Frequency-Dependent Charge-Pumping: The Depth Question Revisited

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Abstract— A popular defect depth-profiling technique, frequency-dependent charge-pumping is carefully re-examined. Without complicated math of modeling, the physics behind the technique is examined clearly. It is shown that there is no unique relationship between the measurement frequency and the probed depth. The conclusion is that frequency-dependent charge-pumping is not a defect depth-profiling technique.

Keywords-frequency dependent charge pumping

I. INTRODUCTION

Frequency-dependent (FD) charge-pumping (CP) is considered a "power technique" to profile defect depths within the gate dielectric. It has been used to illustrate that electrical stress can increase defect density in the high-k layer [1]. However, this claim is disputed [2] by data obtained using the same technique. This dispute is at the heart of a raging controversy on how to correlate depth with frequency in the FD-CP experiments. The disagreement is, however, only on quantitative level. Everyone involved expects that a relationship between depth and frequency exists and is sufficiently unique. **It is the purpose of this paper to show that a simple correlation does not exist and that the technique cannot be used for the stated purpose.**

II. "BASIC PRINCIPLE" OF FD-CP

The basic CP process consists of a two steps. The principle is as shown in figure 1. The basis of FD-CP is that if the time spent in inversion/accumulation is sufficiently long, "near interface" traps can also contribute the CP current as illustrated in figure 2. This formalism has been around for more than 30 years [3], and has been treated by several groups [2-7]. The relationship between the maximum depth at which oxide traps contribute to CP current and the time spent (τ) in inversion/accumulation (half of a CP period) is usually expressed using the tunneling-front formalism [8]:

$$\tau = t_0 e^{2\beta x} \qquad (1)$$

where β is the characteristic length, x is the maximum depth, and t_0 is a pre-factor, or the time required when the depth is zero. β has to do with the barrier height and effective mass of the tunneling process – something that can be well-defined if the model is clear. The controversy surrounds the proper choice of the value of t_0. Every group seems to champion its own

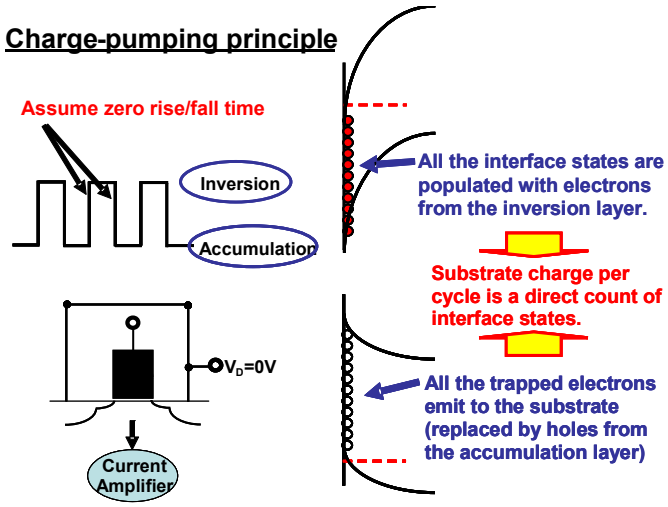

Figure 1. The basic charge-pumping principle involves switching the MOSFET from strong accumulation to strong inversion (and back) rapidly while keeping the source/drain grounded. The DC component of the substrate current is measured at zero volts and is taken as a direct measure of the recombination events happening at the SiO_2/Si interface.

value with very little agreement from group to group. Within the groups involved, it is generally believed that if t_0 can be pinned down, then a unique relationship between frequency and probing depth within the dielectric can be attained.

The standard way to obtain t_0 is via its relationship with the mean capture cross section (σ):

$$t_0 = \frac{1}{\sigma v_{th} n} \qquad (2)$$

where v_{th} is the thermal velocity of the carriers and n is the carrier density. The value of n is often taken as the inversion charge density (on the order of 10^{13}cm^{-2}). Problems arise when one realizes that a survey of the literature yields reported σ values which vary widely (from 10^{-14} cm^2 to 10^{-19} cm^2) [9]. While most groups choose σ values between 10^{-15} cm^2 to 10^{-17} cm^2, the utilized value of t_0 varies from 6.6 x 10^{-14} to 10^{-8} s (depending the details of the model). This leads to a significant difference in the depth associated with a given CP frequency and hence the surrounding controversy.

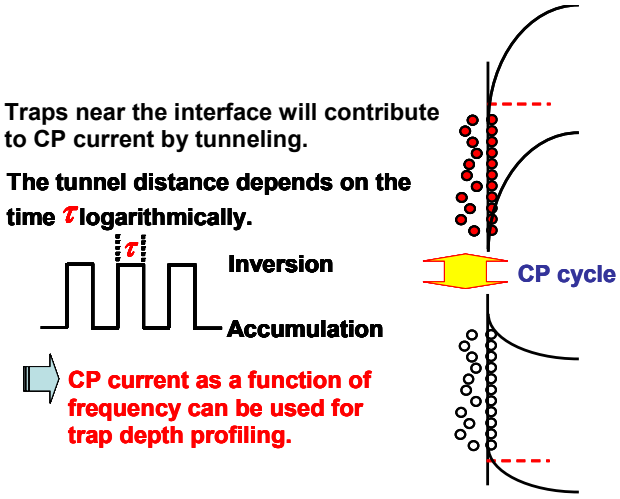

Figure 2. Frequency-dependent charge-pumping (FD-CP) assumes that when given enough time at inversion/accumulation, near interface oxide traps can also participate in producing CP current through tunneling. Lower frequency means longer time available for tunneling, and deeper oxide traps can be accessed.

While the disagreement on the correct choice of t_0 is well noted [10], the majority of the groups agree that there is a simple logarithmic relationship between CP frequency and the maximum probed depth. In this study, we will show that (1) a simple logarithmic relationship between CP frequency and the maximum depth probed does not exist, and (2) that the surrounding controversy is indeed unjustified because FD-CP cannot be used for the stated purpose.

III. Physcial Process Details

Many groups have published models on the FD-CP depth relationship [2-7], but the complex mathematics utilized renders these works somewhat difficult for readers to gauge the appropriateness of the physics. Here, we focus on the physics of the phenomenon involved and present a clear argument, without complex modeling, that there is flaw in the basic concept itself.

In FDCP, the sequence involves four steps (fig. 3). To simplify matters, let us assume that (1) hole capture has the same rate as electron capture, and (2) that hole-tunneling has the same probability of electron-tunneling. Immediately, we come to the conclusion that the proper expression for τ is not equation (1). Instead, it should be:

$$\tau = t_{if} + t_0 e^{2\beta x} \qquad (3)$$

where t_{if} is the interface trap-fill time. If t_{if} is very small compared to τ, the equation reduces back to (1). Some reports take t_{if} as t_0 with values from 10 ns [6] to a fraction of ns [2]. They are obviously in error because t_{if} and t_0 are referring to different physical processes.

The physical pictures responsible for the two terms in (3) are quite different and are shown in fig.4. Fig 4a schematically illustrates the spatial picture of the two charge capturing processes of eqn. (3). The first term, filling of interface traps, involves inversion layer charge capture. These charges can

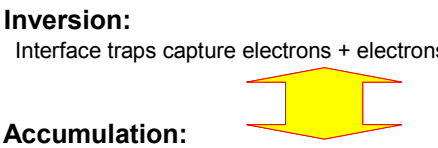

Figure 3. 4-steps sequence of the frequency dependent charge-pumping process: (1) Interface traps capture electrons, (2) electrons tunnel into oxide traps, (3) trapped electrons capture holes, and (4) holes tunnel into the oxide traps.

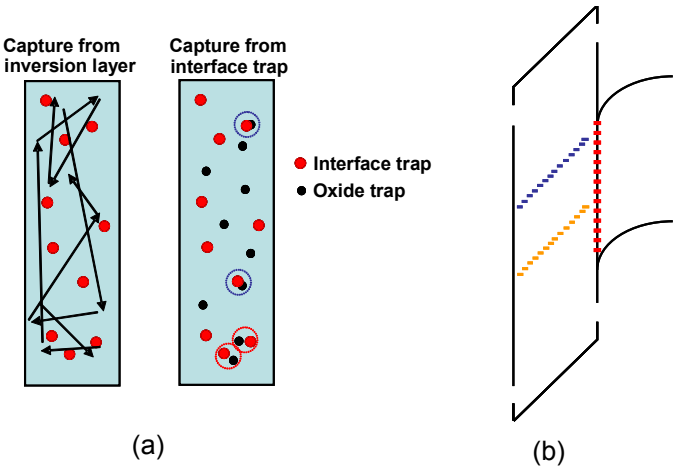

Figure 4. (a) spatial picture of carrier-capture by interface states (left), and carrier-tunneling from interface states to oxide trap states (right). (b) Energy band diagram showing a uniform energy distribution of interface states and two oxide trap states that are uniformly distributed (in depth) within the oxide layer.

move within the inversion layer and every charge has a finite chance of being captured by any one of the interface traps. In this case, equation (2) can be used, burying all the physics of the capture process into a capture cross section σ. (As mention above, the reported cross section varies wildly.)

The right hand side of fig. 4a is a more correct picture for the second term in eqn. (3), and by extension FD-CP. Interface traps are fixed in space and interface state captured charge can only tunnel into oxide traps that have a spatial overlap the interface states (in this 2-D view). This is shown as those traps in the broken blue circles. If an oxide trap and interface trap are sufficiently close (like those in the broken red circles), tunneling is still possible. The probability of tunneling reduces rapidly with the separation of these two traps. We can immediately see that not only does oxide trap depth relate to τ, the lateral position also plays just as big a role. This point alone already eliminates any possibility of a simple relationship between CP frequency and depth, like many have hoped.

The FD-CP depth profiling picture gets even more complicated when we account for the interface and oxide trap energies (schematic band diagram is shown in fig. 4b). In fig. 4b, we depict uniformly distributed (in energy) interface traps and two different oxide traps with uniform distribution in depth. These are both commonly used simplifications. The key point here is that even if the interface trap overlaps with an

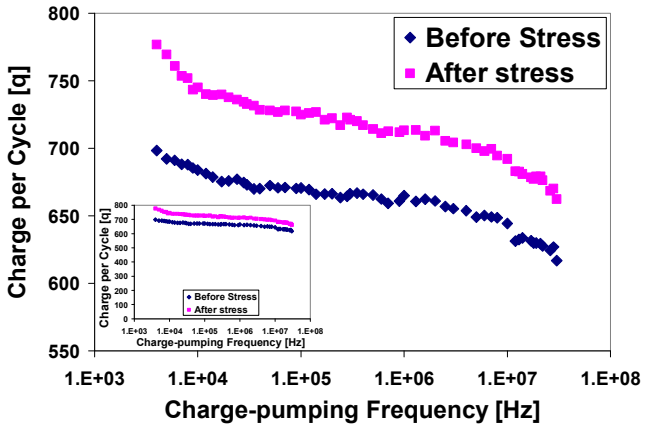

Figure 5. CP charge per as a function of frequency for a production quality transistor where little bulk traps exists. (V_{acc} = -1.5V, V_{inv} = 1V, t_{rise}=t_{fall} = 2ns)

oxide trap spatially in the 2-D view, it may not be at the same energy level. Since tunneling is only possible when the energy is identical, a deeper oxide trap with better energy alignment may have a higher probability of capturing an interface charge than a shallower oxide trap with poorer energy alignment.

Note that even with all the constraints discussed above, it is still possible to have CP current coming from oxide traps. However, the combined constraints of spatial overlap, spatial separation and energy matching completely destroy the relationship between depth and time (frequency). Thus, any hope of depth profiling using FD-CP is dashed. Furthermore, if the interface-trap energy distribution and/or oxide trap depth distribution are not uniform, the picture becomes even murkier.

It should be noted that while the frequency/depth relationship is seemingly impossible to determine, all the factors discussed thus far still support the common observation of increased CP charge per cycle with decreasing frequency due the contributions of near interface oxide traps. If the oxide-trap density increases, CP charge per cycle will increase as well. We just cannot quantitatively relate the CP frequency to any oxide depth or trap density.

On the other hand, an increase in CP charge per cycle with decreasing frequency does not necessary denote participation by near interface oxide traps. If we take the CP process as filling the available traps with electrons during the inversion cycle and then emptying these electrons during the accumulation cycle, then the filling and emptying processes are given by the first order kinetic equations:

$$N_e = N_0\left(1 - e^{-Kt}\right) \quad (4)$$

$$N_c = N_e e^{-Kt} \quad (5)$$

where N_0, N_e, and N_c are the number of traps, the number of trapped electrons, and the number of charges contributing to the CP current, respectively, K is the capture time constant, and t is the time spent in either accumulation or inversion. Here we maintain the assumption that hole- and electron-capture has the same time constant (emptying an electron from a trap is the same as capturing a hole). As the CP frequency decreases, t increases for both electron capture and emptying, N_e increases, and N_c will increase even more. Thus, even in the absence of slower (oxide) traps, one should still expect a CP charge per cycle increase with decreasing CP frequency. When $t >> K$, the effect is relatively small; otherwise, the effect can be large. Fig. 5 shows the FD-CP for a production-quality pure thermal oxide (2.4 nm physical thickness) 15.6 x 0.16 μm^2 nMOSFET. Oxide traps densities in these devices are expected to be very low (if not absent). Yet, the charge per cycle increases as the frequency decreases. This increase is mild but unmistakable.

This device was subject to a gate injection mode stress to increase the interface state density. We note that stress does increase the CP charge per cycle but also increases the absolute slope of the FD-CP curve. The stress is relatively mild (interface state density increase by ~10%), yet the increase in FD CP slope is evident. While we cannot rule out that oxide traps are also created, it is well-known that interface states are much more readily generated than bulk traps. Thus, this indicates that the FD-CP slope can possibly be due purely to interface defect participation.

IV. CONCLUSIONS

In summary, we showed that the FD-CP technique is fundamentally unsuitable for defect depth profiling. Here we forgo the complicated mathematics and fuzzy concepts employed by other groups for a clear physical argument. We clearly show that a relationship between the frequency of FD-CP and the probed oxide depth cannot exist. In addition, we show that while stress does induce an increase in the absolute FD-CP slope, it cannot necessarily be explained solely by an increase in near interface oxide trap density. The interpretation is therefore not unique.

V. ACKNOWLEDGMENTS

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