Frequency-Modulated Charge Pumping: Defect Measurements With High Gate Leakage

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Abstract—Charge pumping is one of the most relied techniques used to quantify interface defects in metal-oxide-semiconductor devices. However, conventional charge pumping is easily hindered by excessive gate leakage currents, which render the technique unsuitable for advanced technology nodes. We demonstrate a new frequency-modulated charge pumping methodology in which we transform the quasi-dc charge pumping measurement into an ac measurement. The ac detection scheme is highly resistant to gate leakage currents and extends the usefulness of charge pumping as a defect monitoring tool for future technologies.

Index Terms—Charge pumping, defects, leakage current.

I. INTRODUCTION

Advanced research and development relies heavily on the ability to “gauge” defects, which limit the performance and reliability of ultrascaled devices. Ironically, successful device scaling actually limits the ability of many device characterization techniques to “gauge” these defects. Charge pumping (CP), e.g., is a seemingly ubiquitous characterization technique often used to study the density and energy distributions of interface defects in metal-oxide-silicon field-effect-transistors (MOSFETs) [1]–[8]. However, an unfortunate side effect of successful scaling is increasingly large gate leakage currents. In modern devices, leakage currents are so large that they can easily mask the CP signal and render conventional CP techniques essentially unworkable. Even with advanced high-k gate stacks, the leakage current can be sufficiently large to completely obscure the CP signal. Without a feedback mechanism (such as CP) to determine the relationship between processing changes and defect densities, advanced development teams are left to blindly drive further research efforts.

In this letter, we demonstrate a new CP methodology called frequency-modulated charge pumping (FMCP), which robustly treats the leakage current issue and extends the usefulness of the CP technique to future highly scaled technology nodes. The key concept of FMCP is transforming traditional “quasi-dc” detected CP into an ac detected measurement, thereby exploiting the 1/f noise curve and effectively suppressing the dc leakage background. This is accomplished via lock-in amplifier detection.

In conventional CP, a square wave voltage pulse (50% duty cycle) is applied to the gate electrode such that the MOSFET is pulsed between strong accumulation and strong inversion at some frequency (typically in the kHz to MHz range) [1]–[3]. This gate pulse scheme cyclically populates interface defects with both electrons and holes. The source, drain, and substrate electrodes are grounded while the (quasi-dc) CP recombination current (ICP) is measured at the substrate terminal. In the absence of bulk dielectric defects, ICP scales linearly with the CP gate pulse frequency [1], [2]. Often, ICP is measured as a function of CP frequency with the slope of this line proportional to the number of defects in the device [1], [2].

This simple view of CP is complicated by the presence of a gate leakage current component in ICP. In devices with thick gate dielectrics, the leakage component is negligible. However, in modern devices with highly scaled gate dielectrics, the leakage component is the overwhelming majority of the measured substrate current.

This issue is often treated by presuming that the gate leakage current component is independent of CP frequency. Typical gate leakage corrections usually involve either: 1) a multifrequency CP measurement in which the extrapolated value of the substrate current at 0 Hz CP frequency (assumed to be entirely due to leakage) is subtracted from the data [5] or 2) a subtraction of a low-frequency swept base voltage/constant amplitude CP measurement (Elliot curve [4]) from a higher frequency Elliot curve [6], [7]. Other methodologies have also been proposed [8].

However, when the gate leakage component becomes too large compared to the CP signal, these conventional correction approaches begin to fail due to measurement precision issues. Simply speaking, it is difficult to precisely measure a very small signal (ICP) riding on a very large background (leakage) utilizing the above approaches.

II. EXPERIMENTAL PROCEDURE

The key innovation of FMCP is the utilization of lock-in amplifier detection to eliminate unwanted signals (dc leakage current, drift/offset, and other noise) from the measurement. In FMCP, the gate electrode voltage pulse is modulated...
between two (or more) frequencies while the source, drain, and substrate terminals are kept at ground potential. The difference in I_{CP} between the two CP frequencies is measured at the substrate using a lock-in amplifier. In all lock-in measurements, the modulation frequency was 103.3 Hz and the time constant was 100 ms. An ac-coupled digital storage oscilloscope can be used to visualize the modulated CP response and also as a verification of the accuracy of the lock-in approach. However, the lock-in amplifier is much more robust and is the preferred FMCP detection scheme.

In the schematic illustration of Fig. 1, the substrate current oscillates between two values, I_{CP}(f_1) and I_{CP}(f_2), corresponding to the CP current at the two different frequencies used (f_1 and f_2). Since the measured FMCP current (∆I_{FMCP}) is the difference between I_{CP} at two frequencies, the ac-coupled lock-in amplifier measurement nearly eliminates any leakage current background (as well as any measurement drift or amplifier offset) and minimizes all the precision uncertainties associated with conventional CP measurements.

In addition, the frequency modulation depth [defined in Fig. 1(b)] can be limited to further increase the degree of precision. Doing so allows for more sensitive instrument settings (essentially zooming in), which support a more precise measure of signal amplitude. It is worth noting that the presumption of frequency-independent leakage strongly depends on the pulse generator’s ability to maintain frequency-independent constant pulse amplitude. Additionally, in order to obtain quantitative information from the lock-in measurement, the shape of the I_{CP} waveform must be known. A good approximation is a square wave for which the fundamental frequency RMS amplitude (from Fourier analysis) is given by π/4 times the lock-in output voltage.

III. RESULTS AND DISCUSSION

FMCP is first illustrated on a production quality 5.5 nm SiO2 16.45 × 0.24 µm nMOSFET, which was chosen to limit the gate leakage current and verify the accuracy of FMCP in comparison to more conventional dc detected CP measurements. Fig. 2(a) illustrates the close agreement between conventionally measured frequency-dependent CP, and our new FMCP measured using either the oscilloscope or lock-in amplifier detection. For the two FMCP measurements, the frequency axis (x-axis) refers to the modulation depth (the center frequency is kept constant at 1 MHz while the modulation depth is varied from 10 to 1.8 MHz). In all cases, the gate voltage amplitude is 3 V, the rise/fall times are 5 ns. For all three methodologies, we obtain a frequency-dependent CP slope of 711.84 pA/MHz corresponding to about 4450 interface defects (1.1 × 10^{11} cm⁻²).

Further confirmation of the accuracy of FMCP is illustrated in Fig. 2(b). In this measurement, the lock-in amplifier was used to measure ∆I_{FMCP} as a function of center frequency for various modulation depths. The flat FMCP response is further an indication of a linear frequency-dependent slope and validates the robustness of this technique. Again, the gate voltage amplitude is 3 V and the rise/fall times are 5 ns.

Thus far, we have demonstrated, using relatively low leakage devices, that FMCP is a robust and accurate CP methodology. However, the real power and utility of FMCP is best demonstrated with highly scaled devices in which the leakage current component causes great difficulty in conventional CP methodologies.

The devices chosen for this purpose are production quality 1.4 nm SiON 10 µm×0.055 µm nMOSFETs. For comparison, Fig. 3(a) illustrates the gate current density versus gate voltage for the 5.5 nm SiO2 device (leakage below detection limit) and the 1.4 nm SiON device. As expected, the scaled device displays orders of magnitude higher gate leakage current.

Fig. 3(b) illustrates an attempt at conventional swept base voltage/constant amplitude (Elliot curve) CP measurements on the 1.4 nm SiON device for several CP frequencies. The voltage amplitude is 2 V and the rise/fall times are 5 ns.
Clearly, the measured substrate current is dominated by gate leakage and the CP signal is completely unresolvable. The curves display little, if any, characteristic Elliot curve behavior [4]. As mentioned above, attempts can be made to extract useful CP information by utilizing a high-frequency–low-frequency subtraction. Also shown in Fig. 3(b) is a 1 MHz and 100 kHz high–low subtraction. Unfortunately, the subtraction still contains no useful information.

Furthermore, assuming an interface state density of $2 \times 10^{10}$ cm$^{-2}$, the expected $I_{CP}$ at 1 MHz for this device would be roughly 10 pA, a far cry from the tens of nA leakage background. From a precision viewpoint, it is immediately clear that measuring this small signal is a difficult endeavor.

Despite the overwhelmingly large gate leakage background, FMCP is capable of providing useful CP information in these leaky devices. Shown in Fig. 4(a) is lock-in detected frequency-dependent FMCP data taken on the same device of Fig. 3(b). A linear relationship exists (well within one standard deviation), with a frequency dependent CP slope of 11.13 pA/MHz, corresponding to about 70 defects within one standard deviation), with a frequency dependent CP slope of 11.13 pA/MHz, corresponding to about 70 defects in the device ($1.3 \times 10^{10}$ cm$^{-2}$). This information was obtained despite the suffocating levels of gate leakage current, which rendered the conventional approaches useless. Additionally, Fig. 4(b) shows the reproducibility across several different center frequencies with constant modulation depth. $\Delta I_{FMCP}$ displays a flat response, resolved well within one standard deviation despite the gate leakage current, and is indicative of a linear frequency dependent slope. Together, Figs. 3 and 4 illustrate the capabilities of FMCP and the precision boost gained from the lock-in amplifier ac detection scheme. Furthermore, these figures clearly demonstrate why FMCP is a much needed and powerful technique for advanced devices where gate leakage stymies defect related development feedback.

The success of FMCP is based solely on the ability to precisely measure the ac variation of the total substrate current such that the difference between two frequencies produces a nearly leakage-free measurement of substrate recombination. This FMCP sensitivity improvement can be further demonstrated in Fig. 5, where a much more exotic five frequency-modulated gate pulse is applied to the gate and the substrate current is measured with a digital storage oscilloscope. Note that this more exotic scheme does not support lock-in detection and is used here as a visual demonstration. In this figure, the leakage current background was removed by aligning the $f_1 = 200$ kHz $I_{CP}$ with the 200 kHz $\Delta I_{FMCP}$ value of

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\Delta I_{FMCP} = I_{FMCP} - I_{CP}
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This "staircase" response is further evidence of the accuracy and precision of FMCP even on very leaky devices. Data has been normalized to Fig. 4(a) to remove the leakage current background.

Fig. 4(a), essentially normalizing the data to the more reliable lock-in detected data in Fig. 4(a). The measured substrate current faithfully reproduces all five frequency levels and further illustrates the accuracy and precision of this ac-coupled CP technique.

IV. CONCLUSION

We demonstrated a new CP methodology that provides a vast improvement in precision and is highly resistant to gate leakage currents. In relatively low leakage devices, FMCP faithfully reproduces values obtained with more conventional CP methodologies. In high leakage devices, where conventional approaches break down, FMCP easily provides the sought information. FMCP provides a clear path towards defect measurements and energy profiling in highly scaled advanced technologies where leakage becomes problematic and hinders advanced development progress.

REFERENCES


