A New Interface Defect Spectroscopy Method

J.T. Ryan[1], L.C. Yu[1,2], J.H. Han[1], J.J Kopanski[1], K.P. Cheung[1,*], F. Zhang[3], C. Wang[4,5], J.P. Campbell[1], J.S. Suehle[1], V. Tilak[2], and J. Fronheiser[2]
[1]NIST, Gaithersburg, MD; [2]GE Global Research, Niskayuna, NY; [3]Michigan State University, East Lansing, MI; [4]Purdue University, West Lafayette, ID; [5]Fudan University, Shanghai
*kin.cheung@nist.gov

***Abstract*— A new interface defect spectroscopy method based on variable height charge pumping capable of observing the amphoteric nature of Si/SiO$_2$ interface states in production quality sub-micron devices is demonstrated. It can help to resolve the long standing debate about the true nature of interface states.**

Keywords; interface states, P$_b$ centers, charge pumping

I. INTRODUCTION

There is a long standing debate on whether P$_b$ centers account for all electrically observed Si/SiO$_2$ interface states. The inability to establish the amphoteric nature of Si/SiO$_2$ interface states in high quality samples is a key obstacle for resolving this issue. In this work, we introduce a new interface defect spectroscopy method and report the amphoteric signature of interface states in production quality samples for the first time. The new technique is demonstrated on submicron devices, highlighting the exceptional level of sensitivity.

Our new technique is a modified charge-pumping (CP) measurement. When applied to a production quality MOSFETs, we can be confident that the CP signal is due only to interface states. Fig. 1 shows the key result demonstrating the new technique. The signature double peaks (which maintain their shape and increase in magnitude following moderate gate stress) at expected energy locations clearly show that the interface states are of the P$_b$ center family. Please note the absolute number of defects (left vertical axis) and the defect density (right vertical axis). This is the first ever reported double peak signature on a high quality submicron device.

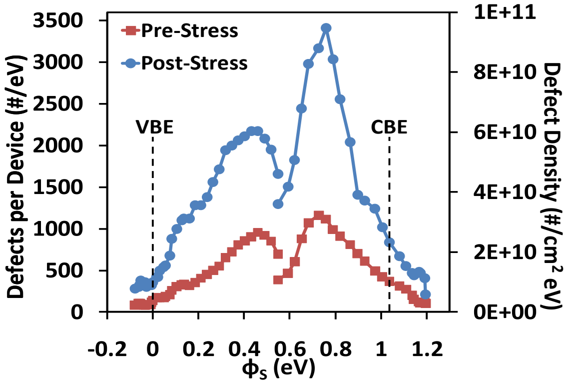

Fig. 1: Amphoteric nature of Si/SiO$_2$ interface states.

All previously reported successful electrical observations of the amphoteric nature of Si/SiO$_2$ P$_b$ centers relied on devices with very poor quality interfaces ($D_{it}>10^{11}$ cm^{-2}) and/or very large area [1-14]. In some cases, the amphoteric nature was only observable after very harsh irradiation [2, 7, 8, 12, 14]. In addition to a high density of interface states, these samples also exhibit high densities of non-interface defects. As most measurements are not capable of truly excluding non-interface defects, the results fueled the controversy [15, 16].

Using CP to perform defect spectroscopy is not new [1-3, 11]. Previous attempts are based on trapped charge emission which have difficulty probing mid-gap and (in some cases) require complicated pulse trains that limit access near the band edges (slower pulse rise time (t_r) and fall time (t_f)) [1-3, 11]. Our approach utilizes a simple square wave, relies on charge capture rather than emission, is able to probe defects through mid-gap, and allows the use of faster t_r and t_f to probe closer to the band edges. Additionally, **choosing a CP frequency low enough to ensure complete trap filling is the key new aspect** in our approach.

II. EXPERIMENTAL

The devices used are production quality 16.45 x 0.24 μm^2 nMOSFETs with 5.5nm SiO$_2$ dielectrics. CP was performed by applying a square wave to the gate while shorting source and drain to ground. The substrate current (I_{CP}) is measured with an ultra-low noise current preamplifier. The CP method is very similar to the variable pulse height method [17]. The upper half of the band gap is measured by setting the low level (V_{GL}) at strong accumulation (V_{GL} = -2V) while varying the high level (V_{GH}) from strong inversion to depletion. The lower half of the band gap is measured by setting V_{GH} at strong inversion while varying V_{GL} from strong accumulation to depletion. t_r and t_f are both held at 2.3ns for all measurements. Fig. 2 schematically illustrates the pulse conditions. For each bias level, CP current was measured at 1, 2, 3, and 4 kHz. Such low frequency is of key importance and separates our approach from the conventional variable pulse height method, as explained later. The linear plot of CP current vs. frequency (fig. 3) allows leakage current and amplifier offset to be corrected and the CP current at 2 kHz be extracted accurately.

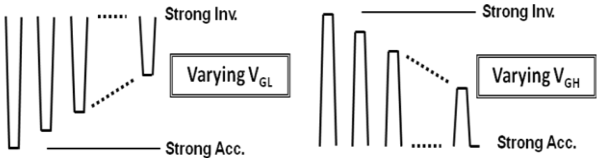

Fig. 2: Schematic illustration of the pulse conditions.

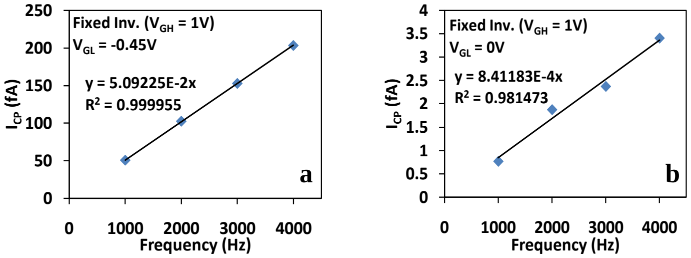

Fig. 3: Linear fits at fixed inversion for (a) V_{GL} = -0.45V and (b) V_{GL} = 0V.

III. DISCUSSION

As mentioned above, choosing a CP frequency low enough to ensure complete trap filling is a vital necessity. Since we vary the pulse height deep into depletion, the carrier density can become very small. This will mean the traps are not filled completely if sufficient time is not given. This is the reason we perform CP at 2 kHz. This frequency is experimentally determined by measuring the CP current as a function of frequency for various biases as shown in fig. 4 for the case of fixed V_{GL}. It clearly shows that as the frequency is increased and V_{GH} is reduced, charge per cycle decreases; this is caused by insufficient time to ensure complete filling of the traps and **must** be avoided. **Ensuring the measured result is free from incomplete trap-filling effects separates our new method from conventional variable pulse height CP**, which is usually done at higher frequency.

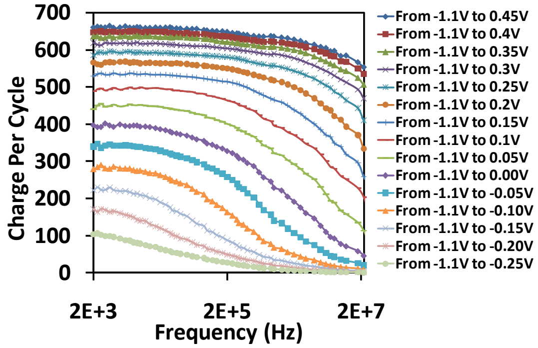

Fig. 4: Charge loss due to incomplete trap filling clearly occurs with increasing frequency and decreasing pulse height. **This effect must be avoided**.

Fig. 5 shows the measured defect density vs. gate voltage (V_G) for both fixed inversion and fixed accumulation cases at a frequency of 2 kHz. Superimposed is the simulated [18] pre-stress capacitance vs. V_G (CV) curve. By taking the derivative of the measured defect density with respect to V_G, we can extract the density of states (DOS) of the traps participating in the CP process. This derivative is shown in fig. 6 (the pre-stress curves of fig. 1) after converting V_G to surface potential (ϕ_s) using the simulated CV curve (superimposed). The left hand curve (extracted from fixed inversion) peaks at about 0.45eV above the valence band edge (VBE) and the right hand curve (extracted from fixed accumulation) peaks at about 0.76eV above the VBE.

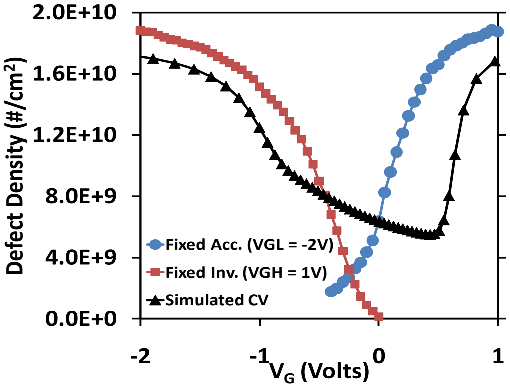

Fig. 5: Defect density vs. V_G extracted at 2kHz and simulated CV.

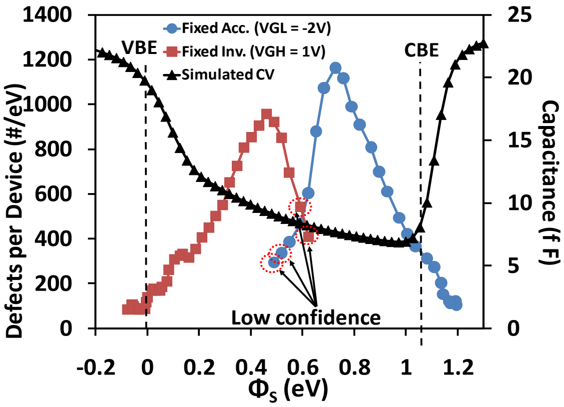

Fig. 6: DOS illustration computed from fig. 5 and simulated CV.

An obvious question is why the two sides of the measured DOS seem not in agreement where they overlap? The answer involves the accuracy of the measurement falling off as the pulse is pushed into deep depletion. As mentioned above, for each pulse condition, frequency dependent CP was performed at frequencies of 1, 2, 3, and 4 kHz, and CP current at 2kHz was extracted from a linear fit. As we push deep into depletion, incomplete trap filling starts to set in and the linear fit will no longer be appropriate (R^2 in fig. 3b is worse than in 3a which is in part due to this). Fig. 7a compares the linear fit R^2 values for fixed inversion with $V_{GL} = -0.7$ to 0V. At certain V_{GL} levels, the linear fit R^2 value clearly starts to degrade. This is indicative of the on-set of incomplete trap filling (as well as signal to noise degradation). Similarly, the phenomenon is also clearly observed in the fixed V_{GL} case (fig. 7b). Clearly, the reliability of the last three points in fig. 7a and the first three data points in fig. 7b should not be trusted. The first four points are already dropped in fig. 1 while only the first two points are dropped in fig. 6. The reason for dropping four points instead of two in fig. 1 is that the third point is, as we discussed already, unreliable. The fourth point also becomes unreliable because the differentiation routine propagates the influence of the preceding two points. As differentiation tends to amplify small errors, the influence at the first point is significant and thus dropped. The next point is still affected, but to a lesser degree. (We circle the data points that should be removed in fig. 6.) Once we realize that the first point of each curve (the mid-gap end) is only partly accurate, the disagreement disappears.

To illustrate the new technique and to show that the peak locations are not measurement artifacts, we apply this technique to a different system, namely SiC/SiO_2 nMOSFETs (400 x 2 μm^2, t_{ox} = 50nm). For this system, one would intuitively expect silicon dangling bonds as well as carbon dangling bonds each with two DOS peaks. Fig. 8 shows the results of applying our new technique on a SiC MOSFET and four peaks are clearly observed. Measured CV curves are superimposed and the VBE and CBE markers are estimates only.

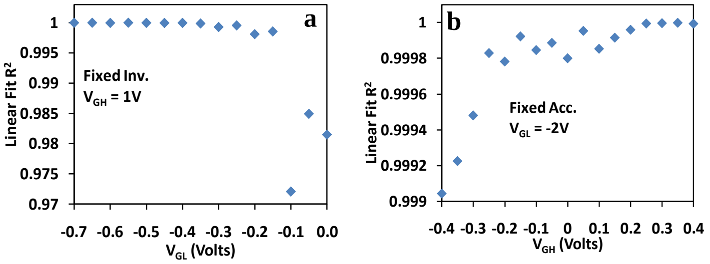

Fig. 7: R^2 vs. pulse level for fixed inversion (a) and accumulation (b). The degraded linear fit data has low confidence.

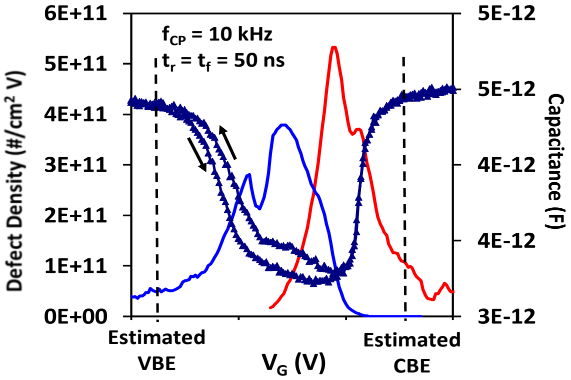

Fig. 8: DOS illustration and measured CV for a SiC MOSFET.

We have shown, for the first time, the amphoteric nature of Si/SiO_2 interface states in production quality sub-micron devices with excellent sensitivity and resolution. This work should help resolve the ongoing debate as to whether or not P_b centers are responsible for the “true” electrically measured interface states. Performing the measurements at sufficiently low frequency to ensure complete trap filling separates this method from conventional variable height CP, and is crucial to the accurate extraction of defect density as a function of energy in the band-gap.

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