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Determination of Interface Trap Capture Cross Sections Using Three-Level Charge Pumping

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Abstract—**A modified three-voltage level charge pumping technique is described for measuring interface trap parameters in MOSFET's. With this technique, interface trap capture cross sections for both electrons and holes may be determined as a function of trap energy in a single device.**

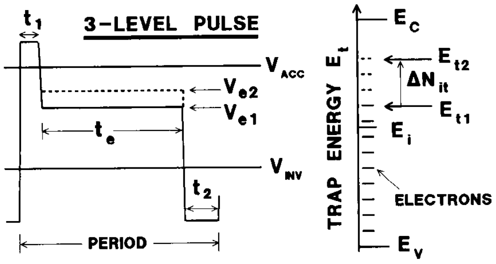
CHARGE PUMPING (CP) is a technique for studying traps at the Si-SiO$_2$ interface in MOS transistors. In the CP technique, a pulse is applied to the gate of the MOSFET which alternately fills the traps with electrons and holes, thereby causing a recombination current I_{cp} to flow in the substrate. The number of traps N_{it}, and the geometric mean of the trap electron and hole capture cross sections (σ_e and σ_h), may be determined as a function of trap energy E_t by varying the pulse rise and fall times [1]. Unfortunately, this method requires that σ_e and σ_h be independent of energy [1].

Recently, Tseng [2] introduced an improved CP technique which eliminates this assumption by using a three-level gate pulse where the new third level is at voltage V_e with duration t_e (Fig. 1(a)). During t_1, all interface traps are filled with electrons. When the pulse is switched to V_{e1}, many trapped electrons are emitted back to the conduction band if their emission times $\tau_e(E_t)$ are short. If t_e is long enough, all trapped electrons above energy E_{t1} (determined by V_{e1}) will be emitted, and the trap occupancy will reach equilibrium. Finally, during t_2, holes are brought to the interface which recombine with the remaining trapped electrons, giving rise to I_{cp}. By changing the voltage V_{e1} to V_{e2} (Fig. 1(a)), the equilibrium trap occupancy level will change (Fig. 1(b)). From the resulting change in I_{cp}, the density of electron traps D_{it} between E_{t1} and E_{t2} can be deduced using [2]

$$D_{it}(E_t) = \frac{1}{qfA} \frac{dI_{cp}}{dV_e} \frac{dV_e}{d\phi_e} \tag{1}$$

where q is the electron charge, f is the pulse frequency, A is the MOSFET area, and ϕ_e is the surface potential established by V_e. (The hole trap density may be obtained similarly using the complement three-level pulse.)

In this letter, we demonstrate a three-level CP technique which is improved over Tseng's technique in that σ_e and σ_h may be accurately determined as a function of trap energy. This technique also does not require that σ_e and σ_h be independent of energy. We emphasize that these capture cross sections are not obtained using previous three-level CP methods [2]–[6].



(a) (b)

Fig. 1. (a) The three-level CP pulse. The bias levels above V_{ACC} and below V_{INV} are used as in standard charge pumping [1]. Using three-level CP, the duration (t_e) and voltage (V_e) of the third level are varied to determine trap parameters. (b) Diagram of interface trap occupancy after filling with electrons. At long times t_e, the traps are filled to levels E_{t1} or E_{t2} depending on bias levels V_{e1} and V_{e2}.

The test devices are p-channel MOSFET's with 10-μm gate length, 100-μm width, and a 48-nm gate oxide. The three-level pulse used here is identical to that of Tseng but with both V_e (as in [2]) and t_e (as in [3]) variable. The pulse is applied to the MOSFET gate and I_{cp} measured at the substrate [1]. A 100-Hz pulse with 50-ns rise and fall times was used to explore a wide range of trap time constants.

Experimental I_{cp} data obtained as a function of t_e for different values of V_e are shown in Fig. 2. At small t_e, I_{cp} decreases approximately as $\ln(t_e)$. This behavior is expected since [1], [2]

$$D_{it}(E_t) = -\frac{1}{qkTfA} \frac{dI_{cp}}{d\ln(t_e)} \left[1 + \frac{kT}{\sigma} \frac{d\sigma}{dE_t}\right] \tag{2}$$

where k is Boltzman's constant and T is the absolute temperature. If σ is independent of E_t, this reduces to

$$D_{it}(E_t) = -\frac{1}{qkTfA} \frac{dI_{cp}}{d\ln(t_e)}. \tag{3}$$

As discussed above, when t_e is long, the traps above the Fermi level determined by V_e emit their electrons. Therefore, the traps reach equilibrium, and I_{cp} saturates, at long times, as observed in Fig. 2. That a clean saturation characteristic is indeed obtained indicates that the trap levels are associated with a single emission time and thus each is characterized by a single value of σ. D_{it} may then be determined using Tseng's method [2] from the variation of saturated I_{cp} with V_e using (1).

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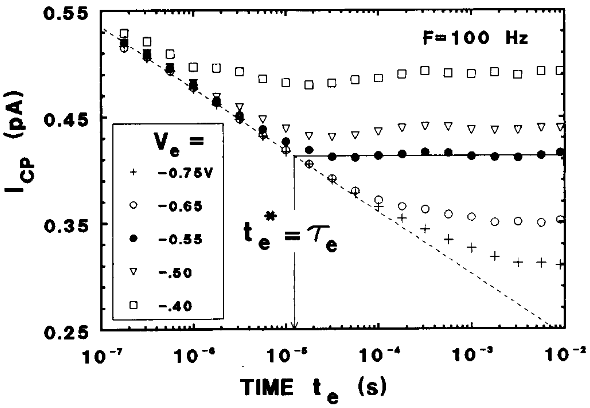

Fig. 2. I_{cp} as a function of t_e for electron emission, with pulse bias V_e as a parameter. I_{cp} falls with ln (t_e) according to (3) until saturation is reached at large t_e. The trap emission time τ_e is determined from the I_{cp} saturation value (see text).

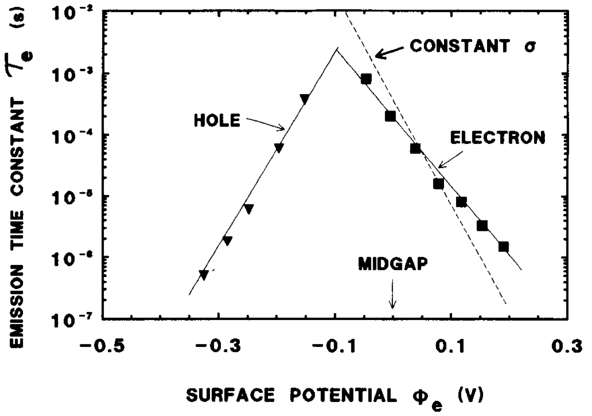

Fig. 3. Electron and hole emission times τ_e as function of ϕ_e, determined as shown in Fig. 2. The hole emission time varies exponentially with ϕ_e as given by (4). The electron emission time also varies exponentially with ϕ_e, but with a smaller slope than predicted from (4) (shown by the dashed line where σ_e is assumed independent of energy).

Our improved technique is based on the essential fact that the time at which saturation first occurs is given by $t_e^* = \tau_e$, where

$$\tau_e = (1/\sigma_e v_{th} n_i)e^{(-\phi_e/kT)} \tag{4}$$

and v_{th} is the electron thermal velocity, n_i is the intrinsic carrier density, and ϕ_e is measured with respect to midgap. τ_e (for energies not too close to midgap) is obtained by graphical extrapolation as shown in Fig. 2. Values for ϕ_e are determined within ± 0.05 V from V_e by standard methods [2].

Electron and hole emission times τ_e are shown in Fig. 3 as a function of ϕ_e. Using these data and (4), σ_e and σ_h may readily be determined as a function of energy (Fig. 4). The hole emission time depends exponentially on ϕ_e with a slope of q/kT, in agreement with (3). σ_h is small ($\approx 1 \times 10^{-16}$ cm^2) and independent of energy, in reasonable agreement with previous work using ac conductance on capacitors ($\sigma_h = 2$-4×10^{-16} cm^2 for $\langle 100 \rangle$ silicon) [7]. However, the slope of the electron emission time data versus ϕ_e is not equal to q/kT (dashed line in Fig. 3). This difference may be caused by experimental error (although the apparent error is larger than we can account for), or it may be due to the energy dependence of σ_e. σ_e is found to be surprisingly large ($\approx 1 \times 10^{-13}$ to 3×10^{-15} cm^2), and it decreases towards the conduction-band edge. This result does not agree with [7]; however, others have reported energy-dependent σ_e [8], [9]. Of particular interest is the recent report of Haddara and El-Sayed [9], who, using ac conductance on MOSFET's, observed a similar energy dependence. The physical origin of this dependence is presently unclear. The large magnitude of σ_e may arise from interface trap response to charge pumping, which is a large-signal nonequilibrium method as compared with small-signal ac measurements [7]-[9]. In addition, results reported here have been obtained on a single set of devices and may not be representative of "typical" devices.

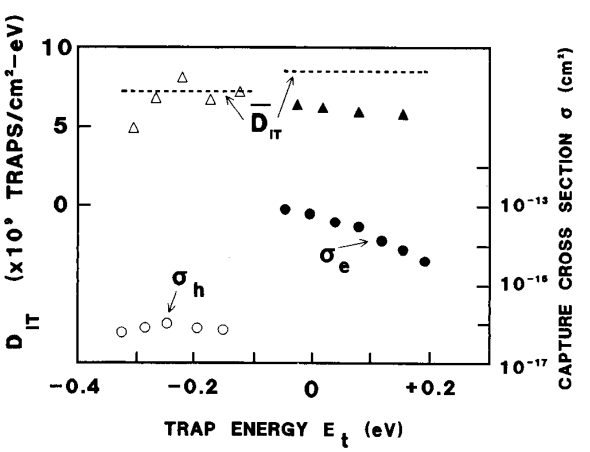

Fig. 4. Experimental values for D_{it}, σ_e, and σ_h as a function of trap energy E_t (measured with respect to midgap). σ_e decreases with increasing energy, while σ_h is nearly energy independent. The dashed lines are average D_{it} values obtained using previous CP methods [1], while the triangles are obtained using our improved three-level CP technique. The disagreement observed for electron traps above midgap occurs because σ_e is not energy independent as assumed in [1].

In Fig. 3, we observe that the experimentally determined energy at which electron and hole emission times are equal occurs well below midgap. This offset is due to the fact that σ_e is considerably larger than σ_h. The offset is calculated from $(kT/2q)$ ln (σ_h/σ_e) [10]. Using near-midgap σ values, an offset of -0.10 eV is obtained, in excellent agreement with Fig. 3.

Experimental values for D_{it} obtained by two different methods are also shown in Fig. 4. Using the three-level CP technique with (1) (triangles), trap densities are found to be small (6-7 $\times 10^9$ traps/cm^2·eV), nearly independent of energy, and about the same for electrons and holes. The *average* D_{it} values obtained from the slopes of I_{cp} versus $\ln(t_e)$ using (3) are shown by the dashed lines in Fig. 4. Agreement between the two methods is excellent for the hole traps below midgap, but differ significantly above midgap. This discrepancy occurs because σ_e is not independent of energy as assumed in the derivation of (3). If the actual energy dependence of σ_e is taken into account using (2), then D_{it} is about 30% smaller and is in much better agreement with the data. This comparison shows that average D_{it} values obtained by the standard

CP approach [1] may have large errors when σ varies rapidly with energy.

In summary, we have shown that a modified three-level charge pumping method may be used to determine not only interface trap densities as in [2] but also capture cross sections as a function of trap energy. The trap parameters are obtained for both electrons and holes using a single MOSFET. This is a significant advantage over the conventional ac conductance technique [7], which is limited to one-half of the bandgap. The values obtained for σ_h are in good agreement with previous results. However, values obtained for σ_e have a surprisingly large magnitude and strong energy dependence. Clearly, further experiments, including direct comparisons to ac conductance as in [9], are warranted.

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