Application Note

Measuring Electron Trapping in AlGaN/GaN HEMTs by C-OTF

Zurich Instruments

Applications: Failure analysis, Capacity Measurements
Products: HF2LI, HF2TA, HF2LI-MF option

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Introduction

Wide band gap materials such as silicon carbide (SiC) and gallium nitride (GaN) have promising material properties in comparison to silicon (Si) for semiconductor applications. These material properties have, for instance, high electric breakdown fields and high thermal conductivities which permit higher device temperatures during operation. Both properties are important for power electronics. Additionally, high charge-carrier drift velocities at large electric fields allow fast-switching devices which are essential for high-frequency applications. In GaN-based devices, several research topics focus on charge trapping phenomena during operation which reduce the device reliability and performance. One important mechanism is charge trapping near the interface between different layers.

We employ the so called capacitance-on-the-fly (C-OTF) technique which is a fast measurement of capacitance transients. The C-OTF approach was developed to investigate degradation mechanisms in silicon metal oxide field effect transistors (MOSFETs) [1]. The aim of this method is to directly measure the device degradation during a stress measurement. Here we apply C-OTF to GaN/AlGaN/SiN metal insulator semiconductor (MIS) structures by measuring fast capacitance changes during gate voltage stress pulses. These capacitance changes are due to electron trapping at the AlGaN/SiN interface [2]. Such MIS structures are frequently used in high electron mobility transistors (HEMTs).

For a single electron trap level, the trapping leads to an exponential function $C(t) \propto e^{-t/\tau}$, where τ is the characteristic time constant of this trap. This exponential function spans over approximately 2-3 decades in time. However, real devices have a broad distribution of trap levels which lead to temporal evolutions spanning many more decades in time [3]. Thus, it is important to measure the capacitance changes as quickly as possible after the stress process has begun. The HF2LI Lock-in Amplifier from Zurich Instruments offers a fast demodulation of dynamic signals with a time resolution of 2 µs [4], enabling the measurement of seven decades in time [2].

The C-OTF method

The employed C-OTF method measures fast capacitance transients as a result of a voltage switch over the MIS structure. The applied voltage on the top of the MIS structure is called V_G and it is distributed across the structure as

$$V_G = V_{FB} + \phi_{GaN} + \phi_{AlGaN} + \phi_{diel},$$

where ϕ_{GaN}, ϕ_{AlGaN} and ϕ_{diel} are the potential drops at the GaN surface, at the AlGaN/dielectric interface and through the dielectric layer, respectively.

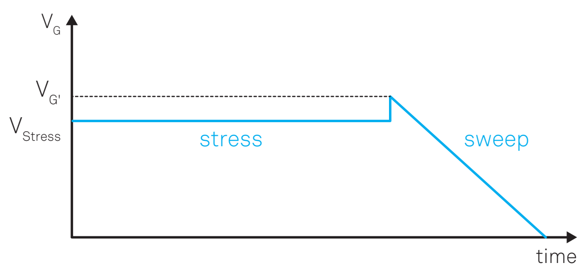

Figure 1. Schematic diagram of the capacitance on-the-fly method, in which a device is stressed for some time at a certain stress voltage V_{stress} followed by afterwards a sweep of the gate voltage starting from V'_G and going to zero is applied.

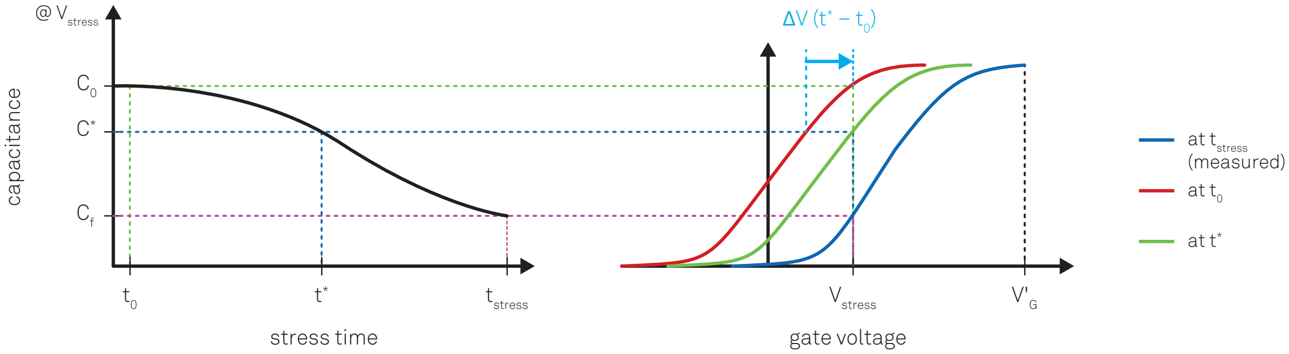

Figure 2. Time dependent capacitance during a constant stress voltage corresponds to a shift to the right in the capacitance voltage curve (indicated by the orange arrow).

The evaluation of trapped charge $Q_{trapped}$ at interface defect sites is done via calculation of the flat band voltage shift ΔV_{FB} . This shift represents the difference between the ideal value of the flatband voltage V^0_{FB} and the actual measured value V_{FB} . This leads to following equation

$$V_{FB} = V^0_{FB} - \Delta V_{FB} = V^0_{FB} - \frac{Q_{trapped}}{C_{diel}}, \qquad (1)$$

where C_{diel} is the dielectric capacitance of the SiN layer. This is valid, if we assume the defects to be located at the dielectric interface and there is no charge distribution inside the SiN. Figure 1 illustrates the C-OTF method in more detail. First, there is a stress phase for a certain duration followed by a sweeping of the gate voltage V_G starting from bias extrema V'_G downwards to zero voltage. A capacitance measured at constant DC bias stress V_{stress}. If the stress voltage is large enough to bring the structure into electron trapping conditions, a capacitance decrease with respect to time can be interpreted as a shift of the capacitance voltage (CV) curve to the right. This is illustrated in Figure 2. This assumes that the shape of the CV curve does not change during stress. This change of the capacitance can directly be related to the main result of the

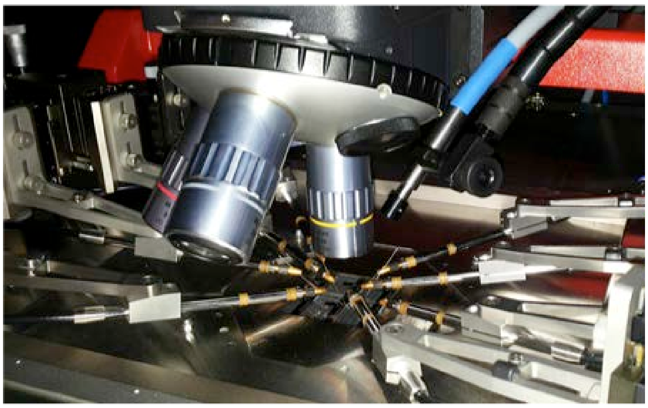

Figure 3. Needle probe station with mounted sample.

experiment, the number of electrons trapped at the AlGaN/SiN interface $Q_{trapped}$ using Equation 1. In C-OTF investigations, the sweep parameters such as the sweep rate, the sweep bias extrema V'_G and the sweep direction have to be chosen carefully.

The HF2LI Lock-in Amplifier can be used for a more detailed investigation of the flatband voltage shift ΔV_{FB} with respect to the experimental parameters. Furthermore, the programming interface of the lock-in amplifier allows an efficient reduction of measurement data density on the host computer through logarithmic sampling. Since we are interested in resolving charge trapping phenomena over a wide range of time constants, logarithmic sampling is very important for data gathering.

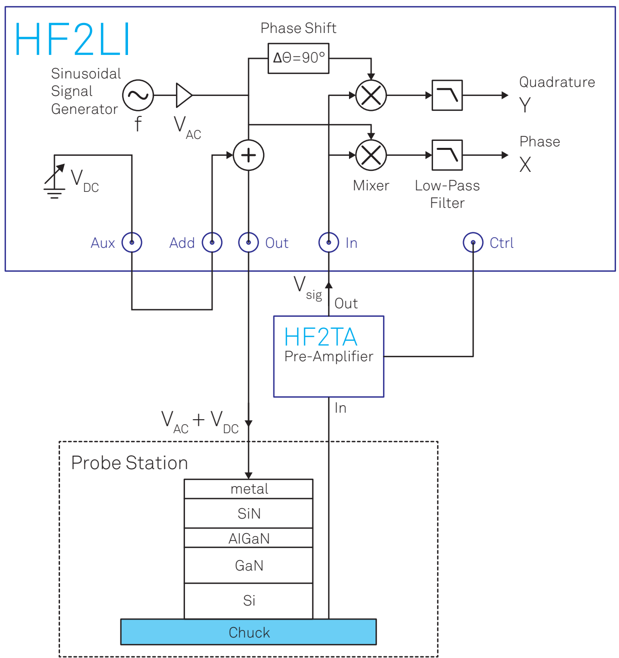

Figure 4. Schematic diagram of the experimental setup including the lock-in HF2LI, the pre-amplifier HF2TA and the probe station as well as the HF2LI electronics using phase sensitive detection in order to get phase X and quadrature Y.

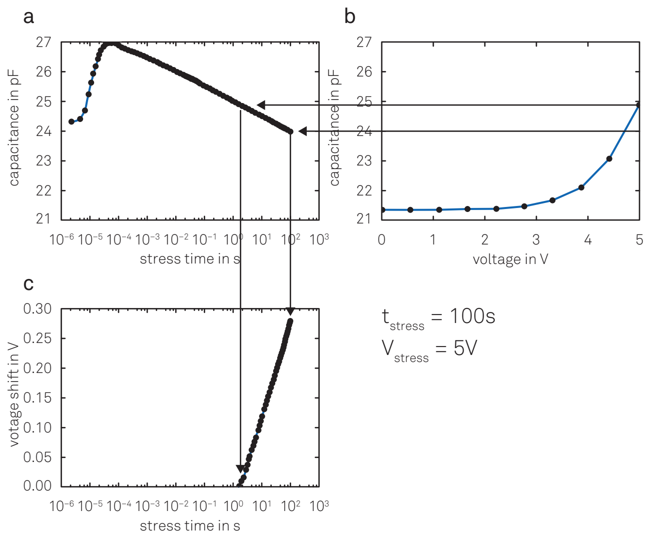

Figure 5. (a) Capacitance transient during the stress voltage V_{stress}. (b) CV curve obtained from the stress voltage extrema V_G' downwards. (c) Calculated flatband voltage shift using the capacitance transient and the CV curve.

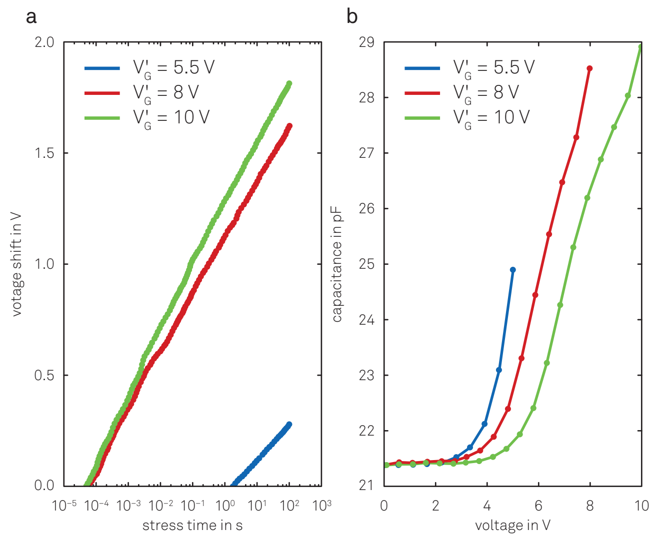

Figure 6. C-OTF measurement results including its dependence on the sweep voltage extrema V_G'. (a) Flatband voltage shift during the stress time (b) CV curve.

Experimental Setup

The experimental setup consists of a probe station (Figure 3) the HF2LI lock-in amplifier and the HF2TA pre-amplifier, illustrated in Figure 4. An industrially produced GaN/AlGaN/SiN MIS sample is mounted on the chuck of the probe station and contacted via a needle. The HF2LI acquires data using phase sensitive detection (PSD) with respect to a reference signal. The reference signal provides a small ac signal of frequency f = 100 kHz and with sinusoid peak voltage V_{AC} = 100 mV to the DUT. A DC bias V_{AC} is added to the output $V_{AC}(t)$ using the ADD connector of the HF2LI. After the DUT, the HF2TA current amplifier amplifies the resulting current signal by a user defined gain which can be chosen over a wide range from 100 V/A to 100 MV/A. The measured input signal $V_{sig}(t)$ is then demodulated with respect to the reference signal $V_{AC}(t)$. The demodulation results in a baseband signal which can be represented by a complex vector $Z = X + iY = Re^{i\phi}$. Unwanted noise is filtered using a 4^{th} order low-pass filter with 20 µs time constant. Assuming a parallel conductance-capacitance model for the DUT, one can calculate the capacitance C and the conductance G from X and Y with

$$C = \frac{X\sqrt{2}}{R_G V_{AC}} \text{ and } G = \frac{Y\sqrt{2}}{\omega R_G V_{AC}}, \quad (2)$$

where R_G is the total gain of the current preamplifier and V_{AC} is the peak value of the amplitude of the small AC signal .

Experimental Results

The experimental results in Figure 5 shows the fast capacitance transient measurement, the CV curve and the calculated flatband voltage shift.
This flatband voltage shift can be attributed to the amount of trapped charges at the AlGaN/SiN interface as described above. The resulting value of $Q_{trapped}$ is the main result of our experiment and allows us to judge the quality of the interface and the dielectric.
The transient data above 25 pF cannot be attributed to a flatband voltage shift due to the missing data in the CV curve. However, increasing the sweep bias voltage extrema V_G' induces a slight distortion of the CV characteristic, as shown in Figure 6 (b). This small distortion impacts the flatband voltage shift calculation and induces errors. By choosing 8 V for V_G', we limit this source of error, as one can see in Figure 6, but we are able to record the flatband voltage shift 10^{-4} s after the stress voltage is adjusted. The voltage shift of the first point is purposely set to zero. Its dependence on time is studied over six decades in time, namely between 10^{-4} s and 10^2 s. The experimental result of a logarithmic dependence of the flatband voltage shift on with time can only be explained by a broad distribution of exponential decaying functions. This in turn indicates a very broad distribution of electron trap levels. The microscopic reason for this broad distribution might be found in the rough surface morphology of the AlGaN material prior to SiN deposition.

Conclusion

The HF2LI allows us to investigate charge trapping phenomena in GaN based power devices. Measuring the capacitance transient after a voltage step gives insight into electron trapping at the AlGaN/SiN inter-face. The HF2LI is used to create the AC reference signal as well as the DC bias step and measures phase X and quadrature Y with respect to the reference. The capacitance transient as well as the capacitance-voltage characteristic is calculated from X and Y assuming a parallel capacitance-conductance model. Our experiment shows a logarithmic dependence of the flatband voltage shift on time, which corresponds to the number of trapped electrons near the interface. The logarithmic dependence is due to a uniform distribution of underlying time constants τ and energy levels of traps at that interface.

Key Advantages

Zurich Instruments offers a versatile lock-in amplifier HF2LI that can be used in various semiconductor testing applications. The flexibility of the device allows fast capacitance measurements with a high signal-to-noise ratio. The time constant and the filter order of every demodulator can be chosen independently according to the user's needs.
The fully digitally implemented electronics have following advantages compared to analog solutions:

- Fast demodulation of dynamic signals (up to 2 μs time resolution)
- Easy adjustment of measurement frequency f and signal amplitude V_{AC}
- Built-in bias source capabilities
- Precise measurement of small capacitances
- Straightforward remote control via API

With this integrated set of advantages we demonstrate extremely fast capacitance transients can be measured and analyzed much more rapidly and conveniently than with any other commercially available equipment.

Acknowledgements

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