-3})	Crystal orientation	Oxide thickness (Å)	Field plate area (cm^2)	Oxidation and annealing processes used
MOS$_1$	3×10^{15}	$\langle 111 \rangle$	1200	$4{\cdot}3 \times 10^{-3}$	Oxygen mixes with 5% HCl was used at 1050°C.
MOS$_2$	3×10^{15}	$\langle 111 \rangle$	1000	$5{\cdot}15 \times 10^{-3}$	Dry oxidation at 1000°C.
MOS$_3$	3×10^{15}	$\langle 111 \rangle$	920	$6{\cdot}5 \times 10^{-3}$	Dry oxidation at 1000°C and annealed in N_2 ambient.

was deposited on this side also by the same technique. Contact to the Al dot was made using spring probe having gold ball tripped ends. To check the applicability of the method for different densities of surface-states, MOS capacitors with different oxide thicknesses grown under different oxidation conditions were fabricated and analysed. Particulars of three different types of samples are given in table 1. The results obtained by two different methods *i.e.* Nicollian-Goetzberger and Hill-Coleman are compared in figure 5. In order to check the reproducibility and reliability of the results, measurements were made on ten sample capacitors fabricated on each wafer of the Si crystal. The data obtained for different MOS capacitors on the same wafer did not vary by more than 15%. Results of only a sample MOS capacitor of each wafer are therefore presented in this paper.

2.2 *Evaluation of the surface potential* ψ_S

The relation between surface potential ψ_s and applied gate voltage V_G was obtained from the comparison of the experimental and theoretical *C-V* curves. It has been assumed that the *C-V* curve obtained at signal frequency=100 kHz was of high frequency type *i.e.* the surface states did not follow the signal of this frequency and hence did not contribute to the measured capacitance (Singh and Srivastava 1981). In figure 1, two curves for MOS_1 are shown. The dashed curve is experimental capacitance *versus* voltage curve and the solid curve is the theoretically (Sze 1969) computed one. In this figure, C_{FB}, Q_{SS} and Q_S represent capacitance at flat band voltage, surface state charge and space charge in the semiconductor respectively. Experimental ψ_s values were obtained by matching the capacitance values of both the *C-V* curves (theoretical and experimental). The experimental and theoretical ψ_s *vs* V_G curves shown in figure 2, were obtained on the line of Bigrogne *et al* (1980).

2.3 *Determination of the interface state density*

2.3(a) *Nicollian and Goetzberger conductance technique:* In this case capacitance C_m and the corresponding a.c. conductance G_m of the MOS structure are experimentally

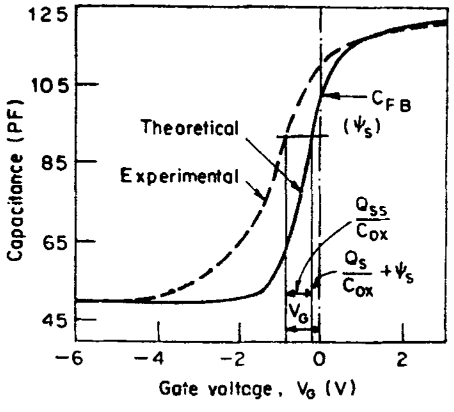

Figure 1. Theoretical and experimental *C-V* curves.

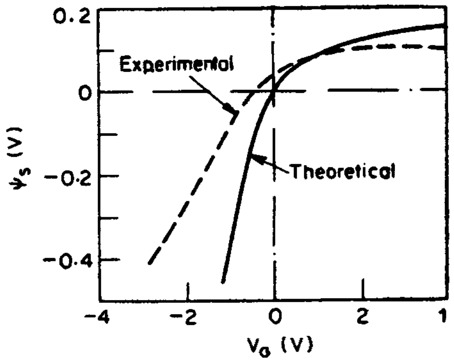

Figure 2. Surface potential ψ vs. gate voltage V_G.

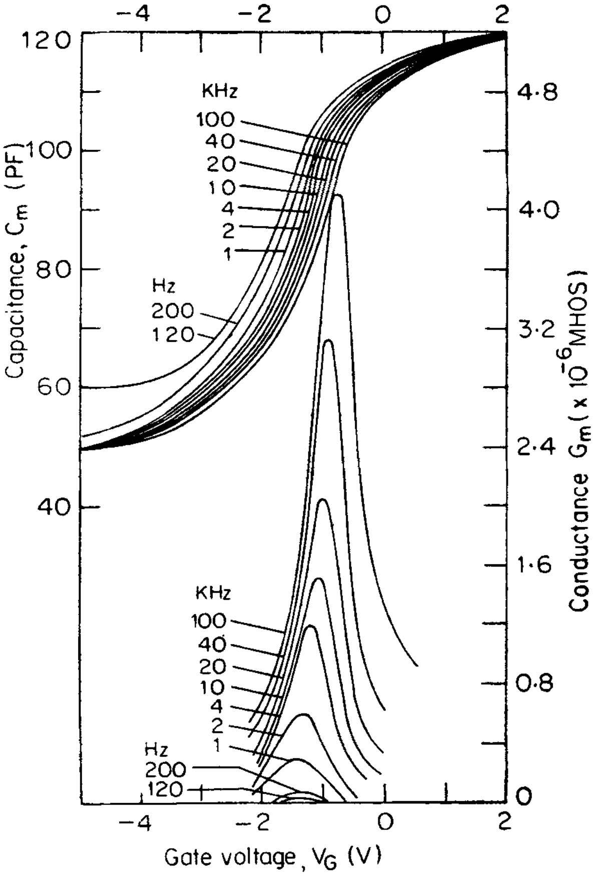

Figure 3. Measured capacitance and corresponding conductance *vs.* gate voltage for frequencies indicated. The multiplying factors to the indicated scale for G_m-V_G curves at frequencies 100 K, 40 K, 20 K, 10 KHz are 1, 0·5, 0·375, 0·25 respectively and for 4K, 2 K, 1 K, 0·2 K and 0·12 KHz is 0·125.

determined for different gate biases V_G and for different signal frequency $\omega = 2\pi f$. These curves for MOS$_1$ are shown in figure 3. From the values of C_m and G_m corresponding to any bias and frequency parallel conductance G_P and capacitance C_P of the semiconductor space charge and surface state combination are evaluated on the line of Goetzberger *et al* (1976). Plots of G_P/ω vs. ω with bias as parameter are obtained (figure 4). Similar curves for different gate biases are obtained and surface state density corresponding to each bias (or surface potential ψ_s) is calculated from (Goetzberger and Nicollian 1967);

$$C_{SS} = 2\left(\frac{G_P}{\omega}\right)_{\max} = q\,N_{SS}$$

N_{SS} thus can be determined for any bias or ψ_s values.

2.3(b) *Conductance approximation method:* According to Hill and Coleman (1980), surface state density N_{SS} can be determined from;

$$N_{SS} = \frac{2}{qA}\,\frac{(G_{m,\,\max}/\omega)}{(G_{m,\,\max}/\omega\; Cox)^2 + (1 - C_m/Cox)^2}$$

where A is the dot area, ω the signal frequency, $G_{m,\,\max}$-peak value of the measured conductance and C_m the corresponding measured capacitance value. Since $G_{m,\,\max}$ was found to shift to different values as the measuring signal frequency was changed, the authors have used this behaviour of G_m vs. V_G curves to estimate the surface state density at different ψ_s values.

3. Experimental results and discussion

The C_m-V_G and the corresponding G_m-V_G curves for different samples were obtained and the data analysed. Measurements were done at various frequencies (120 Hz to 100 kHz) by means of Hewlett Packard (HP) multifrequency LCR meter Model 4274A. The a.c. signal amplitude was not allowed to exceed 25 mV so that

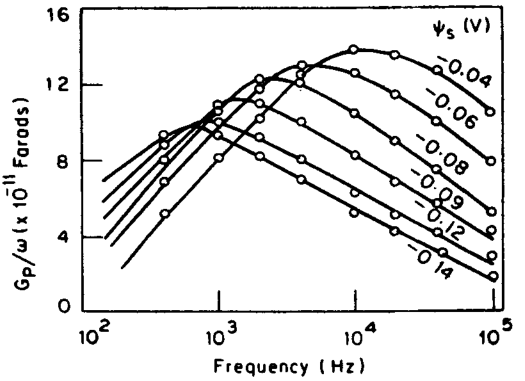

Figure 4. G_P/ω *vs.* ω for different surface potential (ψ_s).

the small signal conditions prevailed. In figure 3, C_m-V_G and G_m-V_G curves for a typical MOS_1 capacitor are shown. Frequency dispersion in C_m-V_G curves is clear whereas the shift of the G_m-V_G curves are also evident. It may be noted that with decreasing frequency, the magnitude of the G_m peak as well as its sharpness decrease. In figure 4 G_p/ω vs. ω are plotted for different values of ψ_s. It is evident from the figure that as the surface potential ψ_s increases from $-0{\cdot}04$ V to $-0{\cdot}14$ V the peak on the G_p/ω vs. ω plot is found to shift towards lower frequencies. This is most probably due to the dispersion in the surface state time constant. In the evaluation of surface state density on the basis of Nicollian and Goetzberger conductance technique, single time constant τ for all the surface states around any surface potential has been assumed. According to this assumption, the peak appears at $\omega\tau = 1$ (Goetzberger *et al* 1967). The time constant τ of the surface state at any bias, can thus be evaluated from the shift of the peak in G_p/ω vs. ω curve given in figure 4. It may be noted that the time constant τ increases as the surface potential increases.

Figure 5 shows the distribution of surface state density evaluated by two different methods described above for three different MOS samples. The surface state density distribution from the conductance approximation technique was obtained from the shifted positions of the G_m peaks along the voltage axis as the signal frequency was varied. In the figure E_c the conduction band edge, E_F the Fermi-level and E_i the intrinsic Fermi-level of the Si are shown. The density of surface state was also obtained by the Terman (1962) method. However, the density obtained by this method was always larger than those obtained by conductance techniques. This is not surprising because of the limitation of graphical differentiation method. Further, this method gives somewhat inaccurate results because of the frequency dispersion effects of C_m-V_G curves. It is clear from the figure that the approximate conductance method of Hill *et al* gives reasonable results. However, these are consistently 25% lower than the Nicollian and Goetzberger exact conductance techniques. Further, this method can be used with reasonable accuracy upto 2 kHz instead of 20 kHz which was taken as the lower limit of the probing signal frequency by Hill and Coleman.

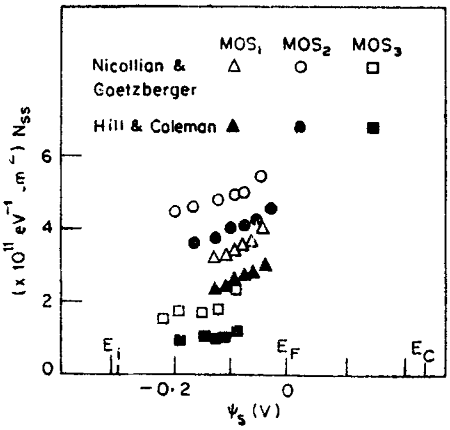

Figure 5. Distribution of surface state density (N_{SS}) in the Si band gap.

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