CONTRIBUTIONS OF SURFACE STATES TO MOS IMPEDANCE

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The broad time constant dispersion of states at the Si-SiO₂ interface can be explained by the tunneling model introduced by F. P. Heiman and G. Warfield. The spectrum of time constants is caused by the exponential decay of the effective capture cross section for larger tunneling distances. A good agreement between theory and experiments was obtained for the oxide traps concentrated within about 10Å from the interface.

The parallel conductance of an MOS structure shows a maximum as a function of frequency as expected by theory for a single energy level of the surface states. However, the observed maximum is rather broad, and decays less steeply with increasing frequency than predicted by theory. There have been attempts to account for this behavior by a quasicontinuous energy spectrum of surface states and by a statistical distribution of the oxide charge. These models involve a spectrum of time constants, the former due to the postulated distributed energy states and the latter, in addition, due to a distribution of electron concentration, nₛ, at the surface resulting from statistical fluctuations. The assumption of distributed energy states alone could not explain the experimental results. The additional assumption of statistical fluctuations of the space charge voltage had to be made to obtain agreement.

In what follows, an alternative explanation is suggested based on surface states located in the oxide close to the interface. The charge between the oxide states and the semiconductor is exchanged by tunneling. This causes a spectrum of time constants due to the exponential decay of the effective capture cross section with the tunneling distance. The effects of such oxide traps on the MOS capacitance were described in detail by Heiman and Warfield.

In this section we shall summarize the pertinent results of ref. 1. The admittance due to the oxide states is

\[ \Sigma = j \omega C₀x \frac{dV_{ss}}{d\psiₜ} \]  

(1)

where

\[ \frac{dV_{ss}}{d\psiₜ} = \frac{q²}{C₀x} \int_{E₁}^{E₀} \int_{0}^{x₀} K_i(x, E₁)g(x, E₁) \]  

\[ \times [1 + j \omega \tau_c(x, E₁)]^{-1} \frac{df}{dE₁} dE₁ dx \]  

(2)

The meanings of the symbols are listed in ref. 1. \( K_i(x, E₁) \) is the space and energy distribution of the oxide states and \( g(x, E₁) \) measures the deviation of the trap occupancy from the equilibrium occupancy at the time of the impedance measurements. In general, \( g(x, E₁) \) will be a function of the time, \( T_m \), of application of the bias voltage at which the impedance is measured. Starting with traps which are completely empty before application of the bias, it can be shown that after the time \( T_m \) all traps up to a certain distance \( x_m(T_m) \) have reached equilibrium, i.e., \( g(x, E₁) = 1 \) for \( x < x_m \) while all traps for larger distances are still empty, i.e., \( g(x, E₁) = 0 \) for \( x > x_m \). The transition from \( g(x, E₁) = 1 \) to \( g(x, E₁) = 0 \) at \( x = x_m \) is rather abrupt. Since the time constant, \( \tau_c \), corresponding to the measurement frequency is quite small compared to the time of measurements, \( T_m \), one may assume that only those traps can interact ac-wise with the silicon for which \( x < x_m \) and we may substitute, therefore, \( g(x, E₁) = 1 \) for the important terms of the integrand (1).

The time constant \( \tau_c \) for the case of an n-type semiconductor and interaction of traps with majority carriers is

\[ \tau_c = \int (n, \gamma_n e^{-2\kappa_0 x}) \]  

(3)

where \( \gamma_n \) is the capture coefficient of the traps and \( \kappa_0 \) is the attenuation constant for the wave function of an electron of energy \( E₁ \) penetrating into the insulator.

In what follows, we shall derive the real part of \( \Sigma \) divided by \( \omega \) by evaluating the integral (2) for special trap distributions.

(i) \( K(x, E₁) = K \) is constant with respect to position (x) and energy (E₁). In this case

\[ (R²\omega)^{-1} = q²K \int_{E₁}^{E₀} \ln \left[ 1 + \frac{(\omega \kappa_0 e^{2\kappa_0 x})^2}{2\omega \kappa_0} \right] dx \]  

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By partial integration this integral can easily be solved and we get
\[
(R^p\omega^qK)^{-1} = \frac{1}{2K_0} \left[ \arctg u - \arctg \omega^* \right] - \frac{\ln (1 + u^2)}{2u} + \frac{\ln (1 + \omega^{*2})}{2\omega^*} \quad (4)
\]
where
\[
u = \omega^*e^{2\gamma_nx} \quad \text{and} \quad \omega^* = \omega/\gamma_n . \quad (5)
\]

In obtaining (4) from (1) and (2) we have assumed that \(K_0\) is independent of \(E_t\).

In the case of a barrier height of a few eV, \((2K_0)^{-1}\) is about 1 Å. We computed \((R^p\omega^qK)^{-1}\) from Eq. (4) with this value for \(K_0\) and for different \(\omega^*\) values. \((R^p\omega^qK)^{-1}\) is plotted in Fig. 1(a). This curve, \(d = \infty\), does not show a maximum.

(ii) \(K(x, E_t)\) does not depend on \(E_t\) and the traps are uniformly distributed over a narrow region: \(K(x) = K\) for \(0 < x < d\), \(K(x) = 0\) for \(x \approx d\). Note that the previously discussed case is the limit for \(d \rightarrow \infty\).

Values of Eq. (4) with \(w_{ox}\) replaced by the thickness \(d\) of the trap-rich layer are plotted also in Fig. 1(a). For \(d = 15\) Å the result is already the same as for \(d \sim \infty\).

(iii) \(K(x, E_t)\) does not depend on \(E_t\) and decreases exponentially with \(x\): \[K(x) = Ke^{-ax} . \quad (6)\]

Figure 1(b) shows the \(\omega^*\) dependence of \((R^p\omega)^{-1}\) for an exponential distribution of the concentration of oxide traps and various values of the attenuation constant \(\alpha\).

(iv) A single trap level with uniform concentration of traps, \(N_t\), through the oxide. In this case
\[
E_t(x) = E_t(0) - q\varepsilon_{ox}x \quad (7)
\]
where \(\varepsilon_{ox}\) is the electric field strength in the oxide which will be assumed to be uniform. The double integral (2) reduces to a single integral over position, with \(E_t\) the function (7) of position. This leads to
\[
(R^p\omega)^{-1} = \frac{N_tq^2}{kT} \int_0^{w_{ox}} \frac{f^2(1 - f)\omega^{*2e^{2\gamma_nx}}}{1 + \omega^{*2f^2e^{2\gamma_nx}}} dx \quad (8)
\]
with
\[
f = (1 + \exp [(E_t(0) - q\varepsilon_{ox}x - E_F)/kT])^{-1} \quad (9)
\]
which can be evaluated as function of \(\omega^*\) and \(\varepsilon_{ox}\).

There is a maximum at a frequency \(\omega^*\) which depends on \(\varepsilon_{ox}\) and thus on bias. Therefore, no conclusion on capture cross section could be drawn from the frequency at which the maximum occurs in contrast to the other theoretical interpretations.\(^2,4,5\) By extrapolation to states at the very interface \((x = 0)\) only, one obtains
\[
(R^p\omega)^{-1} = \frac{N_tq^2}{kT} \int_0^{w_{ox}} \frac{f^2(1 - f)\omega^{*2e^{2\gamma_nx}}}{1 + \omega^{*2f^2e^{2\gamma_nx}}} . \quad (10)
\]

The maximum appears at \(\omega^* = 1\) only if \(f\) is close to 1. In general, the maximum appears for \(\omega^* = 1\).

The height of the maximum is strongly dependent on the Fermi factor \(f\).

The experiments were performed on a sample consisting of a 2 Ω-cm n-type Si wafer \((n_0 = 3.3 \times 10^{15}/\text{cm}^3)\) covered by a 5500-Å-thick thermally...
Table I. Electron Capture Coefficient of Surface States Obtained by Two Different Methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Parameters</th>
<th>γs (cm²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y = parameter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-8.2</td>
<td>2.3 × 10⁻⁹</td>
</tr>
<tr>
<td></td>
<td>-5.8</td>
<td>2.9 × 10⁻⁹</td>
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<tr>
<td></td>
<td>-3.8</td>
<td>3.3 × 10⁻⁹</td>
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<tr>
<td></td>
<td>f dependence</td>
<td></td>
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<tr>
<td></td>
<td>1 kc</td>
<td>4.3 × 10⁻⁹</td>
</tr>
<tr>
<td></td>
<td>10 kc</td>
<td>2.4 × 10⁻⁹</td>
</tr>
<tr>
<td></td>
<td>100 kc</td>
<td>3.4 × 10⁻⁹</td>
</tr>
</tbody>
</table>

grown oxide layer and provided with a filament-evaporated Al electrode. The parallel resistance $R_p$ was measured vs frequency at different bias voltages and vs bias at different frequencies. The $(R_pω)^{-1}$ curves had a definite maximum, from which the capture coefficient was derived using the model for a quasicontinuous energy spectrum of surface states with no tunneling effects considered. The results are contained in Table I. The $γ_s$ values show a good agreement. This leads to the conclusion that $(R_pω)^{-1}$ can be represented as a function of $ω*$ only, i.e., without including $ω$ or the bias voltage explicitly. Cases (ii) and (iii) remain as possible explanations for the shape of the $(R_pω)^{-1}$ curves, provided that the tunnel model applies.

The experimental points of $(R_pω)^{-1}$ vs frequency at a reduced voltage of $Y = -5.8$ are shown in Figs. 1(a) and 1(b). The values are in good agreement with experimental points obtained by Nicollian and Goetzberger, also shown in Fig. 1(a). The theoretical curve for $d = 7$ Å in Fig. 1(a) fits the experimental data better than the curve for $α = 0.2$ Å⁻¹ in Fig. 1(b).

The degree of fit can be judged even better from a semilogarithmic plot of $(R_pωq^2K)^{-1}$ vs $ω*$ as shown in Fig. 2 obtained for $d = 6.5$ Å by adjusting the maxima of the theoretical and experimental curves. The degree of fit appears of the same order as that by ref. 6. The present theory deviates (as does that of ref. 6) from the experimental points in the higher frequency tail of the curve. The maximum of the curve $d = 6.5$ Å appears at about $ω* = 1 × 10^{-1}$. From this we arrive at $γ_s = 4.4 × 10^{-9}$ ($v_{max} = 7$ kc). The capture coefficients derived from this model are about one order of magnitude larger than the ones obtained from the previous models (listed in Table I).

The experimental results interpreted by means of the cases (ii) and (iii) assume a large oxide trap concentration within about 10 Å, i.e., a few atomic layers from the interface. From the maximum of the curve $d = 6.5$ Å in Fig. 2 and the measured maximum value of $R_p$ we obtain for the volume density of oxide states

$$K = \frac{1}{R_{p_{max}} N_{o} \gamma q} \approx 2.45 \times 10^{18} \text{ cm}^{-3} \text{ (eV)}^{-1}.$$  

Since these states are located within about 6.5 Å of the interface, the density of states is about $1.6 \times 10^{11}$ cm⁻² (eV)⁻¹. From the flat band voltage and the oxide capacitance we obtained for the effective charge density of the entire oxide $Q_{ox}/q = 4.4 \times 10^{11}/\text{cm}^2$, neglecting the work function difference.

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