Deep-Level Transient Spectroscopy with the MFIA and PPMS® DynaCool®

This application note illustrates the ease of setting up deep-level transient spectroscopy (DLTS) with the Zurich Instruments MFIA Impedance Analyzer and PPMS DynaCool cryostat from Quantum Design. To demonstrate, we measured a GaAs Schottky diode at variable temperatures from 350 K to 230 K and evaluated the transients for defect characterization.

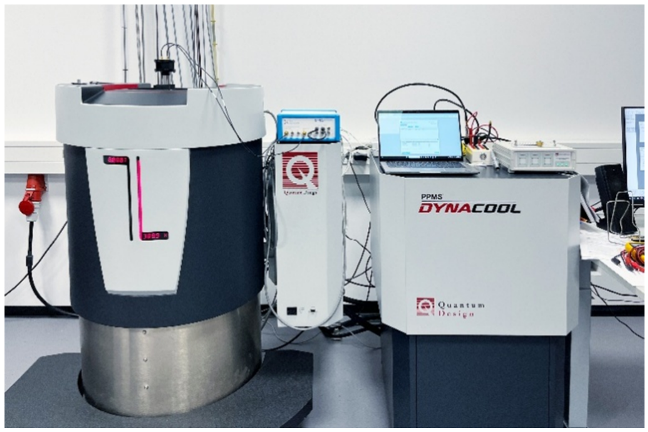


Figure 1: *Typical setup of deep-level transient spectroscopy with the PPMS DynaCool and MFIA Impedance Analyzer.*

Introduction

Deep-level defects influence both the electrical and the optical properties of materials, which can severely affect device performance. It is therefore critical to have access to an experimental procedure for the characterization of the defects. The equipment should be able to determine location (energy level), concentration, and the charge type of the defect.

Deep-level transient spectroscopy (DLTS) is one of the most versatile techniques to determine the above-mentioned electrical properties of electrically active defects over a wide range of depths in semiconductor materials. This technique was introduced by D.V. Lang to characterize electronic traps in semiconductors **[1]**. Later on, the theory has been extended to probe ionic defects and is referred to as transient-ion-drift **[2]** in the literature.

The principle of the measurement technique can be summarized as follows: the device under test (DUT) is probed by a voltage pulse. After this so-called filling pulse, trapped charge carriers relax back to a steady state condition. The relaxation time is related to the emission rate of the electron or holes from the defect state. Thermally activated emission rate processes are measured as capacitance transients, which in turn allow for the trap level, concentration, and charge carrier type to be obtained. To reduce noise, several transients are measured for each temperature and averaged.

Such sensitive defect characterization requires instruments that are capable of detecting small changes in capacitance at different time scales and a precise and stable temperature control.

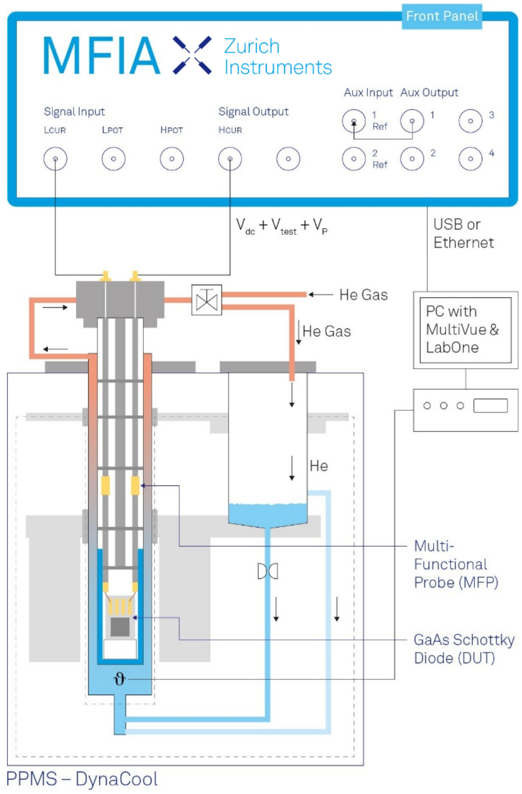


Figure 2: *Schematic view of DLTS setup with the Zurich Instruments MFIA and the Quantum Design PPMS DynaCool.*

Acquisition of Capacitance Transients with Lock-In Detection Technology

The MFIA 500 kHz / 5 MHz Impedance Analyzer measures impedance based on the lock-in detection technique – i.e., the complex impedance is determined by simultaneous phase-sensitive voltage and current measured at the DUT. The MFIA operates over a frequency range from 1 mHz to 500 kHz (up to 5 MHz as optional upgrade) and covers an impedance range from 1 mΩ to 1 TΩ with either two-terminal or four-terminal configurations possible.

In addition to the DUT, every other component in the electrical current path (i.e. cabling) contributes a parasitic impedance which needs to be compensated for in order to ensure an accurate measurement. For this purpose, the MFIA offers a user compensation functionality to perform short-open-load compensation.

Once the parasitic fraction is removed, the raw data i.e., real and imaginary parts of impedance and the corresponding phase, can be transformed to capacitance, resistance, inductance, loss tangent, conductivity etc., by using a suitable equivalent circuit model. The MFIA instrument control software, LabOne offers 8 built-in models with 2 circuit elements. Furthermore, it is possible to export the data into third party software for complex equivalent circuit modeling. For this Application Note the GaAs Schottky diode was modeled as a capacitor and resistor in parallel C ‖ R.

Figure 2 illustrates the schematic 2-terminal setup: the device under test was driven by a sinusoidal signal voltage of 300 mV (V_{test}) from the signal output H_{CUR}, while the current was measured with the signal input L_{CUR}. To keep the GaAs Schottky diode under reverse bias condition, an internal DC offset of -5 V (V_{DC}) was added to the test signal at signal output.

To apply the necessary filling pulses, the MFIA itself can produce rectangular pulses with a definable voltage offset and amplitude of up to ±10 V. In this Application Note, a pulse with an amplitude of -0.5 V (V_p) was generated with the **Auxiliary Output 1** channel and was fed into the **Auxiliary Input 1** channel of the MFIA front panel, and then internally added to the AC test signal.

DLTS transients were acquired at 1 MHz for this demonstration. The resulting transients normalized to its geometric value can be seen in Figure 4 (A). We optimized the acquisition by selecting a suitable number of transients to average.

Detecting electronic traps usually requires high temporal resolution to capture fast transients. The MFIA can transfer impedance data at a continuous rate of 107 kSa/s, which corresponds to a temporal resolution of 9.3 µs. For cases where even higher temporal resolution is required, the resolution can be increased up to 1.1 µs by implementing gated data transfer.

In contrast, a slow process such as atomic defect migration requires longer transient acquisition. By adjusting the data transfer rate, the data acquisition can be optimized to obtain the transients with good temporal resolution while avoiding unnecessarily large data sets. For additional guidance regarding optimizing measurement parameters using the MFIA for DLTS, reach out directly to your local Zurich Instruments application specialist.

Temperature Control with PPMS DynaCool

The Physical Property Measurement System PPMS DynaCool is a cryogen-free measurement platform with a sample temperature range of 1.8 K to 400 K. Figure 1 shows an image of the PPMS DynaCool with the cryostat on the left and the cabinet placed on the right.

The cryogenic system includes an integrated pulse tube cooler and an external compressor. The cooler is connected to the magnet and the temperature control system by a solid thermal connection and therefore uses only a small amount of helium in a closed loop to control the temperature of the sample chamber. The sample temperature control is designed so that helium gas of a defined temperature flows around the sample chamber wall, which then sets the temperature at the sample area. The sample chamber pressure in the PPMS DynaCool is independently controlled. The result is a very stable sample temperature with fluctuations of only a few millikelvins for the cryogenic temperature regime. In addition, very smooth temperature sweeps can be obtained without impact from the transition points of helium.

All aspects of the cryostat system such as sample temperature or sample chamber pressure are controlled by the software MultiVu, and no manual operator intervention is required. The system is available with either ±9 T, ±12 T and ±14 T, superconducting solenoids. The system can be equipped with several off-the-shelf measurement options for a wide range of material characterizations such as magnetic, electrical, or thermal properties within the full temperature and magnetic field range of the system.

In addition to these "plug and play" measurements, the PPMS DynaCool can also be used as a versatile cryostat in combination with third party measurement equipment. A suite of customizable multifunction probes (MFPs) enable such third party measurements.

A modified model D450A MFP was used as an insert to enable high frequency (1 MHz) measurements. Cryogenic coaxial cables were integrated into the D450A MFP. Figure 3 shows the lower part of the MFP with the GaAs sample mounted on the platform.

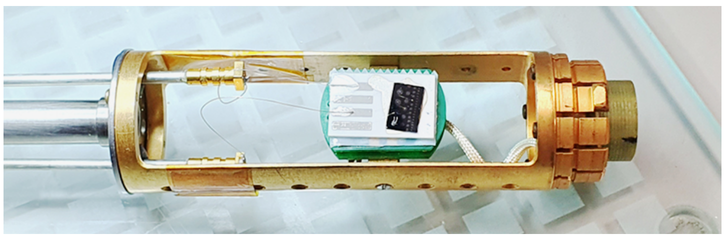


Figure 3: *Multi-functional probe with GaAs sample.*

The sample temperature was manually set and stabilized for each measurement. However, for future DLTS measurements with the MFIA, software embedding could be considered. Both MFIA and PPMS DynaCool can be controlled by using application programming interfaces such as LabView or Python.

Analysis of Capacitance Transients

Deep-level transient spectroscopy utilizes a short rectangular pulse added on top of the small sinusoidal test signal. Initially, when no rectangular voltage pulse is applied the device capacitance corresponds to its geometric value under equilibrium condition C_0.

Depending on the type of the defect, a voltage pulse will lead to either a rise or a fall in capacitance compared to its equilibrium value causing a capacitance step ΔC. After the pulse, the relaxation of defects back to the initial equilibrium condition is observed as capacitance transient

$$C(t) = C_0 \pm \Delta C \exp\left(\frac{-t}{\tau}\right).$$

The time constant τ represents the emission rates of the defects. By collecting these time constants as a function of temperature, the respective activation energy of the defects can be obtained. The sign of the transient is used to identify the charge type of the defects. However, each transient may contain contributions of more than one defect. Therefore, the transients are analyzed with the help of the double boxcar method, where the response of different defects can be separated.

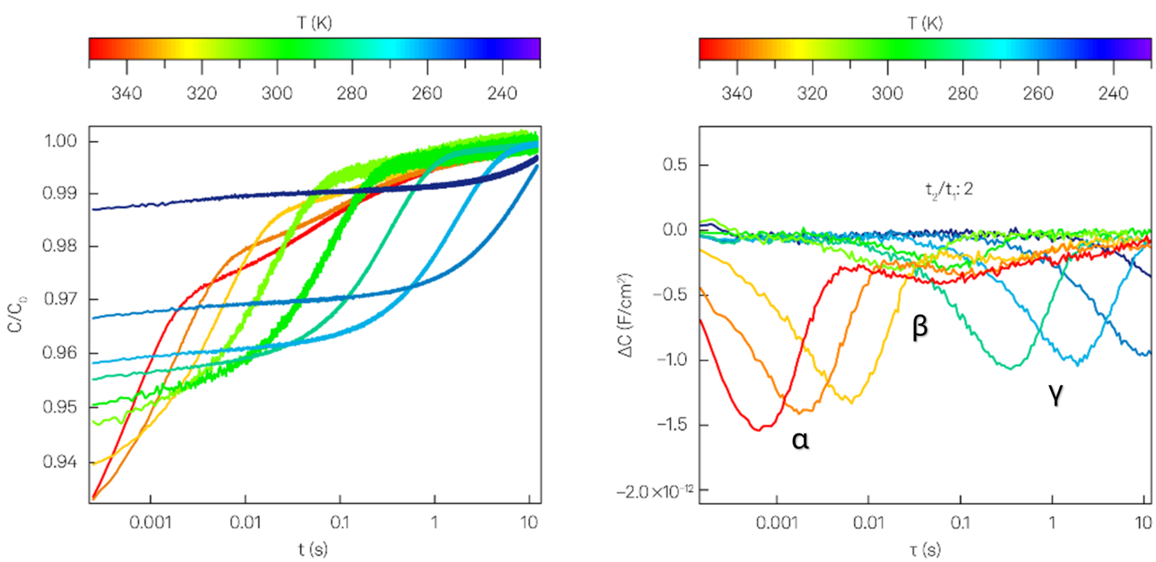
The boxcar signal is the capacitance difference between two time steps, normalized to its geometric capacitance,

$$Boxcar = \frac{C(t_2) - C(t_1)}{C_0}.$$

The ratio of the two times $\frac{t_2}{t_1}$, also called the rate window, is kept constant while the boxcar signal is evaluated by varying the time t_1. This allows us to define a time constant τ_{Boxcar} as

$$\tau_{Boxcar} = \frac{t_2 - t_1}{\ln[\frac{t_2}{t_1}]}.$$

At a given rate window, the boxcar signal shows a maximum at a time constant τ. This time constant at maximum value of boxcar signal corresponds to the emission rate ($1/\tau$) of a particular defect **[3]**.



(A) **(B)**

Figure 4: *Capacitance transients of GaAs Schottky diode at different temperatures **(A)** and respective double boxcar at a rate window $t_2/t_1 = 2$ **(B)**.*

As can be seen in Figure 4 (B) we observe three distinct defects at different timescales α, β and γ. The position of the boxcar peak maxima corresponds to the characteristic time constants. By plotting the inverse of these time constants as function of temperature, a so called Arrhenius diagram can be obtained. The corresponding slopes will lead to activation energy of the defect while the change in capacitance ΔC is proportional to defect concentration **[4]**.

Additional DLTS Modes and Defect Characterization Methods

In addition to the capacitance DLTS as described in this Application Note, complementary information about defects can be obtained from current DLTS, optical DLTS, and impedance spectroscopy. The MFIA can be used for all of these techniques, offering comprehensive defect analysis with a single instrument.

For current DLTS, a current transient is measured while the sample is excited with the same voltage pulse. Fast migration rates can therefore be better evaluated with current DLTS. However, the information about the charge type is lost using this method.

Optical DLTS, an optical pulse e.g. from a laser diode is used to excite the sample instead of a voltage pulse. The light pulse also changes the internal electrical field through the formation of photo-generated charge carriers. The MFIA can be used to control the light source controller and can capture the current transient along with the capacitance transient simultaneously.

Complementary to DLTS, impedance spectroscopy (or dielectric spectroscopy) is one of the most common and powerful tools for the investigation of defects in materials. By applying an alternating electric field, the complex permittivity can be obtained. The dielectric response of a material consists of different micro and macroscopic contributions. After removal of the electric field, each of these processes decays with its characteristic time constant τ.

The MFIA can be used for impedance spectroscopy over a wide frequency range 1 mHz to 5 MHz. Therefore, the time constants can be identified in the dielectric spectrum and can be studied as function of temperature to obtain the defect parameters.

In addition to defect characterization, the combination of the MFIA and the PPMS DynaCool can also be used for other material characterization techniques such as quantum transport measurements, Hall-effect , AC susceptibility.

Conclusion and Outlook

In this application note, we have demonstrated DLTS measurements with the Zurich Instruments MFIA Impedance Analyzer and the PPMS DynaCool measurement system from Quantum Design. The DLTS measurements were performed on a GaAs Schottky diode over the temperature range 350-230 K. The measured capacitive transients are analyzed for defect characterization.

Acknowledgements

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References

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[2] Heiser, T. and Mesli, A. (1993). Determination of the copper diffusion coefficient in silicon from transient ion-drift. *Appl. Phys. 57*, 325-328.

[3] Tammireddy, S. (2024). Study of ionic defects and hysteresis in perovskite solar cells. *Technische Universität Chemnitz*(https://nbn-resolving.org/urn:nbn:de:bsz:ch1-qucosa2-938328).

[4] See reference **[1]**.