Charge Pumping at Radio Frequencies

G.T. Sasse, H. de Vries and J. Schmitz
MESA* Research Institute, University of Twente.
Hogekamp, P.O. Box 217, 7500 AE, Enschede, The Netherlands.
Phone: +31 (0)534894394 Fax: +31 (0)534891034.
E-mail: g.t.sasse@utwente.nl.

Abstract: In this work for the first time charge pump results are shown that are obtained at frequencies in the GHz range. A comparison is made with charge pump results at lower frequencies. A very good agreement is seen between the low frequency charge pump data and the RF charge pump data. Measurement results on dielectrics that suffer from a high leakage current show that a charge pump current can be measured at frequencies above 500 MHz. At lower frequencies the charge pump current is completely overwhelmed by the leakage current and therefore normal charge pump currents are not usable for measuring the interface state density. This indicates that the RF charge pump technique is very promising for measuring the interface state density on ultra thin dielectrics.

INTRODUCTION

The charge pumping technique [1] is well known for its high accuracy of measuring the interface state density at the Si-SiO2 interface of MOSFET devices and has been widely used for this purpose. With the increasing thickness of the oxide layer in present day CMOS technologies a considerable leakage current can be seen which is due to tunneling. This tunneling current can severely affect the correctness of the extracted interface state density from charge pump data on these devices [2, 3]. In order to obtain reliably extracted interface state densities, 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]:

\[ I_{\text{cp}} = 2 \pi q D_o \cdot f \cdot A_o \left[ \ln \left( \frac{1}{\sigma_n} \right) \sqrt{\frac{\sigma_n}{\sigma_p}} \right] \left[ \ln \left( \frac{1}{\sigma_n} \right) \right] \]

where \( t_e \) and \( t_h \) are the times available for the nonsteady state emission of electrons and holes respectively. From this expression it is easy to see that the charge pump current increases with increasing frequency. In the situation that a sinusoidal gate voltage is used, the emission times \( t_e \) and \( t_h \) are also frequency dependent, and as is shown in [4] the charge pump current increases even more than linear with increasing gate voltage frequency.

In the common 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. An excellent agreement with the expected frequency dependence is seen for the charge pump data up to 2 GHz.

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 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 1.

Because of reflections occurring at the input of the device, it is preferable to make use of sinusoidal gate waveforms. We make use of an Agilent E8251A signal generator for this purpose. The emission times for holes and electrons have the following frequency dependence when using sinusoidal gate waveforms [4]:

\[ I_{\text{cp}} = 2 \pi q D_o \cdot f \cdot A_o \left[ \ln \left( \frac{1}{\sigma_n} \right) \sqrt{\frac{\sigma_n}{\sigma_p}} \right] \left[ \ln \left( \frac{1}{\sigma_n} \right) \right] \]
The parameter \( Z \) can be calculated from the flatband voltage, threshold voltage and the applied gate voltage levels. The DC voltage \( V_{\text{bias}} \) 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 \( V_{\text{base}} \), except that not the base voltage level is swept, but the mid-voltage level of the gate voltage signal. A HP 4156 A semiconductor parameter analyzer is used to set this \( V_{\text{bias}} \) and to measure the charge pump current.

**TEST STRUCTURES**

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 ground; this makes it possible to measure the charge pump current, by measuring the current at the drain/source terminal.

**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 1. Therefore it is not straightforward to realize a specified gate voltage at device level, due to reflections at the input of devices without a constant 50 \( \Omega \) input impedance. The test structures used in this work do not have such a 50 \( \Omega \) input impedance and therefore a way has to be found to know the gate voltage that is actually delivered to the device.

If the input impedance of the device is known one can calculate the realized input voltage by making use of the following expression, which follows from basic transmission line theory:

\[
t_s = t_b = \frac{Z}{f}
\]

The input impedance \( Z_0 \) is a function of the gate voltage \( V'_{\text{gate}} \) which is equal to \( V'_{\text{gate}} + V_{\text{bias}} \). In figure 2 an example is shown of the gate voltage level, estimated using this approach for an n-type device with \( L = 0.15 \mu m \), \( W = 220 \mu m \) 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

\[
\frac{V'_{\text{gate}} + V_{\text{bias}}}{Z_{\text{in}}} = \frac{V_{\text{gate}}}{Z_{\text{in}}} + \frac{V_{\text{bias}}}{Z_{\text{in}}}
\]
procedure we are able to perform charge pump measurements at frequencies in the GHz range.

![Figure 3: Measured charge pump characteristics on a 3 nm oxide device at three different frequencies, plotted against the DC voltage \(V_{\text{bias}}\). The input power is set so that \(V_{\text{in}} = 3\) V.](image)

**RESULTS ON LOW LEAKAGE DEVICES**

We have investigated the RF charge pump technique on two types of devices. We tested the applicability of the technique on devices with 3 nm thick oxides. These devices do not suffer from very large leakage currents and the interface state density can be determined using the common charge pump technique with frequencies of up to a few MHz. The devices are n-type transistors with a channel length of 0.15 \(\mu\)m and a gate width of 220 \(\mu\)m consisting of 20 fingers of 11 \(\mu\)m. The common charge pump results have been compared to the RF charge pump data in order to verify the correctness of the RF charge pump technique.

In figure 3 charge pump curves at three different frequencies are plotted. Note that the voltage on the x-axis is \(V_{\text{bias}}\), this is different from the commonly used \(V_{\text{bias}}\). The power level that the signal generator provides is set to the value that corresponds to a voltage amplitude of 1.5 V (\(V_{\text{in}} = 3\) V). This power level is estimated using the approach described in the previous section. The figure clearly shows that the measured charge pump current increases with increasing frequency. In order to get a better understanding of how the charge pump curves correspond to the increasing frequency, we plotted the maximum charge pump curve against frequency. This is shown in figure 4. This plot shows a very nice fit of the RF charge pump data to what can be expected from theory. The solid line is fitted to the data using the expressions of (1) and (2), with an interface state density of \(2.56 \times 10^{10}\) eV\(^{-1}\)cm\(^{-2}\). This solid line fits very well to the measured data. In order to verify that we are actually seeing the charge pump effect, we also tested devices with an increased number of interface states. To realize this we performed a constant gate voltage stress on the device of -3.5 V. 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 5 the increase in measured \(I_{\text{p, max}}\) compared to the measured \(I_{\text{p, max}}\) of the unstressed device is shown.

![Figure 4: 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.](image)

![Figure 5: Increase of measured charge pump curve after a constant gate voltage stress of -3.5 V.](image)

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 interface state density of \(1 \times 10^8\) to \(3 \times 10^9\) eV\(^{-1}\)cm\(^{-2}\), \(5 \times 10^8\) to \(1 \times 10^9\) eV\(^{-1}\)cm\(^{-2}\), and \(1 \times 10^9\) to \(3 \times 10^9\) eV\(^{-1}\)cm\(^{-2}\), for the stress times of 10 s, 100 s and 1000 s respectively. From the results shown in figure 5 we can safely state that the RF charge pump results are a measure for the interface state density.

In [4] it was shown that for sinusoidal gate waveforms the interface state density can be accurately extracted using the following expression:
A nice way of applying this expression is to plot the pumped charge per cycle ($I_{pump}$) against the logarithm of the frequency. The slope of this plot is a direct measure for the interface state density. In figure 6 this is shown for the charge pump data of figure 4. The solid line is the calculated $I_{pump}$, based on the fitting parameters of figure 4 and expression (5). We clearly see a very nice fit between measured data and calculated data for frequencies up to 100 MHz. To the best of our knowledge there has never been a report of accurate charge pumping measurements at these high frequencies. Above 100 MHz we see a decrease of the pumped charge per cycle as a function of frequency. The cause for this fall-off is unknown. It could be attributed to the response time of the interface states [1] but it could also very well be due to the fact that the applied gate voltage level is not exactly the desired 3V.

$$\bar{D}_i = \frac{\log(e)}{2qkT_A} d\left(\frac{I_{pump}}{f}\right) \frac{d\left(\log(f)\right)}{d\left(\log(f)\right)}$$

(5)

When we look at the RF charge pump data we do recognize the charge pump effect. This indicates that the RF charge pump technique is very promising for characterizing the interface state density of very leaky devices. As we have done for the low leakage devices we also plotted the maximum measured charge pump current against frequency; this is shown in figure 9. From this plot it is even more clear that the charge pump data below 300 MHz is completely overwhelmed by the leakage current. At frequencies above 300 MHz we see the expected frequency dependence of the charge pump data. The solid line in this graph is fitted to the RF charge pump data using the expressions of (1) and (2) and an interface state density of $5 \times 10^{12} \text{ cm}^{-2}$. The extraction method using (5) is unfortunately not possible for this device because we see the same behavior of the pumped charge per cycle for frequencies up to 300 MHz.
RF charge pump technique is an interesting approach for radio frequencies as we have seen for the low leakage devices. The plot of figure 9 does however show 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. The measured charge pump curves plotted against frequency fit very nicely to the frequency response expected from theory. When we want to extract the interface state density from the pumped charge per cycle however, we see an unexpected fall-off of the measured pumped charge per cycle above 100 MHz. The cause for this effect is unknown at this moment. A possible explanation to this could be attributed to the inaccuracies caused by the gate voltage analysis. The procedure that we have used to determine this gate voltage only gives an estimation of the actually applied gate voltage level. From theory it follows that the pumped charge per cycle is very sensitive to the gate voltage level. Furthermore in [1] it was stated that with increasing frequencies the interface states can no longer respond to the gate voltage. If we look at the plots of figure 4 and figure 6 we see that the charge pump current increases with increasing frequency. The difference between measured and expected data is very small. Also the plot of figure 5 shows that the charge pump current increases over the entire frequency range after new interface states have been generated. Therefore we believe that the effect of the response time cannot completely explain this fall-off.

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 is very valuable in its sense that for very leaky devices the interface state density cannot be measured at all using the common charge pump technique. We have also shown that the RF charge pump current increases after new interface states have been generated. Therefore this technique is a very attractive measure for the damage created on devices with very leaky dielectrics. The technique as presented in this paper is still under development. Some effects that are seen from measurements can still not be explained and might be attributed to inaccuracies caused by the current technique. We can state however that the RF charge pump technique is a very attractive tool for measuring the interface state density in present day CMOS technologies.

ACKNOWLEDGEMENTS

The authors would like to thank F.N. Cubaynes from Philips Research, Leuven for providing us the test structures. This work is financially supported by the Dutch Technology Foundation (STW).

REFERENCES