Application Note
MTSAP3

An Introduction to the Solartron ModuLab MTS Platform for the Characterization of Semiconductors including I-V, Pulse I-V, C-V and Impedance/Admittance

1) Introduction

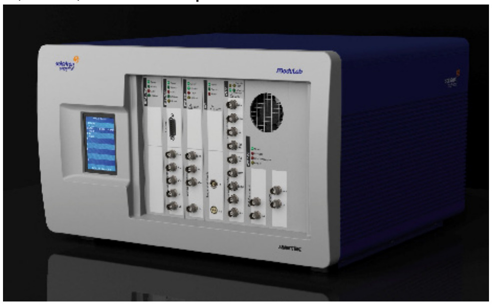
Semiconductor materials continue to receive much interest in the academic and industrial community as the requirements for more efficient devices and new applications arise. Electrical characterization offers a powerful, non-destructive means to determine many important properties of semiconductor materials and devices such as dopant density and dopant profiling, electron-hole recombination kinetics, identification of mobility carriers and oxide electrical integrity.

This application note describes some of the electrical characterization methods and techniques that are available with the ModuLab MTS instrument including time domain techniques (I-V and pulse characterization) and frequency domain methods such as impedance/admittance and C-V analysis. A range of semiconductor materials and devices were used to generate the results including polycrystalline solar cells, OLED's, diodes and MOSFET's.

2) ModuLab MTS

The ModuLab MTS platform is a modular plug and play module instrument that allows the semiconductor research scientist to build measurement capability depending upon the techniques and AC/DC levels applicable for each measurement. The system be configured to apply and measure time domain signals, AC Impedance or a combination of both. Until now scientists often had to purchase mulitple instruments for their measurements such as Impedance analyzers for wide bandwidth measurements and semiconductor parameter analyzers for I-V and C-V measurements. ModuLab MTS was designed to offer the greatest degree of flexibility of measurement in **one** instrument thus reducing cost of ownership AND offering a fully integrated hardware/software solution for ease of use. Key highlights include;

- Wide frequency, 1 MHz to 10 μHz C-V and impedance measurements
- μV's to 100 V bias voltage capability allowing impedance, C-V, I-V and pulse characterization across a wide DC offset range
- Ability to measure 20V/2A with addition of option module expanding Impedance, I-V and pulse characterization capability for power devices
- High resolution, high accuracy femto-ammeter option for leakage current tests and high impedance samples
- Sample/Reference module for improved accuracy of measurement of dielectric materials



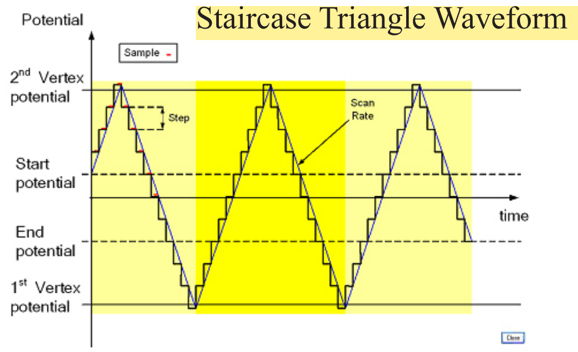
The tables below briefly summarize the measurement capability for time domain (DC) and frequency domain measurements (C-V, Impedance) assuming that all option modules are fitted

DC Technique	Min/Max Voltage	Min/Max Current	Max Scan rate / Pulse Duration	Data Acquisition
I-V (linear, staircase, triangle waveforms)	1 µV / 100V	150 aA (resolution) / 2 A	1.8 MV s^{-1}	1 Million Samples s^{-1}
Pulse (normal and differential modes)	1 µV / 100V	150 aA (resolution) / 2 A	1 µs	1 Million Samples s^{-1}
AC Technique	**Min/Max DC offset Voltage**	**Min/Max Impedance**	**Frequency Range**	**Techniques**
C-V (linear, staircase, triangle waveforms)	1 µV / 100V	< 100 µOhm to >100 TOhm	10 µHz to 1MHz	Single Frequency, Single Sine and Multisine/FFT
Impedance/ Admittance	1 µV / 100V	< 100 µOhm to >100 TOhm	10 µHz to 1MHz	Single Frequency, Single Sine and Multisine/FFT

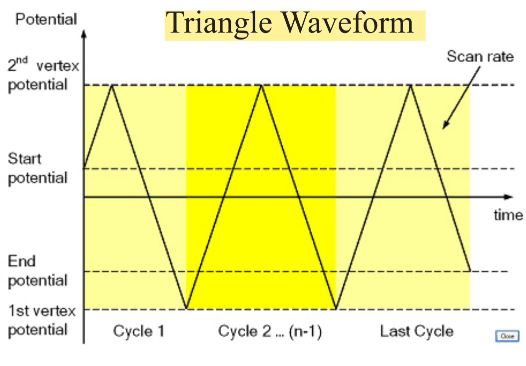
Often not all of these specifications are required for all applications. Since the MTS is modular, a system can be configured to suit the measurement requirements of the device under test. As requirements change, modules can be added at a later date. The software was designed to operate with all possible module configurations. Thus integration of measurement capability (hardware) and measurement techniques (software) is performed automatically in the control software.

3) Time Domain (DC) Techniques

The MTS software has a number of voltage controlled time domain techniques that allow precise control of the applied voltage as a function of time. Some of these techniques are illustrated in Figure 1. The ability to apply triangular waves is particularly useful for characterization of devices in which hysteresis effects are observed such as the charge trapping mechanism in OLED's. This is illustrated in Figure 2 in which the I-V characteristics of the cell were monitored as a function of scan direction and scan rate.



Figures 1 a,b Description of a Triangle Voltage Waveforms (linear and staircase) for I-V characterization.



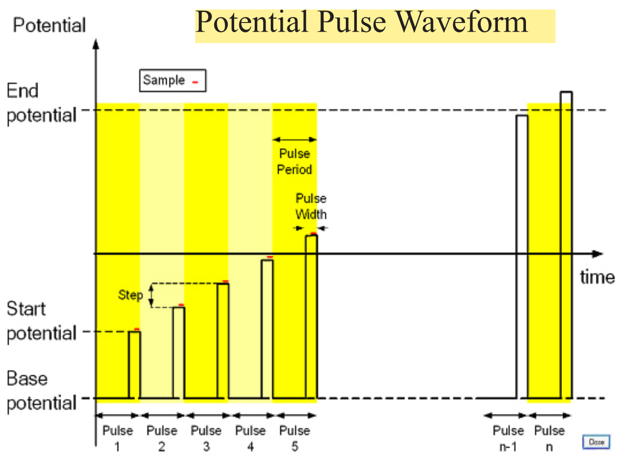


Figure 1 c Description of Potential Pulse Waveform. Normal, Differential and Square Wave options included

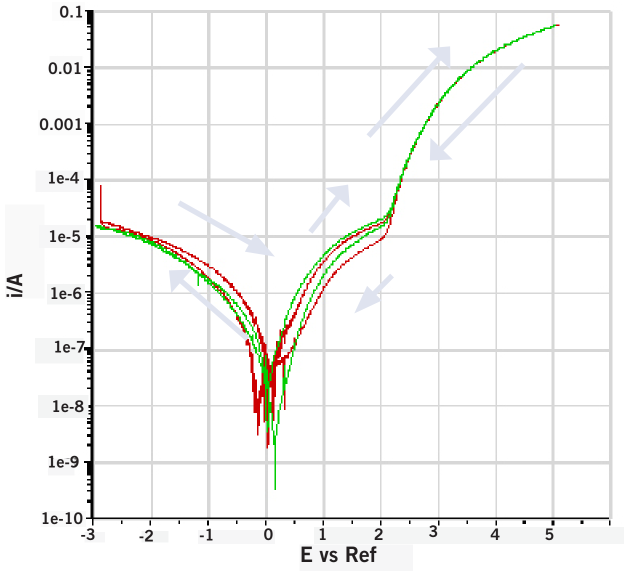


Figure 2: I-V curve of an OLED pixel as a function of scan direction (indicated by arrows) and scan speed. Green line = 100 mV s^{-1}, red line = 300mV s^{-1}. Hysteresis indicative of charge trapping

A number of features are included in the Solartron software that allow the user to precisely control the applied waveform to the cell (refer to Figure 1). Highlights of these features include;

- Ability to apply linear and triangular voltage waveforms. Some cells exhibit a dependency on the sweep direction and this can be determined by cycling the voltage in both the forward and reverse directions (see Figure 2).
- Staircase voltage ramps techniques allowing users to look at the step delay response of the cell. The user can define where the current is sampled on the step.
- Pulse potential techniques with ability to define pulse height and pulse width. This can be used to understand the dynamic response of the device under rapid changes in load.

The MTS platform can be configured to measure extremely low currents with the addition of the femto-ammeter module (current resolution of 150 aA). Low current measurements are important for a number of applications including leakage current measurements of solar cells and diodes, (see application note MTSAP1 for more details) and low frequency C-V measurements of MOSFET's and MOS capacitors.

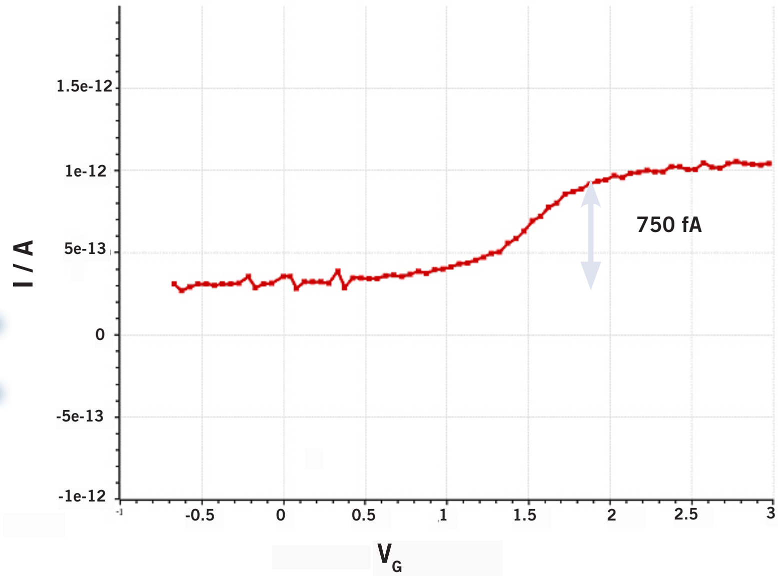


Figure 3: I-V curve of a 3N701 MOSFET device (gate to drain/source). This experiment demonstrates excellent stability and resolution of the femto-ammeter module. Note the magnitude of change from inversion to depletion of approximately 750 fA

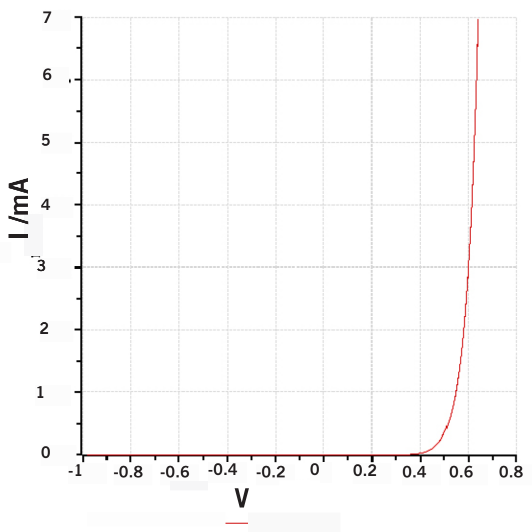


Figure 4: I-V curve of a diode operated in forward bias

Leakage current measurements of devices are performed in reverse bias mode. A typical reverse bias scan for a polycrystalline solar cell is shown in Figure 5. In this instance, the current sensitivity of the MAT core module was sufficient for leakage measurements of the device. However, leakage currents can often be in the order of pA's and even fA's for small devices. With the addition of the femto-ammeter option module, the measurement range of the MTS can be extended to 0.15 fA resolution (see Figure 3 for indication of sensitivity and stability of this option module). Furthermore, all techniques are still supported with this module including C-V, I-V, pulse and impedance.

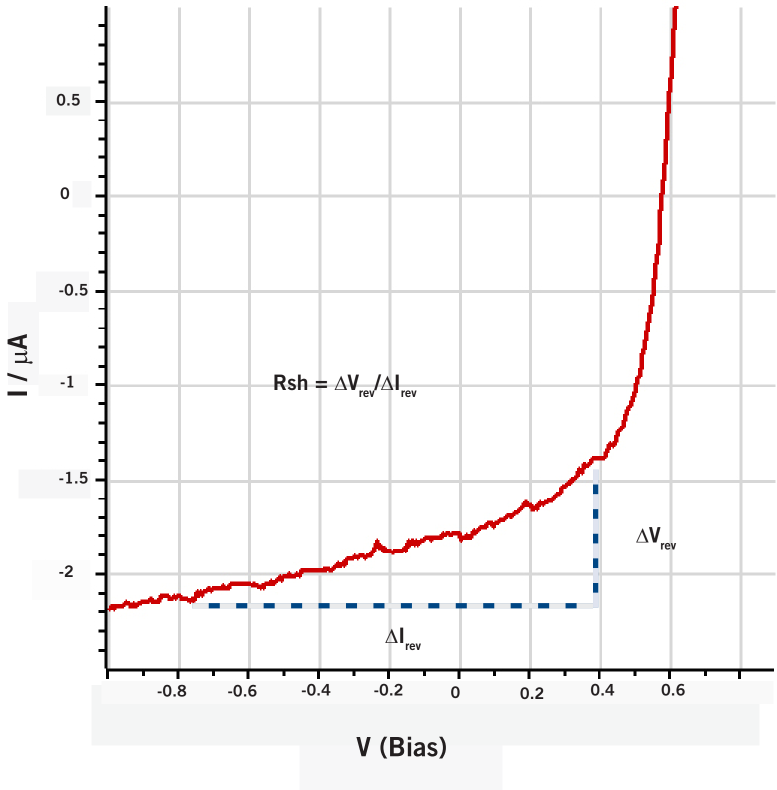


Figure 5: Reverse Bias characteristics of an 18 V PV cell indicating method of calculating the shunt resistance. Analysis can be performed in software with regression tool. Note that for very low leakage current devices, Solartron systems have options to increase current resolution down to 0.15 fA.

Quasi-static low frequency C-V measurements are important for determining the density of interface traps. This is normally performed using a voltage ramp technique since the current is proportional to the capacitance if the ramp rate is sufficiently slow. The MTS ramp generator has the ability to apply very slow ramps below 1mV s^{-1} making it an ideal instrument for low frequency C-V measurements.

4) C-V Characterization

The carrier density is related to resistivity and this property is usually measured using a Capacitance - Voltage technique (C-V). For many devices such as MOSFETS and MOS capacitors, the capacitance changes as a function of applied DC voltage.

A C-V (green) and Mott-Schottky plot (red) of a MOSFET device (3N701) is presented in Figure 6.

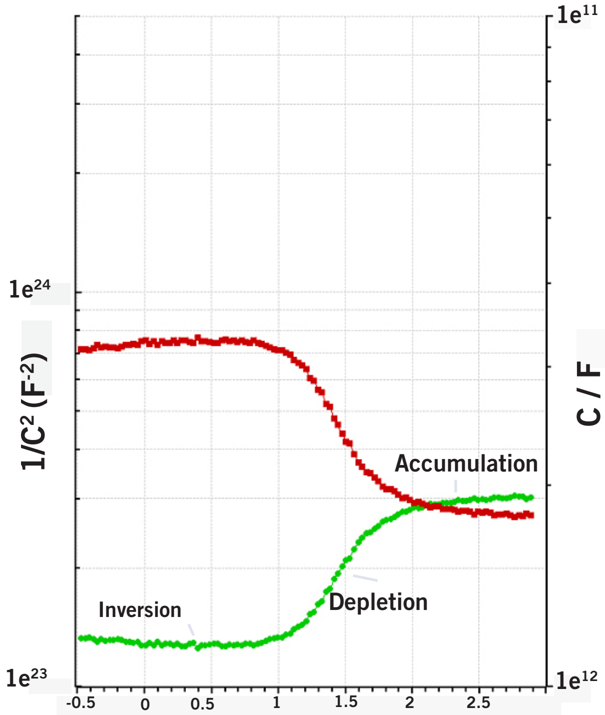


Figure 6: C-V and Mott-Schottky plots ($1/C^2$ vs V) of a 3N701 MOSFET. Stimulus frequency = 100kHz, AC level = 10mV

For an n-type device, the capacitance passes through three regions; inversion, depletion and accumulation (green curve Figure 6). In brief,

- Accumulation: when a positive voltage is applied between the gate and drain/source, electrons accumulate in the valence band at the oxide - semiconductor interface. The capacitance is essentially constant in this region and can be used to determine the oxide thickness
- Depletion: As the voltage is swept to a negative bias, the majority carriers are depleted at the oxide/semiconductor interface. This region of the device acts as a dielectric
- Inversion: Beyond the threshold voltage, minority carriers accumulate at the interface

There are several techniques available in the ModuLab MTS software that allow one to measure the C-V characteristics of the material including linear ramp voltage, stepped voltage and triangle voltage waveforms. A typical stepped voltage experiment with a superimposed AC sine wave is presented in Figure 7. The user has the option to define the step height and width, frequency of AC stimulus and amplitude. Figure 7 shows a low frequency AC stimulus for the sake of clarity. A unique feature of the MTS C-V techniques is the ability to measure both the high and low frequency capacitance without changing the hardware configuration. Whether one chooses to use the I-V or C-V method to measure the low frequency quasi static capacitance, both techniques are supported in a single instrument.

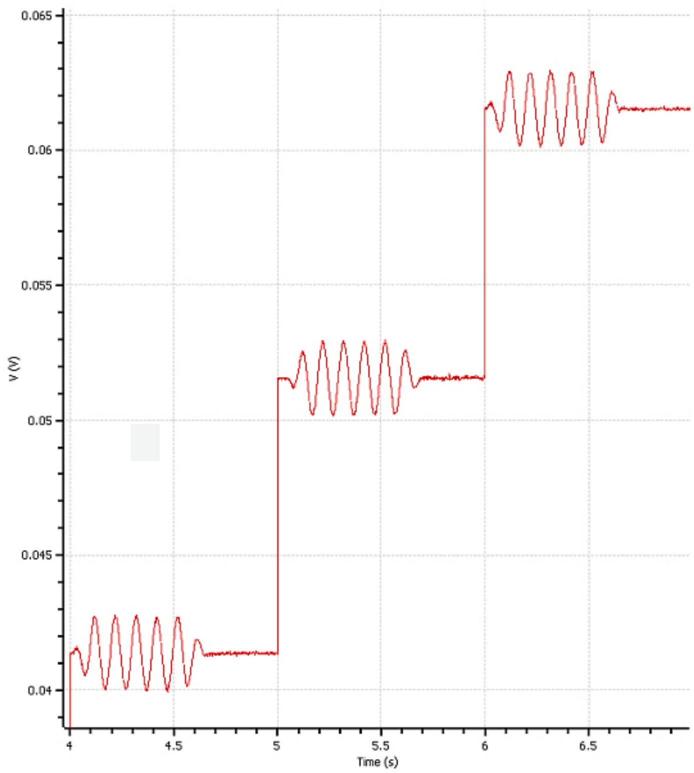


Figure 7: AC stimulus level superimposed upon stepped voltage level.

Figure 8: Control settings for linear sweep C-V experiments.

Figure 8 shows a set-up screen for control of the applied waveform. In addition to the control of the voltage, sweep rate and AC stimulus levels, the software also includes a number of other useful features including the ability to control the integration period of the measurement to optimise both speed and accuracy.

An important feature of C-V measurements is the ability to determine the doping concentration as a function of depth. The analysis of the data is covered in detail elsewhere. In brief, this analysis is accurate only in depletion and therefore care must be taken in the interpretation of the C-V and $1/C^2$ - V plots. An understanding of these limitations and correct analysis of data can yield the depth profile using some simple calculations. For each bias voltage, one needs to compute the depletion thickness from,

$$\omega(V_G) = \varepsilon_{Si}\left(\frac{1}{C_{HF}} - \frac{1}{C_{ox}}\right) \qquad (1)$$

where $\omega(V_G)$ is the depletion thickness, ε_{Si} is the permittivity of Silicon, C_{HF} and C_{ox} are the high frequency and oxide capacitance respectively. The doping concentration, $n(V_G)$ is given by the slope of the Mott-Schottly ($1/C^2$-V) plot vs. V_G given by,

$$N_c(W) = \frac{2}{qK_s\varepsilon_0 A^2\left[\frac{d\left(1/C^2\right)}{dV}\right]} \qquad (2)$$

where N_c (W) is the charge density, q is the charge on an electron, Ks is the relative permittivity of the substrate, A is the surface area, ε_0 is the permittivity of free space. A typical Carrier Density - Depth profile is shown in Figure 9

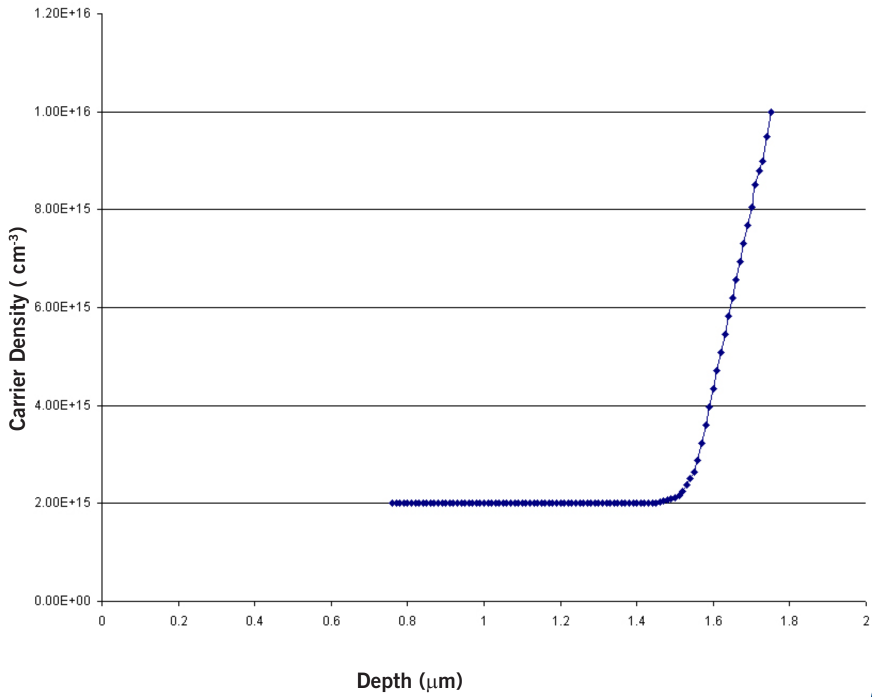


Figure 9: Typical Carrier Density -Depth profile of a metal oxide structure computed from equations 1 and 2.

In summary, the key features of the MTS platform for C-V measurements include;

- Ability to measure C-V profiles from ± 100 V DC (with hardware options),
- User can define AC stimulus level and frequency (from 10 μHz to 1MHz) that is suitable for the device under test. In addition to impedance magnitude, phase is measured to verify that results are capacitive in nature i.e. $\theta \sim 90°$. Furthermore, the ability to vary the AC stimulus level can be used to derive the drive-level capacitance profile (DLCP). DLCP experiments can be automated in software.
- Choice of linear or staircase ramp techniques with user defined ramp rates.

5) Characterization using Wide Bandwidth Impedance/Admittance spectroscopy

Impedance measurements of solar cells are performed over a wide range of frequencies which typically cover 1 MHz to < 0.1Hz. This technique has received considerable attention within the academic community. It has helped researchers build equivalent circuits that represent the processes occurring in solar cell device over 7 decades of frequency. The benefits of this technique include;

- Ability to separate processes in the frequency domain including series resistance, chemical capacitance, recombination resistance and the impedance of blocking electrode contacts
- All parameters can be determined in a single experiment
- Data can be analyzed using equivalent circuit analysis and processes are represented by simple passive circuit elements. Such models are used to quickly determine the processes that limit the performance of the device.

An example of a wide spectrum impedance sweep of a solar cell under illumination at varying drive voltages is presented in Figure 10.

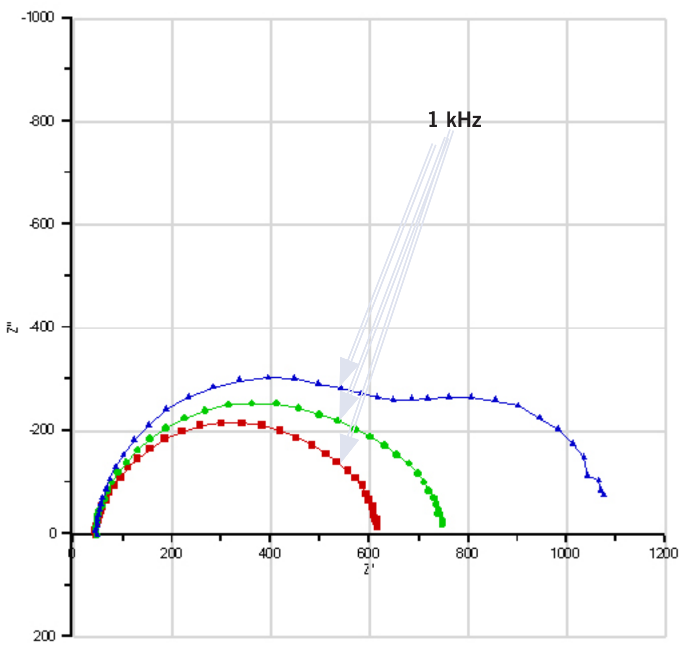


Figure 10: Nyquist / Cole-Cole diagrams of a solid-state solar cell under varying DC bias (note this experiment was performed under illumination). AC stimulus level was 100 mV.

In this example, the impedance is presented in the Nyquist or Cole-Cole format in which the imaginary and real impedances are plotted at discrete excitation frequencies. The frequency was swept from 200 kHz to 20 Hz using Solartron's Single Sine Correlation technique. For many cells, it is necessary to sweep the frequency below 1 Hz as important information about the inductive behaviour of cells is contained in the region of approximately 100 Hz to 10 mHz. In this particular example, inductive behaviour was not observed at low frequencies.

There are a number of alternative methods of presenting the impedance data which are supported in Solartron software including, Bode (Impedance, Phase vs. Frequency), complex capacitance and permittivity vs. Frequency, AC voltage and AC current vs. frequency. The use of these methods of data presentation are presented elsewhere in the literature but all have been shown to be useful in the development of our understanding of the fundamental electrical properties of the solar cell.

Some interesting observations are made with the example presented in Figure 10. As the bias voltage approached the inversion region for the device , the impedance spectrum clearly shows the presence of two time constants (indicated by two semi-circle arcs at V = 1.0V). The presence of the low frequency arc (freq <1 kHz) possibly reflects the influence of the recombination impedance upon the operation of the device at low drive voltages. As the drive voltage increased, the influence of this process became less pronounced. However, this information does allow the engineer to understand and characterise the efficiency of the current collecting materials and the recombination kinetics within the cell and make the necessary improvements.

Several equivalent circuit models have been proposed in the literature that represent the underlying processes within solar cells. Equivalent circuit analysis is offered with Solartron software and a generalised circuit that was created within the software is shown in Figure 11. A number of simple and distributed elements are available which have been developed to model many physical processes such as Warburg and Gerischer elements. However, for the purposes of this exercise, the model only contains simple resistors and capacitors. The user has the option to model the frequency dependence of the impedance of the circuit in simulation or fitting mode. The simulation mode is a useful tool for the scientist to evaluate if the proposed circuit accurately models the impedance behaviour of the real device. In fitting mode, the values of the components are adjusted to fit the real data.

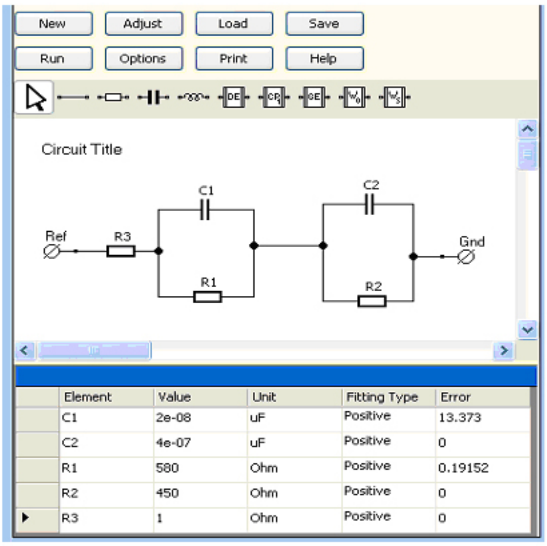


Figure 11: Equivalent Circuit Modeling tool. Elements can be selected from a drag and drop menu. The circuit shown in this figure was used to model the impedance response of the solar cell from 200 kHz to 100 Hz.

An example of the comparison between theory and experiment is shown in Figure 12. There is reasonable agreement between the model and the real data although improvements to the model will improve the relationship between theory and experimental data. The model assumes a recombination resistance and chemical capacitance (R_1 and C_1) and contact parameters (R_2 and C_2). At high drive voltages, the time constants are similar (the relationship R_1C_1/R_2C_2 » 1 is valid) and therefore the impedance plot shows apparently one time constant. This condition is not met when the drive voltage approaches the inversion region where $R_2C_2 << R_1C_1$. This might indicate that recombination kinetics dominate the performance of the cell within this region although further experimentation would be required to validate this assumption.

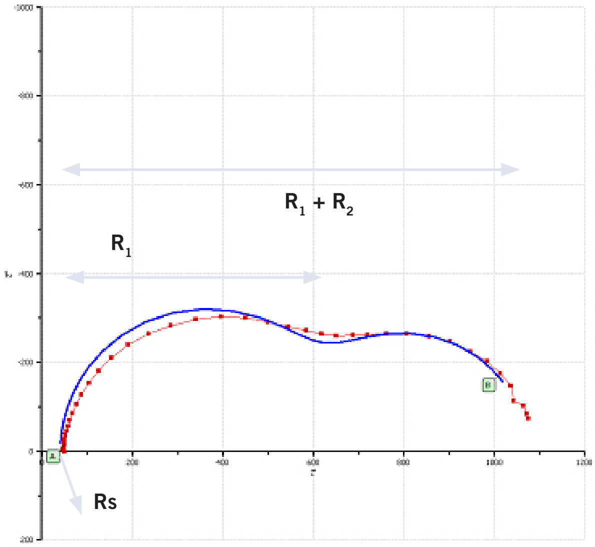
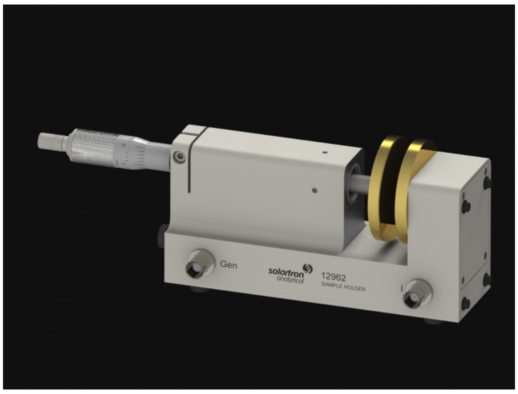


Figure 12: Comparison between the theoretical impedance response of the circuit shown in Figure 11 (blue line) vs. the real cell response (red line and dots). There is reasonable agreement between theory and experiment. The impedance values of R_1(contact) and R_2 (recombination) are shown on the plot. In addition, the series resistance Rs can be calculated by determining the impedance at the point in which the high frequency measurement intercepts the real (Z') axis.

6) Miscellaneous Techniques and Measurement Possibilites with the MTS

6.1 Temperature Control

Solartron has a range of temperature control systems including a cryostat (He and liquid Nitrogen) for low temperature studies and high temperature furnaces. Control of these devices is performed in the software for ease of use. A range of low and high temperature sample holders are available. The use of temperature control is particularly useful for techniques such as Deep Layer Transient Spectroscopy (DLTS)



Room Temperature Sample holder for thin film measurements

Cryostat Available from Solartron. Key benefits include:

- wide temperture operation from 5K to 600K (liquid He cryogen)
- 2 and 4 terminal testing for low and high impedance devices
- Ability to switch between N_2 and He operation
- Sample holder available
- Unlike other systems, the sample is contained in an exchange gas to protect sample from swelling or cracking thus improving accuracy and repeatability of measurements

6.2 Other Measurement Techniques

Since the the options modules were designed to work with one another, this offers the possibility to perform many other types of measurement including;

- Noise Measurements: although complicated to perform, these measurements can yield information about the system that is not readily available with bulk techniques such as I-V curve analysis. The sensitivity of the femto-ammeter option coupled with the resolution of the voltage measurement device could open opportunities for the application of the MTS system in this research
- Deep Level Transient Spectrocopy (DLTS) : this technique is used to detemine defect levels within the semiconductor and is usually performed from low to high temperatures (<80K T > 400K). A number of pulse techniques were discussed earlier in this note and these could be used to stimulate the device. Furthermore, the software can acquire data before, during and after the pulse and this forms the basis of the technique
- The MTS card can also be configured to include auxilary voltage measurements and are useful for recording external devices such as photomultiplier tubes for photoelectron studies and electroluminescence
- Electrochemical C-V Profiling: Solartron offers a module specifically designed to control electrochemical cells and this is useful for electrochemcial profiling and etching of samples to determing dopant density.

Conclusion

This technical note described how the Solartron ModuLab MTS instrument can be used to characterize the electrical properties of a semiconductors. Common techniques such as I-V, C-V and Impedance/Admittance spectroscopy were shown to yield valuable information regarding the devices under test. The software solutions allow researchers to quickly combine DC and AC measurements and control complex experiments without the need to develop their own test programs. The software features are further enhanced with the addition of powerful fitting techniques such as regression analysis and equivalent circuit analysis which are use to model the underlying processes of the materials.

Finally, Solarton offers integrated temperature control instrumentation that further enhances the measurement capablity of the MTS platform.

Recommended Reading:

Semiconductor Material and Device Characterization, Dieter Schroder

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19/03/2010