The RF Charge Pump Technique for Measuring the Interface State Density on Leaky Dielectrics

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Abstract— In this work the RF charge pump technique is presented. It is shown that this technique can provide charge pump data of devices that have a leakage current too high for classical charge pump measurements. The methodology of accurately performing RF charge pump measurements is discussed and measurement results on devices with both a very high leakage current and moderate leakage current are shown. Charge pump data obtained at frequencies of up to 2 GHz are shown. It is verified that the RF charge pump data can indeed be used for extracting the interface state density and it is also investigated how this extraction can be performed accurately.

***Index Terms*—Charge Pumping, MOS devices, thin gate oxides, tunneling current, RF.**

I. INTRODUCTION

The charge pumping technique [1] is well known for its high accuracy of measuring the interface state density at the Si-SiO$_2$ interface of MOSFET devices and has been widely used for this purpose. With the decreasing thickness of the oxide layer in present day CMOS technologies a considerable leakage current can be seen which is due to tunneling. As an example the gate leakage current of an MOS device that has a gate-oxide thickness of 1.4 nm is shown in figure 1. This tunneling current can severely affect the correctness of the extracted interface state density from charge pump data on these devices [2, 3]. This effect is illustrated in figure 2 where charge pump curves are shown that are obtained on a device that has a moderate gate leakage current and on the device with the leakage current density shown in figure 1. From this figure it is clear that the charge pump current is completely overwhelmed by the tunneling current of the ultra-thin oxide and therefore it is not possible to extract the interface state density from these measurements. In order to be able to measure the interface state density using the charge pump technique the tunneling component of the measured charge pump current should be made negligible with respect to the actual charge pump component. In this work this is realized by making use of the frequency dependence of the charge pump current, whereas the tunneling component is frequency independent. The charge pump current can be expressed using the following equation [1]:

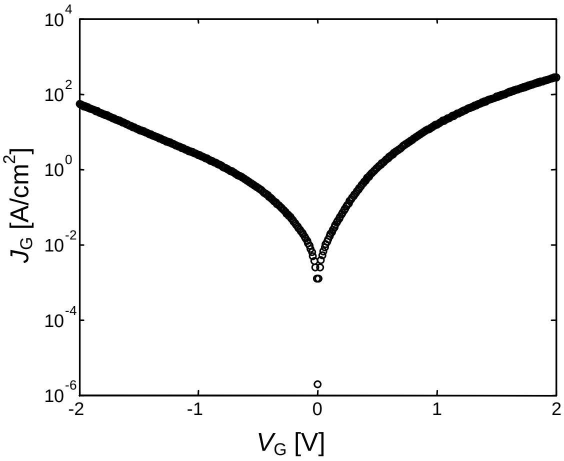

Figure 1: The measured gate leakage current density of an MOS device with 1.4 nm thick oxide.

$$I_{cp} = f \cdot q \cdot \overline{D_{it}} \cdot A_G \cdot \Delta E \qquad (1)$$

In this expression ΔE represents the energy window in which traps are located that contribute to the charge pump current. From expression (1) the frequency dependence of the charge pump current is clearly visible. In the classical charge pump technique frequencies of up to a few MHz are used. In this work we will show that the tunneling component of very leaky dielectrics can be overcome by performing charge pump measurements at frequencies of up to 2 GHz. We will also show the applicability of the RF charge pumping technique by comparing the RF charge pump data to charge pump data obtained using frequencies in the MHz range.

II. MEASUREMENT SETUP

The basic idea of the charge pump technique is to rapidly switch a MOSFET from accumulation towards inversion and back. During inversion electrons originating from the drain and source region get trapped in interface states. If the device is switched back rapidly, the trapped electrons do not have sufficient time to get detrapped from the interface states and the detrapping process will take place with holes originating from the substrate. A similar process holds for the switching

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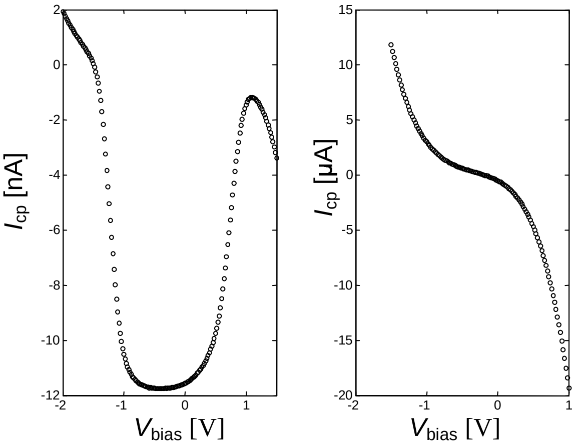

a) b)

Figure 2: Charge pump characteristics on devices with different gate-oxide thickness. The curves are obtained with sinusoidal gate voltages of 10 MHz. In a) the charge pump curve is shown for a device with 3nm thick oxide and in b) for the 1.4 nm thick oxide that has the leakage current density of figure 1.

from accumulation; in this way a net amount of charge is transferred ("pumped") from the bulk to the drain and source regions. By repeatedly switching the gate voltage, a DC current can be measured at either the substrate contact or the drain/source contacts. In this work we have used the measurement setup as illustrated in figure 3. The test structures used for this work are MOS transistors connected in a gated diode structure (source and drain tied together). The devices are optimized for two-port RF measurements in a ground-signal-ground configuration. The channel length is kept small to suppress NQS effects and to minimize the geometric component [5] of the charge pump current. The gate is folded into 20 fingers with connections on both ends. In common RF test structures the well is connected to the source. In the structures we used in this work the well is connected to ground; this makes it possible to measure the charge pump current, by measuring the current at the drain/source terminal.

Because of reflections occurring at the input of the device, it is preferable to make use of sinusoidal gate waveforms. We make use of use an Agilent E8251A signal generator for this purpose. The DC voltage V_{bias} is used to sweep the charge pump characteristic through all of the regions of operation as explained in [1]. It is similar to the commonly used V_{base}, except that not the base voltage level is swept, but the mid-voltage level of the gate voltage signal. A HP 4156AA semiconductor parameter analyzer is used to set this V_{bias} and to measure the charge pump current. In order to accurately extract the interface state density from charge pump measurements the amplitude of the sinusoidal gate voltage needs to be well known. It is however not straightforward to determine this amplitude from the power level of the signal generator, because of the occurrence of standing waves on the cables.

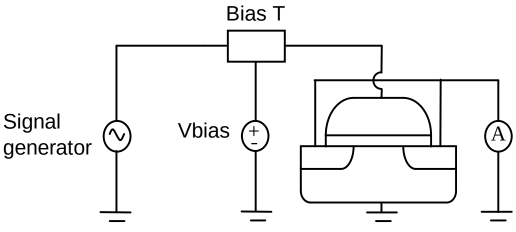

Figure 3: Schematic drawing of the RF charge pump measurement setup.

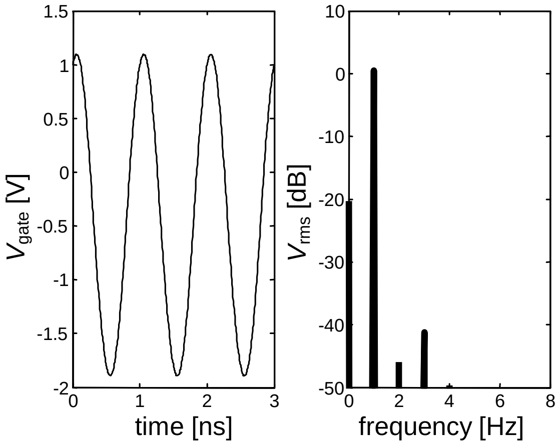

Figure 4: Estimated gate voltage waveform and the harmonic content of the time-varying signal. The voltage is calculated at a frequency of 1 GHz, input power of 9.3 dBm and applied bias voltage of -0.5 V.

III. RF GATE VOLTAGE ANALYSIS

At frequencies above 10 MHz the wavelength of the gate voltage signal is in the same order of magnitude as the length of the measurement cables used in the setup of figure 3. If the input impedance of the device is not exactly 50 **Ω**, reflections will occur at the input of the device. The input impedance of the device in figure 3 is the impedance of an MOS device seen from gate to substrate. This input impedance is both dependent on the frequency of the gate signal as well as the magnitude of the gate voltage. For the purpose of RF charge pump measurements we want to generate voltage levels with a large voltage swing. This means that we must take into account this voltage dependence of the input impedance. Using simple transmission line theory it is not possible to find an analytical expression to calculate the gate voltage from a given power level that is available from the RF signal generator. In order to determine the gate voltage level for the purpose of interface state extraction we have used the following procedure:

First we measured the small signal s_{11} parameter of the measurement setup as shown in figure 3 at different DC bias levels using an HP 8510 network analyzer. From this data we extrapolated the relation between the gate voltage and the small signal input impedance. Because of the fact that the input impedance is voltage dependent, higher harmonics are

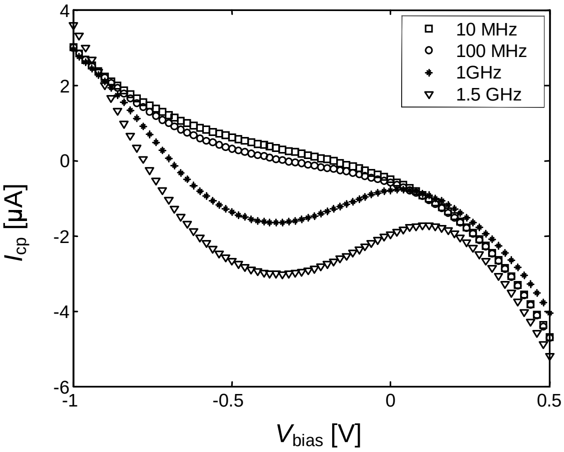

Figure 5: Measured charge pump characteristics on a device with 1.4 nm oxide thickness, for different frequencies. The input power is set so that $V_{\text{pp}} = 1.8$ V.

introduced by the reflections at the input of the device. Therefore it is not possible to determine that realized gate voltage in the frequency domain and therefore we calculate it in the time-domain. From the available input power we can calculate the amplitude of the incoming traveling wave V^{+}_{gate}. We divided one period of this time varying signal into 200 time steps and for every time-step we numerically found the reflected wave V^{-}_{gate} so that the following relation would hold:

$$\frac{V^{+}_{\text{gate}}(t)-V^{-}_{\text{gate}}(t)}{Z_{\text{o}}}=\frac{V^{+}_{\text{gate}}(t)+V^{-}_{\text{gate}}(t)}{Z_{\text{in}}(t)} \qquad (2)$$

The input impedance Z_{in} is a function of the gate voltage V_{gate} which is equal to $V^{+}_{\text{gate}} + V^{-}_{\text{gate}} + V_{\text{bias}}$. In figure 4 an example is shown of the gate voltage level, estimated using this approach for an n-type device with $L = 0.15$ µm, $W = 220$ µm and oxide thickness of 3 nm. The frequency and the available power of the signal generator are 1 GHz and 9.3 dBm respectively, with a bias voltage of -0.5 V. In this plot also the harmonic components of the signal are shown. It can be seen that, due to the voltage dependent input impedance, higher harmonics of the 1 GHz signal are present at the gate, but they do not seriously influence the shape of the sinusoidal waveform. Besides this a DC component is also introduced (in the example of figure 2 this is 0.1 V); this does not influence the measurement of the maximum charge-pump current, but the bias voltage generated by the DC source can no longer be interpreted as the mid voltage level of the gate signal. The procedure used for the gate voltage level analysis gives a good estimation of the realized voltage level. Using this procedure we are able to perform charge pump measurements at frequencies in the GHz range.

IV. MEASUREMENT RESULTS

We have investigated the RF charge pump technique on ultra-thin oxide devices leaky devices in order to verify that charge pump curves can indeed be obtained on leaky dielectrics. In figure 5 the measured charge pump characteristics are shown on the 1.4 nm oxide device with leakage current as shown in figure 1. The peak-to-peak voltage that we have used for the gate voltage was set to 1.8 V. This voltage level was determined using the technique as explained in section III. The devices used are n-type devices with a channel length of 0.15 µm and a gate width of 220 µm consisting of 20 fingers of 11 µm. From figure 5 we see that at frequencies above 100 MHz the charge pump effect becomes visible. The charge pump current at these frequencies is now in the order of several µA the same order of magnitude as the tunneling current. In order to extract the interface state density from charge pump measurements, use can be made of the frequency dependence of the charge pump current. In figure 6 we plotted the maximum charge pump current $I_{\text{cp,max}}$ against frequency. This $I_{\text{cp,max}}$ is defined as the maximum charge pump current that is measured over an entire V_{bias} sweep. At frequencies above 100 MHz we clearly see an increase in $I_{\text{cp,max}}$ with increasing frequency. The solid line indicates the frequency response of $I_{\text{cp,max}}$ as can be expected from (1). These results indicate that the RF charge pump technique is indeed suitable of obtaining charge pump curves on leaky dielectrics. In order to determine the accuracy of obtaining the interface state density from RF charge pump results, we also tested this technique on devices with a moderate gate leakage. These devices have an oxide thickness of 3 nm with a gate leakage current is so low that classical charge pump results can also be used. These devices are also n-type transistors with a channel length of 0.15 µm and a gate width of 220 µm consisting of 20 fingers of 11 µm. In figure 7 the frequency response of the charge pump current obtained on these devices is shown. The peak-to-peak gate voltage was set to 3 V. The solid line in this figure is the expected frequency response of $I_{\text{cp,max}}$ for sinusoidal gate voltages and an interface state density of $2.56 \cdot 10^{10}$ eV^{-1}cm^{-2}. From figure 7 it can be seen that the increase of the charge pump current follows (1) up to the GHz range.

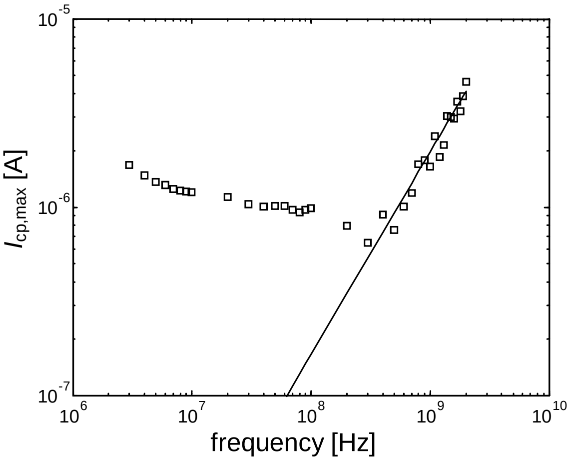

Figure 6: Maximum charge pump current as a function of frequency. The solid line is fitted to the data using the theoretical frequency response of the charge pump current.

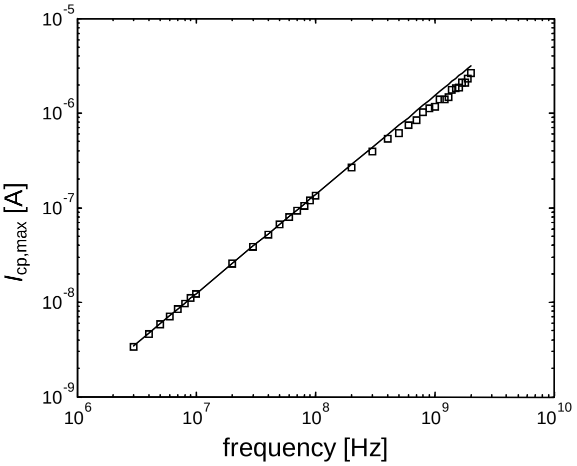

Figure 7: Measured maximum charge pump current plotted against frequency for a device having a 3 nm thick oxide. The solid line is fitted to the data using the expression for the charge pump current with sinusoidal gate waveforms.

V. INTERFACE STATE EXTRACTION

In order to verify whether the RF charge pump technique can indeed be used for extracting the interface state density, we tested the response of the charge pump current to an increased number of interface states. We generated interface states by applying a constant gate voltage stress to the 3nm thick oxide device. The tunneling current that flows through the gate-oxide is known to generate new interface states (see e.g. [6]). We stressed the device for 10 s, 100 s and 1000 s and measured the RF charge pump curves. In figure 8 the increase in measured $I_{\text{cp,max}}$, with respect to the measured $I_{\text{cp,max}}$ of the unstressed device is shown. From this plot we clearly see an increase of the charge pump current after new interface states have been generated. The solid lines were fitted to the data using values for the extra generated interface state densities of $1\cdot10^{8}$ $\text{eV}^{-1}\text{cm}^{-2}$, $5\cdot10^{8}$ $\text{eV}^{-1}\text{cm}^{-2}$ and $1\cdot10^{9}$ $\text{eV}^{-1}\text{cm}^{-2}$, for the stress times of 10 s, 100 s and 1000 s respectively. From the results shown in figure 8 we can safely state that the RF charge pump results are a measure for the interface state density. In order to extract the number of interface states from charge pump measurements with a sinusoidal gate voltage we make use of the following expression for the charge pump current [1]:

$$I_{\text{cp}} = 2ktq\overline{D_{\text{it}}}\cdot f\cdot A_G\left[\ln\left(v_{\text{th}} n_{\text{i}}\sqrt{\sigma_{\text{n}}\sigma_{\text{p}}}\right)+\ln\left(\sqrt{t_{\text{e}} t_{\text{h}}}\right)\right] \tag{3}$$

In this expression t_{e} and t_{h} represent the times available for the nonsteady-state emission of electrons end holes respectively. They can be found to be [4]:

$$t_{\text{e}} = t_{\text{h}} = \frac{Z}{f} \tag{4}$$

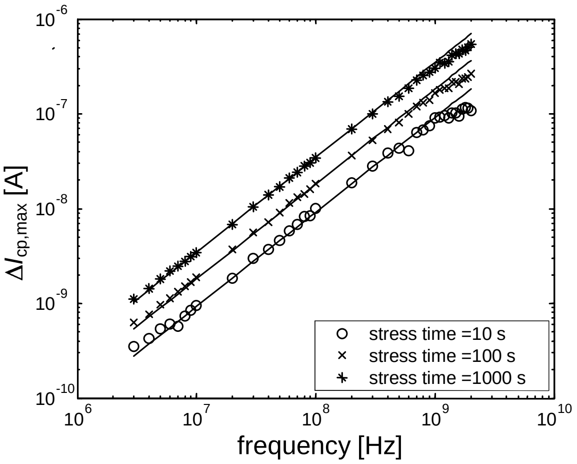

Figure 8: Increase of measured charge pump curve after a constant gate voltage stress of -3.5 V.

The parameter Z can be calculated from the flatband voltage, threshold voltage and the applied gate voltage levels. Using (3) and (4) an expression can be found for extracting the interface state density from charge pump measurements with sinusoidal gate voltages [4]:

$$\overline{D_{\text{it}}} = \frac{\log(e)}{2qkTA_{\text{G}}}\cdot\frac{d\left(I_{cp}/f\right)}{d\left(\log(f)\right)} \tag{5}$$

In this expression the term I_{cp}/f appears, which is the pumped charge per cycle. A nice way of applying expression (5) is to plot the pumped charge per cycle against the logarithm of the frequency. The slope of this plot is a direct measure for the interface state density. In figure 9 this is shown for the charge pump data of figure 7. The solid line is the theoretical frequency response according to (3) and (4) and fitted to the charge pump data of figure 7. We clearly see a very nice fit between measured data and calculated data for frequencies up to 100 MHz. Above 100 MHz we see a decrease of the pumped charge per cycle as a function of frequency.

VI. DISCUSSION

From the results shown in this paper we can conclude that the RF charge pump technique is a possible solution to the problems that arise when the interface state density of very leaky dielectrics need to be determined. In figure 5 it was shown that this technique can provide charge pump date on devices that have a leakage current too high for use of the classical charge pump technique. The results shown in figure 8 are very valuable in the sense that they indicate that the RF charge pump current increases with an increased number of interface states. In order to accurately extract the interface state density using the RF charge pump technique however, an explanation has to be found for the fall-off in the pumped charge per cycle at frequencies above 100 MHz. In [1] it was

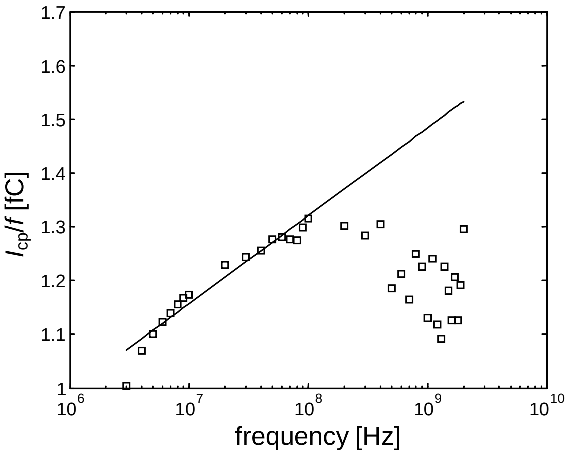

Figure 9: Measured charge per cycle plotted against the logarithm of frequency for the device with 3 nm thick oxide. The solid line is the frequency response according to classical charge pump theory.

already stated that a limited time available for the capture process during a charge pump cycle may lead to a decrease in measured charge pump current. The results of figure 9 could be explained by this effect, but an accurate description of what is exactly happening is needed. Furthermore the result shown in figure 9 shows that a very large spread is present on the data. This could be attributed to inaccuracies caused by the used methodology of obtaining the desired gate voltage. From theory it follows that the pumped charge per cycle is very sensitive to the gate voltage level.

VII. CONCLUSIONS

In this work we have shown that charge pump data can be obtained on very leaky dielectrics when measurements are performed at radio frequencies. Up to 100 MHz we see that the interface state density can be extracted very accurately by making use of the measured pumped charge per cycle. Charge pump data obtained at higher frequencies are very valuable in their sense that for very leaky devices the interface state density can not be measured at all using the classical charge pump technique. This indicates that the RF charge pump technique can become a very valuable tool in extracting the interface state density on leaky dielectrics. In order to fully utilize the data obtained at frequencies above 100 MHz an accurate description of the fall-off of the pumped charge per cycle needs to be found. It could be attributed to the limited time available for the capture process of electrons and holes.

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