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Frequency dependence of the surface states at the N-type Si-SiO$_2$ interface

R J SINGH and R S SRIVASTAVA
Department of Physics, Banaras Hindu University, Varanasi 221 005, India

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Abstract. The response of the surface states at the *n*-type Si-SiO$_2$ interface to the different a.c. signal frequencies has been studied. The response values have been computed from both the measured capacitance voltage (C-V) and conductance-voltage (G-V) techniques. The results presented show that the frequency response of the effective density of states to different a.c. signal frequencies is proportional to the log of the applied frequencies.

Keywords. Metal-oxide semiconductor structure; *n*-type Si-SiO$_2$ interface; interface state response; frequency dependence.

1. Introduction

The capacitance-voltage (C-V) characteristics of metal-oxide-semiconductor (MOS) structure are frequency-dependent, and can be attributed to either the generation of minority carriers in the depletion layer or to the response of interface states present at the Si-SiO$_2$ interface or to the combination of both (Zohta 1974). The effect of signal frequency on the C-V curves has been studied by many authors *e.g.* (Terman 1962; Lehovec and Slobodoskoy 1963; Hofstein and Warfield 1965; Zaininger and Warfield 1965; Castagne and Vapaille (1971) but the results obtained and reported in the present study are different from those reported earlier. The behaviour of C-V curves of MOS capacitors to different frequencies is reported. Since the generation of minority carriers in the depletion regions is negligibly small the change in capacitance due to signal frequency has been attributed to the response of surface states alone. If the signal frequency is high only that fraction of surface states can follow the signal whose time constants are shorter than the period of the signal. If the frequency is low most of the surface states can follow the signal and the measured surface state capacitance will correspond to the total number of states. The surface state density at different signal frequency was evaluated by measuring the frequency-dependent surface state capacitance by Castagne and Vapaille (1971) and Goetzberger *et al* (1967). The surface potential ψ_s has been evaluated by comparing the high frequency experimental C-V curve with the ideal (computed) curve. In the results reported here 100 kHz has been taken to be of a reasonably high frequency and thus the response of surface state to this frequency is negligibly small. This is supported by the experimental observation presented in § 3.

In the depletion or accumulation mode of operation the frequency dependence of MOS capacitance arises due to the interface states whereas in the inversion mode of operation the same arises due to the lifetime of minority carriers. Thus in the former regime the MOS capacitance at different signal frequencies should show a dispersion in surface states. Results based on such studies are presented in § 4.

2. Experimental procedures

Silicon single crystal of *n*-type and (111) orientation having $2 \times 10^{15}/\text{cm}^3$ donor impurity concentration was used for the fabrication of the MOS capacitors. The lapped wafers were mechanically polished with polishing machine using 1 μ alumina powder suspension in deionised water. The wafers were then subjected to mechanical-cum-chemical polishing treatment for 20 min. For this a combined solution of 60 g of $CuSO_4$ in 500 cc of deionised water and 150 g of NH_4F in 500 cc of deionised water was used. Finally they were thoroughly cleaned with high resistivity deionised water and then were subjected to resistance heated furnace at 1150°C for oxidation. Oxygen mixed with steam and 4 per cent gaseous HCl was used for this purpose. This provides surface states of considerably low density ($\sim 10^{11}$ $\text{cm}^{-2}\,\text{eV}^{-1}$). The thickness of the oxide grown was about 1030 Å. This was determined by the MOS capacitance in the strong accumulation region and also checked from the colour of the oxidized wafer. Al dots of about 0·74 mm diameter were deposited on the oxide through mask and using vacuum vapour depositing technique. Oxide from the backside of the wafer was etched out using a dilute solution of NH_4F and HF. Al was deposited on this side also using the same technique. Contact to the Al dots was made using a spring probe with golden ball-tipped ends to prevent scratching of Al. Capacitance and conductance measurements were made at room temperature (27°C) with the help of Hewlett Packard (HP) Multifrequency inductance-capacitance-resistance (LCR) meter model 4274A at frequencies from 100 Hz-100 kHz.

3. Determination of surface potential

The relationship between surface potential ψ_s and the applied gate voltage V_G can be obtained using the experimental high frequency and theoretical C-V curves for any known oxide thickness. It has been assumed that for *n*-type samples surface states do not follow the a.c. signals of frequency 100 kHz and above. This is somewhat approximate as the frequency used is not very high, nevertheless it will provide at least their qualitative if not the quantitative behaviour.

In the theoretical C-V curve of figure 1 each value of the high frequency capacitance corresponds to a definite value of the effective voltage (V_G-ϕ_{MS}) and hence to a definite value of ψ_s (Terman 1962 and Bigorgne *et al* 1979). Experimental ψ_s values were obtained by matching the capacitance values from both the C-V curves (theoretical and experimental). It has been assumed that the same value of capacitance (C) in the two curves correspond to the same ψ_s value.

The frequency-dependent surface state capacitance can be written according to Zaininger and Warfield (1965) as

$$C_{ss}(\omega) = \frac{C(\omega)}{1 - C(\omega)/C_{ox}} - \frac{C_{hf}}{1 - C_{hf}/C_{ox}}, \tag{1}$$

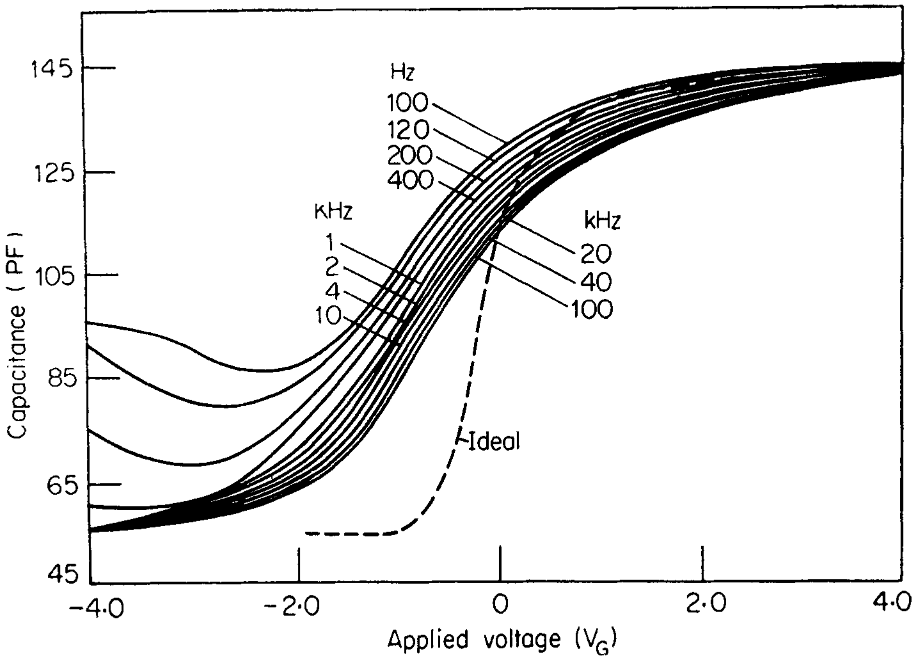

Figure 1. MOS C-V curves at different frequencies.

where $C(\omega)$ is the MOS capacitance at any angular frequency $\omega \leqslant 2\pi 10^5$ Hz, C_{hf} the high frequency capacitance and C_{ox} is the oxide capacitance.

According to Goetzberger *et al* (1976) the parallel capacitance $C_s(\omega)$ of the MOS structure can be written as

$$\frac{C_s(\omega)}{C_{ox}} = \frac{1 - C(\omega)/C_{ox}}{(1 - C(\omega)/C_{ox})^2 + (G(\omega)/\omega C_{ox})^2} - 1 \tag{2}$$

where $C_s(\omega) = C_{sc} + C_{ss}(\omega)$, C_{sc} = semiconductor space-charge capacitance and $G(\omega)$ = the measured conductance at any frequency ω. The surface state density $N_{ss}(\omega)$ (per cm² per eV) can be obtained from the relation,

$$C_{ss}(\omega) = q\, N_{ss}(\omega)\,. \tag{3}$$

4. Experimental results and discussion

Figure 1 shows the C-V characteristic of a typical MOS capacitor at different signal frequencies. The theoretically calculated C-V curve of the structure is also shown in the figure for comparison. The surface state capacitance at the different signal frequencies were determined using equations (1) and (2). It is seen from figure 1 that the C-V curve of the structure obtained at a signal frequency of 100 kHz is of a reasonably high frequency type. It is presumed that there is slight inaccuracy in the results presented because the high frequency used for the analysis was not very high. However the trend of the curves presented in figure 1 indicates that the error would be negligibly small. It is also to be noted that the ideal (theoretically calculated) curve

(Sze 1969) intersects the experimental curves. In the accumulation region the experimental curves lie on the right side of the ideal curve whereas in the depletion and weak inversion regime of operation the latter lies on the right side of the former. This clearly indicates that both donor and acceptor types of surface states were present in the structure studied. This inference is drawn from the work of Hughes (1977) and Razouk and Deal (1979). The latter have reported experimental C-V curves similar to the one obtained by the present authors. Since the shift of the ideal curve from the experimental curves is small $\sim$0·5 V the surface state density in the system investigated was also small $\sim 10^{10}$ cm^{-2} eV^{-1}. The surface state density N_{ss} at different signal frequencies was evaluated using (1) and (2) *via* (3). The density of state obtained by (1) is based on the capacitance measurements alone whereas that obtained by (2) depends on both the frequency dependent capacitance and the conductance of the structure. The measured conductance-voltage values of a typical MOS capacitor at various signal frequencies are tabulated in table 1. The measured G-V curves for different frequencies obtained from table 1 would be somewhat peculiar and different from those reported earlier; these are being analysed and will be reported separately. The variation of the N_{ss} value computed using (1) and (2) as against signal frequency for different gate biases are given in figures 2a and 2b respectively. The results obtained by the two equations agree quite well with each other. It can be inferred from the figures that the density of surface states is a strong function of surface potential and that the density of surface states at any surface potential which can respond the applied signal frequency decrease with increasing frequency.

Table 1. Measured conductance G in nano-Siemens (nS) at different frequencies (Hz) and applied gate voltages V_G.

Appl. Gate Voltage V_G Volts	G(nS)										
	100 Hz	120 Hz	200 Hz	400 Hz	1 kHz	2 kHz	4 kHz	10 kHz	20 kHz	40 kHz	100 kHz
+3·0	1	1	1	1	2	4	8	25	66	195	977
+2·0	1	1	1	1	2	4	8	25	68	202	1000
+1·0	1	1	1	1	2	5	13	48	137	402	1755
+0·5	1	1	1	1	5	13	33	120	310	795	2764
+0·2	1	1	1	3	9	24	59	191	448	1037	3084
0·0	1	1	2	4	14	34	78	227	496	1068	3040
−0·2	1	2	3	7	20	43	91	238	488	1011	2851
−0·4	2	3	5	10	24	47	91	223	454	959	2795
−0·6	4	4	7	11	24	45	85	213	451	983	2889
−0·8	4	5	7	11	23	43	85	224	484	1051	2960
−1·0	5	5	7	11	24	46	93	246	520	1085	2851
−1·2	6	6	8	13	27	51	103	261	526	1040	2530
−1·4	7	7	10	15	31	57	108	257	489	910	2046
−1·6	7	9	12	19	35	60	106	230	412	720	1512
−1·8	9	11	15	22	38	59	96	188	315	517	1039
−2·0	13	14	18	25	38	55	82	143	223	347	691
−2·2	15	17	21	27	38	50	67	105	151	225	472
−2·4	17	19	24	29	36	44	54	76	103	153	357
−2·6	19	22	28	32	37	41	46	58	77	117	303
−2·8	20	23	27	32	35	37	40	50	65	102	279
−3·0	18	24	29	34	37	40	44	52	69	103	281

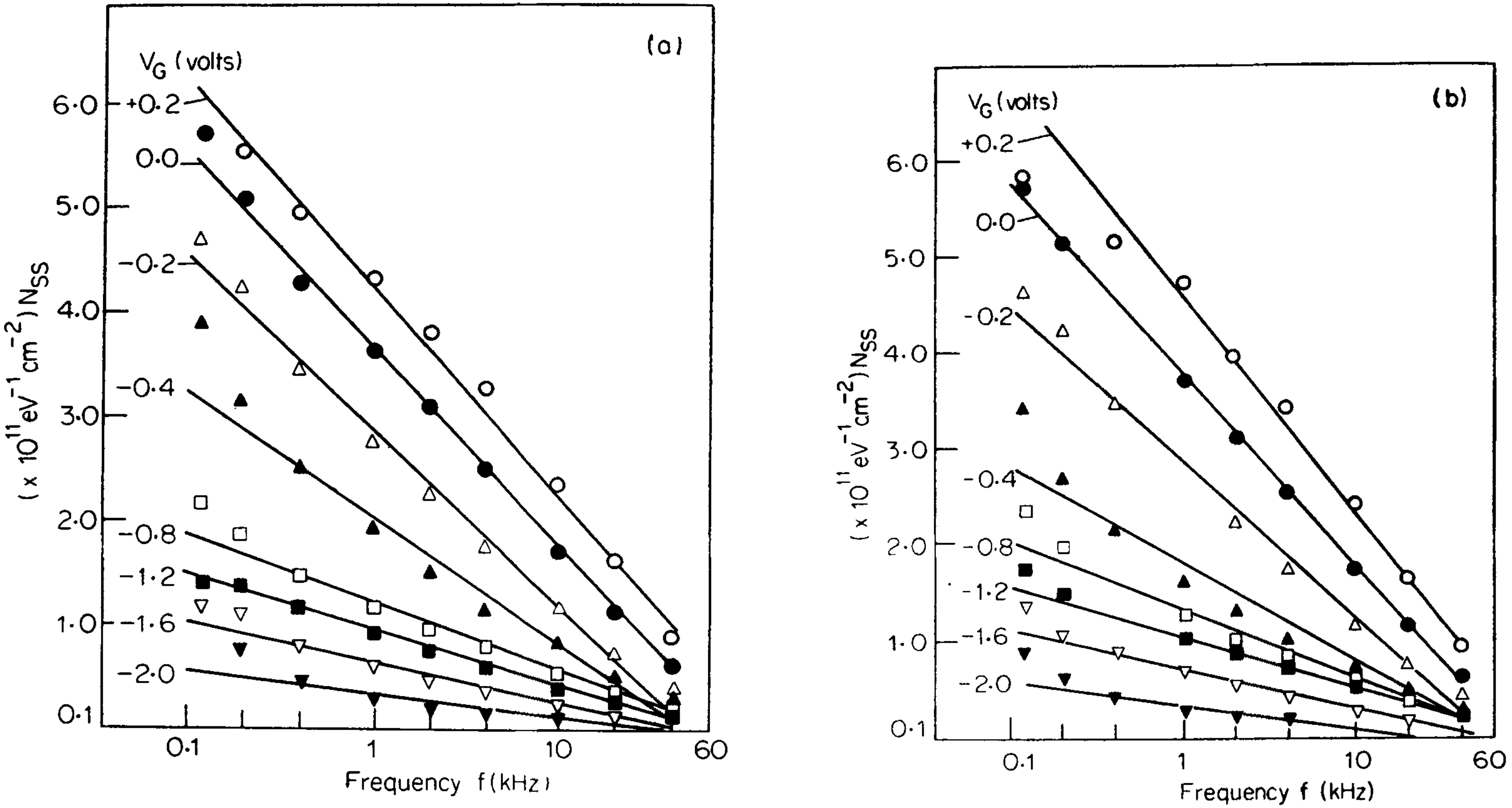

Figure 2. Surface state density N_{ss} as a function of frequency with gate voltage as parameter evaluated from **a.** equation (1), **b.** equation (2).

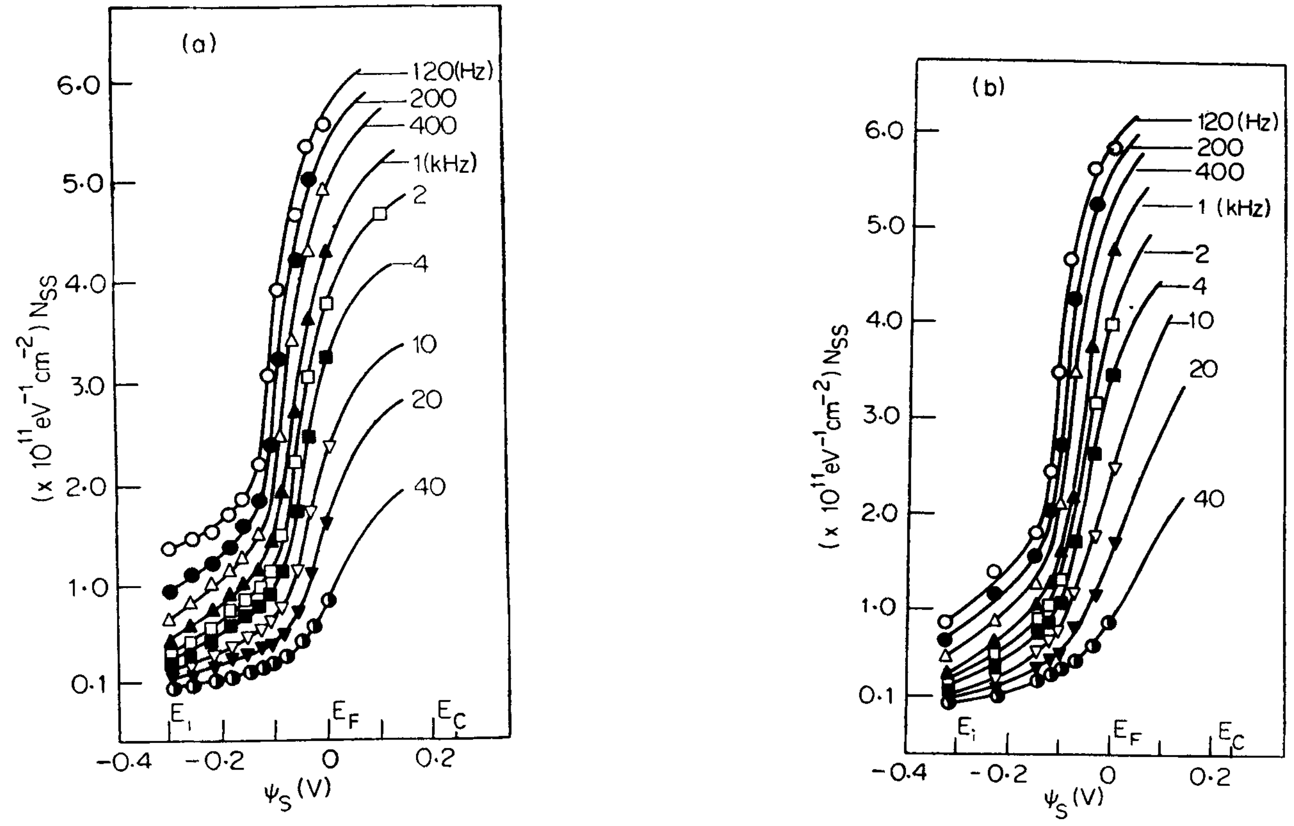

Figure 3. Distribution of surface state densities (N_{ss}) in the band gap of Si for different frequencies evaluated from a. equation (1), b. equation (2).

The relation between N_{ss} and f can be written as $N_{ss} \propto \log f$. It is clear from figure 2 that the slopes of N_{ss} vs $\log f$ for different surface potentials have different values with the maximum value for the curves in the accumulation region *i.e.* for surface states lying near the conduction band edge. The slope is minimum for the weak inversion regime i.e. for surface states near the midgap. Curves for different surface potentials tend to converge at high frequency. Zaininger and Warfield (1965) also reported results similar to that of figure 2 but their results differ in the following respects. In their graphs N_{ss} vs $\log f$ curves for different surface potential ψ_s are almost parallel to each other *i.e.*, they have the same slopes. The computation of N_{ss} by Zaininger and Warfield is based on equation (1) only *i.e.* with the help of experimental capacitances at high and at any other signal frequency ω. It is now well recognised that the conductance technique provides more reliable results.

Zohta (1974) has reported that for structures having surface state densities of the order 5×10^{10}cm^{-2} eV^{-1} the frequency dispersion of surface states is almost negligible. The present results do not agree with Zohta's contention. The structure studied and presented here also had surface state density of the same order but the frequency dispersion observed was quite pronounced even in a frequency range smaller than that used by Zohta (f ranged from 30 Hz to 5 MHz).

In figure 3 (a, b) the distribution of effective density of surface states for different signal frequencies in the upper half of the band gap of Si is presented. These curves can also be obtained from figures (2a) and (2b) respectively. If one assumes a uniform distribution of N_{ss} in a certain region of band gap (*e.g.* near the midgap region) the measured value of surface state capacitance at any frequency ω will lead to the determination of time constant of surface states (Goetzberger *et al* 1967). The general nature of variation of N_{ss} in the gap is similar to those reported by earlier workers who however have not indicated the frequency dispersion of the surface states. The maximum frequency dispersion in surface states occurs near the flat band condition where the effective density of surface states changes from 6×10^{11} to 1×10^{11} cm^{-2} eV^{-1} as the frequency changes from 120 Hz to 40 kHz. The curve for 40 kHz is comparatively more flat than the curves for lower frequency say 120 Hz.

5. Conclusion

A study of frequency response of MOS capacitors can provide the effective number of surface states which will participate when a signal of frequency ω is impressed on the system. The frequency behaviour of N_{ss} is a function of energy or surface potential ψ_s.

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