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-SiO₂ 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 Icp to flow in the substrate. The number of traps Nt, and the geometric mean of the trap electron and hole capture cross sections (σe and σh) may be determined as a function of trap energy Ei by varying the pulse rise and fall times \( t_e \). Unfortunately, this method requires that \( \sigma_e \) and \( \sigma_h \) 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)). 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 \( \sigma \). \( D_{it} \) may then be determined using Tseng’s method \([2]\) from the variation of saturated \( I_{cp} \) with \( V_e \) using (1).

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 \([1, 2]\).

\[
D_{it}(E_i) = \frac{1}{qfA} \frac{dI_{cp}}{dV_e} \frac{dV_e}{d\sigma_e} (1)
\]

where \( q \) is the electron charge, \( f \) is the pulse frequency, \( A \) is the MOSFET area, and \( \phi_e \) is the surface potential established by \( V_e \). (The hole trap density may be determined 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 \( \sigma_e \) and \( \sigma_h \) may be accurately determined as a function of trap energy. This technique also does not require that \( \sigma_e \) and \( \sigma_h \) be independent of energy. We emphasize that these capture cross sections are not obtained using previous three-level CP methods \([2]\)–\([6]\).

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The electron emission time also varies exponentially with 

\[ t_e \sim e^{-q/N}\text{eV}/kT \]  

and \( N \) is the intrinsic carrier density, as assumed in (3). However, others have reported energy-dependent \( \sigma_e \), which is determined from the (6-7) \( \sigma_e/\sigma_i \) of the three-level CP technique. The disagreement between the two methods is excellent for the hole traps below midgap, but varies significantly above midgap, which is not independent of energy as assumed in (2).

In Fig. 3, we observe that the experimentally determined energy at which electron and hole emission times are equal occurs well above midgap. This offset is due to the fact that \( \sigma_e \) is considerably larger than \( \sigma_i \). The offset is calculated from (KT/2q) in (\( \sigma_h/\sigma_i \)) of near-middle potential (7-9). Using near-middle potential \( \sigma \) as an offset of \(-0.10 \text{ eV}\) is obtained, in excellent agreement with the data. This comparison shows that the average \( D_{it} \) obtained by the standard method is approximately 20% smaller than that obtained by the three-level CP technique.
CP approach [1] may have large errors when $\sigma$ 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 $\sigma_h$ are in good agreement with previous results. However, values obtained for $\sigma_e$ 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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